Life Cycle Analysis of LPG Transportation Fuels under the Californian LCFS

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Terms and Abbreviations

AFV	Alternative Fuel Vehicle
ARB	California Air Resources Board
atm	Atmosphere
Btu	British thermal unit
CA	California
CI	Carbon Intensity
CO	Carbon Monoxide
EPA	Environmental Protection Agency
GHG	Greenhouse gas
GREET	Greenhouse gas, Regulated Emissions and Energy Use in Transportation
GWP	Global Warming Potential
HC	Hydrocarbon
IPCC	International Panel on Climate Change
LCA	Life cycle assessment
LCFS	Low Carbon Fuel Standard
LCI	Life cycle inventory
LHV	Lower heating value
MJ	Mega Joule
ml	Milliliters
mmBtu	Million Btu
NG	Natural gas
NO_x	Oxides of Nitrogen
NREL	National Renewable Energy Laboratory
RFS	Renewable Fuel Standard
S.I.	Spark Ignition
TTW	Tank-to-wheels
U.S.	United States

Executive Summary

This study examines the total greenhouse gas (GHG) emissions associated with liquefied petroleum gas (LPG) production, refining, and end use, in both the U.S. and California. LPG is a co-product of crude oil refining and natural gas liquids processing. Additionally, a renewable form of LPG, called bio-LPG[1] is co-produced with many renewable biogas and biomass production processes. The goal of this study is to develop the best estimate of LPG lifecycle GHG emissions and provide recommendations for the appropriate treatment of LPG in future fuel LCA studies.

The full fuel cycle emissions from LPG and other transportation fuels are examined in Well-To-Wheel (WTW) models such as the Greenhouse gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), developed by Argonne National Laboratory (ANL). Specialized regional versions of GREET are also used as certification tools for low carbon fuel policies. The regional GREET model for use in California is called CA_GREET. The CA_GREET model provides that basis for the analyses in this study and the results are compared to other WTW model results.

The WTW fuel pathways in GREET are broken into two phases, the Tank-To Wheel (TTW), and the Well-to-Tank (WTT) phase. The WTT phase includes upstream fuel cycle emissions such as the production of the feedstock, transport to a refinery/processing plant, fuel refining/ processing as well as transport and distribution of the finished fuel. The TTW emissions are the end use (combustion) emissions of the fuel. The GHG emissions are expressed in grams of carbon dioxide equivalent per megajoule of fuel (g CO_2e/MJ).

Figure S.1 shows the comparative GHG emissions from LPG based on the analysis and methods outlined in this study, alongside California Reformulated Blendstock for Oxygenate Blending (CARBOB) and Federal RBOB. CARBOB is the gasoline blend stock that is blended with ethanol in California reformulated gasoline.

The results presented in Figure S.1 show that on a life cycle basis, LPG-fueled vehicles emit about 20% lower GHG emissions compared to conventional California gasoline-fueled vehicles. Emissions from bio-propane propane from tallow are approximately 70% lower than conventional fuels with the same carbon intensity as co-produced renewable diesel. These results include reductions in emissions from both the TTW phase and the WTT phase as outlined below:

- Reduced TTW emissions: The reduced carbon content (g C/MJ fuel) of LPG compared to gasoline and/or diesel fuel
- Reduced WTT emissions: Reduced upstream refining energy for LPG compared to gasoline and diesel fuel

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[1] Feedstocks such as used cooking oil (UCO), tallow, soy, canola, etc. are used to produce renewable diesel. Biomass is also a feedstock for renewable Fischer-Tropsch (FT) diesel. Renewable LPG or Bio-LPG is a co-product of the renewable or FT diesel process.

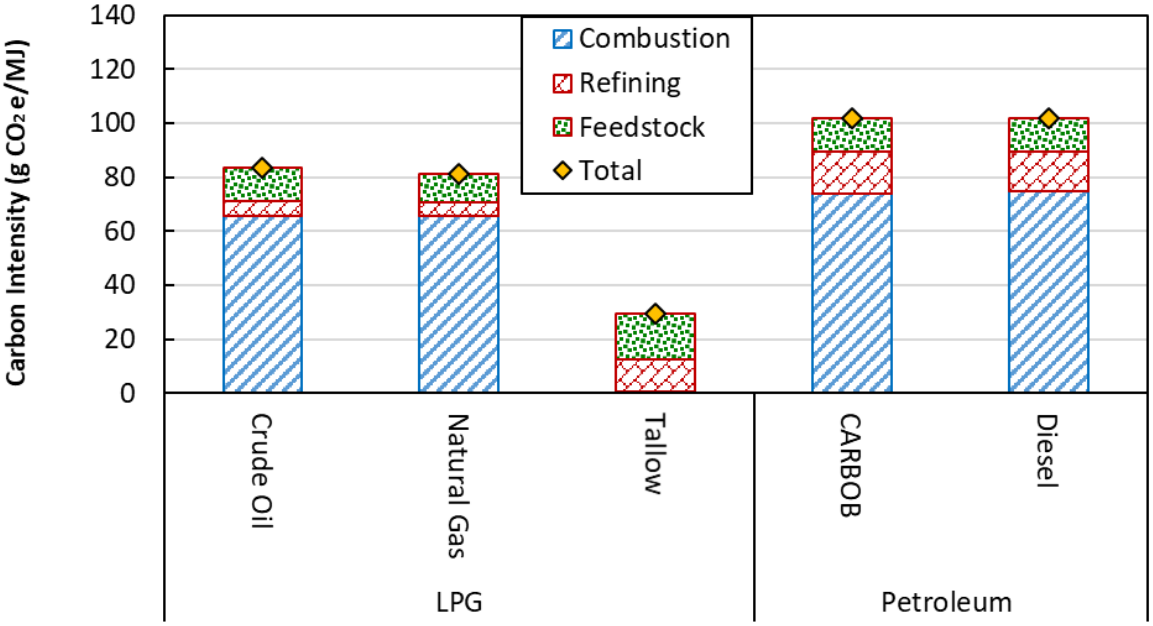

Figure S.1. Comparison of WTW Emissions from LPG analyzed using CA_GREET3.0.

The TTW emissions occur when the carbon in the fuel is converted into CO_2 via combustion. Since LPG has a lower carbon content than both gasoline and diesel, the TTW emissions are correspondingly lower.

The WTT inputs are based on the set of direct upstream inputs. In the case of LPG derived from crude oil, the default CA_GREET model inputs for refining energy assume that LPG production is a co-product of crude oil refining and the refining efficiency is only slightly higher for LPG than for gasoline. However, the majority of refinery LPG produced derives from the intense processing of long chain hydrocarbons into high value products, such as gasoline, diesel, etc. The refinery processes are designed to make these higher value primary products, and the refinery configuration is focused on maximizing yields. More intensive refining results in higher emissions. Assigning these emissions to primary fuels rather than co-products like LPG reflects the intended use of refinery units such as hydrocrackers. Because LPG is not an intended product, the environmental impacts of primary products such as hydrocracker diesel should be assigned to the gasoline and diesel blending components produced from these units. This study assigns the refinery unit operation emissions to the intended product, and treats LPG as the incidental co-product, resulting in lower GHG emissions assigned to LPG.

For LPG produced as a co-product of natural gas processing, the CA_GREET inputs for processing efficiency indicate that LPG processing is slightly less efficient than the conversion of raw natural gas to pipeline quality natural gas. This treatment reflects the fact that processing and separation of the natural gas liquids into the separate components that include LPG requires more energy than separating natural gas into pipeline gas and natural gas liquids.

Bio-LPG will result in an energy co-product that has the same carbon intensity as the primary energy product. This treatment is consistent with the GREET methods for the production of other biofuels. Additionally, since the feedstock is either biogenic, or a waste product, the TTW, or combustion emissions will be zero, since the CO_2 emitted is CO_2 that was either uptaken from the atmosphere during biomass production, or waste CO_2, that would have ended up in the atmosphere regardless of processing into an energy product.

Comparative GHG Emissions

The carbon intensity (CI) results from this study, other GREET model configurations and the EU Fuel Quality Directive are shown in Table S.1 for LPG and petroleum gasoline and diesel.
CI varied with model assumptions.

The base CA_GREET3.0 model results for LPG from petroleum are 89.96 g CO_2e/MJ compared with a gasoline baseline of 100.73 gCO_2e/MJ. The analysis in this study reallocates refinery energy inputs and emissions with a resultant CI of 83.64 gCO_2e/MJ for petroleum LPG. Reassigning the refinery energy intensity to higher value products also leads to an increase in the CI of those products. The CI of gasoline increases to 101.66 gCO_2e/MJ and diesel increases to 101.72 gCO_2e/MJ when the correct upstream emissions for crude oil are taken into account. The revised LPG CI represents an 18% reduction in emissions compared to the gasoline baseline. Additionally, the GHG impact of bio-LPG is approximately 70% lower than conventional fuel blends.

Table S.1. Carbon Intensity results for LPG, Gasoline Blending Component, and Diesel

GREET Model Base[a]	**Data Source**		**LPG**		**Crude Oil**	
		Region	**Petroleum**	**NG**	**CARBOB**[b]	**Diesel**
WTW Carbon Intensity, g CO_2e/MJ)						
CA_3.0	This Study	CA	83.64[b]	81.09	101.66[c]	101.72[b]
1_2016	CA_3.0	CA	88.49	81.09	100.7	100.7
1_2013	CA_2.0	CA	89.93	78.96	99.8	102.0
1_2016	1_2016	US	86.19	81.05	98.8	92.2
1_2014	1_2014	U.S.	84.6	80.2	94.6	89.7
1.8c	OR_GR	OR	76.8	76.1	90.2	91.3
1_2013	WA_GR	WA	93.4	80.6	100.7	101.7
JRC[d]	EU FQD	E.U.	74.5	73.6	93.2	95

[a] The base model represents the original spreadsheet from which the analysis was derived. For example, GREET1_2016 is indicated as "1_2016".

[b] Gasoline blending component for CA_3.0 and this study are for CARBOB. U.S. RBOB results are shown for 1_2016, 1_2014, OR_GR, and WA_GR results.

[c] Crude oil inputs modified such that CA crude matches OPGEE result (CA_GREET2.0, Petroleum!D62 and D70). Some crude oil upstream emissions are counted in the fuel phase in GREET; thus a separate CA Crude column in required in GREET.

[d] EU Commission results from 2014 FQD methodology.

The CA_GREET methodology also provides the basis for a temporary look up CI for bio propane. Using the energy allocation approach, the energy inputs and emissions for bio propane are the same as those for renewable diesel for hydroprocessed oils and fat feedstocks. Using a conservative assumption that propane is made up with natural gas, the CI for bio-propane would be 2.8 g/MJ higher than that of renewable diesel where the propane is burned as process fuel. The CI for bio propane from tallow and vegetable oils would be 35 and 56 g CO_2e/MJ respectively for the 2015 temporary fuel pathway codes.

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1. Introduction

1.1 Liquefied Petroleum Gas

Liquefied Petroleum Gas (LPG) is a co-product of natural gas production and crude oil refining. It is an odorless, non-toxic hydrocarbon gas, consisting of propane, butane, and traces of other light C_2 to C_5 hydrocarbons. LPG is a gas at ambient pressure and temperatures. It is stored in a liquefied state to facilitate transport and storage. Two hundred seventy units of propane vapor condense to one unit of liquid. At 70°F, the pressure in an LPG tank is about 100 psi, depending on composition. For safety reasons LPG is odorized to indicate the presence of the gas in air (DOE, 2015b).

1.2 Objectives

The objective of this study is to examine the GHG emissions associated with LPG transportation fuel. This study reviews the methods and treatment of LPG in the Greenhouse gases, Regulated Emissions and Energy in Transportation (GREET) model and regional variants that are used to assess the GHG impact of transportation fuels. GREET was developed by the Argonne National Laboratory. Variants of the GREET models are used by the U.S. Environmental Protection Agency (EPA), the California Air Resources Board (ARB), the Oregon Department of Environmental Quality (DEQ) and the Washington Department of Ecology (DE). This study aims to develop the best estimate of LPG lifecycle GHG emissions, termed carbon intensity (CI), and provide recommendations for the appropriate treatment of LPG in future fuel LCA studies. The results compare the GREET1 and CA_GREET treatment of LPG as a fuel. This "carbon intensity value" is expressed in terms of grams of CO_2-equivalent per mega joule of energy (g CO_2e/MJ).

The CA_GREET framework provides the basis for calculations. The assumptions used in this study are compared to the range of inputs used over the years in other fuel LCA studies. This provides California-specific detail on GREET inputs including transportation logistics, refinery energy inputs, and bio-propane. The bio-propane inputs provide the basis for a temporary pathway code under the LCFS.

1.3 Low Carbon Fuel Standard

California's low carbon fuel standard (LCFS) is designed to reduce the greenhouse gas emissions from transportation fuels inside California. An executive order was passed in 2007 that called for a reduction in the carbon intensity of California's transportation fuels by 2020 by at least 10%. Carbon intensity is measured in g CO_2e/MJ of fuel and is quantified on a lifecycle basis. The California Air Resources Board (ARB) became responsible for implementing this standard in 2009. The standard was re-adopted in 2015 with a revised set of requirements. The LCFS utilizes a market-based solution to the need to reduce carbon emissions. Regulated parties include all producers of transportation fuel sold in the state. Petroleum refiners who produce gasoline and diesel transportation uses are typically regulated entities. Renewable fuel producers of low carbon intensity products can opt into the system in order to be able to sell carbon credits. Each fuel provider is required to ensure that the carbon intensity of the suite of fuels they produce meets the carbon intensity target for that year. Yearly CI targets are reduced each year until 2020, at which point they should have achieved a 10% reduction. In 2017, the ARB is examining the extension of the regulation to the year 2020 with GHG reduction targets shown in Figure 1.1.

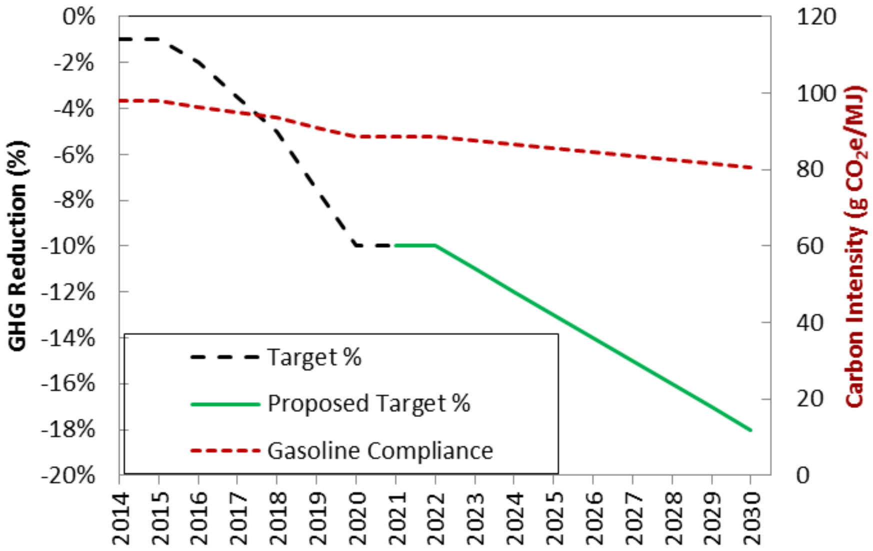

Figure 1.1. LCFS Compliance Curve and Gasoline Compliance Schedule

Also shown is the required CI for fuels that displace gasoline. Fuels with CI values below the gasoline compliance curve are credit generators and fuels with CI above the curve are deficit generators. The actual credit or deficit generation depends on the fuel efficiency of the vehicle fuel/combination as discussed in Section 2.5.

1.4 LPG History

For those with a limited working knowledge of LPG, often the term “liquefied gas” is a self-contradiction. The mystery is easily solved by considering a clear plastic butane lighter. The liquid is butane, an odorless, tasteless, colorless gas, remains a liquid at 20 psi. The strength of the plastic is sufficient to maintain the vapor pressure of the butane. Pressing the small lever of the lighter and holding the device close to the ear (without lighting) reveals a slight hissing sound from the butane passing through the nozzle. By continuing to hold down the lever, bubbles will appear in the liquid. This demonstrates the “boiling” action of the fuel as the butane draws heat from the plastic to aid in its vaporization. So LPG is both a liquid and a gas depending on whether it is subjected to pressure or low temperature at which point it becomes a liquid.

In the 1960s the marketing label for LPG was “The World’s Most Versatile Fuel”. LPG is indeed versatile because it can provide heat, light and power virtually any place on earth because it is portable and has infinite shelf life.

1.4.1 A Brief History of LPG in and Around California

LPG for use in the transportation sector is often termed “LP autogas”. The first known use of LPG for the transportation sector in California was in 1912 when a gasoline powered truck in Long Beach was converted to operate on LPG. The fuel was butane, the storage tank was a riveted cylinder. Butane was the fuel of choice because it has a lower vapor pressure than propane and was easier to work with than the higher vapor pressure propane. Throughout the ensuing 40 years LPG consisted of a mixture of butane and propane since butane had not yet found a new market in gasoline blending. With the demand for butane in gasoline blending, the retail LPG industry switched to the more preferable propane because of its higher vapor pressure at freezing temperatures. For example, butane is a liquid at 30˚F with a vapor pressure below 1 psi while the vapor pressure of propane is 53 psi at the same temperature.

During the 1920s many end use applications developed including refrigeration, lighting, steel cutting, cooking, space heating and drying. In the 1930s the first motor transport trailer for LPG was designed and built by General Petroleum. The 10th summer Olympics (1932) in Los Angeles used LPG to fuel stationary torches, and for heating, and cooking in the Olympic Village. Parkhill-Wade developed the first stationary service station for vehicle sales in the Los Angeles area and city buses began using LPG in larger quantities for fleet fueling.

In the 1940s the Carnation Dairy used butane to power more than 100 medium- and heavy-duty trucks. Hall Scott Motor Car delivered more than 500 heavy-duty trucks fueled with butane. Moline Tractor built the first original equipment manufacturer (OEM) propane farm tractor. A train using butane ran from Los Angeles to Las Vegas. Many small fleets began using LPG as the primary transport fuel.

By the 1950s International Harvester and Reo Motors brought out the first quantity production models to be factory equipped to run on propane. Based on the successful experience in California, Chicago Transit began using butane in its fleet which ultimately came to number more than 800 vehicles. Numerous California cities also began converting fleets from gasoline to butane and propane. During the 1960s multiple end use markets developed including irrigation engines and forklifts. Ford and Chevrolet offered OEM LPG vehicles.

In the 1970s the LPG industry found itself subject to price controls and supply allocations in response to the Middle East crude oil embargoes. These events spurred vehicle conversions from gasoline as lines formed at service stations. The Los Angeles Times converted its entire fleet to LPG and installed a 30,000 gallon storage tank in downtown. Fleets, concerned about gasoline supplies, embarked on wholesale conversions to propane. Conversion shops opened up all over the country, many in California.

1.5 LPG Fuel Properties

Propane (C_3H_8) is the main component of LPG along with small quantities of butane (C_4H_{10}) and propylene (C_3H_6).[2] At atmospheric pressure, propane is a gas, but can be liquefied when subjected to pressures above 100 PSI. Liquefied propane has an energy density 270 times greater than gaseous propane, thereby making it practical and economical to store and transport as a liquid (DOE, 2015b). Table 1.1 shows the properties of CARBOB (gasoline), diesel, and LPG based on data from the CA_GREET2.0 tier 1 model (ARB, 2014b).

Table 1.1 shows the fuel properties of diesel, gasoline and LPG. One gallon of LPG contains approximately 75% and 66% of the energy in one gallon of CARBOB or diesel respectively. The auto-ignition temperature of LPG is higher than that of CARBOB or diesel, providing a lower ignition risk when exposed to hot surfaces. The stoichiometric air-fuel ratio is only slightly higher than CARBOB and diesel. As a liquid, the density of LPG is about 70% and 60% of CARBOB and diesel respectively. The lower heating value of LPG is higher than CARBOB or diesel on a mass basis, but is lower on a volume basis. The octane rating of LPG is higher than that of gasoline. Hence higher compression ratio engines can take advantage to the higher octane number.

Table 1.1. Fuel Properties of Diesel, Gasoline and LPG

Properties[a]	**CARBOB**	**Diesel**	**LPG**
Carbon Number	C_4 to C_{12}	C_8 to C_{25}	C_2 to C_5
Density (lb/gal)	6.10	6.98	4.24
Specific Gravity	0.73	0.84	0.51
Lower Heating Value			
Btu/gal	113,300	129,488	84,950
Btu/lb	18,573	18,397	20,038
MJ/L	31.62	35.85	23.71
MJ/kg	43.20	42.79	46.61
Latent Heat of Vaporization (kg/kg)	305	275	425
Motor Octane Number	87 to 90	--	100 to 105
Carbon Content (wt% C)	85.9 %	86.5 %	82.0 %
Carbon Factor (g CO_2e/MJ)	73.94	74.86	65.55
Stoichiometric air/fuel ratio	14.70	14.60	15.50
Auto-ignition temperature (° C)	246°C	210°C	410-580°C

[a] Fuel Properties are based on data from the ANL GREET model, physical characteristics are based on information from the U.S. DOE Alternative Fuels Data Center (ANL, 2014; DOE, 2015a), Oilngasprocess.com.

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[2] The majority of refinery butane is used as a gasoline blending component or a feedstock for petrochemicals. Propylene has a high market value as a stand-alone product and is often stripped out of the LP gases.

1.5.1 Specific Gravity and Density

The specific gravity of a liquid is the ratio of the weight of a given volume of that liquid to the weight of an identical volume of water, measured at the same temperature and pressure.

The specific gravity of water is 1.0, while the specific gravity of LPG is about 0.504, depending upon composition. Propane as a vapor is about 1.5 times denser than air. Therefore, if LPG is spilled over water, it will float above the water surface, where it evaporates. Once vaporized, however, the propane gas remains close to the ground/water surface until it disperses.

When propane is compressed, it condenses to form a liquid. The vapor pressure of propane represents the pressure in a closed tank when propane is in liquid/vapor equilibrium. The vapor pressure of propane/butane depends on the composition is shown in Figure 1.2. At a temperature of 100 °F the vapor pressure increases to about 180 psig for pure propane, (it is lower for a propane-butane mixture). The pressure in an LPG tank at equilibrium would be at around that pressure. The vapor pressure increases as temperature rises. LPG condenses to form a liquid. The vapor pressure of propane represents the pressure in a closed tank when propane is in liquid/vapor equilibrium. The vapor pressure of propane/butane depends on the composition as illustrated in Figure 1.2.

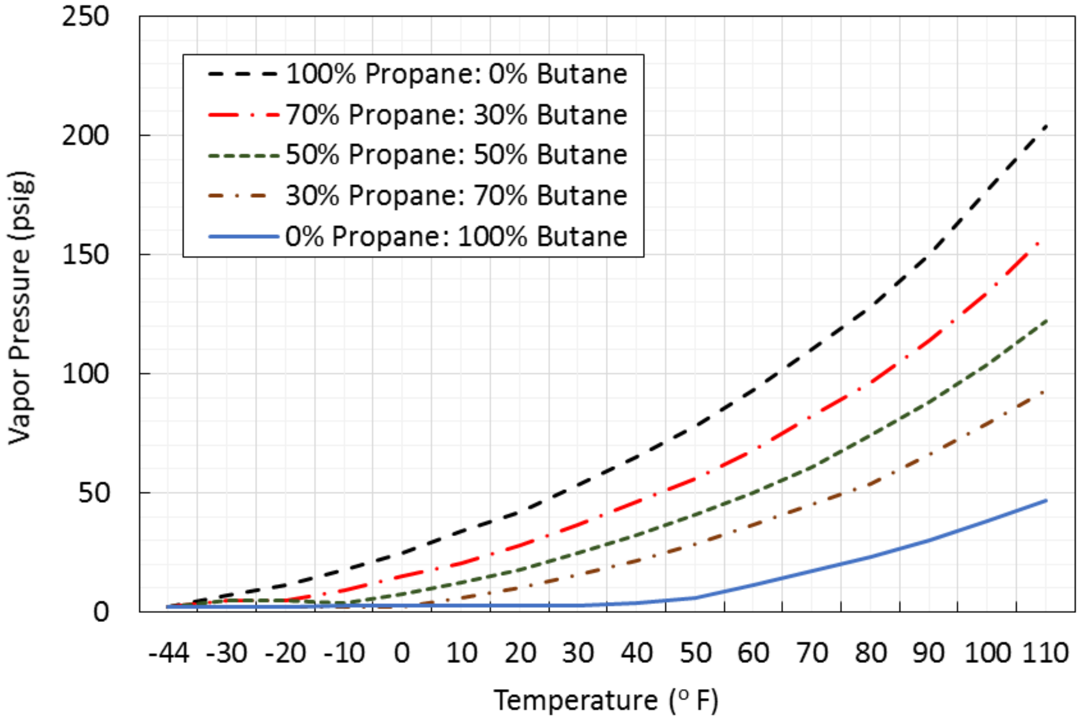

Figure 1.2. Propane–Butane Mix Vapor Pressure vs. Temperature
Source: Engineering ToolBox, 2016

1.5.2 Expansion Ratio

LPG will expand when heated, the same as most other liquids. Propane expands 1.8% for every 10 °F increase in temperature. LPG fuel tanks are never completely filled with liquid because of the expansion factor. LPG tanks are filled to about 80% capacity to allow room for thermal expansion.

1.5.3 Flammability Limits

The flammability limit represents the range where a combustible mixture forms. The lower and upper limit correspond to the minimum or maximum concentration of fuel needed in an air-fuel mixture to support combustion. Combustion occurs when air and fuel are ignited by the introduction of heat. The upper limit is the maximum concentration of fuel (richest air-fuel mixture) that will support combustion. The lower limit is the minimum concentration of fuel (leanest air-fuel mixture) that will support combustion. LPG will only burn when the mixture of propane and oxygen is within the range of flammability. This value is given in both an upper and lower limit of flammability. The lower flammability limit (LFL) of LPG is 2.2% and the upper flammability limit (UFL) is 9.6%. (DOE, 2015b).

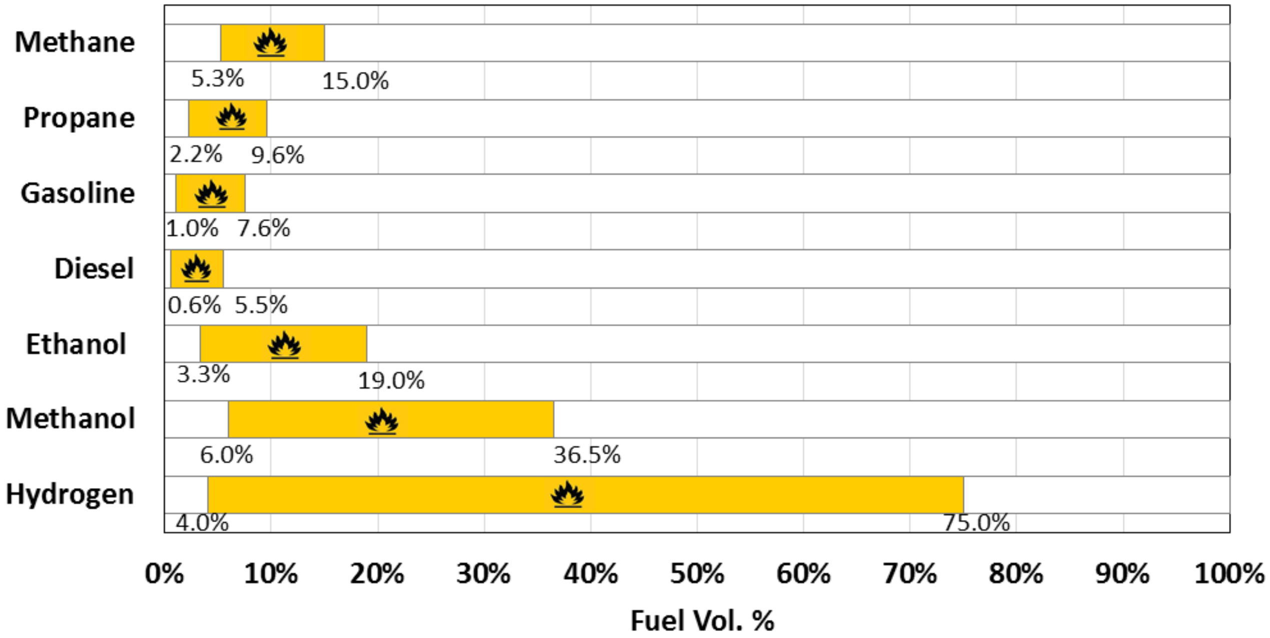

Figure 1.3. Flammable range for fuel-air mixtures.
Source: AFDC, Properties of Fuels, http://www.afdc.energy.gov/afdc/pdfs/fueltable.pdf.

1.5.4 Combustion Characteristics

Propane is a vapor at standard temperature and atmospheric pressure. (Atmospheric pressure at sea level is 14.7 psi-absolute.) Liquid propane must vaporize before it is able to effectively mix with combustion air. In fuel-injected spark ignition (SI) engines, liquid fuel is injected under pressure into the intake manifold. It then vaporizes and combines with air from a pre-mixed mixture prior to ignition and combustion. The Roush CleanTech and CleanFUEL USA (CFUSA) LPI system introduces liquid propane into the intake manifold after it travels through a pressure regulator.

Under complete combustion conditions, fuels yield heat, carbon dioxide and water vapor. The ideal combustion of propane, propylene, and butane are expressed through following basic reactions:

Propane combustion: $C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O +$ 🔥
Propylene combustion: $2\ C_3H_6 + 9\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O +$ 🔥
Butane combustion: $2\ C_4\ H_{10} + 13\ O_2 \rightarrow 8\ CO_2 + 10\ H_2O +$ 🔥

Under ideal conditions, oxygen in the air would convert all the hydrogen in the hydrocarbon fuel to water and all the carbon in the fuel to carbon dioxide. Nitrogen in the air would remain unaffected. However, the combustion process occurs under non-ideal conditions and results in unburnt Hydrocarbons (HC's), Carbon Monoxide (CO) and Nitrous Oxide (NOx) species.

1.5.5 LPG Fuel Grades

LPG fuel is used for a wide range of commercial, governmental, and residential applications. The Gas Processors Association publishes "GPA Liquefied Petroleum Gas Specifications and Test Methods". GPA lists four specifications: commercial propane, commercial butane, commercial B-P mixtures and propane HD-5. For each product characteristic, the appropriate American Society of Testing and Materials (ASTM) test protocol is designated. It should be noted that there is no regulatory requirement to use a particular specification for a particular end use application.

The description of each specification is:

1. Commercial propane: predominantly propane and/or propylene.
2. Commercial butane: predominantly butanes and/or butylenes.
3. Commercial boiling point mixtures: predominantly mixtures of butanes and/or butylenes with propane and or/propylene.
4. Propane HD-5: not less than 90 liquid volume percent propane: not more than 5 liquid volume percent propylene.

For purposes of this study the concentration is on "commercial grade" and "propane HD-5" since most butane ends up as an aerosol charge or in the gasoline pool; the butylene and propylene are directed to the petrochemical market. In some cases propylene is left in the commercial and HD-5 product if there is no immediate outlet to a refinery or petrochemical plant.

As indicated in Table 1.2 the principal differences between the two specifications are the maximum allowable percent propylene (5%) and butane (2.5%) in HD-5, and the sulfur content. All other characteristics and limitations are the same. No federal or state specifications explicitly address LPG transportation fuel other than California.

Table 1.2. Specifications for Liquefied Petroleum Gases

Parameter	**Product Designation**			
	Commercial Propane	**Commercial Butane**	**Commercial Propane/Butane Mix**	**Special-Duty Propane (HD-5)** [a]
Vapor pressure at 100°F (37.8°C), psig	208	70	208[b]	208
kPa	1434	483	483	1434
Evaporated temperature, °F	−37	36	36	−37
°C	−38.3	2.2	2.2	−38.3
Butane & heavier, vol %	2.5	…	…	2.5
Pentane & heavier, vol %	…	2	2	…
Propylene content, vol %	…	…	…	5
Residue on evaporation 100 mL, max, mL	0.05	0.05	0.05	0.05
oil stain observation	Pass[d]	Pass[d]	Pass[d]	Pass[d]
Relative density at 60/ 60°F (15.6/15.6°C) [e]	[e]	[e]	[e]	…
Corrosion, copper, strip	No. 1	No. 1	No. 1	No. 1
Sulfur, ppmw	185[g]	140[g]	140[g]	123[g]
Hydrogen sulfide	pass	pass	pass	pass
Moisture content	pass	…	…	pass
Free water content	…	None[h]	None[h]	

Source: Lawresources.Org: ftp://law.resource.org/pub/us/cfr/ibr/003/astm.d1835.1997.html

[a] Equivalent to Propane HD-5 of GPA Standard 2140.

[b] The permissible vapor pressures of products classified as propane/butane mixtures must not exceed 208 psig (1430 kPa) and additionally must not exceed that calculated from the following relationship between the observed vapor pressure and the observed relative density:

Vapor pressure, max = 1167 − 1880 (relative density 60/60°F) or 1167 to 1880 (density at 15°C)

A specific mixture shall be designated by the vapor pressure at 100°F in pounds per square inch gage. To comply with the designation, the vapor pressure of the mixture shall be within + 0 to − 10 psi of the vapor pressure specified.

[c] In case of dispute about the vapor pressure of a product, the value actually determined by Test Method D 1267 shall prevail over the value calculated by Practice D 2598.

[d] An acceptable product shall not yield a persistent oil ring when 0.3 mL of solvent residue mixture is added to a filter paper, in 0.1-mL increments and examined in daylight after 2 min as described in Test Method D 2158.

[e] Although not a specific requirement, the relative density must be determined for other purposes and should be reported. Additionally, the relative density of propane/butane mixture is needed to establish the permissible maximum vapor pressure (see Footnote *B*).

[f] This method may not accurately determine the presence of reactive materials (for example, H_2S) in liquefied petroleum gas if the product contains corrosion inhibitors or other chemicals, which diminish the reaction with the copper strip.

[g] The total sulfur limits in these specifications *do include* sulfur compounds used for odorant purposes.

[h] The presence or absence of water shall be determined by visual inspection of the samples on which the relative density is determined.

California's Section 2292.6 of Title 13, California Code of Regulations Specifications for LPG[3] lists a minimum propane volume percent of 85.0%, maximum butane volume of 5.0% and maximum propylene (propene) content of 10.0%. (An erroneous reference to "HD-10" as the label for the California specification is occasionally seen in the literature. No such specification exists in California or anywhere else.)

California Specifications for Commercial LPG Fuel

The commercial specifications for LPG sold in California are shown in Table 1.3. The specifications include a minimum propane content and maximum limits on butanes and heavier species.

When ARB adopted the specifications for vehicular LPG, and other alternative fuels, it set essentially identical standards for the motor vehicle fuel sold commercially in California and the fuel used for emission standard certification testing of new motor vehicles. The purpose for the commercial fuel specifications is to ensure that motor vehicles certified on LPG will receive in-use fuel having a quality similar to that of the certification fuel, so that the vehicles will achieve their emission standards in use.

Table 1.3. California Specifications for LPG Certification Fuel

LPG Component	Specification Limit
Propane	85 vol. % minimum
Propene	Up to 10 vol. %
Butene	Up to 2 vol. %
Pentenes and heavier	Up to 0.5 vol. %
Butanes and heavier	Up to 5 vol. %
Sulfur	Up to 80 parts per million by weight
Residual matter [a]	0.05 ml

[a] Residue on evaporation of 100 ml fuel

End Uses of Commercial Grade and HD-5 Grade LPG

Commercial Grade

Any LPG introduced into commerce in the U.S. must meet the specifications listed in Table 1.2. These specifications control the vapor pressure, volatile residue, corrosion, sulfur and moisture, regardless of the percentage of the mix represented by propane and butane. Since the burning characteristics of the two fuels are roughly similar (propane has higher octane but less Btu per gallon than butane) there are no marketing issues as to the usefulness of commercial grade or

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[3] ARB adopted this specification with phase-in amendments in 1993 for end use as well as certification. The regulation imposes the responsibility for compliance on the person fueling the vehicle to make sure that only LPG meeting the California specification is used. However, there is no corresponding obligation on the part of the fuel supplier to disclose the fuel's composition so the person fueling the vehicle has no way of knowing if the fuel being dispensed complies.

HD-5 for all non-transportation fuel uses. Even though commercial grade LPG is "predominantly propane and/or propylene" which might allow unspecified volumes of butane, reality dictates that butane has a higher value use as a blending feed for the gasoline pool. This means very little butane shows up in commercial grade or HD-5 grade LPG.

HD-5

The term designates an LPG specification ascribed to heavy-duty engines containing no more than 5 volume % propylene (propene). The specification is the only one isolated for consideration when LPG is used as an engine fuel whether on-road or off-road. The specification was proposed to GPA in October 1962 in response to engine manufacturer's concerns with engine failure attributed to high concentrations of propylene. Farm tractors from John Deere, International Harvester, Minneapolis-Moline and J I Case were in wide use in the 1960s. This severe duty cycle caused high temperatures and stress, and the variable temperature at which propylene pre-ignites cause engine knock and ultimately piston damage. The specification was designed for engines of a compression of 9.5:1 or higher. Ironically, no one ever built an engine for LPG with that high of a compression ratio then or since.

1.6 Domestic LPG Production and Exports

In the U.S., approximately three quarters of the LPG produced derives from natural gas and associated gas from crude oil production. The balance of LPG is produced from crude oil refinery operations (EIA, 2014). Domestic production exceeds demand, with excess capacity exported; mainly to Latin America and Asia (Fattouh, 2014; True, 2015). The upsurge in LPG production is driven by the expansion of the U.S. shale gas industry (ICF, 2015), leading the U.S. to become one of the largest exporters of LPG in the world (EIA, 2015h; Fattouh, 2014). In 2013, the U.S. produced over 1 billion barrels of LPG, of which 11.5% was exported (EIA, 2015f). California produced over 41 million barrels of LPG in 2013, of which 9.1% was exported (EIA, 2015i). In California the ratio of LPG produced from natural gas and crude oil was 53% : 47% respectively, compared to the U.S. ratio of 78%:22% respectively (EIA, 2015f).

1.6.1 LPG production by PADD.

In the U.S. production of crude oil and natural gas raw materials and products are reported by Petroleum Administration Defense District (PADD) levels (EIA, 2015b, 2015h).

The PADDs are geographic aggregations of the 50 States and the District of Columbia into five districts: PADD 1 is the East Coast, PADD 2, the Midwest, PADD 3 the Gulf Coast, PADD 4 the Rocky Mountain Region, and PADD 5 the West Coast. Figure 1.4 shows the U.S. PADD districts.

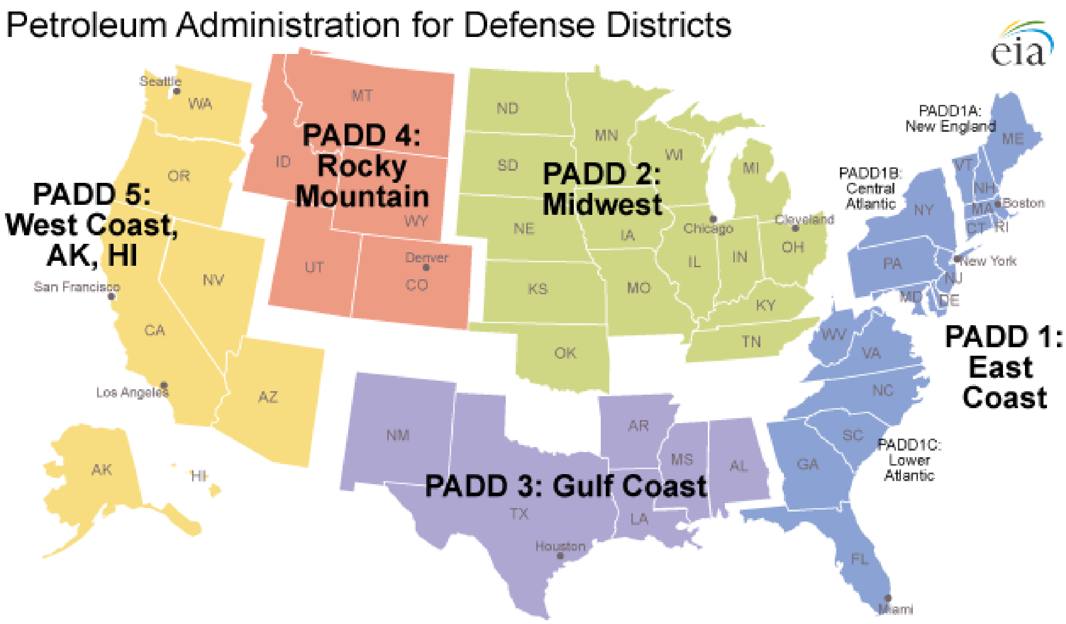

Figure 1.4. Petroleum Administration for Defense Districts (PADDs)
Source: U.S. Energy Information Administration.

Crude oil refined by U.S. refineries differs in API gravity and sulfur content (EIA, 2015c). The refinery configurations, including the complexity of the processing units, are tailored to the types of crude oil refined in each refinery in each PADD (EIA, 2015d). This means that the product yields of refineries and the slate of finished products differs by PADD region (EIA, 2015f), as shown in Table 1.4 and Table 1.5 shows the breakdown of liquefied refinery gases (in mmbbl) by PADD region in the U.S. in 2013.

Table 1.4. Refining production and product slate (in mmbbl and volume % of total production) by PADD region in the U.S., 2013

Product	**Total**	**PADD**				
	U.S.	**1**	**2**	**3**	**4**	**5**
Refining products (mmbbl)	6,973,710	1,309,865	1,542,379	2,762,540	235,776	1,123,150
Shares						
Gasoline	48.3%	81.1%	54.9%	27.5%	49.6%	52.0%
Distillate Fuel Oil	24.8%	10.1%	24.0%	34.3%	30.1%	18.5%
Jet	8.0%	2.0%	5.3%	10.3%	4.0%	13.5%
Heavy products[a]	12.0%	4.7%	10.0%	17.4%	11.1%	10.2%
Still gas	3.7%	1.1%	3.1%	5.0%	3.6%	4.1%
Liq. Refinery Gases	3.3%	1.0%	2.7%	5.6%	1.8%	1.7%

[a] Heavy products includes residual oil and asphalt.

Table 1.5. Liquefied Refinery Gases (in mmbbl and volume % of total production) by PADD region in the U.S., 2013.

Product	Total U.S.	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5
Liquefied Refinery Gases (mmbbl)	232,116	13,558	41,633	155,125	4,310	19,338
Shares						
Ethane	1.1%	0.0%	0.0%	1.6%	0.0%	0.0%
Ethylene	0.1%	0.5%	0.0%	0.1%	0.0%	0.0%
Isobutane	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Normal Butane	10.1%	4.7%	3.3%	11.5%	15.7%	15.3%
Isobutylene	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Normal Butylene	0.0%	3.5%	2.5%	0.0%	7.6%	0.0%
Propylene	44.1%	34.6%	30.5%	52.8%	4.2%	15.0%
Propane	44.6%	56.7%	63.6%	34.0%	72.5%	69.7%

1.7 LPG Markets

LPG is used widely in the industrial, residential, commercial, and agricultural sectors. The petrochemical industry uses LPG as a feedstock; while in the residential and commercial sectors, LPG is used for ambient heating, water heating, cooking, drying, and grilling. In the agricultural sector, LPG is used for crop and feed drying, power generation, pest control, irrigation engines, swine and chicken brooding (Werpy, Burnham, & Bertram, 2010). LPG is used in rural applications because it is highly portable and is not dependent on transmission lines or pipeline grids (CEC, 2015; Laughlin & Burnham, 2014). LPG also has a long history as a transportation fuel. When used for transportation, LPG is referred to as “LP autogas” or more simply “propane”. Globally, LP autogas is the most widely used alternative fuel in vehicles, representing more than 25 million vehicles worldwide, including over 7 million vehicles in Europe, with about 140,000 in the United States (DOE, 2015b; WLPGA, 2014).

1.7.1 LPG Market Sectors

LPG is sold as a heating, cooking and transportation fuel in the U.S. The American Petroleum Institute (API) maintains annual statistics on the sales and use of LPG within the U.S.[4] The LPG sales data from the API report groups LPG sales by market sector. The sectors included are residential, commercial, sales-to-retail, internal combustion fuel for on road and off road applications, chemical, industrial, and agricultural. For safety reasons, LPG used as a process or transportation fuel contains trace amounts of highly odorous compounds, which give the fuel a distinctive smell. Non-odorized LPG use is limited to the chemical industry.

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[4] Each year, the API sends out a survey to sellers of LPG, to collect data on the sales and distribution of LPG This annual report is entitled the “Sales of Natural Gas Liquids and Liquefied Refinery Gases”. The report is issued in December of the following year, i.e. the 2013 API report was issued in December of 2014.

- Residential – Sales to private homes primarily for heating, water heating, cooking and clothes drying.
- Commercial – Sales to restaurants, hotels, laundries, churches and other commercial entities, primarily for heating and cooking.
- Cylinders (Sales-to-Retail) – Sales to bottle fillers at places such as gas stations or hardware stores and sales to cylinder exchange programs.
- Internal Combustion Fuel – Sales to on-road vehicles and forklifts.
- Industrial – Sales to industrial plants for space heating, flame-cutting, and metallurgical furnaces.
- Chemical – Sales to chemical plants for use in reactions. The chemical industry uses a non-odorized LPG product distinct from LPG used as a vehicle fuel
- Agricultural – Sales to farms and other agricultural facilities for the production, harvesting, and processing of agricultural products. This includes LPG for heating buildings, powering equipment, and drying crops.

Table 1.6 shows the U.S. and Californian LPG sales data breakdown by market sector.[5] The API data does not discriminate between LPG for on-road and off-road internal combustion fuel applications, so LPG used for forklifts is aggregated with data for heavy and light duty vehicles. This data aggregation means it is difficult to estimate LPG on-road transportation fuel use.

Table 1.6. 2013 LPG Sales by Market Sector [a]

	Volume (mm gal)	
Sector	**U.S.**	**California**
Residential	4,844	212
Commercial	1,658	92
Cylinders	224	34
Internal Combustion Fuel[b]	573	67
Chemical	10,027	130
Industrial	476	26
Agricultural	1,060	52
Total	8,835	484

[a] Source API annual statistics (API, 2014)

[b] On-road and forklift applications.

LPG: A New Transportation Fuel for California?

LPG has a long history as a transportation fuel in California. Approximately 135,883,000 gallons of LPG transportation fuel was sold in California in the year 1985. This includes on-road vehicles and forklifts since the reporting system includes both end uses. (California's definition of "transportation fuel" includes forklifts.) There was a gradual reduction in fuel sales in following years, as evident by the California LPG transportation fuel sales shown in Table 1.7 (NPGA Market Facts).

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[5] The California LPG sales are estimated from the ICF report: Impact of the U.S. Consumer Propane Industry on U.S. and State Economies in 2012 (ICF, 2015).

Table 1.7. California LPG Transportation Fuel Sales

Year	mm gal
1985	136
1986	122
1987	112
1988	97
1989	87
1990	82
2014	67

Most of the declining sales were from the vehicle sector as the forklift market has remained relatively stable. The primary reason for the sales decline were a lessening of concern about gasoline supplies following crude oil embargoes from the Middle East, increased testing and certification requirements for conversions, OEMs focusing on other mandated alternative fuel strategies, and uncertain pricing of LPG.

1.8 LPG On-Road Vehicle Applications

LPG on-road vehicles are either dedicated or bi-, or dual-fuel models that contain spark ignition engines or, as a supplement in compression ignition engines. Bi-fuel vehicles contain both gasoline/diesel and LPG reserves, but each fuel is used separately. Dual fuel vehicles contains both fuels, which are used together. The low GHG emissions profile of LPG vehicles over gasoline and diesel alternatives is well known (Atlantic Consulting, 2009; Boureima et al., 2009; CEC, 2015; DOE, 2015b; Laughlin & Burnham, 2014; Liu, Yue, & Lee, 1997; Stefan Unnasch, Waterland, & Associates, 2011; Werpy et al., 2010; Yousufuddin & Mehdi, 2008). Redirecting LPG exports away from other markets such as cooking or heating fuels and instead towards transportation fuels offers a low emission solution to growing transportation energy demand.

1.8.1 LPG Vehicle Populations

Approximately 140,000 LPG vehicles operate in the U.S. (DOE, 2015b), with circa 10,000 LPG vehicles operating in California (CA_DMV, 2014). Government and municipal fleets, school bus fleets, state agencies and propane providers are the main users of LPG vehicles. More than 80,000 bus, taxi and delivery services, and other fleets are fueled by LPG (DOE, 2015b). U.S. automobile and truck manufacturers produce a limited range of vehicles equipped with LPG-powered dedicated and bi-fuel engines. However, LP vehicle sales are somewhat constrained by the limited number of OEM LPG vehicles currently available, but retrofit kits are approved for several hundred models. Also, the high cost of vehicle certification presents additional market entry challenges. Recent investments by the Propane Education Research Council (PERC), ROUSH CleanTech, Bluebird Bus, CleanFUEL USA, Alliance Autogas and others have led to the introduction of a number of new LPG-powered vehicles. Industry partnerships with additional original equipment manufacturers (OEMs), including the existing PERC partnership, with Freightliner Custom Chassis is expanding the number of vehicles to the market. For 2016 Ford is offering several models of trucks with the LPG option (ICF, 2013). In the U.S., propane vehicles are most commonly found in commercial fleets in applications such as pick-up trucks, taxis, buses, and airport shuttles (ICF, 2013). Figure 1.5 shows the number of LPG vehicles in use in the U.S. between 1995 and the latest years data available, 2011 (DOE, 2015b; EIA, 2015a). The declining population exists because the number of vehicles made available for sale has fallen, and the high cost of certification is a deterrent to conversion of gasoline powered vehicles.

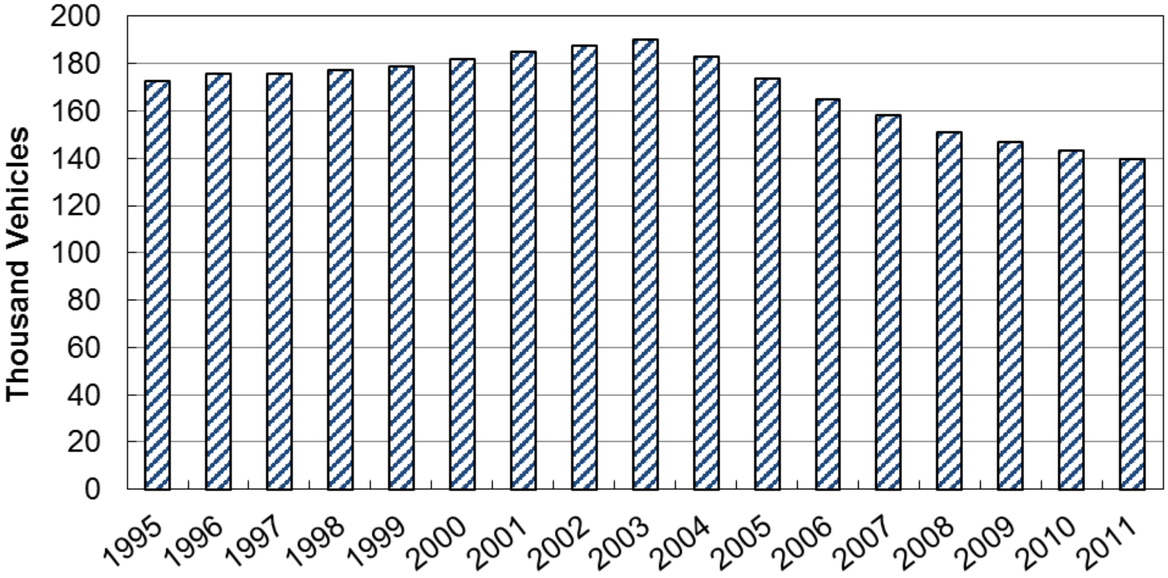

Figure 1.5. LPG Vehicle Population in the U.S

Source: EIA, 2015a

Statewide LPG vehicle populations are difficult to estimate. EIA provides data on state vehicle populations (EIA, 2015g), which can be compared to local DMV data (if available). In California, the Department of Motor Vehicles (DMV) has documented the number of LPG on-road vehicles in use in the State since 2012. Earlier estimates can be found in the 2006 CEC Alternative Fuels Market Assessment (TIAX, 2006). Figure 1.6 shows the number of LPG vehicles in use in California based on EIA, DMV, and TIAX estimations. EIA and DMV data indicate that the LPG vehicle populations have undulated between 9,000 and 16,000 vehicles in use, during the period 2003 to 2014. Earlier estimations from TIAX places the number of LPG vehicles at 33,000 in 1999 and 22,000 in 2004 (TIAX, 2006). The TIAX estimations are based on a range of assumptions and data from EIA and survey data from PERC (CA_DMV, 2014; EIA, 2015a).

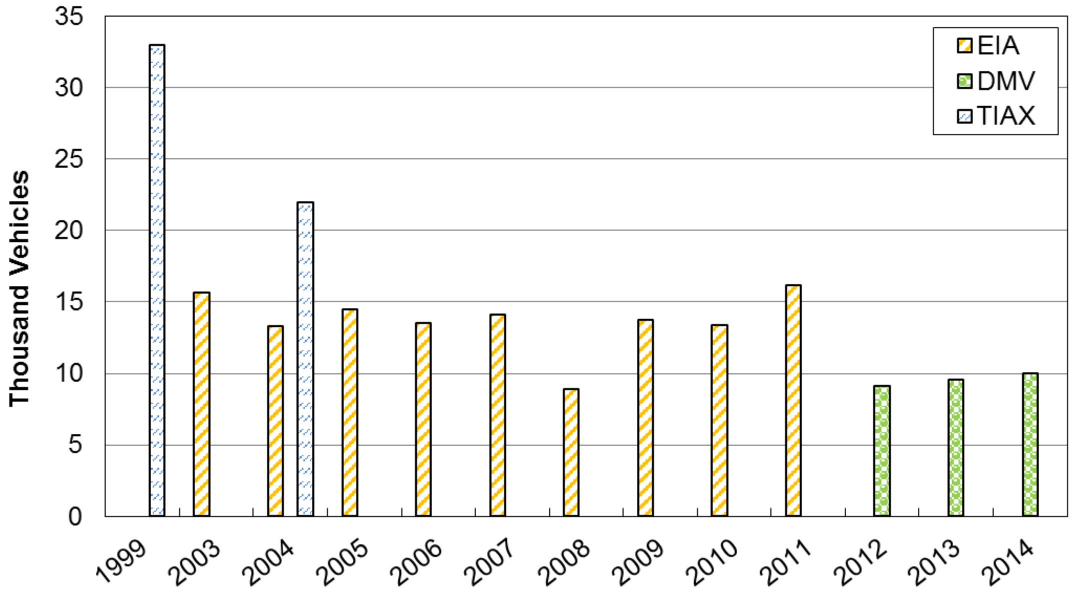

Figure 1.6. LPG Vehicle Population in California

Source: EIA 2015; State of California DMV 2014; TIAX, 2006.

1.8.2 LPG Vehicle Technology

The availability of LPG-fueled light-duty passenger vehicles is currently limited. Several car manufacturers offer OEM models of LPG fueled vehicles; alternatively, suitable engines can be retrofitted with components capable of the safe handling and combustion of LPG. Since LPG is stored as a liquid in pressurized fuel tanks rated to 300 psi, LPG conversions consist of installing a separate fuel system if the vehicle will run on both conventional fuel and LPG, or a replacement fuel system for dedicated LPG operation.

Retrofit vehicles and engines can be converted to dedicated configurations, meaning they operate exclusively on LPG, or "bi-fuel" configurations. In "bi-fuel" configurations, the vehicles have two separate tanks - one for conventional fuel and another for an alternative fuel. Bi-fuel vehicles are designed to operate on the alternative fuel with gasoline being the default fuel. The usual operation mode for bi-fuel vehicles is for the engine to start on gasoline, and automatically switch to propane when certain operating parameters have been reached.

OEM Configurations

OEM models are designed to accommodate LPG and are not constrained by the original design of a retrofit engine. Table 1.8 shows a selection of the OEM vehicles available in 2015 (DOE, 2015c). LPG vehicles are typically medium- or heavy-duty vehicles such as buses, trucks, and vans.

Table 1.8. 2015 LPG OEM Vehicles

Category	Model	Manufacturer

Vocational/Cab Chassis	Express 3500/4500	Chevrolet
Vocational/Cab Chassis	E-350/450	Ford
Truck	Super Duty F-250/350/450/550	Ford
Van	Transit Connect	Ford
Vocational/Cab Chassis	Transit T-150/250/350	Ford
Vocational/Cab Chassis	Savana 3500/4500	GMC
Van	Express, Cutaway 4500	Chevrolet
Truck	Transit 150/250/350	Ford
Van	Savana, Cutaway 4500	GMC
School Bus	Micro Bird G5	Blue Bird Corp.
Tractor	TJ5000/TJ7000	Capacity Trucks
School Bus	NexBus Propane	Collins Corp.
Street Sweeper	Broom Bear/Crosswind/Eagle	Elgin
Step Van	E-Series Cargo Van/Wagon	Ford Motor Co.
Step Van	Chevrolet Express 4500	General Motors
School Bus	CE Series	IC Bus
Shuttle Bus	President	StarTrans

Source: http://www.afdc.energy.gov/vehicles/propane_availability.html

Gasoline

LPG is used mostly in bi-fuel vehicles, which start on gasoline. Spark ignition (SI) engines options for LPG include bi-fuel engines which change the fuel system or adding a parallel fuel system for LPG. LPG is stored as a liquid under pressure and is introduced into the inlet ports of the engine.

- In vaporized systems, liquid LPG travels along a fuel line into the engine compartment. Propane passes through a regulator or vaporizer, which converts the liquid propane to a vapor. The vapor is fed to a mixer located near the intake manifold, where it is metered and mixed with filtered air before being drawn into the combustion chamber where it is combusted, just like gasoline.
- Liquid LPG injection engines function in the same manner as the vapor-injected systems where the LPG vaporizes after it exits the injector.

In SI engines, similar compression ratios are used with LPG as with gasoline, even though the octane number of LPG is higher than that of gasoline. This is due to the fact that the adiabatic flame temperature is higher when LPG is used and this lowers the knock limit at high engine loads. Exceptions to this are the engines in which LPG is injected in liquid form. In bi-fuel cars, the upper limit for compression ratio is restricted by gasoline properties. The efficiency of LPG engines is similar to gasoline engines because the engine does not take advantage of the LPG fuel properties.

Diesel

Dual fuel engines that run on diesel with supplemental LPG at higher loads are referred to as “fumigation” engines. In fumigation engines, the LPG is injected into the intake air manifold in the engine compartment. These engines are used in medium duty vehicles such as buses and trucks, and use compression ignition to ignite the fuel mix. Figure 1.7 shows a schematic for a diesel fumigation engine.

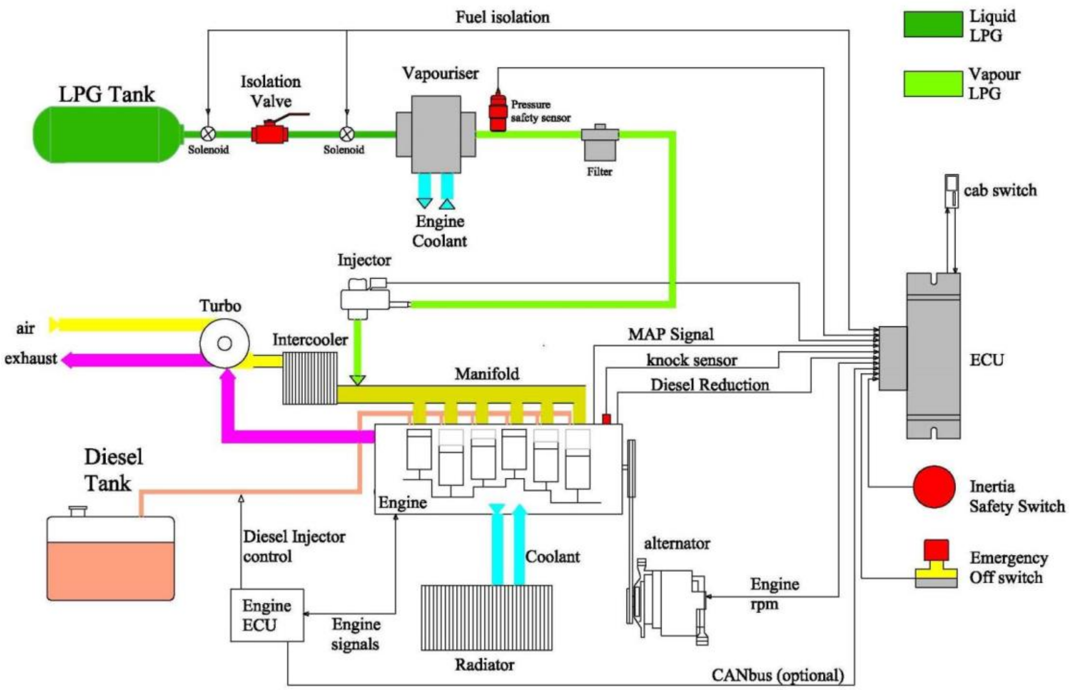

Figure 1.7. Diesel Fumigation Engine Schematic.
Source: http://dizel-gaz.ru/fotografii.html

1.8.3 Fuel Injection Components

The fuel line from the tank to the engine is typically made of stainless steel, and it must meet the requirements of National Fire Protection Association (NFPA) 58: LP-Gas code section 11-7 (Piping, Hose, and Fittings). The pressure regulator and other components must also meet NFPA requirements. NFPA is an international nonprofit organization, whose mission is to reduce fire hazards by providing and advocating consensus codes and standards, research, training, and education. NFPA codes are frequently adopted and/or referenced by local, state, and federal governments.

A Liquid Propane Injection (LPI) system injects liquid propane fuel into the intake manifold where it rapidly vaporizes; with liquid fuel injection a vaporizer is not required. Vaporization of the liquid fuel injected into the intake manifold cools the air/fuel mixture, increasing its density and power potential. Direct injection technology is now entering the market. Direct injection deposits the fuel in the combustion chamber rather than the intake manifold thus providing lower NOx and better fuel efficiency.

1.8.4 Vehicle Emissions Regulations

All vehicle and engine conversions must meet standards instituted by the EPA and state agencies like ARB. Certification is required to ensure that the vehicles demonstrate compliance with the necessary emission, warranty, and durability requirements.

EPA

Under the Clean Air Act, EPA has the authority to regulate vehicle emissions from vehicles for sale in 50 states[6]. Vehicles and engines from OEMs and retrofits must be certified to meet applicable emissions standards. Regulations are in place to ensure that emissions do not increase because of changes made to a vehicle or engine, including a retrofit.

ARB

Manufacturers selling conversion systems for use in California must meet ARB requirements and obtain approval from ARB. California regulations prohibit the conversion of emission-controlled vehicles with retrofit systems to operate on an alternative fuel, such as natural gas, propane, or ethanol, in lieu of the original gasoline or diesel fuel unless the retrofit systems have been evaluated and certified by the ARB. The vehicle manufacturer or vehicle importer must obtain the certification of an alternative fuel retrofit system. ARB issues certification documents once the manufacturer demonstrates compliance with the emission, warranty, and durability requirements in the form of an Executive Order.

California's requirements for alternative fuel converters are different than EPA's requirements. Revisions to California's Alternative Fuel Conversion regulation and test procedures were approved in 2013. The revisions provided for some streamlining of the conversion approval process for 2004 Model year and later Light Duty (LD) vehicles/Heavy Duty (HD) engines. Small volume manufacturers were given some additional relief which sunsets after the 2017 model year.

Safety Regulations

Vehicle conversions that require the addition of heavy battery systems or additional fuel tanks that may alter a vehicle's center of gravity, payload capacity, or handling characteristics may need to be safety crash tested and certified to comply with Federal Motor Vehicle Safety Standards (FMVSS) and/or other NHTSA regulations.

Demonstrating Compliance with Regulations

All manufacturers must prove that a given vehicle or engine conversion complies with EPA and ARB emissions regulations. Required demonstration and notification procedures differ according to the age of the converted vehicle or engine.

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[6] California has successfully petitioned EPA for exemption to EPA authority and the ability to self regulate.

1.9 LPG Vehicle Certification

All road-going vehicles, including cars, trucks, motorcycles, agricultural vehicles, buses and coaches, ambulances, fire engines and recreational vehicles must be tested and certified to air emissions standards defined by EPA and state agencies, such as ARB.

ARB's regulations and emission standards are more stringent and more costly to satisfy than those of the EPA. This increased stringency results in substantially greater conversion system testing and much higher certification costs, increases emissions system warranty requirements and risks to manufacturers, and limits consumer choices for OEM alternative fuel vehicles (AFVs).

EPA and ARB certification procedures and or emissions limits are different. Vehicles undergoing EPA certification must follow the tier and bin structure, whereby vehicles are categorized according to emissions standards (Tiers), and certification limits (bins). ARB certifies engine families or test groups according to California's emissions standards.

1.9.1 EPA Certification

The EPA Tier program considers the vehicle and its fuel as an integrated system, setting vehicle emissions standards. The vehicle standards reduce both tailpipe and evaporative emissions from passenger cars, light-duty trucks, medium-duty passenger vehicles, and some heavy-duty vehicles.

The Tiers are structured such that manufacturers must certify vehicles into one of seven available "certification bins". Each vehicle in the certification bin must meet the fleet-average emission standards in a given model year.

- Both the certification limits (bins) and the fleet average standards are expressed using the sum of NMOG + NOx emissions,
- The bins are named using their corresponding NMOG + NOx limit in mg/mi. For example, the highest emission bin—Bin 160 (NMOG + NOx = 160 mg/mi)—is equivalent to Tier 2 Bin 5,
- The fleet average NMOG + NOx emissions must reach 30 mg/mi (Bin 30 = Tier 2 Bin 2) by 2025,
- The required emission durability has been increased to 150,000 mi, up from 120,000 mi.

Light-duty vehicles

Two sets, or "tiers", of emission standards for light-duty vehicles in the United States were defined as a result of the Clean Air Act Amendments of 1990. The "Tier I" standard was adopted in 1991 and was phased in from 1994 to 1997. Tier II standards were phased in from 2004 to 2009.

Within the Tier II ranking, there is a sub-ranking ranging from BIN 1–10, with 1 being the cleanest (Zero Emission vehicle) and 10 being the dirtiest. The former Tier 1 standards that were effective from 1994 until 2003 were different between automobiles and light trucks (SUVs, pickup trucks, and minivans), but "Tier II" standards are the same for both types. These standards specifically restrict emissions of carbon monoxide (CO), oxides of nitrogen (NO_x), particulate matter (PM), formaldehyde (HCHO), and non-methane organic gases (NMOG) or non-methane hydrocarbons (NMHC).

1.9.2 ARB Certification

For certification purposes, vehicles are grouped in engine families or test groups for exhaust emissions (hereinafter, engine families) and evaporative families for evaporative emissions. Within each family, the vehicles share similar designs and are expected to have similar emission characteristics. An Executive Order is issued to certify an engine family in combination with one or more evaporative families. An Executive Order is valid for production during the specified model year. Vehicles produced for another model year require another Executive Order.

Pertinent certification information is included in an Executive Order. Among the information available are the vehicle model year, engine and evaporative families, vehicle category, emission standard category, engine displacements, operating fuel, emission control systems, values of the exhaust and evaporative emission standards and certification emissions, and vehicle models.

Note that Executive Orders are issued to whomever applies for certification, e.g. equipment or vehicle manufacturers can receive Executive Orders. Some manufacturers have multiple brands ("Makes") of vehicles that are certified as an engine family.

1.10 The Role of LPG in Transportation Fuel LCA

The role of LPG as both a transportation fuel and as an intermediate product in the production of other fuels affects its life cycle analysis and GHG impact. Some of the uses and intermediate roles of LPG include the following:

- Co-product of natural gas production
- Co-product of crude oil refining
- Fuel for light- and heavy-duty vehicles
- Fuel for drying corn used in ethanol production
- Co-product of renewable diesel production
- Co-product of Fischer Tropsch fuel production

The production of LPG from fossil resources is integral to all fuel LCA models and discussed in Section 3.

1.10.1 Key LCA Principles

Several key principles factor into an LCA of LPG. The allocation of energy inputs and emissions to natural gas and petroleum fuels as well as LPG co-product are closely linked. Fuel LCA approaches must account for all of the emissions. Section 1.11 examines the current fuel LCA approaches, the issues related to analyses and the secondary effects of LPG in fuel LCA.

Complicating the life cycle analysis of LPG is the fact that oil refineries are not trying to make LPG, rather, the LPG is a non-discretionary co-product of refining processes. Some LPG naturally occurs in the crude oil, but most is the product of refinery units that are configured to make more valuable fuel productions. More intensive refining results in higher emissions, which need to be assigned to primary fuels products rather than co-products like LPG. Because LPG is not an intended product, the environmental impacts of primary products such as hydrocracker diesel should be assigned to the gasoline and diesel blending components produced from these units. Therefore, the allocation approach used to assign emissions within the oil refinery to co-products requires careful examination.

Since LPG is a non-discretionary co-product, a share of the emissions from petroleum or natural gas refining and production is assigned to LPG (See section 2.3 for more detail.). The goal of this study is to develop the best estimate of LPG lifecycle GHG emissions and provide recommendations for the appropriate treatment of LPG in future fuel LCA studies. The results compare the GREET1 and CA_GREET treatments of LPG as a fuel.

Table 1.9. Steps for LPG Fuel Pathways

Step	Petroleum LPG	Natural Gas LPG
Feedstock Production	Crude Oil Extraction, Associated gas venting and flaring[a]	Natural gas extraction, fugitive losses. Natural gas recovery[b]
Feedstock Transport	Transport of crude oil to oil refinery[a]	Transport of raw natural gas to LPG separation plants
Refining	Crude oil refining	LPG separation
Product Transport	Transport of LPG to distribution centers Transport to local fuel station	
Fuel Combustion	Carbon in fuel converted to CO_2 plus vehicle CH_4 and N_2O emissions	

[a] Same emissions applied to crude oil for gasoline and for LPG (energy allocation)
[b] Same emissions applied to natural gas and LPG (energy allocation)

1.10.2 Attributional and Consequential LCA

The current use of LCA for transportation fuel GHG emissions reporting tends not to distinguish between the two different LCA approaches: consequential LCA and attributional LCA. These two approaches aim to answer different questions, and failure to distinguish them can result in the wrong method being applied, a mixture of the two approaches within a single assessment, or misinterpretation of results.

- Attributional LCAs assess how energy, emissions, material properties, etc. flow within a chosen production time period.

- Consequential LCAs include the activities contributing to the environmental consequence of the change, i.e. how flows change in response to a decision or shock to the system (Ekvall & Weidema, 2004).

The LCFS relies heavily on an attributional approach, while indirect effects such as Land Use Conversion (LUC) are modeled consequentially.

The process of system expansion (to avoid or deal with the allocation problem in multi-product systems) is an inherent part of consequential LCA studies. Because consequential LCA includes additional economic concepts like marginal production costs, elasticity of supply and demand, dynamic models (instead of the linear and static models of traditional LCA), etc. it is typically more conceptually complex and the results obtained are highly sensitive to assumptions made. The failure to identify inadequate implicit assumptions will lead to a poor analysis.

1.10.3 Transportation Fuels and the Marginal Gallon

This study considers the GHG emissions associated with the production of LPG as a transportation fuel. Emissions are examined on a marginal basis (Stefan Unnasch, 2001), which represents the incremental emissions associated with LPG production from expanded sources that would meet a growing transportation market.

For example, if the population of LPG vehicles grew significantly, then the question becomes “where does the next gallon of LPG come from”? This is both an economic and industrial process question. Both natural gas and crude oil refineries have the potential to extract more LPG from product streams; however, increasing LPG production will reduce the production of the other petroleum and natural gas products.

Other fuels such as natural gas can substitute for LPG; so, if existing LPG were diverted substantially to transportation use, a global shift in the use of energy would need to be examined. However, with today's transportation fuels, increased demand for low sulfur products results in the additional production of LPG from hydrotreating and other energy intense refining processes. LPG resulting from more intense refining is growing faster than the demand for LPG as a transportation fuel. Therefore, energy inputs associated with more intensive crude oil refining should not be attributed to with LPG. Other examples in fuel LCA provide a similar framework for analysis. For example, corn oil used in biodiesel is treated as a residue and not burdened with the energy inputs to produce ethanol (ARB, 2009).

In transportation fuel LCA, the “marginal unit of fuel” corresponds to the incremental demand for fuel that is associated with either a policy change or any action that leads to an increase or decrease in the production or use of a transportation fuel, as described above. In order to meet the projected Business as Usual (BAU) demand for fuels, new sources of fuel must be incrementally absorbed “from the margins”. For example, the shale boom has led to an influx of natural gas and LPG fuels on the margin, and these fuels, incorporated into the BAU, lead to a change in the demand of other fuels. Quantifying the value of the marginal gallon of LPG is important because a life cycle comparison of fuels is intended to reflect either the policy or the expanded use of the fuel displacing a marginal gallon of gasoline. The marginal gallon impacts are, therefore, an integral part of a consequential LCA. The appropriate calculation of the emissions impact would correspond to the marginal gallon of displaced petroleum or avoided capacity expansion. The transportation fuel demand modelled in fuel LCA scenario is shown in Figure 1.8.

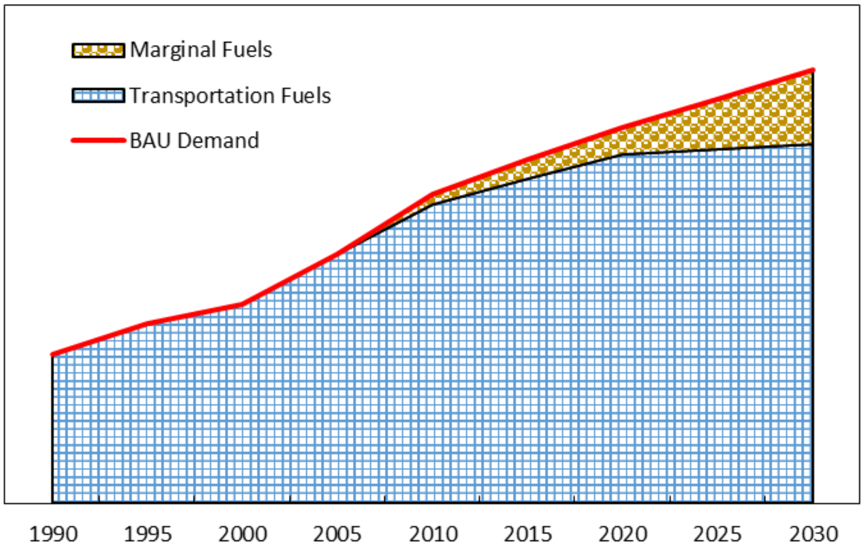

Figure 1.8. Transportation Fuel Demand and the Marginal Impact

The emissions associated with the production of transportation fuels are developed from the Business as Usual (BAU) case, which includes emissions from the production of marginal fuels, however, the emissions associated with the BAU case are not the same as the emissions on the margins.

Marginal LPG Sources

Oil and gas both contain naturally occurring fractions of propane and other low molecular weight hydrocarbons. The LPG composition depends on the fossil fuel source. For example, light crude oils from hydraulic fracturing in the Bakken contain approximately 3.7 % by volume of dissolved gasses, of which about 0.8% is propane (Wybenga, 2014). Additionally, refining crude oil also produces propane from many unit operations; for example, the hydrocracker splits long chain hydrocarbons into diesel and kerosene as well as small chain hydrocarbons such as propane. LPG production grows with more intense hydrocracking and other refinery unit operations.

Propane in products

Processing of oil and gas results in various propane fractions in all of the products; therefore, the incidental amount of LPG produced is flexible. Economics, yields, and the performance of refinery units can affect the amount of LPG produced in refineries. Propane recovery operations in refineries are flexible, allowing the operators to maximize plant profits based on parameters such as feedstock cost, fuel gas cost, and liquids product economics. Absent the recovery of propane for sale as LPG it would burned as a process fuel.

Additionally, LPG must be removed from the raw natural gas (mostly methane) in order to meet pipeline specifications. If the liquids are not removed they will “drop out” and affect grid pipelines, and the gas mixture will have an incorrect Wobbe Index[7].

On the margin, LPG displaces natural gas for energy production. The marginal sources of LPG are:

- Swing fuel in oil refineries as fuel gas
- Composition variation in pipeline gas
- Intensive refinery operations such as hydrocracking
- Incidental product of butane/propane splitters
- LPG exports

Marginal LPG Uses

The marginal uses of LPG are to sell as a fuel, use as a refinery fuel or feedstock, or export from the state. Selling additional LPG for vehicle use would displace LPG sales to other customers and also displace LPG as a refinery fuel where it might be replaced with natural gas. Oil refineries may burn propane if the demand for it as a home heating or vehicle fuel is low. However, higher market prices (demand) would probably divert propane to use as a vehicle fuel (refineries would burn natural gas as a replacement).

Flexibility in the use of propane affects the following uses on the margin:

- LPG for power generation[8,9]
- Include propane in pipeline gas
- Burn propane as refinery fuel
- Switch between propane and butane in other markets
- Export LPG outside U.S.

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[7] In the case of natural gas (molar mass 17 g/mol), the typical heating value is around 1,050 Btu per cubic foot and the specific gravity is approximately 0.59, giving a typical **Wobbe index** of 1,367 Btu/scf (51 MJ/m^3)”; Wikipedia; https://en.wikipedia.org/wiki/Wobbe_index,

[8] LPG is used to provide thermal energy in power plants around the world: http://www.tepco.co.jp/en/challenge/energy/fuels/lng-lpg-e.html

[9] LPG is used to provide thermal energy in power plants around the world: http://www.transtechenergy.com/lpg-power-generation

For a comprehensive consequential LCA, the emissions from LPG are based on the production of the marginal gallon of LPG, which reflects its expanded use as a transportation fuel (Stefan Unnasch, 2001; Stefan Unnasch, Riffel, & Sanchez, 2011; Weidema, 2001). Since LPG has many uses, determining the marginal source of LPG associated with the marginal use is challenging. In the view of the authors, examining the marginal use of LPG with an econometric modeling system results in a broadening of assumptions and complexity such that the effort would not add certainty to the analysis of LPG (Stefan Unnasch, Riffel, et al., 2011). Therefore, given the opportunities for displacing LPG from refinery use, and the source of current LPG, this study assumes refinery-based and natural-gas-based LPG production as the marginal gallon. The marginal assumptions used in this study are compared to the range of inputs used over the years in other fuel LCA studies.

Refinery Energy Allocation

Assigning energy inputs to refinery products is challenging due to the complexity of oil refineries and effort required to represent refinery energy flows. Fuel LCA models continue to use refinery modeling to account for energy flows within the refinery (Cai, Han, Forman, & Wang, 2013; Forman, Divita, Han, Cai, Elgowainy, et al., 2014; Palou-rivera & Wang, 2010; Stefan Unnasch & Browning, 2000; Michael Wang, Lee, & Molburg, 2004). The approaches for estimating refinery energy inputs are shown in Table 1.10. Most of these studies assign energy intensive refinery unit emissions to gasoline and diesel blendstocks (ANL, 2014; ARB, 2014a, 2017; Edwards, 2007; W. Keesom, Blieszner, & Unnasch, 2012; William Keesom, Unnasch, & Moretta, 2009).

The simplest method to distribute refinery emissions involves calculating the average emissions per barrel of oil and assigning the emissions based to liquid fuels and other energy products. With this energy allocation approach the emissions are the same per MJ of each product. More sophisticated methods track the energy through the oil refinery with different refinery modeling approaches including linear programming (LP) models or unit-specific process models. LP modeling studies examine the incremental emissions associated with the incremental production of gasoline and no major studies address LPG with the unusual question of “what are the incremental emissions from the production of additional LPG”. Other studies track the flows through refinery units.

Allocation methods used for petroleum-based fuels (e.g., gasoline, diesel, and LPG) are based primarily on mass, energy content, or market value shares of individual fuels from a given refinery. The aggregate approach at the refinery level does not account for the energy use and emission differences associated with producing individual fuels at the next sub-level: individual refining processes within a refinery. The approach ignores the fact that different refinery products go through different processes within a refinery. Allocation at the sub-process level (i.e., the refining process level) instead of at the aggregate process level (i.e., the refinery level) is advocated by the International Standard Organization. This study allocates the total refinery energy use among various refinery products at the level of individual refinery processes.

Table 1.10. Fuel Cycle Models and Treatment of Refinery Emissions

Reference	Organization, LCA Model	Refinery Efficiency Input	Challenges
Wang, 2004	ANL, GREET_1	EIA data aligned with refinery energy intensity	No LPG specific analysis. Treats LPG and gasoline in the same manner even though refinery units are built to produce gasoline and diesel.
Wang , 2014, Algowainy 2014	ANL, GREET1_2014	EIA data aligned with linear programming model by PADD	
O'Conner, 2011	S&T2, GHGenius	GHGenius uses the Solomon EII refinery efficiency for Canadian refineries. The Solomon EII is a measure of energy efficiency and thus could be used as a proxy for joules consumed per joule delivered for individual refineries.	
Keesom, 2012	Jacobs, PetroPlan, GREET	Process based energy allocation through all refinery units.	Energy and emissions used for producing primary fuels are assigned to propane. Alternate approach was substitution with natural gas LPG CI.
This Study	LCA, GREET	Crude unit and gas plant energy inputs.	Preferred approach since it assigns emissions from gasoline and diesel production to those fuels.

The roles for LPG make it imperative that the analysis is performed correctly. Determining an accurate carbon intensity for LPG affects not only the vehicles but also all of the other fuel pathways involving LPG. If emissions are incorrectly allocated to LPG then they are also incorrectly allocated to gasoline and diesel fuels. The LCA should reflect the fact that LPG is an incidental product of oil refining. Operating refinery units with greater intensity results in more cracking of hydrocarbons, which results in the incidental production of LPG.

The current representation of LPG in the GREET model with a refinery efficiency comparable to gasoline does not appropriately captured the role of LPG in refineries. The current CA_GREET2 model has a refinery efficiency input of 89.3% for both LPG and CARBOB production. Thus, petroleum LPG has the same refining intensity as gasoline, when in fact much of the LPG in refineries is the result of operating units designed to make gasoline and diesel components. Assigning emissions from the incomplete conversion of refinery feedstocks to LPG misallocates these emissions. The corresponding energy inputs and emissions should be assigned to gasoline and diesel. A suitable approach assigns LPG the same energy use for the crude distillation unit. In this study, the energy inputs for LPG are based on the energy to operate the distillation column and LPG recovery unit.

1.11 History of LPG LCA

1.11.1 Literature for Life Cycle Analysis Models, Studies, and Data

LPG is included in fuel LCA models for the applications described in section 1.10. The literature on life cycle studies includes an LPG component because LPG is a co-product of oil and gas production. Emissions are often included because LPG is used for corn drying or other industrial uses. The treatment of LPG varies considerably among LCA studies due primarily to differences in allocation procedures, energy intensity for oil refining, and leakage rates for natural gas processing.

The following summarizes fuel LCA studies, which include a variety of fuels as well as LPG. The documentation and issues with fuel LCA studies are described in a study by the Coordinating Research Council (Stefan Unnasch, Riffel, et al., 2011). Each of the LCA models discussed is described by the developers as indicated in Table 1.11. Issues with co-products, system boundaries, and other factors are addressed to a limited degree in all of these studies ((Connor, 2011), (Wang et al., 1999), (Messagie, Boureima, Coosemans, Macharis, & Mierlo, 2014)). Unfortunately, no consensus on key LCA issues such as co-products, system boundaries, land use conversion, and many other parameters has been reached in the literature. Several studies from ANL document the GREET model and inputs. The JRC in Europe has completed a series of studies examining fuels in the European context (Edwards, Larive, Rickeard, & Weindorf, 2013). The JRC study provides the basis for the BioGrace model (JRC, 2012). All of the models examine fuel pathways that are parallel to aviation pathways such as petroleum diesel, rapeseed renewable diesel (RD), and biomass FT diesel. The documentation does not focus on LPG, but the analysis of kerosene is essentially the same as that of LPG with different yields and changes in energy inputs. Modifying the models for LPG pathways is straightforward assuming that data on energy inputs and yields are available.

LPG, as a co-product of natural gas and petroleum fuel production, plays a key role in all fuel LCA studies. First, LPG represents approximately 23% and 5%, of the energy produced from these resources respectively (EIA, 2015j). Therefore, LCA studies distribute emissions associated with oil and natural gas production between the primary products and secondary co-products. Most fuel LCA studies use some variant of energy allocation to distribute emissions between LPG and other petroleum products. Secondly, LPG is used as a process fuel in many industrial applications. For example, LPG is used for corn drying and is a contribution to corn ethanol pathways.

Table 1.11. Fuel Cycle Models and Studies -Model Documentation

Primary Author	Year	Organization	Location of Use	Primary Feedstocks	Models
Delucchi	1998	UC Davis	U.S.	Crude Oil Natural Gas Veg Oils	LEM
JRC	2011	JEC	Europe	Crude Oil Natural Gas Veg Oils	JRC/ LBST Database
Neeft	2012	Intelligent Energy Europe	Europe	Crude Oil Natural Gas	BioGrace
O'Connor	2011	(S&T)2	Canada	Crude Oil Natural Gas	GHGenius
Wang	1999	ANL	U.S.	Crude Oil Natural Gas Veg Oils	GREET
Wang	2014	ANL	U.S.		
Messagie	2014	Universiteit Brussel	Europe	Crude Oil Natural Gas	JRC/ LBST Database

These studies support a range of policies including the Renewable Fuel Standard (RFS2). EPA documented the analysis for the RFS2 in an extensive regulatory impact analysis (EPA, 2010). Several studies support policies for California State agencies (Pont et al., 2007; S Unnasch & Pont, 2007). The ARB also documents fuel pathways for the LCFS. This study identifies the key differences in feedstock to fuel yield and other energy inputs for LPG compared to on-road diesel and gasoline.

Table 1.12 summarizes many of the LCA studies that focus on a single fuel pathway with applicability to either renewable or baseline petroleum fuels. The studies ((Morais, Mata, & Ferreira, 2010), (Brinkman, Wang, Weber, & Darlington, 2005), (Wallace, Wang, Weber, & Finizza, 2001)) include a range of feedstocks and fuel products. On-road transportation fuels are the focus of most of the studies. Nonetheless, they provide a great deal of detail on feedstock production and fuel conversion. Again, the co-product methods and sources of LCI data are key differences among the studies. Some studies are based on process simulations or projections for future fuel production facilities. ARB requires fuel producers to publish their pathway documents to determine the CI and the LCFS. However, fuel producers normally do not reveal LPG yields in their LCFS applications. The stoichiometric quantity of bio-propane propane from renewable diesel (RD) is about 5% of the RD; which provides a basis for estimating the CI of bio-propane.

Table 1.12. Fuel Cycle Models and Studies – Pathway Comparison and Policy Support

Primary Author	Year	Organization	Location of Use	Primary Feedstocks	Models
Morais	2008	Polytech Portugal	Portugal	Soybean Oil	GaBi
ARB	2009a 2009b	ARB	CA	Crude Oil Veg Oils	CA_GREET1.8b
Brinkman	2005	GM/ANL	USA	Crude Oil	GREET1.6
EPA	2010a	EPA	USA	Veg Oils B	GREET1.8c
Pont	2007	TIAX	CA	Crude Oil Natural Gas Veg Oils	CA_GREET1.7
Unnasch	1996	Acurex	CA	Crude Oil Natural Gas	Database Calculation
Wallace	2001	GM/ANL	USA	Crude Oil	GREET
Unnasch	2001	Arthur D. Little	CA	Crude Oil Natural Gas	Database Calculation

1.11.2 Challenges with LPG Life Cycle Analysis

Several challenges are related to the analysis of LPG in transportation fuel LCA, such as natural gas and oil refinery co-product allocation, vehicle criteria emission pollutants, and vehicle efficiency. Table 1.13 outlines the issues with the current studies, the methods used, and an assessment of the issues. The most significant issue is the role of LPG as a co-product and the higher levels of LPG production with more intense refining to produce cleaner gasoline and diesel. Higher levels of hydrocracking and other operations will produce more LPG. Hydrogen production and unit operations associated with these steps are inappropriately distributed to LPG rather than to the gasoline and diesel fuels that are the intended output of these refinery units.

Table 1.13. Issues with LPG Fuel LCA

Study	Methods	Assessment/Issues
Natural Gas Allocation		
ANL, GREET1	Develop production and extraction efficiency inputs from U.S. aggregate statistics (Wang 1999). Energy inputs used to calculate efficiency are allocated between natural gas and LPG externally to GREET.	Method appears appropriate. Aggregate data are not reviewed and converted to GREET inputs. Uncertainty in methane emissions result in wide range in CI for different model releases.
ARB, CA_GREET3.0	GREET approach, allocation to natural gas	Relies on data with limited review.
JRC, WTW	Considered the marginal LPG imported to Europe from natural gas field condensate.	Limited review of data. No input from crude oil derived LPG
Oil Refinery Allocation		
ANL, GREET1	Input refinery efficiency based on EIA data and refinery modeling. Most recent modeling based on LP study by PADD for gasoline and diesel.	Approach does not reflect unintentional co-product nature of LPG.
ARB, CA_GREET3.0	Based on GREET1_2016	No review of LPG approach. Does not reflect low value co-product.
Jacobs Crude Oil	Tracked flows of all feeds and products through refinery units using PetroPlan model. Substitution approach to assign natural gas based LPG to LPG co-product, coal to petroleum coke, and hydroskimmer fuel oil to residual oil.	Interim CI for LPG is misleading. Assigns hydrogen production and energy for cleaner gasoline and diesel production (hydrocracking, etc.)
JRC, WTW	EU-wide aggregated refining model for gasoline and diesel	Limited review of data. No input from crude oil derived LPG
This Study	Assign refinery efficiency based on straight run LPG from crude distillation column.	Same approach as used for kerosene in GREET. Does not assign emissions for producing cleaner gasoline and diesel to LPG.

Table 1.13 Ctd. Issues with LPG Fuel LCA

Study	Methods	Assessment/Issues
Vehicle Criteria Pollutants		
ANL, GREET1	Assumed same criteria pollutant emissions as baseline gasoline vehicles. 80% of evaporative VOC. Fugitive emissions are zero.	Assessment of emission reductions depends on which category (bin) vehicles are certified in and engine manufacturer's certification strategy. Comparison of vehicle emissions would also need to take into account degradation over time. Data from emission tests is limited. LPG is expected to have intrinsically lower emissions such as particulate matter due to its molecular structure, but such benefits need to be examined to appropriate baseline vehicles.
CEC AB1007	Assumed same criteria pollutant emissions as baseline gasoline and diesel vehicle because vehicle must be certified to same standards. Baseline vehicle data from EMFAC model. Evaporative emissions are zero.	
JRC, WTW	No criteria pollutants in upstream fuel cycle. Modeling of vehicle performance and energy consumption based on compliance with emission standards.	Vehicles assumed to comply with comparable standards for optimized vehicles.
This Study	Reviewed emission results for LPG vehicles.	Review data. Assessment of criteria pollutant effects are not in the study scope.
Vehicle Efficiency		
ANL, GREET	Assumed EER of 1.05 for passenger car and light truck LPG vehicles.	Limited modeling data to support efficiency improvement based on higher octane and other fuel properties.
CEC AB1007	Assumed EER of 1.00 for light-duty LPG vehicles.	Reasonable estimate given limited certification and chassis dynamometer data for LPG vehicles.
JRC, WTW	Perform drive cycle modeling with ADVISOR based on hypothetical identical vehicles. Model result was EER of 1.00 for LPG passenger car.	Uncertainty in choice of engine map.

1.11.3 Secondary effects of LPG in fuel LCA

The issues highlighted in Table 1.13 are pervasive to all fuel pathways where LPG is a co-product. The consequence of incorrect allocation or emissions inventories assigned to LPG is that all other pathways where LPG is a co-product are also incorrect.

2. LPG Life Cycle Analysis

2.1.1 Fuel Life Cycle Analysis

Fuel LCA is a distinct discipline within LCA methods, the objective of which is to use one model with a consistent set of assumptions. The analysis is designed to treat broad categories of fuels on a consistent basis, generally using a single model, i.e. GREET. A fuel cycle analysis typically includes impacts related to the production of feedstocks, transport, refining, distribution, and vehicle fuel consumption. The CI of a new transportation fuel depends on the energy inputs to the fuel production system as well as agricultural inputs, treatment of co-products, location-specific parameters (e.g. electricity grid), and fuel blending requirements.

LCA models calculate a range of environmental flows including energy inputs, GHG emissions, criteria pollutants, air toxics, water use, land use, and others. Such analyses are typically limited to the set of traditional direct and upstream fuel cycle impacts, i.e. the Well-To-Tank (WTT) or upstream emissions. The fuel combustion emissions, i.e. Tank-To Wheel (TTW) or direct emissions are treated as invariant amongst the different pathways. ARB performs external analyses to determine the TTW emissions of various fuel pathways. The results are published annually in a series of lookup tables (ARB, 2013).

The total fuel life cycle is termed the Well-To-Wheels (WTW) and is the sum of the WTT and TTW emissions (Stefan Unnasch & Riffel, 2012; M Wang, 1999). WTW pathway steps include impacts related to the production of feedstocks, transport, refining, and distribution. Some LCA parameters or process steps are either excluded from the analysis or considered separately. For example, the impact of constructing fuel production facilities, vehicle production, and recycling are not included in a fuel pathway analysis. The pathway steps considered in an LCA are defined in a system boundary diagram. Figure 2.1 shows the generic fuel pathway steps and their association in the overall WTW fuel pathway.

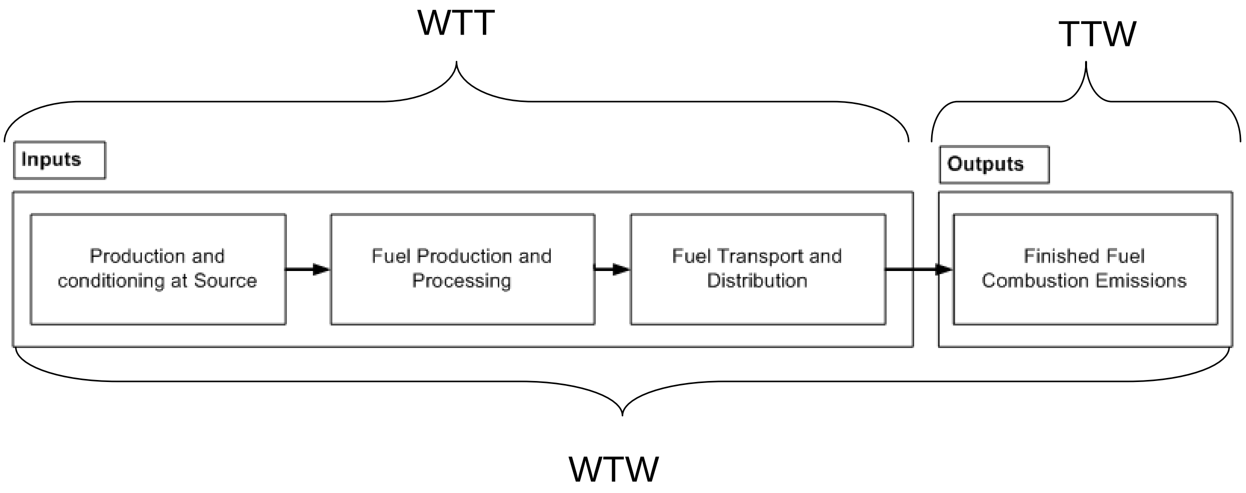

Figure 2.1. Fuel Pathway Steps in WTW Analysis

2.2 Goal and Scope Definition

The goal of this study is to calculate the WTW GHG emissions for LPG vehicles and other end use applications using the modeling tools consistent with the California LCFS and other fuel policy regimes. The carbon-intensity of each fuel is calculated on a full WTW lifecycle basis, which includes GHG emissions from production of a feedstock, transport, refining of the fuel product, finished fuel distribution, and end-use combustion.

The steps in the fuel cycle of petroleum fuels are shown in Figure 2.2. The primary pathways for LPG are as a co-product of petroleum- or natural gas-derived fuels. LPG is assigned a share of the emissions from oil production and transport to oil refineries. The generic pathway steps for crude oil and natural gas production are shown in parallel. The steps in the fuel pathway are consistent with conventional oil and gas pathways, with different assumptions on processing efficiency and transportation mode.

The sources of emissions for each step in the full fuel lifecycle are shown in Table 1.9 in Section 1.10.1. These groupings correspond to the calculation steps in the GREET model. This scope of emission sources is consistent with fuel pathways examined under the LCFS. Construction of fuel production and processing systems as well as vehicles are not included in the analysis.

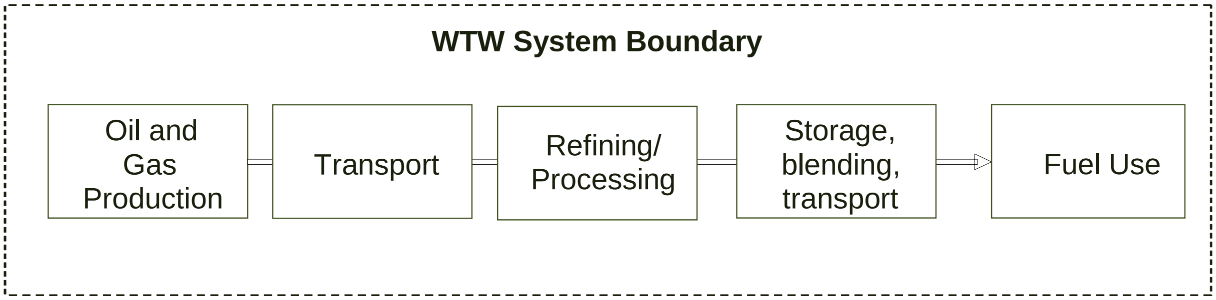

Figure 2.2. Steps in Fossil Fuel Life Cycle

This study examines the energy inputs and emissions associated with LPG vehicle operation based on the environmental impact of LPG as a co-product of natural gas production and crude oil refining as well as other sources. Model inputs reflect the incidental production of LPG from refinery unit processes. The inputs reflect the lower co-product value of the LPG and allocate the emissions to the marginal unit of LPG.

For renewable feedstocks, bio-propane can be considered a co-product based on energy allocation as the fuel is a new transportation fuel product. The burden of emissions would be shared between bio-propane and renewable diesel.

2.3 Scope

This study examines the WTW emissions for LPG productions from petroleum, natural gas and bio-oil. The steps in the process are shown in Table 2.1 for each step in the WTW process.

Table 2.1. WTW Emissions Step

Feedstock	Natural Gas	Crude Oil	Bio-Oil
Fuel	LPG	LPG	Bio-LPG
WTT Feed	NG Production	Crude Oil Production	Veg Oil Production
	Fugitives emissions	Fugitives emissions	Fugitives emissions
WTT Fuel	NG Processing	Refining	Veg. Oil Hydro-processing
	LPG transport	LPG transport	LPG transport
	LPG fueling	LPG fueling	LPG fueling
TTW Phase	Vehicle emissions	Vehicle emissions	Vehicle emissions

2.4 Life Cycle Criteria

2.4.1 GHG Emissions

GHG impacts are compared through the global warming potential (GWP) weighted emissions for the primary GHG emissions associated with fuel combustion – CO_2, CH_4, and N_2O. GHG emissions are weighted according to the International Panel on Climate Change (IPCC) Fourth Assessment Report (2007) assessment. Emissions of these gases are weighted by factors of 1, 25, and 298 respectively. These values are used in the CA_GREET2.0 and 3.0 models used for the LCFS. In GREET1_2014, the Global Warming Potential (GWP) values are revised to 1, 30, and 265 for CO_2, CH_4, and N_2O respectively based on the IPCC Fifth Assessment Report (2013).

The GWP value of 25 for methane does not include the fully oxidized CO_2 from methane combustion, which would add 2.75 to the GWP of methane if it were included in the GREET calculations.

2.4.2 Functional Unit

The GREET model calculates emissions in WTT and TTW steps. The WTT emissions include those associated with producing feedstock through to its distribution. These emissions are presented per million Btu (mmBtu) of fuel in the model. The vehicle emissions are represented per mile traveled and are calculated based on the carbon in fuel per mmBtu and fuel use per mile. GREET outputs are all presented in g/mi. These outputs are highly aggregated and difficult to compare to other LCA model results. For example, when comparing results from different LCA models, a different baseline gasoline vehicle fuel economy would prevent a simple comparison all the g/mi results from alternative fuel options.

In this study, WTW emissions are reported per MJ of fuel. The TTW emissions include fully oxidized carbon as CO_2, as well as CH_4 and N_2O emissions from vehicle fuel combustion. This approach is used within California LCFS regulations. GHG emissions presented in this manner are referred to as the particular fuel’s carbon intensity (CI). The effect of vehicle efficiency on TTW emissions is also adjusted with an energy economy ratio (EER).

2.5 Energy Economy Ratio

The vehicle fuel efficiency differs among some alternative fuels. The Energy Economy Ratio (EER) compares the fuel economy values of different alternative fuel vehicles against comparable gasoline and diesel vehicles. This ratio is based on the lower heating value of the fuel. The fuel consumption or efficiency of engines is important because different types of vehicles use the energy in fuel more or less efficiently. For example, ARB estimates an electric car will travel 3.4 times as far as a comparable gasoline vehicle for the same amount of fuel energy. Similarly, ARB estimates that a heavy-duty natural gas vehicle travels 0.9 times as far as a comparable diesel heavy-duty vehicle for the same amount of fuel energy.

The EER is defined as the fuel economy of the alternative fuel vehicle in miles per gallon equivalent (mpge) of the alternative fuel, divided by the fuel economy of a reference fuel, such as gasoline or diesel. ARB uses the EER values to adjust LCFS credits by taking the differences in fuel economy into account, where necessary, by multiplying the EER by the number of MJ in the alternative fuel. For example, for diesel, biodiesel, or renewable diesel, the EER is 1.0, so no adjustment is necessary, however, for natural gas used in heavy-duty diesel applications the EER is 0.9, so the energy in the alternative fuel is multiplied by the relevant EER value to account for the fuel economy.

The properties of LPG could enable a more efficient spark-ignited engine compared to gasoline due to the higher octane number of LPG compared to gasoline. The greater heat of vaporization of low molecular weight hydrocarbons and propane’s rapid rate of vaporization can also provide improved charge air cooling, which can reduce engine pumping losses. These properties could result in propane engines with EER values above 1.0.
Table 2.2 shows the ARB LCFS EER values for fuels used in light-, medium-, and heavy-duty applications as well as the assumed EER values for LPG fuel. The EER for LPG is assumed to be the same as for natural gas applications. For heavy-duty fumigated diesel engines, the same efficiency as diesel is possible and assumed here.

Table 2.2. Energy Economy Ratio (EER) Values for Fuels Used in Light- and Medium,-Duty, and Heavy-Duty Applications.

Light/Medium-Duty Applications (<u>Fuels used as gasoline replacement</u>)		**Heavy-Duty/Off-Road Applications (<u>Fuels used as diesel replacement</u>)**	
Fuel/Vehicle Combination	**EER Relative to Gasoline**	**Fuel/Vehicle Combination**	**EER Relative to Diesel**
Gasoline/ SI ICEV	1	Diesel / DI ICEV	1
		Biodiesel. / DI ICEV	1
E10, E85/ SI ICEV	1	Renewable Diesel / DI ICEV	1
CNG / ICEV	1	CNG or LNG / SI ICEV	0.9
LPG / SI ICEV (Assumed)	1	LPG / SI ICEV (Assumed)	0.9
		LPG / DI ICEV (Assumed)	1
Electricity / BEV, or PHEV	3.4	Electricity/ HD Bus	4.2
Hydrogen (H_2) / FCV	2.5	H_2 / FCV	1.9

BEV = battery electric vehicle, PHEV=plug-in hybrid electric vehicle, FCV = fuel cell vehicle, SI ICEV = spark-ignited internal combustion engine vehicle.

Source: (ARB, 2014c, 2015)

3. Fuel Pathways and TTW Emissions

Fuel LCA models provide a range of methods for calculating the energy inputs and emissions for fuel pathways involving LPG. This section describes how natural gas, petroleum and the bio-oil pathways are used to calculate life cycle GHG emissions. Each feedstock is processed to a variety of fuels and co-products, including LPG. The default approach in GREET is described followed by an assessment of the treatment of LPG that reflects its role in the California energy production system.

A key factor in the evaluation of LPG emissions is the allocation approach to products and co-products. Several principles have been considered for LPG, natural gas, and petroleum fuels in various studies identified in Section 1 (Edwards, 2007; W. Keesom et al., 2012; William Keesom et al., 2009; M Wang, 1999). The primary allocation approaches are:

- Allocate emissions to all transportation fuels equally
- Perform process specific allocation based on refining intensity
- Analyze incremental emissions for fuel production based on refinery model
- Treat LPG as a co-product with marginal source from natural gas

Allocation methods are discussed in further detail in Section 3.4.

Briefly, the GREET allocation methods used for crude oil refining, natural gas recovery, and bio-oil hydro-processing are based primarily on tracking the energy flows in the fuel production system. The GREET approach follows material and energy flows through individual oil refining processes or natural gas processing and allocates energy use to finished fuel products and co-products. The GREET model runs based on energy inputs, where an external allocation share defines the input for each fuel, i.e. the inputs are based on energy allocation and the calculations are based on a post-allocation energy/unit product.

This study examines the approaches in numerous LCA models and then develops a case based on the incremental effect of the using LPG as a transportation fuel. The base case for this study is consistent with the GREET approach with refinery emissions that reflect the role of LPG in an oil refinery (see section 3.4.2 for more detail on the refinery energy and emissions allocation). Table 3.1 shows the fuel pathway feedstock and emissions allocation approach used in GREET and this study.

Table 3.1. Fuel pathway feedstock and emissions allocation approach.

Feedstock/Process	Products	Allocation approach
Natural Gas/ Gas Processing Plant	Pipeline gas LPG Condensate	Energy Allocation
Crude Oil [a] /Oil Refining	Gasoline Diesel, Jet, LPG, Residual Oil, Pet. Coke, Naphtha	Sub-process Allocation
Bio-Oil/ Hydro-processing	Diesel, Jet, Naphtha, LPG	Mass Allocation [b] & Energy Allocation
Municipal Solid Waste / Gasification, FT Synthesis [c]	Diesel, Naphtha, LPG	Energy Allocation

[a] The base case for this study treats LPG as a straight run product with similar refinery efficiency and fuel shares to naphtha.

[b] Animal feed from soybean meal and other oil seeds is treated with mass allocation. Soybean meal has the same GHG intensity as the oil seed on a per kg basis.

[c] GREET is configured with a biomass to FT fuel pathway. The same allocation approach could be applied to other thermochemical biomass to FT fuel pathways.

3.1 Natural Gas to LPG

Natural gas wells, crude oil wells, and associated gas wells from hydraulic fracturing, “fracking”, are all sources of natural gas. Most natural gas in the U.S. is produced from conventional gas wells with a substantial growth in production from hydraulic fracturing in recent years. GHG emissions from natural gas (NG) production are associated with well operation, separation, and fugitive emissions. The energy inputs for production are expressed as extraction efficiency. Extraction occurs mostly in isolated areas with heavy infrastructure requirements for safe extraction and processing. Gas transportation requires pressurized pipeline networks or liquefaction equipment.

Raw natural gas is composed of mainly methane (CH_4), with varying quantities of amounts of light hydrocarbons (C_2 to C_5), termed natural gas liquids (NGLs), and inert gases (N_2 and CO_2). The C_3 and C_4 hydrocarbons are the LPG components (propane and butane). NGLs represent approximately 23% of the unprocessed gas stream, and LPG constitutes approximately 87% of the NGL stream (EIA, 2015j).

Natural gas pathways consist of extraction, processing, and transmission of gas for end use. The GREET approach allocates emissions between natural gas and LPG. Calculations external to the GREET model treat LPG as a proxy for all natural gas liquids (condensate). This approach reduces the emissions burden on natural gas and shares the emissions with LPG.

3.1.1 Natural Gas System Boundary

The system boundary diagram for natural gas to LPG is shown in Figure 2.1. LPG is treated as a co-product of natural gas production. Energy inputs and emissions for the natural gas recovery (extraction) and processing steps are allocated between natural gas and LPG. The allocation is performed externally to GREET. The emissions per MJ fuel for these steps are the same for the natural gas and LPG pathways.

The transmission step is modeled as pipeline transport to an LPG production facility where LPG is separated from other natural gas liquids. Finally LPG is distributed for end use by rail, pipeline and/or truck.

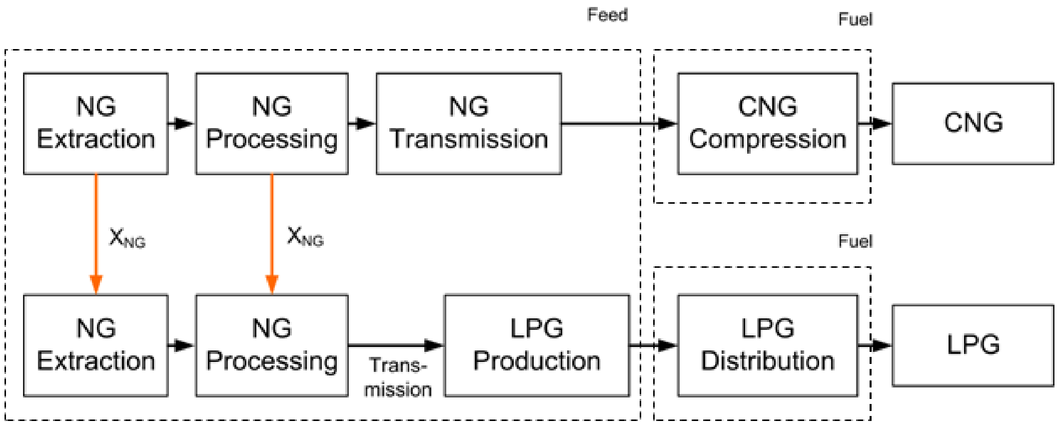

Figure 3.1. System Boundary Diagram for Natural Gas Fuel Pathways, GREET Allocation and Refinery Efficiency Method.

3.1.2 Natural Gas Pathways

The energy and emission intensity depends on the processing steps, transport, and fugitive methane emissions. The life cycle GHG emissions are calculated in the GREET models based on extraction and production efficiency, fugitive leakage, and transport distance. Upstream fuel cycle data for natural gas are constructed from aggregate extraction and processing efficiencies and fugitive emission data (ARB, 2014c; Elgowainy et al., 2014; Forman, Divita, Han, Cai, Elgowainy, et al., 2014; S Unnasch & Pont, 2007; M Wang, 1999). The GREET model represents data on gas production and recovery as efficiencies. For gas recovery based on 100% natural gas for processing fuel, the emissions for gas recovery (E_{NGRec}) are calculated as;

$$E_{NGRec} = (1/\eta_R - 1) \times (EF_{NGICE} + E_{NG})$$

Where EF_{NGICE} represents the emissions factor for natural gas combustion equipment and E_{NG} represents the upstream fuel cycle emissions for natural gas. A recovery efficiency of 97.2% corresponds to 22,016 J of natural gas input per MJ of natural gas that is recovered. E_{NG} is based on a recursive calculation that includes gas recovery and processing steps (Section 3.1.4).

3.1.3 Natural Gas Production

Natural gas production involves energy inputs to operate pumps, separators, and other equipment. Emissions from the venting and flaring of produced gas are also part of the natural gas fuel cycle (ARB, 2014c, 2015; Adam R Brandt & Unnasch, 2010; El-houjeiri & Brandt, 2013; William Keesom et al., 2009; Michael Wang et al., 2004). Hydraulic fracturing (fracking) uses high pressure liquids injection to increase natural gas output, though most of the energy inputs are associated with compressor energy.

The GREET model estimates emissions from natural gas processing and assigns the emissions to CNG, LNG and LPG. The key input is the extraction efficiency, which translates into energy used per mmBtu of product fuel. Emissions from fugitive methane correspond to the variations in GREET model estimates of the carbon intensity of natural gas based pathways. The inputs that correspond to methane leaks and losses in CA_GREET3.0 are shown in Table 3.2.

Table 3.2. Methane Leak Assumptions in CA_GREET3.0

	Emissions (g/MMBtu of NG)	
Natural Gas Processing Step	Conventional NG	Shale gas
Recovery - Completion CH_4 Venting	0.5	11.8
Recovery - Workover CH_4 Venting	0	2.4
Recovery - Liquid Unloading CH_4 Venting	9	9
Well Equipment - CH_4 Venting and Leakage	134.9	134.9
Processing - CH_4 Venting and Leakage	26.2	26.2
Transmission and Storage - CH_4 Venting and Leakage per 680 miles	74.6	74.6
Distribution - CH_4 Venting and Leakage	17.7	17.7

Table 3.3 summarizes the extraction and processing assumptions used in CA_GREET models, and the ANL GREET models. All GREET results are modeled for the year 2015. Estimates of the methane loss have varied considerably as estimates of leaks associated with shale gas and other gas production processes have been evaluated over the years (A. R. Brandt, Boak, & Burnham, 2010; Burnham, 2012). For this study, the CA_GREET3 inputs are used for the analysis of natural gas based LPG. The fugitive methane emissions are based on GREET1_2016.

Table 3.3. Key Inputs for Natural Gas Recovery

GREET Version [a,b]	**This Study**	**CA _3.0**	**CA_ 2.0**	**1_2016**	**1_2014**	**1_2013**	**1_2012**	**1_1.8c**	**CA_ 1.8b**
Scenario Year	2014	2014	2010	2015	2015	2015	2015	2010	2014
Share of Conventional and Shale Gas for North America NG Supply									
Conventional Gas	49.8%	49.8%	77.2%	48.5%	77.2%	77.2%	77.2%	100.0%	100.0%
Shale Gas [c]	50.2%	50.2%	22.8%	51.5%	22.8%	22.8%	22.8%	--	--
Recovery Efficiency									
NA NG	97.5%	97.5%	97.2%	97.5%	97.2%	97.2%	95.7%	97.2%	97.2%
NA Shale Gas	97.6%	97.6%	97.1%	97.6%	97.1%	97.1%	96.5%	--	--
NG Recovery and Processing Energy Use (Btu/mmBtu)									
Total	79,979	79,979	75,442	79,426	76,758	73,554	86,783	63,966	64,418
Fossil fuels	79,454	79,454	74,507	78,984	75,849	73,138	86,376	63,552	64,020
Coal	1,473	1,473	390	1,248	3,301	1,763	1,724	2,004	2,009
Natural gas	73,892	73,892	69,961	73,784	68,481	67,256	80,578	57,402	57,809
Petroleum	4,090	4,090	4,156	3,953	4,068	4,118	4,074	4,146	4,202
Natural Gas Processing Fugitive Emissions (g/mmBtu)									
Natural gas flared	10,486	10,486	8,370	10,486	8,370	6,870	7585	0	0
VFF CH_4 [f]	171	171	89	171	89	107	430	107	105
GHG Emissions (g CO_2e/MJ)									
Feedstock Recovery	10.61	10.61	7.49	10.59	8.19	8.09	14.38	7.56	7.70

[a] All GREET results modeled for the scenario year stated. Note that CA_GREET3.0 opens up in scenario year 2014. Changing the scenario year has about a 0.03 g/MJ effect on the GHG emissions.

[b] ANL (Argonne National Lab) updates GREET refinery efficiency periodically, supported by brief reports from ANL

[c] Data for Natural Gas production and processing, Shale gas parameters added to GREET from 2012 onwards.

[e] Non combustion emissions from North American natural gas processing

[f] Venting, Flaring and Fugitive Emissions.

3.1.4 Natural Gas Processing

Similarly, natural gas processing emissions (E_{NGP}) are calculated from an aggregate processing efficiency (η_P) and emission factor for natural gas boilers (EF_{NGB}) such that:

$$E_{NGP} = (1/\eta_P - 1) \times (EF_{NGB} + E_{NG})$$

with the total upstream for natural gas production given by the recursive calculation:

$$E_{NG} = EF_{NGRec} \times L + E_{NGP}$$

where L represents the losses from processing and transmission.

The amount of each fuel type utilized in each different combustion device to produce a unit of natural gas, is an input ($S_{i,k}$). The WTT results is based on the weighted average for each fuel resource.

Table 3.4 shows the natural gas recovery efficiency and product specific energy efficiency for each of the natural gas products.

Table 3.4. Natural Gas Recovery and Product Processing Energy Efficiency

Processing Step	**CA_3.0**	**CA_2.0**	**1_2016**	**1_2014**	**1_2013**	**1_2012**	**1_1.8c**	**CA_ 1.8b**
Scenario Year	2014	2010	2015	2015	2015	2015	2010	2010
Natural Gas recovery	97.5%	97.2%	97.9%	97.2%	97.2%	95.7%	97.2%	97.2%
<u>Natural Gas Processing</u>								
Natural Gas to Pipeline Gas	97.0%	97.9%	97.9%	97.9%	97.9%	97.1%	97.3%	90.0%
Natural Gas to LPG	96.5%	96.5%	96.5%	96.5%	96.5%	96.5%	91.0%	96.5%

The specific energy consumption for each fuel type provides the calculation basis for combustion emissions. As mentioned above, specific energy is the amount of each type of fuel consumed per unit of NG produced (Btu/mmBtu) for each combustion device. The fuel resource mix, combined with efficiency of each generation device provides the basis to calculate the specific energy. Table 3.5 shows the key processing inputs for natural gas to LPG with the recent GREET models.

Table 3.5. Processing Inputs for Natural Gas to LPG

GREET Version	**This Study**	**CA_GR_3.0**	**CA_GR_2.0**	**1_2016**	**1_2014**	**1_2013**	**1_2012**	**1_1.8c**	**CA_GR_1.8b**
Scenario Year	2014[a]	2014	2010	2015	2015	2015	2015	2010	2010
Efficiency	96.5%	96.5%	96.5%	96.5%	96.5%	96.5%	96.5%	96.5%	96.5%
Energy Use (Btu/mmBtu)[b]									
Residual oil	0	0	0	0	0	0	0	0	0
Diesel fuel	363	363	363	363	363	363	363	363	363
Gasoline	0	0	0	0	0	0	0	0	0
Natural gas	34,819	34,819	34,819	34,819	34,819	34,819	34,819	34,819	34,819
Electricity	1,088	1,088	1,088	1,088	1,088	1,088	1,088	1,088	1,088
Non Combustion Emissions (g/mmBtu)									
CO_2	819	819	849	819	810	849	0	0	0
GHG Emissions (g CO_2e/MJ) [c]									
Loss factor	1.0001	1.0001	1.0001	1.0001	1.0001	1.0001	1.0001	1.0001	1.0001
Fuel Processing	**5.01**	**5.01**	**4.66**	**4.91**	**6.43**	**6.79**	**3.38**	**3.25**	**3.18**

[a] Scenario year is specified in CA_GREET. The effect of newer scenario year is minor.

[b] This is the direct energy use in the fuel processing (excludes upstream energy). This energy is calculated by (1-1/efficiency) × fuel share

[c] Region for natural gas LPG is US Average.

3.2 Petroleum to LPG

Crude oil refineries produce refined petroleum products (petroleum, diesel), liquid refinery gases (ethane, propane and butane) and a range of other co-products such as residual oil, petroleum coke, sulfur, waxes and asphalt. The refinery operates to provide gasoline and diesel to meet various specifications. LPG is the incidental co-product of many refinery unit operations, such as atmospheric distillation, reforming, cracking, etc. U.S. refineries convert between 1% and 6% of crude oil into LPG (EIA, 2015f, 2015j). This yield depends on the type of crude oil, the degree of complexity of the oil refinery, as well as the market values of propane and butane compared to other refined products and refinery fuels.

The GREET approach allocates emissions between other transportation fuels and LPG and this approach reduces the emissions burden on gasoline and diesel and increases the emissions assigned to LPG.

3.2.1 Petroleum System Boundary

The system boundary diagram for refinery-based LPG production with the allocation system used in GREET is shown in Figure 3.2. Energy inputs and emissions for crude oil are based on inputs that reflect an allocation to crude oil and natural gas production.[10] GREET inputs for refining emissions are based on a refining intensity calculated from "refinery efficiency" inputs for each product. ANL has refined this approach to take into account the combustion of fuel, such as petroleum coke (Forman, Divita, Han, Cai, Elgowainy, et al., 2014). This refinery allocation scheme does not, however, accurately reflect the impact of LPG as discussed in Section 3.4. LPG is then transported to storage terminals by pipeline, (in some parts of the US), rail car and truck and delivered to fuel stations.

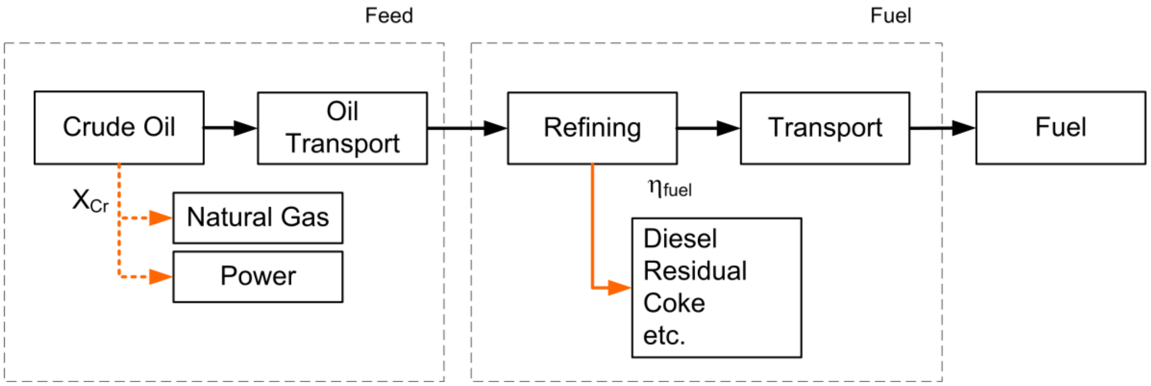

Figure 3.2. System Boundary Diagram for Petroleum Fuel Pathways, GREET Allocation and Refinery Efficiency Method.

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[10] Note that the OPGEE model used under the LCFS has the flexibility to use the substitution method for co-produced natural gas.

3.2.2 Petroleum Pathways

The petroleum fuel cycle includes energy inputs and emissions related to the production of crude oil, transport of crude oil to refineries, refining of the oil, and distribution of the finished products as illustrated in Figure 3.2. The fuel cycle analysis takes into account energy inputs, emissions, and losses associated with each step in the petroleum production process. Losses in the fuel cycle are accounted for by applying a loss factor to the amount of upstream energy used.[11]

3.2.3 Crude Oil Production

Crude oil production involves energy inputs to operate pumps, separators, and other equipment. Emissions from the venting and flaring of produced gas are also part of the petroleum fuel cycle (Adam R Brandt & Unnasch, 2010; W. Keesom et al., 2012; William Keesom et al., 2009; M Wang, 1999; Michael Wang et al., 2004). In California, thermally enhanced oil recovery (TEOR) projects use steam to increase crude oil output. Some steam generation systems co-generate electric power.

Field Specific Crude Oil Estimates

The Oil Production Greenhouse gas Emissions Estimator (OPGEE) model developed by researchers at Stanford University is designed to measure the GHG emissions from the production, processing, and transport of crude oil (El-houjeiri & Brandt, 2012, 2013). ARB uses OPGEE to quantify emissions from crude oil pathways in California from site specific blends. The California crude oil average GHG intensity is the volume weighted contribution of each blend to the total refinery stocks.

The California crude oil average CI is the volume weighted contribution of each crude oil stock to the total refinery stocks. The crude stocks and imports to California and average CI are publish yearly in lookup tables (ARB, 2012, 2013).

Fuel pathway GREET inputs are based on the crude oil type, energy to operate equipment, and fugitive emissions. These parameters vary with different versions of GREET and by crude oil type and region (El-houjeiri & Brandt, 2012, 2013). Table 3.5 shows the inputs for crude oil production with the GREET models and California OPGEE. The resultant GHG intensity for crude oil production is also shown.

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[11] Note that the GREET model only applies the loss factors for fuel cycle activities to the transportation, storage, and distribution activities of the well-to-tank portion of the fuel cycle for petroleum fuels.

Table 3.6. Key Refinery Inputs for Production of Crude Oil Feedstock

GREET Version [a,b]	**This Study**	**CA_3.0**	**CA_2.0**	**1_2014**	**1_2014**	**1_2013**	**1_2012**	**1_1.8c**	**CA_1.8b**
Scenario Year	2014	2014	2010	2015	2015	2015	2015	2010	2010
API Gravity	34.9	34.9	30.7	36.0	30.7	30.7	--	--	--
Extraction Efficiency	93.87%[c]	98.0%	92.6%[c]	98.00%	98.00%	98.00%	98.00%	97.20%	98.00%
Energy Use (Btu/mmBtu)[d]									
Crude oil / SCO	0	204	0	204	204	204	204	0	204
Residual oil	0	204	0	204	204	204	204	255	204
Diesel fuel	26	3,057	32	3,057	3,057	3,057	3,057	2,806	3,061
Gasoline	0	408	0	408	408	408	408	255	408
Natural gas	65.042	12,635	79,826	12,635	12,635	12,635	12,635	21,940	12,633
Electricity	170	3,872	208	3,872	3,872	3,872	3,872	255	3,878
Crude Production Fugitive Emissions (g/mmBtu)									
Flared natural gas	0	0	0	0	0	0	0	0	16,800
VFF CH_4 [e]	155	155	89	155	108	89	89	83	83
VFF CO_2[f]	524	524	1,430	524	120	1,430	1,430	1,237	0
GHG Emissions (g CO_2e/MJ)									
Crude Oil Production	12.29	12.29	11.98	10.25	8.69	8.29	8.06	7.42	7.42

[a] GREET models released from ANL and ARB regional variants

[b] GREET refinery efficiency has been updated periodically, supported by studies from ANL.

[c] The CA_GREET estimates crude oil recovery based on OPGEE. The results from OPGEE are imputed into the GREET model

[d] This is the direct energy use in the fuel processing (excludes upstream energy). This is calculated by (1-1/efficiency) × fuel share. Total life cycle energy is calculated in GREET.

[e] Corresponds to CH_4 emissions during crude processing in oil fields., including amount of CH_4 vented in associated gas.

[f] Venting Flaring and Fugitive (VFF) CO_2 emissions are described in Hao et al.

Crude Oil Refining

For fuel refining, GREET allocates energy inputs and emissions between all products including asphalt. The "refining efficiency" and fuel shares for each refined product encompasses the bundled assumptions regarding allocation of energy inputs and emissions for each fuel product. Refining includes combustion of process fuels including petroleum coke and fuel gas. Combustion energy inputs are based on modeling studies. The energy per mmBtu is represented as a refinery efficiency for each fuel type.

Refinery Emissions

The refinery efficiency and fuel shares are the inputs for calculating energy inputs and emissions for fuel combustion in oil refineries. The fuel use by fuel type (S_i) is based on the refinery efficiency for each fuel, propane in this case (η_{RefP}) and the fuel shares (F_i), such that:

$$S_i = (1/\eta_{RefP} - 1) \times F_i$$

Total refinery emissions are grouped by emissions from fuel combustion plus emissions from internal refinery fuels, and fugitives. Upstream fuel cycle energy from fuel combustion corresponds to the specific energy for each fuel plus the specific energy times the upstream fuel cycle energy for each fuel, such that the energy in the fuel is represented on a per million Btu basis; therefore, the WTT energy for each fuel share consists of 1 plus the upstream fuel cycle components. The upstream emissions to produce 1 mmBtu of crude oil contribute only to the crude oil feed phase.

To calculate the emission, the term that represents 1 million Btu of fuel is replaced with the emission factor for fuel combustion, $EF_{i,k}$, where i and k are fuels and types of combustion equipment, respectively. The following calculation shows the fuel combustion emissions for boilers.

The Fuel Phase includes crude oil refining and finished fuel transport, natural gas combustion, electric power and fugitive emissions from the plant. Minor chemicals are not included in GREET because the emissions are below the cutoff criteria. Transport and distribution of the fuel is also included in the fuel phase.

Sources of Refinery Data

Petroleum refineries convert crude oil into a mix of finished products. U.S. petroleum refineries receive crudes oil from various countries and regions, in addition to domestic crude oil. In 2013/2014, the U.S. had 139 operating refineries with a total annual operating capacity of 6.5 billion barrels (Bbbl) (EIA, 2015e).

Energy efficiencies of petroleum refineries provide the basis for determining the total amount of process energy used for refinery operation. Furthermore, because refineries produce multiple products, the allocation of energy use and the emissions associated with petroleum refineries to various petroleum products is needed to perform WTW analysis of individual fuels, such as gasoline and diesel. In GREET, the overall energy efficiencies of petroleum refineries are used to determine energy efficiencies specific to petroleum products. Table 3.7 shows the overall refining efficiency by PADD based on EIA statistics in 2010 (Cai et al., 2013). These efficiencies serve as inputs for the GREET crude oil pathways. This efficiency metric represents all of the refined product divided by the crude oil and other energy source inputs. Determining the aggregate refinery efficiency does not distinguish between the energy intensity of different fuel products.

Table 3.7. Aggregate Refinery Efficiencies in GREET (LHV Basis)

	PADD					**U.S.**
	1	**2**	**3**	**4**	**5**	**Average**
Refinery Efficiency, η	93.6%	89.7%	89.9%	87.8%	90.1%	90.2%

Source: Cai, et al., 2013

The GREET model estimates emissions from oil refining and assigns the emissions to gasoline blendstock, diesel, LPG, and residual oil. The key input is the refinery efficiency, which translates into energy used per mmBtu of product fuel. Table 3.8 summarizes the refinery efficiency assumptions used in CA_GREET models, and the ANL GREET models. The inputs differ considerably for both baseline gasoline and diesel. The earlier refinery efficiency values were derived from an ANL study that assigns a refining intensity to each petroleum product (Wang, 2004) . This study assumes that LPG is a straight run product and assigns LPG the same efficiency as residual oil or naphtha. See Section 2.4 for a more detailed explanation of the refinery efficiency allocation to co-products. The CA_GREET3.0 inputs were adapted from the GREET1_2016 with some adjustments.

The inputs for petroleum refining have evolved over the years, and differ considerably values for both baseline gasoline and diesel. The CA_GREET inputs were adapted from the GREET 1.8b model with adjustments for CA RFG production. These values were derived from the original 2004 paper from ANL that attempts to assign a refining intensity to each petroleum product (Wang, 2004).

Most recently, Argonne National Laboratory published two papers that examined crude oil refinery emissions in GREET. One paper discusses the linear programming approach to determining refinery emissions (Elgowainy, 2014). A second paper examines variability in refinery efficiency based on regional refinery configuration (Forman, 2014). The Forman paper shows the latest refinery data by PADD, (Forman, 2014). These studies provide a more solid basis for the determination of GREET inputs. A series of reports by Jacobs Consultancy also examined how refinery emissions varied with different crude oil types (Keesom, 2012, 2009). The study found that refinery emissions assigned to gasoline and diesel were higher for heavier crude oils and for more complex refineries. Distinct differences in GHG emissions for gasoline, diesel, and residual oil were determined by following product flows though refinery unit operations. The method of tracking energy flows showed that the yield from crude oil to gasoline was not a 1:1 ratio. The crude to gasoline yields are not explicitly reported but can be deduced by inspecting Tables 5-4, 8-8, and 8-9 in Keesom, 2009. Refining crude oil to gasoline requires about 1.01 to 1.04 Btu of crude oil per Btu of gasoline, depending upon refinery configuration and crude oil type.

The recent studies have provided improved data on the effect of crude oil type, API gravity, and refinery configuration for fuel-specific refinery emissions.

Table 3.8. Key Inputs for Crude Oil Refining

GREET Version [a]	This Study	CA_3.0	CA _2.0	1_2016	1_2014	1_2013	1_2012	1.8c	CA _1.8b
API Gravity[b]	25.2	25.2	30.7	36.0	30.7	30.7	--	--	--
Refining Efficiency									
Gasoline	87.0%	87.0%	89.3%	92.6%	88.6%	89.3%	90.6%	87.7%	87.7%
CA Gasoline	87.2%	87.2%	89.0%	88.6%	88.7%	89.3%	90.6%	87.7%	87.7%
LPG	94.0%	89.5%	89.3%	88.7%	90.8%	89.3%	90.6%	94.3%	94.3%
Residual Oil	94.0%	94.0%	95.7%	90.8%	94.8%	95.7%	96.3%	94.3%	94.3%
Conv. Diesel	85.9%	85.9%	89.3%	94.8%	90.9%	89.3%	90.6%	90.3%	90.3%
Low-S Diesel	85.9%	85.9%	88.0%	90.9%	90.9%	89.3%	90.6%	89.3%	89.3%
Pet Coke	92.2%	92.2%	85.0%	93.2%	92.6%	85.0%	85.0%	85.0%	85.0%

[a] GREET refinery efficiency has been updated periodically, supported by brief reports from ANL.

[b] Efficiency for CA Gasoline corresponds to CARBOB. API gravity shown for CA Crude oil in CA_GREET models.

Alternative Approach To Fuel Refining Used In This Study

Alternative approaches to petroleum pathways have been developed in other fuel LCA studies (William Keesom et al., 2009). Figure 3.3 illustrates how co-products such as residual oil, sulfur, and petroleum coke can be treated as substitute products rather than by allocation, see Section 3.4 for detailed discussion on the allocation approach. The results from the substitution approach depend on other details of the refinery analysis including the carbon intensity of alternative residual oil (for example European hydro-skimming refineries or hydrocracker residual oil) and petroleum coke (substitute for coal or substitute for mix of fuels).

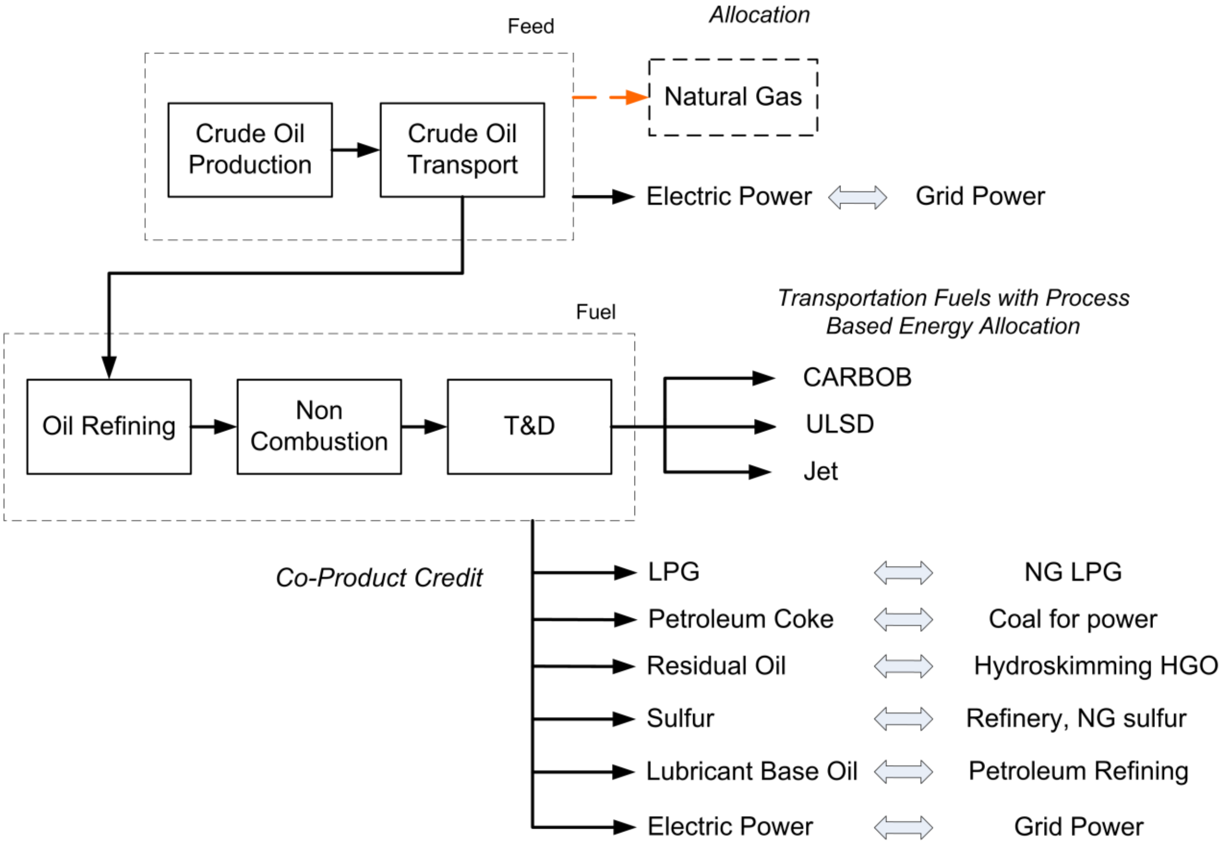

Figure 3.3. Example System Boundary Diagram for Crude Oil to Transportation Fuels Using Substitution Method.[12]

Table 3.9 shows the key refinery inputs for LPG production in crude oil refineries used in this study and the assumptions used in CA_GREET models, and the ANL GREET models. See Section 3.4 for a more detailed explanation of the refinery efficiency allocation to co-products.

Note that GREET1_2014 adjusts the yield factor from crude oil to refined product. This factor differs for each refined product.

This study makes the following assumptions:

- Set refinery efficiency input to same value as residual oil
- Set pet coke combustion to same value as residual oil since Fluid Catalytic Cracking (FCC) unit is not intended to produce propane
- Set hydrogen to zero because hydrocracker is not intended to produce propane
- The emissions from pet coke combustion were re-assigned to gasoline
- The emissions from hydrogen were re-assigned to gasoline and diesel.

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[12] Co-Product Credits describe the amount of emissions which are avoided by the displacement of another product

Re-assigning emissions away from LPG production results in higher emissions from gasoline and diesel. Since LPG corresponds to 1.8% of refinery output and gasoline and diesel correspond to 73.1%, gasoline blendstock and diesel emission increase by 0.14 g CO_2e/MJ. The detailed inputs are in Section 3.4.3.

Table 3.9. Key Refinery Inputs for Refining of Crude Oil to LPG

GREET Version[a, b]	This Study	CA_3.0[c]	CA_2.0[c]	1_2016	1_2014	1_2013	1_2012	1_1.8c	CA_1.8b
LPG Refinery Efficiency	94.0%	89.5%	89.3%	90.8%	90.6%	89.3%	90.6%	94.3%	94.3%
Energy ratio of crude oil feeds to product (mmBtu of crude/mmBtu of fuel throughput)[d]									
Ratio	1.001	0.880	1.000	0.880	0.880	1.000	1.000	1.000	1.000
Energy Use (Btu/mmBtu)[e]									
Residual oil	31,282	113,436	47,643	105,629	106,949	47,862	41,301	1,813	1,813
Natural gas	28,186	47,674	32,093	44,393	44,948	32,241	27,821	18,134	18,134
Coal	0	0	34	0	0	34	29	7,858	7,858
LPG	0	0	9,752	0	0	9,797	8,454	0	0
Electricity	1,548	3,177	5,096	2,958	2,995	5,120	4,418	2,418	2,418
Hydrogen	1,663	7,610	25,065	7,086	7,175	25,181	21,729	0	0
Butane	83	65,169	0	60,684	61,176	0	0	0	0
Pet Coke	10,227	28,212	17,248	28,212	28,212	17,327	14,952	0	0
Refinery Still Gas	37,265	61,176	49,800	61,176	61,176	50,030	43,171	30,223	30,223
Non-Combustion Emissions (g/mmBtu)									
CO_2	445	445	1,172	445	445	1,172	1,172	543	543
GHG Emissions (g CO_2e/MJ)[f]									
Loss factor[g]	1.001	0.88	1.0001	0.88	0.88	1.0001	1.0001	1.0001	1.0001
Feedstock	12.29	12.29	11.98	10.25	8.69	8.29	7.55	6.96	5.85
Fuel	5.79	12.12	12.41	11.62	11.42	12.97	11.52	5.70	5.57
WTT	**18.09**	**22.94**	**24.38**	**20.64**	**19.07**	**21.27**	**19.06**	**12.65**	**11.42**

[a] GREET models released from ANL and regional variant from ARB.

[b] GREET refinery efficiency has been updated periodically, supported by brief reports from ANL.

[c] U.S. Average electricity mix is used to model LPG production.

[d] When gasoline is mixed with additives, the upstream energy should be adjusted by the energy share of petroleum gasoline. The number in this cell is the energy ratio of crude inputs to fuel.

[e] This is the direct energy use in the crude processing (excludes upstream energy). This is calculated by (1-1/efficiency) * fuel share

[f] Result shown for LPG refining. Non-combustion CO_2 is an input for gasoline and scales with refinery efficiency in GREET.

[g] The loss factor (LF) represents the fuel lost in the fuel life cycle due to evaporation, spillage, or self-use and requires additional upstream activity to make up for these losses. GREET1_2014 includes the energy ratio of crude inputs to fuel in the LF.

3.3 Bio-LPG

Bio-LPG is a co-product of several biomass based processes including renewable diesel from oils and fats and Fischer Tropsch synthesis from biomass gasification. Feedstocks such as used cooking oil (UCO), tallow, soy, canola, etc. are used to produce hydro-processed renewable diesel. Biomass can also be used to create hydro-processed renewable Fisher-Tropsch (FT) diesel and LPG co-product. Waste-to-fuels facilities can also thermally extract fuel gases and natural gas liquids from municipal solid waste. Gaseous products include propane, butane, acetylene, and C_5+ liquids. The pathway for renewable diesel is examined here.

3.3.1 Vegetable Oil System Boundary

The steps in the fuel cycle of renewable diesel (RD) fuels are shown in Figure 3.4. Bio-LPG is a co-product of RD production. LPG is assigned a share of the emissions from RD production and transport to refineries. Soybeans are harvested, collected, and transported to a biorefinery. Harvesting involves establishing the crop, applying fertilizer inputs, and collecting biomass with harvesting equipment. Fuel processing involves biomass pre-treatment and conversion to biofuel. Finished fuel is transported to fueling stations for blending and/or vehicle operation. The processing steps for the conversion of soybean biomass to biofuel are shown in Figure 3.4.

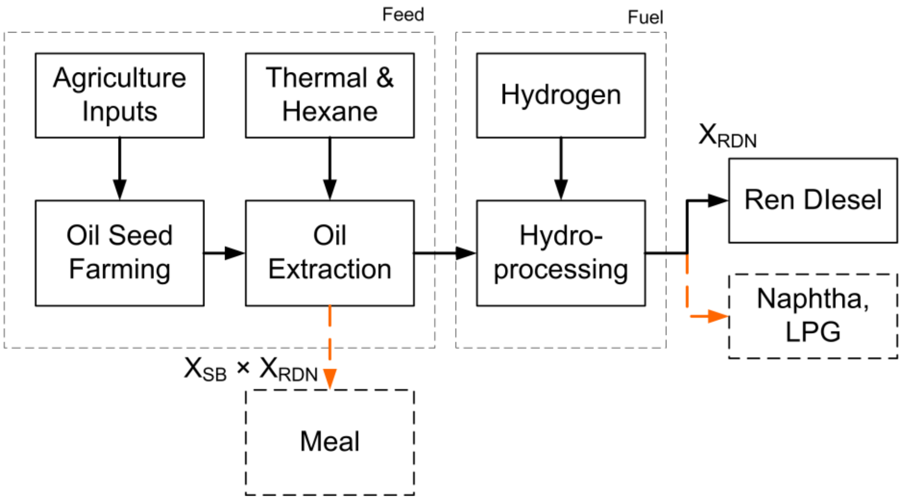

Figure 3.4. System Boundary Diagram for Bio LPG Co-Production with Renewable Diesel

3.3.2 Bio-LPG Pathways

Soybean, tallow, and rapeseed oils are most commonly used oils for renewable diesel production. Co-products include naphtha and LPG. The example of soybean renewable diesel is used here to discuss the Bio-LPG inputs and production process.

3.3.3 Hydroprocessed Oils and Fats

The renewable diesel production process, hydro-treating or hydroprocessing, requires vegetable oil or animal fat and hydrogen as primary inputs. Hydroprocessing uses the hydrogen to remove oxygen from the tri-glyceride molecules via competing decarboxylation and hydrodeoxygenation reactions. The extent of the reactions and ultimate yield of renewable diesel depend on the catalyst used and the process conditions. The process yields a primary product in renewable diesel, which by virtue of the saturation of olefinic bonds, is a purely paraffinic product. The primary co-product derived from the three-carbon backbone is propane. Other process byproducts include water and carbon oxides (CO and CO_2). For every kg of renewable diesel produced, approximately 0.06 kg of bio-LPG is co-produced.

Renewable diesel systems either burn propane in their fuel gas or send the fuel gas to an adjacent facility where it is used as process fuel or captured as propane. In current hydroprocessing pathways, the LPG in fuel gas is treated with energy allocation as a co-product, reducing the overall CI of the renewable diesel product. In a configuration where LPG is captured and sold as fuel, some of the LPG used as process fuel may need to be replaces with make-up natural gas.

Bio LPG Composition

The LPG derived from hydroprocessing is primarily the product of the propane knuckle on a triglyceride. Smaller factions of C4 through C6 hydrocarbons are also produced from cracking the bio oil feedstock. Table 3.10 shows the composition of LPG that would be derived from tallow hydroprocessing. The fuel gas composition without light gases such as methane and hydrogen is first calculated. The resultant product contains 89.5% propane. The composition is recalculated for LPG that meets the California specification in Table 1.3 where the butane and heavier components are limited to 5%. Note that the propane contains zero propene or other olefins, which results in a fuel with lower photochemical reactivity than the California or HD-5 specification.

Table 3.10. Composition of Bio-LPG from Tallow Hydroprocessing.

	Composition (mol%)	
Component	**No Gases**	**At Spec**
Propane	89.5%	95.0%
Normal Butane	2.7%	1.3%
Isobutane	5.6%	2.7%
Normal Pentane	0.3%	0.1%
Isopentane	1.0%	0.5%
C6+	0.9%	0.4%
Propene, olefins	0%	0%
Sulfur	0 ppm	0 ppm
Total	100.0%	100.0%

Source: Alt Air, Paramount, CA, Data from fuel mixing drum with methane, ethane, hydrogen, and 80% of C6+ removed.

Bio- and renewable- diesel yields and co-products

The renewable diesel hydrogenation process has the highest yield (in terms of energy content from 1 ton of soybeans) of the three new fuels, while it generates less energy co-product than the other processes. Because all of the processes produce other products (besides the target fuel), the energy value or market value of the co-products of these processes is an important factor in evaluating the energy and emission benefits of each soybean-based fuel.

Renewable diesel production requires hydrogen. Because hydrogen production is energy intensive, determining which process is more energy intensive simply on the basis of inputs and outputs would not lead to a proper conclusion. Therefore the fuel cycles of hydrogen and other types of energy inputs must be taken into consideration.

GREET treats soy co-products through displacement of an equivalent product replaced by each co-product. Soy meal, which is primarily used as a livestock feed in the United States, is assumed in this study to replace soybeans. Table 3.11 lists the products that are to be displaced by the co-products from soybean-based fuel production.

Table 3.11. Amount of Co-product Produced Along with Soybean-based Fuels, Btu or lb of co-product per lb of main fuel product

Production Process	Co-products	lb/lb primary product	Allocation Factor to Co-product
Soy oil extraction	Soy meal	4.16	0.8
Renewable diesel	Propane fuel mix	0.059	0.059

Table 3.12 shows the effect of diverting LPG from fuel gas to liquid fuel product and making up the balance of the energy from natural gas. This conservative estimate assumes that 4% of the LPG must be replaces with natural gas.

Table 3.12. CI for Equivalent Temporary Fuel Pathway Codes for Bio Propane

Feedstock	Tallow	Vegetable Oil
RD Temporary Fuel Pathway Code	RNWD300T	RNWD300T
Renewable Diesel CI (g CO_2e/MJ)	32.26	53.21
Additional fired NG (g CO_2e/MJ)[a]	2.88	2.88
Adjusted LPG CI (g CO_2e/MJ)	35.14	56.09

[a] 4% LPG x 72 g/MJ NG

3.4 Natural Gas, Crude Oil and Bio-Oil Allocation to Co-Products

Each of the pathways described produces not only a primary fuel product but also a range of other co-product streams. Each system has its own set of allocation issues; for example, the petroleum and natural gas pathways allocate emissions between other fossil transportation fuels and LPG. This approach reduces the emissions burden on the intended pathway products, such as gasoline, diesel, compressed natural gas, etc., and increases the emissions assigned to LPG. Bio-oil to LPG allocates the emissions equally between the primary renewable diesel product and the bio-LPG co-product.

The GREET model is configured with several methods for accounting for theses co-products:

- Mass Allocation: Oil seed meal is treated as a substitute product for oil seed on lb for lb basis.
- Energy Allocation: All energy and emissions generated by the process are allocated to the main or desired product of that process.
- Substitution: The co-product generates an energy and emission credit equal to the energy and emissions saved by not producing the material that the co-product displaces.

The distribution of GHG emissions among fuel and co-products differs based on the allocation approach employed. When energy allocation is employed, the emissions per MJ are the same for fuels and all products. With substitution, all of the emissions for feedstock and processing are assigned to fuels and the co-products are accounted for by displacement. This latter approach results in higher emissions for the feedstock and fuel phase which are offset by the co-product displacement credit (if any), thereby more accurately representing the impact of the co-products.

3.4.1 Factors Affecting Allocation Approach

The choice of allocation method becomes challenging when processes like those described above generates a mix of both fuels and co-products. For example, renewable diesel, derived from soybean oil hydro-processing results in both soybean meal and naphtha as a co-product. Some studies calculate a substitution credit for both soybean meal and propane fuel mix (Forman, Divita, Han, Cai, Elgowainy, et al., 2014; Forman, Hahn, & Jensen, 2011; Price Waterhouse Coopers, 2003; Shonnard, Williams, & Kalnes, 2010), while others allocate emissions to both propane fuel mix and diesel fuel products based on energy content (JRC, 2012; Stratton, Wong, & Hileman, 2011). Allocating emissions among fuel products appears sound because the ultimate functional unit for transportation fuels is miles driven. However, providing a substitution credit in cases where the functional unit fuel in question is only a minor component of the lifecycle has the potential to overly leverage the impact of the fuel product (S. Unnasch, Riffel, Sanchez, Junquera, & Plevin, 2010; M Wang, Huo, & Arora, 2011; Weidema, 2001).

3.4.2 Allocation Approaches use in Fuel LCA Studies

The GREET model (ANL, 2013, 2014) and the CA_GREET 2.0 model (ARB, 2014a), which is based upon GREET1_2013 estimates the refinery efficiencies based on linear programing (LP) modelling results. ANL does not discriminate between different refined products in the latest version of GREET (ANL, 2014). LPG is assigned the same refinery efficiency as diesel, ultra-low sulfur diesel, and CARBOB. These inputs challenge the Author’s intuition since some refinery operations clearly require additional steps to produce the desired product. Producing ultra-low sulfur diesel requires additional hydo-treating with additional energy input. Gasoline production from a fluid catalytic cracker results in emissions from coke combustion. A more detailed understanding of oil refinery operation could be used to better assign the emission intensity of these fuels.

3.4.3 Alternative Approach to Refinery Energy Inputs and Allocation

Petroleum refineries produce liquefied petroleum gases (LPG), motor gasoline, jet fuels, kerosene, distillate fuel oils, residual fuel oils, lubricants, asphalt (bitumen), and other products through distillation of crude oil, cracking, or reforming of unfinished petroleum derivatives. Refineries can take many different forms depending on the crude oil processed and the demand for products in the local area.

The flow of intermediates between the processes will vary by refinery, and depends on the structure of the refinery, type of crude processes, as well as product mix. The first process unit in nearly all refineries is the crude oil or “atmospheric” distillation unit (CDU). Different conversion processes are available using thermal or catalytic processes, e.g., delayed coking, catalytic cracking, or catalytic reforming, to produce the desired mix of products from the crude oil. The products may be treated to upgrade the product quality (e.g. sulfur removal using a hydro-treater). Side processes that are used to condition inputs or produce hydrogen or byproducts include crude conditioning (e.g., desalting), hydrogen production, power and steam production, and asphalt production. Lubricants and other specialized products may be produced at special locations. Petroleum refineries are significant consumers of energy and almost all of the energy consumed in the refinery is fossil in origin. In addition to the combustion related sources (e.g., process heaters and boilers), there are certain processes, such as fluid catalytic cracking units (FCCU), hydrogen production units, and sulfur recovery plants, which have significant process emissions of CO_2.

Much of the refinery LPG results from the conversion of process unit feeds through the intense processing of long chain hydrocarbons into high value products, such as gasoline, diesel etc. The refinery processes are designed to make these higher value primary products, and the refinery configuration is focused on maximizing yields. The LPG cut from refineries includes products from straight run sources, combined with the products from intermediate processes such as the cracking and the naphtha reforming processes. The finished LPG specification (except for some mild desulfurization) is met by the distillation of the crude oil feedstock streams and central light end units. No further blending components are added, except for odorizing chemicals for the detection of leaks (Jones, 2008). LPG is not the intended product of the refinery processes, but rather the incidental co-product of gasoline and diesel production.

More intensive refining results in higher emissions. Assigning these emissions to primary fuels rather than co-products like LPG reflects the intended use of refinery units such as hydrocrackers. Because LPG is not an intended product, the environmental impacts of primary products such as hydrocracker diesel should be assigned to the gasoline and diesel blending components produced from these units and should not be assigned to LPG.

The baseline approach in this study assigns the refinery unit operation emissions to the intended product. No hydrogen is assigned to LPG since the hydrogen is intended to remove sulfur from primary fuels and to crack high molecular weight molecules into high value gasoline and diesel. For example, the emissions from the fluid catalytic cracker coke combustion are assigned to gasoline. Hydro-treating for sulfur removal could be assigned to the products from this refinery unit. In this study, LPG is treated as a straight run product, similar to naphtha or residual oil, and has been assigned the same refining efficiency as those products. Table 3.13 shows the default and revised CA_GREET3.0 process inputs for LPG production, as well as the default inputs for residual oil.

Table 3.13. Process Inputs for LPG and Residual Oil Production in Oil Refineries

Parameter	**CA_GR.3.0 Default**		**This Study**
Fuel	LPG	Residual Oil	LPG
Refinery Efficiency	89.20%	94.04%	94.04%
Energy Ratio of crude oil feeds to product	0.880	0.999	1.001
Shares of process fuels			
Residual oil	47.9%	48.7%	48.7%
Natural gas	20.1%	43.9%	43.9%
LPG	0%	0%	0%
Electricity	1.3%	2.4%	2.4%
Hydrogen	3.2%	2.6%	2.6%
Energy use: Btu/mmBtu of fuel throughput			
Total	261,285	111,712	108,609
Residual oil	113,436	31,282	30,502
Natural gas	47,674	28,186	27,484
Coal	0	0	0
LPG	0	0	0
Electricity	3,177	1,548	1,509
Hydrogen	7,610	1,663	1,622
Petcoke	28,212	10,227	10,227
Refinery still gas	61,176	37,265	37,265

4. LPG Fuel Transport and Distribution

Transportation of feedstocks and finished fuels is an important component of the overall fuel cycle, impacting local emissions, energy consumption, and WTW GHG emissions. Emissions and energy consumption vary with transportation mode, delivery distance, cargo capacity, and mode specific energy use (S Unnasch & Pont, 2007). Such variables depend on the fuel production scenario, including the location of feedstock and fuel production facilities. For this study the feedstock delivery modes in the crude oil, natural gas and bio-oil pathways are the default GREET inputs. The transportation and distribution of LPG fuels are discussed in this section.

4.1 LPG Fuel Delivery Modes

4.1.1 Rail Car

When LPG is transported more than about 300 miles, rail car transportation is typically used. A standard rail car has a capacity of 30,000 gallons of LPG. This is the volume for rail car transport used in this study.

A tower with pivoting connections is used to offload rail cars. This permits loading and unloading of multiple rail cars without repositioning (moving) cars.

LPG unloading from rail cars is accomplished using a compressor. This compressor moves LPG vapor from the receiving tank vapor space into the rail car, causing liquid to be transported out. After most of the liquid is removed from the rail car, the compressor removes the remaining pressurized vapor from the car. This practice is referred to as “vaporing” the rail car. Typically, rail cars are vapored to 20 psig during the winter months and 50 to 60 psig during the summer months.

4.1.2 Truck

Truck transports are used when moving LPG within about a 300 mile radius of the source. Truck transports typically have a 10,600 gallon capacity, and they deliver the entire amount to one customer. After leaving room for vapor, the truck typically carry about 9,500 gallons of actual LPG.

Truck transports can be divided into four categories, depending on the type of transport and the equipment available onboard. Transports either have one tank the size of a traditional semi-trailer or a smaller tank with a towed trailer. Also, truck transports have either a pump or a compressor onboard to offload LPG at the destination. Truck transports exist with all four combinations.

All transports are filled at the terminal using two liquid lines and one or more vapor lines. Two liquid lines are used so that the tanks can be filled in a reasonable time without cavitating the pumps used for filling. Transports with one tank use only one vapor return line, but transports using a tank and trailer use two vapor return lines when filling.

When offloading LPG from a tank and trailer style transport, a jump line is used to connect the two tanks together. The jump line lets liquid pass from one tank, through the other when offloading the LPG. Without a jump line, a pump or compressor would be needed on both the tank and the trailer. When disconnected, this jump line becomes a source of fugitive emissions. Truck transports either use a pump or a compressor to offload LPG at the destination. A compressor permits the truck transport and all transfer lines to be emptied of liquid LPG. When using a pump, the liquid transport line still contains an amount of liquid in the hose. As such, transports with compressors emit less fugitive LPG per transfer than those with pumps.

4.1.3 Bobtail Truck

Bobtails are used to transport LPG locally from retail bulk plants to homes and businesses that store less than 10,000 gallons of LPG. Bobtails are trucks with a water capacity of 3,000 gallons and are designed to offload LPG to multiple customers.

Bobtails are able to deliver LPG efficiently, with a small amount of fugitive emissions due to their design. The bobtail gets its name from the long flexible hose that is spooled on the back of the truck. When delivering LPG, this hose is extended to the storage tank and no vapor return line is used. A liquid pump is used to transport LPG from the bobtail to the customer storage tank. When the transfer is complete, the hose is rolled back onto the spool without emptying the line. This design prevents unnecessary fugitive emissions of LPG.

4.2 LPG Distribution Facilities

4.2.1 Terminals

The majority of the LPG imported from out of state and LPG produced within California is sent to a terminal. A small proportion is sent directly to retail plants. These distribution facilities have towers to transfer LPG from rail cars and equipment to efficiently load and unload transport trucks. Terminals do not sell or provide LPG services directly to the public. For this study it is estimated that all LPG leaving a terminal does so by transport truck.

4.2.2 Retail Bulk Plants

Retail bulk plants are the local distribution hubs for LPG. Bobtails load at these facilities for local delivery. Retail bulk plants also refill forklift cylinders and 20 lb cylinders.

A limited number of these facilities also act as a terminal for LPG distribution. In this study, a terminal bypass is defined as the amount of LPG that does not go through a terminal before going to a retail bulk plant.

4.2.3 Refueling and Fuel Transfer Emissions

LPG is stored and distributed in pressurized tanks. The fuel is stored in a liquid state at ambient temperature and the pressure in the tank is in equilibrium. At 70°F the storage pressure is 105 psig. When LPG is transferred from a storage tank to a tank truck, or to a vehicle fuel tank, a

transfer pump provides about 50 psi of differential pressure. When fueling vehicle tanks, the fuel enters the tank and the LPG condenses. This process can be accelerated with top loaded tanks where the liquid spray can absorb some of the heat from condensing the vapors.
The tank trucks are filled at refineries with a two hose system with one hose acting as a vapor return. Hoses are evacuated after fuel transfer operations at the refinery.

Tank trucks can be filled to a safe fraction of its water capacity by weighing the truck during fueling (Lowi 1994), although this is not the current practice. However, current regulations require the use of a fixed liquid level gauge (FLLG) outage valve that indicates when the tank is full. Some LPG also enters the atmosphere from the fuel transfer fitting.

The fuel transfer losses that occur during vehicle fueling and fuel transfers include

- Transfer tank outage
- Bulk tank outage
- Truck fill outage
- Truck fill hose
- Local tank hose
- Local tank outage
- Vehicle tank outage

4.3 LPG Fugitive Emissions Sources

Trapped Volumes

A trapped volume is the volume enclosed between two disconnection points in an LPG transfer system. When a connection is broken, the volume between the two shutoff valves is released to the atmosphere.

The trapped volumes can contain either LPG vapor or liquid. To estimate the fugitive emissions from vapor trapped volumes, the vapor pressure of LPG at ambient temperature is used. To estimate the fugitive emissions from liquid trapped volumes, the liquid density at the trapped pressure is used.

The trapped volume measurements for this study were completed on conventional LPG transfer equipment that is found commonly in the field. For this study, it was estimated that 25% of the transfer equipment has been replaced with low-emissions equipment. Low-emissions connections are currently being deployed as retrofits in the field and are found on all new equipment purchases.

Fixed Maximum Liquid Level Gauges

Fixed maximum liquid level gauges (FLLGs) are used within the LPG industry to determine when a tank is full. These gauges also serve as a safety device to prevent overfill of the tanks.

FLLGs are present on most LPG containers. Transport trucks and bobtails use FLLGs as a safety device to prevent overfill. LPG storage tanks at residential, commercial, industrial and agricultural sites are equipped with FLLGs. Also, FLLGs are used on forklift, RV and 20 lb. cylinders.

LPG Fueling

The connections between LPG transfer equipment and LPG storage containers consists of multiple connections, hoses, valves, FLLGs, compressors and pumps. Furthermore, each type of LPG transfer is unique. For example, a bobtail does not use the same methods or transfer equipment that a transport truck uses.

To understand the connections, trapped volumes, and fugitive emissions from LPG transfers, a schematic of common transfers is shown in Figure 4.1. This diagram shows valves, connections, pumps, and compressors for the major types of LPG transfers that occur within California.

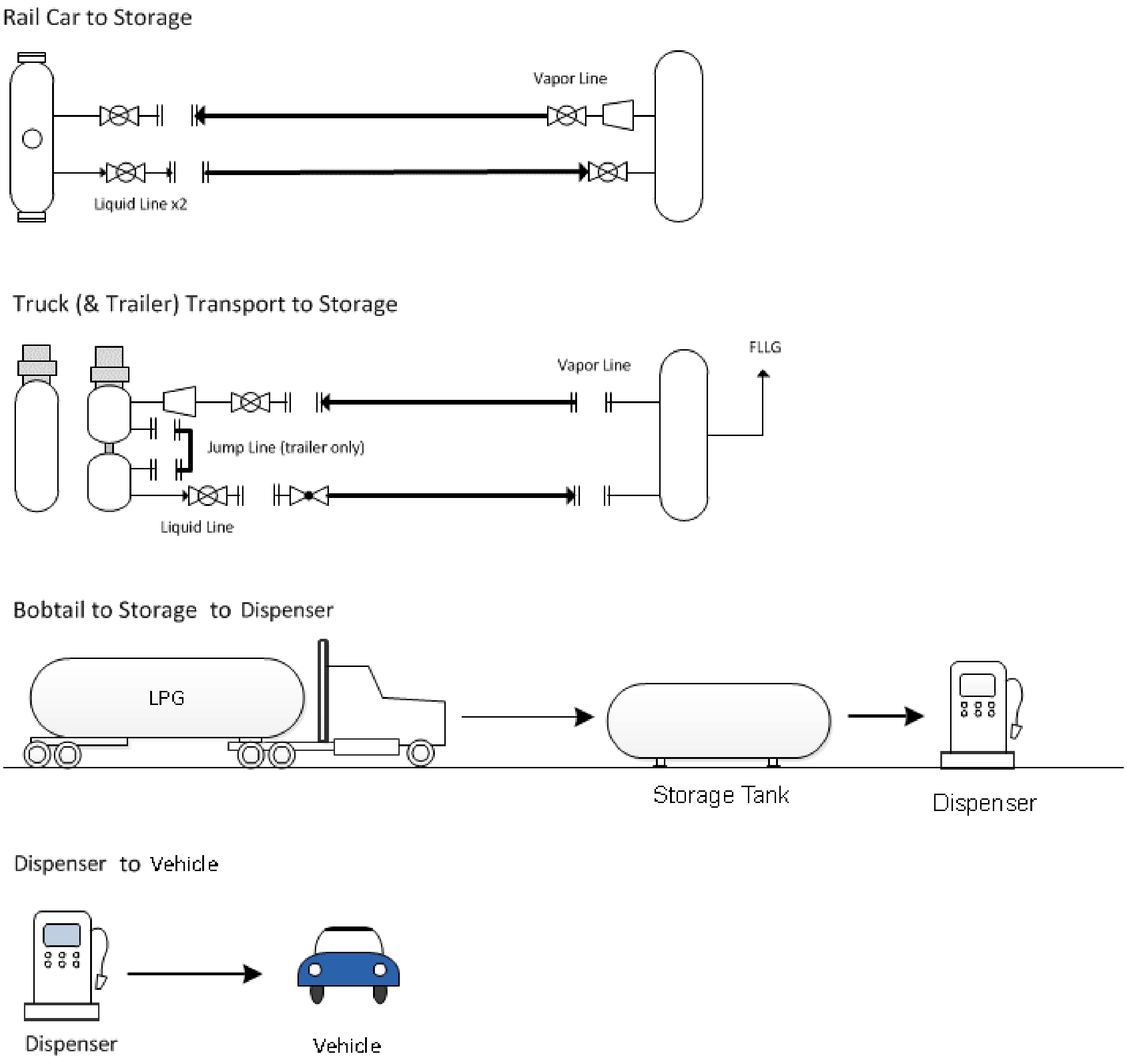

Figure 4.1. Connection Schematics for Common LPG Transfers

4.4 LPG Transport and Distribution in GREET

Figure 4.2 Shows the LPG transportation and distribution (T&D) modes, mode shares and distances in the CA_GREET3.0 model. The natural gas transport was adjusted to 100% railcar as none of the product is imported by barge or pipeline to California. Similarly, refinery based LPG was estimated to be shipped 34% by rail and 66% by truck.

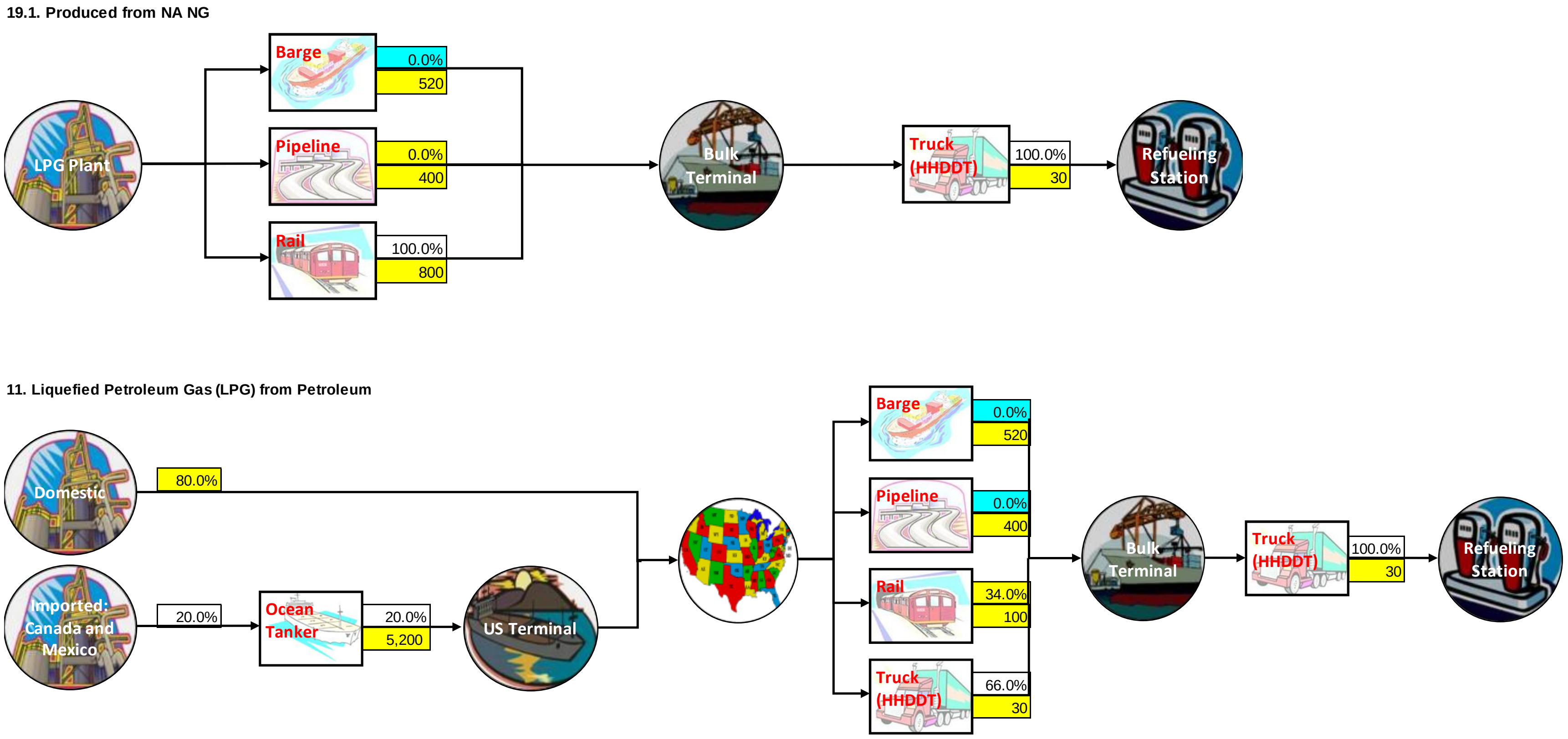

Figure 4.2. CA_GREET3.0 LPG Transport and Distribution Mode Shares and Distances for LPG produced for natural gas and petroleum.

5. Vehicle End Use and TTW Emissions

Vehicle end use emissions, termed Tank- To-Wheel (TTW) emissions include vehicle evaporative emissions and vehicle tailpipe emissions. These are the emissions generated during fuel combustion. Vehicle use emissions are the same regardless of how the LPG was produced (i.e. from crude oil or natural gas pathway). Vehicle emissions are estimated from the relative emissions compared to gasoline for a light duty vehicle or diesel in the case of a heavy-duty vehicle. In the case of CO_2, these emissions are proportional to fuel consumption and are estimated based on the relative energy economy ratio (EER) combined with the carbon content of the fuel. The carbon in fuel in LPG is about 10% lower than that of gasoline, which accounts for the lower GHG emissions from a LPG fueled vehicle, all other factors being equivalent.

5.1 Vehicle Combustion Emissions

The TTW emissions generated during end use combustion in the vehicle phase account for approximately 70% of the total WTW fuel cycle emissions. The TTW emissions consist of the CO_2 and criteria air pollutant emissions created from fuel combustion. Criteria air pollutants include Volatile Organic Carbon, (VOC), and carbon monoxide (CO), Particulate Matter (PM 10 & 2.5) nitrous oxide (NOx) and oxides of sulfur (SO_x). VOC and CO are expressed as equivalents of CO_2 by multiplying by the ratio of VOC and CO to CO_2. The collective CO_2 emissions from the carbon in the fuel is termed CO_2c and includes the CO_2, VOC and CO.

The CO_2 emissions are created as a result of the conversion of the carbon in the fuel into CO_2c,. Because LPG has an inherently lower carbon content than gasoline or diesel, the CO_2 emissions will be lower. Table 5.1 shows the grams of CO_2c per megajoule of fuel (gCO_2c/MJ) for Diesel, CARBOB and LPG.

Table 5.1. Fuel Carbon Content (as CO_2c)

	Diesel	CARBOB	LPG
Carbon Content (wt%)	87%	86%	82%
g CO_2c/MJ	74.1	71.2	65.5

6. Life Cycle Results and Discussion

The full fuel cycle emissions from LPG and other transportation fuels are examined in WTW models such as GREET and specialized regional variants of GREET such as the CA_GREET model discussed earlier. Washington and Oregon both use State customized variants of GREET for GHG reporting under the respective low carbon fuel initiatives. In the European Union (EU), BioGrace is the model used to analyze fuels under the Fuel Quality Directive (FQD). This study used the CA_GREET3.0 model to develop the analyses for the alternative treatment of LPG presented in this report.

The default LPG, gasoline blending component and diesel CI results from ANL GREET, regional GREET variations, and the EU Fuel Quality Directive are shown in Table 6.1. LPG from petroleum results in a carbon intensity of 89.96 g CO_2e/MJ compared with a gasoline baseline of 101.66 gCO_2e/MJ based on the default CA_GREET3.0 model.

The analysis in this study reinterprets the allocation of energy and emissions, and the revised CI of LPG is 83.63 gCO_2e/MJ. The reallocation of emissions away from LPG also results in a higher CI for CARBOB and low sulfur diesel. This represents an 18% reduction in emissions compared to the gasoline baseline and an approximate 21% reduction compared to the diesel baseline. Additionally, the GHG impact of bio-LPG is approximately 70% lower than conventional fuel blends. These results depend on two factors:

- The reduced carbon content (g C/MJ fuel) of LPG compared to gasoline and diesel fuel
- Reduced upstream refining energy for LPG compared to gasoline and diesel

Table 6.1. Carbon Intensity Results for LPG, Gasoline, and Diesel

GREET Model Base	Original Model	Region	LPG		Crude Oil	
			Petroleum	**NG**	**CARBOB[a]**	**Diesel**
WTW Carbon Intensity, g CO_2e/MJ)						
CA_3.0	This Study	CA	83.63	81.09	101.66	101.72
1_2016	CA_3.0	CA	89.96	81.09	100.73	100.71
1_2013	CA_2.0	CA	89.93	78.96	99.8	102.0
1_2016	1_2016	US	86.19	81.05	98.8	92.2
1_2014	1_2014	U.S.	85.2	79.7	94.6	89.7
1.8c	OR_GR	OR	76.3	75.7	90.2	91.3
1_2013	WA_GR	WA	92.9	81.3	100.7	101.7
JRC	EU FQD	E.U.	74.5	73.6	93.2	95

[a] Gasoline blending component for CA_3.0 and this study are for CARBOB. RBOB results are shown for 1_2014, OR_GR, and WA_GR results. EU Commission results from 2014 FQD methodology.

[b] Default value for Tallow based Renewable Diesel in CA_GREET3 should be 30 g/MJ with allocation of emissions to propane and renewable diesel.

The lower carbon content of LPG compared to gasoline or diesel is well known. CA_GREET model inputs for refining energy assume that LPG production is a co-product of crude oil refining and the refining efficiency is slightly better for LPG than that of gasoline. However, as previously mentioned in Section 3.4.3 the majority of refinery LPG produced derives from the intense processing of long chain hydrocarbons into high value products, such as gasoline, diesel etc. The refinery processes are designed to make these higher value primary products, and the refinery configuration is focused on maximizing yields. More intensive refining results in higher emissions. Assigning these emissions to primary fuels rather than co-products like LPG reflects the intended use of refinery units such as hydrocrackers. Because LPG is not an intended product, the environmental impacts of primary products such as hydrocracker diesel should be assigned to the gasoline and diesel blending components produced from these units. The baseline approach used in this study assigns the refinery unit operation emissions to the intended product, and treats LPG as the incidental co-product, resulting in lower GHG emissions assigned to LPG.

Bio-propane[13] vehicles are now an important component of the California Low Carbon Fuel Standard. Petroleum and natural gas-based LPG were previously not included in the LCFS. Renewable based LPG would generate LCFS credits when used in vehicle applications. LPG is a co-product of renewable diesel production from vegetable oils as well as from biomass to Fischer Tropsch fuel production. Recent LCFS pathways from ARB staff have shown very low GHG emissions from renewable CNG pathways (ARB 2012b). Low GHG results are also possible with renewable LPG facilities that process corn oil renewable diesel and other biofuels become operational. Fuel pathways such as renewable diesel from corn oil or used cooking oil result in a carbon intensity of about 32 g CO_2e/MJ for both the diesel and LPG fractions[14]. Such bio-LPG pathways would help achieve LCFS compliance.

6.1 Treatment of LPG with regional Variants of GREET

Figure 6.1 shows the comparative GHG emissions from petroleum derived LPG with the various GREET models. The differences in results are mainly due to the underlying differences in the base GREET models from which the regional variant was developed. For example, the Oregon analysis shows that LPG has the lowest CI, due to a high refinery efficiency of 94.3% carried over from GREET1.8c, the model upon which OR_GREET is based.

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[13] Feedstocks such as used cooking oil (UCO), tallow, soy, canola, etc. are used to produce renewable diesel. Biomass is also a potential feedstock for renewable Fisher-Tropsch (FT) diesel. Renewable LPG or Bio-LPG is a non-discretionary co-product of the renewable or FT diesel process.

[14] Bio-LPG and renewable diesel receive the same CI score under the LCFS when the Bio-LPG is produced as a non-discretionary co-product of the renewable diesel process.

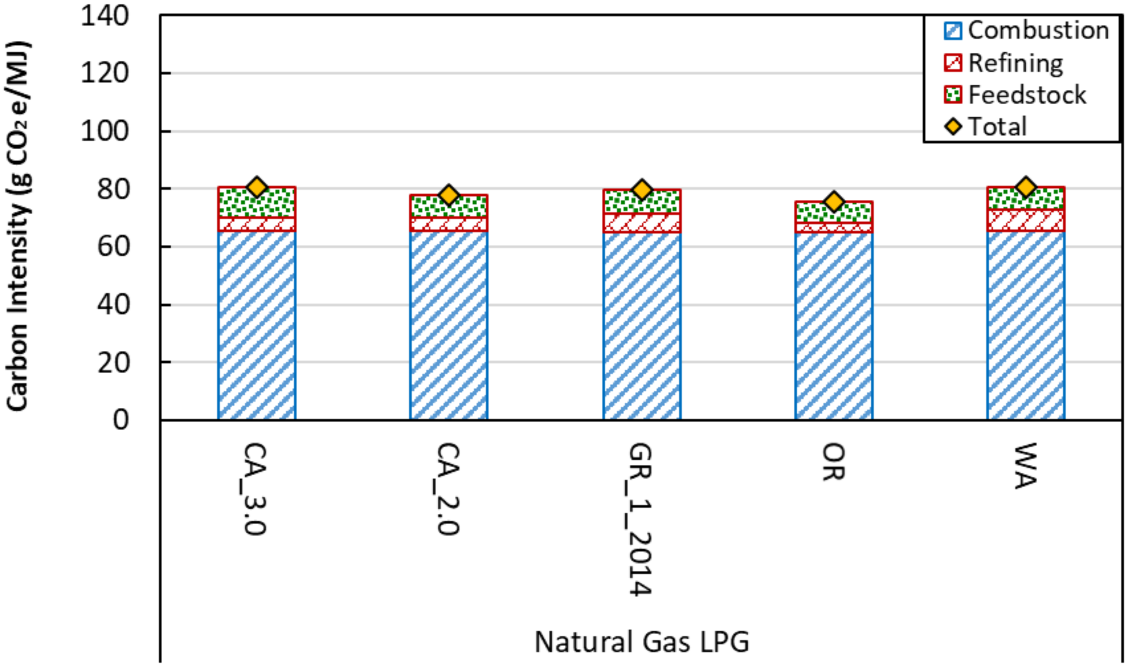

Figure 6.1. Comparison of WTW Emissions from LPG using the various GREET models

6.2 Impact of LPG in Transportation Fuel LCA

LPG is a co-product for natural gas and petroleum fuel production, and represents approximately 23% and 5% of the total energy produced from these resources, respectively (EIA, 2015j).

Determining an accurate carbon intensity for LPG affects not only the vehicle fuel use type, but also all of the other fuel pathways involving LPG. If emissions are incorrectly allocated to LPG then they are also incorrectly allocated to gasoline and diesel fuels. The LCA should reflect that fact that LPG is an incidental product of oil refining. ARB has not appropriately captured the role of LPG in refineries. The current CA_GREET2 model has as a refinery efficiency input of 89.3% for both LPG and CARBOB production. Thus, petroleum LPG the has the same refining intensity as gasoline, when in fact much of the LPG in refineries is the result of operating units that are designed to make gasoline and diesel components. Assigning emissions from the incomplete conversion of refinery feedstocks to LPG misallocates these emissions. The corresponding energy inputs and emissions should be assigned to gasoline and diesel. A suitable approach would be to assign LPG the energy use for the crude distillation unit.

The latest GREET1_2016 model moves a step in the right direction with an LPG refinery efficiency of 90.8% and a CA RFG blendstock refinery efficiency of 88.7%. Even this refinery efficiency is too low, however, and does not reflect the fact that LPG is an unintended co-product. GREET1_2016 has a refinery efficiency of 95.7% for residual oil because it is a straight-run product. The same treatment is appropriate for LPG.

Finally, LPG vehicles provide the opportunity for another low carbon fuel option. Developments in LPG vehicle technology are potentially promising. As a fuel, LPG has a high octane number and its simple molecular structure leads to low particulates and toxic air contaminant emissions. Sources of Bio LPG also provide a potential low CI fuel, which can help achieve LCFS compliance.

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