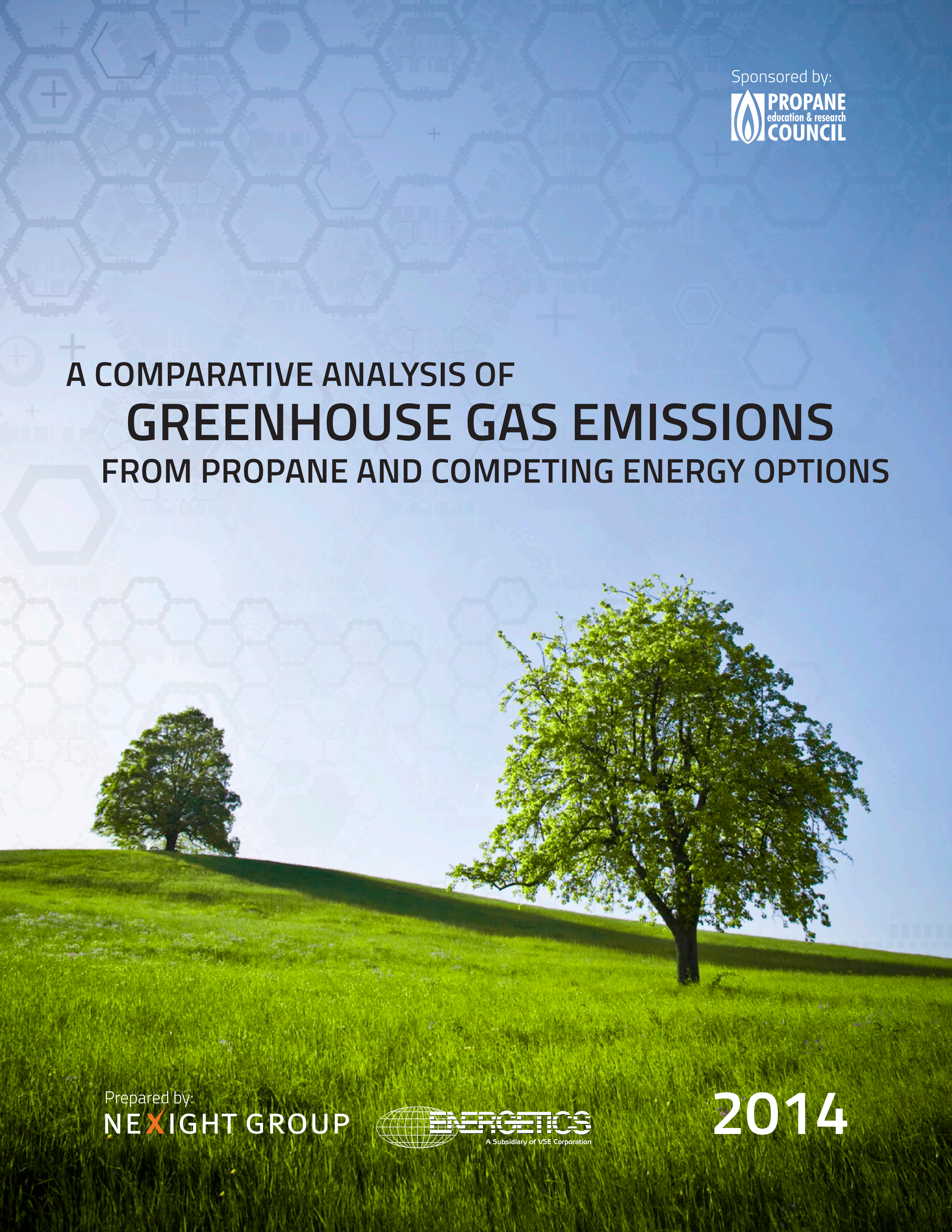

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A COMPARATIVE ANALYSIS OF GREENHOUSE GAS EMISSIONS FROM PROPANE AND COMPETING ENERGY OPTIONS

Prepared by:

NEXIGHT GROUP

ENERGETICS
A Subsidiary of VSE Corporation

2014

Acknowledgements

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Executive Summary

Energy production and use generates greenhouse gas (GHG) emissions that can contribute to climate change. While government and business leaders as well as consumers are increasingly concerned with climate change, they also understand that energy plays an essential role in daily life. As a result, many leaders are currently seeking ways to reduce GHG emissions while also promoting economic development and consumer choice, and many consumers are taking more of an active role in determining their personal energy mix. In order to make informed choices in this area, these decision-makers require unbiased, credible information about available energy options.

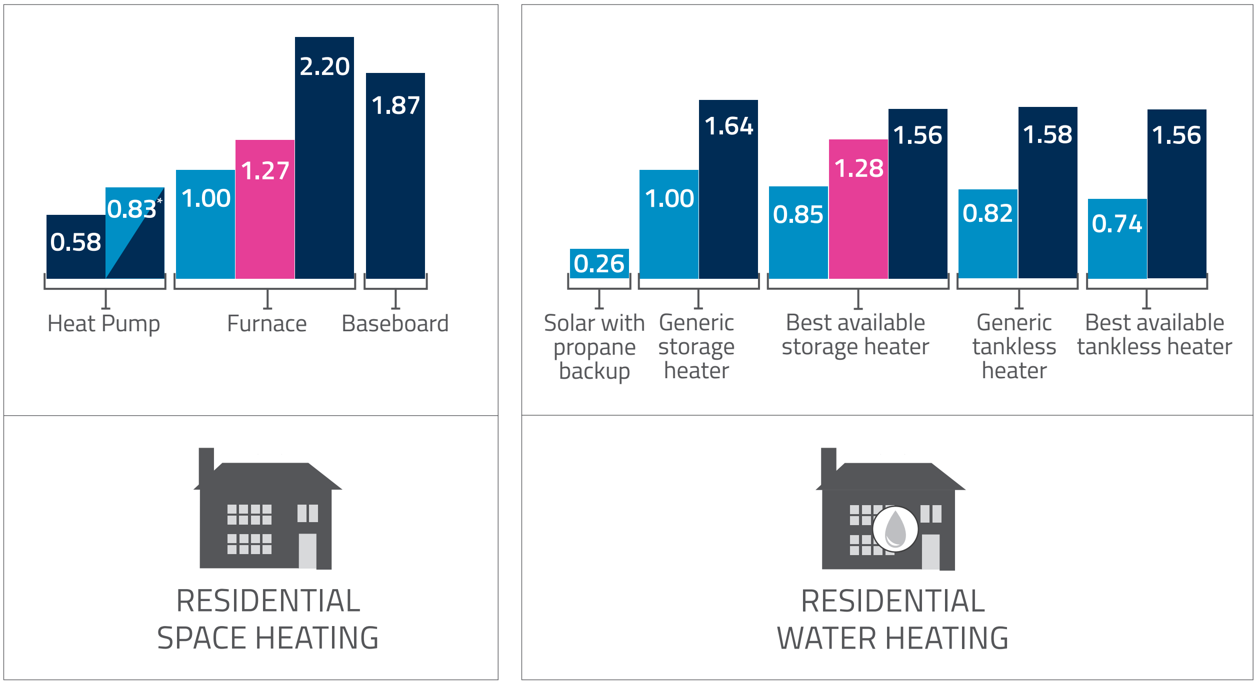
This study aims to provide both leaders and consumers with the type of information they need by quantifying the greenhouse gas emissions produced by the use of propane and other energy sources in 14 selected applications important to the U.S. propane industry. These applications cover the major propane markets: residential buildings, commercial buildings, off-road applications, on-road vehicles, and agricultural applications. The study's methodology considers not only emissions generated at the point of use but also all upstream emissions produced during the extraction, production, and transportation of each energy source. Because equipment efficiency plays an important role in the amount of energy required to perform a useful task, such as heating a home, the study's methodology also considers efficiency, which can vary significantly depending on the energy source used.

The results of this study show that propane is a low-carbon fuel source that produces fewer greenhouse gas emissions than many competing energy options in a wide range of applications. Propane's chemistry—its molecular structure—provides it with relatively low carbon content compared to liquid fuels like diesel and gasoline and compared to electricity, much of which is generated from coal in the United States. As a result, propane is a favorable energy option across the market areas featured in this study, as demonstrated by the graphs in Figure ES1.

Energy choice is a complex issue. Greenhouse gas emissions are just one of the many factors that decision-makers must consider when weighing their energy options; factors such as cost, performance, reliability, and safety also play a significant role. As leaders and consumers grow increasingly aware of the potential impact of their energy choices, their access to sound information about their options will grow increasingly critical as well. The results of this study offer new insights that can aid decision-makers considering propane as a low-carbon energy source.

Figure ES1. Comparative Analysis of GHG Emissions from Propane and Competing Energy Options (GHG emissions relative to propane = 1.00)

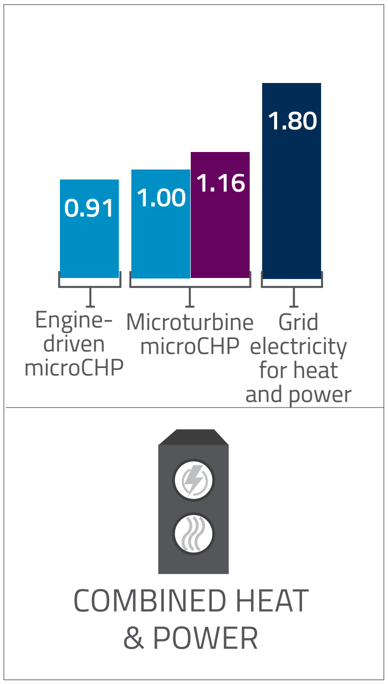
■ PROPANE
■ ELECTRICITY
■ FUEL OIL



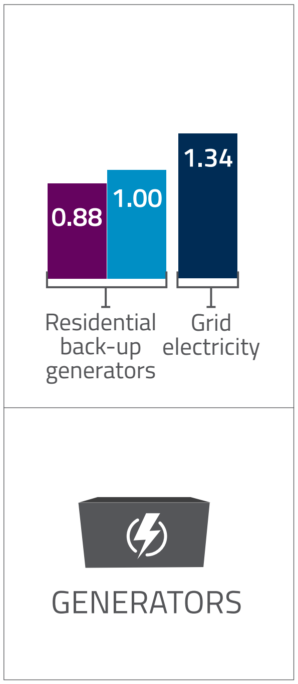
*Electric air source heat pump with propane furnace backup

*High-efficiency electric heat pump

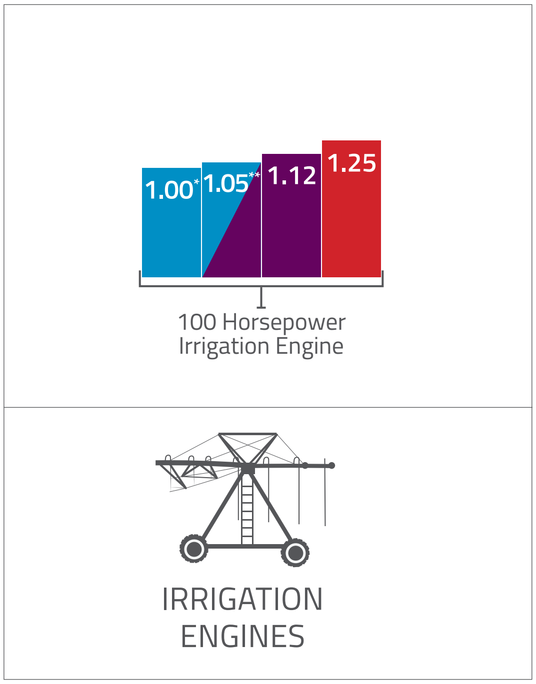
🟦 PROPANE
🟨 NATURAL GAS
⬛ ELECTRICITY
🟥 GASOLINE
🟪 DIESEL
🟪 FUEL OIL
🟧 E85



COMBINED HEAT & POWER

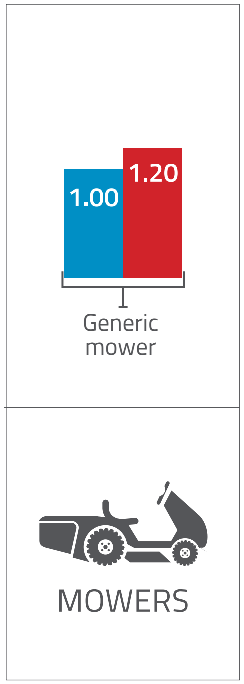


GENERATORS

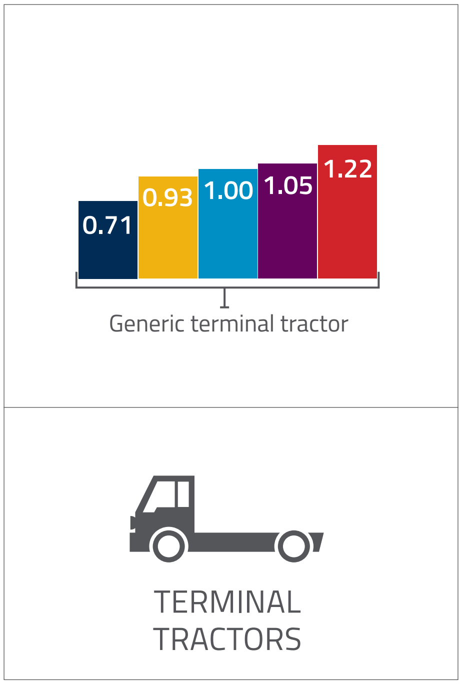


IRRIGATION ENGINES

*Propane irrigation engine
**Propane and diesel dual fuel irrigation engine



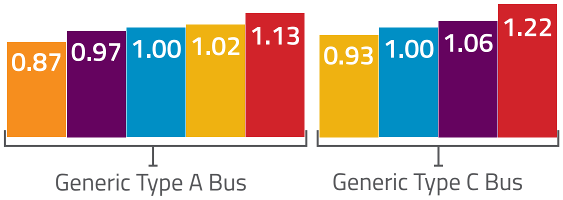
MOWERS



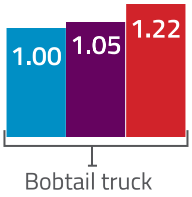
TERMINAL TRACTORS

FORKLIFTS

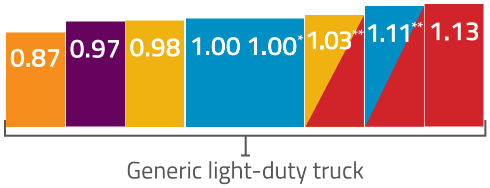
🟦 PROPANE
🟨 NATURAL GAS
⬛ ELECTRICITY
🟥 GASOLINE
🟪 DIESEL
🟪 FUEL OIL
🟧 E85



TYPE A/C
BUSES

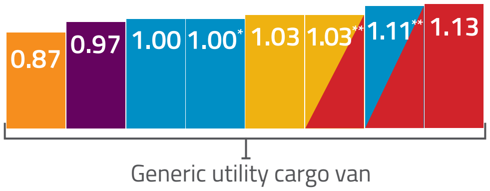


BOBTAIL
TRUCKS



LIGHT-DUTY
TRUCKS

*Light-duty truck with propane conversion kit
**Gasoline bi-fuel light-duty truck



UTILITY
CARGO VANS

*Utility cargo van with propane conversion kit
**Gasoline bi-fuel utility cargo van

Purpose of this Report

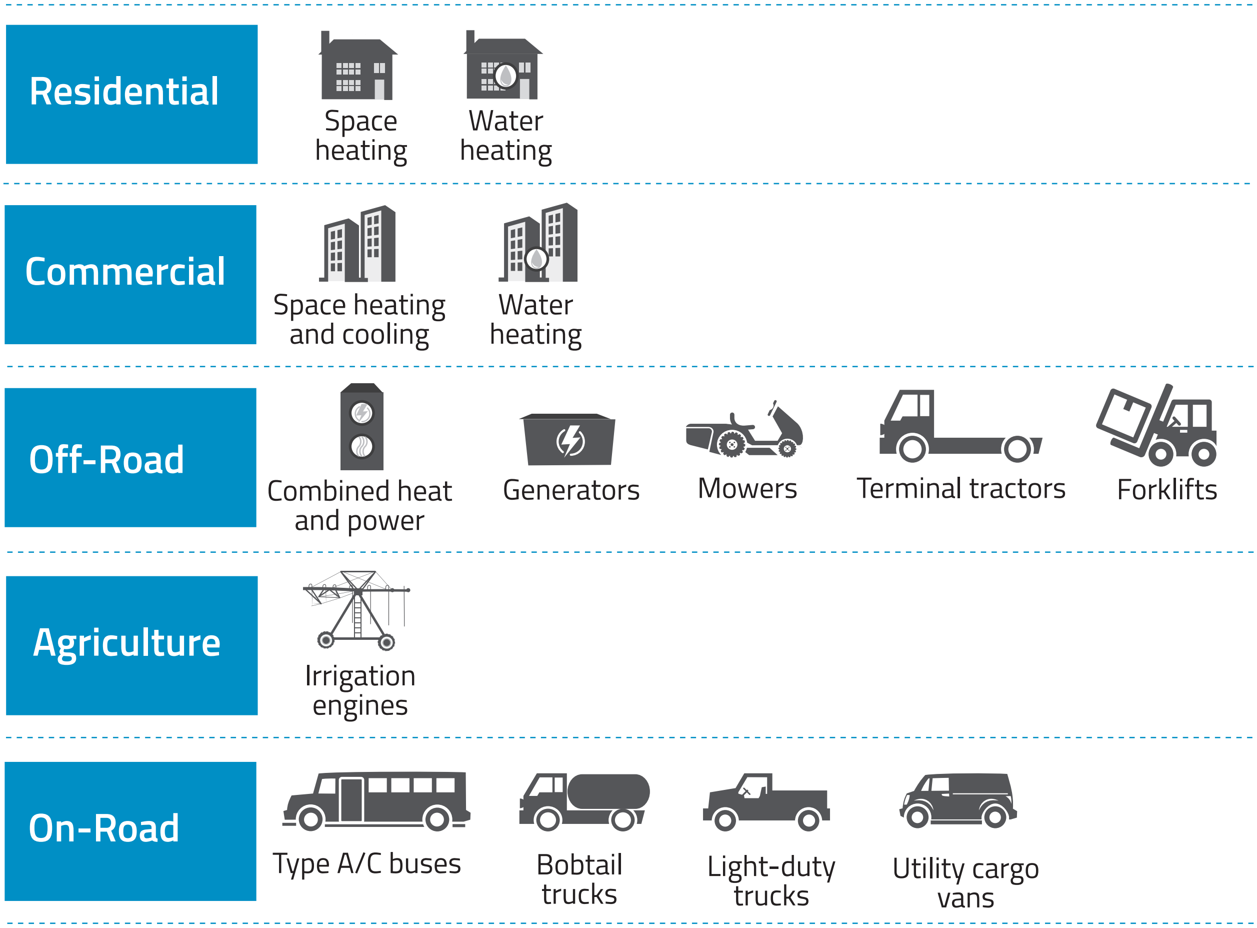
Energy production and use generates greenhouse gas (GHG) emissions that can contribute to climate change. Government and business leaders are increasingly concerned with climate change but also understand that energy plays an essential role in our daily lives. Public and private sector decision-makers are therefore seeking ways to reduce GHG emissions while also promoting economic development and consumer choice.

The purpose of this study is to quantify the GHG emissions associated with the production and use of propane and other fuels in 14 selected applications of importance to the U.S. propane industry. These applications address a range of major propane markets, including residential buildings, commercial buildings, off-road vehicles, on-road applications, and agricultural applications (see Figure 1).

This study builds on previous GHG analyses commissioned by PERC, the most recent of which was published in 2009. Since then, the propane industry has witnessed the following significant changes and developments:

- In 2009, approximately 60% of domestic propane was produced from natural gas production, with the remainder being produced during petroleum refining. With the rapid development of shale gas resources in recent years, this ratio has shifted; now more than 70% of domestic propane originates from natural gas production, which is a change that affects the carbon intensity of propane (ICF International 2013).
- Since 2009, many new propane-fueled products have been successfully commercialized, including several engine-based products that were not included in the previous study.
- The full fuel cycle model used to estimate upstream emissions—the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) published by Argonne National Laboratory—has been updated several times since the previous study, most recently in October 2013 (ANL 2013b).

Figure 1. Selected Applications Included in this Report



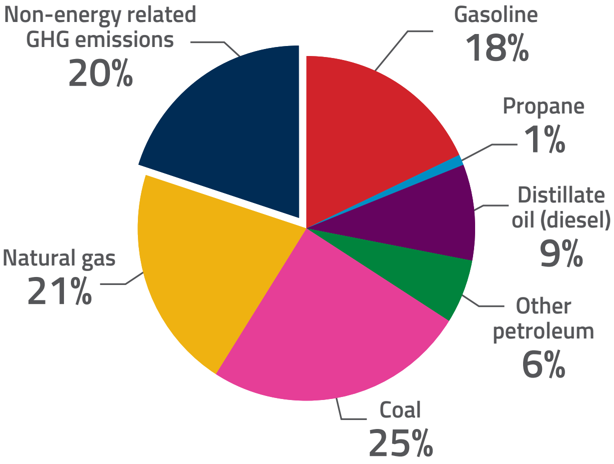
About Greenhouse Gases and Climate Change

Greenhouse gases affect the earth's climate by trapping heat from the sun. While these gases keep the earth at a temperature suitable for human life, elevated levels of greenhouse gases in the atmosphere cause global warming. Scientists have concluded that increasing concentrations of greenhouse gases emitted by human activity are contributing to changes in the earth's climate (IPCC 2013) that are threatening ecosystems and public health (EPA 2013). If greenhouse gas (GHG) emissions continue to increase, climate change is predicted to continue and accelerate significantly (USGCRP 2009).

Greenhouse gases are emitted from several sources, but 80% of the emissions from human activity can be attributed to the combustion of fossil fuels for energy. Figure 2 shows the sources of greenhouse gases emitted from human activity in the United States by energy and non-energy sources (EPA 2014).[1] The majority of these GHG emissions are carbon dioxide (CO_2), but other gases represent a significant share of the total.

After energy use, the remaining balance of GHG emissions from human activity is from industrial processes that emit CO_2 directly (e.g., cement kilns), methane (e.g., landfills and natural gas leaks), nitrous oxide (e.g., agricultural fertilizer), and fluorine-containing halogenated substances (e.g., hydrofluorocarbons [HFCs], perfluorocarbons [PFCs], and sulfur hexafluoride [SF6] from refrigerants and industrial processes).

Figure 2. Source of U.S. GHG Emissions (2012)
(Total: 6,301 million metric tons CO_2e)



The global warming impact of these other gases is typically quantified in terms of its "global warming potential" (GWP) or the relative impact of how much heat is trapped by the gas compared to CO_2. Methane gas, for example, is 28 times more potent than

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[1] Energy-related emissions shown in the figure are emitted as CO_2 from fossil fuel combustion.

CO_2 at warming the atmosphere, so total methane emissions are multiplied by a GWP of 28 to express emissions in terms of “CO_2 equivalent.” The results in this analysis are all expressed in terms of CO_2 equivalent (CO_2e).

The three greenhouse gases of primary concern for the purposes of this study are CO_2, methane, and nitrous oxide, because they are associated with fuel production and use. Other greenhouse gases are not included in this analysis because they are not significantly related to the production or use of the fuels evaluated.

Greenhouse Gases and Criteria Air Pollutants

When considering emissions from fuel combustion, it is useful to distinguish between criteria air pollutants, which have been regulated by the EPA since 1970, and GHG emissions. While criteria pollutants are relatively short-lived and cause regional environmental problems such as smog and acid rain, they are not the primary gases contributing to climate change. In contrast, GHG emissions remain in the atmosphere for decades to centuries and cause global effects (IPCC 2001b).[2] Other important differences between criteria pollutants and GHG emissions are summarized in Table 1.

Although GHG emissions and criteria pollutants are both products of combustion reactions, CO_2—the most significant greenhouse gas—is the unavoidable product of the chemical conversion of carbon-based fuels into energy. Criteria pollutants such as ozone and particulate matter are the byproducts of undesired processes including fuel leaks, incomplete combustion, and secondary chemical reactions, among others. Criteria pollutants can often be mitigated by pollution control equipment and operational and maintenance practices. In contrast, CO_2 emissions can only be reduced by improving fuel efficiency or by switching to a fuel with a lower carbon content, such as propane.[3]

Table 1. Important Differences between Greenhouse Gases and Criteria Air Pollutants

	GREENHOUSE GASES	CRITERIA POLLUTANTS
EXAMPLES	Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20)	Ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulates (PM10, PM2.5)
CAUSE OF EMISSIONS	Carbon dioxide is the principal product of fuel combustion	Fuel leak, undesired byproduct of combustion, or secondary reactions
QUANTITY RELEASED	Depends on the carbon content of fuel and amount of fuel used	Sensitive to many factors, such as side reactions or leaks
SCALE OF IMPACT	Global	Local or regional
LIFETIME IN ATMOSPHERE	Decades to centuries	Days to months

Upstream vs. End-Use GHG Emissions

This analysis takes a lifecycle approach to estimating the greenhouse gases emitted

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[2] The greenhouse gases described in this report refer to “well-mixed” GHGs, meaning that the lifetimes of these gases are long enough to be thoroughly mixed in the lower atmosphere. Some GHGs are short-lived, but they are not included in this study because they are minor contributors to global warming from the fuels and applications examined in this analysis.

[3] Carbon capture and storage (CCS) technologies can also be employed to reduce CO_2 emissions released to the atmosphere. Although CCS is being considered for large point sources such as power plants and industrial facilities, it is not considered for the types of applications examined in this study.

by different energy and technology combinations. A lifecycle approach accounts for not only the emissions generated when using energy at the point of use (e.g., heating a building, driving a vehicle), but also the emissions generated in all processes used to extract, process, and transport the energy to its point of use.

The GHG accounting begins where the raw feedstock is extracted from the well or mine and ends where the fuel is consumed to power a vehicle, appliance, or other product. This report refers to emissions released at the point of final use as "end-use emissions" and refers to those emissions that occur along the delivery pathway as "upstream emissions."

GHG Emissions from Fuel Production (Upstream Emissions)

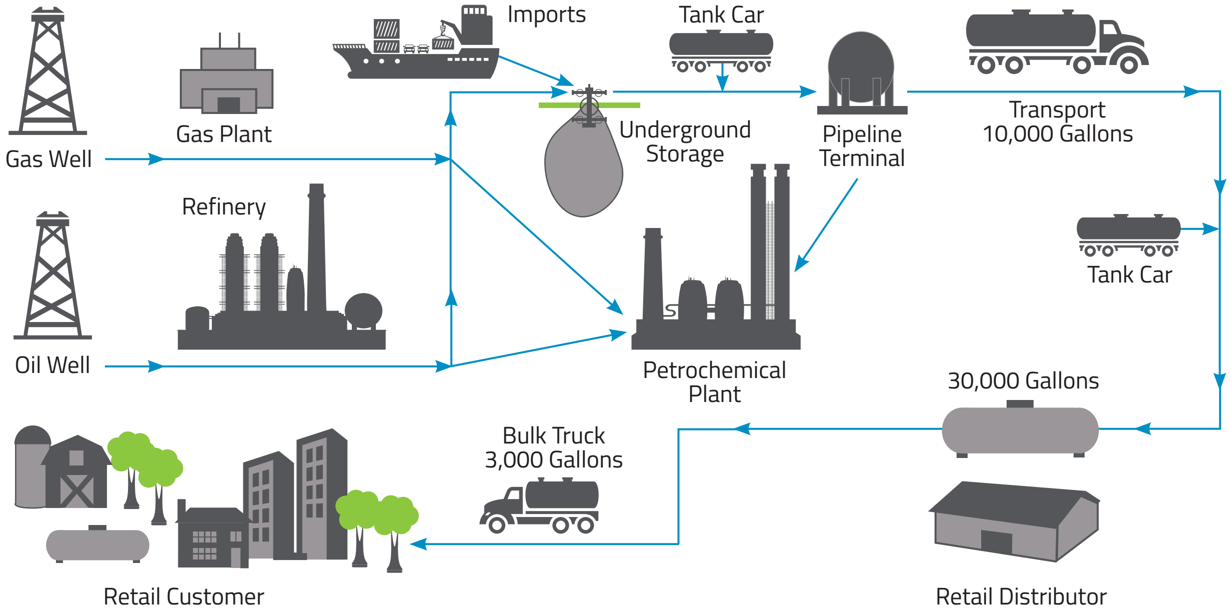
Upstream emissions as defined in this analysis are the sum of all emissions resulting from the recovery, processing, and transport of fuel from the point of extraction to the point of delivery to the end user.

Including upstream emissions in an analytical comparison of different energy sources has a significant impact on results. For example, a GHG comparison of end-use emissions would give the false impression that electricity, with zero end-use emissions, is an energy source with no GHG emissions. This approach fails to account for the substantial release of emissions by the combustion of fossil fuels to generate electricity.

Just as fossil-based power plants are responsible for GHG emissions associated with electricity use, GHG emissions are also emitted in the extraction, production, and transportation of fuels such as gasoline and propane before they are used by consumers. To illustrate the types of processes that are included in an upstream emissions analysis, Figure 3 shows the numerous processes involved in the production and distribution of propane from its two principal sources: natural gas processing and petroleum refining (EIA 2012).

Greenhouse gases are emitted from upstream processes as a result of combustion for the heat and energy that is required during the

Figure 3. Upstream Supply Chain for Propane



Source: Energy Information Administration production and delivery of fuels. But energy use is not the only source of upstream emissions; other production processes also release greenhouse gases. For example, growing crops for ethanol production requires the application of nitrogen fertilizer, which causes the formation of nitrous oxide, while natural gas production and processing releases fugitive methane emissions. GHG emissions from these processes have been quantified by the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model developed by Argonne National Laboratory on behalf of the U.S. Department of Energy, which is a valuable tool for comparative lifecycle analyses of fuel systems.

GHG Emissions from Fuel Combustion (End-Use Emissions)

The principal greenhouse gas emitted during fuel combustion is CO_2, though very small amounts of methane and nitrous oxide are also emitted during combustion.

The carbon content of a fuel determines how much CO_2 will be released when the carbon in the fuel is burned and oxidized. Lighter hydrocarbons, such as propane, have fewer carbon atoms per molecule than heavier fuels, such as diesel. Heavier fuels tend to emit more CO_2 per unit of chemical energy. This trend is evident in Table 4 of the Methodology section, which outlines the range of different fuels in terms of mass of CO_2 released per unit of energy.

The carbon content of a fuel is only one part of the end-use emissions equation. The amount of fuel consumed plays an equally important role. Diesel has a higher carbon content than gasoline, but since diesel engines are generally more fuel efficient than spark-ignition engines, a diesel-fuel technology may still produce less CO_2 than a gasoline technology that requires more fuel to do the same amount of work. To compare GHG emissions from different fuels, the technologies and fuel efficiencies of each specific application must be considered.

Greenhouse Gas Emissions from the Use of Propane and Natural Gas

When released into the air, propane is considered to be a part of the volatile organic compounds (VOC) class. These compounds have a short atmospheric lifetime and a small direct impact on climate (IPCC 2001a). Although precipitation and chemical reactions remove VOC from the atmosphere, some reactions convert VOC into other compounds, such as organic aerosols, methane, and ozone, which do influence climate. The largest source of VOC emissions by far is natural vegetation (IPCC 2001a), and the overall impact of all energy-associated VOC on global temperature is very small (IPCC 2013).

Natural gas (methane) generates fewer CO_2 emissions per Btu than propane, but unlike propane, natural gas is a powerful greenhouse gas. When released into the air, natural gas is slow to break down and produces a global warming effect 28 times that of CO_2.[4] Furthermore, new research suggests that methane leaks from the North American natural gas infrastructure are higher than previously estimated (Brandt et al. 2014).

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[4] Based on GWPs provided in the IPCC's Fifth Assessment Report (AR5).

Methodology

This section describes the general methodology used to prepare this report. Application-specific assumptions are provided with their respective applications in the Summary of Findings section of this report.

Basis for Comparison of Emissions by Application

This study quantifies lifecycle greenhouse gas (GHG) emissions for fourteen different applications that use propane as a fuel source. The applications in the analysis represent a diverse set of market segments that include well-established propane-fueled products, such as forklifts, and emerging propane applications, such as the propane-fueled light-duty truck or the propane-fueled heat pump for commercial heating and cooling.

Each propane application was compared to systems using other fuels for the same application. For each application, competing technologies were evaluated based on an equivalent unit of energy service, such as hours of operation, miles traveled, or heat delivered.

For some fuels, such as electricity, energy efficiency differences from propane are the result of two different technology designs. For other fuels, there are only slight differences in technology design. To ensure a consistent basis for comparison, the highest available energy efficiency for each technology was used whenever possible. Where application-specific data was not available, the relative efficiencies of the fuel systems under comparison were based on the efficiencies reported for similar technologies.

Upstream Emissions Analysis

Upstream emissions as defined in this analysis are the sum of all emissions resulting from the recovery, processing, and transport of fuel from the point of extraction to the point of delivery to the end user. These emissions are quantified by the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) model, which was used to estimate the upstream portion of the lifecycle greenhouse gas (GHG) emissions of each application evaluated in this study.

The emission factors used in this study to calculate upstream emissions are shown in Table 2, which outlines the amount of each gas (in grams) released upstream for each unit of energy (in million Btu)[5] of fuel consumed. The amounts reported for each individual gas were obtained using the GREET model. The values shown for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the output of the "Well-to-Pump" table in the GREET model spreadsheet using the input parameters described below. The total CO_2 equivalent (CO_2e) shown in the right-hand column of Table 2 is calculated as the sum of each greenhouse gas after it has been multiplied by its global warming potential. The global warming potentials used in this analysis for CH_4 and N_2O reflect the most up-to-date values as reported by the IPCC for a 100-year timescale: 28 for CH_4 and 265 for N_2O (IPCC 2013).

Table 2. Upstream Emissions Factors (grams per million Btu)[6]

	CO_2	CH_4	N_2O	TOTAL CO_2 EQUIVALENT
ETHANOL (E85)	-14,409	113	41.0	-387
NATURAL GAS	6,995	317	1.34	16,228
PROPANE	12,867	188	0.26	18,204
GASOLINE	16,010	118	3.95	20,368
COMPRESSED NATURAL GAS	10,985	324	1.40	20,429
DIESEL	18,727	118	0.31	22,104
FUEL OIL	18,727	118	0.31	22,104
ELECTRICITY	182,897	317	2.84	192,523

For each application evaluated in this analysis, the total energy use (in million Btu) was multiplied by the upstream emissions factor for that energy source (in grams of CO_2e per million Btu). Accordingly, the upstream emissions factor and the energy efficiency of the end-use technology were both important in determining the total upstream emissions resulting from an application.

The GREET model is a convenient tool for upstream emissions analysis in part because it allows users to modify input parameters to test hypotheses and answer specific research questions. The values for each of the three greenhouse gases shown in Table 2 are the output of the GREET model, run under defined process parameters. These parameters include the type, fractional share, and efficiency of power plants used to generate electricity; market shares of different fuel formulations; fuel feedstock shares and refining efficiencies; and fuel transportation mode, distance, and mode share.

In order to reflect the most current market landscape and to evaluate the use of standard pressure natural gas as an application fuel, the default values in the GREET model were modified for several user-defined input parameters. Specifically, the share of natural gas feedstock used for propane production was changed from a default value of 65% to the present market share of 70% in North America (ICF International 2013).[7]

Second, because the GREET model was designed for transportation fuel analysis, the only natural gas fuels listed in the

---

[5] Based on lower heating values (LHV).

[6] End-use emissions are based on the lower heating value, density, and weight ratio of carbon atoms per unit volume of each fuel provided in the GREET model software. All carbon is assumed to be released as CO_2.

[7] Based on most current industry data. Propane is produced from both natural gas and petroleum sources. The natural gas share of propane supply has increased due to the expansion of shale gas, and ICF International currently represents more than 70% of total propane production. The upstream emissions attributed to propane depend on the relative contribution of these two sources to overall propane supply. In the GREET model, propane produced from crude oil refining has higher GHG emissions than propane produced from natural gas processing.

model's well-to-pump output table are liquefied or compressed natural gas (LNG or CNG). However, the scope of this analysis includes standard pressure (i.e., pipeline delivered) natural gas in several non-vehicle applications. As a proxy for upstream emissions of uncompressed natural gas, the parameter value for natural gas compression efficiency was set to 100%. All other input parameters in GREET were left unchanged from the model's default values.

End-Use Emissions Analysis

For each technology and fuel combination evaluated in this analysis, end-use emissions were determined by calculating the CO_2 emissions resulting from fuel combustion at the point of technology end use.

First, an equivalent level of energy service was chosen as a basis for comparison for each application (e.g., 10,000 miles per year for a light-duty truck). The estimated energy efficiencies of each technology were then used to calculate the total energy required to provide the energy service to the end user. Whenever possible, the highest reported energy efficiency was selected for each technology from published data. When appropriate, systems losses (such as heat loss through ducts in residential space heating) were also included in the calculation of total end-use energy consumption.

Many of the technologies evaluated in this analysis are subject to well-defined and regulated standards for energy efficiency. Standards such as annual fuel utilization efficiency (AFUE), energy factor (EF), solar energy factor (SEF), heating season performance factor (HSPF), coefficient of performance (COP), and energy efficiency rating (EER) were used to evaluate building energy applications such as space heating, air conditioning, and water heating.

Most of the vehicle applications examined in this analysis include propane-fueled technologies that have either recently emerged on the market or are in sectors not regulated by fuel efficiency standards. As a result, it was not possible to obtain standardized fuel efficiency values for many of these new technologies, especially on a basis that would allow a valid comparison to conventional vehicles. However, the AFLEET model developed by Argonne National Laboratory (as a module of GREET) is designed to help fleet managers assess alternative-fuel vehicle options.[9] Because the model uses fuel efficiency values that are specific to each vehicle weight class and fuel type, and because it is frequently updated with data reflecting new advances in alternative fuel technologies, it was deemed the most appropriate source for comparing alternative fuel vehicles in this analysis. As a result, the default fuel efficiency values used by AFLEET Tool 2013 ("Background Data" sheet) were used to calculate vehicle fuel consumption for all of the vehicle applications evaluated as part of this study.

In many cases, the data sources used for this analysis were specific to the application under evaluation. Technology-specific data was obtained from published test results, vendor-supplied specifications, government studies, and other sources. Please refer to the Summary of Findings section for the

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[9] AFLEET is a decision-making model developed by Argonne National Laboratory to help fleet managers evaluate the costs, benefits, and life-cycle GHG impacts of their vehicle purchasing decisions. Source: https://greet.es.anl.gov/afleet

assumptions and methodologies used for individual applications. The List of References includes a complete list of sources.

The fuel specifications used in the GREET model were used to calculate both the energy consumption and CO_2 emissions for technology end-use. For applications in which conversion from volumetric units (gallons or cubic feet) was required, the default energy contents[10] in the GREET model (sheet “Fuel Specs”) were used to convert volumetric fuel consumption to total energy consumption in mmBTU. Total end-use energy consumption was then multiplied by the CO_2 emissions factor for the fuel being used.

In addition to being the source for fuel energy content, the GREET model was also used to obtain CO_2 emissions factors. The CO_2 emissions factors were calculated from the lower heating value, density, and carbon content of the fuel (also in sheet “Fuel Specs”). Although combustion can produce other compounds containing carbon (such as VOC, CO, and particulates), these products are typically short-lived and are oxidized to CO_2. For the purposes of this analysis, all of the carbon in each fuel is assumed to be converted to CO_2 during end-use,[11] and is shown in Table 3.

Table 3. CO_2 Released per Btu[12]

FUEL TYPE	KG CO_2 PER MILLION BTU
NATURAL GAS	59.41
PROPANE	68.06
ETHANOL (E85)	75.19
GASOLINE	76.71
DIESEL	78.20
FUEL OIL	85.08

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[10] Based on lower heating values

[11] Although small amounts of CH_4 and N_2O are released during combustion of fuel during end use, this analysis does not quantify end use emissions for these two gases. Emissions levels are specific to variable combustion conditions such as temperature, and there is insufficient data to accurately estimate emissions of CH_4 and N_2O for many of the different technologies in this report. However, since they are very small contributors to end-use GHG emissions for most technologies, this is not expected to significantly influence the outcome of this analysis. For comparison, end-use emissions in the GREET model show that CH_4 and N_2O together represent 21% of upstream GHG emissions for a gasoline vehicle, but less than 1% of all end-use GHG emissions.

[12] End-use emissions are based on the lower heating value, density, and weight ratio of carbon atoms per unit volume of each fuel which were provided in the GREET model software. All carbon is assumed to be released as CO_2.

Summary of Findings

This section presents a summary of this study's findings, organized by application area. For each application area, the study provides a brief description of the application followed by two-page sections providing the following information:

1. A brief description of the application, including important technologies used to meet the application's needs
2. A data table that presents this study's results, including:
    - The major technology classes investigated with this study
    - The fuels analyzed for each technology class
    - Total greenhouse gas emissions, indexed to the GHG emissions for a reference case of a selected technology class using propane
    - The energy use for the basis for analysis as defined for each application
    - Upstream, end-use, and total greenhouse gas emissions for each technology and fuel
3. A detailed list of assumptions used to arrive at the results

Readers are cautioned from comparing total values for energy use and GHG emissions across applications, as the basis for analysis can vary significantly from one application to the next and greatly affect the total energy use and emissions results. However, the comparative emissions results (i.e., the indexed results) may be compared across applications to assess the magnitude of differences of GHG emissions by fuel type and technology class.

Application Overview

Residential Space Heating

Homes are most commonly heated by either a centralized system that moves warm air through ducts (or hot water through pipes), while others have separate heating units (usually electric) distributed throughout the home. Furnaces can be gas-fired (natural gas or propane), oil-fired, or electric. Approximately 8.4 million U.S. households rely on propane for home heating (EIA 2013).[13]

Residential Water Heating

Residential water heaters include both tank storage units as well as instantaneous ("tankless") water heaters. Both types of water heaters can be gas-fueled or electric. Fuel oil and solar power are also used for storage tank water heating. Approximately 4.5 million U.S. households use propane for water heating purposes (EIA 2013).[14]

Commercial Space Heating and Cooling

Heat pumps provide both heating and cooling in commercial buildings, combining the functions of furnaces and air conditioners into a single unit. Most furnaces are fueled by gas or oil (EIA 2003), while nearly all commercial buildings use electricity for cooling (EIA 2003). Nearly 80 percent of commercial buildings with packaged heat pumps use electricity as the energy source for heating (EIA 2003), and nearly 100 percent use electricity for cooling, although interest in propane- and natural gas-fueled engines for cooling is growing (EIA 2003).

Commercial Water Heating

The majority of commercial buildings use a centralized water heating system to provide hot water to tenants. More than half of commercial buildings use electricity as an energy source for heating water, while slightly less than half of buildings use natural gas or propane (EIA 2003).

Combined Heat and Power

Combined heat and power (CHP) generates both electricity and useful heat from a single fuel source. Power plants use cogeneration to recapture heat and boost efficiency, and in some cases provide thermal energy to nearby homes, which is known as district heating. MicroCHP does this at a smaller scale, allowing homes and offices to generate heat and power closer to the point of use, reducing energy losses associated with electricity transmission and distribution from the electrical grid.

Generators

Generators are used as a primary source of electricity or as a backup energy source when power cannot be distributed by a utility provider. These units range in capacity from a few kilowatts to several hundred kilowatts depending on the application.

Irrigation Engines

More than 150,000 farms in the United States rely on approximately 570,000 irrigation pumps to deliver water from reservoirs, lakes, streams, and wells for crop production (USDA 2010). The majority of irrigation pumps operate using electric motors and diesel fuel. The smallest pumps are often operated by electric motors, while higher capacity wells tend to be operated by diesel, natural gas, and propane engines.

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[13] Based on main and secondary heating equipment.

[14] Based on main and secondary water heating equipment.

Mowers

Turfgrass and lawncare management in the United States is a $62 billion industry (Haydu et al 2006) with more than 40 million acres (Milesi et al 2005) of residential lawns, sports fields, golf courses, parks, roadsides, and public and commercial land. While commercial mowers have historically been fueled by gasoline or diesel, small engine technology advancements, alternative fuel technologies, and the need for low-emission equipment to comply with Ozone Action Days in some parts of the country have allowed propane-fueled mowers to successfully enter the market.

Terminal Tractors

Terminal tractors are slow-moving, heavy-duty vehicles that are capable of towing freight weighing more than 50 tons. These vehicles operate continuously and, due to emissions regulations at some freight yards (California Environmental Protection Agency 2005), some yard operators are seeking alternative fuel options such as propane for their tractors.

Forklifts

Forklifts use fuel for both vehicle propulsion and load lifting work. Indoor air quality concerns restrict the use of diesel and gasoline for heavy-duty jobs; electric forklifts are normally used for light-duty jobs, while propane can be used for both.

Type A/C Buses

Type A buses are used as small school buses and light transit shuttle buses, and are constructed by placing bus bodies on the chassis of cutaway vans. Type C buses hold approximately twice the capacity as Type A buses, and are the most common bus types for school districts across the United States. Although diesel currently fuels the majority of school buses in the United States, several studies have raised concerns about high levels of exposure to diesel exhaust, which has been recognized by the World Health Organization as a known human carcinogen (WHO 2012). Many fleet owners have replaced their diesel buses with alternative fuels such as propane and compressed natural gas to reduce emissions and realize other benefits.

Bobtail Trucks

Bobtail trucks are often used to transport fuel (up to 6,000 gallons) and are considered the “workhorse” of the propane industry for delivering fuel. While most bobtails run on diesel, Freightliner Custom Chassis has manufactured a propane-fueled delivery that uses an advanced liquid propane injection (LPI) system that provides more power and fuel efficiency than conventional vapor injection systems.

Light-Duty Trucks

Light-duty trucks, such as the Ford F-250 or Chevrolet Silverado, constitute nearly one-third of the U.S. vehicle fleet (DOT 2010). While gasoline fuels the majority of light-duty trucks in the United States, ethanol (E85) and propane have gained greater use in recent years.

Utility Cargo Vans

Utility cargo vans, such as the Ford E-Series, are commonly used for light-duty cargo transport and ambulance services. Several models can now be purchased to run on alternative fuels, while older models can be retrofitted.

Residential Space Heating

Homes are most commonly heated by a centralized system that moves warm air through ducts, such as a furnace or heat pump, a centralized system that uses a boiler to heat water and move it through pipes and radiators, such as radiant floor heating, or by separate heating units (usually electric) distributed throughout the home. This analysis focuses on the following residential space heating technologies:

- **Furnaces**, which can be gas-fired, oil-fired, or electric; most gas furnaces can be fueled by either natural gas or propane.
- **Heat pumps** use electricity to move heat from outdoor air into the home and rely on a backup source such as electrical resistance when they cannot gather enough heat from the air; as a result, they are more efficient than electric radiators and can deliver more Btus of heat energy than they consume using electricity.
- **Hybrid systems**, which combine electric-powered heat pumps with gas-fueled furnaces, and can be favorable if electric heat pumps struggle to meet heating demand, or if users prefer to use electric heat pumps for cooling and furnaces for heating.

🟦 PROPANE
■ ELECTRICITY
🟥 FUEL OIL

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (░ = upstream; ■ = end-use)
HEAT PUMP	Electric air source heat pump (ASHP)	0.58	15.8	3,050 3,050 total
	Electric air source heat pump (ASHP) with propane furnace backup	0.83	43.1	1,890 2,500 4,390 total
FURNACE	Propane furnace	1.00	61.3	1,110 4,170 5,280 total
	Fuel oil furnace	1.27	62.4	1,380 5,310 6,690 total
	Electric furnace	2.20	60.3	11,600 11,600 total
BASEBOARD	Electric baseboard/ wall vent	1.87	51.3	9,870 9,870 total

Because boilers have the same range of energy efficiencies as furnaces, they were not added to this analysis. Similarly, a number of different electric resistance heating units can be used to heat rooms, but because they all convert nearly 100 percent of electricity into useful heat, their emissions impact will be similar to electric baseboard heating. In addition, this analysis does not cover cooling because gas- or oil-fired technologies that provide cooling to residential homes are not commercially relevant and electric cooling would provide the same energy use to cool a residential space for all of the technologies included in this analysis.

Assumptions

1. All technologies are assumed to deliver an equivalent energy service, which for this application is 51.2 mmBTU of space heating. The total annual energy consumption used for residential space heating is based on the most recent Residential Energy Consumption Survey (RECS) data by the U.S. Energy Information Administration of homes that used propane for space heating purposes. After factoring for the average annual fuel utilization efficiency (AFUE) for a propane furnace of 98.5 and estimated duct losses, a typical home receives 51.2 mmBTU of delivered heat energy. This value has been used as the baseline in the analysis for space heat delivered in a typical year (EIA 2013).
2. According to DOE, the average duct system uses “R-4” insulation which has 15% leakage on each side (supply and return), totaling 30%. In new construction, a duct efficiency of 100% is possible if construction is done in a manner that leaves no hidden leakage paths. Therefore, it is assumed that there is a 15% efficiency loss split between the supply and return of a duct system. This thermal efficiency has been applied to the all furnaces, heat pumps, and air conditioning systems in the analysis. The energy efficiency of a furnace or boiler is designated by its annual fuel utilization efficiency (AFUE), which is the ratio of heat output of the furnace or boiler compared to the total energy consumed by a furnace or boiler (DOE EERE 2004a).
3. The following AFUE values for generic commercial space heating technologies are based on the highest reported values in the AHRI Directory of Certified Product Performance (AHRI 2012):
    a. Furnaces: fuel oil = 96.7; propane = 98.5
4. Typical AFUE values for electric furnaces are not provided by AHRI. According to Energy Star, the AFUE of electric furnaces ranges from 95–100. An AFUE of 100 was assumed for the electric furnace based on the upper end of the range (DOE 2012).
5. The energy efficiency of a heat pump is designated by its heating season performance factor (HSPF), which is the ratio of heat delivered in Btu to the electricity consumed in watt-hours. This efficiency standard was selected to measure energy use in this analysis of commercial heat pumps, though it is designated for temperature profiles of Climate Region IV, and generally varies significantly with climate (Fairey et al 2004).
6. The following HSPF value for an electric air source heat pump is based on the highest reported values in the AHRI Directory of Certified Product Performance (AHRI 2012):
    a. Air source Heat Pump (HSPF): electric = 13.
7. The electric air source heat pump (ASHP) with propane furnace backup is assumed to handle 40% of the heating load with the backup system handling the remaining 60%. This assumption coincides with a ratio used in a separate analysis of residential heating systems (Newport Partners 2013).

Residential Water Heating

Residential water heaters include both tank storage units and instantaneous (“tankless”) water heaters. This analysis includes both types of water heaters:

- **Storage water heaters** keep a constantly available supply of hot water and can be gas-fueled (propane or natural gas), electric, fuel oil, or solar power (solar water heaters frequently use electricity to pump water through the collector, and solar water heating systems almost always require a conventional heater as a backup for cloudy days [EERE 2012]).
- **Tankless water heaters** heat water as it is supplied to the end user units and can be gas-fueled (propane or natural gas) or electric.

■ PROPANE ■ FUEL OIL
■ ELECTRICITY

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (░ = upstream; ■ = end-use)
SOLAR	Solar storage tank, propane backup	0.26	3.84[1]	157 227 385 total
GENERIC STORAGE	Generic propane storage tank	1.00	16.9	307 1,150 1,450 total
	Generic electric storage tank	1.64	12.4	2,390 2,390 total
BEST AVAILABLE STORAGE	Best available propane storage tank	0.85	14.4	262 979 1,240 total
	Best available fuel oil storage tank[2]	1.28	17.4	384 1,480 1,860 total
	Best available electric storage tank	1.56	11.8	2,270 2,270 total
GENERIC TANKLESS	Generic propane tankless	0.82	13.9	253 945 1,200 total
	Generic electric tankless	1.58	11.9	2,290 2,290 total
BEST AVAILABLE TANKLESS	Best available propane tankless	0.74	12.4	226 845 1,070 total
	Best available electric tankless	1.56	11.8	2,270 2,270 total

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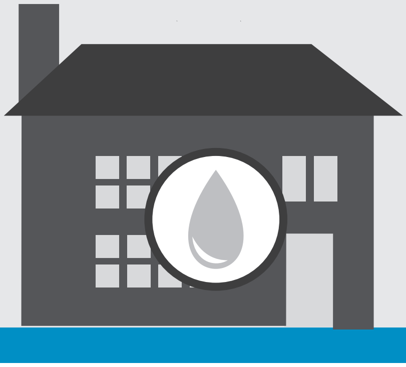
[1] The energy use accounts for only the consumption of fuel from the propane storage tank, and the electrical energy required to circulate heat-transfer fluids.

[2] Typical ranges of energy factors for generic fuel oil storage tank water heaters are not provided by Energy Star. According to the AHRI Directory of Certified Product Performance, the highest reported energy factor is 0.68. Since this energy factor is already at its highest level, fuel oil has not been included in the analysis of generic storage tank water heaters (AHRI 2012).

Heat pump water heaters use electricity to move heat rather than to generate heat directly. They are more efficient than electric water heaters, but very few are commercially available. Therefore, electric heat pumps have been omitted from the study.



Assumptions

1. The energy efficiency of a water heater is designated by its energy factor (EF), which is the ratio of the heat delivered (as hot water) to the energy consumed.
2. All technologies are assumed to deliver an equivalent energy service, which for this application is 10 mmBTU of hot water. The total annual energy consumption used for residential water heating is based on the most recent data for homes that use electricity for water heating, reported in the U.S. Energy Information Administration's Residential Energy Consumption Survey (RECS). After applying the energy factors of generic storage tank and tankless water heaters while accounting for the number of homes by fuel type, and applying the estimated efficiency losses of 15% due to piping, a typical home receives approximately 10 mmBTU of delivered hot water. This value has been used as the baseline in the analysis for hot water delivered in a typical year (EIA 2013).
3. It is assumed that 15% of energy is lost to piping in residential homes (City of Santa Monica 2010).
4. Energy factors for residential storage tank and tankless water heater technologies
   (Factors for generic models are based on values reported in an independent study by Energy Star [Global Energy Partners 2005] and factors for best-available models are based on highest reported values in the AHRI Directory of Certified Product Performance [AHRI 2012].)

	Electric	Propane
Generic tankless water heaters	0.99	0.85
Generic storage tank water heaters	0.95	0.70
Best-available tankless water heaters	1.00	0.95
Best-available storage tank water heaters	1.00	0.85

5. Solar energy factors (SEF) range from 1.0 to 11 with 2 or 3 as the most common. A SEF of 3 has been used in this analysis with a propane storage tank energy factor of 0.70 (EERE 2012).
6. According to a study of 88 solar heating systems by the Energy Savings Trust, all systems in the trial used an electric pump to circulate the solar heat-transfer fluid to and from the solar collector. The majority of these systems used power from the electrical grid to run the pump and heater controller, ranging from 1–23% of the total heat energy delivered (10 kWh to 180 kWh per year in total) with a median value of 5%. It is assumed that the solar storage tank system with propane backup uses power from the electrical grid equal to 5% of the total heat delivered by the storage tank (The Energy Savings Trust 2011).

Commercial Space Heating and Cooling

The most common type of heating and cooling equipment used in commercial buildings combines a furnace for heating in cold weather with residential-type central air conditioners for cooling in warm weather. Heat pumps use electricity to move heat rather than to generate electricity and are capable of providing both heating and cooling without the need for two separate devices. These systems place refrigerants with low boiling points under high pressures so that they absorb heat at a high rate, enabling the heat pump to pull heat from both a fuel source and room temperature air to deliver more energy than is consumed by the system.

■ PROPANE
■ ELECTRICITY
■ FUEL OIL

		GHG Index	Energy Use (mmBTU per unit per year)		Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (▨ = upstream; ■ = end-use)
			Heating	Cooling	
AMMONIA ABSORPTION	Propane-fueled ammonia absorption heat pump	1.19	329	705	▨ 18,800 ■ 70,400 89,200 total
ELECTRIC	High-efficiency electric heat pump	0.68	132	133	▨ 51,000 51,000 total
	Generic electric heat pump	0.71	141	135	▨ 53,100 53,100 total
FURNACE & ELECTRIC CENTRAL AIR SOURCE AIR CONDITIONER	Propane furnace & electric central air source air conditioner	1.00	566	135	▨ 36,300 ■ 38,500 74,800 total
	Fuel oil furnace & electric central air source air conditioner	1.16	567	135	▨ 38,500 ■ 48,200 86,700 total
	Electric furnace & electric central air source air conditioner	1.54	465	135	▨ 115,000 115,000 total

This analysis includes the following types of commercial space heating and cooling systems:

- **Absorption heat pumps**, which use the heat from a gas burner to operate an ammonia-water absorption cycle.
- **Electric heat pumps**
- **Furnace and electric central air source air conditioner systems**

Assumptions

1. All technologies are assumed to deliver an equivalent energy service, which for this application is 442 mmBTU of space heating, and 454 mmBTU of space cooling (heat removal). These values were calculated by applying the thermal efficiency of a generic propane furnace (82.2%) including duct losses (5%) for space heating, and applying the cooling efficiency of an electric central air source air conditioner (12.1 EER) including duct losses for space cooling, to average heating and cooling energy use for commercial buildings surveyed by the EIA. (EIA 2003).
2. Thermal efficiencies for commercial furnace technologies
(Based on the highest reported values in the AHRI Directory of Certified Product Performance [AHRI 2012])

	Fuel Oil	Propane
Furnaces	82.0%	82.2%

3. The energy efficiency of a heat pump is designated by coefficient of performance (COP), or energy efficiency ratio (EER). COP is may often exceed a value of 1 as it is defined as the ratio of heating provided to the heat equivalent of energy consumed (e.g., electricity, natural gas, propane). The EER is the ratio of cooling in Btus to the energy consumed in watt-hours.
4. Energy efficiencies for commercial electric heat pumps
(Based on the highest reported values in the AHRI Directory of Certified Product Performance [AHRI 2012])

Heating coefficient of performance (COP)	3.52
Cooling energy efficiency ratio (EER)	12.3

5. There are no apparent federal standards for the thermal efficiency of commercial electric furnaces. It is assumed that the thermal efficiency of commercial electric furnaces is 100%.
6. The furnaces analyzed in this study are assumed to use a water-cooled or evaporative-cooled electric air conditioner, and are based on current federal standards with cooling capacities of 65,000–135,000 Btu/hr. The cooling efficiency (EER) of the electric air conditioner is 12.1 (EERE 2012).
7. The propane and natural gas commercial heat pumps in the analysis are based on manufacturer specifications of the Fulton Reversible Air Source Ammonia Absorption Heat Pump IVS-095-AR (Fulton 2012).
8. According to a study by LBNL, duct leakage flows were measured on 10 large commercial duct systems at operating conditions: three had less than 5% leakage, and seven had substantial leakage ranging from 9 to 26% percent). The average duct efficiency for both heating and cooling for all technologies is therefore assumed to be 95% (Wray, Diamond, and Sherman 2005).

Commercial Water Heating

Commercial water heaters include storage tank units, instantaneous (“tankless”) units, and heat pumps. Most non-mall commercial buildings use centralized water heating systems, while some buildings require more than one water heating unit to adequately provide hot water to their tenants.

🟦 PROPANE
■ ELECTRICITY
🟪 FUEL OIL

Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (▢ = upstream; ■ = end-use)

		GHG Index	Energy Use (mmBTU per unit per year)	Upstream	End-use	Total
HEAT PUMP	Propane-fueled heat pump[1]	0.44	31.8	579	2,160	2,740 total
GENERIC STORAGE	Generic propane storage tank	1.00	73.0	1,330	4,970	6,300 total
	Generic fuel oil storage tank	1.39	81.8	1,810	6,960	8,770 total
	Generic electric storage tank	1.99	65.1	12,500		12,500 total
BEST AVAILABLE STORAGE	Best available propane storage tank	0.88	64.5	1,170	4,390	5,560 total
	Best available fuel oil storage tank	1.32	77.8	1,720	6,620	8,340 total
	Best available electric storage tank	1.95	63.8	12,300		12,300 total
GENERIC TANKLESS	Generic propane tankless	1.00	72.9	1,330	4,960	6,290 total
BEST AVAILABLE TANKLESS	Best available propane tankless	0.90	65.8	1,200	4,480	5,680 total
	Best available fuel oil tankless[2]	1.39	81.8	1,810	6,960	8,770 total
	Best available electric tankless	1.97	64.5	12,400		12,400 total

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[1] Although heat pump water heaters may be used for tankless water heating, there were no commercial tankless heat pump models listed in the AHRI Directory of Certified Product Performance; the propane and natural gas commercial tankless heat pumps in the analysis are based on manufacturer specifications of the Ilios High Efficiency Water Heater (Ilios Dynamics).

[2] The AHRI Directory of Certified Product Performance only reported one fuel oil tankless water heater. Therefore, this technology is analyzed only for best-available models.

This analysis includes the following technologies[3]:

- **Air-source heat pumps**,[4] which can run on electricity or gas, have the ability to extract a significant amount of heat from the outside air to heat water to help offset the high initial purchase price of the unit.
- **Storage water heaters** and **tankless water heaters**, which can both run on propane, natural gas, fuel oil, and electricity.

Assumptions

1. Many commercial buildings with more than one water heating unit have centralized water heating equipment while the rest have a distributed system or a combination of both, meaning it is possible to have more than one water heating unit per building. To adjust for the number of water heating units per building, it is assumed that there are 1.5 water heaters per commercial building. The results presented in this application therefore represent the energy and emissions from more than a single water heater (EIA 2003).
2. All technologies are assumed to deliver an equivalent energy service, which for this application is 64 mmBTU of water heating. The total annual energy consumption used for water heating per commercial building is based on the most recent Commercial Buildings Energy Consumption Survey (CBECS) data by the U.S. Energy Information Administration (EIA 2003). After factoring in the assumption that each commercial building uses 1.5 water heaters, and using an average EF of 0.80, the estimated annual energy consumption is 64 mmBTU per commercial building for water heating purposes (EIA 2003).
3. The energy efficiency of a hot water heater is designated by its energy factor (EF) or coefficient of performance (COP). The EF is the ratio of heat delivered (as hot water) to the energy consumed (e.g., electricity, natural gas, propane, or oil). COP is designated for heat pump systems, and may often exceed a value of 1 as it is defined as the ratio of heating provided to the heat equivalent of energy consumed (e.g., electricity, natural gas, propane).
4. Energy factors for generic commercial storage tank water heater technologies
(Based on the average and highest reported values in the AHRI Directory of Certified Product Performance, and are applied to the analysis of generic and best-available models [AHRI 2012].)

	Electric	Fuel Oil	Propane
Generic storage tank water heaters	0.98	0.78	0.87
Best available storage tank water heaters	1.00	0.82	0.99

Energy factors for commercial tankless water heater technologies
(Based on the average and highest reported values in the AHRI Directory of Certified Product Performance, and are applied to the analysis of generic and best-available models, respectively [AHRI 2012].)

	Electric	Fuel Oil	Propane
Generic tankless water heater	---	---	0.88
Best-available tankless water heaters	0.99	0.78	0.97

5. Typical ranges of energy factors for tankless electric water heaters are not provided by the AHRI Directory of Certified Product Performance. According to Energy Star, the highest reported energy factor of electric tankless water heaters is 0.99, and has been applied to the analysis of best-available models (Global Energy Partners 2005).

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[3] Some commercial water heaters common in hotels are equipped with separate recirculation loop systems to quickly deliver hot water to individual dwelling units. Due to the lack of data available on pipe losses which are assumed to be dependent on the size of the system, recirculation loop systems have not been included in this analysis.

[4] While electricity may be used for heat pumps in commercial water heating, these units did not appear in the AHRI Directory of Certified Product Performance. They were not included in the analysis due to a lack of reliable information.

Combined Heat and Power

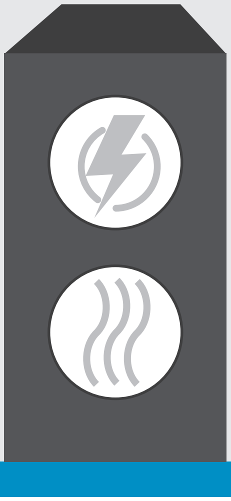
Combined heat and power (CHP) units generate electricity and efficiently capture and use of waste heat. Also known as “district heating,” power plants may use CHP to save energy by redirecting the heat emitted from electricity generation and providing it to nearby homes and buildings for space and water heating. Micro-combined heat and power (microCHP) is a small-scale version of power plant cogeneration that generates heat and power closer to its point of use, resulting in fewer losses of energy that are inherent in the transmission and distribution of electricity from power plants and utility substations. MicroCHP units may be used in combination with renewable energy sources, such as wind and solar, or in conjunction with the electrical grid to provide users with a backup option in the event of electrical grid failure. Some regulations in the U.S. allow owners of microCHP units to sell excess generated electricity back to the national grid.

■ PROPANE ■ DIESEL
■ ELECTRICITY

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (■ = upstream; ■ = end-use)
ENGINE-DRIVEN MICROCHP	10 kW propane engine-driven microCHP	0.91	862	15,700 58,600 74,300 total
MICROTURBINE MICROCHP	Generic propane microturbine	1.00	948	17,300 64,500 81,800 total
	Generic diesel microturbine	1.16	948	20,900 74,100 95,100 total
GRID-SUPPLIED ELECTRICITY	Commercial electric furnace and tankless water heater	1.80	2,410	147,000 147,000 total

This analysis focuses on the following technologies:

- **MicroCHP units**, which are typically defined as CHP units that generate less than 50 kW and uses different types of electricity generation technologies, such as internal combustion engines, fuel cells, and microturbines.
- A **commercial electric furnace and tankless water heater**; a combination that relies on grid-supplied electricity to provide heat and power for larger-scale applications.



Assumptions

1. According to the Biomass Energy Centre, a typical CHP system powered by an internal combustion engine or gas microturbine has a heat to electrical output ratio of 2:1 (Forestry Commission n.d.).
2. The microCHP technologies and grid-supplied electrical systems are assumed to deliver an equivalent energy service in both heat and power. The heat delivery is based on the combined energy service for commercial space heating and water heating, which is equal to 505 mmBTU per commercial building (see previous applications: Commercial Space Heating and Cooling, and Commercial Water Heating). After applying the heat to electrical output ratio of 2:1 for a typical microCHP system, all applications are assumed to deliver an additional 253 mmBTU of electrical power output (EIA 2003).
3. The total CHP efficiency of the 10 kW engine-driven microCHP unit is based on the propane-fueled Yanmar CP10WN model, which is equal to 88% (Yanmar 2012).
4. The total CHP efficiencies of the generic microturbine-powered CHP units are assumed to be 80% based on a claim from Capstone that CHP units may achieve total efficiencies in excess of 80% (Capstone 2009).
5. The electricity application is assumed to deliver the equivalent energy service for heat using high efficiency commercial appliances for both space heating (furnace) and water heating (tankless water heater). The combined efficiency of these systems is assumed to be 99%.

Generators

Generators are used in residential, commercial, and industrial sectors as a primary, backup (“standby”), or portable source of electricity. These units contain a combustion engine that drives an electrical generator to produce power ranging from a few kilowatts to several hundred kilowatts.

Primary generators are used in areas where the consumer does not purchase power from a utility provider, either because the consumer is not connected to the power grid or because he or she requires greater reliability than the utility provider can provide. Standby, mobile, and portable generators, have a range of uses, including emergency backup power, construction, and recreation.

■ PROPANE
■ ELECTRICITY
■ DIESEL

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (□ = upstream; ■ = end-use)
RESIDENTIAL BACK-UP GENERATOR	**7–15 kW diesel generator**	0.88	6.97	154 545 699 total
	7–15 kW propane generator	1.00	9.20	167 626 793 total
GRID-SUPPLIED ELECTRICITY	**Electricity**[1]	1.34	5.51	1,060 1,060 total

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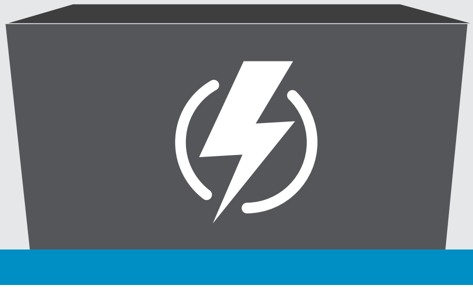
[1] The efficiency of utility power generation and transmission is assumed to be 10,500 BTU/kWh, which represents average values for the national grid (DOE EERE 2004b).

This analysis focuses on the following generators:

- **Standby power generators**, which provide emergency or backup power for homes, office buildings, hospitals, factories, telecommunication centers, and other critical operations.
- **Grid-supplied electricity**, which is generated by power plants, transmitted to regional electrical substations, and finally distributed to consumers.



Assumptions

1. The propane and diesel generators in the analysis are assumed to operate for 50 hours per year.
2. End-use energy consumption data is based on reported fuel use in vendor specifications of representative generators. The annual energy use for each respective fuel type is based on the average energy consumption between the two generator power supply capacities. Representative generators are:
    a. Propane
        i. Generac CorePower 7 kW (Generac 2013a)
        ii. Generac Guardian 14 kW (Generac 2013b)
    b. Diesel
        i. Kubota GL7000 7 kW (Kubota 2014)
        ii. Generac Protector 30 kW (Diesel) (Generac 2013c)
3. Annual energy use for grid-supplied electricity is based on delivering the same energy service of the propane generators in the analysis. The average delivered energy service between the 7 kW and 14 kW propane generator models is equal to 525 kWh.

Irrigation Engines

Irrigation pumps deliver water from reservoirs, lakes, streams, and wells to fields at essential times to ensure productive crop harvests. Most irrigation pumps are centrifugal, driven by an engine connected to the drive shaft. The smallest pumps are often operated by electric motors, while higher capacity wells tend to be operated by diesel, natural gas, and propane engines.

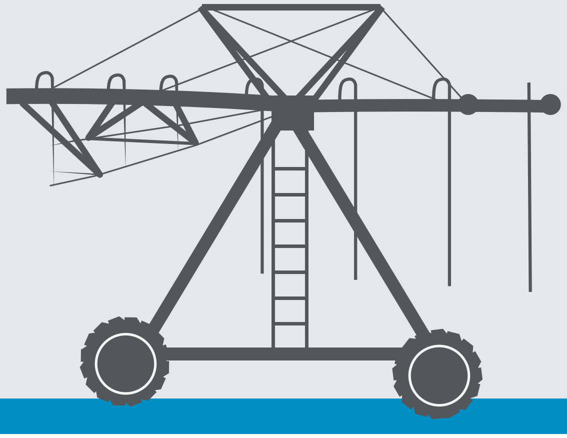
The energy required to run a pump is measured in terms of fuel consumption or electric power use of the engine driving the shaft. Most irrigation pumps range in size from 30 to 300 horsepower and operate at a steady speed and load for many hours, often 24–48 hours nonstop. The effectiveness in converting fuel or electricity to mechanical power to drive the irrigation pump varies based on the

🟦 PROPANE
🟥 GASOLINE
🟪 DIESEL

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (⬜ = upstream; ⬛ = end-use)
100 HORSEPOWER IRRIGATION ENGINE	Propane irrigation engine	1.00	945	17,200 64,300 81,500 total
	Propane and diesel dual fuel irrigation engine	1.05	927	18,500 67,400 86,000 total
	Diesel irrigation engine	1.12	910	20,100 71,200 91,300 total
	Gasoline irrigation engine	1.25	1,050	21,400 80,700 102,000 total

type of engine, operating conditions, engine load, and maintenance. Operating an irrigation pump at speeds outside of its optimal range can increase engine load, drastically decreasing engine performance and increasing fuel consumption.

This analysis compares properly loaded and maintained standard 100-horsepower 5.7L **irrigation engines**.



Assumptions

1. Fuel consumption of irrigation engines is calculated using power unit performance standards reported by the University of Florida that represent the effectiveness in converting fuel to mechanical power. These standards allow the effects of loading on the engine to be compared between fuels. The performance standards used are based on fully loaded irrigation power units with respect to each fuel type using direct pump drives with 100% efficiency, and pump efficiencies of 75% (Boman 2002).
2. All engines are assumed to be 5.7L of displacement with 100 horsepower.
3. According to propane industry estimates, irrigation engines operate for 1039 hours per year on average. All engines in this analysis are assumed to operate the same number of hours (Propane's Advantage 2009).

Mowers

Commercial mowers are used on a daily basis to maintain the health and appearance of residential lawns, sports fields, golf courses, parks, roadsides, and other public and commercial lands. Due to the vast amount of lawns and turfgrass in the United States requiring this level of care, mowing contributes significantly to criteria pollutant emissions to the point where many cities have banned the use of gasoline-fueled commercial mowers before 1 p.m. on Ozone Action Days. As a result, smaller and cleaner commercial mowers are highly desirable and sometimes mandated by law.

🟦 PROPANE
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (░ = upstream; ■ = end-use)
GENERIC MOWER	**Generic propane mower**	1.00	84.1	1,530 5,720 7,250 total
	Generic gasoline mower	1.20	89.7	1,830 6,880 8,710 total

Propane-fueled mowers deliver propane from tanks mounted on the mower to the engine through a clean, closed fuel system. As a result, fewer burned hydrocarbons enter the crankcase oil, which extends oil life, reduces maintenance needs, and improves overall system efficiency. This analysis, which compares **propane-fueled mowers** and **gasoline-fueled mowers**, demonstrates propane's additional potential to reduce greenhouse gas emissions when used to power commercial mowers.

Assumptions

1. Fuel consumption values are based on estimates provided by Kohler Engines for electronic fuel injection (EFI) mowers that run on propane or gasoline. The engines are assumed to have the same displacement and mower: Gasoline = 1.03 gallons/hour; Propane = 1.32 gallons/hour (Kohler Engines 2013).
2. According to the Austin Parks and Recreation Department, mowers used by the city operate for approximately 750 hours per year, which is the equivalent of operating for 25 hours per week and 30 weeks per year (Texas Alternative Fuel Fleet Pilot Program 2011).

Terminal Tractors

Terminal tractors are vehicles specifically designed to move trailers within or about freight operation yards, such as rail and marine intermodal terminals. Also known as yard trucks, jockeys, spotting tractors, port tractors, shunt trucks, and utility tractor rigs, these heavy-duty vehicles have maximum speeds of less than 30 miles per hour and are capable of towing freight in excess of 50 tons.

Freight operations yards often operate continuously at all times, resulting in heavy fuel consumption by terminal tractors. As more freight yards must comply with emerging emissions laws (CARB 2005), demand has increased for alternative fuel options to meet new regulations.

🟦 PROPANE
🟨 NATURAL GAS
⬛ ELECTRICITY
🟪 DIESEL
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (⬜ = upstream; ⬛ = end-use)
GENERIC TERMINAL TRACTOR	Electric terminal tractor	0.71	125	24,100 24,100 total
	Compressed natural gas terminal tractor	0.93	393	8,030 23,400 31,400 total
	Propane terminal tractor	1.00	393	7,160 26,800 33,900 total
	Diesel terminal tractor	1.05	354	7,820 27,700 35,500 total
	Gasoline terminal tractor	1.22	425	8,650 32,600 41,200 total

State-of-the-art propane-fueled terminal tractors with advanced liquid propane injection (LPI) engines offer comparable fuel consumption rates as conventional fuels while significantly reducing greenhouse gas emissions. This analysis compares **terminal tractors** that use a wide range of energy sources.

Assumptions

1. Because there was little data available giving metrics of appropriate terminal tractor energy efficiencies (e.g. tons of freight moved per gallon), total energy use for propane tractors was assumed to be 5,000 gallons per year. Total energy consumption of tractors using other fuels was determined using relative fuel efficiency values.
2. According to a conservative estimate by PERC and Tug Technologies, propane-fueled ground service equipment uses an average 5,000 gallons of propane per year (Propane Diesel Injection 2009).
3. Relative fuel efficiencies used are based on those in the AFLEET model for vehicles with an equivalent weight rating. The ratio of the fuel economy of each vehicle type (in miles per gasoline gallon equivalent) relative to a gasoline-fueled vehicle are as follows: CNG = 1.08; diesel = 1.20; electric = 3.4; gasoline = 1.0; propane = 1.08 (ANL 2013a).
4. The relatively high efficiency of large propane engines reported by the AFLEET model for combination short-haul tractor-trailers is attributed to a recent case study data suggesting that new liquid propane injection (LPI) engines have similar fuel efficiencies to diesel engines (ANL 2013a).

Forklifts

Forklifts are used to engage, lift, and transfer palletized loads in warehousing, manufacturing, materials handling, and construction applications. They are rated into one of six classes: Classes 1–3 are electric-motor driven and Classes 4–6 are driven by internal combustion engines. More than 670,000 propane-fueled forklifts currently operate in the United States (ITA 2006).

Unlike most vehicles, forklifts use fuel not only for vehicle propulsion (with typical maximum speeds of 10–15 mph) but also for load lifting work. Propane fuels a wide variety of forklifts; other common energy sources include electricity, compressed natural gas, gasoline, and diesel.

🟦 PROPANE
🟨 NATURAL GAS
■ ELECTRICITY
🟪 DIESEL
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (░ = upstream; ■ = end-use)
GENERIC FORKLIFT	**Electric forklift**	**0.76**	**28.3**	5,440 **5,440 total**
	Compressed natural gas forklift	**0.96**	**85.6**	1,750 5,080 **6,830 total**
	Propane forklift	**1.00**	**82.7**	1,500 5,630 **7,130 total**
	Diesel forklift	**1.03**	**73.0**	1,610 5,710 **7,320 total**
	Gasoline forklift	**1.14**	**84.0**	1,710 6,440 **8,150 total**

Forklift fuel choice may depend on load size and air quality concerns. For example, electric forklifts are normally used for light-duty jobs while diesel forklifts are typically used for heavy-duty loads and are restricted to outdoor use for air quality reasons. Propane forklifts, on the other hand, are used for both light- and heavy-duty applications and approved for both indoor and outdoor use. This analysis compares **forklifts** powered by these and other energy sources.

Assumptions

1. Average fuel use of 973 gallons of propane per year is based on market data provided by Delucchi, which cites 400,000 forklifts using 389 million gallons of propane (Delucchi 2001).
2. The analysis used the assumption by Delucchi that two-thirds of forklift energy use goes to vehicle propulsion and one-third goes to lifting (Delucchi 2001).
3. For forklifts powered by fuels other than propane, the relative efficiencies of lifting and propulsion compared to a propane-fueled system were used to estimate the fuel consumption of those vehicles.
4. Relative fuel efficiencies used are based on those in the AFLEET model for forklifts with a similar gross vehicle weight rating to vehicles. The ratio of the fuel economy of each vehicle type (in miles per gasoline gallon equivalent) relative to a gasoline-fueled vehicle are as follows: CNG = 0.95; diesel = 1.20; electric = 3.4; gasoline = 1.0; propane = 1.0 (ANL 2013a).
5. Thermal engine efficiencies were used to calculate fuel use for equivalent lifting work in Btu. Forklift engine thermal efficiencies used were those used by Delucchi: propane and CNG = 28.0%; gasoline = 26.7%; diesel = 28.5% (Delucchi 2001).
6. According to ANL, the thermal efficiency of electric forklifts is 64% (ANL 2008).

Type A/C Buses

“Type A” buses, also known as mini-buses or shuttle buses, are the smallest classification of buses capable of transporting up to about 40 passengers. The construction of Type A buses uses a bus body placed on the chassis of a cutaway van. These vehicles have medium-duty engines and are capable of running on most fuel types. New dedicated propane Type A buses, such as the Thomas Built Saf-T-Liner C2, are using liquid propane injection (LPI) systems, which are far more effective than vapor injection systems in terms of power, durability, and fuel economy.

Capable of transporting twice as many passengers as a Type A bus, Type C buses are a bus body mounted on top of a medium-duty truck chassis. Also known as “conventional-style” buses, Type C buses continue to be the most common bus type for school districts across the United States.

🟦 PROPANE
🟨 NATURAL GAS
🟧 E85
🟪 DIESEL
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (⬜ = upstream; ⬛ = end-use)
GENERIC LIGHT COMMERCIAL TRUCK: SHUTTLE/ PARATRANSIT VAN (TYPE A BUS)	E85 Type A bus	0.87	160	(62.0) 12,000 12,000 total
	Diesel Type A bus	0.97	133	2,950 10,400 13,400 total
	Propane Type A bus	1.00	160	2,910 10,900 13,800 total
	Compressed natural gas Type A bus	1.02	177	3,620 10,500 14,200 total
	Gasoline Type A bus	1.13	160	3,260 12,300 15,500 total
GENERIC SCHOOL BUS (TYPE C BUS)	Compressed natural gas Type C bus	0.93	464	9,490 27,600 37,100 total
	Propane Type C bus	1.00	464	8,450 31,600 40,100 total
	Diesel Type C bus	1.06	422	9,330 33,000 42,300 total
	Gasoline Type C bus	1.22	505	10,330 38,700 49,000 total

While diesel fuel is the most common fuel type used in Type A and C buses, many fleet owners have replaced their buses with alternative fuel buses in response to concerns echoed by the World Health Organization that diesel engine exhaust is a known human carcinogen (IARC 2012). This analysis compares **Type A buses** and **Type C buses** that run on a range of fuels.

Assumptions

1. Each vehicle was assumed to travel 20,000 miles per year.
2. Relative fuel efficiencies used are based on those in the AFLEET model for vehicles with the same vehicle weight rating as a Type A bus. The fuel economies of each vehicle type (in miles per gasoline gallon equivalent) are as follows: CNG = 13.1; diesel = 17.4; E85 = 14.5; gasoline = 14.5; propane = 14.5 (ANL 2013a).
3. Relative fuel efficiencies used are based on those in the AFLEET model for vehicles with the same vehicle weight rating as a Type C bus. The fuel economies of each vehicle type (in miles per gasoline gallon equivalent) are as follows: CNG = 5.0; diesel = 5.5; gasoline = 4.6; propane = 5.0 (ANL 2013a).
4. The relatively high efficiency of large propane engines reported by the AFLEET model for Type C buses is attributed to a recent case study data suggesting that new liquid propane injection (LPI) engines have similar fuel efficiencies to diesel engines (ANL 2013a).

Bobtail Trucks

There are two types of fuel delivery trucks: large semi-trailer trucks, and small bulk delivery trucks, known as “bobtails.” Bobtail trucks are designed to transport up to 6,000 gallons of fuel, and are generally considered the workhorse of the propane industry for delivering fuel. Although most bobtail trucks operate on diesel, Freightliner Custom Chassis has manufactured a new dedicated propane-fueled delivery truck that runs on an 8.0L engine and uses new liquid propane injection (LPI) systems that are far more effective than vapor injection systems in terms of power, durability, and fuel economy. This analysis compares **bobtail trucks** that use a range of fuel types.

🟦 PROPANE 🟪 DIESEL
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (▨ = upstream; ■ = end-use)
BOBTAIL TRUCK	**Propane bobtail truck**	1.00	537	 9,780 36,600 46,400 total
	Diesel bobtail truck	1.05	484	 10,700 37,800 48,500 total
	Gasoline bobtail truck	1.22	580	 11,800 44,500 56,300 total

Assumptions

1. Each vehicle was assumed to travel 20,000 miles per year.
2. Relative fuel efficiencies used are based on those in the AFLEET model for vehicles with the same vehicle weight rating as a combination short-haul tractor-trailer. The fuel economies of each vehicle type (in miles per gasoline gallon equivalent) are as follows: diesel = 4.8; gasoline = 4.0; propane = 4.3 (ANL 2013a).
3. The relatively high efficiency of large propane engines reported by the AFLEET model for combination short-haul tractor-trailers is attributed to a recent case study data suggesting that new liquid propane injection (LPI) engines have similar fuel efficiencies to diesel engines (ANL 2013a).

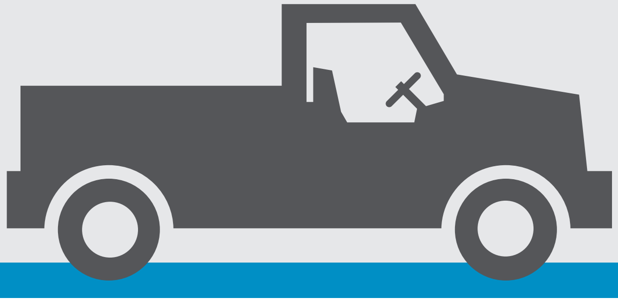
Light-Duty Trucks

Light duty trucks constitute a significant portion of the U.S. vehicle fleet. While gasoline fuels the majority of light-duty trucks in the United States, the use of ethanol (E85) and propane has increased in recent years.

The alternative fuel vehicle manufacturer ROUSH CleanTech has developed a dedicated propane light-duty vehicle that directly replaces the original equipment manufacturer (OEM) gasoline injection system with a liquid propane injection (LPI) system. In addition, manufacturers such as Prins, Technocarb, and ICOM offer gasoline-to-propane conversion kits and bi-fuel conversion kits, which allow the vehicle to start on gasoline fuel and immediately switch to propane autogas. This analysis compares **light-duty trucks** that use a range of fuels.

🟦 PROPANE
🟨 NATURAL GAS
🟧 E85
🟪 DIESEL
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year)	(⬜ = upstream; ⬛ = end-use)	
GENERIC LIGHT-DUTY PASSENGER TRUCK (6,001–8,500 LBS GWVR)	E85 light-duty truck	0.87	65.6	(25.4)	4,930	4,910 total
	Diesel light-duty truck	0.97	54.8	1,210	4,280	5,490 total
	Compressed natural gas light-duty truck	0.98	69.1	1,410	4,110	5,520 total
	Propane light-duty truck	1.00	65.6	1,190	4,460	5,660 total
	Light-duty truck with propane conversion kit	1.00	65.7	1,200	4,470	5,670 total
	Compressed natural gas and gasoline bi-fuel light-duty truck	1.03	72.4	1,480	4,370	5,850 total
	Propane and gasoline bi-fuel light-duty truck	1.11	72.4	1,330	4,960	6,290 total
	Gasoline light-duty truck	1.13	65.6	1,340	5,030	6,370 total



Assumptions

1. Each vehicle was assumed to travel 10,000 miles per year.
2. Relative fuel efficiencies used are based on those in the AFLEET model for vehicles with the same vehicle weight rating as a light-duty pickup truck. The fuel economies of each vehicle type (in miles per gasoline gallon equivalent) are as follows: CNG = 16.8; diesel = 21.2; E85 = 17.7; gasoline = 17.7; propane = 17.7 (ANL 2013a).
3. The bi-fuel vehicles in the analysis are assumed to be converted from gasoline vehicle models. The base fuel economies are assumed to be the same as gasoline vehicles.
4. According to an NREL study of propane autogas conversion kits, vehicles experience a volumetric fuel economy reduction of 27% when converting from gasoline, which was consistent with the energy content difference between fuels. This loss has been applied to the analysis of the gasoline-to-propane converted vehicle (Bass 1993).
5. The Prins [Bi-fuel] Vapor Sequential Injection System starts on gasoline and immediately switches to autogas. Depending on the number of starting cycles, as much as 10 percent of total fuel consumption may be gasoline, or as little as 2 percent if the vehicle is driven primarily on the highway. For the purposes of the analysis, the total consumption of gasoline is 6% (PERC 2012).
6. According to a study by the International Energy Agency (IEA), bi-fuel gasoline-CNG vehicle experience a 5-10% loss of efficiency while running on CNG. It is assumed that the CNG and LPG bi-fuel conversions of gasoline vehicles will experience a 6% loss in fuel economy while running on CNG or LPG, respectively. Because CNG is a compressed gas, the bi-fuel analysis assumes that the volume of CNG fuel consumed is based on gasoline gallon equivalents. The volume of propane fuel consumed is based on the equivalent energy content as gasoline gallons (IEA 2010).

Utility Cargo Vans

Utility cargo vans are often used by businesses to make deliveries, are converted for ambulance services, and serve as the chassis for Type A buses. These vehicles typically operate on gasoline or diesel fuel, although some manufacturers are offering alternative fuel options such as E85, compressed natural gas, and propane.

The alternative fuel manufacturer ROUSH CleanTech offers a propane-fueled conversion retrofit system for the Ford E-350 on model years 2012 or newer. Manufacturers such as Prins, Technocarb, and ICOM offer gasoline-to-propane conversion kits as well as bi-fuel conversion kits, which allow the vehicle to start on gasoline fuel and immediately switch to propane autogas. This analysis compares **utility cargo vans** that use a range of fuels.

🟦 PROPANE
🟨 NATURAL GAS
🟧 E85
🟪 DIESEL
🟥 GASOLINE

		GHG Index	Energy Use (mmBTU per unit per year)	Annual Life Cycle GHG Emissions per unit (kg CO_2 equivalent per unit per year) (⬜ = upstream; ⬛ = end-use)		
GENERIC UTILITY CARGO VAN	E85 utility cargo van	0.87	116	(44.9)	8,730	8,680 total
	Diesel utility cargo van	0.97	96.7	2,140	7,570	9,700 total
	Propane utility cargo van	1.00	116	2,110	7,900	10,000 total
	Utility cargo van with propane conversion kit[1]	1.00	116	2,120	7,920	10,000 total
	Compressed natural gas utility cargo van	1.03	129	2,640	7,660	10,300 total
	Compressed natural gas and gasoline bi-fuel utility cargo van	1.03	128	2,620	7,740	10,400 total
	Propane and gasoline bi-fuel utility cargo van	1.11	128	2,350	8,790	11,100 total
	Gasoline utility cargo van	1.13	116	2,360	8,910	11,300 total

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[1] The propane vehicle with conversion kit is based on converting a gasoline vehicle to run on propane. Numbers appear similar to the indexed dedicated propane vehicle due to rounding.

Assumptions

1. Each vehicle was assumed to travel 10,000 miles per year.
2. Relative fuel efficiencies used are based on those in the AFLEET model for vehicles with the same vehicle weight rating as a utility cargo van. The fuel economies of each vehicle type (in miles per gasoline gallon equivalent) are as follows: CNG = 9; diesel = 12; E85 = 10; gasoline = 10; propane = 10 (ANL 2013a).
3. The bi-fuel vehicles in the analysis are assumed to be converted from gasoline vehicle models. The base fuel economies are assumed to be the same as gasoline vehicles.
4. According to an NREL study of propane autogas conversion kits, vehicles experience a volumetric fuel economy reduction of 27% when converting from gasoline, which was consistent with the energy content difference between fuels. This loss has been applied to the analysis of the gasoline-to-propane converted vehicle (NREL 1993).
5. The Prins [Bi-fuel] Vapor Sequential Injection System starts on gasoline and immediately switches to autogas. Depending on the number of starting cycles, as much as 10 percent of total fuel consumption may be gasoline, or as little as 2 percent if the vehicle is driven primarily on the highway. For the purposes of the analysis, the total consumption of gasoline is 6% (Hofmann 2012).
6. According to a study by the International Energy Agency (IEA), bi-fuel gasoline-CNG vehicle experience a 5-10% loss of efficiency while running on CNG. It is assumed that the CNG and LPG bi-fuel conversions of gasoline vehicles will experience a 6% loss in fuel economy while running on CNG or LPG, respectively. Because CNG is a compressed gas, the bi-fuel analysis assumes that the volume of CNG fuel consumed is based on gasoline gallon equivalents. The volume of propane fuel consumed is based on the equivalent energy content as gasoline gallons (IEA 2010).

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Appendix B. Sensitivity Analysis

A sensitivity analysis was conducted to identify the relative influence of key variables and assumptions on the GHG emissions results reported in this study. Each sensitivity scenario examines a base case, low case, and high case. The base case represents the variables used to produce the results of this study. The low and high cases are perturbations on the base case variables to determine how much the results change as a result. Sensitivities were conducted on variables relevant to both upstream emissions factors and end-use emissions results.

The results of this sensitivity analysis show that while individual variables and assumptions do affect the total energy use and GHG emissions values reported in this study, the relative GHG emissions values (i.e., the indexed values with propane = 1.00) do not significantly change in response to changes in assumed values. In most cases, changes in assumed values for thermal efficiency, fuel efficiency, and other variables affect all fuels equally, resulting in no change in the GHG index values. For those variables that do affect different fuel types differently, such differences are very small (less than 1%) and do not materially alter the study's findings.

Upstream Emissions Factors

The upstream sensitivity analysis focused on two key variables: global warming potentials (GWPs) and the proportion of propane sourced from natural gas and crude oil feedstocks. These variables are defined in this study as follows:

- **Global warming potential** — The GWP base case uses IPCC AR5 global warming potential values, and the sensitivity analysis examines the GWPs used in the 2009 version of this report (low case), and the GWPs with climate-carbon feedback in IPCC AR5 (high case). Climate-carbon feedback is a mechanism in which certain global warming processes trigger one another to intensify or weaken the overall impact of climate change.
- **Source of Propane Supply** — To test the influence of the propane source on upstream GHG emissions factors, the base case scenario of 70% propane sourced from natural gas and 30% sourced from crude oil was changed to 65% natural gas (low case) and 75% natural gas (high case).

Table B1. CO_2 Released per Btu

	ALL FUELS	**PROPANE**
VARIABLE	Global warming potentials	Source of propane supply
LOW CASE	IPCC AR4 GWPs: CO_2=1; CH_4=25; N_2O=298	65% Natural Gas 35% Crude Oil
BASE CASE	IPCC AR5 GWPs: CO_2=1; CH_4=28; N_2O=265	70% Natural Gas 30% Crude Oil
HIGH CASE	IPCC AR5 (with climate-carbon warming feedback) GWPs: CO_2=1; CH_4=34; N_2O=298	75% Natural Gas 25% Crude Oil

Sensitivity of Global Warming Potentials

When testing GWP values against the base case, the upstream emissions factors for gasoline and diesel show the smallest change in total GHG emissions, while E85 and natural gas show the largest change. Compared to the base case, the IPCC AR4 GWPs weaken methane (CH_4) potentials and intensify nitrous oxide (N_2O) potentials, while the IPCC AR5 climate-carbon feedback GWPs intensify both CH_4 and N_2O potentials. Diesel and gasoline have the lowest levels of upstream methane of the fuels considered in this study and emit very small amounts of upstream N_2O and therefore are less sensitive to changes in the GWPs.

The sensitivity analysis shows that varying GWPs does not significantly alter total GHG emissions for all applications in the study with respect to the indices to propane technologies, ranging from a 0.01 to 0.05 point difference in index scores.

Sensitivity of Propane Feedstock Ratio

When the share of propane refined by natural gas feedstock is increased (high case), both N_2O and CO_2 emissions decrease, while CH_4 emissions increase. The resulting change in upstream CO_2e emissions is only a 1.8% decrease with when increasing the share of natural gas feedstock by 5 percentage points, which translates to a decrease in total lifecycle GHG emissions of only 0.4%.

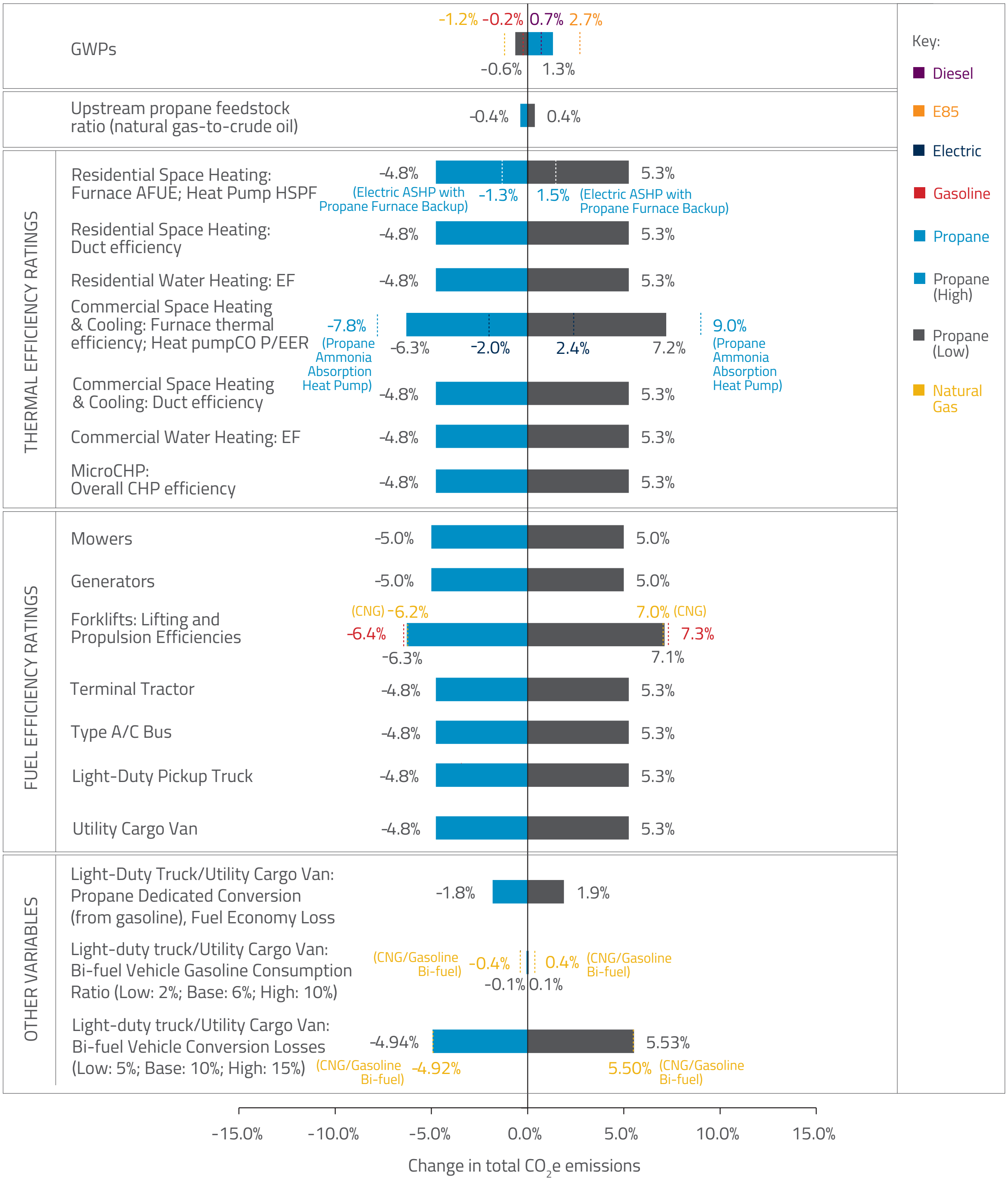
Upon examination of the indices of across all technologies, this only results in a difference of 0.01 index points or less.

Sensitivity of Efficiency and Other Variables

A sensitivity analysis was also applied to thermal efficiencies, fuel economies, and other key variables in this study to understand the impact of these variables on total lifecycle GHG emissions for each technology. In general, a ±5% change was applied to the efficiencies of each technology. For other applications, the low and high cases reflected the range of values that were provided by the source materials. While each fuel experiences a different change in emissions relative to its base value in the analysis, many fuels experience the same percent change in emissions. Other technologies may experience a different percent change due to using more than one efficiency variable, or using different load ratios of energy use between fuels or functions of the technology.

The results of the sensitivity analysis reveal that system efficiencies have the largest impact on the total lifecycle emissions for each technology in the analysis. This reaffirms the methodology used in this study to use a consistent approach for incorporating energy efficiencies (i.e., using the highest-reported efficiencies) available from source materials, and to present multiple system efficiencies when possible by providing lower efficiencies of “generic” systems, and higher efficiencies of “best-available” systems.

Figure B1. Sensitivity Analysis of Key Variables



Appendix C. List of Acronyms

AC	air conditioning
ASHP	air source heat pump
ASHRAE	(formerly known as) American Society of Heating, Refrigerating, and Air Conditioning
AHRI	Air Conditioning, Heating, and Refrigeration Institute
AFUE	annual fuel utilization efficiency
Btu	British thermal units
CAS	central air source
CO	carbon monoxide
CO_2	carbon dioxide
COP	coefficient of performance
CH_4	methane
CHP	combined heat and power
CBECS	Commercial Buildings Energy Conssumption Survey
CNG	compressed natural gas
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EER	energy efficiency ratio
EF	energy factor
EFI	electronic fuel injection
EIA	Energy Information Administration
EPA	Environmental Protection Agency

E85	ethanol
GM	General Motors
GWP	global warming potential
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GVWR	gross vehicle weight rating
hp	horsepower
HFC	hydroflurocarbons
HSPF	Heating Seasonal Performance Factor
ITA	Industrial Truck Association
IPCC	Intergovernmental Panel on Climate Change
kg	kilograms
lb	pound
LPG	liquefied petroleum gas
LPI	liquid propane injection
mmBTU	million British thermal units
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NREL	National Renewable Energy Laboratory
O_3	ozone
Pb	lead

PFC	perfluorocarbons
RECS	Residential Energy Consumption Survey
SEER	Seasonal Energy Efficiency Ratio
SEF	solar energy factor
SO_2	sulfur dioxide
SF_6	sulfur hexaflouride
USGCRP	U.S. Global Change Research Program
VOC	volatile organic compounds