Propane Reduces Greenhouse Gas Emissions: A Comparative Analysis

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Acknowledgements

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Executive Summary

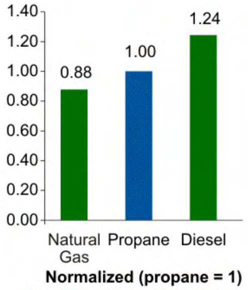
This study quantifies the greenhouse gas profile of propane and other fuels in selected applications. Cutting across propane market segments including residential, power generation, engine fuel, agriculture, and other applications, this analysis uses energy consumption rates, emissions factors, and equipment efficiencies for various energy options to estimate greenhouse gas emissions associated with the use of those energy options. The applications analyzed include:

- Distributed Generation
- Irrigation Pumps
- Forklifts
- Medium-Duty Engines
- Light-Duty Trucks
- Residential Water Heaters
- Residential Space Heating

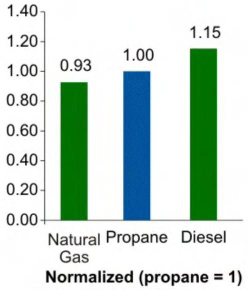
The results of the analysis show that propane is among the most attractive options for avoiding greenhouse gas emissions in every application considered. At the point of use, propane has a lower carbon content than gasoline, diesel, heavy fuel oil, or ethanol. Natural gas (methane) generates fewer carbon dioxide (CO_2) emissions per Btu than propane, but natural gas is chemically stable when released into the air and produces a global warming effect 25 times that of carbon dioxide. This means that one pound of methane produces the same effect on climate change as 25 pounds of carbon dioxide.

With propane’s short lifetime in the atmosphere and low carbon content, it is advantageous from a climate change perspective in comparison to other fuels in many applications. The graphs on the following page (p. v) demonstrate propane’s climate change performance across the applications analyzed in this study. (Propane emissions = 1, and all other fuels are normalized against it for comparison).

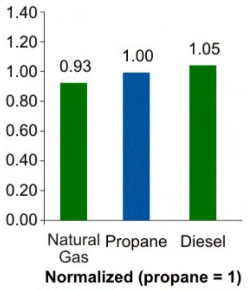
Distributed Generation



30 kW prime microturbine

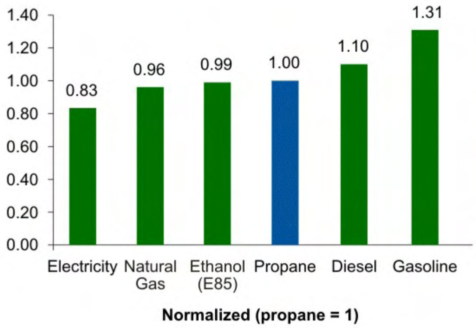


100 kW standby genset

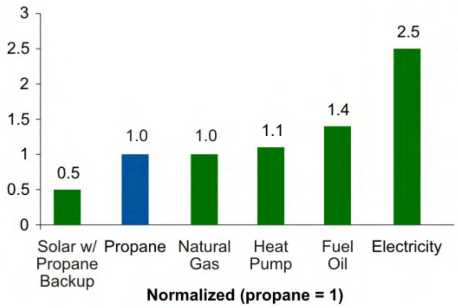


200 kW prime genset

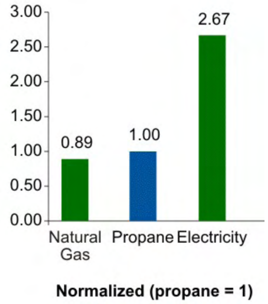
Irrigation Pumps



Residential Water Heaters

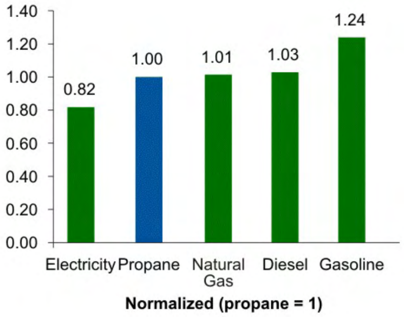


Storage Tank Heater

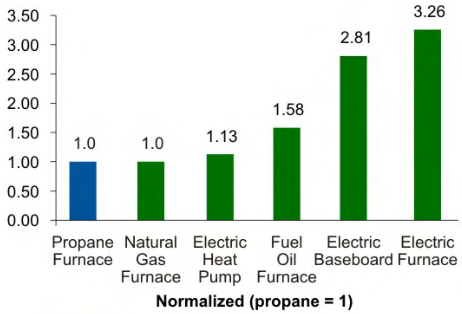


Tankless Water Heater

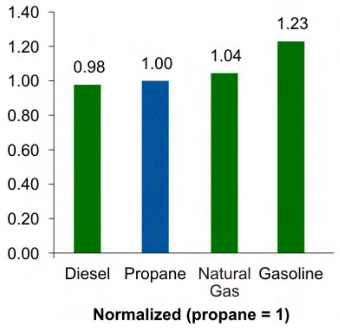
Forklifts



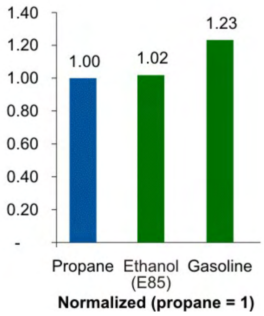
Residential Space Heating



Medium-Duty Engines



Light-Duty Trucks



I. Purpose of Report

With the causes of climate change becoming more evident, there is an increased focus on technologies and energy sources that can reduce emissions of greenhouse gases. While scientists continue to debate the magnitude of potential impacts from climate change, policymakers in the United States and abroad are considering options for addressing the issue. As an Environmental Protection Agency (EPA)-approved clean alternative fuel, propane offers lower greenhouse gas emissions than many other fuel options without compromising performance in a wide range of applications.

This study quantifies the greenhouse gas profile of propane and other fuels in selected applications. Cutting across propane market segments including residential, power generation, engine fuel, agriculture, and other applications, this analysis uses energy consumption rates, emissions factors, and equipment efficiencies for various energy options to estimate greenhouse gas emissions associated with the use of those energy options. The applications analyzed include:

- Distributed Generation
- Irrigation Pumps
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The substantive and carefully documented information in this report is intended to inform policymakers, the propane industry, and other interested parties as they make important decisions regarding climate change.

II. About Climate Change

Greenhouse gases keep the earth at a comfortable temperature, allowing most of the energy from the sun to pass through the atmosphere and warm the earth while blocking much of the outward radiation from the earth. However, increasing concentrations of greenhouse gases in the atmosphere are cause for concern. Rather than maintaining equilibrium, high concentrations of greenhouse gases are now affecting the global climate system, leading to “climate change.”

Greenhouse Gases Compared to Criteria Air Pollutants

Greenhouse gases are different than the criteria air pollutants that have been regulated by the EPA since 1970. Criteria pollutants, which include ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, lead, and particulate matter, are released in the atmosphere from fuel leaks, secondary reactions, or undesired side-products during combustion. While these pollutants cause health problems and contribute to smog and acid rain, they do not directly contribute to climate change. The amount of criteria air emissions depends on several variables including fuel characteristics, combustion conditions, and use of pollution control equipment, and it is sensitive to maintenance and operational practices (Climate Leaders 2004).

In contrast, greenhouse gases are not federally regulated and cause changes to the environment on a global scale. Unlike criteria pollutants, the most prevalent GHG – carbon dioxide – is a necessary byproduct of fossil fuel combustion. The amount of carbon dioxide released depends not on leaks or side reactions, but on the amount of carbon in the fuel and the amount of fuel consumed. While chemically reactive criteria air pollutants stay in the air for days or months, greenhouse gases are non-reactive and remain in the atmosphere for decades to centuries (Rubin and Rao 2002).

Table 2.1. Carbon dioxide and criteria air pollutants have several important differences

	Carbon dioxide	Criteria pollutants
Source of emissions	• necessary byproduct of combustion	• fuel leak or undesired side product of combustion
Regulation	• currently unregulated at federal level in the U.S.	• federally regulated by Clean Air Act
Quantity released	• depends mainly on carbon content of fuel and amount of fuel consumed	• depends on many factors
Scale of impact	• global	• local or regional
Lifetime in atmosphere	• decades to centuries	• days to months

Greenhouse Gas Emissions from Fuel Combustion

In general, lighter hydrocarbons release less carbon dioxide during combustion than heaver hydrocarbons, because lighter hydrocarbons consist of fewer carbon atoms per molecule. The mass of carbon dioxide released per Btu of fuel – the “carbon content” – is a good first-order indicator of the CO_2 emissions comparison between fuels. The carbon content for eight common fuels is shown in Table 2.2.

Table 2.2. Carbon dioxide released per Btu

Fuel Type	**kg CO_2 per million Btu**
Natural Gas	52.8
LPG	62.7
Ethanol (E85)	66.6
Motor Gasoline	70.5
Kerosene	70.7
Distillate Fuel (Diesel)	72.5
Residual Fuel (Heavy fuel oil)	78.6
Bituminous Coal	92.1

Estimates based on chemical composition of the fuel with 99 percent combustion.
Source: DOE 1994.

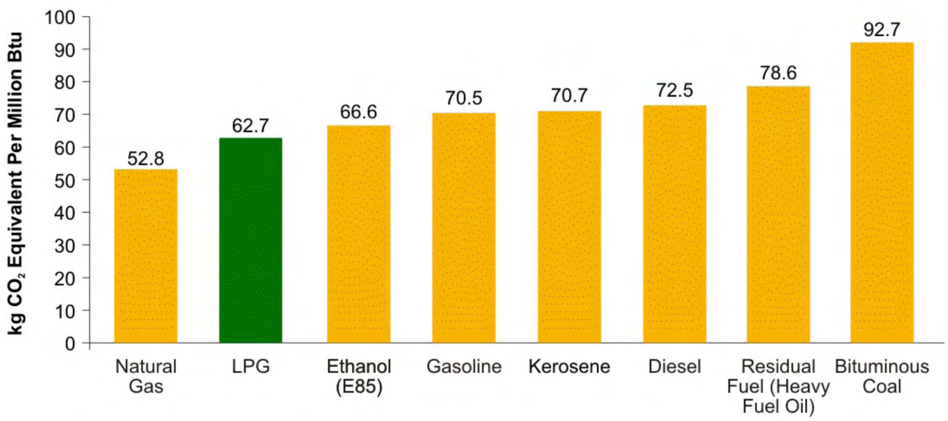
While it is a good indicator, carbon content represents only part of the CO_2 emissions equation. The amount of fuel consumed plays an equally important role. Fuel consumption varies by fuel type and technology for each application. For example, since diesel (compression) engines are generally more efficient than spark-ignition engines, some of the CO_2 emissions disadvantage of diesel compared to other fuels is offset. (Further details for estimating CO_2 emissions are provided in the Methodology section.)

Small amounts of methane and nitrous oxide are also emitted during combustion, though they play a minor role in affecting climate change as compared to carbon dioxide. In the U.S., methane and nitrous oxide together represent less than 1% of the total CO_2-equivalent emissions from stationary combustion sources (Climate Leaders 2004).

The Greenhouse Gas (GHG) footprint of LPG is relatively small compared to other fuels in terms of total emissions and emissions per unit of energy consumed. LPG has the lowest on-site emission rate of the major energy sources, with the exception of natural gas (see Figure 1). In terms of life-cycle greenhouse gas emissions, LPG produces significantly lower emissions than gasoline, diesel, and electricity on a per-Btu basis. Actual life-cycle emission levels depend on the nature and efficiency of the end-use application, however, and therefore must be estimated on an application-specific basis.

Figure 1:

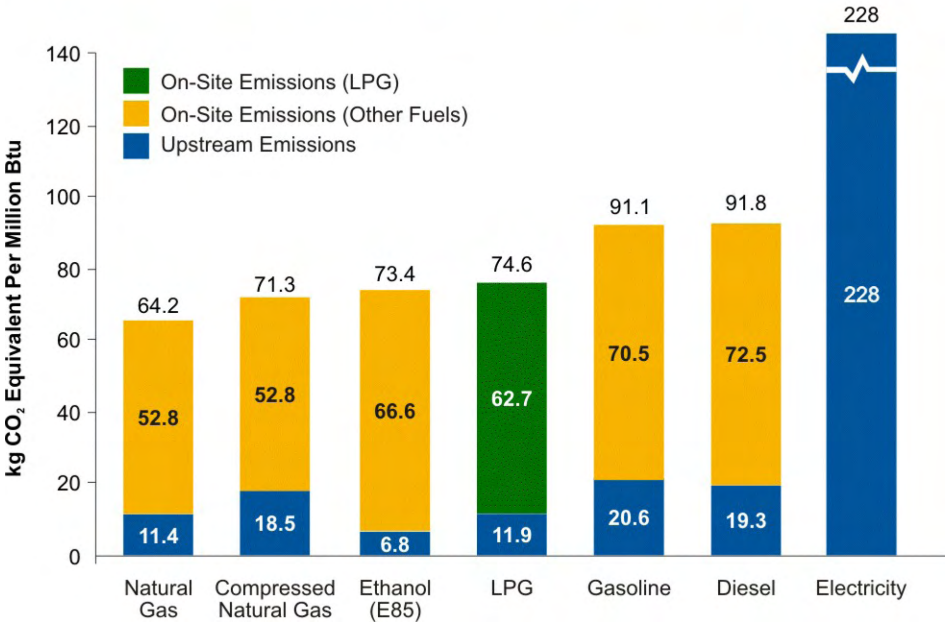
On-Site Carbon Emissions for Various Fuels



Sources: DOE 1994, EPA 2007
On-site emissions estimates based on chemical composition of the fuel with 99 percent combustion.

Figure 2:

Total Carbon Emissions for Various Fuels



Sources: DOE 1994, EPA 2007, GREET 2007
On-site emissions estimates based on chemical composition of the fuel with 99 percent combustion.
Actual life-cycle emissions vary by application; in many cases, electricity provides more useful energy on a per-Btu basis.

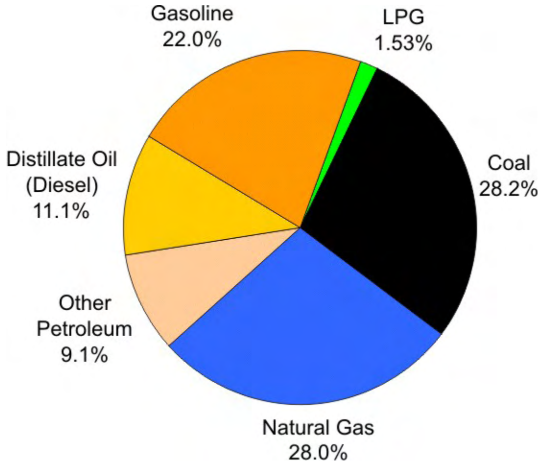
LPG represents a small but important part of the U.S. energy consumption. Figure 3 shows the contribution of the major fuels (U.S. EPA 2007) and LPG represents 1.53% of energy consumed in the U.S. in 2005.

Because of LPG's relatively low GHG emission rate, its share of GHG emissions is smaller than its share of energy supply. Figure 4 shows the relative contribution to total U.S. GHG emissions by fossil fuel combustion and from other sources. CO_2 emissions from fossil fuel combustion represent 79% of total emissions, while LPG combustion represents only 1.05% of total U.S. emissions.

The balance of emissions (21%) is from industrial processes that emit CO_2 directly (i.e., cement kilns), methane (i.e., landfills and natural gas leaks), nitrous oxide (i.e., agricultural fertilizer), and fluorine-containing halogenated substances (i.e., hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) from refrigerants and industrial processes).

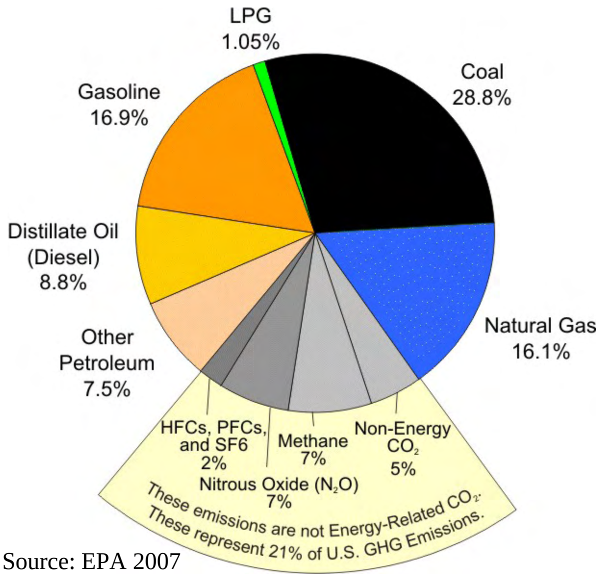
Figure 5 illustrates the relative contribution to total energy-related CO_2 emissions for the U.S. in 2005. Although LPG contributes 1.53% of the U.S. energy supply, its share of energy-related CO_2 emissions is 1.32%. Coal, the highest-emitting major fuel, represents 28.2% of the U.S. energy supply and 36.4% of energy-related CO_2.

Figure 3: Shares of U.S Energy Consumption (2005)
(Total: 78,742 trillion Btu)



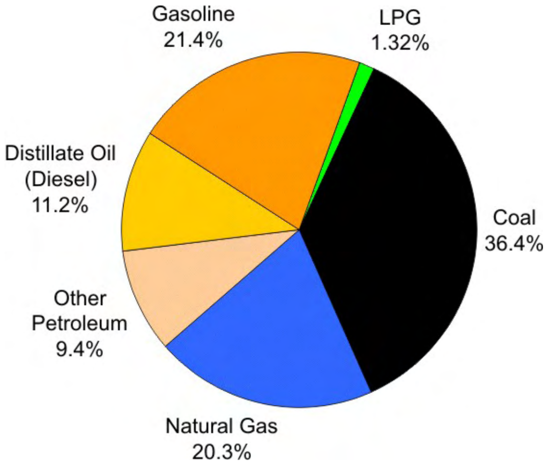
Source: EPA 2007

Figure 4: Shares of Greenhouse Gas Emissions (2005)
(Total: 7,260 million MT $C0_2$)



Source: EPA 2007

Figure 5: Shares of Energy-Related Greenhouse Gas Emissions (2005)
(Total: 5,751 million MT $C0_2$)



Source: EPA 2007

Propane's Effect on Climate Change

Propane is not a direct greenhouse gas when released into the air. Propane vapor is unstable in the atmosphere—it is chemically reactive and commonly removed by natural oxidation in the presence of sunlight or knocked down by precipitation. It is also removed from the atmosphere faster than it takes for it to become well-mixed and have impacts on global climate. Current measurements have not found a global climate impact from propane emissions.[1,2]

When used as a fuel, propane does emit carbon dioxide and small amounts of nitrous oxide and methane. Upstream extraction and production of fuels such as propane from natural gas or crude oil generates greenhouse gas emissions, and end-use combustion of any hydrocarbon releases carbon dioxide as discussed above. However, compared to conventional fuel supplies, propane generates fewer GHG emissions in almost every application. At the point of use, propane has a lower carbon content than gasoline, diesel, heavy fuel oil, or ethanol (Table 2.2). Natural gas (methane) generates fewer CO_2 emissions per Btu than propane, but natural gas is chemically stable when released into the air and produces a global warming effect 25 times that of carbon dioxide. This means that one pound of methane produces the same effect on climate change as 25 pounds of carbon dioxide.

With propane's short lifetime in the atmosphere and low carbon content, it is advantageous compared to other petroleum fuels in many applications.

Upstream vs. End-Use Emissions

When quantifying the greenhouse gas emissions that result from the use of energy, it is important to distinguish between the emissions released at the location where the energy is consumed and the emissions released as a result of extracting and processing a refined and usable energy product to that location. The fuel lifecycle 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 technology.

Emissions released at the point of use are termed "end-use emissions," while those emissions that occur along the delivery pathway are termed "upstream emissions." Upstream emissions include all emissions resulting from the recovery, processing, and transport of fuel to the point of delivery to the end-user.

Energy use is not the only source of upstream emissions. Other production processes also release greenhouse gases. For example, the growing of crops for biofuels production requires the application of nitrogen fertilizer, which causes the formation of nitrous oxide, while natural gas refining causes the release of fugitive emissions of methane. These processes have been quantified by the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (GREET 2007), making it a valuable tool for comparative lifecycle analyses of fuel systems.

The inclusion of upstream emissions in an analytical comparison of different fuel options can have a significant impact on the results. Limiting the comparison to end-use emissions only, for example, can give the impression that electricity, with zero end-use emissions, is an energy source with no greenhouse gas emissions. Limiting the analysis to end-use emissions would therefore mask the very large fraction of upstream emissions caused by the combustion of fossil fuels for the purpose of electricity generation.

This analysis is intended to give a full lifecycle accounting of greenhouse gas emissions resulting from the use of propane and other fuels for specific applications. By reporting upstream and end-use emissions separately, it is intended that this report will provide a better picture of the impacts of different fuels, and a more useful and informative data set than would be provided by aggregating emissions or restricting the analysis to end-use emissions only.

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[1] The Intergovernmental Panel on Climate Change (IPCC) reports that "Given their short lifetimes and geographically varying sources, it is not possible to derive a global atmospheric burden or mean abundance for most VOC from current measurements." VOCs explicitly include propane (IPCC TAR 2001).

[2] While VOCs participate in the formation of tropospheric ozone, the climate effect from ozone is not highly understood by scientists and is not one of the six greenhouses gases being considered for regulation by Congress.

III. Methodology

This section describes the general methodology used for all applications. Application-specific assumptions are provided in Appendix B.

Basis for Comparison of Applications

Ten different propane applications were analyzed in order to quantify the lifecycle greenhouse gas emissions of propane fuel systems compared to other fuels. These ten applications were selected to represent not only a variety of market sectors, but also a range of market shares – from well-established propane markets such as forklifts to emerging propane technologies such as the propane-powered light-duty truck.

Each propane technology was compared to alternative fuels commonly used for the same application. Operational variables such as size, hours of operation, and frequency of use were chosen to represent an average or typical use of the technology. Data were obtained from published test results, vendor-supplied specifications, and government studies, and were supplemented with other sources to determine what constituted a typical use. These sources were also used to estimate the energy efficiency of each fuel system. For most applications, the efficiencies were used to determine the amount of fuel needed to deliver an equivalent energy service (e.g., miles traveled or heat supplied) for propane and for each competing fuel option. For some fuels, such as electricity, energy efficiency differences from propane are the result of two different technology designs. In other instances, however, there are only slight differences in technology design between the propane-configured technology and alternate fuel configurations. Where application-specific data was not available, the relative efficiencies of the fuel systems under comparison were based on efficiencies reported for similar technologies.

Upstream Analysis

Upstream emissions as defined in this analysis are the sum of all emissions resulting from the recovery, processing, and transport of fuel from wellhead to the point of delivery to the end-user. These emissions are conveniently quantified by the GREET Model, which was used to estimate the upstream portion of the lifecycle GHG emissions of each fuel system evaluated in this study. The model is used to calculate emissions, in grams per million Btu, of multiple pollutants, including the three greenhouse gases evaluated in this study: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Table 3.1 gives the upstream emission factors used in this study, which were obtained by running the GREET model.

Table 3.1. Upstream emissions factors (grams per million Btu)

	CO_2	CH_4	N_2O	Total CO_2 equivalent
LPG	8,938	115	0.16	11,855
NG*	5,407	239	0.09	11,397
CNG	12,207	248	0.19	18,455
Electricity	219,707	296	3.12	228,036
Gasoline	17,476	109	1.31	20,595
Diesel	16,629	105	0.27	19,346
E85	-6,810	114	36.08	6,789

* Model output for CNG with compression efficiency set to 100% (removing emissions from compression).

Source: GREET 2007

Upstream emission factors will vary depending on the model's input 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. For all fuels except uncompressed natural gas, the default parameter values in the model were used to calculate upstream emission factors.[3]

The upstream emissions associated with LPG production depend on its feedstock – natural gas or crude oil. LPG is separated from natural gas during production and from crude oil during refining. The model attributes to LPG, on a Btu-fractional basis, emissions produced from the recovery and refining of these feedstocks before the separation of LPG.[4] As a result, the upstream emissions attributed to LPG depend on the relative contribution of natural gas and crude oil to LPG production. The feedstock shares for LPG used for this analysis are 60% from natural gas and 40% from crude, which are the default values in GREET. LPG produced from crude oil has slightly higher GHG emissions than LPG produced from natural gas refining.

Table 3.2 shows the formulas used to calculate total upstream GHG emissions. Upstream emission factors (in grams per million Btu) were multiplied by total fuel consumption required by each fuel system (in million Btu) in order to obtain total upstream emissions for CO_2, CH_4, and N_2O. The total mass of each gas was multiplied by its global warming potential (GWP). Total upstream emissions of GHGs, in metric tons of CO_2 equivalent, was obtained by summing the terms. The values used for global warming potential were those developed by the Intergovernmental Panel on Climate Change (IPCC 2007). Following the widely accepted convention established by the IPCC, results were reported in metric tons of CO_2 equivalent.

Table 3.2. Upstream GHG emissions

For each fuel:
metric tons (GHG) = grams (GHG)/MMBtu (fuel) * MMBtu of fuel consumed / 10^6

Total metric tons of CO_2 equivalent = metric tons CO_2*(1) + metric tons CH_4*(25) + metric tons N_2O*(298)

End-use Analysis

End-use emissions are specific to the technology used for each application, and therefore different sources were necessary to estimate various end-use emission factors. The U.S. Department of Energy and the Environmental Protection Agency publish end-use carbon content emission factors for a number of different technologies, and were the source of some of the end-use emission factors used in the applications analyzed. Other sources of end-use emission factors include Delucchi 2000 and GREET

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[3] GREET is designed to quantify the lifecycle emissions of vehicles, and because vehicles using natural gas run on compressed natural gas (CNG), the model does not allow the user to select uncompressed natural gas as a fuel choice. Some applications in this study, however, required the comparison of propane to uncompressed natural gas. Because the compression of natural gas requires a significant amount of energy (and therefore adds to its upstream emissions), the GREET model input for natural gas compression efficiency was set to 100% in order to remove the emissions associated with compression. Compression efficiency as defined by the GREET model is equal to HV/(energy in + HV), where HV is the heating value of the fuel. Setting efficiency at 100% therefore makes energy in equal to zero.

[4] In other words, all products produced from either crude or natural gas are assumed to begin their lifecycle at the wellhead, even though they have not been physically separated from the feedstock. If a given product stream represents 5% of the Btu content of the feedstock, for example, then that product is assigned 5% of the emissions attributed to the feedstock before refining and separation. This method of assigning emissions is not influenced by the economic value of the product or feedstock.

2007. For vehicle applications, end-use emission factors were based on those used in the GREET model for 2005 model year vehicles.[5]

Total end-use emissions were obtained in the same way as total upstream emissions, by summing the GWP-adjusted end-use emissions of CO_2, CH_4, and N_2O. Unlike upstream emissions factors, however, the units used for end-use emission factors depended on the application. While Btu-based emission factors were applied to some of the applications, the total mass of GHGs emitted from light- and mid-duty trucks was calculated on a grams-per-mile basis, rather than a grams-per-mmBtu basis. The formulas used to calculate end-use emission factors are shown by application in Table 3.3.

Table 3.3. End-use GHG emissions

Water heaters, forklifts, irrigation pumps, space heaters:
For each fuel:
metric tons (GHG) = grams (GHG)/MMBtu (fuel) * MMBtu of fuel consumed / 10^6

Light-duty trucks, mid-duty trucks:
For each fuel:
metric tons (GHG) = grams (GHG)/mile * miles traveled / 10^6

All applications:
Total metric tons of CO_2 equivalent = metric tons CO_2*(1) + metric tons CH_4*(25) + metric tons N_2O*(298)

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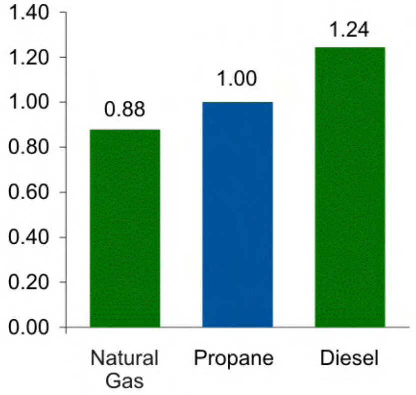
[5] These emission factors were obtained from the spreadsheet "greet1.7.xls." Vehicle performance data is tabulated for every fifth model year. The user must select the year 2015 to get performance data for 2010 model year vehicles.

IV. Summary of Findings

Distributed Generation

30 kW prime microturbine



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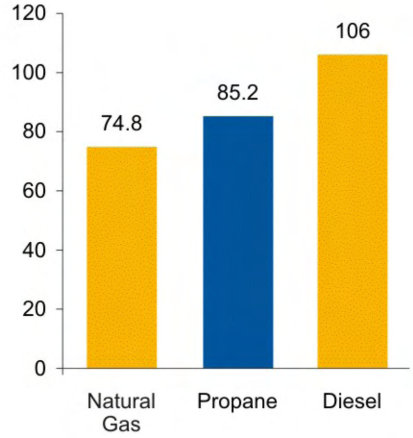
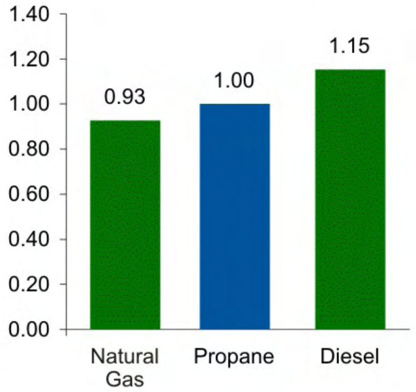


Raw Data (metric tons CO_2 equivalent per unit per year)

100 kW standby genset



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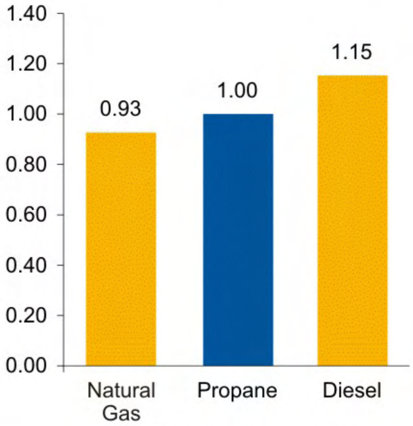
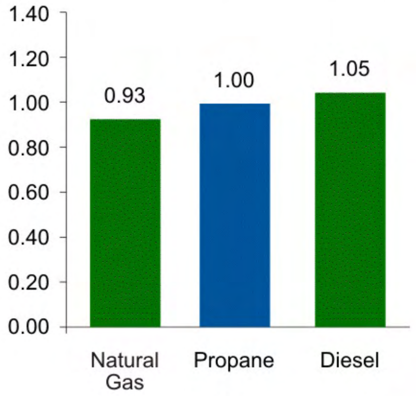
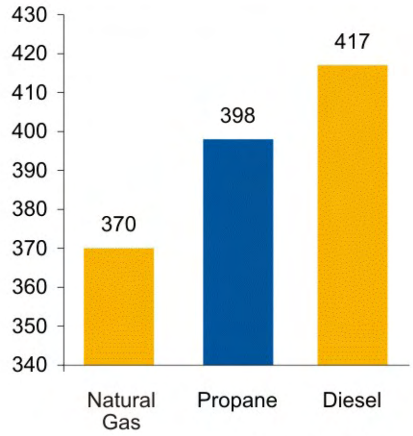


Raw Data (metric tons CO_2 equivalent per unit per year)

200 kW prime genset

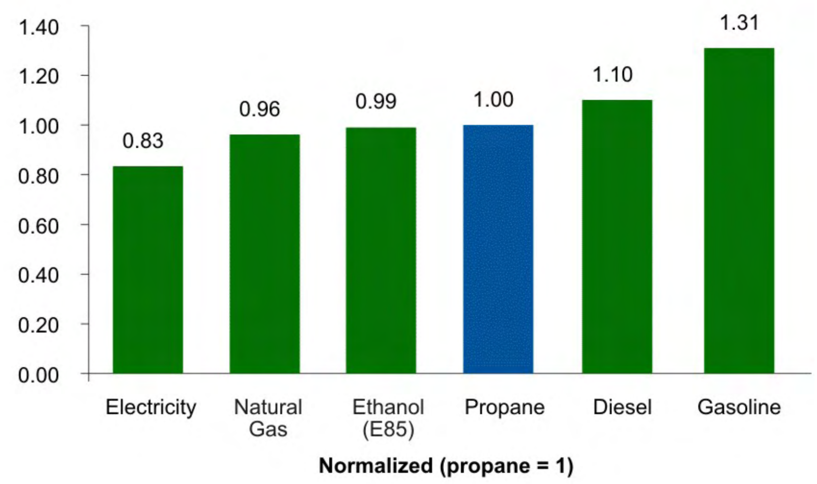


Normalized (propane = 1)

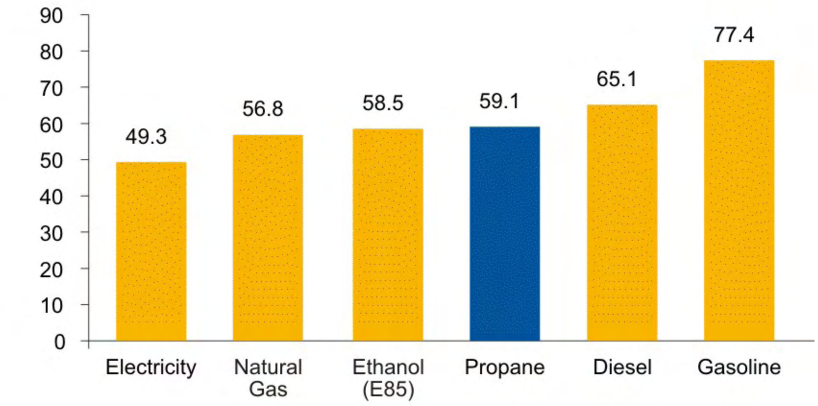


Raw Data (metric tons CO_2 equivalent per unit per year)

Irrigation Pumps

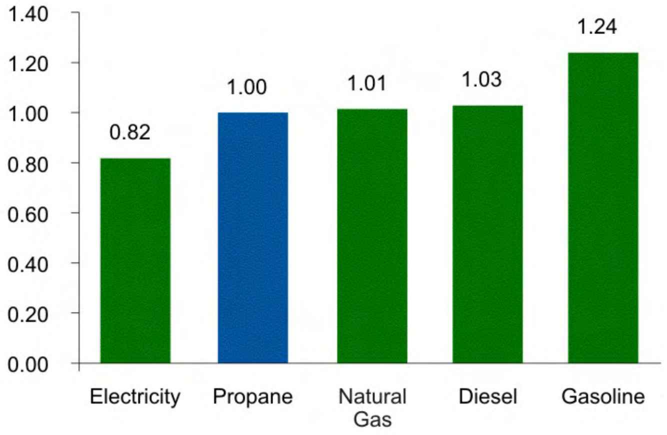


Normalized (propane = 1)

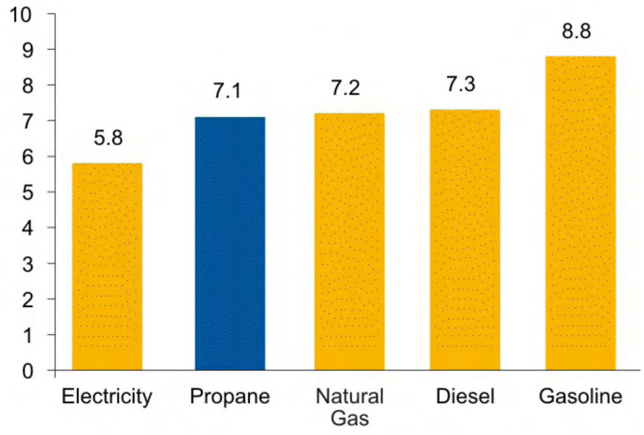


Raw Data (metric tons CO_2 equivalent per unit per year)

Forklifts

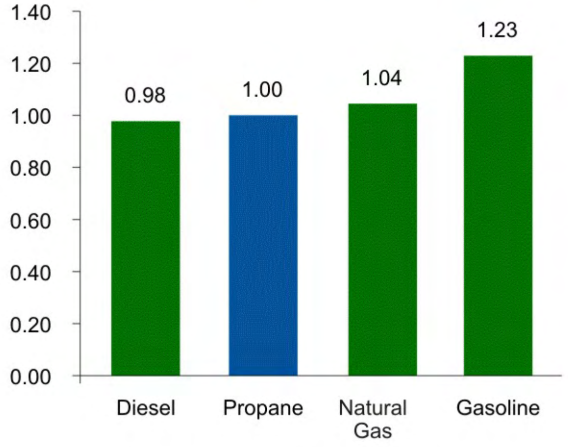


Normalized (propane = 1)

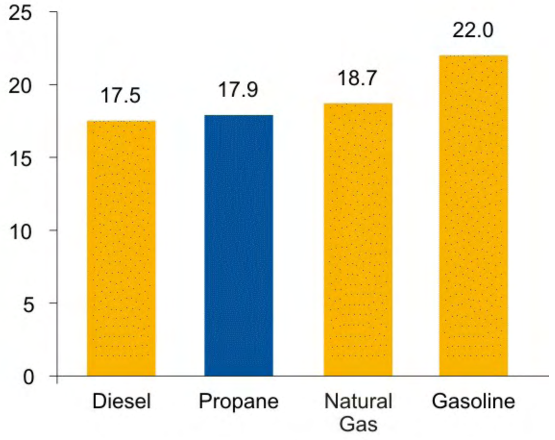


Raw Data (metric tons CO_2 equivalent per unit per year)

Medium-Duty Engines

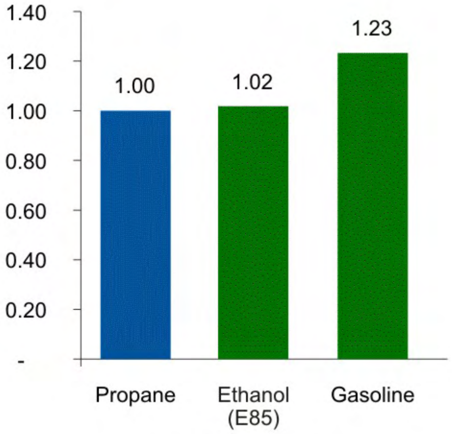


Normalized (propane = 1)



Raw Data (metric tons CO_2 equivalent per unit per year)

Light-Duty Trucks



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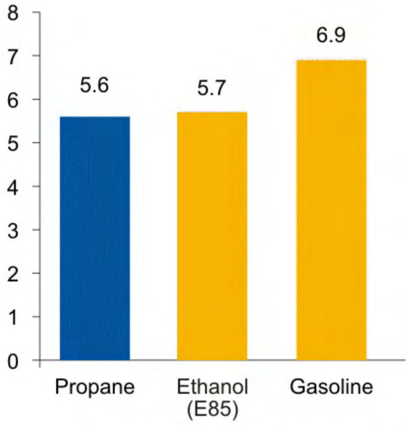
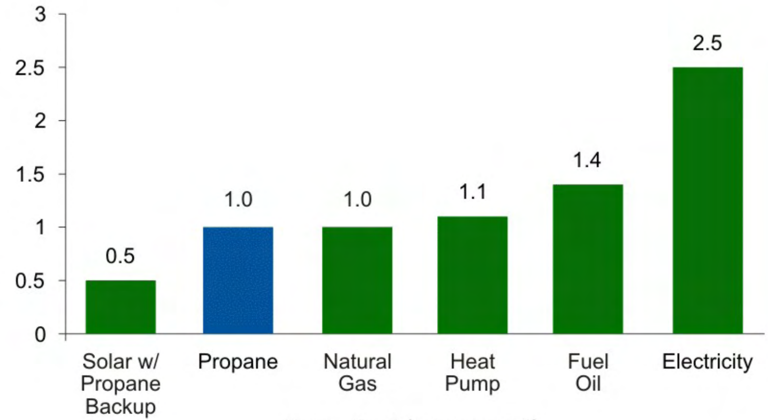


Raw Data (metric tons CO_2 equivalent per unit per year)

Residential Water Heaters

Storage Tank Heater



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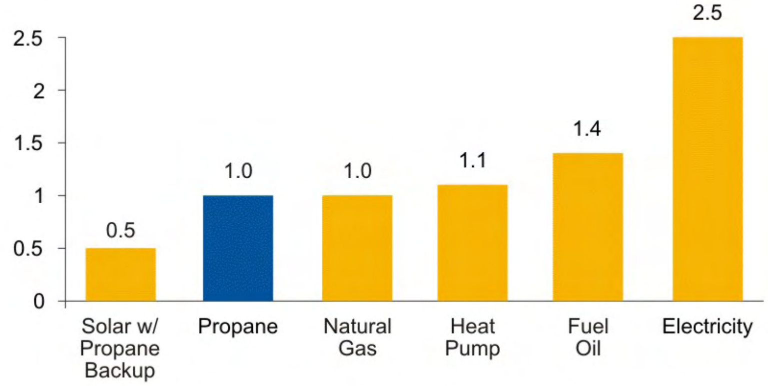
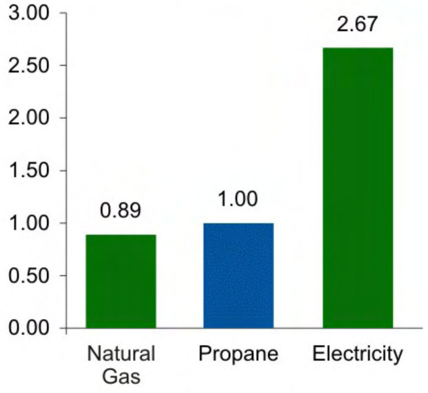
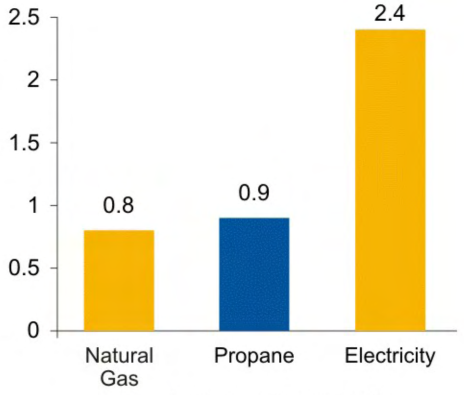


Raw Data (metric tons CO_2 equivalent per unit per year)

Tankless Water Heater

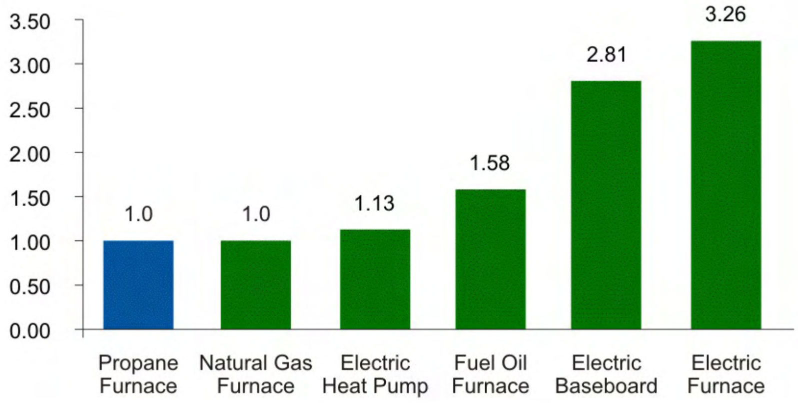


Normalized (propane = 1)



Raw Data (metric tons CO_2 equivalent per unit per year)

Residential Space Heating



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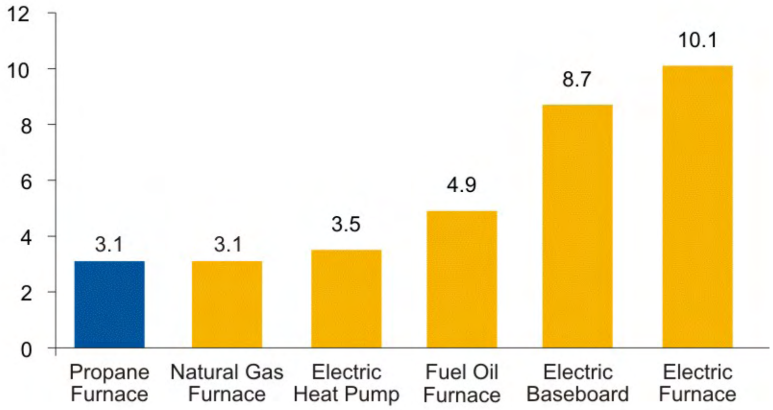


Raw Data (metric tons CO_2 equivalent per unit per year)

V. Applications

The following pages present a series of one-page summaries for the ten applications considered in this study. Each summary contains energy end-use data, market data, and a comparison of the climate change effects of fuels used in the application. The summaries also include a listing of key assumptions and references. A complete list of assumptions and references for each application is shown in Appendix B.

- **Distributed Generation** – Distributed generation (DG) technology provides electricity to off-grid areas and serves as a backup source of power for hospitals, factories, telecommunication centers, and other crucial operations. In total, approximately 12.3 million DG units are currently installed in the U.S., running mainly on diesel fuel, although the use of systems that use propane and natural gas are rapidly growing**.**

- **Irrigation Pumps** – U.S. farms rely on approximately 500,000 irrigation pumps to deliver water from reservoirs, lakes, streams, and wells for crop production. 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.

- **Forklifts** – Unlike most vehicles, forklifts use fuel not only for vehicle propulsion but also for load lifting work. Indoor air quality concerns restrict the use of diesel for heavy-duty jobs; electric forklifts are normally used for light-duty jobs, while propane can be used for both.

- **Medium-Duty Engines** – Medium-duty engines are used for many commercial and municipal vehicles, including school buses. Diesel currently fuels the majority of school buses in the U.S., despite the EPA considering its exhaust as one of the air pollutants that pose the greatest risks to public health. Many school districts have been moving to alternative fuels such as propane and compressed natural gas to address this issue.

- **Light-Duty Trucks** – Light-duty trucks, such as the Ford F-150, constitute a significant portion of the U.S. vehicle fleet. While gasoline fuels the majority of light-duty trucks in the U.S., ethanol (E85) and propane have gained greater use in recent years.

- **Residential Water Heaters** – 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.

- **Residential Space Heating –** Homes are most commonly heated by either a centralized system that moves warm air through ducts, or by separate heating units (usually electric) distributed throughout the home. Furnaces can be gas-fired (natural gas or propane), oil-fired, or electric. Nearly five million U.S. households rely on propane for home heating (EIA 2001).

Distributed Generation

Distributed generation (DG) refers to the production of electricity at or near the point at which the power is used. Distributed generators are used in residential and industrial sectors as a prime source of electricity or as a backup source in case of emergency. Prime generators are often used in remote areas not reached by the power grid, or by users that require greater reliability than the local utility can provide. Backup generators include standby supply for hospitals, factories, telecommunication centers, and other critical operations.

Generation capacities for onsite usage typically range from a few kilowatts to several hundred kilowatts. Types of DG that are fueled by propane include microturbines, generator sets (gensets), polymer electrolyte membrane (PEM) fuel cells and solid oxide fuel cells (SOFC).[1] Microturbines operate like jet engines that produce electricity instead of thrust, while gensets consist of a combustion engine driving an electrical generator. Fuel cells generate electricity by the chemical combination of fuel and oxygen. GHG emissions analyses were conducted for three combinations of capacities, operating use (prime/standby), and type (microturbine/genset), and are intended to present an emissions profile representative of common distributed generation use.

Market Data

In total, there are approximately 12.3 million DG units installed in the U.S. with an aggregate capacity of 222 GW (DG Monitor 2005). In the commercial sector, about 5% of businesses have the ability to generate electricity onsite, with 78% of those businesses using DG for emergency backup generation (EIA 2006). Most of the installed DG capacity is combustion gensets, with alternative types of DG rapidly growing. The microturbine industry is an emerging technology, with the leading supplier – Capstone – having delivered about 2,500 units (30 kW and 60 kW units) (Gas Plants, Inc. 2006).

Climate Change Comparison

Annual Greenhouse Gas Lifecycle Emissions per unit (metric tons CO_2 equivalent)

	Total	End-use	Upstream
30 kW prime microturbine			
Diesel	106	84.3	22.0
Natural gas	74.8	62.7	12.1
LPG	85.2	72.3	12.9
100 kW standby genset			
Diesel	1.88	1.50	0.39
Natural gas	1.51	1.27	0.24
LPG	1.63	1.38	0.24
200 kW prime genset			
Diesel	417	331	86.0
Natural gas	370	311	58.5
Propane	398	338	59.2

Energy End-Use Data

Performance and Energy Use Characteristics of Representative DG[2]

Fuel	Electrical Efficiency, HHV (%)	Energy Use (MMBtu/unit/yr)
30 kW prime microturbine		
Diesel	22.7	1151
Natural gas	23.6	1107
LPG	23.6	1107
100 kW standby genset		
Diesel	33.5	20.3
Natural gas	31.0	22.0
LPG	32.7	20.9
200 kW prime genset		
Diesel	38.8	4493
Natural gas	32.5	5359
LPG	34.2	5091

Key Assumptions

1. Energy use is based on vendor specs for power-only (no CHP) 60Hz gensets operating at 100% nameplate load for 7 hours per day for prime and 20 hours per year for standby.
2. Emissions from point of extraction to point of use based on GREET model.

See Appendix B for full list of assumptions and references.

Footnotes

[1] GHG emission profiles for PEMs and SOFCs have not been separately evaluated in this study.

[2] Representative generators for 30 kW microturbines: Capstone C30 Liquid Fuel, Capstone C30 Natural Gas; 100kW genset: John Deere J150U, Cummins 100GGHH; 200kW genset: Armstrong AJD200, Caterpillar G3508

Irrigation Pumps

Irrigation pumps deliver water from reservoirs, lakes, streams, and wells to farm fields for crop production. Most irrigation pumps are centrifugal, driven by an engine connected to the drive shaft (see diagram). 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 hp and operate at a steady speed and load for many hours, often 24 to 48 hours nonstop. The effectiveness in converting fuel or electricity to mechanical power to drive the irrigation pump varies based on the type of engine, operating conditions, engine load, and maintenance. This emissions analysis compares properly loaded and maintained 100 hp engines driving centrifugal irrigation pumps.

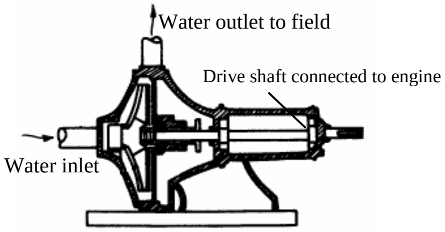
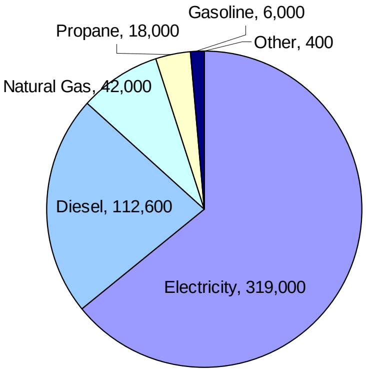


Diagram of centrifugal irrigation pump.

Source: Scherer 1993.

Market Data

In the U.S. there are approximately 500,000 irrigation pumps, powered by fuels and electricity.



The smallest pumps are often operated by electric motors, while higher capacity wells tend to be operated by diesel, natural gas, and propane engines.

Source: USDA 2004.

Energy End-Use Data

Energy Use from 100hp Irrigation Pumps (MMBtu/unit/yr)

Fuel	Fuel Use Rate	Source
Ethanol (E85)	829	Smajstrla and Zazueta 2003; DOE-EPA 2007.
Diesel	704	Smajstrla and Zazueta 2003.
Gasoline	829	Smajstrla and Zazueta 2003.
Natural gas	843	Evans, Sneed, and Hunt 1996.
LPG	767	Smajstrla and Zazueta 2003.
Electricity	217	Smajstrla and Zazueta 2003.

Climate Change Comparison

Annual Greenhouse Gas Lifecycle Emissions for 100hp Irrigation Pump (metric tons CO_2 equivalent)

Fuel	Total	End-use	Up-stream
Electricity	49.3	0	49.3
Natural gas	56.8	47.5	9.2
Ethanol (E85)	58.5	57.3	1.1
LPG	59.1	50.2	8.9
Diesel	65.1	51.6	13.5
Gasoline	77.4	60.5	16.9

(a) Credit is given to biodiesel for carbon sequestration during crop production

Key Assumptions

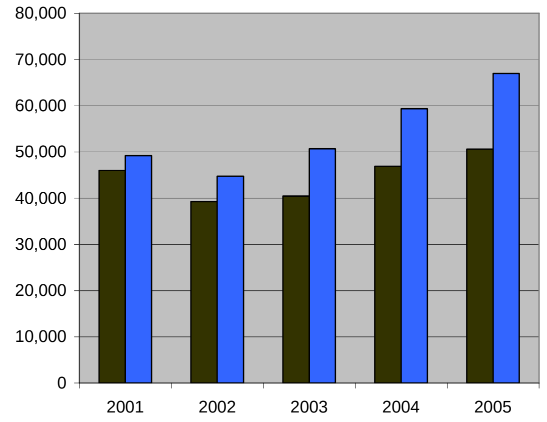
1. Upstream emissions (from point of extraction to point of use) are based on GREET model.
2. Emissions at point of use are based on 100 hp irrigation pump operating 749 hours per year.

See Appendix B for full list of assumptions and references.

Forklifts

Forklifts are used to move and stack loads, usually in warehouses. Unlike most vehicles, fuel is used not only for vehicle propulsion (with maximum speeds usually between 10-15 mph), but also for load lifting work. A large variety of forklifts can run on propane. Other fuels commonly used for forklifts are electricity, compressed natural gas (CNG), gasoline, and diesel. Fuel choice may depend on load size and air quality concerns – electric forklifts are normally used for light-duty jobs, while diesel fuel is typically used for extremely heavy-duty loads and is restricted to outdoor use for air quality reasons. Propane is used for both light- and heavy-duty applications.

Market Data



Forklift Units Shipped:
Electric (■) vs. Propane (🟦)

Source: ITA 2006

Energy End-Use Data

Fuel	MMBtu per forklift per year
Electric	26
LPG	88
CNG	92
Diesel	74
Gasoline	90

Based on an average LPG forklift using 973 gallons per year (Delucchi 2000) and under 100 horsepower.

Climate Change Comparison

	Metric tons CO_2 equivalent per forklift per year		
Fuel	**Total**	**End-use**	**Up-stream**
Electric	5.8	0.0	5.8
LPG	7.1	6.1	1.0
CNG	7.2	5.6	1.7
Diesel	7.3	5.9	1.4
Gasoline	8.8	7.0	1.9

(Note: Totals may not add due to rounding)

Key Assumptions

1. Assumes as in Delucchi 2000 that two-thirds of forklift energy use goes to vehicle propulsion and one-third goes to lifting.
2. For forklifts powered by fuels other than propane, the relative efficiencies of lifting and propulsion compared to a propane-based system were used to estimate the fuel consumption of those vehicles.
3. Thermal engine efficiencies estimated by Delucchi were used to calculate fuel required for lifting work.
4. Relative fuel efficiencies used by the GREET model for 6000-8500 lbs. GVW vehicles were used to calculate fuel required for propulsion.

See Appendix B for full list of assumptions and references.

Medium-Duty Engines

Medium-duty engines are used for many commercial and municipal vehicles, including school buses. Diesel currently fuels the majority of school buses in the U.S. today, despite the fact that exposure to diesel exhaust is known to cause a number of adverse health effects. Diesel exhaust is also among the air pollutants considered by the EPA to pose the greatest risks to public health (CARB 1998, EPA 2003). As a consequence, many school districts across the country have been looking for alternatives to diesel in order to fuel their school bus fleets. A propane-powered school bus using an EPA-certified 8.1L Liquid Propane Injection (LPI) system is one such alternative.

Market Data

There are approximately 450,000 school buses transporting 24 million school children each school day (School Bus Fleet 2007). Propane fuels more than 1,400 of those school buses in the United States (PERC 2000).

Energy End-Use Data

Fuel	MMBtu per bus per year
Diesel	189
LPG	240
CNG	252
Gasoline	240

Based on a standard size (Type C) school bus traveling 9,000 miles per year.

Climate Change Comparison

	Metric tons CO_2 equivalent per bus per year		
Fuel	Total	End-use	Up-stream
Diesel	17.5	13.9	3.7
LPG	17.9	15.1	2.8
CNG	18.7	14.0	4.7
Gasoline	22.0	17.0	4.9

(Note: Totals may not add due to rounding)

Key Assumptions

1. Assumes fuel efficiencies for diesel and CNG buses reported in ANTARES Group 2004.
2. Fuel efficiencies for LPG and gasoline vehicles were estimated by applying the ratio of fuel efficiencies used by the GREET model for 6000-8500 lbs. GVW vehicles (the largest size class in the model) to CNG school bus fuel efficiency reported by ANTARES Group.

See Appendix B for full list of assumptions and references.

Light-Duty Trucks

Light-duty trucks, such as the Ford F-150, constitute a significant portion of the U.S. vehicle fleet. While gasoline fuels the majority of light-duty trucks in the U.S., ethanol (E85) and propane have gained greater use in recent years. The Roush F-150 pickup uses Liquid Propane Injection (LPI) technology to make the F-150 a dedicated propane vehicle. Using an engine computer specifically calibrated for propane, the LPI system directly replaces the OEM gasoline injection system. The propane-powered F-150 offers the same performance as a gasoline-powered pickup truck. Ethanol (E85) may also be used in Ford's flex-fuel model of the F-150, which can be fueled by either regular gasoline or E85. E85 is composed of 85% ethanol and 15% petroleum by volume.

Market Data

The Ford F-series pick-up trucks have been the top-selling vehicle in the United States for 25 consecutive years, with close to 1,000,000 vehicles sold in each of the past several years (Forbes.com 2006).

Energy End-Use Data

Fuel	MMBtu per vehicle per year
LPG	75
E85	75
Gasoline	75

Based on a pickup truck traveling 10,000 miles per year.

Climate Change Comparison

	Metric tons CO2 equivalent per vehicle per year		
Fuel	Total	End-use	Up-stream
LPG	5.6	4.7	0.9
Ethanol (E85)	5.7	5.2	0.5
Gasoline	6.9	5.3	1.5

(Note: Totals may not add due to rounding)

Key Assumptions

1. Fuel efficiencies used by the GREET model for 6000-8500 lbs. GVW vehicles were used to calculate fuel use for equivalent miles traveled. See appendix for values.
2. GHG emissions factors for E85 are specifically for combustion in a flex-fuel vehicle.

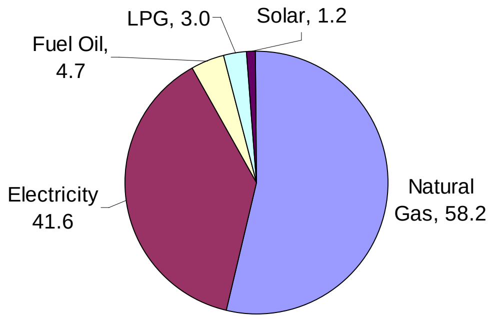
See Appendix B for full list of assumptions and references.

Residential Water Heaters

Propane residential water heaters include both tank storage units as well as instantaneous (“tankless”) water heaters. While storage water heaters keep a constantly available supply of hot water, tankless units heat water as it is supplied to the end user. Both storage and tankless units can be gas-fueled or electric. Gas water heaters are designed to run on either propane or natural gas. Fuel oil and solar power, however, are only used for storage tank water heating. 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 (DOE 2005d). Heat pump water heaters use electricity to move heat rather than generate it directly. They are more efficient than electric water heaters but very few are commercially available.

Market Data

Residential water heaters installed in the U.S. by fuel type (million units)



Sources: EIA 2001, NREL 1998
Includes all types of water heaters.

Energy End-Use Data

Storage tank heater

Fuel	MMBtu per unit per year
Solar w/ LPG backup	7
LPG	16
Natural gas	16
Heat pump	5
Fuel oil	16
Electricity	11

Tankless water heater

Fuel	MMBtu per unit per year
Natural gas	12
LPG	12
Electricity	11

Based on equal hot water delivery compared to a propane storage water heater using an average 15.8 MMBtu/yr (EIA 2001), equal to 173 gallons of LPG per year.

Climate Change Comparison

Storage tank heater

	Metric tons CO2 equivalent per unit per year		
Fuel	total	end-use	up-stream
Solar w/ LPG backup	0.5	0.3	0.2
LPG	1.0	0.8	0.2
Natural gas	1.0	0.8	0.2
Heat pump	1.1	0.0	1.1
Fuel oil	1.4	1.1	0.3
Electricity	2.5	0.0	2.5

Tankless water heater

	Metric tons CO2 equivalent per unit per year		
Fuel	total	end-use	up-stream
Natural gas	0.8	0.7	0.1
LPG	0.9	0.8	0.1
Electricity	2.4	0.0	2.4

Key Assumptions

1. Energy efficiencies based on the highest energy factor reported in the GAMA Directory of Certified Efficiency Ratings (GAMA 2006). Solar water heater energy efficiency based on DOE 2005c.
2. Fuel consumption of propane storage tank heater based on average residential energy consumption for water heating. Tankless propane fuel consumption based on relative efficiency compared to a tank heater. See appendix for efficiency values (energy factors) used.
3. Solar water heater uses electricity for fluid circulation. Solar water heater delivers 60% of water heating load with remaining 40% from a backup LPG system.

See Appendix B for a full list of assumptions and references.

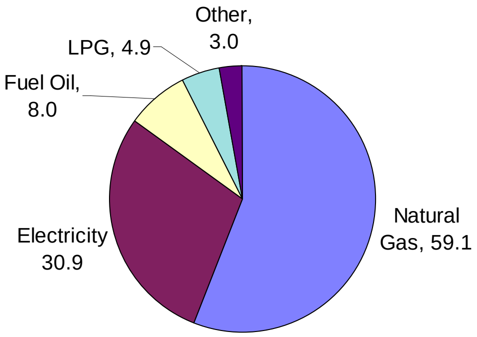
Residential Space Heating

Homes are most commonly heated by either a centralized system that moves warm air through ducts or by separate heating units (usually electric) distributed throughout the home. Furnaces 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 heat air, but do so by moving heat rather than generating heat by electrical resistance. This makes heat pumps more efficient than electric radiators, and allows them to deliver more heat energy than they use in electricity.

Because boilers have the same range of energy efficiencies as furnaces, they were not added to the analysis, but their greenhouse gas emissions can reasonably be assumed to be comparable to those of furnaces. Similarly, a number of different electric resistance heating units can be used to heat rooms, but because they all convert nearly 100% of electricity into useful heat, their emissions impact will be similar to electric baseboard heating.

Market Data

Households in the U.S. by main space-heating fuel (million households)



Source: EIA 2001

Energy End-Use Data

Fuel	MMBtu per heating system per year
LPG Furnace	47
Natural Gas Furnace	47
Electric Heat Pump	15
Fuel Oil Furnace	53
Electric Baseboard	38
Electric Furnace	44

Based on a furnace delivering 38 million Btu of useful heat, typical of a furnace in a winter climate zone such as the mid-Atlantic.

Climate Change Comparison

	Metric tons CO2 equivalent per heating system per year		
Fuel	Total	End-use	Up-stream
LPG Furnace	3.1	2.5	0.6
Natural Gas Furnace	3.1	2.5	0.6
Electric Heat Pump	3.5	0.0	3.5
Fuel Oil Furnace	4.9	3.9	1.0
Electric Baseboard	8.7	0.0	8.7
Electric Furnace	10.1	0.0	10.1

Key Assumptions

1. Estimated useful heat delivered by a propane furnace was 38 million Btu, and was based on an average energy consumption of 52.6 million Btu per year of propane in a region with 4000-5499 heating degree days (EIA 2001) after estimated average efficiency (15%) and duct losses (15%) were applied.
2. Energy efficiencies based on the highest annual fuel utilization efficiency (AFUE) reported in the GAMA Directory of Certified Efficiency Ratings (GAMA 2006) for gas and fuel oil furnaces with greater than 60,000 Btu-hour ratings.
3. Assumed 100% conversion efficiency of electric heaters and electric furnaces.

See Appendix B for full list of assumptions and references.

VI. Appendix A – Glossary

Carbon dioxide (CO_2) equivalent

The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (for example, methane) by its estimated global warming potential (which is 21 for methane). "Carbon equivalent units" are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44) (EIA 2007).

End-use

Pertaining to the ultimate consumption of energy or fuel (adapted from “end user,” EIA 2007).

Global Warming Potential (GWP)

An index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years (EIA 2007).

Greenhouse Gases (GHG)

Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface. (EIA 2007).

Lifecycle

The process from raw material acquisition (including exploration and production) through end-use by the consumer.

Radiative forcing

A change in average net radiation at the top of the troposphere (known as the tropopause) because of a change in either incoming solar or exiting infrared radiation. A positive radiative forcing tends on average to warm the earth's surface; a negative radiative forcing on average tends to cool the earth's surface. Greenhouse gases, when emitted into the atmosphere, trap infrared energy radiated from the earth's surface and therefore tend to produce positive radiative forcing (EIA 2007).

Upstream

Pertaining to any process, or the sum total of processes, used to produce or deliver energy up to the point of consumption by the end-user. Concerns all processes used in the transformation of raw feedstock into fuel, including raw material extraction, processing, transportation, distribution, and storage (adapted from diagram, Argonne National Laboratory 2007).

VII. Appendix B – Assumptions and References

About Climate Change

References

Climate Leaders. 2004. Direct Emissions from Stationary Combustion Sources. *Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance*. U.S. Environmental Protection Agency (EPA) (October). http://www.epa.gov/climateleaders/docs/stationarycombustionguidance.pdf

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U.S. Environmental Protection Agency (EPA). 2007. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005*. Table A-10, EPA 430-R-07-002 (April).

Methodology

References

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. 2007. GREET 2, Version 1.7. UChicago Argonne, LLC.

Intergovernmental Panel on Climate Change (IPCC) 2007. *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

Distributed Generation

Assumptions

1. Energy use is based on vendor specs for power-only (no CHP) 60Hz gensets operating at 100% nameplate load.
2. End-use energy consumption data are based on reported fuel use in vendor specifications of representative generators. Representative generators for 30 kW microturbines: Capstone C30 Liquid Fuel, Capstone C30 Natural Gas; 100kW genset: John Deere J150U, Cummins 100GGHH; 200kW genset: Armstrong AJD200, Caterpillar G3508. (Vendor specs 2007)
3. Capstone C30 microturbine is operated at ambient temperatures above 35°F (a propane pump and vaporizer is unnecessary) (Gas Plants, Inc. 2006).

4. Methane and nitrous oxide emission factors are based on Delucchi 2000.
5. Carbon content (kg CO2/million Btu) of all fuels evaluated assumes 99% combustion. Table B.1 DOE 1994.
6. Energy content of fuels based on EIA 2007 and EIA 2007a.
7. Upstream emissions (from point of extraction to point of use) for all fuels are based on GREET model version 1.5 (GREET Model 2007).
8. Assume representative standby generator operates 20 hours per year. (15 min. per week for exercising = 13 hours, plus 7 hours of operation average in a poor power area). Source: email correspondence with PERC May 15, 2007.
9. Prime power units can operate from 4-10 hours per day. Assume 7 hours per day for an average unit. Source: email correspondence with PERC May 15, 2007.
10. Global warming potentials (GWP) are used to combine the three greenhouse gases into metric tons of carbon dioxide equivalent. GWPs for this study are based on 100 year time horizon: CO2 = 1, methane = 25, nitrous oxide = 298 (IPCC 2007).

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Irrigation Pumps

Assumptions

1. Fuel and electricity use are based on performance standards determined for internal combustion engines using standard accessories, including a water pump, fan, and radiator (Smajstrla and Zazueta 2003).
2. Methane and nitrous oxide emission factors are based on Delucchi 2000 unless otherwise noted below.
3. Assume methane emissions are 2% higher from E85 combustion than gasoline combustion based on a hydrocarbon emissions analysis from small engines in this study: Varde 2002.
4. Carbon content (kg CO2/million Btu) of all fuels evaluated assumes 99% combustion. Table B.1 DOE 1994.
5. Energy content of fuels based on EIA 2007, Bioenergy Feedstock Information Network 2007, and Evans, Sneed, and Hunt 1996.
6. There is no meaningful difference in engine efficiency between E85 and gasoline. Fuel usage of E85 is higher due to ethanol's lower energy content (EPA-DOE 2007).
7. Upstream emissions (from point of extraction to point of use) for all fuels are based on GREET model version 1.5 (GREET Model 2007).
8. Upstream ethanol emissions are based on the GREET model for converting corn to ethanol. The emissions and energy use involved in the production of corn are calculated on the basis of the amount of fuel and chemicals (fertilizer, herbicides, and insecticides) used per bushel. Energy efficiency of 97.7% is assumed for ethanol transportation, storage, and distribution. The figure below presents the stages that are included for the upstream ethanol calculations in GREET 1.5.

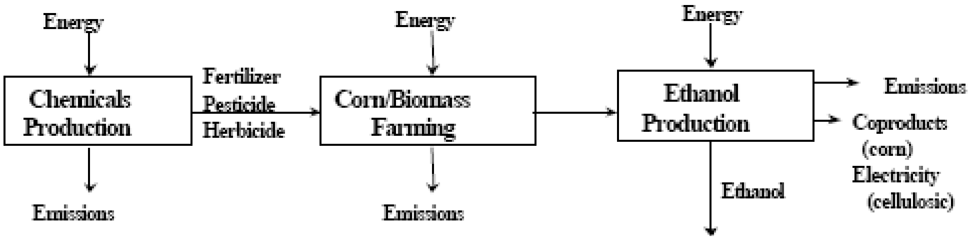

Diagram of upstream elements for calculating emissions from ethanol fuel production. Figure 4.1 from GREET 2007.

9. Assume representative irrigation pump operates 749 hours per year. Source Autumn Wind Associates 2004, page 20.
10. Global warming potentials (GWP) are used to combine the three greenhouse gases into metric tons of carbon dioxide equivalent. GWPs for this study are based on 100 year time horizon: CO2 = 1, methane = 25, nitrous oxide = 298 (IPCC 2007).

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Forklifts

Assumptions

1. Average fuel use of 973 gallons of propane per year is based on market data provided in Delucchi 2000, which cites 400,000 forklifts using 389 million gallons of propane annually.
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. This fraction was not based on actual usage data, but was considered by the author to be a reasonable assumption.
3. For forklifts powered by fuels other than propane, the relative efficiencies of lifting and propulsion compared to a propane-based system were used to estimate the fuel consumption of those vehicles.
4. Relative fuel efficiencies used by the GREET model for 6000-8500 lbs. GVW vehicles, model year 2010, were used to calculate fuel use for equivalent miles traveled. The ratio of the fuel economy of each vehicle type (in miles per gasoline equivalent gallon) relative to a gasoline powered vehicle are as follows: electric – 3.5; LPG and gasoline – 1.0, CNG - .95; diesel – 1.31.
5. Thermal engine efficiencies were used to calculate fuel use for equivalent lifting work in Btus. Forklift engine thermal efficiencies used were those used by Delucchi: LPG and CNG – 28.0%; gasoline – 26.7%; diesel – 28.5%. Electric motor thermal efficiency was assumed to be 95%.
6. Upstream emission factors were based on the output of the GREET model (GREET 2007). See text for a discussion of the assumptions used with this model.
7. End-use emission factors were based on those used in the GREET model for 6000-8500 lbs. GVW vehicles, given in grams-per-mile in the "greet1.7.xls" input file provided with the model. Emission factors were converted from grams-per-mile to grams-per-MMBtu of fuel.

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Medium-Duty Engines

Assumptions

1. Different fuel systems were evaluated based on the emissions resulting from the delivery of an equivalent energy service – miles traveled.
2. The assumption of 9,000 miles traveled per year was based on the same assumption by ANTARES Group (ANTARES Group 2004).
3. The following fuel economy values (in diesel-equivalent gallons) were used in the comparative analysis: LPG school bus – 5.2; CNG school bus – 5.0; diesel school bus – 6.6; gasoline school bus – 5.2. Fuel efficiency for CNG and diesel vehicles were those reported by ANTARES. This source assumed that LPG buses had the same fuel economy as CNG vehicles. But because the fuel tanks of CNG vehicles are heavier than those of LPG vehicles and create a fuel economy penalty, the relative fuel efficiencies used by the GREET model (GREET 2007) were used to get a more accurate estimate LPG fuel economy. Relative fuel efficiencies used by the GREET model for 6000-8500 lbs. GVW vehicles, model year 2010, were used to estimate the fuel economy of LPG as well as gasoline school buses. The fuel economy of the LPG vehicle in the GREET model is 5.3% higher than that of a CNG vehicle (on an equivalent gallon basis). This difference was applied to reported fuel economy for CNG school buses in order to calculate fuel economy for an LPG bus. Because the GREET model assumes that LPG and gasoline vehicles have the same fuel efficiency on an equivalent gallon basis, gasoline bus fuel efficiency was assumed to be equal to the LPG bus value.
4. Upstream emission factors were based on the output of the GREET model. See text for a discussion of the assumptions used with this model.
5. End-use emission factors were based on those used in the GREET model for 6000-8500 lbs. GVW vehicles

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Light-Duty Trucks

Assumptions

1. Different fuel systems were evaluated based on the emissions resulting from the delivery of an equivalent energy service – miles traveled.
2. A typical pickup truck was estimated to travel 10,000 miles per year.
3. The following fuel economy values (in gasoline-equivalent gallons) were those used in the GREET model (GREET 2007), and were used in the comparative analysis: LPG, gasoline, and E85 – 16.7.
4. Upstream emission factors were based on the output of the GREET model. See text for a discussion of the assumptions used with this model.
5. End-use emission factors were based on those used in the GREET model for 6000-8500 lbs. GVW vehicles, given in grams-per-mile in the "greet1.7.xls" input file provided with the model.

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Residential Water Heaters

Assumptions

1. The highest reported energy efficiency for each type of water heater was used in the analysis. The energy efficiency of a water heater is designated by its energy factor, which is the ratio of the heat delivered (as hot water) to the energy consumed (i.e., electricity, natural gas, LPG, or oil) according to a specific test procedure (DOE 2000).
2. Energy factors for all water heaters except solar water heaters were based on the highest reported energy factor in the GAMA Directory of Certified Efficiency Ratings (GAMA 2006) for each type of unit. The GAMA source did not include solar hot water heater efficiency ratings. The energy factor of solar hot water heaters was based on the highest value in the range provided by DOE's Office of Energy Efficiency and Renewable Energy (DOE 2005(b)). This energy factor assumes that some amount of electricity is used to circulate fluid. Energy factors for storage tank water heaters were: solar – 11.0, LPG – 0.67, natural gas – 0.67, heat pump – 2.28, fuel oil – 0.68, electric – 0.95. Energy factors for tankless water heaters were: LPG – 0.85, natural gas – 0.85, electric – 0.99.
3. Although heat pump water heaters may be used for tankless water heating, there were no tankless heat pump models listed in the GAMA directory and therefore were not evaluated in the analysis.

4. Solar water heaters are typically integrated with another hot water heating system running on gas, oil, or electricity. Solar water heaters typically serve 50-75% of the hot water load (DOE 2005(b)). Typical values for LPG was selected as the backup system, with the solar water heater system serving 60% of the load.
5. Fuel consumption of LPG storage tank heater based on the average fuel consumption of a residential hot water heating system of 15.8 MMBtu, based on EIA 2001.
6. Upstream emission factors were based on the output of the GREET model (see text for a discussion of the assumptions used with this model).
7. End-use emission factors were those used in Delucchi 2000.

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Residential Space Heating

Assumptions

1. Different fuel systems were evaluated based on the emissions resulting from the delivery of an equivalent energy service – the amount of useful heat supplied to the home.
2. Estimated useful heat delivered by a propane furnace was 38 million Btu, and was based on an average energy consumption of 52.6 million Btu per year of propane in a region with 4000-5499 heating degree days (EIA 2001) after estimated average efficiency losses (15%) and duct losses (15%) were applied.
3. The highest reported energy efficiency for each type of space heater was used in the analysis. The energy efficiency of a space heater 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 2005a).
4. The energy efficiency for gas and fuel oil furnaces were based on the highest reported AFUE in the GAMA Directory of Certified Efficiency Ratings (GAMA 2006). AFUE values for furnaces were: LPG and natural gas – 95.7, fuel oil – 85.0. An AFUE of 100 was assumed for the electric furnace based on the upper end of the range given in DOE 2005a.
5. Electric heat pump energy efficiency is determined by its heating season performance factor (HSPF), which is the ratio of heat delivered in Btus to the electricity consumed in Watt-hours. A HSPF of 10.0 was used for the heat pump, since it was the highest value in the range reported in DOE 2005b.
6. Duct heat losses of 15% were assumed for the furnace and heat pump systems, and were applied after conversion efficiency losses. The heat transfer efficiency of the electric resistance baseboard heating system was assumed to be 100% based on DOE 2005.
7. It was assumed that gas and oil furnaces met GAMA's guideline for electrical efficiency (GAMA 2006), meaning their electricity usage during a typical heating season is 2% or less of the total energy used by the furnace. Therefore, emissions resulting from electricity consumption by these furnaces was not calculated.
8. Upstream emission factors were based on the output of the GREET model (GREET 2007). See text for a discussion of the assumptions used with this model.
9. End-use emission factors were those used in Delucchi 2000.

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