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GHG and Criteria Pollutant Emissions Analysis

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Prepared for:
Gregory Kerr
Director of Research and Development
Propane Education & Research Council
1140 Connecticut Avenue, NW, Suite 1075
Washington, DC 20036
Email: Gregory.Kerr@propanecouncil.org

GTI Technical Contact:
Neil Leslie
Sr. R&D Director, End Use Solutions
Neil Leslie@gastechnology.org

Patricia Rowley
Senior Engineer, End Use Solutions
Patricia.Rowley@gastechnology.org

Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

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Introduction

Direct use of propane in buildings, transportation, and agriculture applications is a proven, cost-effective, and reliable approach to reducing greenhouse gas (GHG) and other emissions. Propane production and delivery is more efficient than electricity provided by the power grid, which is still dominated by fossil fuel power generation and includes large energy losses at the power plant and transmission lines. In the future, the direct use of propane will remain a sustainable strategy for reducing greenhouse gas and criteria pollutant emissions.

Full-Fuel-Cycle Energy and Emissions

This study includes a comparative emissions analysis of targeted applications in key propane markets, including buildings, agriculture, and transportation market segments. This study leverages ongoing activities and tools developed under GTI's Carbon Management Information Center (CMIC) consortium, especially the Source Energy and Emissions Analysis Tool (SEEAT).[1]

SEEAT is a free, publicly available online tool to calculate full-fuel-cycle (source) energy consumption, greenhouse gas (GHG) emissions (CO_2, CH_4, N_2O), and criteria pollutant emissions (NOx, SOx) associated with annual site energy consumption by selected building and vehicle applications. SEEAT uses government and published data sources to estimate source energy and related air emissions associated with the full-fuel-cycle (extraction, processing, transportation, and distribution) for fossil fuels and electricity consumed at a site. Default power plant efficiency, fuel mix, and emissions data can be selected based on current and previous eGRID databases or values can be input directly by the user. References for emission and source energy factors and default values are described in detail in the tool (see the link "more information").

SEEAT source energy factors and emission factors were used for this analysis for non-engine applications. Emission factors for vehicles and off-road engines (e.g., forklifts, etc.) were based on Argonne's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET®)[2] and supplemented by U.S. Environmental Protection Agency [3] databases.

Figure 1 presents the SEEAT inputs and corresponding source energy and emission factors used in this analysis. The U.S average electricity generation fuel mix was selected based on 2012 eGRID national plant level database. This electricity mix contains 12.4% renewable power generation, including wind, solar, geothermal, biofuels, and hydro. To align with a recent decision by DOE, noncombustible renewable grid power generation were assumed to have a 100% conversion efficiency. The full-fuel-cycle efficiency of the U.S. average electricity mix is 33% corresponding to a source energy factor of 3.03. In other words, for every unit of electricity used at a site, 3.03 units of source energy (oil, natural gas, coal, etc.) must be extracted to generate and deliver that electricity. In contrast, propane has a full-fuel-cycle efficiency of 87%, corresponding to a source energy factor of 1.15.

For residential and commercial buildings, the direct use of propane can reduce source energy use and full-fuel-cycle GHG and criteria pollutant emissions. In many applications, such as water heating or space conditioning, propane reduces GHG emissions with significant savings in NOx relative to oil-fired equipment, and significant savings in SOx relative to electric equipment.

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[1] Carbon Management Information Center Source Energy and Emissions Analysis Tool (SEEAT), Version 7.2, Copyright 2016 Gas Technology Institute. http://seeatcalcbeta.gastechnology.org/Account/login.aspx
[2] Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET®), Argonne National Laboratory, 2016 Release. https://greet.es.anl.gov/
[3] U.S. EPA Emission Factors for Greenhouse Gas Inventories, https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf

Propane also provides environmental benefits in vehicle, industrial, and agriculture engine-driven applications compared to electric, oil, or gasoline alternatives. For vehicle applications, propane vehicles have lower NOx emissions compared to equivalent diesel or gasoline vehicles. Propane vehicles also reduce full-fuel-cycle GHG emissions and source energy use by replacing conventional fuels such as gasoline.

Step 3. Source Energy Efficiency Factors and Emission Factors

Plant Database: ◉ All Plants ○ Non-Baseload Plants

eGrid Database: ◉ 2012 data ○ 2010 data ○ 2009 data ○ 2007 data ○ 2005 data — more information

eGrid Level: ○ 2012 data eGrid National database ◉ 2012 data eGrid National plant level database

Notes: Energy conversion efficiency and specific emissions data for electricity generated using fossil fuels and biomass are based on eGrid 2012 data plant level database screened to verify primary fuel plant classification. Electric distribution efficiency data are based on eGrid 2012 data plant level database. All other default data are based on EIA, NREL, and ANL (GREET 1 2012) data sources.

Electricity generation fuel mix distribution data are based on eGrid 2012 data plant level database screened to verify primary fuel plant classification

☑ Noncombustible Renewables 100% Conversion Efficiency ☐ User-Specified Efficiency ☐ User-Specified Fuel Mix

Energy Efficiency of Electricity Delivered to Building (%)

Fuel	Extraction	Processing	Transportation	Conversion	Distribution	Total
Coal	98.0	98.6	99.0	32.3	91.7	28.3
Oil	96.3	93.8	98.8	32.4	91.7	26.5
Natural Gas	96.2	97.0	99.3	43.0	91.7	36.5
Nuclear	99.0	96.2	99.9	32.6	91.7	28.4
Hydro	100.0	100.0	100.0	100.0	91.7	91.7
Biomass	99.4	95.0	97.5	30.4	91.7	25.7
Wind	100.0	100.0	100.0	100.0	91.7	91.7
Solar	100.0	100.0	100.0	100.0	91.7	91.7
Geothermal	100.0	100.0	100.0	100.0	91.7	91.7
Other	100.0	100.0	100.0	20.3	91.7	18.6

Electricity Generation Fuel Mix (%)

Fuel	Fuel Mix
Coal	37.7
Oil	0.4
Natural Gas	30.2
Nuclear	19.3
Hydro	6.7
Biomass	1.7
Wind	3.5
Solar	0.1
Geothermal	0.4
Other	0

Energy Efficiency of Fuels Delivered to Building (%)

Fuel	Extraction	Processing	Transportation	Distribution	Total
Natural Gas	96.2	97.0	99.0	99.0	91.5
Heating Fuel Oil	94.9	89.1	99.7	99.6	84.0
Propane/LPG	94.6	93.6	99.2	99.2	87.1

View / Edit Emission Factors

Source Energy Factors and Composite Emission Factors

Source Energy Factors

	Electric	Natural Gas	Fuel Oil	Propane
Btu/Btu	3.03	1.09	1.19	1.15

Composite Emission Factors

Energy Form	CO_2	SO_2	NOx	CH_4	N_2O	CO_2e
Electricity (lb/MWh)	1,297.4	2.21	1.32	2.771	0.016	1,371.4
Natural Gas (Building Used, lb/MMBtu)	130.24	0.029	0.172	0.651	0.003	147.30
Fuel Oil (lb/MMBtu)	191.82	0.056	1.212	0.274	0.005	200.11
Propane (lb/MMBtu)	163.22	0.055	0.225	0.128	0.011	169.73
Natural Gas (mCHP NG Engine Used, lb/MMBtu)	137.24	0.029	1.892	1.514	0.000	175.21
Natural Gas (mCHP Fuel Cell Used, lb/MMBtu)	128.94	0.028	0.055	0.649	0.000	145.23

Figure 1 - Input Source Energy and Emission Factors

Methodology

This study presents a comparative analysis of full-fuel-cycle GHG and criteria pollutant emissions for targeted applications in key propane markets, including buildings, agriculture, and transportation. Technology options selected for this analysis are listed below:

- Residential Applications
  - Space Heating: furnaces, boilers, heat pumps
  - Water Heating: conventional storage, tankless, heat pumps
  - Appliances: ranges, clothes dryers
- Commercial Applications
  - Space Heating: furnaces, boilers, heat pumps
  - Water Heating: conventional storage, tankless, heat pump
  - Combined Heat and Power (CHP): engine, microturbine, conventional electric grid
  - Power Generation: engine, conventional electric grid power
- Vehicles
  - Light Duty Trucks
  - School Buses
  - Bobtail Trucks
- Irrigation Engines
- Commercial Lawn Mowers
- Forklifts

Comparative emissions for each technology option are summarized in the following sections. Full-fuel-cycle emissions for each option are normalized with respect to the equivalent baseline propane technology to indicate the relative benefit of propane in comparison to other fuel options. Using this approach, baseline propane options are set to an emissions ratio of 1. Options with higher emissions than the baseline have ratios greater than 1, while those with lower emissions have ratios less than 1.

This analysis incorporates source energy and emission factors based on SEEAT, supplemented by GREET® and other published sources, to calculate source energy consumption, GHG emissions and targeted criteria pollutant emissions for current technology options fueled by propane, natural gas, fuel oil, and electric. Pollutant emissions evaluated include GHG, SOx, and NOx. Since the eGRID database does not include power plant information for several criteria pollutants, including ozone, particulate matter, carbon monoxide, and lead, those pollutants were not evaluated.

All source energy factors and emission factors for electricity are based on SEEAT. Emission factors for fuels used in building applications (e.g. water heating, etc.) are also based on SEEAT. For engine applications, emission factors are based on GREET® and supplemented by other sources as necessary, for vehicles, industrial and agriculture technologies. For non-road engines such as lawn mowers, irrigation engines, forklifts, CHP, and commercial power generation, fuel emission factors are from the EPA GHG emission factors for non-road vehicles, and the corresponding source energy, NOx and SOx emission factors are based on SEEAT.

The report appendix presents a table comparing emission factors from different sources for this analysis. These factors are influenced by multiple inputs and assumptions in the GREET® model related to fuel mixtures, fuel pathways, vehicle parameters, etc. In order to compare fuel emission factors using the same assumptions (i.e. apples-to-apples comparison), this analysis used the emission factors for each application from the same source wherever possible.

Summary of Findings

Propane technologies can provide significant source energy savings and reductions in GHG and criteria pollutants compared to other technologies across a wide range of applications. The following applications show the most potential for reducing full-fuel-cycle emissions through the use of propane technologies:

- **Residential and commercial water heating** are key markets where propane equipment offers marked energy and environmental benefits compared to electric resistance and oil water heaters.
    - **Propane water heaters** use less source energy and generate fewer GHG, NOx, and SOx emissions than conventional electric resistance water heaters.
    - Compared to electric heat pump water heaters, propane water heaters have comparable source energy and GHG emissions, with significant reductions in SOx.
    - Compared to oil water heaters, propane has lower GHG emissions and significantly reduces NOx emissions.
    - Based on this analysis, **a hybrid solar water heater with backup propane** tankless water heater could reduce source energy and emissions by more than half compared to the best available electric technology.
    - **Propane heat pump water heaters** are recent developments that offer potential for lower source energy and emissions.
- Compared to electric resistance heat for both residential and commercial space conditioning, **propane furnaces** can reduce source energy use and GHG emissions by up to 50%.
    - Propane options have significantly fewer SOx emissions than both electric furnace and electric heat pumps.
    - Compared to oil furnaces, propane reduces NOx emissions by as much as 79%.
    - New developments in **absorption heat pumps** show potential to achieve lower emissions than the best available electric heat pumps.
    - Electric heat pumps generate over three times more SOx emissions compared to baseline propane furnaces.
    - A **hybrid heat pump with propane furnace backup** shows potential for reducing source energy, GHG and NOx emissions, but SOx emissions would still be higher than conventional propane furnaces.
- **Propane residential clothes dryers** have significantly lower emissions and source energy use than electric dryers.
- **Propane cooking ranges** also reduce source energy use, GHG emissions, and SOx emissions compared to electric ranges, but to a lesser degree.
- **Propane mCHP** reduces source energy use and GHG emissions by almost half compared to equivalent electric grid power and electric water heating. Propane mCHP also reduces SOx emissions by almost 90% compared to the all-electric case,
- Without heat recovery, propane power generation does not have the source energy and emission benefits provided by mCHP; however, propane engines offered significant reduction in SOx emissions compared to electric grid power.
- **Propane vehicles** have several advantages for fleets, including economic benefits, reliable performance, onsite fueling, and reduced maintenance.

  - **Compared to diesel, LPG vehicles** have lower NOx emissions.
  - **LPG school buses** reduce NOx emissions by 5% to 15% compared to diesel. For Type C school buses, LPG have 6% fewer GHG emissions than diesel.
  - Use of **LPG Type A school buses in place of gasoline** reduces source energy use by 18%, along with 12% fewer GHG emissions, 15% fewer NOx emissions, and 37% SOx emissions.
  - Compared to gasoline, **LPG light-duty vehicles** reduce source energy use by 18%, along with 12% fewer GHG emissions, 5% fewer NOx emissions, and 37% SOx emissions.
- **Propane irrigation engines** have 8% lower GHG and 9% lower NOx emissions compared to diesel.
  - Compared to gasoline, propane irrigation engines reduce source energy use by 21%, along with 18% fewer GHG emissions, 20% fewer NOx emissions and 17% fewer SOx emissions
  - Electric irrigation engines have over three times higher SOx emissions than propane
- **Propane commercial lawn mowers** reduce source energy use by 20%, with 17% lower GHG, 19% lower NOx, and 16% lower SOx emissions compared to gasoline.
- **Propane forklifts** reduce source energy use and all emissions by about 15% to 19% compared to gasoline forklifts
  - Compared to diesel, propane has about 4% lower GHG and 6% lower NOx emissions
  - Electric forklifts have over four times higher SOx emissions than propane

Recommendations

- Hybrid configurations with propane backup show potential savings in source energy use and emissions compared to the best available conventional equipment for water heating or space conditioning. More detailed modeling of these configurations, supplemented by field data, is needed to quantify energy use and full-fuel-cycle emissions more accurately.
- Upstream and end use emission factors need to be validated for emerging technologies with potential for significant emission reductions, such as the gas engine-driven water heater (Ilios), Yanmar mCHP system, or the gas absorption heat pump (SMTI). This can be done using existing data or new data collected from field demonstrations or laboratory tests.
- The majority of emission factors used for vehicles and engine applications in this analysis were based on GREET® 2016 defaults. These defaults vary from SEEAT vehicle emission factors (based on GREET® 2015) and AFLEET 2016 emission factors, as shown in the Appendix table. GTI recommends a more detailed review of GREET® 2016 default assumptions to verify their appropriateness for these applications. Some default emission factors and the associated assumptions warrant further investigation, including:
  - NOx emission factor for LPG medium-duty vehicles is significantly higher than the default for school buses, although both use the same or similar engines
  - NOx emission factor for diesel light-duty vehicles is significantly higher than school bus and medium-duty vehicles
  - Analyses for commercial power generation, CHP, and irrigation engines were based on EPA non-road emission factors, pending more appropriate data for stationary engines
  - Some emission factors may need to be updated based on recent engine developments

Residential Water Heating

Water heating is the second highest energy requirement in a typical home.[4] Currently over 45 million homes in the U.S. rely on electricity for water heating. The use of propane residential water heaters, in place of electric resistance heaters, can significantly reduce source energy use and GHG emissions.

Types of Water Heaters

This analysis includes four types of residential water heaters:

- Conventional storage water heaters
- Tankless (instantaneous) water heaters
- Heat pump storage water heaters
- Hybrid solar water heaters

Conventional Storage Water Heaters

Conventional storage water heaters are typically fueled by propane, natural gas, oil, or electric resistance heat, and can be combined with a solar water heating system. Storage water heaters use a glass-lined steel tank heated by an electric resistance element or burner at the bottom of the tank. Energy Star® certified models feature better insulation, heat traps, and advanced burners to improve efficiency. These improvements have a small impact on price, but can reduce energy use by up to 8 percent. Condensing water heaters use a secondary heat exchanger that extracts more heat from the combustion gas, increasing heating efficiency up to 0.85 EF.

Heat Pump Storage Water Heaters

Electric heat pump water heaters (HPWHs) employ a heat pump, which operates like an air conditioner in reverse, to extract heat from the surrounding air and transfer the heat to water in the storage tank. HPWHs produce cooler exhaust air.

HPWH efficiency and capacity is reduced at lower ambient temperatures when less heat can be extracted from the surrounding air. HPWHs also do not heat water as quickly as conventional water heaters, particularly when recovering after a significant draw. To maintain performance at low ambient temperatures or during periods of high demand, HPWHs switch to less efficient electric resistance heating mode, reducing their annual efficiency by a variable amount depending on the user's behavior and needs. These two heating modes are why HPWHs are sometimes referred to as "hybrids".

Since HPWHs remove heat from the surrounding air, there are some placement restrictions compared to conventional water heaters. Ideally, HPWHs should be installed in unconditioned or semi-conditioned interior spaces, such as a basement, where temperatures remain above 50°F most of the year. If placed in a conditioned space, HPWHs will help cool the space during the summer, but will add to the heating load in the winter. If located in a confined space, such as a utility closet, HPWH cooling can reduce local air temperature and impact its efficiency.

In cold climates, HPWHs should not be placed in garages or outdoors where they will be subject to freezing. Northwest Energy Efficiency Alliance [5] has identified specific HPWH models that can operate efficiently in colder climates. These units generally have larger compressors that cut off at lower ambient temperatures.

[4] Energy Star, https://www.energystar.gov/products/water_heaters
[5] http://neea.org/initiatives/residential/heat-pump-water-heaters

Tankless Water Heaters

Tankless water heaters, also referred to as instantaneous water heaters, can use propane, natural gas or electricity to heat water without a storage tank. When water is drawn from the tap, a flow sensor activates the electric heating element or burner, which warms the heat exchanger. Incoming cold water passes through the heating element or heat exchanger and leaves the heater at the set-point temperature. By heating water only when needed instead of maintaining a tank of hot water, tankless water heaters use less energy while providing continuous hot water delivery. Condensing tankless water heaters use a secondary heat exchanger to extract more heat from the combustion process, increasing efficiency up to 0.95 EF.

One disadvantage of tankless water heaters is a slight delay in delivery of hot water compared to conventional storage water heaters. In addition, the capacity of tankless water heaters may be inadequate for large water draws, especially for electric tankless water heaters.

Hybrid Solar Water Heaters

Solar water heaters come in a wide variety of designs that use the sun's thermal energy to heat water, and generally include an electric or gas back-up water heater. Solar water heaters typically consist of a storage tank and a collector, as shown in Figure 2.[6] Thermal energy from the sun heats the fluid in the solar collectors, which can be a batch, flat plate, or evacuated tube design.

Passive solar systems use natural convection to move water from the collectors to the storage tank as it heats up. Passive systems can only be used in areas that do not require freeze protection.[7] Active or forced-circulation systems are more common, and use electric pumps, valves and controllers to move water from the collectors to the storage tank.

Direct systems circulate water through solar collectors then store the hot water in a tank or use it directly. When used in climates where freezing conditions can occur, freeze protection is needed.

For cold climates, closed-loop or indirect systems are more common, using non-freezing liquid to transfer heat from the solar collectors to water in a storage tank.

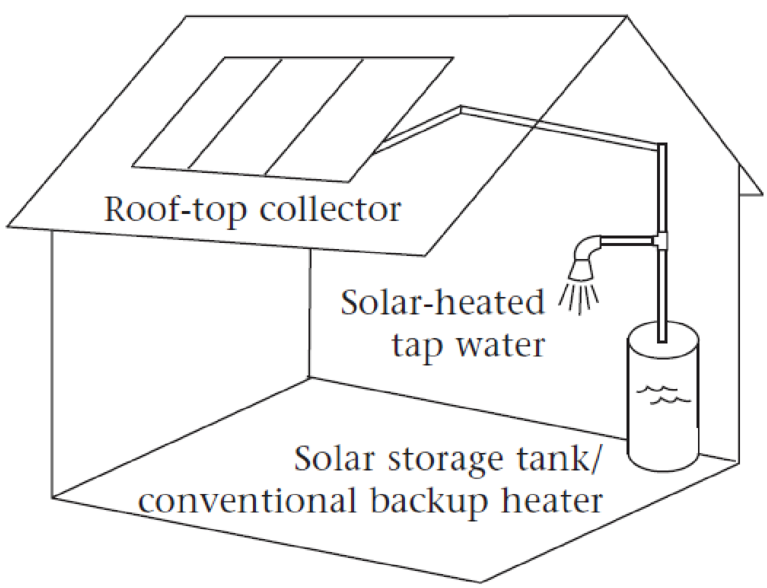

Figure 2 - Simplified representation of a solar water heating system

[6] Consumers Guide to Heating Your Water with the Sun, U.S. Department of Energy, December 2003. www.nrel.gov/docs/fy04osti/34279.pdf

[7] http://www.ases.org/solar-home-basics/solar-water-heating/

Emission Analysis

Assumptions

This analysis is based on a single detached residence with three occupants and an annual water heating load of 11.6 MMBtu. Water heater energy factors (EF) used in the analysis are based on DOE [8] and Energy Star [9] minimum ratings for residential water heater technologies, as listed in Table 1.

For solar water heaters, the solar energy factor (SEF) is defined as the energy delivered by the system divided by the electrical or gas energy input. The higher the number, the more energy efficient. Current systems have SEF ranging from 1.0 to 11; however, SEF of 2 or 3 are most common.[10] This analysis assumes the hybrid solar water heater has a SEF=3 with a propane storage tank efficiency of 0.67 EF. Solar heating systems include electrical pump and heater controller. Electric use for solar water heaters ranges from 1–23% of the total heat energy delivered (10 kWh to 180 kWh per year in total) with a median value of 5%.[11] This analysis assumes electric use is equal to 5% of total heat delivered.

Table 1 – Energy Star Minimum Efficiencies for Residential Water Heaters

	≤ 55 gallons	**> 55 gallons**
Electric Storage	EF ≥ 2.00	EF ≥ 2.20
Gas* Storage Water Heaters	EF ≥ 0.67	EF ≥ 0.77
Gas* Instantaneous Water Heaters	EF ≥ 0.90	
Solar Water Heaters	SEF ≥ 1.8 for electric backup SEF ≥ 1.2 for gas backup	

*Propane or Natural Gas

Comparison of Source Energy & Emissions

Based on this analysis, propane water heaters offer significant savings in source energy, GHG emissions, and targeted criteria pollutants compared to electric resistance water heaters.

Table 2 compares source energy use and full-fuel-cycle emissions for the selected residential water heaters compared to a baseline standard efficiency propane storage water heater. Based on eGRID 2012 plant level database, the source energy efficiency of propane delivered to residential buildings is 87%, while the average U.S. electricity mix has a source energy efficiency of 33%. Based on this analysis, propane water heaters reduce source energy up to 52% when used in place of electric resistance water heaters. The source energy use of propane water heaters is similar to natural gas water heaters and standard efficiency electric HPWHs (2.0 EF). Likewise, replacing electric water heaters with propane units will significantly lower emissions. Propane water heaters have 37% to 46% fewer GHG emissions as compared to conventional electric water heaters. Propane water heaters also generate 13% to 26%% less nitrogen oxides (NOx) emissions. Electric power generation produces significantly higher sulfur oxide (SOx) emissions compared to the direct use of propane or other fuels. Propane water heaters significantly reduce SOx emissions with respect to both electric resistance and heat pump water heaters.

Hybrid solar water heaters with a propane backup are a new option that can significantly reduce source energy use, GHG and other emissions compared to natural gas or oil conventional water heaters. Based on these assumptions, a hybrid solar system would reduce source energy use and GHG emissions to less than one-third generated by conventional storage heaters.

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[8] http://www.regulations.gov/document?D=EERE-2006-STD-0129-0005
[9] https://www.energystar.gov/products/water_heaters/residential_water_heaters_key_product_criteria
[10] http://energy.gov/energysaver/estimating-cost-and-energy-efficiency-solar-water-heater
[11] The Energy Savings Trust 2011

Table 2 – Residential Water Heater Technologies Source Energy and Emissions

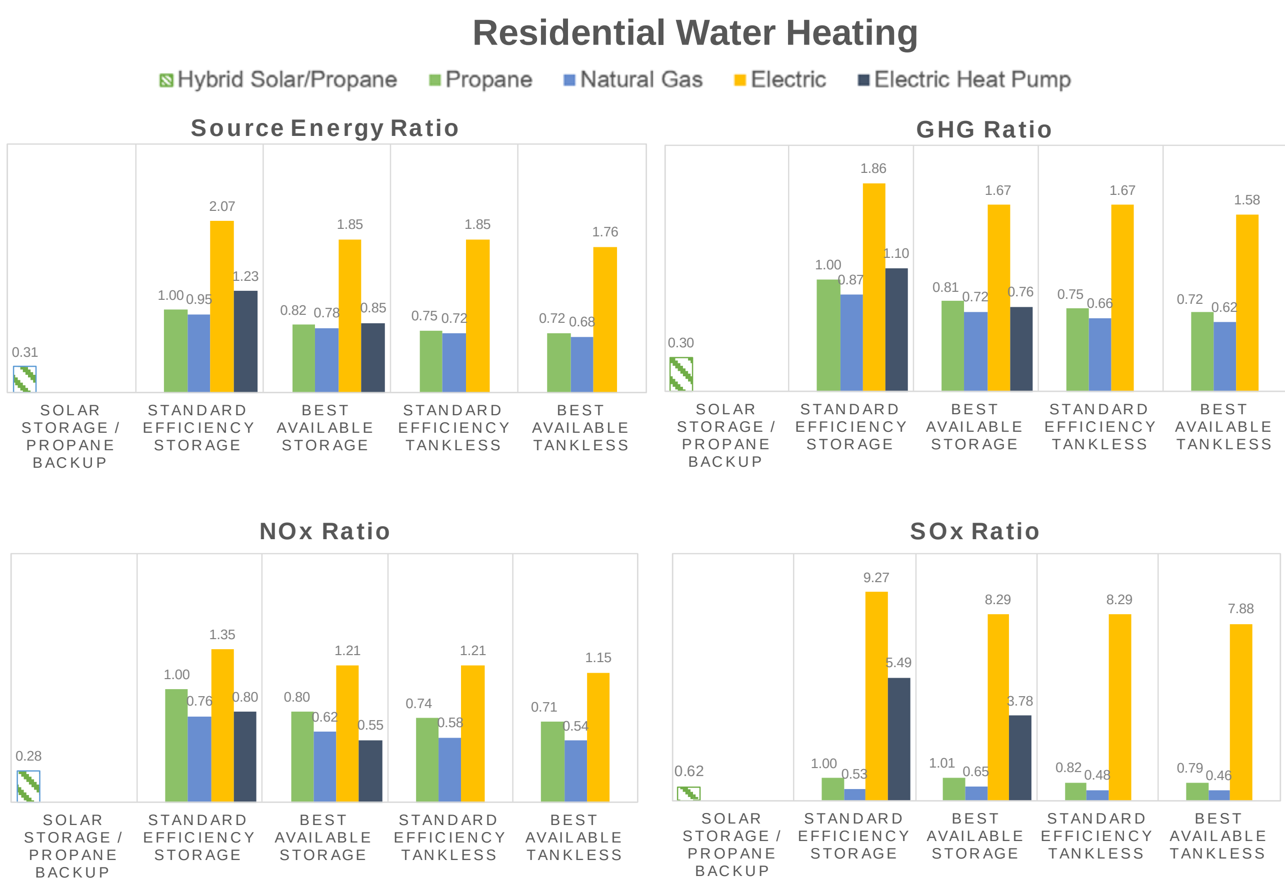
Residential Water Heating	Efficiency (EF)	Final Site (MMBtu)	Final Source (MMBtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Solar Storage / Propane Backup								
Solar Storage (SEF 3) with Propane Storage (0.67 EF)	0.67	2.9	4.1	0.31	265	0.30	0.28	0.62
Standard Efficiency Storage								
Propane Storage (0.67 EF)	0.67	11.4	13.1	1.00	879	1.00	1.00	1.00
Electric Storage (0.85 EF)	0.85	9.0	27.2	2.07	1,637	1.86	1.35	9.27
Natural Gas Storage (0.67 EF)	0.67	11.4	12.4	0.95	761	0.87	0.76	0.53
Electric Heat Pump Storage (2.0 EF)	2.00	5.3	16.1	1.23	969	1.10	0.80	5.49
Best Available Storage								
Propane Storage (0.85 EF)	0.85	9.0	10.7	0.82	715	0.81	0.80	1.01
Electric Storage (0.95 EF)	0.95	8.0	24.3	1.85	1,464	1.67	1.21	8.29
Natural Gas Storage (0.85 EF)	0.85	9.0	10.3	0.78	629	0.72	0.62	0.65
Electric Heat Pump Storage (2.90 EF)	2.90	3.7	11.1	0.85	667	0.76	0.55	3.78
Standard Efficiency Tankless								
Propane tankless (0.90 EF)	0.90	8.4	9.9	0.75	659	0.75	0.74	0.82
Electric tankless (0.95 EF)	0.95	8.0	24.3	1.85	1,464	1.67	1.21	8.29
Natural Gas tankless (0.90 EF)	0.90	8.5	9.4	0.72	576	0.66	0.58	0.48
Best Available Tankless								
Propane tankless (0.95 EF)	0.95	8.0	9.4	0.72	629	0.72	0.71	0.79
Electric tankless (1.0 EF)	1.00	7.6	23.1	1.76	1,391	1.58	1.15	7.88
Natural Gas tankless (0.95 EF)	0.95	8.0	8.9	0.68	545	0.62	0.54	0.46

Notes:

1. Energy factors for residential water heater technologies based on DOE and Energy Star; storage tanks assumed less than 55 gallons
2. Analysis assumes SEF=3 with a propane storage tank energy factor of 0.67.
3. Solar heating systems include electrical pump and heater controller

Analysis assumes electric use equal to 5% the total heat delivered. .

4. Electric tankless water heaters (EF=0.95) were assumed to consume energy similar to electric storage water heaters
5. Water heating demand for all cases was 7.63 MMBtu based on energy models for an average 3 occupants. Piping losses assumed negligible.



Residential Space Conditioning

Based on the 2007 U.S. Census,[12] propane gas is used for space heating in 5.5% of the total occupied units as shown in Table 3. Residential heating fuels are dominated by natural gas, but the market share for electricity continues to increase.

Table 3 – U.S. Residential Space Heating Market

Total Occupied Units	**110,214,000**	
Natural Gas	56,681,000	51.4%
Electricity	38,079,000	34.6%
Fuel Oil, Kerosene	9,317,000	8.5%
Propane	6,095,000	5.5%
Coal, Wood, Other	2,042,000	1.9%

Furnaces are the most commonly used residential heating system in the United States.[13] Conventional forced-air furnaces can be fueled by propane, natural gas, oil or electricity. Furnaces are typically paired with an electric air conditioner. Natural gas and propane furnaces are identical except for orifice changes and other minor differences.

Heat pumps provide both heating and cooling for a home. An air-source heat pump (ASHP) operates like a reversible split-system air conditioner. In cooling mode, it moves heat from inside the home to the outdoor condensing coil. In heating mode, it extracts heat from the outdoor air, transferring that heat to an indoor fan coil. Electric ASHPs are more commonly used in mild climates, and often require a backup heat source in colder climates, which can be either electric resistance or fuel-fired.

Residential gas-fired heat pumps are not common in the U.S., but recent developments may lead to significant improvements in performance and/or economics. Two prototype gas-fired heat pump technologies will be included in this analysis for comparison. Gas heat pumps, both absorption and engine-driven, have higher heating efficiencies than the best available furnaces or boilers.

The following space conditioning technologies will be considered in this emissions analysis:

- Forced-air furnaces
- Electric air source heat pumps (ASHP)
- Gas-fired heat pumps (GEHP, GAHP)

Conventional Furnaces

Furnace efficiency is designated by the Annual Fuel Utilization Efficiency rating (AFUE) which represents the ratio of annual heat delivered to annual fuel consumption. The furnace AFUE rating applies only to the furnace and does not include any heat losses from the duct system, which can be significant if uninsulated and located in unconditioned spaces such as an attic or garage. For conventional furnaces fueled by propane, natural gas or oil, most of the energy loss is due to the exhaust of

Figure 3 – Amana 96% AFUE Gas/Propane Furnace
(Source: www.buildwithpropane.com)

[12] U.S. Census Bureau, Fuels – Occupied Units (American Housing Survey for the US: 2007)
[13] https://www.energystar.gov/ia/partners/publications/pubdocs/HeatingCoolingGuide%20FINAL_9-4-09.pdf?1be3-faf8

combustion gases. The current U.S. Department of Energy national efficiency standard for furnaces is 80% AFUE. Non-condensing furnace manufacturers limit their offerings to efficiencies at or near 80% AFUE to avoid venting condensation issues.

Condensing furnaces use a secondary heat exchanger that extracts more heat from the combustion gas, with resulting heating efficiency from 90% up to 98.5% AFUE. Special venting systems, including freeze protection in attic installations, and condensate disposal approaches are needed to handle the mildly acidic condensing flue gases.

Electric furnaces utilize electric resistance heat and do not have flue losses, resulting in an efficiency near 100% AFUE for indoor installations. This efficiency can be misleading since it only includes the energy consumed at the site, but does not consider source energy, which takes into account the significant conversion losses upstream at the power generating stations. Considering a national average source energy efficiency of 33% for electricity, electric resistance heating has poor source energy performance compared to 80% AFUE fuel-fired furnaces, and is likely to have poor emissions performance as well.

Energy Star Criteria for Furnaces

Energy Star criteria [14] for residential furnaces is based on geographic regions shown below in Table 4. The furnace is defined as a "heating unit with a heat input rate of less than 225,000 Btu per hour whose function is the combustion of fossil fuel (natural gas, propane, or oil) for space heating with forced hot air. Unit must include burner(s), heat exchanger(s), blower(s) and connections to heating ducts". Electric furnaces do not qualify for an Energy Star rating.

Table 4 – Energy Star Criteria for Residential Furnaces

Equipment	Specification
Gas* Furnaces	Rating of 90% AFUE or greater for U.S. South gas furnaces
	Rating of 95% AFUE or greater for U.S. North gas furnaces
Oil Furnaces	Rating of 85% AFUE or greater
Gas) and Oil Furnaces	Less than or equal to 2.0% furnace fan efficiency
	Less than or equal to 2.0% air leakage

*Propane or Natural Gas

Air Source Heat Pumps

Electric ASHPs are typically used in moderate climates, but there is a growing demand for heat pumps in colder climates. ASHP efficiency and capacity is reduced at lower ambient temperatures when less heat can be extracted from the surrounding air. To maintain performance at low ambient temperatures, ASHPs may switch to a less efficient electric resistance heating mode. In colder climates, electric ASHP can also be pared with a propane or gas-fired backup heater. It can also be configured to operate with the existing propane or gas furnace, which operates when the ASHP cannot efficiently deliver the required heating capacity. In this approach, the heat pump operates during the summer and shoulder seasons, then switches to the furnace operation at ambient temperatures below a given threshold.

The heating efficiency rating for ASHPs is the Heating Seasonal Performance Factor (HSPF), which represents the annual space heating required in Btu, divided by the total electrical energy consumed in watt-hours. ASHP cooling ratings include both a Seasonal Energy Efficiency Ratio (SEER) and Energy Efficiency Ratio (EER). SEER represents the total heat removed during the annual cooling season, in Btu, divided by the total electrical energy consumed, in watt-hours. EER is based on a given operating point and is equal to the ratio of the average cooling rate delivered, to the average rate of electricity consumed,

[14] https://www.energystar.gov/products/heating_cooling/furnaces/key_product_criteria

expressed in Btu per watt-hour. The performance of existing ASHPs can range from 10 SEER/7.2 HSPF, up to the best available units with 20.5 SEER/13 HSPF. Energy Star qualified ASHPs have minimum SEER and HSPF ratings as shown in Table 5.

Table 5 – Energy Star Criteria for Air-Source Heat Pumps [15]

Equipment	Specification
Air-Source Heat Pumps	≥ 8.5 HSPF/ ≥15 SEER/ ≥12.5 EER* for split systems ≥ 8.2 HSPF ≥15 SEER/ ≥12 EER* for single package equipment including gas/electric package units.

Gas-fired Engine-driven Heat Pumps

The gas-fired engine-drive heat pump (GEHP) design is similar to an electric air source heat pump, but utilizes an advanced natural gas or propane engine in place of an electric motor. Variable-speed engine controls allow the GEHP to more closely follow the load and maintain efficiency. GEHPs provide high efficiency heating and cooling, reducing operating costs compared to conventional HVAC equipment. During cooling, GEHPs consume natural gas in place of electricity and significantly reduce peak electric demand in comparison to electric air conditioners or heat pumps. During heating, GEHPs are more efficient than the best available gas furnaces or boilers. In addition to extracting heat from the surrounding air, GEHPs also recover heat from the engine cooling jacket and exhaust to supplement the heat output, increasing the overall system efficiency. Engine heat recovery allows GEHPs to maintain heating capacity and deliver a higher supply temperature at low ambient conditions, when heating demand is the greatest. In contrast, electric heat pumps require inefficient resistance heating to supplement the heat pump output at low outdoor temperatures.

GEHPs for commercial space conditioning have an established market share in Asia and Europe, but only recently were available in the U.S. IntelliChoice Energy's GEHP was first introduced in 2009, and currently over 500 units are installed in commercial buildings. A second manufacturer, Yanmar, introduced its GEHP product line to the U.S. market for commercial applications in January 2016.

A residential gas-fired engine-drive heat pump (RGHP) was recently developed by Southwest Gas in partnership with IntelliChoice Energy, U.S. Department of Energy, U.S. Department of Defense, ORNL, Marathon, and the Propane Education & Research Council. Ongoing development is focused on performance improvements and reducing equipment and manufacturing costs.

Preliminary specifications for the RGHP are shown in Table 6. The RGHP is a single zone split-system specifically designed for residential service. The design was developed to operate on natural gas or propane. The RGHP supplies 3 to 5 tons cooling and 75 MBH heating. The unit can also supply up to 40,000 Btu/hr domestic hot water. During performance testing, measured COPs ranged from 1.0 to 1.8 across the range of test conditions.

[15] https://www.energystar.gov/products/heating_cooling/heat_pumps_air_source/key_product_criteria

Figure 4 – IntelliChoice Energy's RGHP Gas Engine-driven Heat Pump

Table 6 – RGHP Performance Specifications

RGHP Rated Specifications	Cooling	Heating
Dry Bulb °F	95	47
Wet Bulb °F	75	65
Engine Speed RPM	2800	3200
Blower SCFM	2024	2134
Return Temp °F	79.9	70.0
Supply Temp °F	61.5	100.9
Fuel Flow Btu/hr	48,997	57,769
Air Side Capacity Btu/Hr	53,119	66,888
Air Side Capacity (ton)	4.43	

Gas-fired Absorption Heat Pumps

Gas-fired absorption heat pump (GAHP) technology is similar to the conventional vapor compression refrigeration cycle, but uses a heat engine or "thermal compressor" in place of mechanical compression. Gas absorption heat pumps can be driven by waste heat (including solar-thermal), but most often are direct-fired with natural gas or propane.

The absorption process relies on the affinity of two liquids for each other to achieve the temperatures and pressures required. Most residential GAHPs use an ammonia/water solution, an environmentally benign refrigerant, eliminating the chlorofluorocarbons (CFCs) with high ozone depletion and global warming potential that are often used in mechanical systems.

GAHPs are well suited for zoned applications and some can provide domestic hot water in addition to space heating. As an air source heat pump, GAHPs extract heat from the surrounding air resulting in higher heating efficiencies than the best available furnaces or boilers. Recent developments have focused on optimizing the GAHP heating performance, rather than the relatively low-efficiency cooling performance (0.7 COP). This indicates a shift in target markets to heating-only applications instead of combined heating and cooling.

In the U.S., GAHPs are more commonly used in commercial and industrial applications to recover waste heat, but recent product developments are targeting the residential market. Only a single commercial GAHP product from Robur has been available in the U.S. over the past decade. Worldwide, thousands of Robur units are sold annually, although very few in the U.S.

GTI is currently working with Stone Mountain Technologies (SMTI) to develop an economical 80,000 Btu/hr GAHP. The GAHP can integrate directly with a hydronic heating system, such as in-floor radiant heating, or can be used with a hydronic air coil for a forced-air heat distribution system. Expected performance for the GAHP is 140% AFUE.

Emission Analysis

Assumptions

This analysis is based on a single detached residence with three occupants and an annual heating load of 51.2 MMBtu, based on the average propane use for heating as reported by Residential Energy Consumption Survey, U.S. Energy Information Administration (EIA 2013)[16]. Energy consumption and emission calculations include an Energy Star SEER 16 electric air conditioner and HVAC blower to allow heat pump technologies to be compared directly to heating-only technologies. Duct losses were assumed consistent between different technologies, and were not included in these calculations.

Air-source heat pump efficiency can vary significantly with climate. This analysis is based on ambient temperature profiles for ASHRAE Climate Zone 4, specifically Nashville, TN. The hybrid ASHP configuration assumes an electric Energy Star ASHP (8.6 HSPF) serves 40% of heating load, representing the shoulder heating seasons, while the propane furnace backup system provides the remaining 60%, with proportional energy use. This assumption based on residential heating systems analysis by Newport Partners, 2013. [17]

GAHP efficiency of 140% AFUE is based on laboratory testing of a prototype unit with natural gas. RGHP energy and emission analysis is based on ETL certified performance specifications, provided by IntelliChoice Energy. This data assumed similar performance for propane as natural gas. The RGHP emission calculations only include upstream full-fuel-cycle emissions. Engine emissions were excluded due to lack of measured data.

Comparison of Source Energy & Emissions

This comparison shows propane furnaces can offer significant environmental benefits compared to other conventional furnaces. As shown in Table 7, propane furnace reduces source energy and GHG emissions by more than 50% compared to electric furnaces. In addition, the propane furnace has 35% lower NOx emissions and less than one-fifth SOx emissions. Compared to oil furnaces, propane furnace reduces source energy with 13% fewer GHG emissions and almost one-fifth NOx emissions.

Compared to standard electric heat pumps (10 SEER/7.2 HSPF), high efficiency propane furnaces (96% AFUE), paired with a comparable air conditioner, has 22% lower source energy use, 16% fewer GHG emissions, with less than half the level of SOx emissions. Compared to Energy Star electric heat pumps, high efficiency propane furnaces (96% AFUE) has 15% lower source energy use, 8% fewer GHG emissions, with less than one-third SOx emissions.

A hybrid configuration of a residential Energy Star electric ASHP with a propane backup furnace not only improves comfort, but also reduces both source energy use and GHG emissions by 9% and 5%, respectively compared to the ASHP alone. This configuration also reduces SOx emissions by 40%.

New technology developments in gas-fired heat pumps show some potential benefits for residential space heating. The GAHP, based on the current prototype specifications, would reduce source energy and GHG emissions by approximately 27% compared with a high efficiency propane furnace, and reduces NOx and SOx emissions by 32% and 8%, respectively.

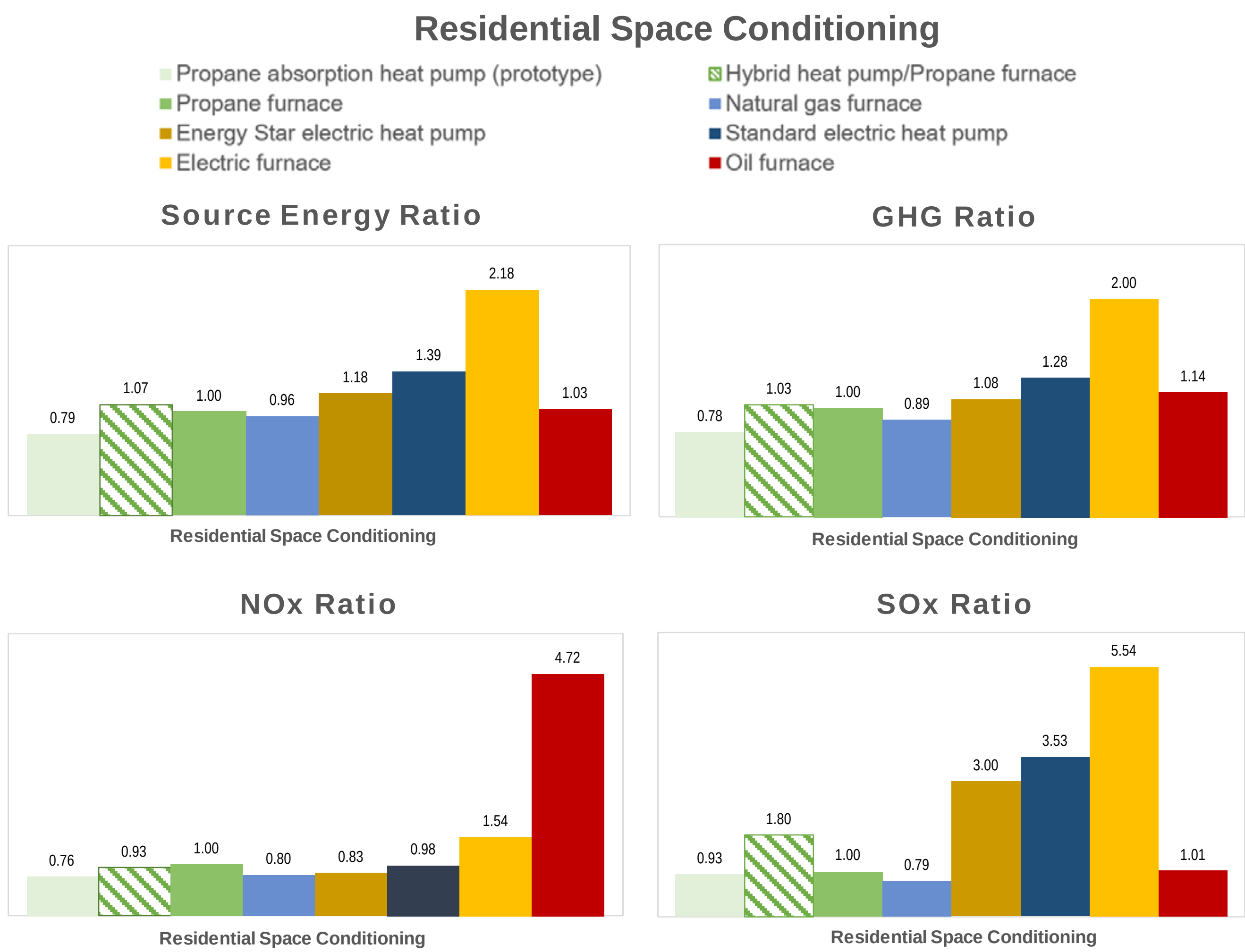
[16] Nexight, 2014.
[17] ibid.

Table 7 – Space Conditioning Technologies Source Energy and Emissions

Residential Space Conditioning	Efficiency	Final Site (MMbtu)	Final Source (MMbtu)	Source Energy Ratio	Total CO2e (kg)	Source Energy Ratio	GHG Ratio	NOx Ratio	SOx Ratio
Energy Star electric heat pump (16 SEER)	8.60 HSPF	30	91	1.18	5,501	1.18	1.08	0.83	3.00
Standard electric heat pump (10 SEER)	7.20 HSPF	36	108	1.39	6,489	1.39	1.28	0.98	3.53
Elec ASHP w propane backup	1.23 COP	47	83	1.07	5,250	1.07	1.03	0.93	1.80
Propane absorption heat pump (prototype)	1.40 COP	43	61	0.79	3,960	0.79	0.78	0.76	0.93
Propane furnace	0.96 AFUE	58	78	1.00	5,083	1.00	1.00	1.00	1.00
Oil furnace	0.96 AFUE	58	80	1.03	5,818	1.03	1.14	4.72	1.01
Electric furnace	1.00 AFUE	56	169	2.18	10,166	2.18	2.00	1.54	5.54
Natural Gas furnace	0.96 AFUE	58	75	0.96	4,547	0.96	0.89	0.80	0.79

Notes:

1. Energy use based on average 51.2 MMBtu annual heating load [Nexight, 2014]; includes HVAC blower energy and SEER 13 A/C;
2. ASHP efficiency can vary significantly with climate. This analysis is based on ASHRAE Climate Zone 4 temperature profiles (Nashville, TN).
3. Hybrid configuration assumes Energy Star electric ASHP serves 40% of heating load; propane furnace provides 60% with proportional energy use. This assumption based on published analysis of residential heating systems by Newport Partners, 2013. [Nexight 2104]
4. GAHP performance specifications based on prototype laboratory data.



Residential Gas Appliances

Customer Preference

A number of recent articles highlight consumers' preference for gas appliances, including stoves and dryers, instead of electric appliances.[18] Although gas dryers and stove/ovens typically have higher first costs, consumers prefer gas appliances because they typically cost less to operate and offer better performance in terms of temperature control. Consumer Energy Center, operated by the California Energy Commission, summarizes the advantages of gas dryers, in addition lower operating costs:

> *Electric dryers use heating coils, while gas dryers use a gas burner to produce heat…Gas dryers tend to operate at a hotter temperature than electric ones, so clothes can tumble in the dryer for shorter periods, sparing the material and reducing energy costs.* [19]

Similarly, gas ovens and cooktops tend to have higher first costs than electric units, but usually cost less to operate. Aside from the cost benefits, a CNBC report highlights performance as a key factor in the preference for gas stove/ovens.

> *In the kitchen, there's some evidence the switch isn't entirely cost-related...Gas tends to be the preferred cooking method, for its fine degree of control….* [20]

Emission Analysis

Assumptions

This analysis is based on a single detached residence with three occupants. The standard minimum efficiency was used for both clothes dryers and stove/cooktops. Electricity source energy and emissions are based on the average U.S. baseload generation mix.

Comparison of Source Energy & Emissions

Both propane clothes dryers and cooking ranges have lower source energy use and emissions compared to electric appliances as shown in Table 8. Propane production and delivery is much more efficient than grid-delivered electricity, which is still fossil fuel-intensive with large energy losses at the power plant and though transmission lines. The full-fuel-cycle or source energy efficiency of propane delivered to residential buildings is 87%, while the average U.S. electricity mix has a source energy efficiency of 33%.

Based on this analysis, propane dryers have substantial source energy and emission benefits. Electric dryers use 47% more source energy than propane dryers. Electric dryers also generate 42% more full-fuel-cycle greenhouse gases, 23% NOx emissions, and over 5 times more SOx emissions.

Propane cooking ranges offer similar benefits compared to electric appliances, but to a lesser degree. Electric cooking ranges use 24% more source energy than propane appliances, and generate 16% more full-fuel-cycle greenhouse gases, and almost 6 times more SOx emissions.

[18] Fidlin, D., "Electric vs. Gas Appliances: Which is the Best Choice for Your Wallet and the Environment?" Recycle Nation, April 02, 2015 http://recyclenation.com/2015/04/electric-vs-gas-appliances-which-is-best-choice-for-your-wallet-and-environment-#sthash.EK0oeomI.dpuf

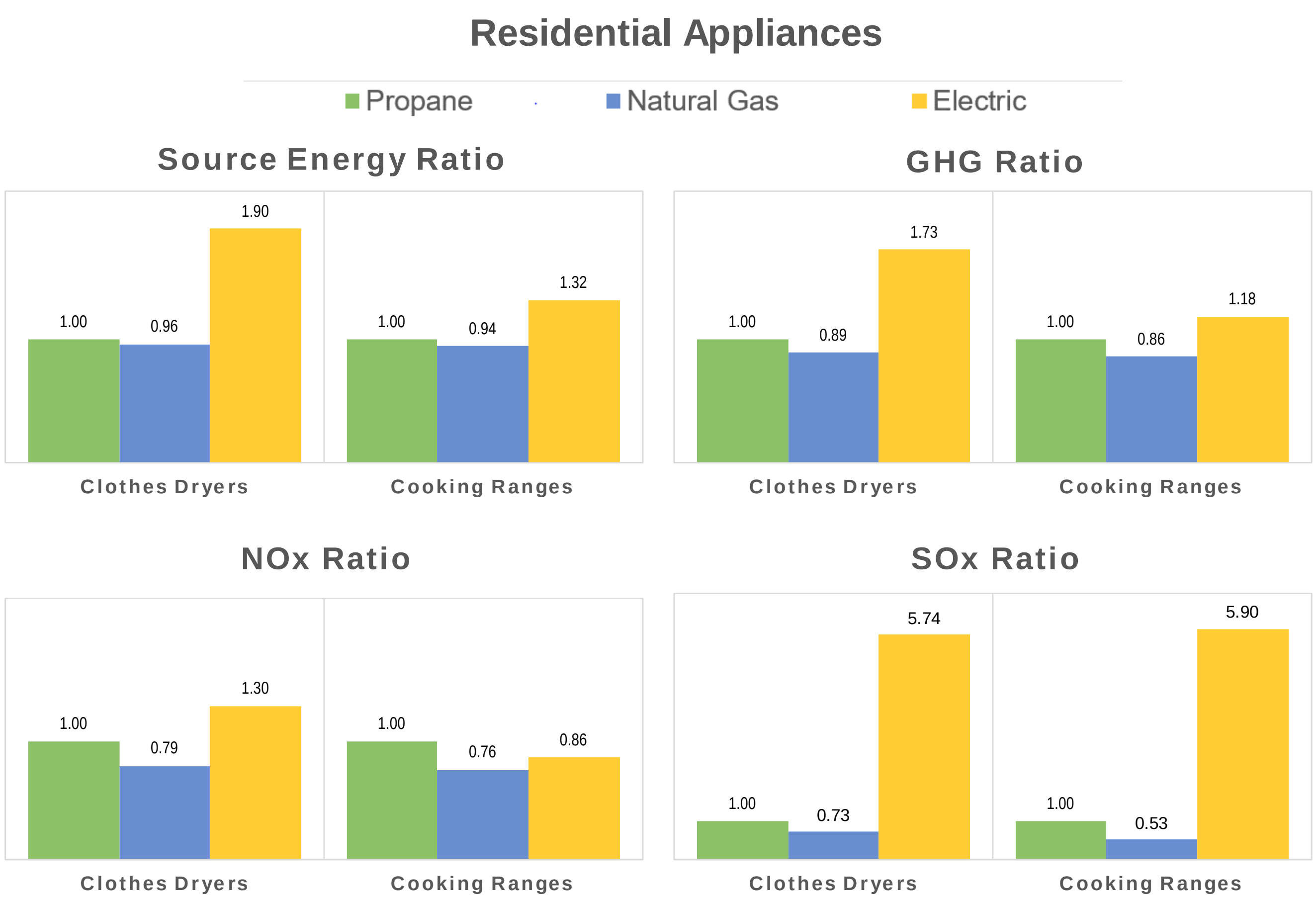
[19] Residential Clothes Dryers, Consumer Energy Center, California Energy Commission, accessed 11/22/2016. http://www.consumerenergycenter.org/residential/appliances/dryers.html

[20] Grant, K.B., "Switching to Gas From Electric Could Cut Energy Bills, CNBC Person Finance", Jun 27, 2013, http://www.cnbc.com/id/100846610

Table 8 – Residential Appliances Source Energy and Emissions

Residential Appliances	Final Site (MMbtu)	Final Source (MMbtu)	Total NOx (kg)	Total CO2e (kg)	Source Energy Ratio	GHG Ratio	NOx Ratio	SOx Ratio
Clothes Dryers								
Propane (EF 2.75)	3.77	4.74	0.40	313	1.00	1.00	1.00	1.00
Electric (EF 3.10)	2.97	8.99	0.52	541	1.90	1.73	1.30	5.74
Natural Gas (EF 2.75)	3.81	4.58	0.32	279	0.96	0.89	0.79	0.73
Cooking Ranges								
Propane	4.12	4.73	0.42	317	1.00	1.00	1.00	1.00
Electric	2.06	6.24	0.36	376	1.32	1.18	0.86	5.90
Natural Gas	4.10	4.47	0.32	274	0.94	0.86	0.76	0.53

Notes:
1. Annual fuel use for clothes dryers and cooking ranges based on GTI's Carbon Management Information Center SEEAT (http://seeatcalcbeta.gastechnology.org/HelpPages/EFHelp.htm) accessed December 2016.



Commercial Water Heating

Technologies for commercial water heating are similar to those for residential applications. As defined in the Department of Energy Code of Federal Regulations (CFR), commercial water have an input rating equal or greater than 4,000 Btu/h per gallon of stored water. In addition, hot water supply boilers are packaged boilers that heat potable water for purposes other than space heating.[21]

Types of Water Heaters

This analysis includes four types of residential water heaters:

- Conventional storage water heaters
- Instantaneous or tankless water heaters
- Heat pump water heaters
- Hybrid solar water heaters

Energy Star certified commercial water heaters include gas storage and tankless units that use 25 percent less energy than a conventional commercial unit by employing more efficient heat exchangers. Currently, the Energy Star label does not include any electric water heaters, but will be available for electric commercial heat pump water heaters in the future.[22]

Conventional Storage Water Heaters

Storage water heaters can be fueled by propane, natural gas, oil, or electric resistance heat. Storage water heaters use a glass-lined steel tank heated by an electric resistance element or burner at the bottom of the tank. Condensing water heaters use a secondary heat exchanger that extracts more heat from the combustion gas, increasing heating efficiency up to 0.95 EF.

Tankless Water Heaters

Tankless water heaters use propane, natural gas or electricity to heat water without a storage tank. When water is drawn from the tap, a flow sensor activates the burner or electric heating element, which warms the heat exchanger. Incoming cold water passes through the heat exchanger and leaves the heater at the set-point temperature. By heating water only when needed instead of maintaining a tank of hot water, tankless water heaters use less energy while providing continuous hot water delivery. Condensing tankless water heaters use a secondary heat exchanger to extract more heat from the combustion process, increasing efficiency up to 0.95 EF.

Heat Pump Water Heaters

Electric heat pump water heaters (HPWH) employ a heat pump, which operates like an air conditioner in reverse, to extract heat from the surrounding air and transfer the heat to water in the storage tank. (Figure 5) HPWHs produce exhaust air that is cool and dry.

[21]"Commercial Water Heating Equipment", Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, accessed 11/22/2016. https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=36&action=viewlive

[22] Energy Star, Commercial Water Heaters, accessed 11/22/2016. https://www.energystar.gov/products/water_heaters/commercial_water_heaters

HPWHs should be installed in unconditioned or semi-conditioned interior spaces, where temperatures remain above 50°F. If placed in a conditioned space, HPWHs will help cool the space during the summer, but will add to the heating load in the winter.

HPWHs do not heat water as quickly as conventional water heaters, particularly when recovering after a significant draw. To maintain performance, HPWHs may switch to a less efficient electric resistance heating mode.

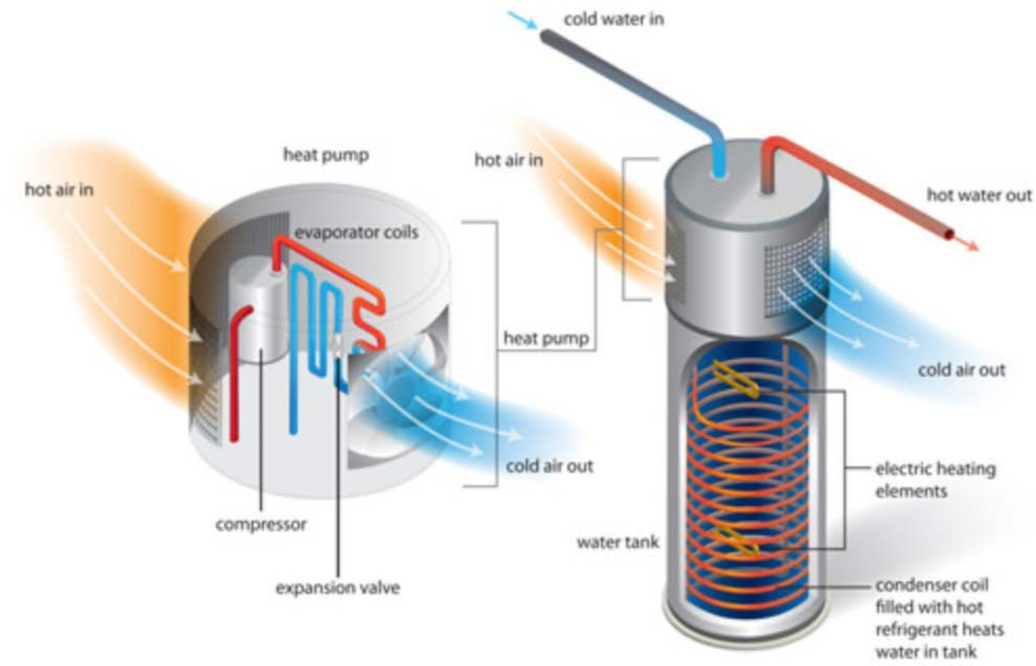


Figure 5 – Energy Star How it Works: Heat Pump Water Heaters (HPWHs)

Propane Engine-driven Heat Pump Water Heaters

The Ilios[23] is a gaseous engine-driven, air-source heat pump water heater from Ilios Dynamics, a subsidiary of Tecogen. The modular unit captures and repurposes waste heat with a 1.2 to 1.8 COP, offering up to twice the efficiency of a conventional gas-fired boiler. This water heater produces 400,000 to 600,000 Btu/hr of hot water for domestic, commercial, and industrial facilities, and it is scalable to serve thermal loads with a gas demand of 4,000 therms per month or more. Water is delivered between 100°F - 160°F at a rate of 50 gpm. The Ilios High Efficiency Water Heater uses a proprietary advanced emission control system and reports ultra-low emissions with near zero criteria pollutants.

A heat pump takes low temperature energy from the environment and with the mechanical work of a compressor, pumps this heat to higher temperature using a standard vapor compression refrigeration cycle. Heat exchangers are used to extract energy from the ambient source and deliver it to the warmed media. While heat pumps can be configured many different ways, in the case of the Ilios, the ambient source is the outdoor air and the warmed media is the domestic or service hot water. While in a conventional heat pump, the compressor is driven by an electric motor, the Ilios uses a gas-fired engine to provide the shaft power, and the refrigeration cycle is supplemented with engine waste heat for added efficiency.

[23] Ilios Dynamics website, www.iliosdynamics.com

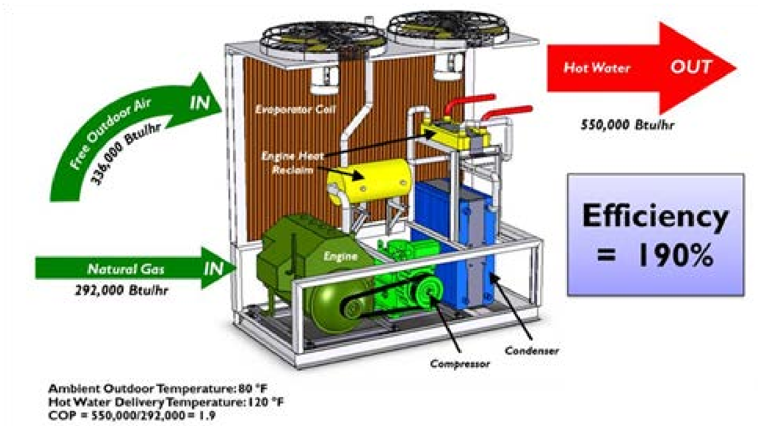


Figure 6 – Ilios High Efficiency Water Heater Visual, Furnished by Ilios Dynamics

New Technology Developments

New developments in gas absorption heat pump water heaters have potential to supply high temperature water up to 160°F at average efficiencies of to 140% AFUE. This design is based on ammonia/water absorption pair, similar to the commercially available Robur unit available for residential space heating/cooling and heating only applications. Current developments by GTI and Stone Mountain Technologies, Inc. are focused on a lower cost option with heating capacities up to 140,000 Btu/hr for residential space heating and small commercial water heating applications. While this prototype has been successfully demonstrated in laboratory settings and field demonstrations in different climates, technical and marketing challenges are still being addressed.

Emission Analysis

Assumptions

This analysis is based on a building energy model for a 2000 s.f. fast food restaurant, Nashville TN, selected from available options [24] with the delivered energy (41 MMBtu) similar to CBECS 2003 average for water heating [Nexight 2014]. Energy use for electric heat pump heaters was extrapolated from residential HPWH data. Energy use for the propane HPWH (Ilios) assumed an average gas COP=1.20 and electric use equivalent to best propane tankless water heater.

Comparison of Source Energy & Emissions

Table 9 compares source energy use and full-fuel-cycle emissions for commercial water heating equipment. Standard efficiency propane and natural gas water heaters use about 46% less source energy than electric resistance water heaters. This reflects the higher full-fuel-cycle efficiency of propane and natural gas compared to the average U.S. electricity mix with a source energy efficiency of 33%. The propane heat pump water (Ilios) heater was the lowest source energy option. Newly developed absorption HPWH, which can be fueled by propane or natural gas, is expected to offer similar source energy efficiencies.

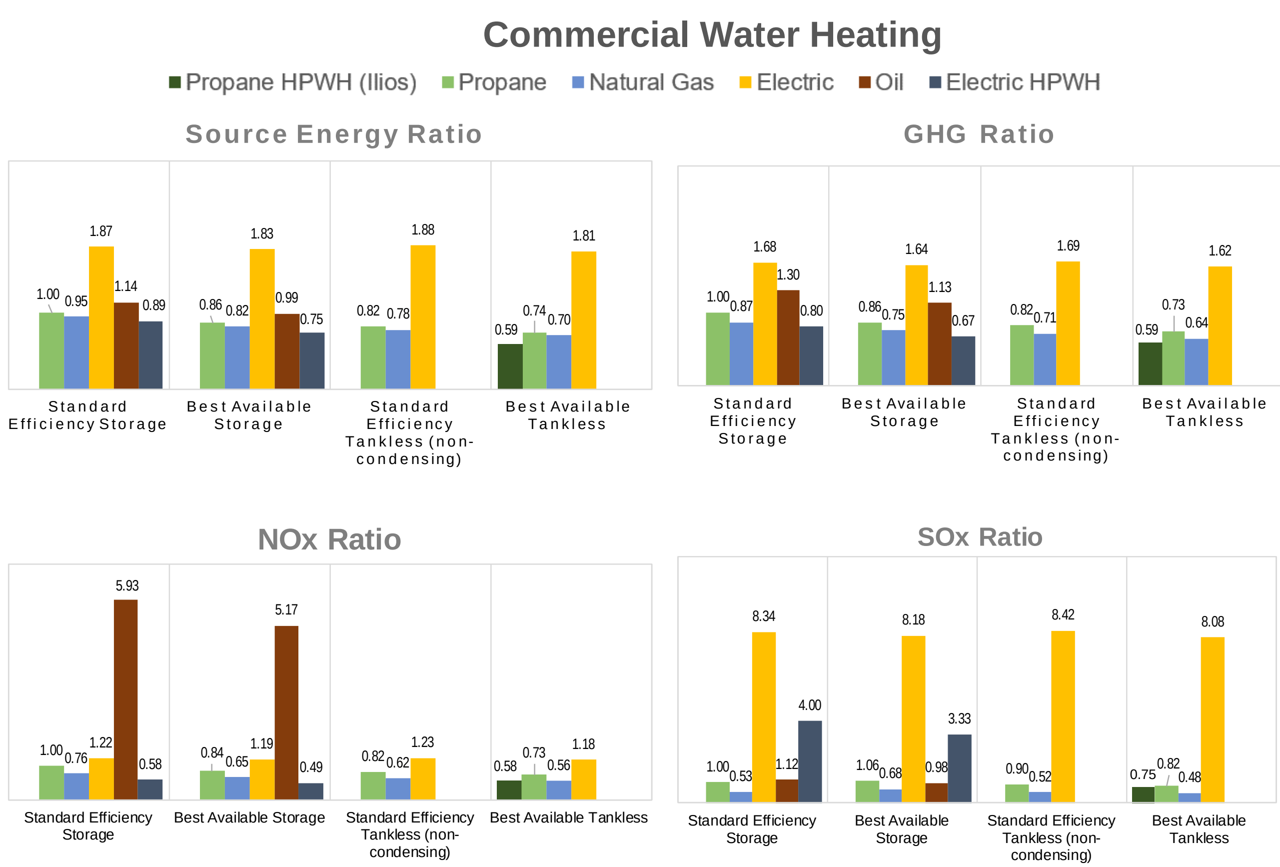
Likewise, high efficiency propane water heaters reduce GHG emissions by about 40% compard to conventional electric water heaters. Propane water heaters also reduce GHG emissions by up to 23% compared to oil water heaters. In addition, propane water heaters produce considerably lower nitrogen oxides (NOx) emissions than oil heaters and significantly lower sulfur oxide (SOx) emissions than either electric heaters or electric HPWHs.

[24] Source Energy and Emission Analysis Tool, © 2016 Gas Technology Institute - Version 7.1.

Table 9 – Commercial Water Heater Technologies Source Energy and Emissions

Commercial Water Heating	Efficiency (EF)	Final Site (MMbtu)	Final Source (MMbtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Standard Efficiency Storage								
Propane Storage (0.86 EF)	0.86	59	68	1.00	4,549	1.00	1.00	1.00
Electric Storage (0.98 EF)	0.98	42	127	1.87	7,628	1.68	1.22	8.34
Natural Gas Storage (0.86 EF)	0.86	59	64	0.95	3,938	0.87	0.76	0.53
Fuel Oil Storage (0.78 EF)	0.78	65	77	1.14	5,900	1.30	5.93	1.12
Electric Heat Pump (HPWH) (2.0 EF)	2.00	20	61	0.89	3,656	0.80	0.58	4.00
Best Available Storage								
Propane Storage (0.95 EF)	0.95	49	59	0.86	3,904	0.86	0.84	1.06
Electric Storage (1.0 EF)	1.00	41	124	1.83	7,475	1.64	1.19	8.18
Natural Gas Storage (0.95 EF)	0.95	49	56	0.82	3,412	0.75	0.65	0.68
Fuel Oil Storage (0.82 EF)	0.82	57	67	0.99	5,138	1.13	5.17	0.98
Electric Heat Pump (HPWH) (2.40 EF)	2.40	17	51	0.75	3,047	0.67	0.49	3.33
Standard Efficiency Tankless (non-condensing)								
Propane tankless (0.85 EF)	0.85	48	56	0.82	3,732	0.82	0.82	0.90
Electric tankless (0.95 EF)	0.95	42	128	1.88	7,697	1.69	1.23	8.42
Natural Gas tankless (0.85 EF)	0.85	48	53	0.78	3,238	0.71	0.62	0.52
Best Available Tankless								
Propane Heat Pump (HPWH) (1.20 EF)	1.20	33	40	0.59	2,680	0.59	0.58	0.75
Propane tankless (0.95 EF)	0.95	43	50	0.74	3,343	0.73	0.73	0.82
Electric tankless (0.99 EF)	0.99	41	123	1.81	7,386	1.62	1.18	8.08
Natural Gas tankless (0.95 EF)	0.95	43	47	0.70	2,906	0.64	0.56	0.48

Notes:
1. Water heater energy use based on building energy model for 2000 s.f. Fast Food Restaurant, Nashville TN, selected from available SEEAT options with delivered energy (41 MMBtu) similar to CBECS 2003 average for water heating
2. Electric heat pump water heaters energy use extrapolated from residential models
3. Propane heat pump water heater assumed average COP=1.20 (Ilios) and electric use equivalent to best propane tankless



Commercial Space Conditioning

Packaged rooftop HVAC units (RTUs) are used in 40% of conditioned commercial floor space in the U.S. RTU typically combine gas furnace and electric air conditioner or a packaged heat pump. Furnace technology for commercial application is similar to residential designs. However, high efficiency condensing furnaces which are well established in the residential market have only recently been introduced in RTUs. Condensing RTUs have been slow to gain market acceptance due to some economic and technical challenges. RTUs are often selected as the lowest first cost option.

For commercial applications, electric air-source heat pumps (ASHP) are available in rooftop packages, as well as variable refrigerant flow (VRF) systems which provide zoned heating and cooling. VRF is a growing market especially in office buildings and schools. Gas engine-driven heat pumps with VRF configurations were recently introduced in the U.S and can operate using natural gas or propane. IntelliChoice Energy's NextAire product was introduced in 2009, and currently over 500 units are installed in commercial buildings. Yanmar entered the market in January 2016.

The following space conditioning technologies will be considered in this emissions analysis:

- Forced-air furnace
- Electric air source heat pump (ASHP)
- Gas Engine-driven heat pump (GEHP)

Emission Analysis

Assumptions

This analysis is based on a building energy model for a 2000 s.f. fast food restaurant in ASHRAE Zone IV (Nashville TN), selected from the available SEEAT commercial building options.[25] This building has an annual heating load of 420 MMBtu and a cooling load of 413 MMBtu.

Energy consumption and emission calculations include an electric DX air conditioner (EER 13) and HVAC blower to allow heat pump technologies to be compared directly to heating-only technologies. Duct losses were assumed consistent between different technologies, and were not included in these calculations.

ASHP performance varies significantly with climate. This analysis is based on ambient temperature profiles for ASHRAE Climate Zone 4. The hybrid ASHP configuration with a propane furnace backup assumes an electric ASHP (8.4 HSPF) serves 40% of heating load, representing the shoulder heating seasons, while the propane furnace backup system provides the remaining 60%, with proportional energy use.

Average annual efficiency (1.2 COP) of the gas engine-driven heat pump is based on field data from the NextAire 15 ton unit monitored in three different applications and climates. VRF fan coils typically heat or cool the space without adding any outside air ventilation. Required outside air ventilation can be ducted directly to the FCU, but it is more common for the VRF system to be paired with a Dedicated Outdoor Air System (DOAS) to provide ventilation to each zone and condition the outside air to be delivered at space neutral conditions. Electric energy use is estimated for the DOAS is based on an unpublished modeling study. This analysis assumes similar performance for propane as natural gas. Emission calculations only include upstream full-fuel-cycle emissions due to lack of measured emission data for the GEHP.

[25] Source Energy and Emission Analysis Tool, © 2016 Gas Technology Institute - Version 7.1.

Comparison of Source Energy & Emissions for Conventional Space Conditioning

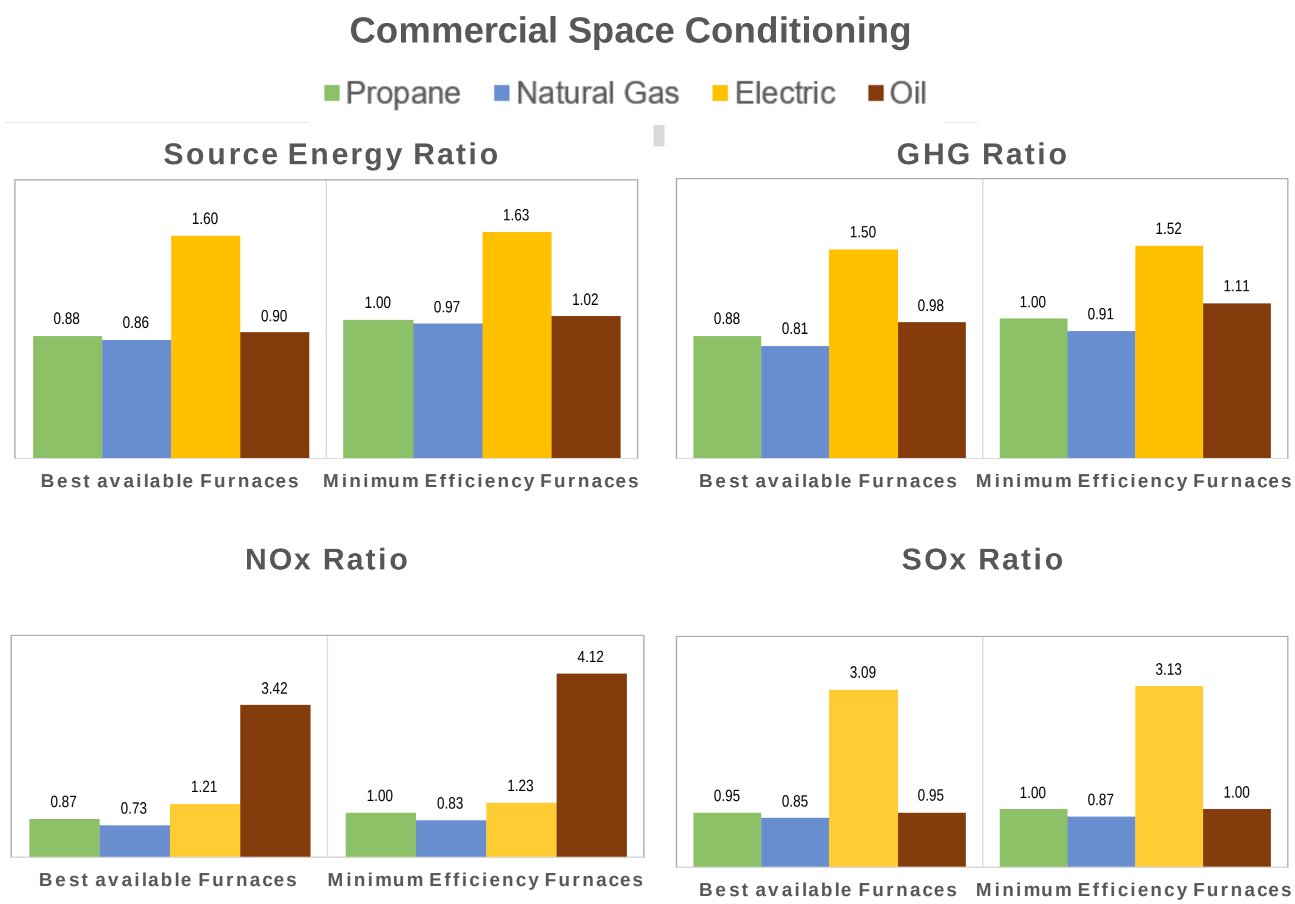
As shown in Table 10, propane commercial furnace reduce source energy by up to 39% and GHG emissions by 34% compared to electric furnaces. In addition, the propane furnace has 18% fewer NOx emissions and less than one-third SOx emissions.

For the commercial furnaces, propane technology has about 10% lower GHG emissions than the equivalent oil furnaces. Propane furnaces also has less than one-fourth NOx emissions relative to comparable oil furnaces.

Table 10 – Commercial Space Conditioning Technologies Source Energy and Emissions

Commercial Space Conditioning	Efficiency (HSPF/ COP)	Final Site (MMBtu)	Final Source (MMBtu)	Source energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Best available Furnaces								
Propane furnace	0.99	585	919	0.88	58,876	0.88	0.87	0.95
Natural Gas furnace	0.99	585	892	0.86	54,184	0.81	0.73	0.85
Electric furnace	1.00	551	1,669	1.60	100,433	1.50	1.21	3.09
Oil furnace	0.98	587	940	0.90	65,296	0.98	3.42	0.95
Minimum Efficiency Furnaces								
Propane furnace	0.80	690	1,040	1.00	66,967	1.00	1.00	1.00
Natural Gas furnace	0.80	690	1,006	0.97	61,183	0.91	0.83	0.87
Electric furnace	0.98	559	1,695	1.63	101,995	1.52	1.23	3.13
Oil furnace	0.80	690	1,062	1.02	74,603	1.11	4.12	1.00

Notes:
Annual space conditioning for a Fast Food Restaurant, 2000 s.f., in Nashville,TN
Analysis for furnaces includes energy for heating, cooling (electric DX 13 EER), and HVAC blower.



Comparison of Source Energy & Emissions for Heat Pumps

A comparison of commercial heat pump technologies is shown in Table 11. The hybrid configuration of an electric air source heat pumps (ASHP) with a propane backup furnace for commercial applications not only improves comfort, but also significantly reduces both GHG emissions and source energy compared to the heat pump alone. This configuration also reduces SOx emissions by about one-half.

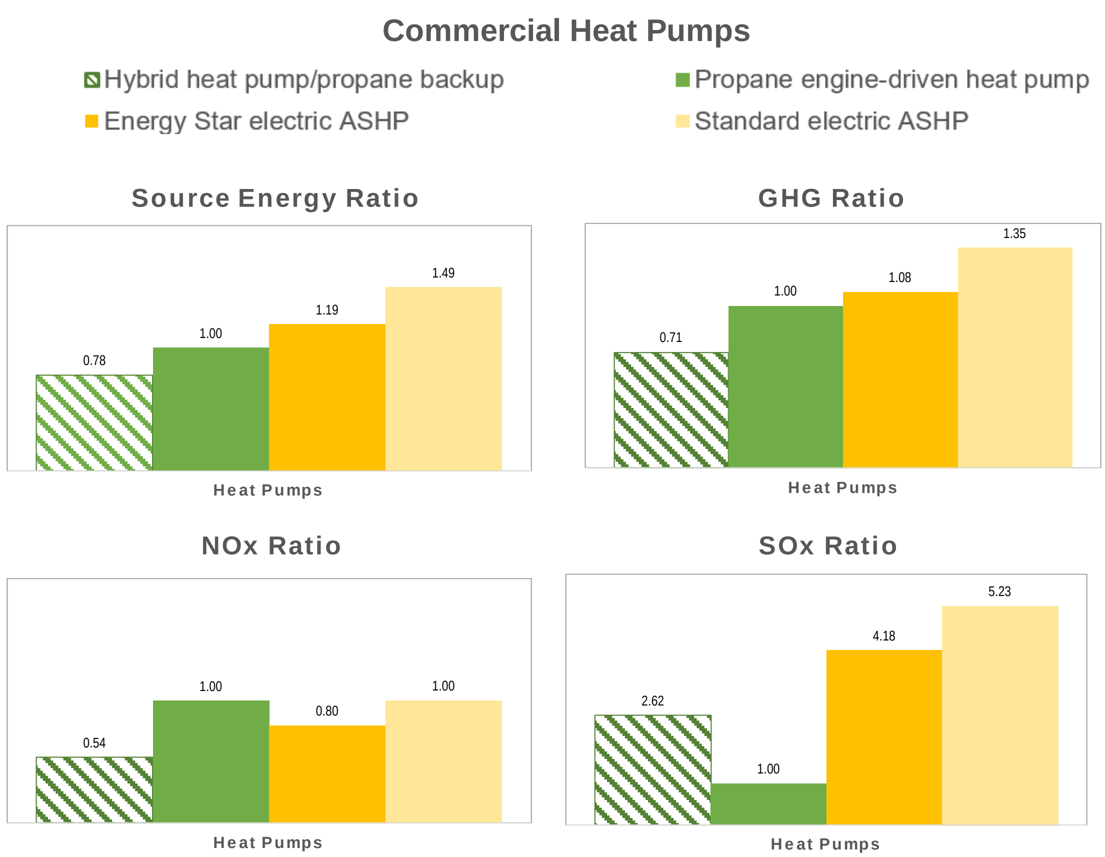
The propane engine-driven heat pump has potential to reduce source energy use and GHG emissions, with less than one-fourth SOx emissions, compared to an Energy Star electric heat pumps.

Note this analysis makes several simplifying assumptions regarding heat pump performance, so these are general estimates. Since heat pump performance varies significantly with climate and part load, these results would vary in actual applications. Also, this analysis excludes engine emissions from the gas engine-driven heat pump due to limited data available.

Table 11 – Commercial Heat Pump Technologies Source Energy and Emissions

Commercial Heat Pumps	Efficiency (HSPF/ COP)	Final Site (MMBtu)	Final Source (MMBtu)	Source energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Heat Pumps								
Energy Star electric ASHP (14 SEER)	8.40	341	1,034	1.19	62,208	1.08	0.80	4.18
Hybrid ASHP (8.4 HSPF) w/	0.00	243	677	0.78	40,982	0.71	0.54	2.62
Propane engine-driven heat pump	1.20	717	867	1.00	57,585	1.00	1.00	1.00
Standard electric ASHP (10 SEER)	7.20	427	1,295	1.49	77,894	1.35	1.00	5.23

Notes:
1. Ratios are based on the propane engine-driven heat pump (ICE NextAire™)
2. Annual space conditioning for a Fast Food Restaurant, 2000 s.f., in Nashville,TN
3. ASHP efficiency varies with climate; estimate based on ASHRAE Climate Zone 4 (Nashville, TN)
4. Hybird configuration assumes Energy Star (ASHP) serves 60% of load; backup propane furnace 40%.
with propane furnace backup system (80% TE) provides the remaining 60%.
5. Engine driven GHP with DOAS assumed average 1.2 COPgas



Combined Heat and Power (CHP)

CHP systems recover waste heat from power generation and use it to create hot water or steam to provide space heating, domestic hot water or air conditioning. Using distributed generation with heat recovery has potential to increase the total system efficiency up to 90%, compared to large scale power generation which is only 30% to 45% efficient. CHP can provide economic and environmental benefits in regions where fuel costs are significantly lower than electricity costs, i.e. a favorable spark spread, or for buildings that can benefit from efficient power generation and also have simultaneous heating loads.

CHP systems can utilize a variety of prime movers, including Stirling engines, internal combustion engines, fuel cells, micro-turbines, and Organic Rankine systems. Each type of system has different electrical efficiencies, heat recovery, and installed costs. In the U.S., more than 25 manufacturers were identified representing about 35 microCHP (mCHP) products ranging in size from 1 kW to 30 kW. This analysis will include two different prime movers, internal combustion engines and microturbines.

Figure 7 – Yanmar 10 kW Engine-driven MicroCHP System CP10WN

http://www.yanmar-es.com/uploads/files/CP10WN%20Spec%20Sheet.pdf

Figure 8 – Capstone 30 kW Microturbine C30

https://www.capstoneturbine.com/products/c30

Reciprocating internal combustion engines are the most common technology for power generation less than 5 MW. These systems can ranging from small, portable generators to large industrial engines and can be fueled by propane, natural gas, diesel, gasoline, or landfill and biogas. Reciprocating engines are a proven technology that can start quickly, follow load well, have good part-load efficiencies, and generally are highly reliable.[26]

Microturbines are smaller, compact and lightweight combustion turbines. Typical outputs range from 30 kW to 300 kW. Many are air-cooled eliminating the need for cooling water. In CHP operation, a heat

[26] http://www.midwestchptap.org/cleanenergy/chp/technologies.aspx

exchanger transfers thermal energy from the hot exhaust to a hot water or low-pressure steam system. Micro turbines can be brought on-line quickly, offer fuel flexibility, require less maintenance fewer moving parts, and have lower NOx emissions than engines. Operation at higher inlet air temperatures (> 59F) reduces output capacity and efficiency.[27]

Emission Analysis

This analysis compares the emissions for two mCHP applications to grid electricity required to meet the same power and thermal loads:

- 10kW engine-based system fueled by propane, natural gas, and diesel
- 30kW microturbine system fueled by propane, natural gas, and diesel

Engine-based mCHP Assumptions

The engine-based mCHP assumes a 10kW system with 3000 hours of operation. The efficiency of the propane engine is based on the Yanmar CP10WNV which can operate on either natural gas or propane. Using natural gas, it has a 30% electrical efficiency; 53% heat recovery efficiency. Using propane, it has a 31.5% electrical efficiency; 58% heat recovery efficiency. Emissions for the mCHP systems are compared to the electric grid power delivering equivalent electric service (30,000 kWh) and the same thermal output (159 MMBtu) using a 99% efficient tankless electric water heater.

Propane and Diesel GHG emission factors were based on EPA non-road vehicles emission factors, with NOx and SOx emission factors based on SEEAT light duty vehicles. All source energy factors and emission factors for natural gas and electricity were taken from SEEAT.

Turbine-based mCHP Assumptions

The turbine-based mCHP assumes a 30kW system with 3000 hours of operation, based on the Capstone C30 specifications. It was assumed to have a 30% electrical efficiency; 50% heat recovery efficiency. Emissions for the mCHP systems are compared to the electric grid power delivering equivalent electric service (90,000 kWh) and the same thermal output (614 MMBtu) using a 99% efficient tankless electric water heater.

Propane and Diesel GHG emission factors were based on EPA non-road vehicles emission factors, with NOx and SOx emission factors based on SEEAT light duty vehicles. All source energy factors and emission factors for natural gas and electricity were taken from SEEAT.

Comparison of Source Energy & Emissions

Based on this analysis, propane mCHP reduces source energy, GHG, and NOx emissions by more than half compared to equivalent electric grid power with electric water heating. This is primarily due to the additional electric resistance heat required to match the mCHP heat delivered. As expected, propane mCHP also significantly reduces SOx emissions compared to electric grid heat and power. Heat delivered is based on the assumption 90% of heat recovered can be utilized. If this utilization factor is lower, the source energy and emission savings will also be reduced.

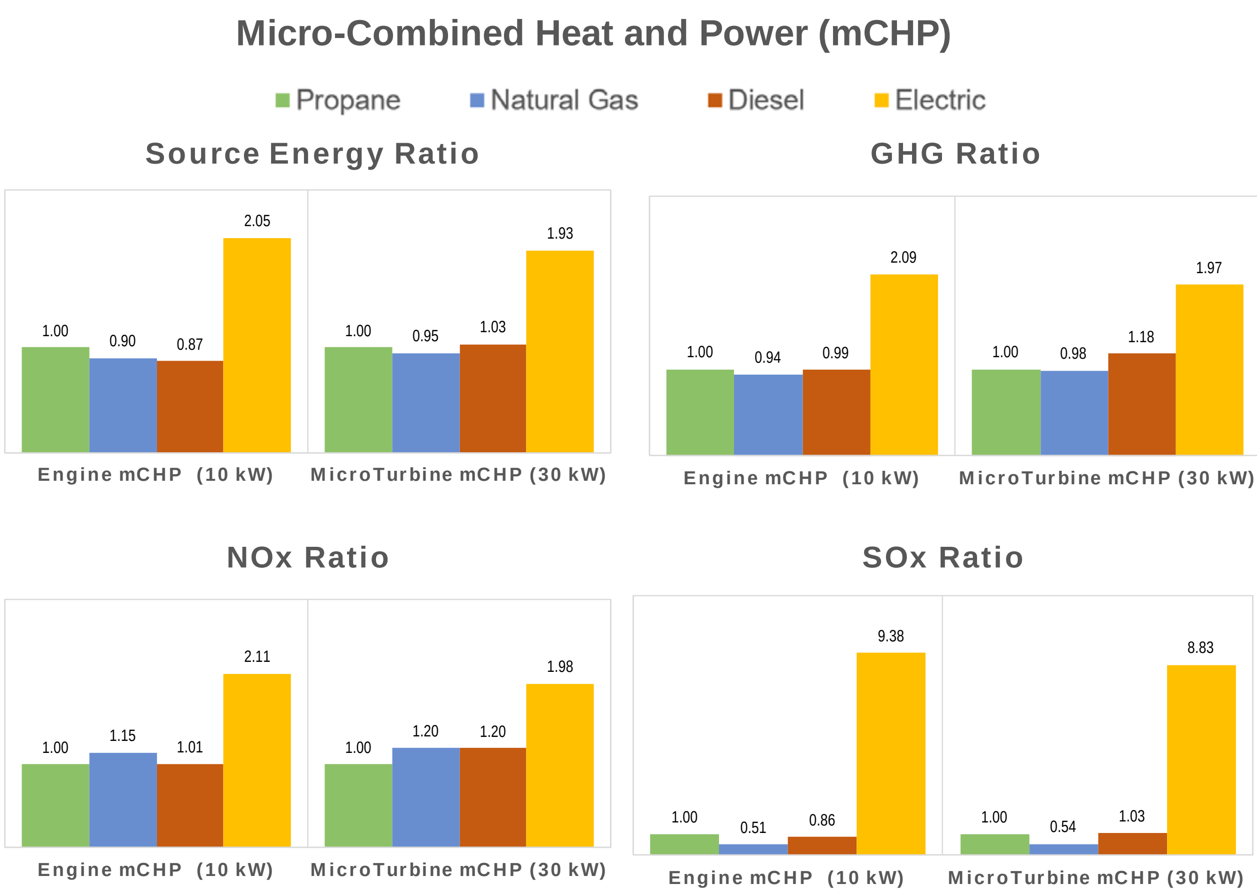
Propane engine-based mCHP systems have similar emissions to natural gas and diesel. Propane microturbines have 15% lower GHG and 16% lower NOx emissions compared to diesel.

[27] http://www.midwestchptap.org/cleanenergy/chp/technologies.aspx

Table 12 – Micro-Combined Heat and Power Technologies Source Energy and Emissions

Micro-Combined Heat and Power	Electric Efficiency (%LHV)	Heat Recovery Efficiency (LHV))	Site Energy Use (MMBtu)	Source Energy Use (MMbtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Engine mCHP (10 kW)									
Propane	32%	58%	338	389	1.00	22,937	1.00	1.00	1.00
Natural gas	30%	53%	323	352	0.90	21,527	0.94	1.15	0.51
Diesel	36%	56%	284	338	0.87	22,675	0.99	1.01	0.86
Equivalent All Electric System			263	798	2.05	48,013	2.09	2.11	9.38
MicroTurbine mCHP (30 kW)									
Propane	26%	50%	1,181	1,359	1.00	80,079	1.00	1.00	1.00
Natural gas	26%	50%	1,181	1,288	0.95	78,861	0.98	1.20	0.54
Diesel	26%	43%	1,181	1,406	1.03	94,190	1.18	1.20	1.03
Equivalent All Electric System			865	2,622	1.93	157,779	1.97	1.98	8.83

Notes:
1. Engine mCHP analysis assumes 3000 hrs operation at full load (10 kW); heat utilization:
2. Engine mCHP efficiency based on CP10WN (http://www.yanmar-es.com/uploads/files/CP10WN%20Spec%20Sheet.pdf); Microturbine based on Capstone C30 (https://www.capstoneturbine.com/products/c30)
3. Microturbine mCHP analysis assumes 3000 hrs operation at full load (30 kW); heat utilization:
4. Grid energy use based on delivering same electric service (30,00 kWh) and same thermal output (183 MMbtu)
5. GHG emission factors for Propane and Diesel based on EPA NonRoad Vehicles; all other emission factors used for natural gas and electric based on SEEAT



Commercial Power Generation

Distributed generation (DG) is an emerging market in the United States. The market for propane DG has been limited, with the majority of applications consisting of emergency generators or small engines at remote sites.[28] DG can provide economic benefits to businesses and organizations by generating power directly with lower cost fuels in areas with high electric prices. Other advantages include power generation in more remote locations where electricity is unavailable, reduced losses due to power transmission, improve reliability or backup power in areas prone to power outages, and improved control over energy distribution and use.

Emission Analysis

Assumptions

This analysis presented in Table 13 assumes the engine-driven generators operate at full load (7 kW) for 100 hours per year. Table 14 presents a similar analysis for large power generation systems (100 kWh) based on two types of Generac power generation systems. Annual fuel use is based on full load specifications of representative generators. Generator emissions are compared to full-fuel-cycle emissions for grid electric power based on same power generation (700 kWh).

Propane and Diesel GHG emission factors were based on EPA non-road vehicles emission factors. SEEAT GHG emission factors were used for natural gas and electricity. All source energy, NOx, and SOx emission factors were based on SEEAT.

Comparison of Source Energy & Emissions

Based on this analysis using the average U.S. electricity generation mix, the 7 kW propane power generation has higher source energy, GHG, and NOx emissions compared to electric grid power. SOx emissions are 62% lower for propane DG relative to the electric grid.

The larger 100 kWh system has similar results. The propane system has higher source energy use, GHG and NOx emissions compared to grid electricity based on the average U.S. electricity generation mix. Propane DG has less than one third SOx emissions than grid electricity.

[28] "Propane Distributed Generation Market Assessment", Resource Dynamics Corporation, Prepared for: Propane Education & Research Council, May 2010.

Table 13 – Commercial Power Generation (7 kW) Source Energy and Emissions

Commercial Power Generation	Final Site (MMBtu)	Final Source (MMBtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Propane	11.04	12.7	1.00	749	1.00	1.00	1.00
Natural gas	13.42	14.6	1.15	896	1.20	1.46	0.66
Diesel	9.19	10.9	0.86	733	0.98	1.00	0.85
Grid Electricity	2.39	7.2	0.57	435	0.58	0.59	2.61

Notes:

1. Generators in the analysis are assumed to operate at full load (7 kW) for (hours per year) :100
2. Fuel use is based on full load specifications of representative generators:
3. Annual energy use for grid electricity is based on same energy service of the generators (700 kWh)
4. GHG emission factors for Propane and Diesel based on EPA NonRoad Vehicles;
 all other emission factors used for natural gas and electric based on SEEAT

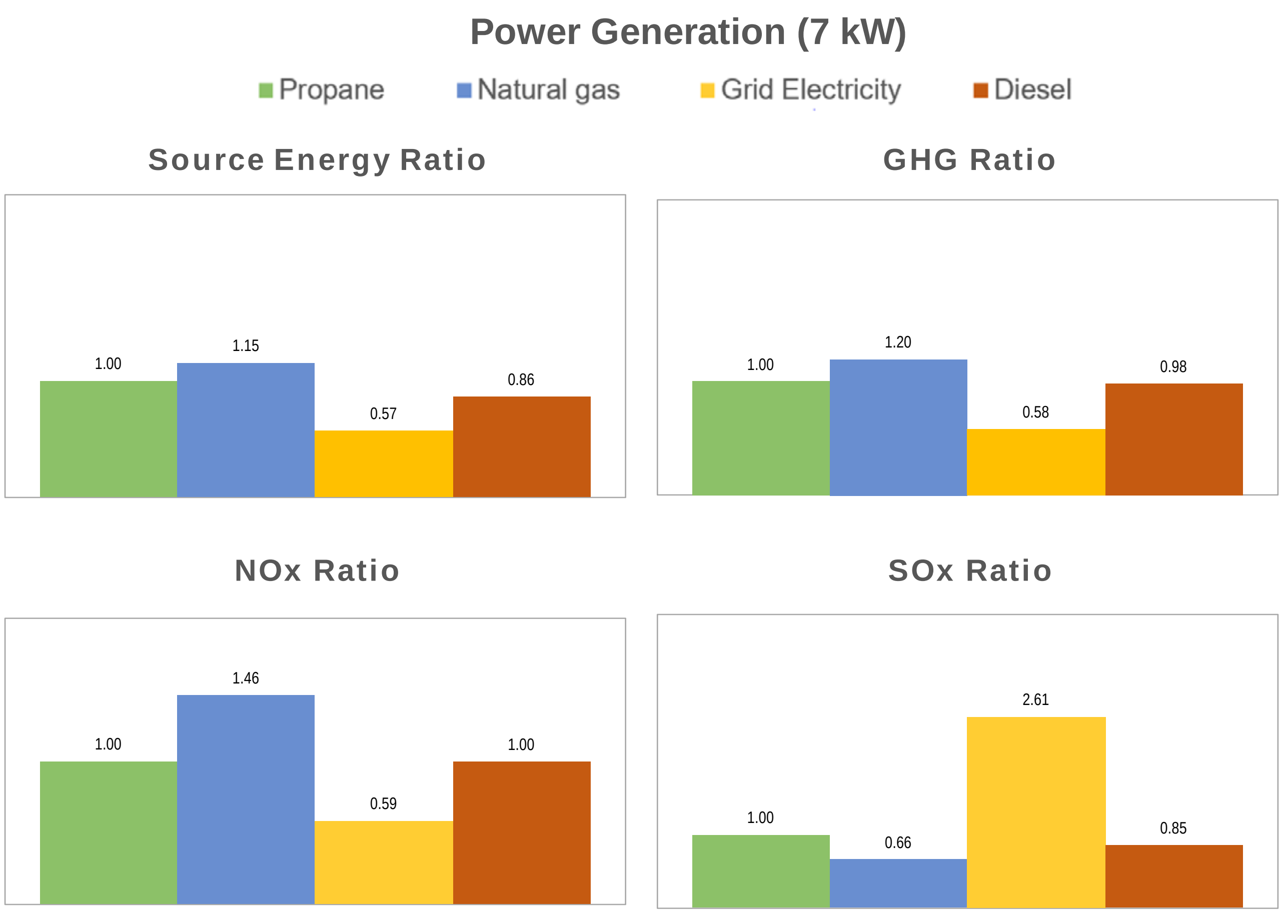
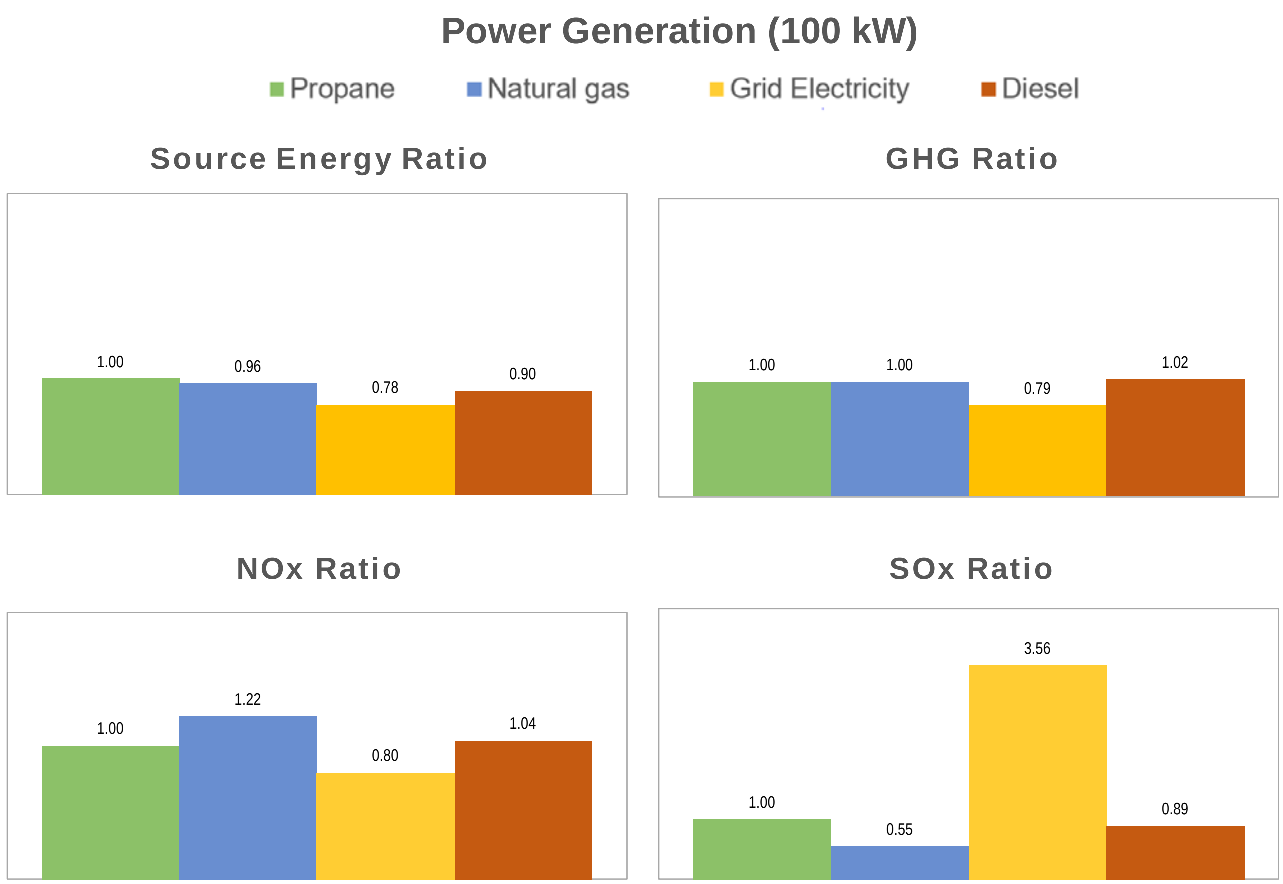


Table 14 – Commercial Power Generation (100 kW) Source Energy and Emissions

Commercial Power Generation	Final Source (MMBtu)	Final Source (MMBtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Propane	1156.89	1330.4	1.00	78,416	1.00	1.00	1.00
Natural gas	1171.80	1277.3	0.96	78,218	1.00	1.22	0.55
Diesel	1002.87	1193.4	0.90	79,955	1.02	1.04	0.89
Grid Electricity	341.20	1033.8	0.78	62,203	0.79	0.80	3.56

Notes:
1. Generators in the analysis are assumed to operate at full load (100 kW) for (hours per year) :1000
2. Fuel use is based on full load specifications of representative generators:
   Generac SG100 (8cyl 8.9L)
   Generac SD100 (6cyl 6.7L)
3. Annual energy use for grid electricity is based on same energy service of the generators (700 kWh)
4. GHG emission factors for Propane and Diesel based on EPA NonRoad Vehicles;
 all other emission factors used for natural gas and electric based on SEEAT



Propane Vehicles

Propane, also known as liquefied petroleum gas (LPG) or propane autogas, is considered an alternative fuel for vehicles. There are over 147,000 on-road propane vehicles in the United States, typically used in fleets, such as school buses and shuttles.[29]

In recent years, propane vehicles have become available in a wide range of light- to medium-duty applications. These are offered by major manufacturers as original equipment manufacturers (OEMs) dedicated vehicles, or as certified conversions. Dedicated propane vehicles operate only on propane, while bi-fuel vehicles have two fueling systems which allow the vehicle to operate on either propane or gasoline. Since propane has a higher octane rating than gasoline, some OEMs offer dedicated engines optimized for this higher rating which can improve performance and fuel economy over non-optimized engines. [30]

Propane has several advantages for fleets, including lower total-cost-of-ownership, comparable performance to conventional fuels, onsite fueling, reduced maintenance, and lower emissions. Small to mid-size fleets with high mileage and based at a single location are one of the most cost-effective applications that can benefit from lower fuel costs and reduced maintenance.

Light-Duty Vehicles

Alternate fueled vehicles have a smaller, but growing, market share in light duty vehicles, such as light duty pickup trucks or passenger vehicles. Light commercial trucks represent a large potential market for propane, as they represent typical fleet vehicles with high annual mileage, averaging 25,000 miles per year.[31] This analysis will compare emission benefits for light duty pickup trucks.

Emission Analysis

Assumptions

The emission analysis includes only dedicated propane light duty vehicles, using light duty pickup trucks as an example. Average annual mileage, based on AFLEET 2016, was assumed 11,400 miles for light duty trucks with the fuel economies shown below in Table 15.

Table 15 – AFLEET 2016 Average Fuel Economy for Light Duty Vehicles

Average Fuel Economy (miles per gasoline gallon equivalent)	Gasoline	Diesel	Propane (LPG)	Compressed Natural Gas (CNG)
Light-Duty Pickup Truck	22.7	27.2	22.7	21.6

Emission factors were based on GREET® 2016 defaults for Light-Duty Vehicles: Conventional and LS Diesel (Light Commercial Truck/LDT2). This vehicle type included options for spark-ignited LPG and CNG, and CIDI low-sulfur diesel fuels, but did not include gasoline. For this analysis, gasoline emission factors were based on spark-ignited internal combustion engine vehicle (SI ICEV Car) with CA reformulated gasoline. Source energy factors for upstream efficiencies were based on SEEAT. Heat content of fuels is based on lower heating value (LHV).

[29]"Propane Vehicle Basics", Energy.gov, https://energy.gov/eere/energybasics/articles/propane-vehicle-basics
[30]U.S. DOE, Alternative Fuels Data Center, http://www.afdc.energy.gov/vehicles/propane_availability.html
[31]U.S. Energy Information Administration, Annual Energy Outlook 2016

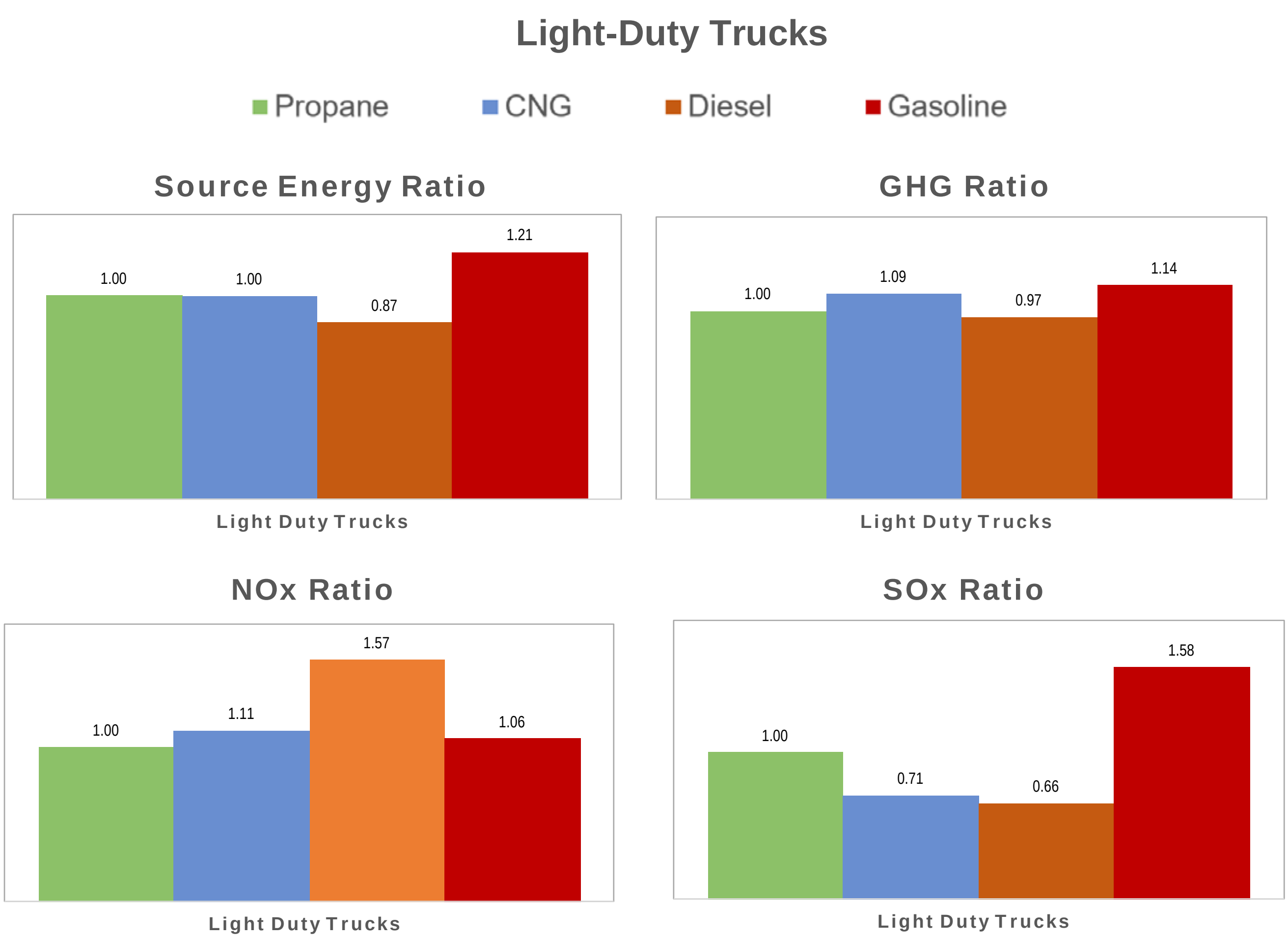
Comparison of Source Energy & Emissions

Based on this analysis, propane light-duty vehicles have fewer NOx emissions than diesel. Compared to gasoline, propane light-duty vehicles significantly reduce both source energy and emissions. Compared to gasoline vehicles, propane light-duty vehicles have 18% lower source energy use, 12% fewer GHG emissions, 5% fewer NOx emissions, and 37% fewer SOx emissions.

Table 16 – Light-Duty Vehicles Source Energy and Emissions

Light Duty Vehicles	Fuel Economy (miles/ gge)	Annual Fuel Use (gge)	Source Energy Use (MMBtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Light Duty Trucks								
Propane	22.7	502	65	1.00	4,854	1.00	1.00	1.00
CNG	21.6	528	65	1.00	5,300	1.09	1.11	0.71
Diesel	27.2	419	56	0.87	4,692	0.97	1.57	0.66
Gasoline	22.7	502	79	1.21	5,518	1.14	1.06	1.58

Notes:
1. Vehicle Mileage and fuel economy based on AFLEET 2016
2. Emission factors based on GREET 2016 for Light-Duty Vehicles: Conventional and LS Diesel (Light Commercial Truck/LDT2), Gasoline emission factors from SI ICEV Car
Fuels: Spark ignited LPG and CNG; CIDI Low-Sulfur Diesel; CA reformulated gasoline
3. Source energy factors based on SEEAT
4. Assume Light Duty Trucks Average Annual Vehicle Miles Traveled: 11,400



School Buses

School buses are an attractive market for propane vehicles due to economic and environmental benefits. A 2014 U.S. Department of Energy Clean Cities case study of propane buses in five school districts found propane to be a promising alternate fuel for school buses:[32]

> *Propane is a promising alternative fuel for school buses because it is widely available, even in rural areas, and it can cost less than diesel or gasoline.*

Economics are the primary reason schools choose propane buses. Emission reductions are also important, but secondary. This case study reported the costs savings of nearly 50% per mile, improved engine efficiency and significant reduction in GHG emissions compared to diesel buses. Blue Bird recently introduced a new gasoline-powered Vision Type C school bus that will utilize a Ford 6.8LV10 gasoline engine.[33] Although some small school buses run on gasoline, this will be the first gasoline-powered Type C school bus offered by a major OEMs in recent years.

This analysis included two types of buses: 1) Type A, the small cutaway-van type buses based on a light-duty van chassis; 2) Type C, the conventional bus design based on a medium-duty truck chassis. Photos and descriptions are shown in Table 17.[34]

Table 17 – Description of School Buses Types

		
Type A School Bus Small cutaway-van type buses carry about 20 passengers. They have a driver's door and are based on a light duty van chassis. Type B Buses are also small and are very similar to Type A, but transport about 30 passengers.	**Type C School Bus** Conventional design is based on a medium duty flat-back cowl truck chassis with the engine in front of the windshield, and the entrance door behind the front wheels.	**Type D School Bus** This model uses medium-duty truck chassis with front, mid, or rear engine locations. The entrance door is in front of the front wheels.

[32] Laughlin, M., A. Burnham, "Case Study – Propane School Bus Fleets", Clean Cities, U.S. Department of Energy, ANL Contract No. 2F-32321, August 2014. http://www.afdc.energy.gov/publications/

[33] "School Bus Fleet", http://www.schoolbusfleet.com/news/686035/blue-bird-reveals-new-gasoline-powered-type-c-school-bus

[34] "A Feasibility Study of Natural Gas Vehicle Conversion in Wyoming Public School Districts", prepared by the Department of Administration & Information Economic Analysis Division, November 2012.

Emission Analysis

Assumptions

For this analysis, the following annual vehicle mileage and fuel economy were assumed:

- Per AFLEET 2016, fuel economies for Type A buses, miles per gasoline gallon equivalent (MPGGE): propane=14.5; CNG= 13.8; diesel=17.4; gasoline=14.5
- Fuel economy for Type C buses was based on AFLEET 2016 (MPGGE): propane=5.6; diesel= 6.7; gasoline=5.6. Fuel economy for LPG Type C buses, 6.3 MPGGE, was based on recent industry data.
- Default annual mileage was assumed to be 15,000 miles for Type A and Type C school buses.
- Emission factors were based on GREET® 2016 defaults for vehicle type: HD Bus: School; and fuels: spark ignited LPG and CNG, and CIDI Low-Sulfur Diesel. Source energy factors were based on SEEAT.

Comparison of Source Energy & Emissions

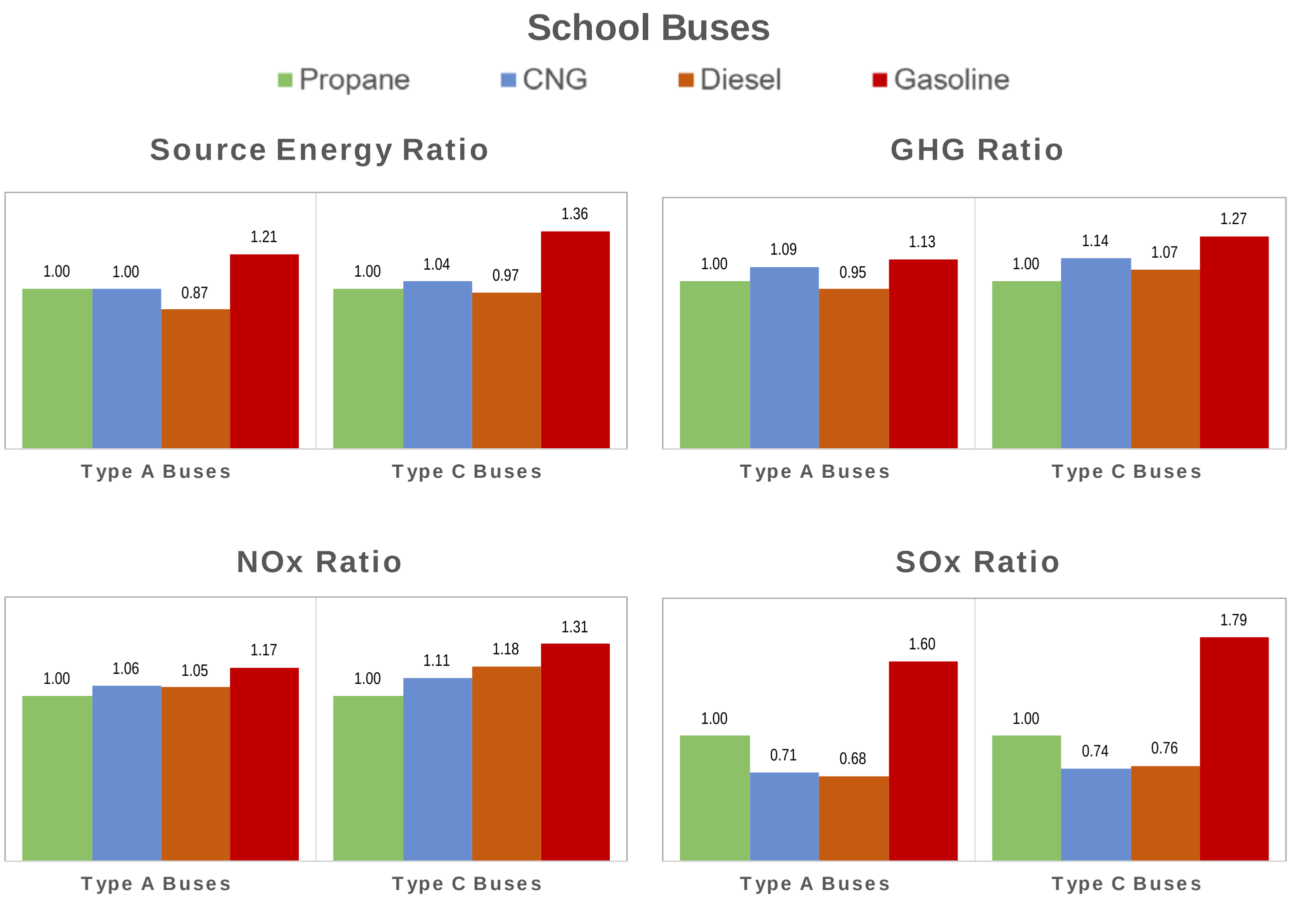
Compared to low-sulfur diesel buses, LPG school buses have 5% to 15% fewer NOx emissions. For Type C buses, LPG has 6% lower GHG emissions compared to diesel.

Based on this analysis, LPG school buses have significantly lower source energy use and emissions than gasoline-fueled buses. Both types of propane buses have 12% to 21% lower GHG emissions, 15% to 24% lower NOx emissions, and 37% to 44% lower SOx emissions.

Table 18 – School Buses Source Energy and Emissions

Buses	Fuel Economy (miles/ gge)	Annual Fuel Use (gge)	Source Energy Use (MMbtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Type A Buses								
Propane	14.5	1,034	133	1.00	10,032	1.00	1.00	1.00
CNG	13.8	1,087	133	1.00	10,910	1.09	1.06	0.71
Diesel	17.4	862	116	0.87	9,547	0.95	1.05	0.68
Gasoline	14.5	1,034	162	1.21	11,366	1.13	1.17	1.60
Type C Buses	**(miles/ gge)**							
Propane	6.3	2,392	309	1.00	23,199	1.00	1.00	1.00
CNG	5.7	2,632	322	1.04	26,414	1.14	1.11	0.74
Diesel	6.7	2,239	300	0.97	24,794	1.07	1.18	0.76
Gasoline	5.6	2,679	419	1.36	29,430	1.27	1.31	1.79

Notes:
1. Vehicle mileage and fuel economy based on AFLEET models (ANL 2016); propane fuel economy for Type C buses (6.3 mpgge) based on recent industry data
2. Emission factors based on GREET 2016 for HD Bus: School, spark ignited LPG and CNG, and CIDI Low-Sulfur Diesel Gasoline emission factors from SI ICEV Car CA Reformulated Gasoline
3. Source energy factors based on SEEAT
4. Assume Type A Buses Annual Miles 15,000
5. Assume Type C Buses Annual Miles 15,000



Medium Duty Vehicles

Bobtail Trucks

Bobtail trucks are local delivery trucks used to transport propane under pressure. These typically hold 3,000 to 5,000 gallons, roughly half the size of propane transport trucks. Bobtail trucks are considered the workhorse of the propane industry, delivering fuel to local propane dealers unable to unload tank cars, or individual home owners primarily in rural areas. Until recently, most bobtail trucks operated on diesel with some converted for propane. In 2014, the Freightliner S2G 8.0L engine was introduced to the market as the first bobtail specifically designed for propane.

Emission Analysis

Assumptions

For direct comparison with the Nexight study[35], similar assumptions were used for this analysis. Bobtail emission analysis assumed an annual vehicle mileage of 20,000 miles per year. Fuel efficiency for diesel bobtail trucks (6.4 MPGGE) was based on AFLEET models (ANL 2013a) for vehicles with the same weight rating, a combination short-haul tractor-trailers. The fuel economy for LPG bobtail trucks was 6.3 MPGGE, based on recent industry data. The higher efficiency for propane engines is demonstrated by a recent case study suggesting that new liquid propane injection (LPI) engines have similar fuel efficiencies to diesel engines (ANL 2013a).

Fuel emission factors were based on GREET® 2016 defaults for medium duty vehicles. Source energy factors and all electric emission factors were taken from SEEAT.

Comparison of Source Energy & Emissions

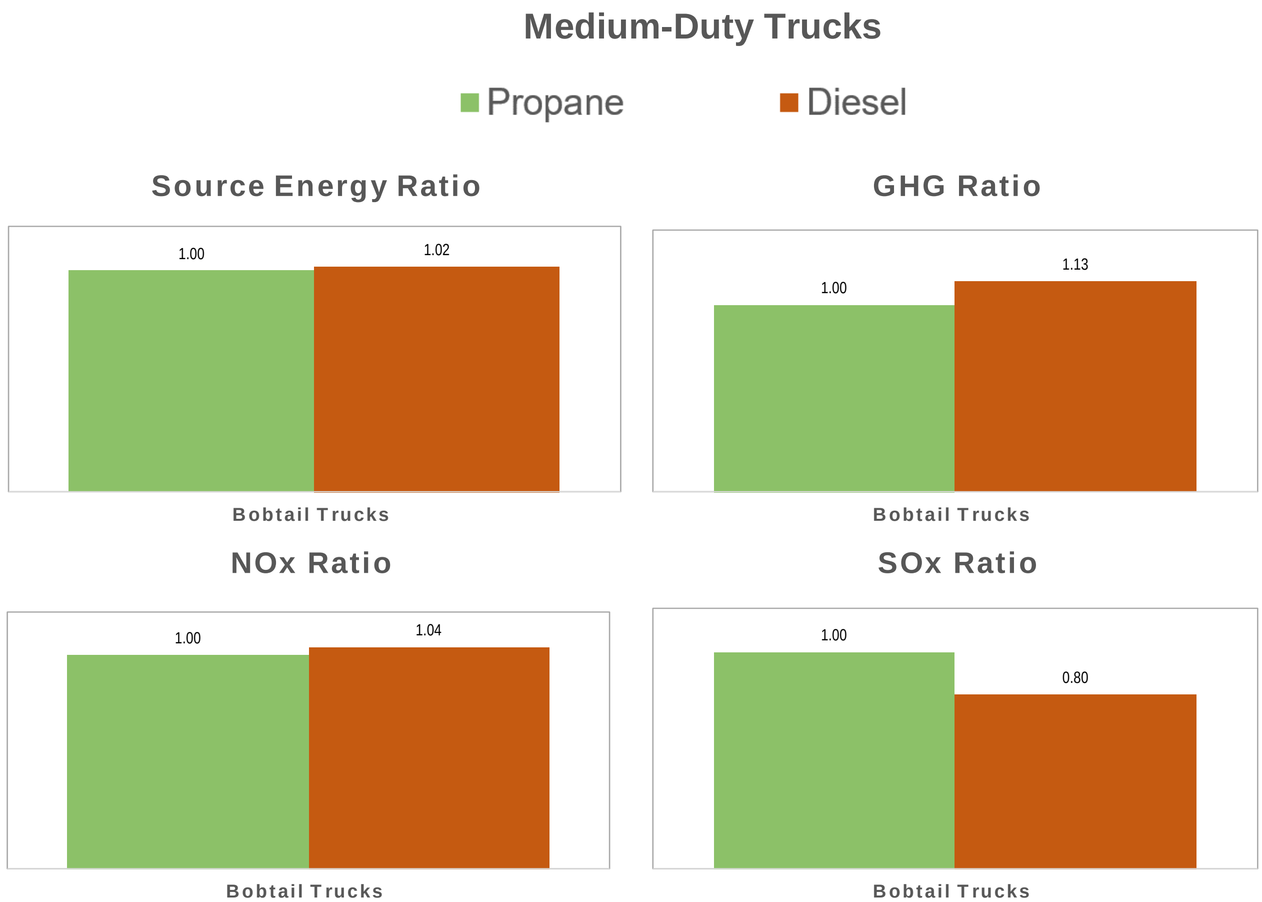
For bobtail trucks, propane GHG emissions are 11% lower and NOx emissions are 4% lower than comparable diesel vehicles.

[35] Nexight, 2014.

Table 19 – Medium-Duty Vehicles Source Energy and Emissions

Medium-Duty Trucks	Annual Fuel Use (gge)	Fuel Economy (miles/ gge)	Site Energy Use (MMBtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Bobtail Trucks								
Propane	3,190	6.3	358	1.00	30,861	1.00	1.00	1.00
Diesel	3,125	6.4	351	1.02	34,751	1.13	1.04	0.80

Notes:
1. Bobtail Trucks mileage and diesel fuel efficiency (6.4 mpgge) based on AFLEET models (ANL 2013a) for a Combination Short-Haul Truck;
2. Propane fuel economy (6.3 mpgge) from recent industry data on new liquid propane injection (LPI) engines
3. Assume 20,000 Annual Miles



Irrigation Engines

Irrigation engines drive the pumps delivering water from wells, streams, or reservoirs to maintain crops during dry periods. In the U.S., a growing number of irrigation engines are fueled by propane. These engines, specifically designed and built for propane, are efficient, reliable, and cost effective. Propane irrigation engines also offer lower emissions compared to gasoline and diesel equipment.

Figure 9 – Irrigation Engines

Emission Analysis

Assumptions

All engines were assumed to be 5.7L with 100 horsepower and operate an average 1039 hours per year [36] (Propane's Advantage 2009). Fuel consumption was based on a University of Florida study on irrigation power unit performance, as shown Table 20. This report identifies the importance of matching the irrigation engine capacity with the load. All irrigation power units operate most efficiently when fully loaded. Both engines and electric motors can maintain high efficiencies when loaded above 60 to 70 percent their continuous horsepower rating. If the power unit is overloaded, both engines and electric motors will waste fuel, wear rapidly and fail prematurely.

Table 20 – Performance standards for fully loaded irrigation power units [37]

Type of Power Unit	Performance Standard	Fuel Use Rate
Diesel	14.75 hp-hr/gal	0.678 gal/hp-hr
Gasoline	11.30 hp-hr/gal	0.0885 gal/hp-hr
LPG (propane)	8.92 hp-hr/gal	0.112 gal/hp-hr
Electric	1.18 hp-hr/kWh	0.847 kWh/hp-hr

[36]Nexight, 2014.
[37]A.G. Smajstrla and F.S. Zazueta, "Loading Effects on Irrigation Power Unit Performance". AE242, University of Florida. Original publication date March 1994. Reviewed June 2003. http://ufdcimages.uflib.ufl.edu/IR/00/00/44/90/00001/AE04700.pdf

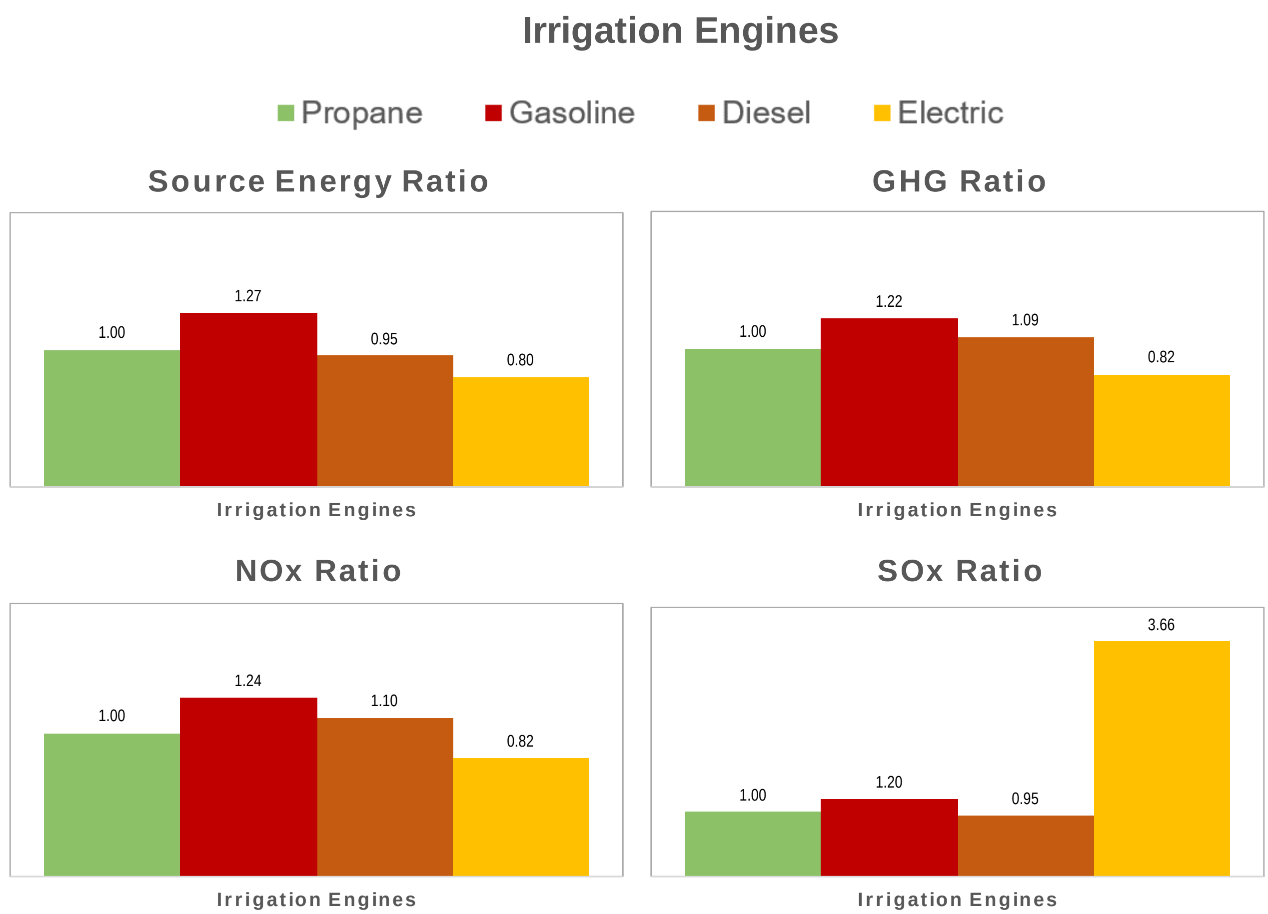
Comparison of Source Energy & Emissions

Propane irrigation engines have significantly lower emissions than competing fuels. Compared to diesel engines, LPG has 8% fewer GHG and 9% fewer NOx emissions. Compared to gasoline engines, LPG has 21% lower source energy use, 18% less GHG, and 20% less NOx, and 17% less SOx emissions than generated by gasoline irrigation engines. Electric irrigation systems have more than three times SOx emissions compared to propane.

Table 21 – Irrigation Engines Source Energy and Emissions

Irrigation Engines	Annual Fuel Use (gge)	Site Energy Use MMBtu	Source Energy Use MMbtu	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Propane	8,811	989	1,137	1.00	67,005	1.00	1.00	1.00
Gasoline	9,195	1,032	1,439	1.27	81,626	1.22	1.24	1.20
Diesel	8,130	912	1,085	0.95	72,723	1.09	1.10	0.95
Electric	2,676	300	910	0.80	54,743	0.82	0.82	3.66

Notes:
1. Irrigation engines 5.7L displacement, 100 hp, operate fully loaded 1039 hrs/yr (Propane's Advantage 2009)
2. Irrigation relative fuel consumption based on University of Florida performance standards
3. Electric GHG emission factors from SEEAT, other fuels based on EPA NonRoad Vehicles. NOx and SOx emission factors based on SEEAT



Lawn Mowers

Propane commercial lawn mowers offer several advantages compared to gasoline equipment. In addition to lower emissions, propane has lower operating costs, reduced maintenance, and better performance. Propane mowers reduce operating cost by up to 50%. The clean burning fuel can reduce maintenance such as less frequent oil changes, and also eliminates the degradation issues associate with gasoline during winter storage. In addition, case studies report propane mowers have better efficiency, including increased horsepower and ground speed with the propane mowers.[38] Propane mowers are available in wide range of models from all the major manufacturers. In addition, gasoline mowers can be converted using EPA- CARB-certified conversion kits.[39]

Emission Analysis

Assumptions - Mowers

This analysis compares the full-fuel-cycle emissions of a propane mower and a gasoline mower. Fuel consumption was based on the Kohler EFI mowers that can run on propane (1.32 gallons/hr) or gasoline (1.03 gallons/hr).[40] Analysis was based on 750 operating hours per year.[41]

Comparison of Source Energy & Emissions

Propane commercial mowers offer a significant reduction in all emissions and source energy use compared to gasoline mowers. Based on this analysis, propane mowers have 17% fewer GHG emissions, 19% fewer NOx emissions, and 16% fewer SOx emissions.

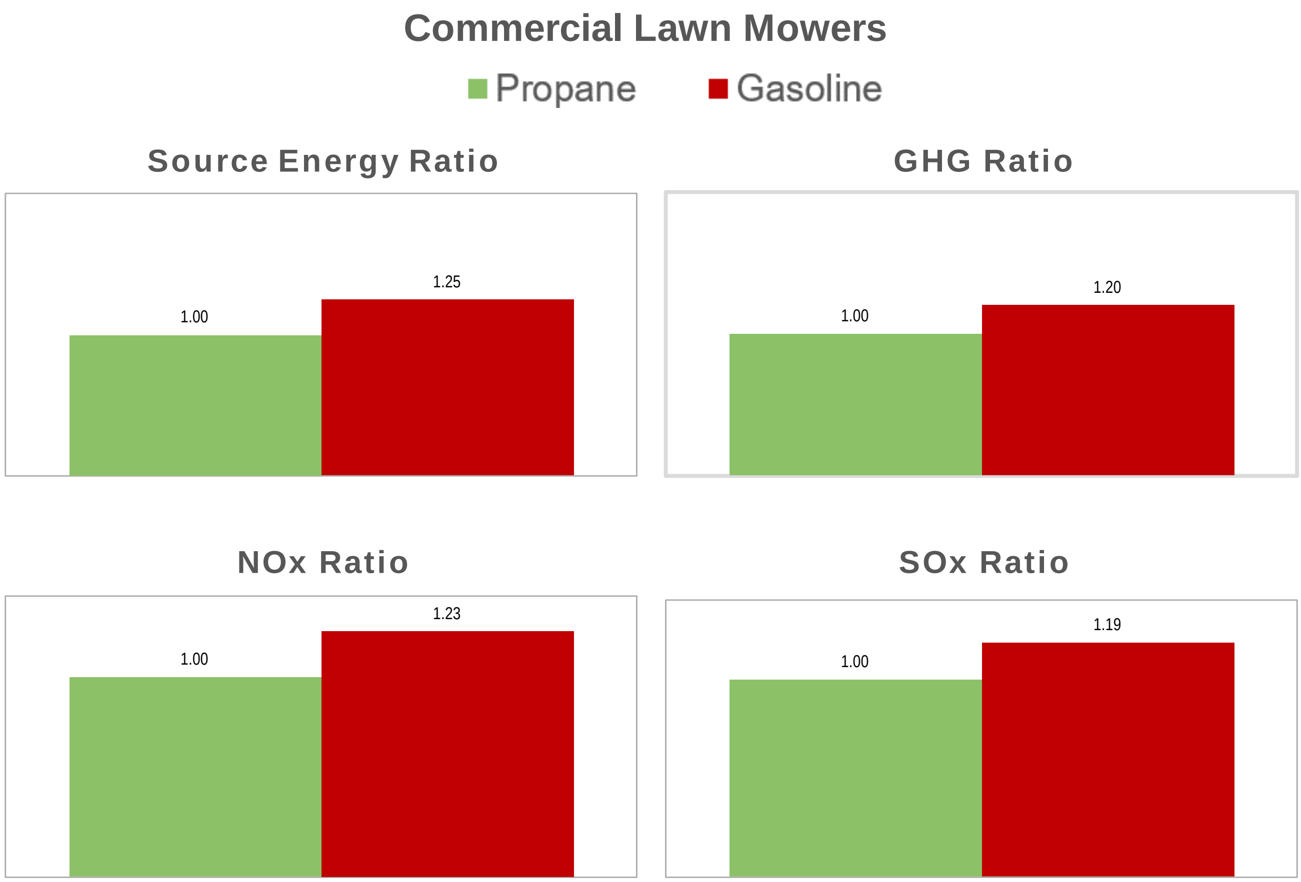
Source: www.propane.com

[38]http://www.propane.com/commercial-landscape/case-studies/
[39]http://www.propane.com/uploadedFiles/PropaneMain/Propane/Commercial_Landscape/CTA_-_Callouts/BusinessCaseMowersBrochure.pdf
[40]Kohler Engines, 2013.
[41]Nexight, 2014.

Table 22 – Commercial Lawn Mowers Source Energy and Emissions

Lawn Mowers	Annual Fuel Use (gge)	Site Energy Use MMBtu	Source Energy Use MMbtu	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Propane	750	84	97	1.00	5,700	1.00	1.00	1.00
Gasoline	773	87	121	1.25	6,858	1.20	1.23	1.19

Notes:
1. Lawn mower fuel use based on Kholer EFI mowers: Propane 1.32 gal/hr, Gasoline 1.03 gal/hr [Nexight Group, 2014]
2. Based on 750 hours/year
3. Gasoline and LPG GHG emission factors based on EPA NonRoad Vehicles; all other factors based on SEEAT



Forklifts

Source: http://www.propane.com

Propane and electric forklifts dominate the light-duty market, while diesel forklifts dominate the heavy-duty market. Propane forklifts are cost effective, easily maintained and quick to refuel compared to electric or compressed natural gas since they do not require charging time. Propane forklifts are consistent in performance and reliable for both indoor and outdoor use, handling a range of terrains, load sizes and operating speeds.[42]

Emission Analysis

Assumptions

Forklifts require fuel consumption for both lifting and moving. For direct comparison to the Nexight study, forklift fuel efficiency for lifting was based on a study by M. Delucchi, assuming an annual fuel use of 973 gallons propane. Electric forklift efficiency is assumed 64% (ANL 2008). It was assumed two-thirds fuel consumption for the forklift energy was for driving and one-third was for lifting.

Relative fuel efficiency for each fuel was based on the AFLEET model:
CNG=0.95; diesel= 1.20; electric =3.4; gasoline =1.0; propane=1.0.

Fuel use for lifting was calculated based on thermal engine efficiencies taken from [Delucchi 2001]: CNG=28.0%; diesel=28.5%; gasoline =26.7%; propane=28.0%.

Comparison of Source Energy & Emissions

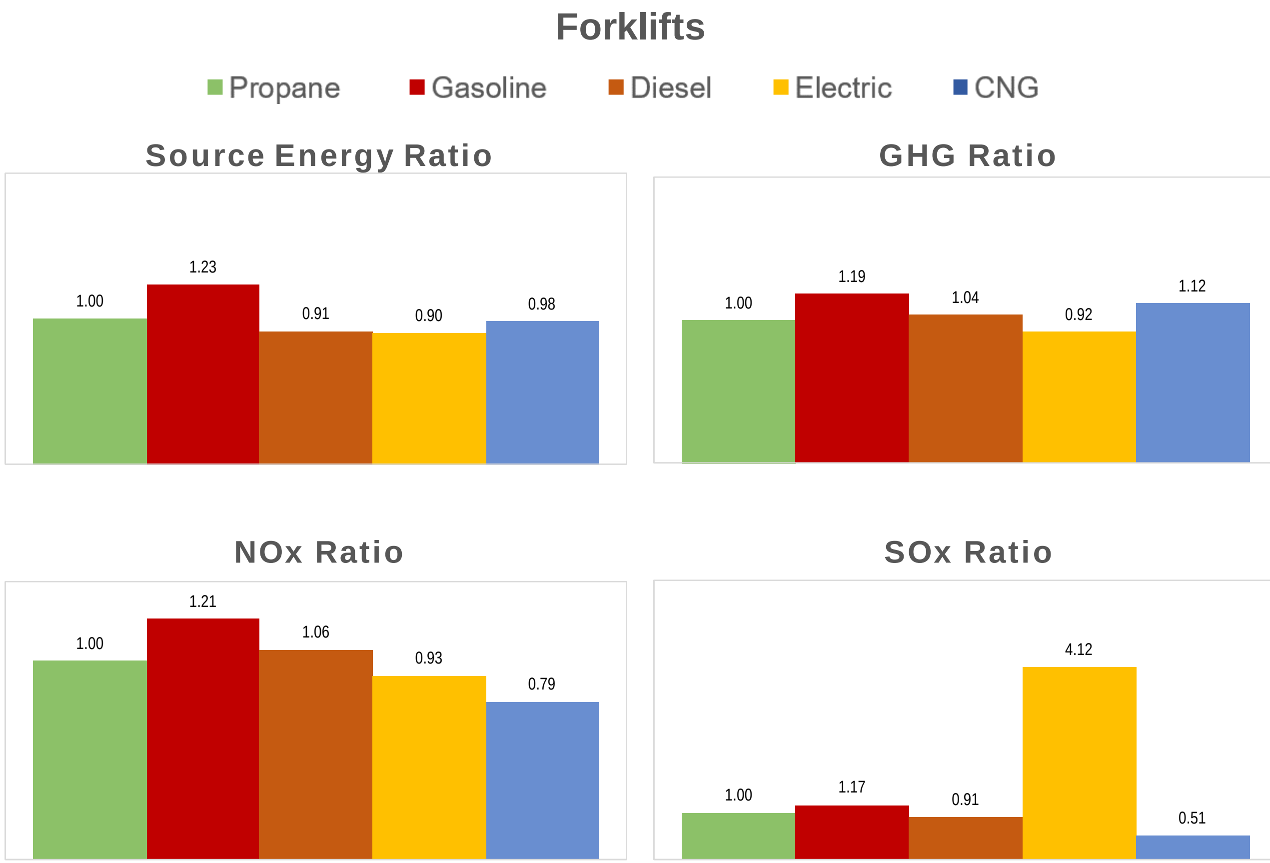
Propane forklifts have several benefits compared to competing fuels. Compared to gasoline forklifts, propane has 19% lower source energy use, 16% fewer GHG emissions, 17% fewer NOx emissions, and 15% fewer SOx emissions. Compared to diesel forklifts, propane generates about 5% fewer GHG and NOx emissions. Electric forklifts generate over four times more SOx emissions compared to propane forklifts.

[42] http://www.nfe-lifts.com/types/propane-forklift/

Table 23 – Forklifts Source Energy and Emissions

Forklifts	Average Annual Fuel Use (gge) [1]	Site Energy Use (MMBtu)	Source Energy Use (MMBtu)	Source Energy Ratio	Total CO2e (kg)	GHG Ratio	NOx Ratio	SOx Ratio
Propane	737	82.7	95.1	1.00	5,603	1.00	1.00	1.00
Gasoline	749	84.0	117.1	1.23	6,646	1.19	1.21	1.17
Diesel	651	73.0	86.9	0.91	5,819	1.04	1.06	0.91
Electric	252	28.3	85.6	0.90	5,152	0.92	0.93	4.12
CNG	763	85.6	93.3	0.98	6,274	1.12	0.79	0.51

Notes:
1. Average annual fuel use for propane forklifts of 973 gallons (Delucchi 2001)
2. Assume 2/3 total forklift energy use for driving; 1/3 for lifting
3. Relative efficiency for each fuel based on AFLEET model. (ANL 2013a)
4. Forklift fuel efficiency for lifting based on Delucchi 2001; electric forklift efficiency assumed 64% (ANL 2008).
5. GHG emission factors for LPG, Diesel and Gasoline based on EPA NonRoad Vehicles; NOx, SOx and emission factors for CNG and electric from SEEA



Appendix – Comparison of Well-to-Wheel Emission Factors

Table 24 presents a comparison of default emission factors for various vehicle types from GREET® 2016 and AFLEET as compared to SEEAT emissions factors (based on GREET Model version 1.8c). These emission factors include the full-fuel-cycle with many assumptions. GTI recommends a more detailed review of GREET® 2016 default assumptions regarding LPG and other fuels to address any inconsistencies and to update vehicle data based on recent engine developments.

Table 24 – Comparison of Default Emission Factors

GREET® 2016 Default Emission Factors			
	LPG	**CNG**	**LS Diesel**
School Bus			
GHG (lb/MMBtu)	190.551	197.237	217.623
NOx (lb/MMBtu)	0.145	0.146	0.182
SOx (lb/MMBtu)	0.058	0.039	0.047
Mileage (mi/DGE)	7.0	7.0	8.2
Medium-Duty Vehicles: Conventional and LS Diesel			
GHG (lb/MMBtu)	190.214	198.193	217.624
NOx (lb/MMBtu)	0.180	0.149	0.189
SOx (lb/MMBtu)	0.057	0.040	0.047
Mileage (mi/GGE)	9.1	6.3	7.4
Light-Duty Vehicles: Conventional and LS Diesel (Light Commercial Truck/LDT2)			
GHG (lb/MMBtu)	190.015	197.324	219.077
NOx (lb/MMBtu)	0.161	0.170	0.301
SOx (lb/MMBtu)	0.058	0.039	0.046
Mileage (mi/GGE)	7.7	7.7	12.6
CA Reformulated Gasoline (SI ICEV Car)			
GHG (lb/MMBtu)	215.901		
NOx (lb/MMBtu)	0.170		
SOx (lb/MMBtu)	0.093		
Mileage (mi/GGE)	28.70		
SEEAT (Light Duty Vehicle)			
	LPG	**CNG**	**Diesel**
GHG (lb/MMBtu)	180.568	161.680	203.457
NOx (lb/MMBtu)	0.143	0.110	0.171
SOx (lb/MMBtu)	0.054	0.026	0.055
AFLEET Emission Factors			
	LPG	**CNG**	**Diesel**
GHG (lb/MMBtu)	184.559	177.330	212.058
NOx (lb/MMBtu)	Provided for gasoline or diesel by vehicle type with an alternative fuel multiplier		
SOx (lb/MMBtu)	N/A	N/A	N/A