Energy Savings, Consumer Economics, and Greenhouse Gas Emissions Reductions from Replacing Oil and Propane Furnaces, Boilers, and Water Heaters with Air-Source Heat Pumps

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July 2018

Report A1803

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Contents

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Steven Nadel has been ACEEE's executive director since 2001. He has worked in the energy efficiency field for more than 30 years and has over 200 publications. His current research interests include utility-sector energy efficiency programs and policies, state and federal energy and climate change policy, and appliance and equipment efficiency standards. He joined ACEEE in 1989 and previously served as deputy director of the organization and director of ACEEE's Utilities and Buildings programs. Prior to ACEEE, Steve planned and evaluated energy efficiency programs for Massachusetts's largest utility. He also ran energy programs for Massachusetts's largest environmental group and for a community organization working on housing rehabilitation in the poorest neighborhoods of New Haven, Connecticut. Steve earned a master of science in energy management from the New York Institute of Technology and a master of arts in environmental studies and a bachelor of arts in government from Wesleyan University.

Acknowledgments

This report was sponsored by Eversource, National Grid, the New York State Energy Research and Development Authority (NYSERDA), Southern California Edison, and United Illuminating. Assistance with the analysis was provided by Jennifer King, and assistance with research was provided by Hannah Bastian, both research analysts in the ACEEE Buildings Program. The author gratefully acknowledges the external reviewers, internal reviewers, colleagues, and sponsors who supported this report. External expert reviewers were Chris Chan and Joe Swift, Eversource; Jeff Deason, Lawrence Berkeley National Laboratory; Keith Dennis, National Rural Electric Cooperative Association; Christopher Dymond, Northwest Energy Efficiency Alliance; Tom Eckman, Northwest Power and Conservation Council; Randall Higa and Michelle Thomas, Southern California Edison; Tony Larson and Brenda Pike, National Grid; Jim Lazar, Regulatory Assistance Project; David Lis, Northeast Energy Efficiency Partnerships; Bill Liss, Gas Technology Institute; Patrick McDonnell and Lisa Boba, United Illuminating; Chris Neme, Energy Futures Group; and Marsha Walton and Donovan Gordon, New York State Energy Research and Development Authority. Internal reviewers were Jennifer Amann, Naomi Baum, Neal Elliott, Maggie Molina, and Lowell Ungar. The author also gratefully acknowledges the assistance of Mary Robert Carter with graphics. External review or support does not imply affiliation or endorsement. Last, the author would like to thank Fred Grossberg for developmental editing; Elise Marton, Kristin Cleveland, Sean O'Brien, and Roxanna Usher for copy editing; Mary Robert Carter for formatting; and Eric Schwass, Dawn Selak, Maxine Chikumbo, and Wendy Koch for helping to launch this report into the world.

Executive Summary

This study looks at the energy, financial, and greenhouse gas emissions (GHG) impacts of converting oil and propane furnaces, boilers, and water heaters to high-efficiency electric heat pumps. We also examine customer satisfaction with heat pumps and emerging program experience promoting electrification of home heating.

Several studies have found that electrification of space and water heating will be needed if the United States is to meet long-term goals for reducing emissions of greenhouse gases. While other studies have examined the economics of heat pumps relative to natural gas furnaces, this study fills a gap in the literature by examining key questions about heat pumps relative to fuel oil and propane, which are the primary sources of heat for 12% of US homes (and much higher percentages in the Northeast, Mid-Atlantic, and rural regions of the country).

ENERGY USE

For this study we primarily examined full replacements of existing oil and propane systems with heat pump systems at various efficiency levels at the time when an existing system fails and needs to be replaced. We found that such replacements will often reduce total source energy use (including energy used at power plants to generate electricity) as long as power comes from an efficient generating plant, such as a combined-cycle natural gas plant, or from renewable energy generation.

CONSUMER ECONOMICS

For replacements at the time when an existing oil or propane system fails, we find that high-efficiency heat pumps (efficiency meeting or exceeding ENERGY STAR® levels) can provide economic benefits to consumers in many applications and regions. Specifically, we find the following.

Water heaters. Heat pump water heaters often have a lower initial cost than oil water heaters, in addition to their lower operating costs. Heat pump water heaters are more expensive than propane water heaters, but the lower operating costs typically pay back to consumers in less than five years.

Furnaces. For most of the country, homeowners will benefit from substantial life-cycle cost savings by replacing an oil or propane furnace with a high-efficiency heat pump at the time the furnace needs replacing. Simple payback periods to consumers are often just a few years. The exception is in the Upper Midwest (we looked at Illinois, Michigan, and Wisconsin) due to high electricity prices and relatively low current and projected oil and propane prices in those states as well as reduced heat pump performance at cold temperatures.

Boilers. Replacement of oil boilers with ductless heat pumps often produces life-cycle cost savings. Outside the Upper Midwest, consumer payback periods are often on the order of five years. Life-cycle cost savings and payback periods vary more substantially when propane boilers are replaced. While a payback of five years or more may not be attractive for many consumers, ductless heat pumps can improve homeowner comfort by providing air-conditioning in homes heated with boilers.

These findings are based on statewide averages and do not assume any financial incentives to convert to heat pumps, nor do they include any price on GHG emissions. Results of our consumer payback analysis for representative products at the regional level are summarized in table ES1.

Table ES1. Representative average simple payback period for installing a heat pump at the time an existing oil or propane system needs to be replaced

	Average simple payback period (years)				
Comparison	US	West	Midwest	Northeast	Southeast
Oil furnace (83% AFUE) vs. HP (8.5 HSPF), includes AC savings	0.9	1.4	1.3 in MO; no savings in Upper MW	1.9	0.8
Propane furnace (80% AFUE) vs. HP (8.5 HSPF), includes AC savings	1.5	1.7	3.4 in MO; no savings in Upper MW	2.0	1.3
Oil boiler (86% AFUE) vs. ductless HP, without AC	4.4	7.3	18.8	6.2	5.1
Propane boiler (84% AFUE) vs. ductless HP, without AC	16.1	12.1	19.8	8.5	9.1
Std. oil water heater to HPWH (2.0 rated EF)	Immediate	Examined only at a national level			
Std. propane water heater to HPWH (2.0 rated EF)	3.9				

We also examined early replacement of furnaces and boilers (before the existing equipment fails) and partial replacement (installing a heat pump but using the existing heating system to provide supplementary heat). For early replacement of oil furnaces, typical consumer paybacks are 4–10 years, while the figures for propane furnaces and oil boilers range from about 5– 20 years. Early replacement of propane boilers and most partial replacements have typical paybacks exceeding 10 years, with the exception of oil furnaces in some states and propane furnaces in a few states.

This study complements a prior ACEEE study that found that switching from electric furnaces to heat pumps is often financially attractive to consumers, as is converting from electric baseboard heat to heat pumps in homes with ducts or homes with above-average energy use for space heating. Work by others has identified highly efficient new homes as another attractive market for heat pumps. On the other hand, another prior ACEEE study found that the economics of converting gas furnaces to heat pumps will often not be compelling to homeowners (e.g., simple payback periods commonly exceed 10 years, although they are lower in the Deep South).

Together, these various studies identify several promising applications for pursuing conversion to heat pumps: homes now using oil or electric resistance heat, and homes with propane furnaces.

GREENHOUSE GAS EMISSIONS

Relative to 2016 average emissions rates for electricity generation by state, we find that in all but a few states, replacing oil or propane space and water heating systems with heat pumps will generally reduce emissions. As the grid gets cleaner over time, emissions reductions will be likely in all states.

CONSUMER ACCEPTANCE

This study also summarizes recent work by others on consumer acceptance of heat pumps and early efforts to promote conversion of fossil fuel systems to heat pumps. Consumer acceptance studies generally find positive public attitudes toward heat pumps but indicate that comfort at cold temperatures, operating costs, aesthetics, noise, and reliability are sometimes issues.

PROGRAM EXPERIENCE

Some early programs to promote heat pumps have met substantial success, and others have been less successful. Programs in Maine, Massachusetts, Vermont, and the Northwest have incentivized the purchase of thousands of heat pumps, primarily ductless models, and the market share of ductless heat pumps now stands at 13% in the Northwest. The most successful programs tend to provide significant upstream incentives (to wholesalers) or midstream incentives (to contractors). They also include contractor training and certification so that systems are properly installed.

Many of the most successful programs, however, have targeted homes with electric resistance heat or homes without air-conditioning, where ductless heat pumps are a way to install air cooling or to reduce use of electric resistance heat. While information is spotty, it appears that full replacements of oil, propane, or natural gas systems have been limited, as illustrated, for example, by the limited participation in the current programs offered in Palo Alto and Sacramento, California. Sacramento in particular is planning to substantially expand its efforts and incentives in order to achieve much higher participation.

RECOMMENDATIONS

We offer the following recommendations to states interested in pursuing heat pump programs as a way to support energy savings and emissions reductions. On the basis of our research, we recommend that policymakers and program implementers in states with substantial use of oil, propane, and electric resistance systems consider the following strategies.

- Offer programs to promote high-efficiency heat pumps to replace less-efficient oil and electric systems and sometimes propane systems as well. Such efforts can build on successful programs in the Northeast and Northwest. In addition, programs to promote heat pumps in new construction deserve attention.
- Provide training and education for contractors on proper installation and for homeowners on good applications for use of heat pumps.
- Conduct more field monitoring of actual heat pump performance and refine performance metrics based on this monitoring.

- Conduct additional research on supplemental heat for heat pump replacements in colder climates that could avoid the need to retain a fossil fuel system for supplemental heat on the coldest days.
- Continue work to develop improved cold-climate electric air-source heat pumps and gas-fired heat pumps.

These results are based on current conditions. The analysis should be repeated in a few years since product costs and performance as well as energy prices are likely to change and more stringent minimum efficiency standards for heat pumps will take effect in 2023.

Through these efforts we can increase the market share of heat pumps in attractive applications while building our understanding of what works and what does not in terms of both technologies and programs.

Introduction

In the past few years, growing concerns about climate change have led to research on how the states and the nation as a whole could achieve very large reductions in greenhouse gas emissions—reductions of 80% or more relative to recent annual emissions. For example, the California Council on Science and Technology found that to achieve even a 60% reduction of greenhouse gases in California would require four key strategies:

- Aggressive efficiency measures for buildings, industry, and transportation to reduce the need for both electricity and fuel
- Electrification of transportation and heat wherever technically feasible to avoid fossil fuel use as much as possible
- Developing emissions-free electricity production with some combination of renewable energy, nuclear power, and fossil fuels accompanied by underground storage of the carbon dioxide emissions, plus a near doubling of electricity production
- Finding supplies of low-carbon fuel to power transportation, such as airplanes and heavy-duty trucks, and for heating that cannot be electrified, such as high-quality heat in industry (CCST 2011)

The second strategy includes converting many homes from fossil fuels to electric space and water heating, with the assumption that much of this power will be clean due to the third strategy. Studies of New England and the United States reach similar conclusions (Howland et al. 2014; Williams et al. 2014).

However, for electrification of space and water heating to take place, new electric space and water heating systems must meet the needs of homeowners who are being asked to make investments in this equipment. These homeowners will generally be interested in the relative economics of electric and fossil fuel systems as well as impacts on home comfort. They may also be interested to know whether the reductions in greenhouse gas emissions are substantial.

In 2016 ACEEE conducted two studies on the use of heat pumps, one on replacement of electric resistance heat and the other on replacement of natural gas furnaces. The electric resistance study (Nadel and Kallakuri 2016) looked at detailed data on nearly 2,000 homes with electric resistance heating systems. It found that conversions are often attractive from an energy-saving and economic point of view in homes that have both electric furnaces and central air-conditioning. Conversion sometimes will make financial sense when an electric furnace needs replacing in homes without central air-conditioning or in homes with electric baseboards that use more heating energy than the average electrically heated home. But for typical homes with electric baseboards, payback periods for installing ductless heat pumps are often more than 10 years.

The natural gas study (Nadel 2016) looked at replacing natural gas furnaces with heat pumps, focusing on 20 large states in all regions of the country. This study also examined the use of heat pump water heaters versus conventional and condensing natural gas water heaters at the national level. This study found that electric heat pumps can save energy in warm states and have moderately positive economics in these states if they are replacing both a furnace and a central air conditioner. In moderately cold states (as far north as Pennsylvania and Massachusetts), energy can be saved if electricity comes from the highest-efficiency power plants, but from an economic point of view, life-cycle costs for gas furnaces in existing homes will be lower than for heat pumps in these states. For cold states, the study concluded, further development of cold-temperature electric heat pumps and gas-fired heat pumps will be useful. Likewise, heat pump water heaters (HPWHs) can save energy if power comes from efficient natural gas combined-cycle power plants or from renewable sources. The study found that life-cycle costs of HPWHs and new gas water heaters (both condensing and non-condensing) are similar.

In other words, according to Nadel 2016, switching to high-efficiency heat pumps can save some energy, but the economic benefits relative to natural gas furnaces are marginal. While the economic calculations were done from a life-cycle cost perspective, we can use the data from the study to calculate the average simple payback periods for a homeowner purchasing a space-heating heat pump instead of a gas furnace when an existing central air conditioner or furnace needs to be replaced. Paybacks range from five years to never paying back, depending on the state.[1]

The Nadel 2016 study used a methodology that compared natural gas use in a home furnace with natural gas burned at a power plant in order to power a heat pump. Thus, where source energy is saved, greenhouse gas emissions are also reduced. Reductions average about 11%, assuming that an 80% AFUE gas furnace (the minimum allowed by federal standards) is replaced with an 8.2 HSPF heat pump (also the federal minimum), and also assuming that the electricity comes from a state-of-the-art combined-cycle natural gas power plant.

Given the potential benefits but marginal economics of converting from gas furnaces to heat pumps, in this new study we explore some conversion opportunities that might be more attractive in the short term. Specifically, in this report we look at the energy savings, economics, and greenhouse gas reductions that could be achieved by converting oil and propane furnaces, boilers, and water heaters to heat pumps. We look at these three aspects of conversion because several states (e.g., California) use all three criteria to decide if converting from one fuel to another is in the public interest (CPUC 2013). We also review studies on consumer acceptance of heat pumps and profile some early programs that are promoting conversions to heat pumps.

By way of background, according to 2015 figures, more than 12% of US homes use oil or propane as their primary heating source; specifically, 5.7% of homes use oil and 6.6% use propane. For water heating the figures are somewhat lower: 2.4% use oil as their primary fuel and 3.9% use propane. However these fuels are more important in some regions than they are in others. For example, 39% of homes in New England are heated with fuel oil, as are 20% of homes in the Mid-Atlantic region. Propane use is above average in New England and in rural parts of the Midwest, South, and West (EIA 2011, 2017b).

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[1] This is for replacing an 80% AFUE gas furnace with a 10.3 HSPF electric heat pump. The lower paybacks were in the Deep South, such as in Florida.

The remainder of this report is divided into seven sections: (1) energy use analysis; (2) economic analysis (including a comparison with several other studies); (3) greenhouse gas analysis; (4) summary of analysis findings; (5) consumer acceptance of heat pumps; (6) program experience to date; and (7) conclusions and recommendations. Most of these sections begin with an explanation of methodology and then discuss results. Readers interested in just the results and not the technical details can jump to the fourth section, which begins on page 39.

This report is intended to provide factual information to help aid program and policy design. Beyond programs, we do not discuss the policy implications of this work, leaving this topic for future papers from ACEEE and others. We note that a number of other papers and reports have recently looked at electrification opportunities and policies, including those by Dennis (2015), EPRI (2018), Lawrence Berkeley National Laboratory (Deason et al. 2018), the National Renewable Energy Laboratory (Wilson et al. 2017 and Jadun et al. 2017), and the Rocky Mountain Institute (Billimoria et al. 2018). In addition, papers by the Southwest Energy Efficiency Project (SWEEP) and the Regulatory Assistance Project (RAP) are now in preparation. We note these other efforts for readers looking for additional perspectives. Some of these studies are discussed at the end of the second section of this report.

Energy Use Analysis

METHODOLOGY

Following from our earlier analysis of gas furnaces versus heat pumps, we began by comparing the total energy use of oil and propane systems with the energy use of heat pumps, including the energy used to generate electricity and transmit it to a home (Nadel 2016). The energy consumption analysis provided a foundation for the other analyses to build on.

At the house level we analyzed the following systems:[2]

Propane furnaces

- 80% annual fuel utilization efficiency (AFUE) furnace (the current federal minimum efficiency standard)[3]
- 95% AFUE furnace (the most common high-efficiency furnace and the ENERGY STAR® level for the North)
- 97% AFUE furnace (the ENERGY STAR Most Efficient level)

[2] There are also dual-fuel heat pumps and ground-source heat pumps on the market. Dual-fuel heat pumps operate in heat pump mode in mild weather but use a furnace in cold weather. Ground-source heat pumps use the relatively stable temperature of the ground to provide higher heat pump efficiencies, but at a significantly greater cost than conventional air-source heat pumps. To keep our project scope within the bounds of available resources, we did not examine these systems. However, as discussed later in this report, we did conduct an economic analysis in which a heat pump serves the majority of the load but the existing heating system is left in place to provide heat on cold days.

[3] DOE 2018a provides information on current federal standards.

Oil furnaces

- 83% AFUE furnace (the current federal minimum efficiency standard)
- 95% AFUE furnace (the most common efficiency for a condensing oil furnace)[4]

Ducted heat pumps

- 8.2 heating seasonal performance factor (HSPF) heat pump (current federal standard for split systems)
- 8.5 HSPF heat pump (the ENERGY STAR level)[5]
- 10.3 HSPF heat pump (the ENERGY STAR Most Efficient level)[6]
- A cold-climate ducted electric heat pump. We used a ducted heat pump because homes with furnaces already have ducts, allowing the installed cost to be substantially lower than if ductless heat pumps are installed. Some cold-climate ducted heat pumps are based on traditional US split air conditioner and heat pump designs, and others are effectively large mini-split systems connected to ducts. This was a preliminary analysis based on one field test that found a seasonal 2.8 coefficient of performance (COP) in Connecticut (Johnson 2013). This COP is approximately a 9.55 HSPF.[7] More products and data are needed.
- A gas-fired heat pump. This was also a preliminary analysis based on projections of 1.31–1.38 COP from one research project (Garrabrant 2014). More data, ultimately including field data, are needed.

Propane boilers

- 80% AFUE (a typical old boiler in the building stock; this was the federal minimum efficiency standard from 1992 to 2012)
- 84% AFUE (the current federal minimum standard)
- 90% AFUE (the ENERGY STAR level)

Oil boilers

- 86% AFUE (the current federal minimum standard)
- 91% AFUE (a common level for condensing oil boilers)[8]

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[4] See ENERGY STAR 2018b. As of May 27, 2018, six units are listed, but it appears that these represent three unique units sold under two different brand names.

[5] Under a recently negotiated rulemaking agreement, the federal minimum standard will rise to 8.8 HSPF in 2023. At that time the ENERGY STAR level will also rise, likely to a value above 9.0.

[6] The ENERGY STAR Most Efficient level requires an HSPF of 9.6, but as of January 2016 the average HSPF of the ENERGY STAR Most Efficient units listed on the Environmental Protection Agency (EPA) website was 10.3 (Nadel 2016).

[7] HSPF estimated by multiplying seasonal COP by 3.412 watt-hours per Btu, which is the heat value of a watt-hour of electricity.

[8] See ENERGY STAR 2018a. As of May 28, 2018, 21 units are listed with an AFUE of 90 or more, although some of these units represent very similar products from the same manufacturer.

Ductless heat pump

- 3.42 seasonal COP (a typical product installed in the Pacific Northwest but adjusted to the average US climate)[9]

Water heaters

- Propane storage water heater with an energy factor (EF) of 0.59 (a typical unit in the building stock; this was the federal minimum standard from 2004 to 2015)[10]
- Propane storage water heater with an EF of 0.62 (the current federal minimum standard)
- Propane storage water heater with an EF of 0.67 (this is the ENERGY STAR level for water heaters with a capacity of 55 gallons or less)
- Propane storage water heater with an EF of 0.80 (this is a typical condensing water heater) (ACEEE 2015)[11]
- Oil storage water heater with an EF of 0.55 (a typical unit in the building stock) (ACEEE 2015)
- Oil storage water heater with an EF of 0.62 (the current federal minimum efficiency standard)
- Oil storage water heater with an EF of 0.85 (a typical oil boiler that supplies hot water to a well-insulated storage tank) (ACEEE 2015)
- Heat pump water heater with an EF of 1.92 (average performance in a 2015 field study) (Ealey and Domitrovic 2015)[12]
- Heat pump water heater with an EF of 2.8 (the best units exceed 3.0, but we reduced this to reflect typical performance in the field) (see ENERGY STAR 2018c)

There are also tankless water heaters, but we did not include them because they are less common and because their installation costs can vary widely depending on site-specific considerations.

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[9] Data for the Northwest from Ecotope 2014. This reference contains data on coefficient of performance (COP) as measured in a sample of installations in locations ranging from 4,222 to 7,035 heating degree days. Nadel and Kallakuri (2016) developed a regression equation to correlate coefficient of performance to annual heating degree days. This analysis does not include any impact that zoning may have on savings from ductless heat pumps. Data from homes heated with electric resistance heat indicate that energy use can be reduced by 20% or more because individual room thermostats allow some unused rooms to be cooler, thereby saving energy (DOE 2018b). While ductless heat pumps often heat a few rooms, they may also benefit from such a zoning effect. We did not include such an effect in our analysis as we could not find any studies that have investigated this effect for ductless heat pumps.

[10] As of January 1, 2018, ratings are expressed in terms of modified EF (MEF). Much more data are available for EF, however, so we used EF for this analysis.

[11] The ENERGY STAR minimum is 0.77, but most condensing units have a somewhat higher efficiency.

[12] We are not aware of systematic differences between rated and field performance of propane and oil water heaters and therefore did not adjust rated performance for these other water heater types.

At the power plant level, we looked at four possible marginal heat rates.[13] Heat rate is what we used to convert electricity consumption into equivalent British thermal units (Btus) of source energy (source energy includes energy consumed at a power plant in order to generate electricity).

- 6,096 Btus/kWh (the best actual heat rate in 2016 as recorded in a database maintained by the federal Energy Information Administration (EIA)[14]
- 7,652 Btus/kWh (the average combined-cycle plant heat rate in 2016, per EIA 2017b)
- 10,362 Btus/kWh (the average steam turbine heat rate in 2016, per EIA 2017b). While gas-fired steam turbines are not common, some coal turbines have been converted to gas, and some additional conversions may happen in the future. This is also something of a proxy for the energy use of a typical coal-fired steam turbine.
- 4,754 Btus/kWh (a scenario with marginal generation coming half from renewables and half from high-efficiency natural gas). We used 3,412 Btus/kWh for renewables (the Btu value of a kWh of electricity[15]) and 6,096 Btus/kWh for natural gas (per the best-performing natural gas plant in 2016 as discussed above). California, Hawaii, New York, Oregon, Vermont, and the District of Columbia have all established renewable energy standards that call for obtaining 50% or more of their electricity from renewable sources (Durkay 2018).

Our analysis included allowances for electric transmission and distribution (T&D) losses of 6%.[16] For oil and propane, we included losses of 0.7% and 1.6%, respectively, based on estimates of transportation and distribution losses by Leslie (2014).

The analysis was conducted for 16 states plus two 2-state regions. The EIA *Residential Energy Consumption Survey* (RECS) for 2009, issued in 2013, examined 16 of the most populous states individually: Arizona, California, Colorado, Florida, Georgia, Illinois, Massachusetts, Michigan, Missouri, New Jersey, New York, Pennsylvania, Tennessee, Texas, Virginia, and Wisconsin (EIA 2013). We included all of these states in our analysis. In addition we

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[13] All are based on higher heating value, meaning that they include the energy recovered by condensing any steam product of combustion.

[14] This represents the most efficient generating unit in 2016. This is Virginia Electric Power Company's Brunswick County Power Station, a new combined-cycle plant that began operation in 2016. Heat rate derived from data available at www.eia.gov/electricity/data/eia923/.

[15] This is consistent with the captured energy methodology developed by DOE for valuing electricity generated with renewable resources (Donohoo-Vallett 2016).

[16] Per EIA data. The 6% figure represents the average over the previous decade. See www.eia.gov/tools/faqs/faq.cfm?id=105&t=3. Other sources have estimated losses as high as 8%, but these appear to include theft and unaccounted-for power. For electric we include both transmission and distribution losses, as these losses occur downstream of the power plant.

examined the two-state pairs of Oregon/Washington and North/South Carolina.[17] Together these states cover a wide range of regions and climates throughout the United States. Our analyses drew on average conditions in each state and did not necessarily apply to regions within each state that are significantly warmer or colder than the state average. Furthermore, by looking at entire states, we may have missed variations in energy prices between different utilities serving the same state.

Our analysis made use of average space-heating consumption data, by state, for oil- and propane-heated homes in the RECS for 2009. We assumed that the average 2009 furnace or boiler captured in the RECS had an 80% AFUE and that more-efficient furnaces or boilers would use proportionally less.[18] We also assumed that if a gas furnace was converted to a heat pump, it would need to supply the same number of Btus that were provided by the current oil or propane system.[19] In many states, according to RECS, oil-heated homes use more energy than propane-heated homes. The survey indicated that oil-heated homes are on average older and often larger. Our analysis did not include oil systems in Arizona, Colorado, Tennessee, or Texas as the RECS sample did not have any oil-heated homes in those states.

We used the RECS figures for 2009 because energy consumption estimates at the state level from the RECS for 2015 are not yet available. Furthermore, the sample size for the 2015 RECS is much smaller than for the 2009 RECS, and only limited state-level data are likely to be available in the 2015 RECS.

We estimated the seasonal efficiency for ducted heat pumps at different locations using a methodology developed by the Florida Solar Energy Center (FSEC), which estimates seasonal heat pump efficiency as a function of local winter design temperature (Fairey et al. 2004). Fairey et al. find that depending on winter temperatures, heat pump seasonal efficiency can be as much as 40% below the rated value (as in Minnesota) or as much as 20% above the rated value (as in Florida). For ductless heat pumps, we estimated seasonal efficiency as a function of annual heating degree days with a regression equation developed

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[17] For OR/WA the RECS data also include AK and HI, but these other two states have only a modest effect on the data. For the states not included in our analysis, RECS generally groups three or more together. These are typically states with lower populations than those examined individually or in pairs.

[18] In 2009 the installed stock of furnaces included a mix of old furnaces and boilers with AFUE below 80%, AFUE 80% units, and some condensing furnaces with AFUE of 90% or above. In some colder states, the average in 2009 may have been above 80%. To the extent that this occurs, our analysis is conservative, as we will have underestimated the gas use of AFUE 80% furnaces and, by extension, also underestimated the gas use of condensing furnaces.

[19] Furnaces contribute to heat losses from a house as heat from the house escapes through the flue. With induced-draft furnaces (i.e., most post-1992 furnaces), these losses are generally modest; for condensing furnaces (with an AFUE of 90% or more), flue losses are smaller still. We did not consider this effect in our analysis. Furthermore, our furnace analysis does not include electricity to power the blower. A small amount of blower power is included in the HSPF ratings of heat pumps, but these ratings essentially assume very low friction in duct systems. In the field, most duct systems have a lot of friction; hence the HSPF ratings include only a fraction of typical blower power.

by Nadel and Kallakuri (2016) using field performance data from Montana and other states in the US Northwest.

ENERGY USE COMPARISON RESULTS

We compared different types of oil, propane, and heat pump systems on total source energy use (e.g., including losses in the generation and transmission of electricity) in order to provide a foundation for analyses in subsequent sections of this report. Details of our analysis are provided in Appendix A. In the sections below we provide key results in graphical form. In these graphs, where the electric heat pump uses less source energy, the bar goes above the zero line; where the oil or gas option uses less source energy, the bar goes below the zero line. In the body of the text we provide examples for oil furnaces, propane furnaces, propane boilers, and water heaters. Additional graphical analyses are provided in Appendix B.

Note that according to 2009 RECS data, the average US home uses a total of about 90 million Btus of energy per year.[20] When upstream losses are added, total source energy is about 161 million Btus per home annually.[21] The differences shown here between heat pumps and oil and propane systems are a fraction of this figure. While there are energy and carbon savings at stake, they are clearly not dramatic at the individual household level. As a result, attracting homeowners' attention to consider fuel switching is likely to be challenging.

Oil Furnaces

Our analysis of relative source energy use for oil furnaces and heat pumps is typified by a comparison between an 83% efficient oil furnace (the current federal minimum efficiency standard) and an 8.5 HSPF heat pump (the current ENERGY STAR level), as shown in figure 1. A heat pump typically uses less energy than an oil furnace provided that the electricity is generated by a high-efficiency combined-cycle gas power plant (e.g., the 6,096 heat rate shown in the figure) or a plant that is even more efficient. For warmer regions of the country, the heat pump uses less energy as long as the power comes from an average combined-cycle power plant (the 7,652 heat rate shown in the figure), and not just the highest-efficiency plants. Regions that mix combined-cycle power plants and a high percentage of renewable energy will also generally save energy in this comparison.

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[20] This represents site energy use and does not include associated energy losses at the power plant and in the T&D system. Over time this figure is likely to decline due to tighter building codes and retrofits to existing homes. We did not factor declining loads into our analysis.

[21] Derived by the author using data in EIA 2013 and 2018b.

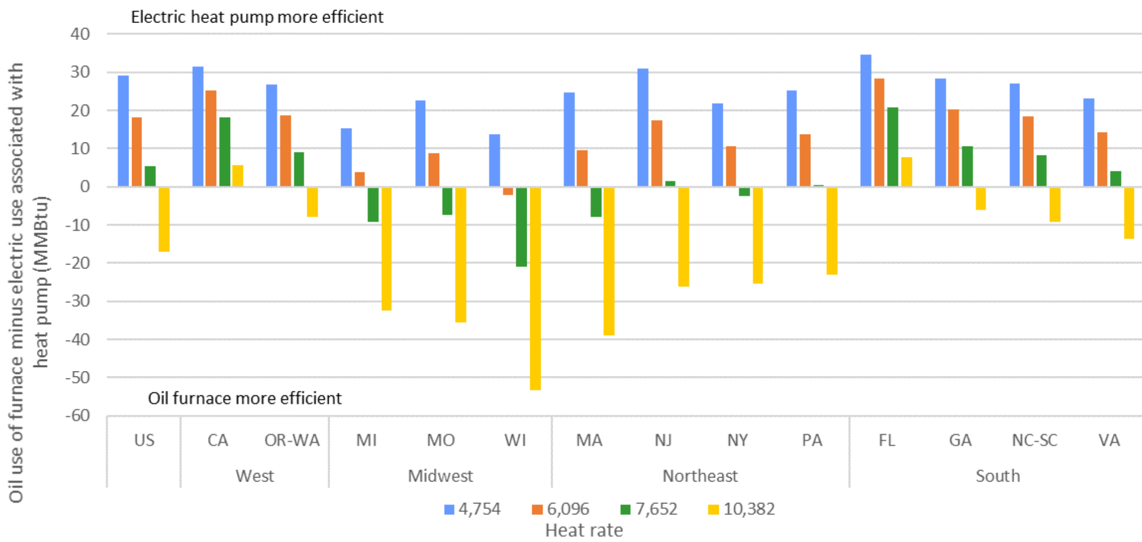

Figure 1. Comparison of annual energy use of an 83% AFUE oil furnace and an 8.5 HSPF electric heat pump

The results are very similar when comparing an 83% efficient oil furnace and an 8.2 HSPF heat pump (the current minimum standard) and when comparing a 95% efficient oil furnace with a very high efficiency heat pump; these results can be found in Appendix B.

If we compare a 95% efficient furnace with a cold-climate heat pump, source energy is saved across most geographies and power plant types, as shown in figure 2.

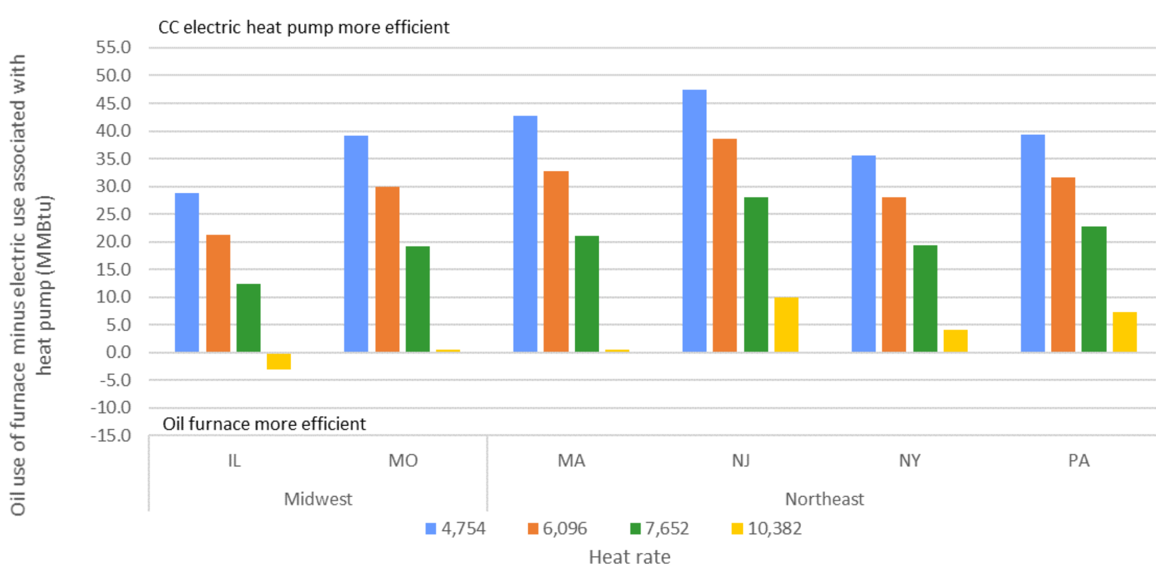

Figure 2. Comparison of annual energy use of a 95% AFUE oil furnace and a cold-climate electric heat pump

Propane Furnaces

For propane furnaces, results are similar to the results above for oil furnaces. Specific results for propane furnaces are provided in Appendix B. In addition to propane comparisons similar to those shown above for oil, we also compared a cold-climate electric heat pump with a propane-fired heat pump. If propane-fired heat pumps are perfected, they could in many cases use less energy than a high-efficiency heat pump, except in applications where the heat rate for power generation is under 5,000 Btu per kWh (see figure 3).

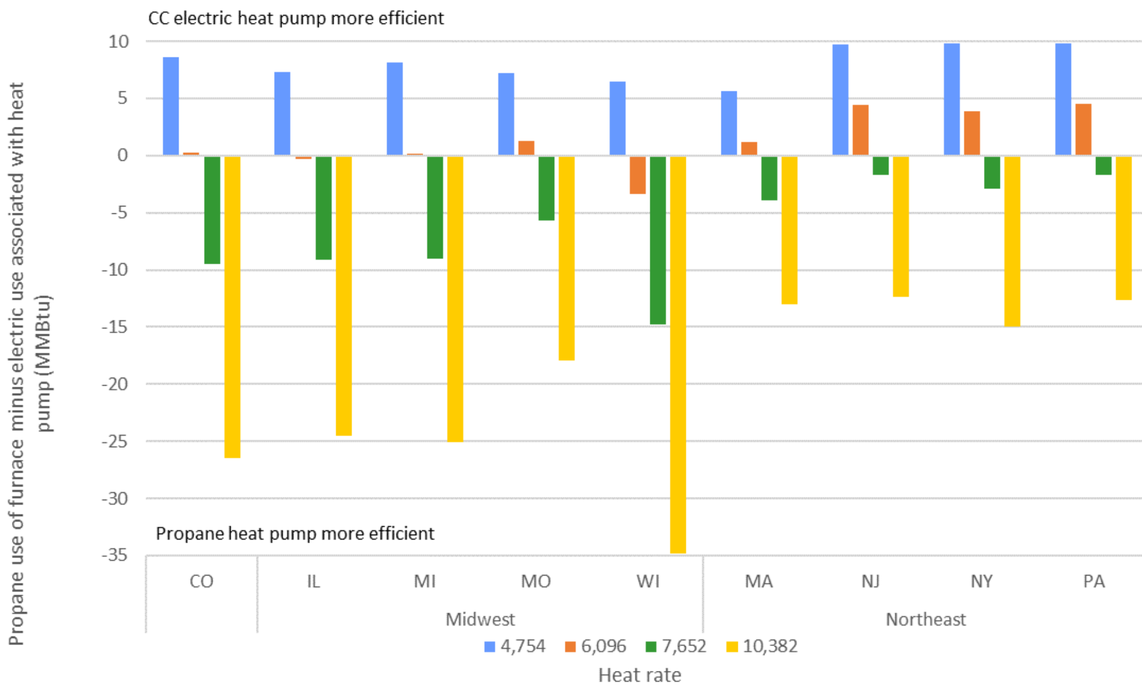

Figure 3. Comparison of annual energy use of a propane heat pump (~135% AFUE) and a cold-climate electric heat pump (in-field HSPF approaching 10). This analysis is highly approximate, as the efficiency of the electric heat pump is based on a single field study in one city and extrapolated to other regions, and the efficiency of the gas heat pump is based on modeling. The design temperature and average temperature by state are also approximate.

Oil and Propane Boilers

Our analysis for oil and propane boilers compared both minimum-efficiency and condensing boilers with ductless electric heat pumps that are designed to work well in cold climates. Most homes with boilers do not have ducts, and therefore ducted heat pumps are not generally an option. Overall, ductless heat pumps have a high efficiency; generally they save energy relative to any combined-cycle power plant and sometimes relative to even the least efficient gas-fired power plant we examined. Typical results are shown in figure 4 for propane boilers. Results for other boiler comparisons can be found in Appendix B.

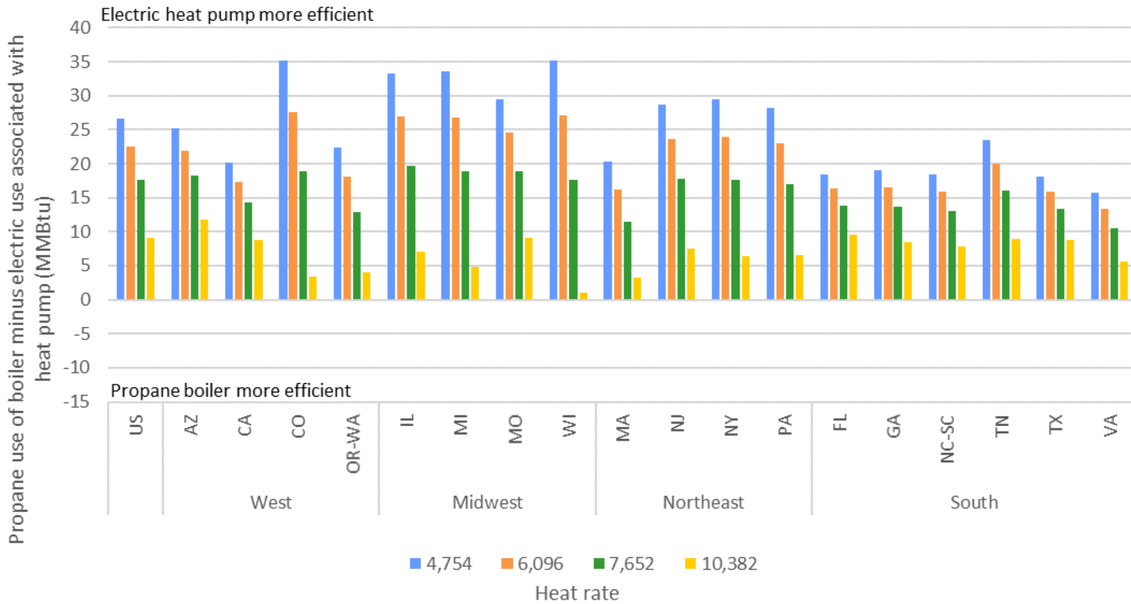

Figure 4. Comparison of annual energy use of an 84% AFUE propane boiler and a ductless electric heat pump

Btu savings are greater for oil than for propane because the average oil-heated home uses more heating energy than the average propane-heated home. This is due to the fact that oil-heated homes tend to be larger and older than propane-heated homes (EIA 2017a).

Water Heaters

Our water heater analysis was done at the national level, as hot water use does not vary as extensively from region to region as space-heating energy use.[22] Our analysis was based on a typical home and did not adjust for the fact that where in a home a heat pump water heater is installed has some impact on its energy use.[23] Our analysis is summarized in figure 5, which shows energy use at different heat rates for electricity generation. In general we found that heat pump water heaters use less source energy than non-condensing water heaters fueled by propane or oil with any electricity-generating technology. Relative to condensing water heaters (efficiency of about 80% or more), a top-tier heat pump water

[22] Water heater energy use does vary somewhat from region to region, but not dramatically. For example, in 2009, the average home in the West used exactly the same amount of energy for water heating as the national average, while homes in the Northeast and Midwest used 11% and 17% more, respectively, and homes in the South used 16% less (EIA 2013).

[23] For example, a field monitoring study by Pacific Northwest National Laboratory found that if the heat pump is located in the conditioned space, about 40% of the heat in the water in the winter comes from increased energy use for space heating, while in the summer about 40% of heat in the water comes from cooling the living space, thereby reducing air-conditioning energy use (Widder et al. 2014). We did not factor this into our analysis because only some heat pump water heaters are located in a conditioned space, and also because making the necessary adjustments would be complex.

heater will use less energy while a more standard heat pump water heater will use about the same amount of energy if the electric power comes from a combined-cycle power plant.

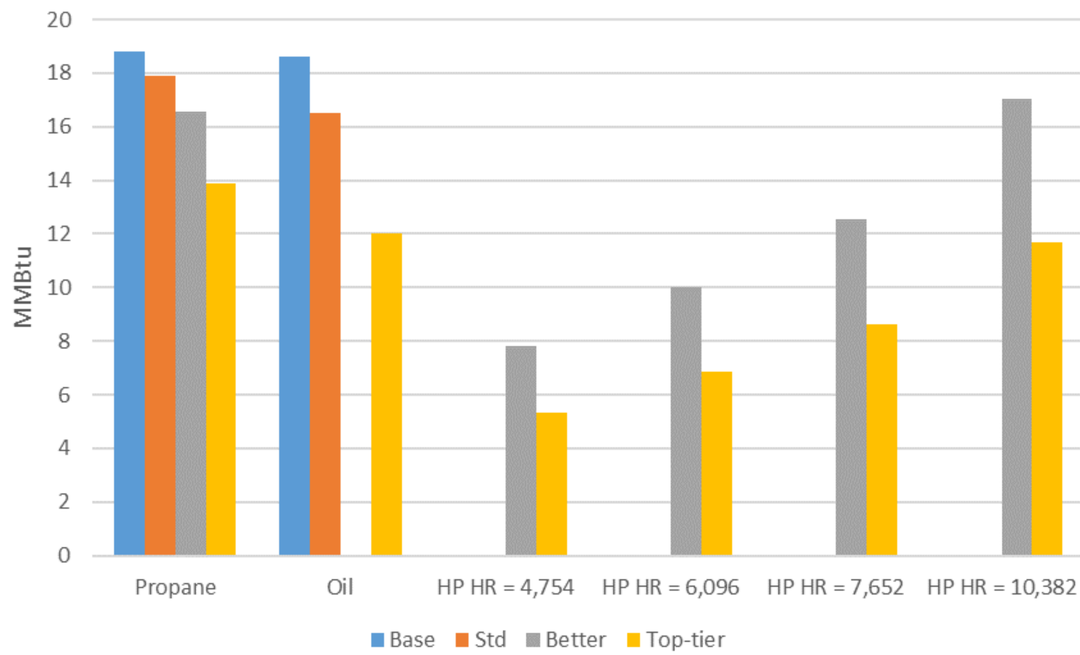

Figure 5. Comparison of annual source energy use of various propane, oil, and electric heat pump water heaters. For heat pump water heaters, we show energy use at four different heat rates for electric generation.

Economic Analysis

We examined the economics of the different options from the homeowner's perspective.

METHODOLOGY

For this analysis we generally used estimates of installed costs from the most recent US Department of Energy (DOE) Technical Support Documents (TSDs) for furnaces, boilers, water heaters, and residential central air conditioners and heat pumps.[24] We also included cold-climate ducted heat pumps as potential replacements for furnaces, and ductless heat pumps as potential replacements for boilers.[25] All of our costs were adjusted to 2017 dollars based on the Federal Reserve Bank's implicit price deflator. We did not include gas heat

[24] These cost estimates assume that a house has adequate electric service to install a heat pump. For houses that have central air-conditioning, this will generally be the case. But for some old houses without central air-conditioning, upgrading the electric service will be needed.

[25] For cold-climate ducted heat pumps, we estimated installed costs at 30% more than a SEER 16 ducted heat pump, based on a suggestion from a major manufacturer that plans to soon introduce a ducted cold-climate heat pump to the US market. For ductless heat pumps, costs come from an ACEEE analysis of a Massachusetts database of installed costs for this equipment. We looked at homes installing two or more multi-head heat pumps, finding an average cost of $7,065 per heat pump. The sample size was 496 homes, nearly all of which purchased two multi-head heat pumps (just six homes installed three). The data covered installations through June 2017 (MassCEC 2017). These ductless heat pump costs are similar to estimates in a recent study for the Electric Program Administrators of Massachusetts (Navigant 2018).

pumps in the economic analysis because products are still in the prototype stage and solid cost estimates are not available.

For our analysis we looked at four cases:

1. Replacing an existing furnace with a heat pump at the time the existing heating system needs replacement, and assuming that a house does not have central air-conditioning.
2. For homes with central air-conditioning, installing a heat pump instead of a central air conditioner at the time the central air conditioner needs to be replaced.
3. Early replacement of a still-functioning oil or propane system with a heat pump. These analyses generally did not include air-conditioning (as discussed below, inclusion of air-conditioning in some of these analyses did not have a substantial impact on the results).
4. Installation of a heat pump to supplement an existing oil or propane heating system; this analysis also generally did not include air-conditioning.

For the first analysis, we looked just at capital and heating costs and did not consider air-conditioning operating costs. For the second analysis, we included reductions in air-conditioning operating costs relative to a base-case central air conditioner that meets current federal minimum efficiency standards. In the 2015 RECS, 65% of US homes had central air-conditioning, including 36% in the Northeast, 71% in the Midwest, 82% in the South, and 55% in the West.[26] The RECS reports that 87% of homes built from 2000 to 2015 included central air-conditioning (EIA 2017a).

For the third and fourth analyses, we assumed that the existing heating system will need to be replaced in five years and included the cost of this replacement in the analysis, discounted by a 5% per year real discount rate. For all but the fourth analysis, we assumed that all heat is provided by the heat pump (see box below, "Supplying All Heating Needs with Heat Pumps"). For the fourth analysis, we assumed that the heat pumps provide 63% of the annual space heating need and the existing systems provide 37%, based on the results of a field study on nine homes in New Hampshire (ERS 2014). For this last analysis, because the heat pumps do not serve all loads, we assumed a 20% reduction in the cost of ductless heat pumps because the units could be sized to meet most loads but not all loads.[27] We did not reduce the cost of ducted heat pumps because while the heat pump can be downsized a little, there are additional costs for an air handler and controls needed to set up a dual heat pump/furnace system.

Our analyses were for existing homes. For new construction, the results might be different, as the cost of oil and propane access and oil storage can be saved. In addition, high-performance ductless heat pumps may be an option for new construction. These systems are

[26] Many of the major cities in the West are on the Pacific coast, where there is less need for air-conditioning than in the interior.

[27] ACEEE estimates based on discussions with experts.

generally more efficient than ducted heat pumps but incur higher capital costs. On the other hand, by avoiding the costs of ducts (and the space taken up by ducts and other inside equipment), they may be cost competitive in many new homes.

We based energy costs in our analysis on data from EIA on average oil, propane, and electric prices by state in 2016.[28] We then adjusted for the expected nationwide increase in energy costs during the operating life of this equipment. Specifically, based on EIA's *Annual Energy Outlook 2018* (AEO) (EIA 2018a), we compared estimated residential oil, propane, and electric prices in 2030 and 2016 and applied this ratio to state-specific energy prices from 2016. While results varied from region to region, at the national level the EIA reference case includes projected increases of 78%, 15%, and 10% in the price of heating oil, propane, and electricity, respectively, over the 2016–2030 period (EIA 2018a).

In many states, energy costs vary by season. Our analysis adjusted for seasonal effects on electricity and propane prices by developing a state-by-state factor comparing 2016 winter prices (January–March and November–December 2016) with annual average prices. In most states, winter propane and electricity prices are slightly lower than annual prices, but the adjustment was generally small. A substantial majority of residential fuel oil is purchased in the winter, and therefore we did not need to adjust for seasonal differences in oil prices.

In many states the price of energy varies with the quantity used. For some residential customers, electricity price varies by time of use, and some states are moving toward default time-of-use rate design. Finally, the usage patterns of space and water heat vary by time of day. Our simple analysis did not address these three factors.

We calculated the life-cycle cost for each system type and location, assuming a 21-year equipment life and a 5% real discount rate. [29] We then subtracted the life-cycle cost of the oil or propane system from the life-cycle cost of the heat pump system to calculate the net life-

[28] www.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm.
www.eia.gov/electricity/sales_revenue_price/pdf/table4.pdf

[29] The DOE estimate of average life for residential furnaces (DOE 2016a). DOE estimates an average life of 15-25 years for central air conditioners and heat pumps (DOE 2016b) and 19-26 years for boilers (DOE 2015). We use the same 21-year period for our analyses on replacing furnaces with heat pumps. Using the same life simplifies the analysis; the small differences in average lifetime will not appreciably affect the results. For the analysis on replacing boilers we use a 20-year life as this is the rated life of a ductless heat pump (Mitsubishi 2018).

The 5% real rate is approximately the weighted average cost of utility capital considering both stock equity and bonds and is close to the cost of a home equity loan. Energy efficiency investments are commonly analyzed using the same discount rate as new generating plants and other energy system infrastructure, as energy efficiency reduces the need for this infrastructure. Currently utility capital cost is lower than 5% real (see pages.stern.nyu.edu/~adamodar/New_Home_Page/datacurrent.html), but 5% real represents a typical capital cost over the last decade. Secured home equity loans are currently running at about 5-6% nominal (see https://www.bankrate.com/finance/home-equity/current-interest-rates.aspx), which is about 3-4% real. But unsecured loans are more, particularly if borrowing is financed with a credit card. On the other hand, at today's low interest rates, returns on homeowner savings will generally be less than 5% real.

cycle cost for each comparison.[30] Boilers, furnaces, and heat pumps have periodic maintenance costs, but we did not include these in this analysis; doing so would have extended our research beyond the time we had available, and we believe the magnitudes to be similar.

Our analysis did not include a price on carbon, except for the modest impact of current cap-and-trade programs on energy prices in California and the Northeast, nor did our analysis consider incentives to promote heat pumps, which a few utilities are starting to offer. If a significant price on carbon or heat pump incentives were included in the analysis, the results would change.

While our main analysis used EIA's reference case for energy prices, we also conducted analyses using higher and lower energy prices, based on the EIA AEO high-oil-price and low-oil-price scenarios. For 2030 in the high scenario, oil, propane, and electricity prices are 63.5%, 25.4%, and 5.2% greater, respectively, than in the reference case. For 2030 in the low scenario, these prices are 38.1%, 20.3% and 4.4% lower, respectively (EIA 2018a).

We present further details of our analysis in tables A7–A15 in Appendix A.

[30] As noted above, we also looked at installing a heat pump at the time when an existing central air conditioner needs replacement. For that analysis we included the incremental cost of a heat pump relative to a central air conditioner, the difference in heating costs between the heat pump and an oil or propane furnace meeting current federal equipment efficiency standards, and the savings in air-conditioning cost relative to a central air conditioner meeting current federal standards.

Supplying All Heating Needs with Heat Pumps

Our study is based on a heat pump providing all or nearly all of the space heat a home needs over the course of the year. Normal heat pumps provide energy savings relative to electric resistance heat down to roughly 15° F, while cold-climate heat pumps are designed to provide energy savings down to at least 5°F. So for locations where the temperature never gets below 15° or 5°F, serving all or nearly all a home's space heating with heat pumps is feasible provided the heat pump is sized for this heating load (and not sized just for the cooling load).

Several studies done for even colder climates show that obtaining most heat with a cold-climate heat pump is feasible. For example, the DOE Building America program did a long-term monitoring study on eight new homes in central Massachusetts (design temperature of about 0°F) that use only cold-climate ductless heat pumps for heating. This study found that the ductless systems provided excellent heating overall, but that the heat pump needs to be adequately sized for a home's maximum heating requirement. It also found that attention must be paid to air circulation, such as getting cool air to upper floors in summer and delivering adequate heat to rooms over unheated garages (Ueno and Loomis 2014).

Efficiency Vermont has also done a lot of work with cold-climate ductless heat pumps. For instance, the organization worked with Habitat for Humanity and other developers on new homes heated primarily with ductless heat pumps, with a small amount of supplemental heat available from an electric resistance coil in the ventilation system when temperatures are well below 0° (Clancy and Schneider 2011). Efficiency Vermont has also supported dozens of projects combining energy efficiency retrofits with ductless heat pumps in existing homes. Over a one-year evaluation period for heating, the group documented five homes heated with heat pumps alone and an additional three homes that used heat pumps with supplemental wood heat (L. Young, senior energy consultant, VEIC, pers. comm., June 11, 2018).

In Minnesota, the Center for Energy and the Environment (CEE) has just completed a project in which ducted or ductless cold-climate heat pumps were installed in homes with propane or electric resistance heat. Over the course of the winter (with temperatures going down to –25°F), the heat pumps provided more than 85% of the heat in homes with electric resistance backup and about two-thirds of the heat in homes with propane backup (Ben Schoenbauer, research engineer, CEE, pers. comm., May 31, 2018). Less heat was provided in propane homes because the controls were set to shut down the heat pump and switch over to the propane system at 5–10°F, while in the homes with electric backup the heat pumps continued to provide some heat at much lower temperatures (Schoenbauer, Bohac, and Haynor 2018).

These projects show that cold-climate heat pumps can provide all of an *efficient* home's heating needs in places like Massachusetts and Vermont, and that heat pumps can provide most of a normal home's heat in Minnesota. It would be useful to have additional studies on cold-climate heat pumps in homes that are not especially efficient.

Life-Cycle Cost Results

In the sections below, we first present the results for installing heat pumps when existing systems need replacement. We then proceed to early replacement and partial replacement.

Installing Heat Pumps When Existing Systems Need to Be Replaced

For Heat Pumps versus Furnaces

Our analysis of life-cycle cost savings for heat pumps relative to oil and propane furnaces is summarized in figures 6 (oil) and 7 (propane). These figures include air conditioner energy savings relative to a base case with a SEER 14 air conditioner in the South and SEER 13 in the North (the current federal minimum standards).[31]

For most of the country, homeowners would reap substantial life-cycle cost savings by replacing an oil or propane furnace with a high-efficiency heat pump at the time the furnace needs replacing. However this conclusion does not apply in the northern Midwest, where the combination of reduced heat pump performance in cold weather, relatively high electricity prices, and relatively low current and projected oil prices makes heat pumps noncompetitive on a life-cycle cost basis. The cost savings are greater in oil-heated homes than propane-heated homes due to the higher average energy consumption of oil-heated homes (attributable to both size and age differences). Among heat pumps, life-cycle cost savings are generally similar for mid-efficiency (HSPF 8.5) and high-efficiency (HSPF 10.3) models.

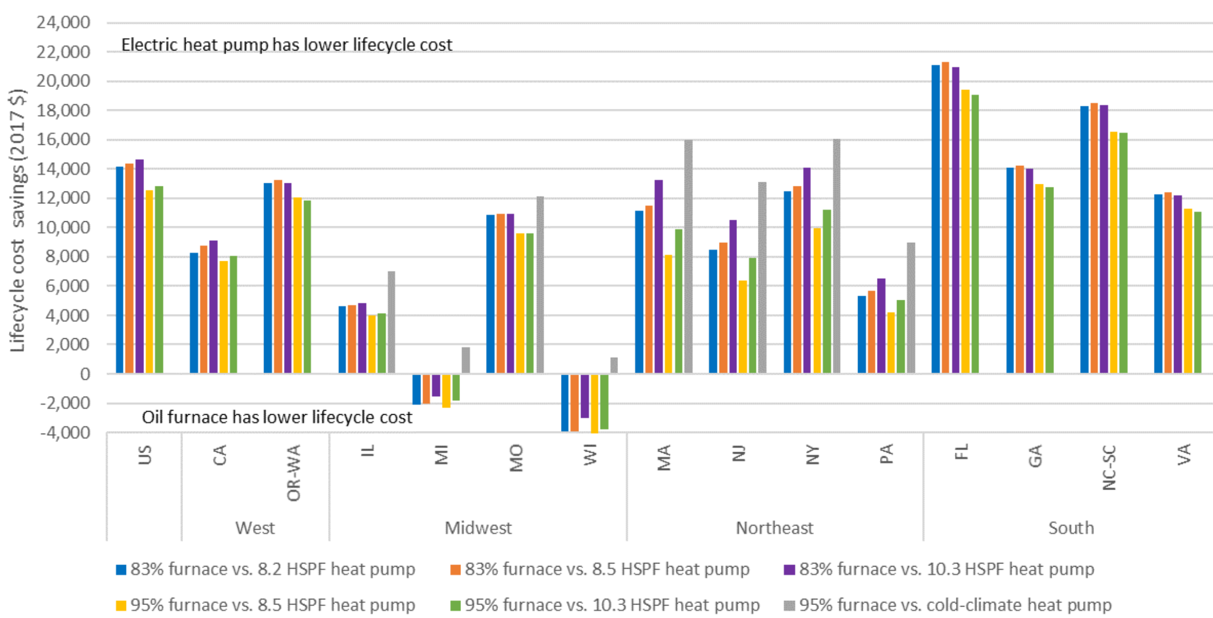

Figure 6. Life-cycle cost savings from replacing an oil furnace with a heat pump; includes air-conditioning savings. Oil furnaces are particularly common in the Northeast.

[31] *SEER* means seasonal energy efficiency ratio.

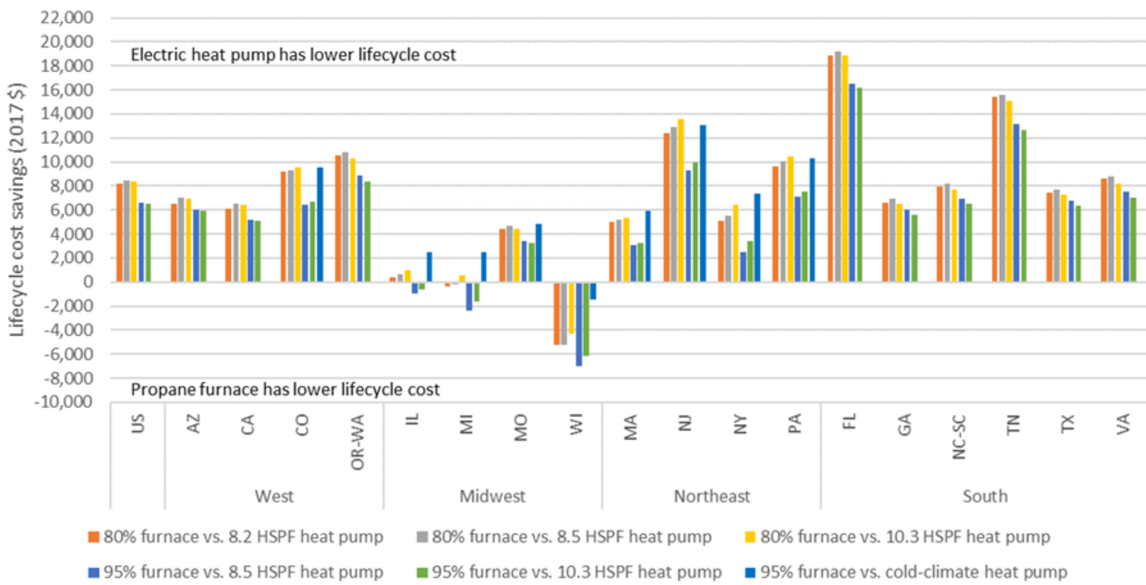

Figure 7. Life-cycle cost savings from replacing a propane furnace with a heat pump; includes air-conditioning savings

In our analysis, we assessed cold-climate heat pumps only for cold or moderately cold states (Colorado, Missouri, New Jersey, Pennsylvania, and states farther north), finding that these cold-climate heat pumps generally have lower life-cycle costs in these states than high-efficiency heat pumps that are not optimized for cold climates. However we caution that this result is based on limited performance and cost data on ducted cold-climate heat pumps. We did not examine gas-fired heat pumps in our economic analysis as mainstream products are not yet commercialized, and we therefore did not have a good foundation for estimating costs. Additional analysis is needed on both electric cold-climate heat pumps and gas-fired heat pumps as soon as additional performance and cost data become available.

While there are presently many ductless cold-climate heat pumps, ducted cold-climate products are very limited, and many of the systems available do not have enough heating capacity to provide adequate heat in an existing home on a cold day (for instance, only a few of the ducted systems listed in Northeast Energy Efficiency Partnership's database of cold-climate heat pumps can provide 40,000 Btus per hour at an outdoor temperature of 5°F, and none can provide 45,000 Btus or more per hour).[32] More ducted cold-climate products are needed, particularly units with enough heating capacity to fully heat homes in cold climates on cold days.[33]

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[32] www.neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump. Accessed April 20, 2018.

[33] Using some electric resistance heat when the temperatures drop below about 5°F may be acceptable in places where this happens only occasionally. If heat pumps with electric resistance backup become widespread, steps may need to be taken to manage power demand in ways that minimize contributions to winter peak power demand, such as by incorporating some thermal storage capabilities in these homes (see for example www.steffes.com/electric-thermal-storage/).

The figures above are for homes with air-conditioning. Appendix B provides results for homes without air-conditioning. Life-cycle cost savings are a little higher in homes with air-conditioning, but for most of the country the additional savings due to air-conditioning are moderate since even the base-case air conditioner is fairly efficient. For homes without air-conditioning, once a heat pump is installed, it can be used to provide air-conditioning. For these homes we did not give credit for air conditioner savings, nor did we include a penalty for increased usage to provide air-conditioning where it is not now available.

Many factors influence the results for each state. For example, a reviewer of an earlier draft of this report asked why replacing an oil furnace with a heat pump is more economically attractive in Massachusetts than in Illinois. Our analysis is based on averages for each state. Comparing these averages for Massachusetts and Illinois, the big difference is that the average Illinois home uses less oil (57.5 million Btus) than the average Massachusetts home (80.9 million Btu) (EIA 2013). Also, Illinois is a little colder on average (design temperature of 2 versus 6°F), which affects heat pump performance. And Illinois had a lower oil price in 2016 ($1.94) than Massachusetts ($2.30) (sources noted in Appendix A). Somewhat compensating is the fact that electricity prices are higher in Massachusetts. Furthermore, electricity prices vary greatly from utility to utility within a region. Ultimately consumers will need to consider local prices and not statewide averages.

FOR HEAT PUMPS VERSUS BOILERS

Our analysis of life-cycle cost savings for heat pumps relative to oil and propane boilers is summarized in figure 8. This figure is for homes without central air-conditioning as homes with boilers generally lack the ducts typically used by central air conditioner systems. For states without many homes using oil, we show the analysis only for propane.

We found that there are often substantial life-cycle savings from replacing oil boilers in many states, but no life-cycle savings in the Upper Midwest, where temperatures are colder and relative energy prices not favorable to conversion. For propane boilers, for many states there are limited life-cycle cost savings, but a few states do have significant savings (e.g., Florida and New Jersey) due to average propane prices in those states. An analysis including air conditioner savings (typically from multiple-room air conditioners) is presented in Appendix B; the inclusion of air-conditioning has just a modest effect on the results, increasing life-cycle cost savings a little.

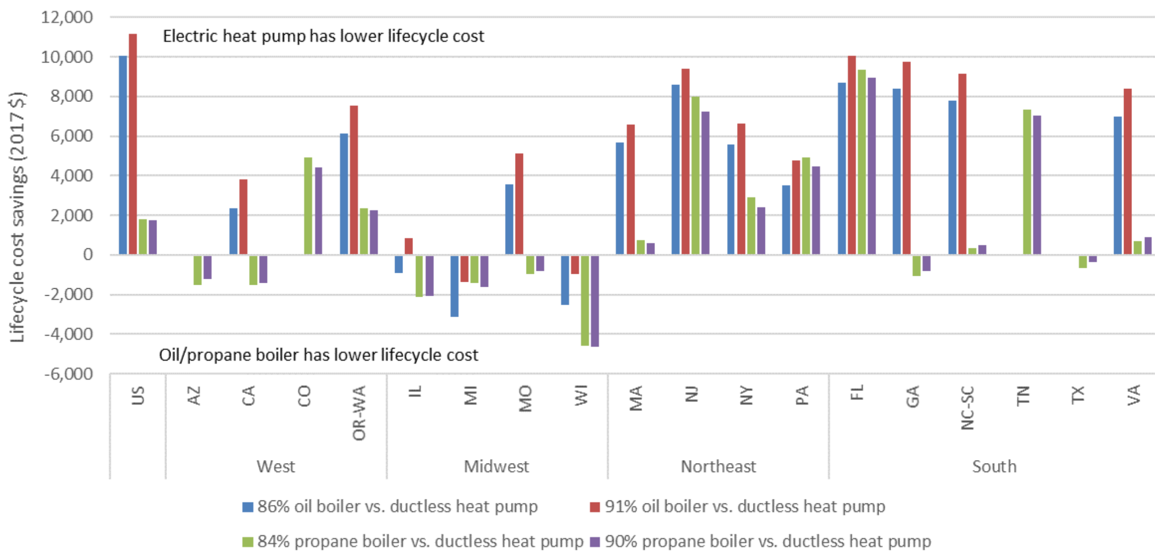

Figure 8. Life-cycle cost savings from replacing an oil or propane boiler with a ductless heat pump; does not include air-conditioning savings

Some reviewers noticed that the savings at the national level are greater than for any of the states. We believe this is because the nationwide numbers are influenced by some states with both a high saturation of oil-heated homes and high oil use per home (e.g., northern New England) that are not included in our state-by-state analysis.

WATER HEATING

Figure 9 summarizes life-cycle costs for different types of water heaters. In general heat pump water heaters (particularly the most efficient models) have the lowest life-cycle costs. Savings are substantial relative to oil water heaters as oil water heaters have significant purchase and operating costs. Savings are more modest relative to propane water heaters.[34]

[34] This analysis is for average installation costs for all US homes as estimated by DOE in various Technical Support Documents. Relative to this average, some homes will have higher costs, and some will have lower costs. For example, heat pump water heaters (HPWH) require 208 or 240 volts of power to operate their backup electric resistance coils. If a home does not have such service, this will incur additional costs that we did not include in our analysis. Likewise, some homes will have higher savings from an HPWH, and some will have lower savings. For example, savings will be somewhat lower in homes where the water heater is located in the conditioned space because the HPWH increases heating load in the winter but provides “free cooling” in the summer. One analysis by Pacific Northwest National Laboratory on instrumented test homes estimated that for heat pump water heaters located in the conditioned space, about 40% of the heat transferred to hot water in the winter needs to be made up by additional space-heating energy consumption, but the reverse happens in the summer (Widder et al. 2014).

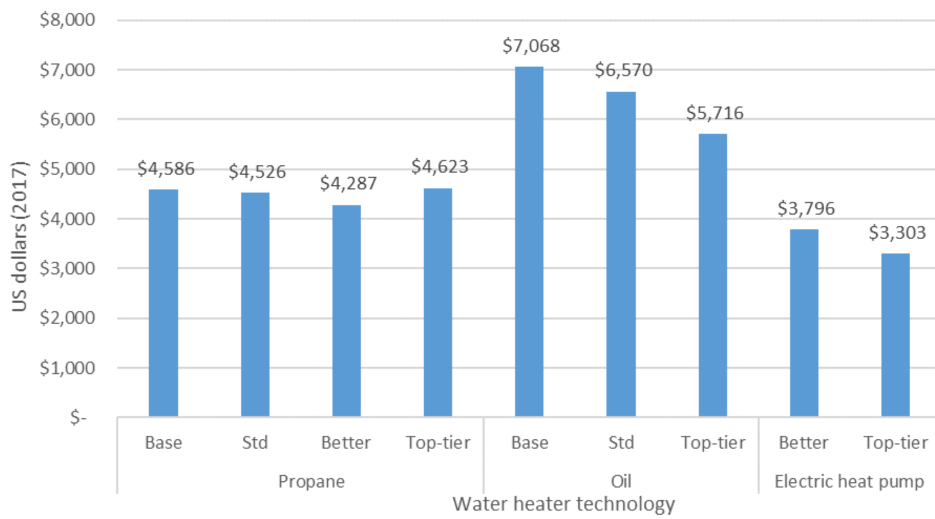

Figure 9. Life-cycle cost comparison of water heaters. Details of the analysis can be found in table A15 in Appendix A.

Early Replacement

For oil furnaces, outside the Upper Midwest there are generally life-cycle cost savings from early replacement (figure 10). The savings are not as large as the savings from installing a heat pump at the time an existing system needs to be replaced (figure 6). For propane furnaces, outside the Upper Midwest there are often life-cycle cost savings, but the savings are small to moderate (figure 11). Propane cost savings are substantially less than oil cost savings.

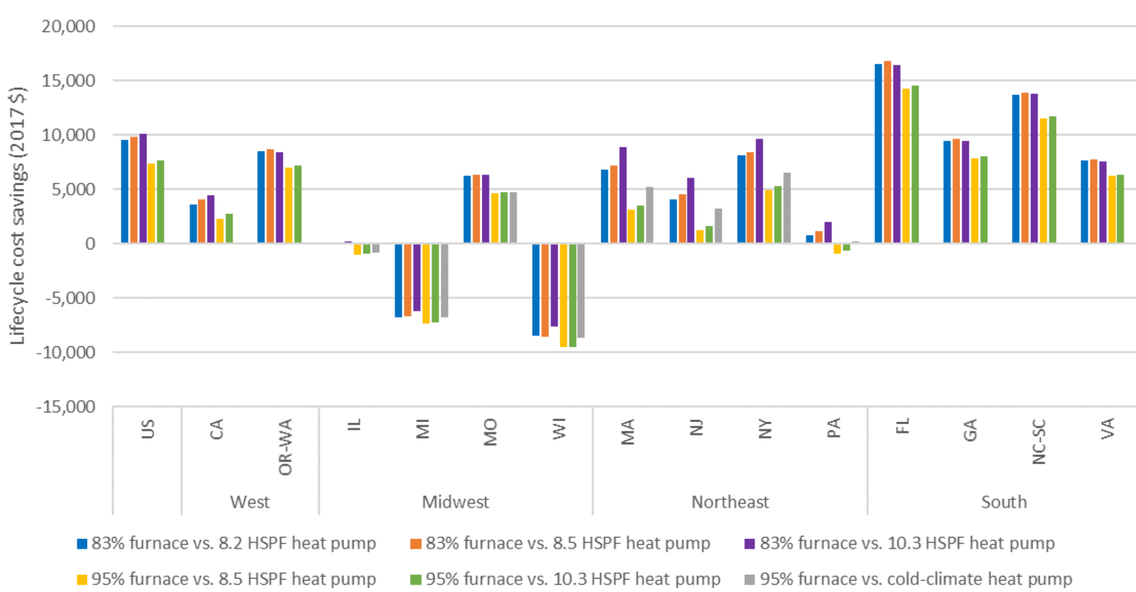

Figure 10. Life-cycle cost savings from early replacement of an oil furnace with a heat pump; does not include air-conditioning savings

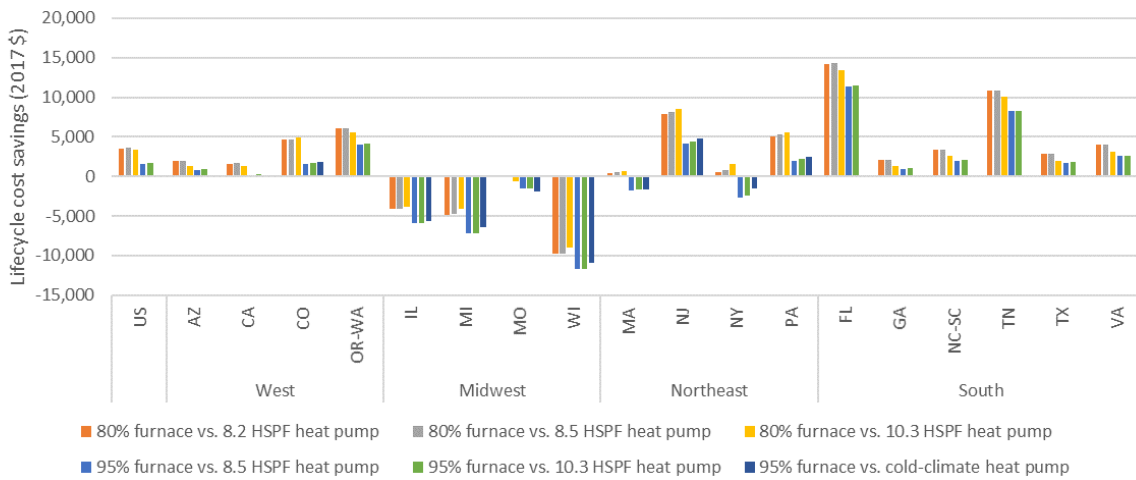

Figure 11. Life-cycle cost savings from early replacement of a propane furnace with a heat pump; does not include air-conditioning savings

Our analysis also found that there are often life-cycle cost savings from early replacement of oil boilers, and that early replacement of propane boilers saves money in some states (e.g., Colorado, Florida, New Jersey, and Tennessee) but not others (figure 12). States with propane cost savings have either high propane prices or above-average propane use per home. Again, there generally are no cost savings in the Upper Midwest.

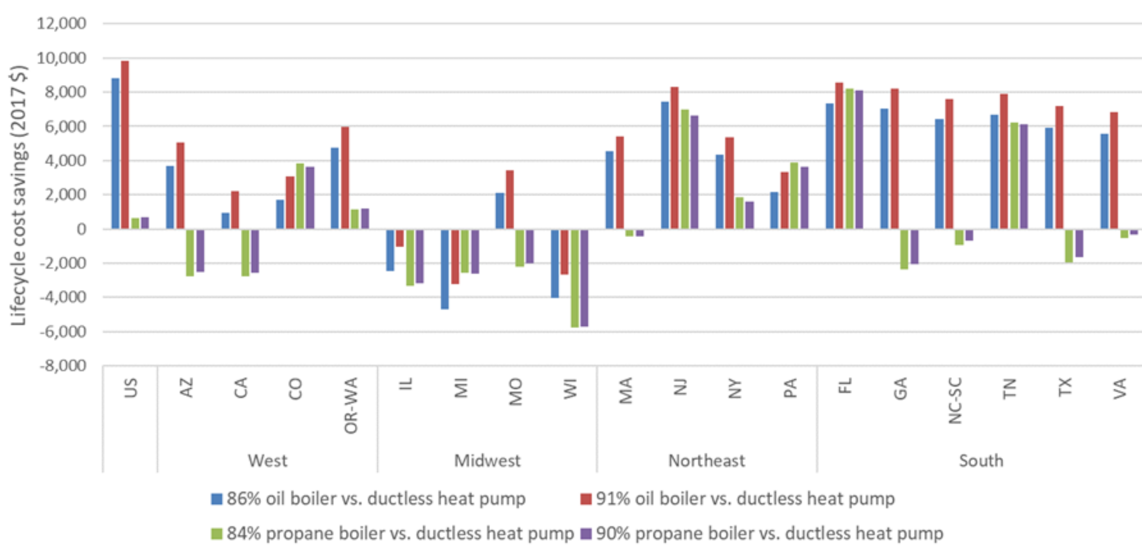

Figure 12. Life-cycle cost savings from early replacement of an oil or propane boiler with a ductless heat pump; does not include air-conditioning savings

Partial Replacement

Partial replacement scenarios are summarized in figures 13, 14, and 15 for oil furnaces, propane furnaces, and boilers (both fuels), respectively. For oil furnaces, there are no life-cycle cost savings in the Upper Midwest or in Pennsylvania, and in other states, cost savings from partial replacement are generally small. For propane furnaces, cost savings do not amount to much in many states, but there are some savings in New Jersey, Pennsylvania, and Tennessee. For boilers, there are also generally no cost savings, although there are modest savings in a few states.

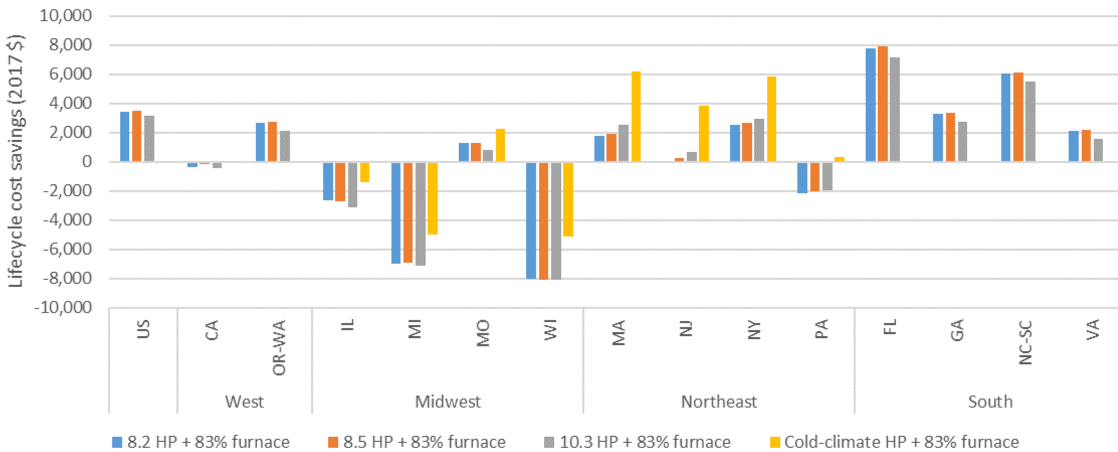

Figure 13. Life-cycle cost savings from partial replacement of an oil furnace with a heat pump; does not include air-conditioning savings

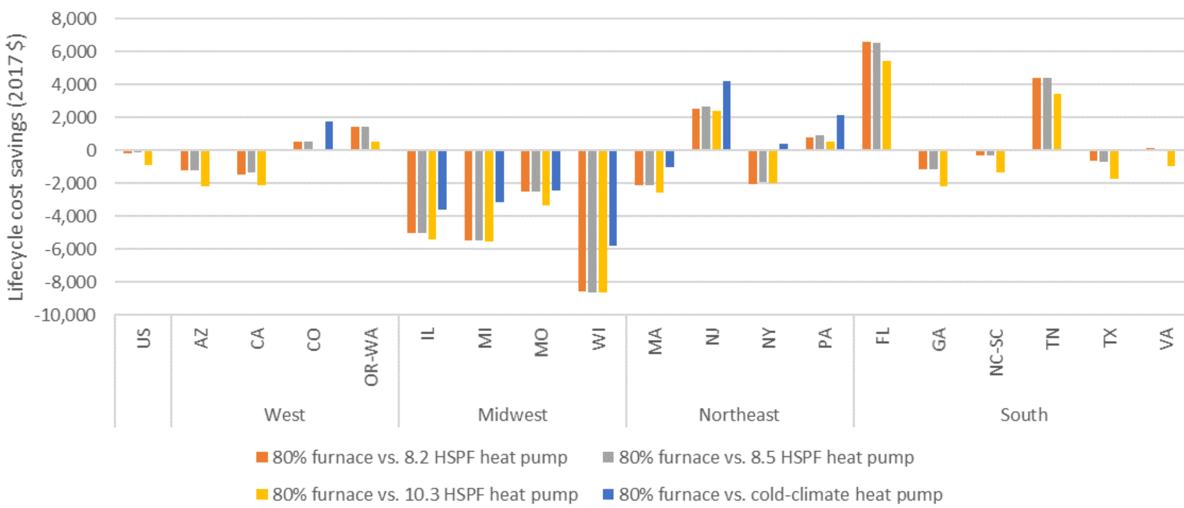

Figure 14. Life-cycle cost savings from partial replacement of a propane furnace with a heat pump; does not include air-conditioning savings

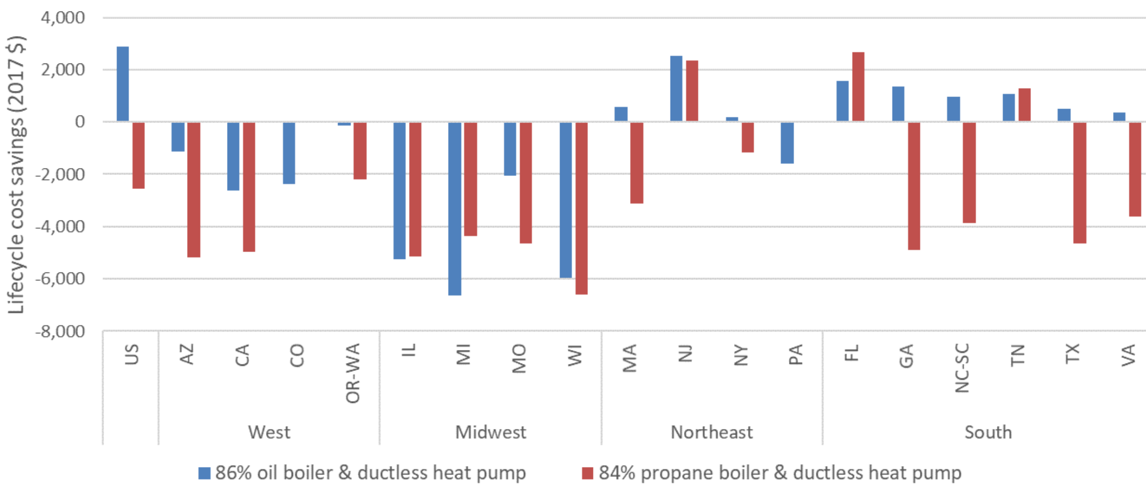

Figure 15. Life-cycle cost savings from partial replacement of an oil or propane boiler with a ductless heat pump; does not include air-conditioning savings

SIMPLE PAYBACK RESULTS INCLUDING ENERGY COST SENSITIVITIES

While life-cycle costs are useful for people familiar with economic analysis, the average consumer may not understand or be motivated by life-cycle cost. For many consumers, a useful metric is simple payback period: how many years it will take to pay back an investment based on the energy savings achieved. For each of our economic analyses, we graphed simple payback periods for different options relative to a base case of a standard-efficiency oil or propane furnace, boiler, or water heater. In these comparisons we also included the effects of high or low energy prices (as discussed in the Methodology section), in addition to the reference price forecast.[35]

Our simple payback analysis is summarized in graphical form (figures 16–22) and also in tabular form (tables 1 and 2). The figures show the simple payback for each comparison as a range, with a colored dot indicating payback using the AEO 2018 reference case for energy costs and endpoints showing payback using the AEO high and low energy price scenarios. Where the top of the graph is cut off, that means a payback is longer than 20 years; we do this so that paybacks shorter than 20 years are easier to read.

We first review the data for installing heat pumps when the existing system needs to be replaced and then proceed to early and partial replacements.

Installing Heat Pumps When Existing Systems Need to Be Replaced

Figure 16 summarizes simple paybacks for replacing oil furnaces with heat pumps at the time the existing furnace needs to be replaced. In general, simple payback periods are attractive (often less than two years) for much of the country, with the Upper Midwest being the exception (in many cases a heat pump does not pay back in this region; reasons for this

[35] While our sensitivity analysis was limited to energy prices, we also note that the cost of conversion can vary substantially from home to home; our analysis is based on typical costs.

were discussed previously in the section on life-cycle costs). Simple paybacks are even better with high oil prices, including simple paybacks of about 2–6 years in the Upper Midwest. With low oil prices, payback periods are typically around 5 years, but more than 20 years in many northern states.

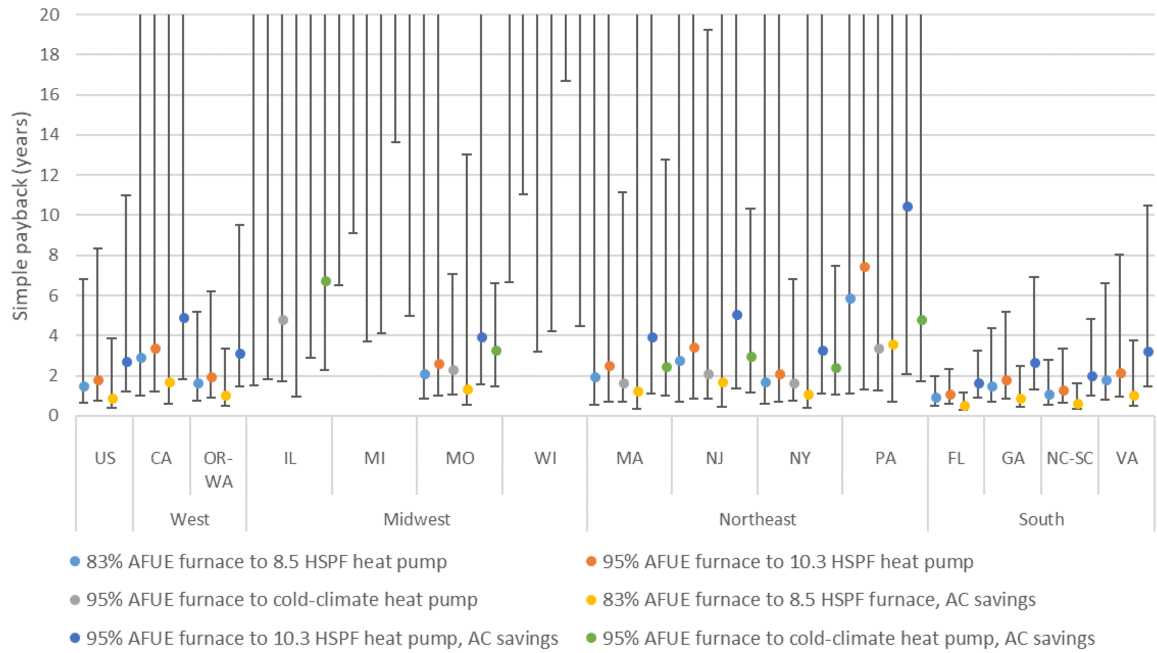

Figure 16. Simple payback periods for replacing an oil furnace with a heat pump at the time the existing equipment fails and needs to be replaced. The first three bars for each state are for when the furnace fails and do not include air-conditioning costs. The next three bars are for when the air conditioner fails and do include changes in air-conditioning operating costs. The colored dots in the middle of each bar use AEO reference case prices; the end points ("whiskers") use the AEO high and low oil price scenarios. Where a bar extends above the top of the graph, that means the electric heat pump does not pay back over the life of the heat pump under the reference case (if there is no colored dot shown on the bar) or under the low price scenario (if the top whisker is not shown).

Figure 17 summarizes simple paybacks for replacing propane furnaces with heat pumps at the time the existing equipment needs to be replaced. We looked at installations when the furnace needs to be replaced and also at installations when a central air conditioner needs to be replaced (for homes with central air-conditioning). In general the simple payback periods are better at the time of air conditioner failure than at the time of furnace failure, since replacement air conditioners generally cost more than replacement furnaces, reducing the cost increment of switching to a heat pump. At the time of air conditioner replacement, simple payback periods are often 1–4 years and can be less than 2 years in many southern states. An exception is the Upper Midwest, where heat pumps (even cold-climate models) often do not pay back. Relative to furnace replacements, heat pumps generally pay back in 2–9 years, except for the Upper Midwest. Paybacks are generally better in the South, where heating loads are lower. Simple paybacks improve with high oil prices, declining to 5–10 years in the Upper Midwest. With low oil prices, payback periods for installing a heat pump instead of a new central air conditioner are still often five years or less in many states, except for the Upper Midwest and the Northeast.

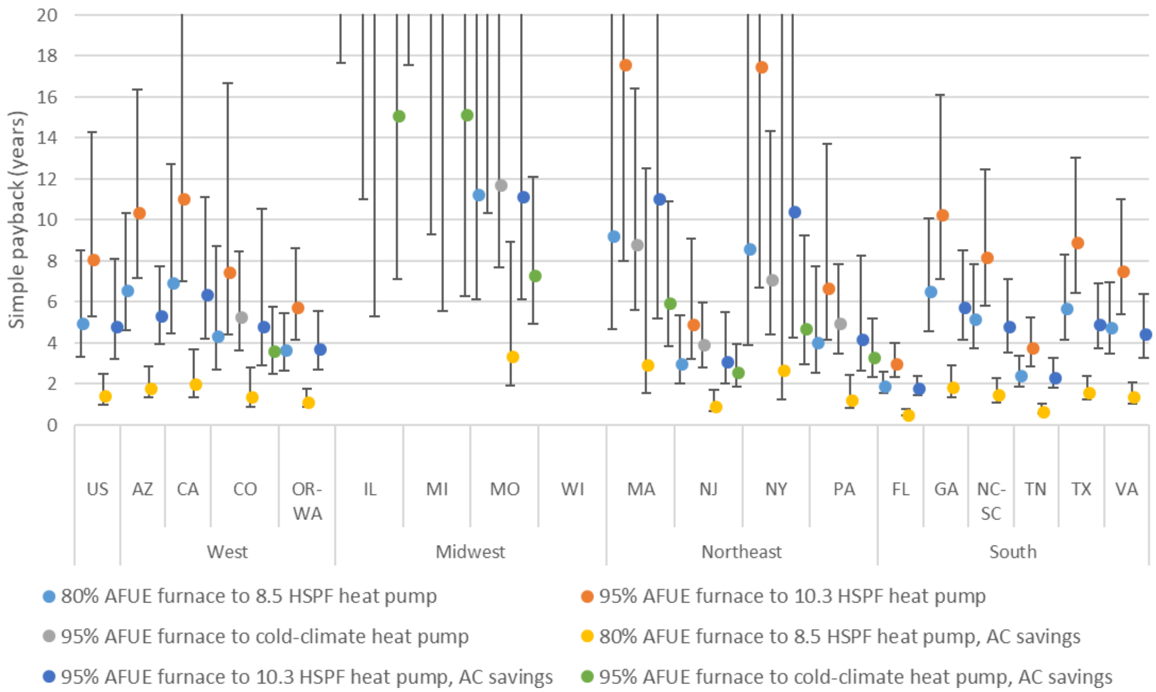

Figure 17. Simple payback period periods for replacing a propane furnace with a heat pump at the time the existing equipment fails and needs to be replaced. The first three bars for each state are for when the furnace fails and do not include air-conditioning costs. The next three bars are for when the air conditioner fails and do include changes in air-conditioning operating costs. The colored dots in the middle of each bar use AEO reference case prices; the whiskers use the AEO high and low oil price scenarios. Where a bar extends above the top of the graph, that means the electric heat pump does not pay back over the life of the heat pump under the reference case (if there is no colored dot shown on the bar) or under the low price scenario (if the top whisker is not shown).

Figure 18 summarizes simple paybacks for replacing oil and propane boilers with heat pumps at the time the existing equipment needs to be replaced. This analysis does not include air-conditioning savings because many homes with boilers do not have central air-conditioning (but many do have window AC units), nor does it reflect net energy consumption increases for cooling where central AC is newly available. In general, paybacks are often under five years for replacing oil systems using reference prices (although paybacks are substantially higher in the Upper Midwest). For replacing propane boilers, paybacks are 5–10 years in Colorado, Florida, New Jersey, New York, Oregon-Washington, Pennsylvania, and Tennessee. Otherwise, paybacks are generally in the neighborhood of 10–17 years (but higher in Wisconsin); such paybacks will generally not be attractive to homeowners. For those homes with central air-conditioning, the savings from a high-efficiency heat pump during the cooling season modestly improves the simple payback period (details are shown in table A13 in Appendix A). Paybacks modestly improve with high oil prices and noticeably lengthen with low oil prices.

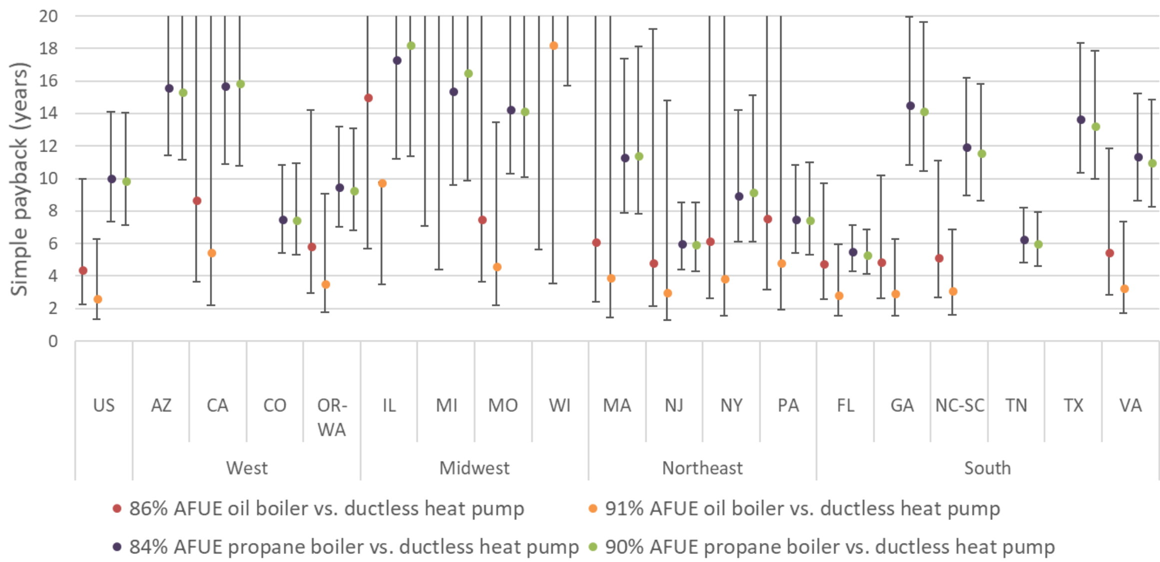

Figure 18. Simple payback period periods for replacing oil and propane boilers with two ductless heat pumps at the time the existing equipment fails and needs to be replaced. The colored dots in the middle of each bar use AEO reference case prices; the whiskers use the AEO high and low oil price scenarios. Where a bar extends above the top of the graph, that means the electric heat pump does not pay back over the life of the heat pump under the reference case (if there is no colored dot shown on the bar) or under the low price scenario (if the top whisker is not shown).

Figure 19 summarizes simple paybacks for replacing oil and propane water heaters with heat pump water heaters at the time the existing water heater needs to be replaced. In general, heat pump water heaters cost less to purchase and install than oil water heaters, so the simple payback relative to oil water heaters is immediate. Relative to propane water heaters, heat pump water heaters typically pay back in about 3–4 years at reference case prices, 2–3 years at high prices, and 5–8 years at low prices.

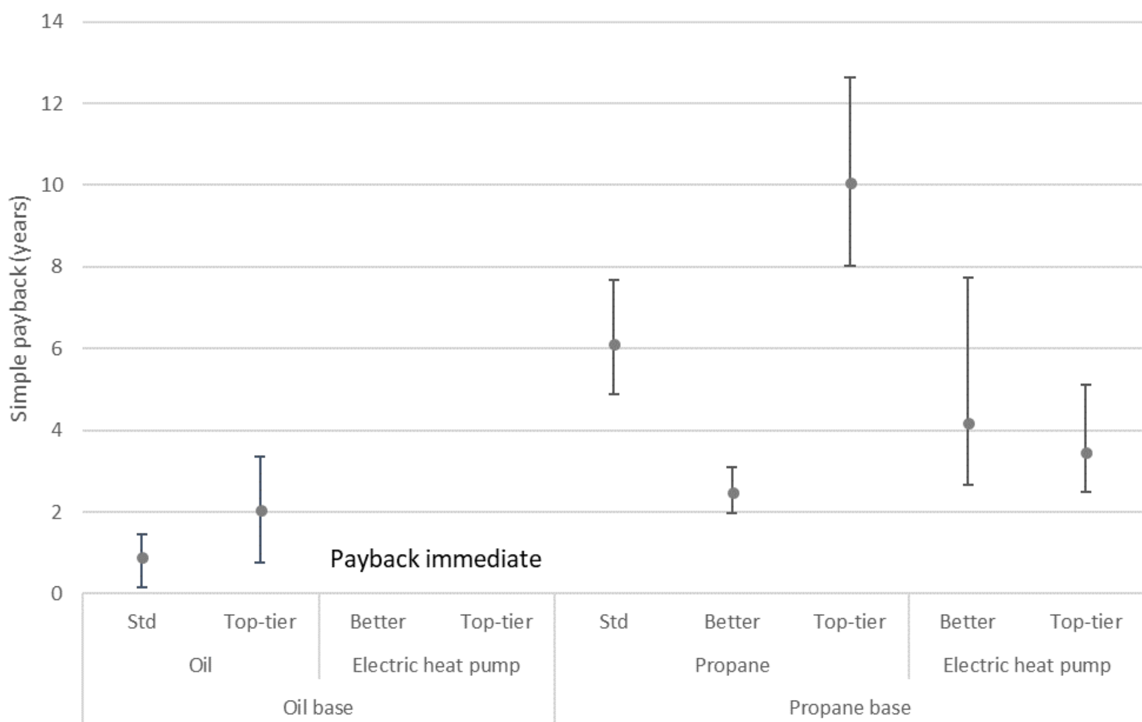

Figure 19. Simple payback periods for replacing oil and propane water heaters with electric heat pumps. We also include an analysis of improved-efficiency propane and oil units. The dots in the middle of each bar use AEO reference case prices; the whiskers use the AEO high and low oil price scenarios.

Table 1 reports average payback numbers for specific states and system types.

Table 1. Average simple payback period by state for replacing oil and propane systems with heat pumps at the time existing equipment needs to be replaced

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Oil furnace																			
At time air conditioner needs replacement (includes AC energy savings)																			
83% AFUE furnace to 8.5 HSPF heat pump	0.9		1.7		1.1	NS	NS	1.3	NS	1.3	1.7	1.1	3.6	0.6	0.9	0.7			1.1
95% AFUE furnace to 10.3 HSPF heat pump	2.7		4.9		3.2	NS	NS	4.0	NS	4.0	5.1	3.3	10.5	1.7	2.7	2.0			3.2
95% AFUE furnace to cold-climate heat pump						6.7	NS	3.3	NS	2.5	3.0	2.4	4.8						
At time furnace needs replacement (does not include AC energy savings)																			
83% AFUE furnace to 8.5 HSPF heat pump	1.5		2.9		1.7	NS	NS	2.1	NS	2.0	2.8	1.7	5.9	0.9	1.5	1.1			1.8
95% AFUE furnace to 10.3 HSPF heat pump	1.8		3.4		2.0	NS	NS	2.6	NS	2.5	3.4	2.1	7.5	1.1	1.8	1.3			2.2
95% AFUE furnace to cold-climate heat pump						4.8	NS	2.3	NS	1.7	2.1	1.7	3.4						
Propane furnace																			
At time air conditioner needs replacement (includes AC energy savings)																			
80% AFUE furnace to 8.5 HSPF heat pump	1.5	1.9	2.1	1.4	1.2	NS	NS	3.4	NS	3.0	1.0	2.8	1.3	0.6	1.9	1.6	0.7	1.7	1.4
95% AFUE furnace to 10.3 HSPF heat pump	4.9	5.4	6.4	4.9	3.8	NS	NS	11.2	NS	11.1	3.1	10.5	4.3	1.8	5.8	4.9	2.4	5.0	4.5
95% AFUE furnace to cold-climate heat pump				3.7		15.2	15.2	7.4	NS	6.0	2.7	4.8	3.4						
At time furnace needs replacement (does not include AC energy savings)																			
80% AFUE furnace to 8.5 HSPF heat pump	5.0	6.7	7.0	4.4	3.7	NS	NS	11.3	NS	9.3	3.1	8.7	4.1	2.0	6.6	5.3	2.5	5.8	4.8
95% AFUE furnace to 10.3 HSPF heat pump	8.1	10.4	11.1	7.5	5.8	NS	NS	20.5	NS	17.7	5.0	17.5	6.8	3.0	10.4	8.3	3.8	9.0	7.6
95% AFUE furnace to cold-climate heat pump				5.3		25.6	23.4	11.8	NS	8.9	4.0	7.2	5.0						
Oil boiler																			
Replacing a boiler, with AC savings																			
86% AFUE oil boiler vs. ductless heat pump	4.1		7.7		5.7	13.5	26.8	7.0	22.1	6.0	4.6	5.9	7.2	4.2	4.5	4.8			5.1
91% AFUE oil boiler vs. ductless heat pump	2.5		4.8		3.5	8.7	20.2	4.2	16.9	3.8	2.9	3.7	4.5	2.5	2.7	2.8			3.0
Replacing a boiler, no AC savings																			
86% AFUE oil boiler vs. ductless heat pump	4.4		8.7		5.9	15.0	29.3	7.5	23.3	6.1	4.8	6.2	7.6	4.8	4.9	5.1			5.5
91% AFUE oil boiler vs. ductless heat pump	2.6		5.5		3.6	9.7	22.9	4.6	18.2	3.9	3.0	3.9	4.8	2.9	2.9	3.1			3.3
Propane boiler																			
Replacing a boiler, with AC savings																			
84% AFUE propane boiler vs. ductless HP	9.1	11.5	13.5	7.4	9.3	15.9	14.8	12.9	30.6	11.0	5.7	8.6	7.2	5.0	12.0	10.5	6.0	11.1	10.1
90% AFUE propane boiler vs. ductless HP	8.9	10.9	13.4	7.3	9.0	16.4	15.9	12.7	39.3	11.1	5.6	8.7	7.1	4.7	11.5	10.1	5.7	10.5	9.7
Replacing a boiler, no AC savings																			
84% AFUE propane boiler vs. ductless HP	10.0	15.6	15.7	7.5	9.5	17.3	15.4	14.3	32.3	11.3	6.0	9.0	7.5	5.5	14.5	11.9	6.3	13.7	11.4
90% AFUE propane boiler vs. ductless HP	9.8	15.4	15.9	7.4	9.3	18.2	16.5	14.2	42.6	11.4	5.9	9.1	7.4	5.3	14.2	11.6	6.0	13.2	11.0

NS=no savings (heat pump costs more to operate). States without much oil use are not included in the analysis of oil options. Cold-climate heat pump analysis is limited to cold states.

Early and Partial Replacements

We looked at early replacements (replacement of a functioning system before it fails) and partial replacements (adding a heat pump with the existing system serving as a supplemental system) separately for oil furnaces, propane furnaces, and boilers. Results are summarized in graphical form in figures 20–22 and in tabular form in table 2.

For oil furnaces, outside the Upper Midwest, early replacements typically have simple paybacks to consumers of 4–10 years (figure 20). These paybacks are longer than the approximately two-year payback for installing a new heat pump when the existing system fails, as shown in figure 16. The paybacks are longer because our analysis includes the full capital cost of a heat pump and not just the incremental cost of a heat pump relative to replacing an existing system.

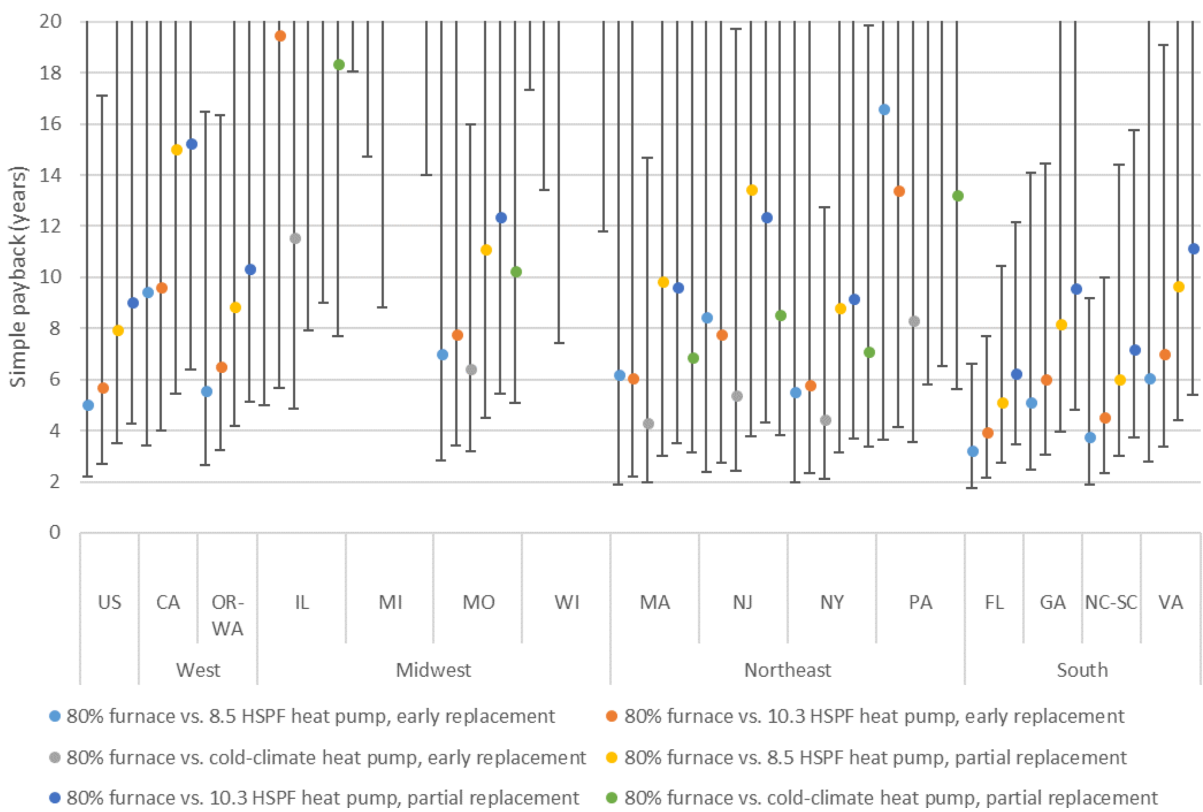

Figure 20. Simple payback periods for early replacement and partial replacement of an oil furnace with a heat pump. The colored dots in the middle of each bar use AEO reference case prices; the whiskers use the AEO high and low oil price scenarios. Where the bar extends above the top of the graph, that means the electric heat pump does not pay back over the life of the heat pump under the reference case (if there is no colored dot shown on the bar) or under the low price scenario (if the top whisker is not shown).

For partial replacements, consumer paybacks outside the Upper Midwest are longer still: 6–15 years (also figure 20). These higher paybacks are due to lower energy savings because heat pumps serve only part of the load. (As discussed in the Methodology section, we assumed that the heat pump serves 63% of the annual load and the oil or propane system serves the remainder.) Paybacks of this length can be difficult to sell to consumers unless there are nonmonetary benefits, such as increased comfort. For example, in homes without air-conditioning, a heat pump will provide space cooling, increasing comfort on hot days.

For propane furnaces, as illustrated in figure 21, consumer paybacks for early replacement are commonly around 10 years, although shorter in a few states (Colorado, Florida, New Jersey, and Tennessee) and longer in the Upper Midwest. Reasons for the quicker paybacks in a few states were discussed in the section on life-cycle costs. Partial replacements typically have consumer paybacks of around 15 years, although lower in a few states.

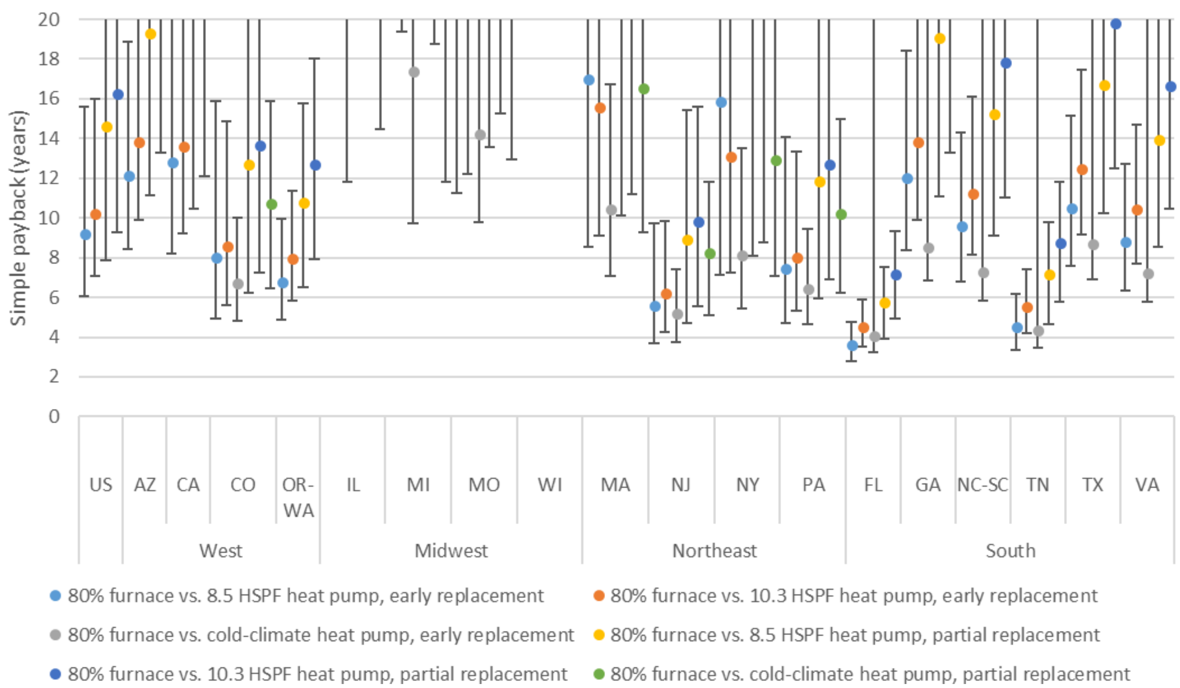

Figure 21. Simple payback period for early and partial replacement of a propane furnace with a heat pump. The colored dots in the middle of each bar use AEO reference case prices; the whiskers use the AEO high and low oil price scenarios. Where the bar extends above the top of the graph, that means the electric heat pump does not pay back over the life of the heat pump under the reference case (if there is no colored dot shown on the bar) or under the low price scenario (if the top whisker is not shown). Nothing is shown for Wisconsin because none of the options have a simple payback below 20 years.

Simple paybacks are commonly around 10 years for early replacement of oil boilers and 10–20 years for propane boilers. Paybacks for partial replacements are generally 13–20 years for oil boilers (except in the Upper Midwest) and 13–30 years for propane boilers (figure 22). Supplemental heat pumps may make sense for households desiring air-conditioning, but otherwise the consumer economics do not look attractive.[36]

[36] Another potential niche market suggested by one reviewer are homes with photovoltaic systems, since once these homes have solar power, some owners may convert other uses to electricity in order to maximize their use of self-generated power.

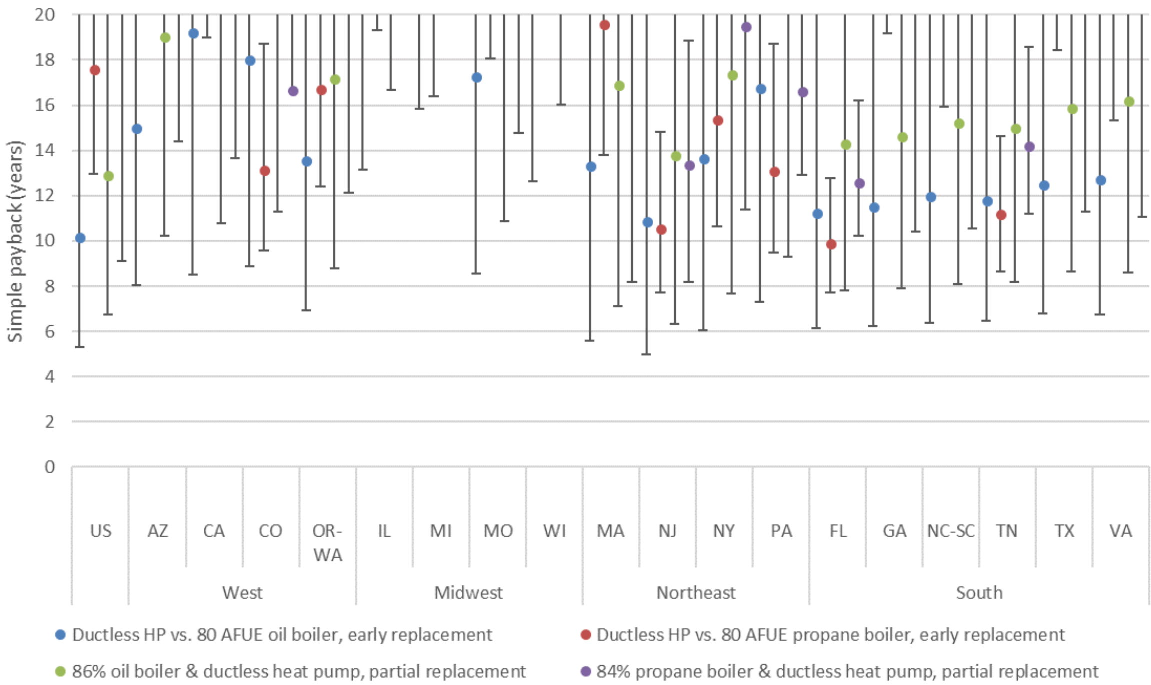

Figure 22. Simple payback period periods for replacing oil and propane boilers with ductless heat pumps, early replacement and partial replacement. The colored dots on each bar use AEO reference case prices; the whiskers below the dots use the AEO high oil price scenario (we did not analyze a low oil price scenario as most of these paybacks will be very long). Where the bar extends above the top of the graph, that means the electric heat pump does not pay back over the life of the heat pump under the reference case (if there is no colored dot shown on the bar) or under the low price scenario (if the top whisker is not shown).

As Van de Grift and Billingsley (2015) found in a survey of consumers in the US Northwest, consumer interest in early replacement of heating systems is low; most consumers intend to purchase only when their current system breaks down. On the other hand, installing ductless heat pumps in homes with an oil or propane boiler will often bring air-conditioning to a home, and this will be attractive to some homeowners. Vitoff et al. (2014) found in a customer survey on ductless heat pump installations in Massachusetts that the majority of ductless heat pump installations were undertaken to improve comfort (particularly for cooling) and not to save energy. Most of these installations were done to supplement rather than replace existing heating systems. Thus, adding cooling to homes that lack it can be an important niche for heat pumps.

Table 2 reports average simple payback periods for early and partial replacement of oil and propane furnaces and boilers.

Table 2. Average simple payback period by state for early and partial replacement of oil and propane systems

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Oil furnace																			
Early replacement (payback relative to existing furnace)																			
80% furnace vs. 8.5 HSPF heat pump	5.0		9.5		5.6	24.1	NS	7.0	NS	6.2	8.5	5.6	16.6	3.2	5.2	3.8			6.1
80% furnace vs. 10.3 HSPF heat pump	5.7		9.6		6.5	19.5	NS	7.8	NS	6.1	7.8	5.8	13.4	4.0	6.0	4.5			7.0
80% furnace vs. cold-climate heat pump						11.6	49.8	6.5	55.4	4.3	5.4	4.5	8.3						
Partial replacement (payback relative to existing furnace)																			
80% furnace vs. 8.5 HSPF heat pump	8.0		15.0		8.9	38.2	NS	11.1	NS	9.8	13.5	8.8	26.4	5.1	8.2	6.0			9.7
80% furnace vs. 10.3 HSPF heat pump	9.1		15.3		10.3	30.9	NS	12.4	NS	9.6	12.4	9.2	21.3	6.3	9.6	7.2			11.1
80% furnace vs. cold-climate heat pump						18.4	79.1	10.2	88.0	6.9	8.6	7.1	13.2						
Propane furnace																			
Early replacement																			
80% furnace vs. 8.5 HSPF heat pump	9.2	12.2	12.8	8.0	6.8	NS	NS	20.7	NS	17.0	5.6	15.9	7.5	3.6	12.0	9.6	4.5	10.5	8.8
80% furnace vs. 10.3 HSPF heat pump	10.2	13.9	13.6	8.6	8.0	108.6	154.6	20.1	NS	15.6	6.2	13.1	8.0	4.5	13.8	11.2	5.5	12.5	10.5
80% furnace vs. cold-climate heat pump				6.8		20.6	17.4	14.2	122.7	10.4	5.2	8.2	6.5	4.1	8.6	7.3	4.4	8.7	7.2
Partial replacement																			
80% furnace vs. 8.5 HSPF heat pump	14.6	19.3	20.4	12.7	10.8	NS	NS	32.8	NS	27.0	8.9	25.2	11.9	5.8	19.1	15.3	7.2	16.7	14.0
80% furnace vs. 10.3 HSPF heat pump	16.2	22.0	21.6	13.7	12.7	172.4	245.4	31.9	NS	24.7	9.9	20.8	12.7	7.2	22.0	17.9	8.8	19.8	16.6
80% furnace vs. cold-climate heat pump				10.7		32.7	27.6	22.6	194.7	16.6	8.2	13.0	10.3						
Oil boiler																			
Early replacement																			
Ductless HP vs. 80 AFUE oil boiler	10.2		19.2		13.5	32.3	54.3	17.3	43.3	13.3	10.9	13.7	16.8	11.3	11.5	12.0			12.8
Partial replacement																			
86% oil boiler & ductless heat pump	12.9		24.4		17.2	41.1	69.0	21.9	55.0	16.9	13.8	17.4	21.3	14.3	14.6	15.2			16.2
Propane boiler																			
Early replacement																			
Ductless HP vs. 80 AFUE propane boiler	17.6	27.4	27.1	13.1	16.7	29.2	25.6	24.9	49.0	19.6	10.5	15.4	13.1	9.9	25.6	21.1	11.2	24.3	32.0
Partial replacement																			
84% propane boiler & ductless heat pump	22.3	34.8	34.4	16.7	21.2	37.1	32.5	31.6	62.2	24.9	13.4	19.5	16.6	12.6	32.6	26.8	14.2	30.8	25.6

NS=no savings (heat pump costs more to operate). Our early and partial replacement analysis does not include air-conditioning savings. States without much oil use are not included in the analysis of oil options. Cold-climate heat pump analysis is limited to cold states.

COMPARISON WITH OTHER STUDIES

A few other studies have examined the economics of heat pumps relative to other energy sources. Their results are largely consistent with our findings, with a few exceptions as noted below. In the following paragraphs we discuss a few of these other studies and their findings.

IESO

The Independent Electricity Systems Operator (IESO) in Ontario prepared *An Examination of the Opportunity for Residential Heat Pumps* (IESO 2017). The study discusses the market opportunity, reviews heat pump technologies and programs, and analyzes what may be applicable to Ontario. The study includes estimates of simple payback periods for replacing an electric furnace or an inefficient oil furnace (AFUE 78%) with an air-source heat pump, and for installing a heat pump as an add-on to the oil furnace, each for various regions in Canada. For the first scenario, IESO reports simple payback periods to the homeowner of 1.6–6.9 years (varying by region, primarily due to differences in electricity prices). These findings are consistent with our analysis. For the second scenario, IESO reports a range of 2.3–6.5 years. These latter paybacks are shorter than our findings for oil furnaces in the Upper Midwest. While heat pump performance will likely be similar for Ontario and the Upper Midwest, there could be differences in base-case energy consumption or energy prices.

Lawrence Berkeley National Laboratory

Deason et al. (2018) summarize several economic analyses on electrification including both California and national studies. For example, they cite an analysis for the Sacramento Municipal Utility District (SMUD) that finds that a fully electric new home is cheaper for the homeowner, the builder (with a utility incentive), and the utility. A somewhat similar study for the city of Palo Alto finds that heat pump space heating is cost effective for new single-family homes and for new and existing multifamily homes. On the other hand, Deason et al. cite a University of California study finding that heat pump water heaters are more expensive than natural gas water heaters. All of these studies use natural gas as the primary comparison, not oil or propane.

At the national level, Deason et al. note two studies by the National Renewable Energy Laboratory (NREL). One study focuses on single-family homes, examining them on a state-by-state basis (Wilson et al. 2017). This study finds that electrification is more cost effective in oil- and propane-heated homes than in gas-heated homes and that electrification is more cost effective when a central air conditioner wears out than when a furnace wears out. We have similar findings. The second study (Jadun et al. 2017) projects the economics of electrification over the long term, finding that none of the heat pump technologies are currently lower in cost than natural gas alternatives, with the exception of residential heat pump water heaters in some scenarios. However they project that over time heat pump costs will come down and by the 2040s will generally have a lower cost per Btu of heat provided than natural gas equipment.

Most of these results are for natural gas and not oil or propane. Many are consistent with our findings; a few are not. We note with interest the conclusion that electrification can be more cost effective in efficient new homes (i.e., homes meeting the California energy code) than in existing homes.

NYSERDA

The New York State Energy Research and Development Authority (NYSERDA) looked at cold-climate heat pumps (both central ducted systems and ductless mini-split systems) as part of its *Renewable Heating and Cooling Policy Framework* (NYSERDA 2017). The study estimated the technical potential for energy savings from electrification and the proportion of technical potential that was cost effective on a life-cycle cost basis under various scenarios. For its 2017 scenario based on current costs and benefits, only 6% of the technical potential was cost effective. By 2021, under business-as-usual conditions, this increases to 10% for ducted systems and 18% for ductless systems. Various other scenarios developed by NYSERDA include efforts to reduce costs and to monetize grid benefits and the value of carbon savings. In the scenario with all of these factors included, the proportion of the technical potential that is cost effective is 31% for ducted systems and 37% for ductless systems.

These percentages include many types of existing heating systems, including electric resistance, natural gas, oil, and propane, making it very difficult to compare with our analysis on homes with oil and propane heat. However, for homes with oil and propane heat in New York State, we find that cold-climate heat pumps are cost effective on average. This implies that they are cost effective in the majority of homes, not the 6–37% of homes estimated by NYSERDA. Some of this difference is due to the significant portion of homes in New York using natural gas, a fuel for which electrification is generally less cost effective. Another reason for the difference in findings is that NYSERDA used a higher cost for ducted cold-climate heat pumps than we used. For ducted systems it estimated cold-climate heat pumps cost $2,787–4,317 per ton of cooling capacity for ducted systems and $2,665–4,857 per ton for ductless systems. We used a cost of about $2,240 per ton for ducted systems and about $3,532 per ton for ductless systems.[37]

Rocky Mountain Institute (RMI)

RMI published a study on *The Economics of Electrifying Buildings* (Billimoria et al. 2018). The study compares fossil fuel heat with high-efficiency heat pumps in four US cites: Oakland, Houston, Providence, and Chicago. Researchers looked at oil and propane heating in Providence and at natural gas in all four cities. They looked separately at new construction and existing homes, considering both space heating and water heating in a combined analysis. For space heating, their analysis is based on high-efficiency cold-climate heat pumps; for water heating, it is based on a standard heat pump water heater. They find that for new construction, heat pumps have lower life-cycle costs. For existing homes, natural

[37] Our costs are per system and not per ton of cooling capacity. In our experience, while system costs increase with cooling capacity, costs do not directly scale with cooling capacity; a system with double the capacity costs more, but not nearly twice as much. Our analysis estimates an average cost for ducted cold-climate heat pumps of $6,720. If the average system is three tons, this works out to an average of $2,240 per ton. For ductless heat pumps, we estimate an average cost of $7,065. If this system averages two tons, this works out to an average of $3,532 per ton.

gas systems often have lower life-cycle costs than heat pumps. For Providence, the only city where they looked at oil and propane, the heat pump had substantially lower life-cycle costs in existing homes relative to propane heat, and slightly lower life-cycle costs relative to oil heat. Our analysis finds better heat pump economics in homes with oil heat than in homes with propane heat. The difference in findings appears to be due to the fact that RMI used current energy prices, while our analysis looked at 2030 energy prices as projected by EIA. As discussed earlier, EIA estimates higher price increases for oil than for propane over the 2018–2030 period.

Greenhouse Gas Emissions

Our final analysis looks at whether installing heat pumps instead of oil and propane systems will reduce greenhouse gas emissions. For oil and propane, following from our energy use analysis, we included emissions on site as well as those associated with distribution. We did not include upstream emissions, as we did not have sufficient time and resources to delve into the debate on how significant these upstream emissions are.

In our analysis of oil, propane, and heat pump systems, emissions vary with the efficiency of the system. For heat pumps, emissions are also affected by the type of fuel used at the margin to produce incremental electricity as well as the heat rate at which the electricity is produced if a fossil fuel is used. Generally, if a heat pump will save source energy, per the first analysis discussed earlier, it will reduce greenhouse gas emissions, if marginal power comes from a natural gas power plant, since combustion of natural gas emits somewhat less CO_2 per Btu produced than burning oil and propane does. Thus, as combined-cycle power plants as well as renewable energy become more common, in most cases heat pumps will reduce emissions in the medium term, if not the short term.

To provide further information on the situation today, for each system type and state we calculated the break-even emissions rate (kg CO_2 emitted per kWh generated) at which a heat pump would have the same CO_2 emissions as an oil or propane system. To the extent that incremental power generation in a state or region is cleaner than this break-even emissions rate, a heat pump will typically reduce emissions. Ideally we would compare these break-even emissions rates with the emissions of *marginal* generation plants in each state—that is, emissions from the plants that would operate more often if electric loads grow due to heat pumps. However obtaining data on marginal emissions rates is very difficult, so as an approximate indicator we derived *average* emissions in 2016 for each state using data compiled by EIA.[38] Details of the analysis can be found in table A16 in Appendix A.

Below, we summarize our results in graphical form in figures 23–25. If the line showing 2016 average emissions is in the middle of a bar, then heat pumps will on average reduce emissions in 2016. If a line for 2016 emissions is above a bar, then emissions from heat pumps will be higher than emissions from oil or propane heating systems. Relative to 2016 average emissions rates by state, we find that heat pumps will perform as follows:

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[38] Available at https://www.eia.gov/electricity/state/unitedstates/. These data are for power plants within a state and do not account for flows of power between states.

- Emissions will be lower in most states relative to an 83% AFUE oil furnace (Missouri is an exception, and Illinois, Michigan, Pennsylvania, and Wisconsin are on the cusp, meaning that emissions can be lower with the most efficient heat pumps but are a little higher with less-efficient heat pumps) (figure 23).
- Emissions will be lower in the majority of states relative to a 95% AFUE propane furnace (with the exception of all the states listed in the previous bullet plus Colorado, with Texas on the cusp) (figure 24).
- Emissions will be lower in nearly all states relative to oil or propane boilers (for propane boilers, Texas is an exception and a few states are on the cusp) (figure 25).
- Heat pump water heaters will generally have lower emissions than oil or propane water heaters (details in table A15 in Appendix A).

Emissions reductions are likely in all states as the grid gets cleaner over time.

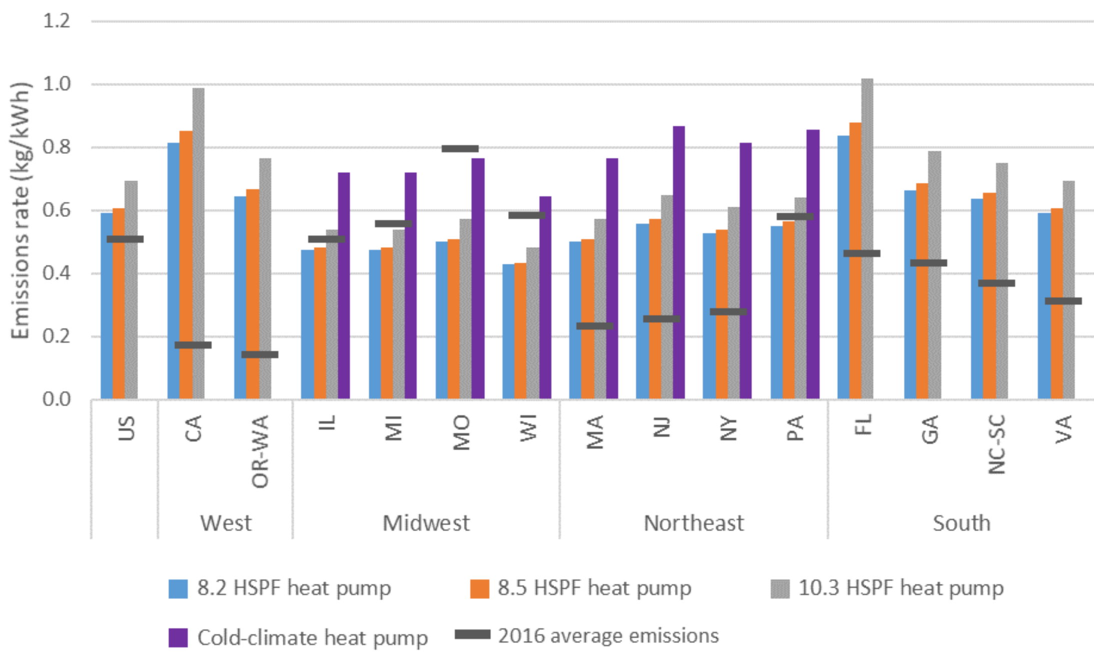

Figure 23. Break-even emissions rate for heat pumps relative to an 83% AFUE oil furnace. If a line showing 2016 average emissions is in the middle of a bar, then heat pumps will on average reduce emissions in 2016. If a line showing 2016 emissions is above a bar, then emissions from heat pumps will be higher than those from oil heating systems. Figure B15 in Appendix B provides break-even emissions rate relative to a 95% AFUE oil furnace.

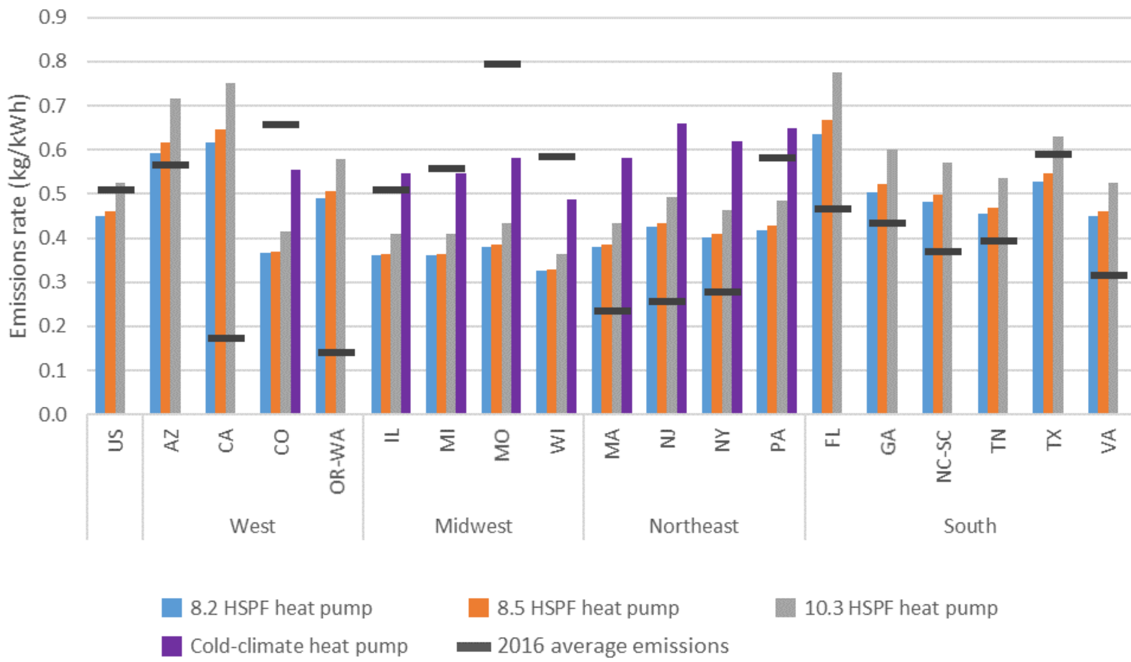

Figure 24. Break-even emissions rate for heat pumps relative to a 95% AFUE propane furnace. If a line showing 2016 average emissions is in the middle of a bar, then heat pumps will on average reduce emissions in 2016. If the line for 2016 emissions is above a bar, then emissions from heat pumps will be higher than emissions from propane heating systems. Figure B16 in Appendix B gives break-even emissions rate relative to an 80% AFUE propane furnace.

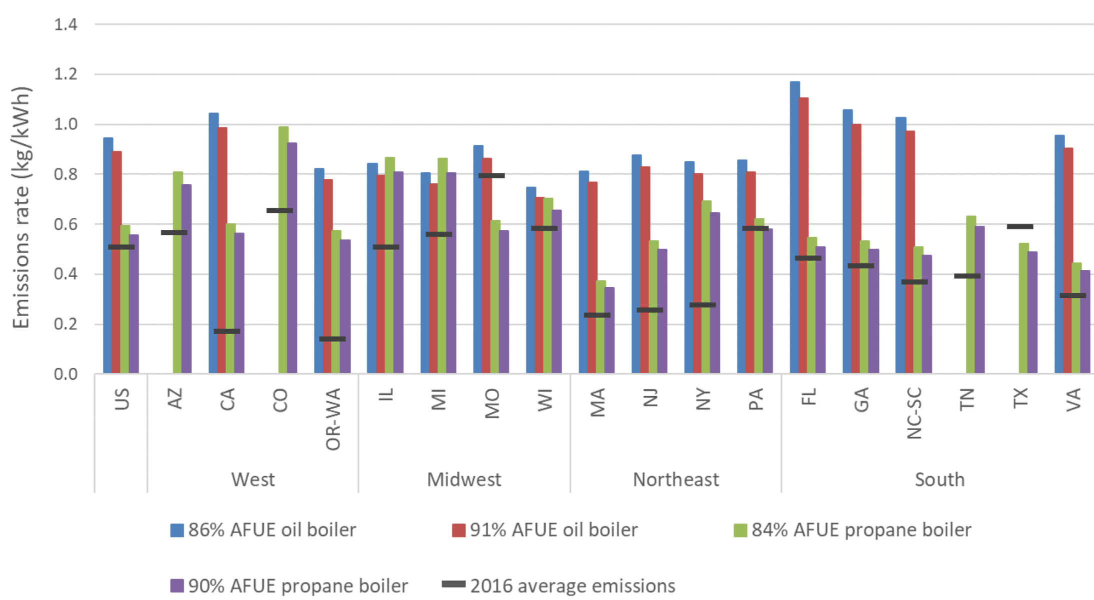

Figure 25. Break-even emissions rate for ductless heat pumps relative to oil and propane boilers. If a line showing 2016 average emissions is in the middle of a bar, then heat pumps will on average reduce emissions in 2016. If a line for 2016 emissions is above a bar, then emissions from heat pumps will be higher than emissions from oil or propane heating systems.

Since propane heat pumps are included in our energy consumption analysis, we were curious about how carbon dioxide emissions compare between propane heat pumps and the various types of electric heat pumps we examined. For this analysis we used the same assumptions regarding average performance as were used throughout this report. These results are summarized in table 3, which shows that propane and natural gas heat pumps can have lower emissions than electric heat pumps, except for the lowest heat rate we examined (half renewable energy and half state-of-the-art natural gas generation) and also for the highest-efficiency electric heat pumps powered by the best combined-cycle power plants. Since the performance of gas-fired and cold-climate heat pumps is not well established, these results are highly approximate. If propane- and gas-fired heat pumps are commercialized for the mass market, this analysis should be refined based on the performance of those systems.

Table 3. Propane and natural gas versus electric heat pump CO_2 emissions per million Btu of home heating load

	Power plant heat rate in Btu/kWh			
	4,754	6,096	7,652	10,382
	CO_2 emissions			
Propane heat pump	46.5	46.5	46.5	46.5
Natural gas heat pump	39.9	39.9	39.9	39.9
Electric heat pump				
8.2 HSPF	37.9	48.6	61.0	82.7
8.5 HSPF	36.9	47.3	59.3	80.5
10.3 HSPF	32.3	41.5	52.1	70.6
Cold-climate	29.3	37.6	47.1	64.0

These estimates are based on US averages for each type of system; details are provided in table A17 in Appendix A. Gas heat pump electricity use is incorporated into the coefficient of performance (COP) and is not separated out, preventing us from differentiating emissions by heat rate. For electric heat pumps, these estimates assume power comes from natural gas power plants at the various heat rates used for our prior energy use analysis. Shaded cells indicate where emissions are lower for electric heat pumps than for propane heat pumps. The calculations incorporate estimated COP as achieved in the field as well as transmission and distribution losses (6% for electric, 2% for natural gas, 1.6% for propane).

Summary of Analysis Findings

We have looked at the energy, economic, and greenhouse gas emissions impacts of converting oil and propane furnaces, boilers, and water heaters to high-efficiency heat pumps at the time existing equipment needs to be replaced. We have also looked at the impacts of installing a heat pump as an early replacement (before the existing equipment fails) and as a partial replacement (leaving the existing system in place to provide supplemental heat, particularly when outdoor temperatures are low).

For replacing worn-out existing equipment, we have found a number of applications where such conversions are attractive, by which we mean that they save energy, reduce emissions, and pay back the extra costs to consumers within about five years.

- *Replacing oil or propane water heaters with heat pump water heaters*. Replacing oil water heaters can be particularly attractive as heat pump water heaters often have a lower initial cost than oil water heaters, in addition to their lower operating costs.[39]
- *Replacing oil and propane furnaces outside the Upper Midwest*. Again, the consumer economics of replacing oil systems are generally the most attractive (consumer paybacks of 1–3 years for oil, 2–6 for propane). Consumer economics are not good in the Upper Midwest (we looked at Illinois, Michigan, and Wisconsin) due to high electricity prices and relatively low oil and propane prices in those states, as well as reduced heat pump performance at cold temperatures.
- *Replacing oil boilers with ductless heat pumps in homes outside the Upper Midwest that can be fully heated with two ductless heat pumps*. The consumer economics of replacing boilers are generally not as good as the economics of replacing furnaces, although the five-year typical payback (outside the Upper Midwest) for replacing an oil boiler will be attractive to some homeowners. Furthermore, ductless heat pumps can be a useful way to provide air-conditioning in homes heated with boilers.

Below we provide these results in tabular form. Table 4 presents the average payback period for each region for each of the major types of oil and propane systems we examined, using a representative oil/propane to heat pump comparison and calculating the simple average of paybacks among the 2–6 states we examined in each region.

Table 4. Representative average simple payback period for installing a heat pump at the time the existing oil or propane system needs to be replaced

	Average simple payback period (years)				
Comparison	US	West	Midwest	Northeast	Southeast
Oil furnace (83% AFUE) vs. HP (8.5 HSPF); includes AC savings	0.9	1.4	1.3 in MO; no savings in upper MW	1.9	0.8
Propane furnace (80% AFUE) vs. HP (8.5 HSPF); includes AC savings	1.5	1.7	3.4 in MO; no savings in upper MW	2.0	1.3
Oil boiler (86% AFUE) vs. ductless HP, without AC	4.4	7.3	18.8	6.2	5.1
Propane boiler (84% AFUE) vs. ductless HP, without AC	16.1	12.1	19.8	8.5	9.1
Std. oil water heater vs. HPWH (2.0 rated EF)	Immediate	Examined only at a national level			
Std. propane water heater vs. HPWH (2.0 rated EF)	3.9				

39 An exception is in homes where a service or circuit upgrade is required and such an upgrade raises conversion costs.

We also looked at the economics of early replacement and partial replacement of furnaces and boilers. For early replacement of oil furnaces, typical consumer paybacks are 4–10 years, while the figures for propane furnaces and oil boilers range from about 5–20 years. Early replacement of propane boilers and most partial replacements have typical paybacks of more than 10 years, with the exception of oil furnaces in some states and propane furnaces in a few states.

The current study concurs with Nadel 2016 that gas-driven heat pumps often have the lowest energy use among the options studied, but because these systems are still largely precommercial, it is too early to examine their economics. This present study has also found that gas heat pumps can have low emissions, although electric heat pumps have even lower emissions at the lowest heat rates we examined.

Nadel and Kallakuri (2016) found that switching from electric furnaces to heat pumps is often financially attractive, as is converting from electric baseboard heat to heat pumps in homes with ducts or homes with above-average space-heating energy use. The present study joins with this earlier work in identifying additional promising applications in which to pursue conversion to heat pumps.

All of these findings are for typical systems of various types that we examined at the state level. But each home is different, and climate and energy prices can vary substantially within a state. The present study is not a substitute for more local analyses that should be undertaken before conversions of individual homes or programs serving portions of states are contemplated. Also, many homeowners have decision criteria in addition to economics; for instance, some customers may want to switch out of oil or propane due to concerns about leaky fuel tanks or the flammability of propane.

Consumer Acceptance of Heat Pumps

In addition to energy, economic, and climate considerations, a key issue is consumer satisfaction with heat pumps. Consumers purchase these systems to heat their homes and hot water, and if they are not happy with the quality of these services, consumer uptake of heat pumps will be slow. To address this issue, we did not do any new research but instead reviewed a variety of studies in the literature. For this work we focused on space-heating heat pumps because these can affect comfort whenever anyone is home, and because the energy used for space heating is much greater than the energy used for water heating in most of the United States.

Heat pumps were first commercialized in the 1950s. Early equipment had a variety of problems including frosting, compressor failure, and poor heating performance. Heat pumps gained a reputation for low reliability, which constrained sales for about a decade (1963–1973) (Brohl 2001; Checket-Hanks 2001; Lazzarin 2007). Equipment eventually improved, although some concerns remained (e.g., Rutkowski 1990 notes concerns about cool supply air temperatures). Currently more than two million heat pumps per year are sold in the United States (AHRI 2018).

We looked for relatively recent studies on consumer satisfaction with heat pumps and found 11 of them. Six were US studies, of which all but one were on ductless heat pumps.[40] The other five were from New Zealand, Switzerland, and the United Kingdom and examined a mix of heat pump types. The results of these 11 studies are summarized in table 5. Overall, satisfaction was fairly high, with 75–98% generally reporting satisfaction levels of 4 or 5 on a five-point scale.[41] However there were some sources of dissatisfaction including noise, comfort on cold days, aesthetics, and reliability. One of these studies reported concerns that coefficient of performance in the field is not as high as equipment ratings (Burrough, Saville-Smith, and Pollard 2015). And several reported concerns about overall heating cost (e.g., Brown, Burke-Scoll, and Stebnicki 2011 and Burrough, Saville-Smith, and Pollard 2015). Furthermore, there are various aspects to satisfaction that the simple analysis in table 5 does not fully reflect. For example, figure 26 shows the various facets of satisfaction from the Brown, Burke-Scoll, and Stebnicki study on hybrid heat pumps (air-source heat pumps with backup, typically electric) in Minnesota. While the sample is small, and overall satisfaction is lower than in the other studies, these results illustrate the range of opinions on different aspects of heat pumps.[42]

[40] The US studies emphasize ductless systems since they are a new technology. More than two million ducted systems are sold annually in the United States, while approximately 700,000 ductless systems are sold annually, although this latter figure is increasing steadily (Schimelpfenig 2017).

[41] This range reflects the midpoint on studies that had multiple ratings.

[42] While the report discusses cold-climate heat pumps, it appears that the hybrid heat pumps installed were not cold-climate models. These homes increasingly relied on their auxiliary heating systems as temperatures fell below about 30°F.

Table 5. Consumer satisfaction with heat pumps

Study	Location	Type of heat pump	% satisfied*	Sample size	Notes
Brown, Burke-Scoll, and Stebnicki 2011	MN	Hybrid (air source with backup)	46–100%	10	Scores were lowest for heating cost, highest for safety. Comfort, cooling cost, reliability, performance in extreme temperatures, and noise were rated in-between.
Herk 2017	San Antonio	Ductless	100%	1	Study also collected detailed data on interior temperature and humidity and found adequate comfort.
Research into Action 2011	NW US	Ductless	92–98%	222	Participants were asked about comfort, noise, and maintenance.
Swift and Meyer 2010	CT and MA	Ductless	95%	40	
Van de Grift and Billingsley 2015	NW US	Ductless			In focus groups, 21% of participants expressed aesthetic concerns.
Vitoff et al. 2014	MA	Ductless		144 with cold-climate HPs	77% said HP provides sufficient heat at cold temperatures; 48% said the same at very cold temperatures (under 15°F)
Burrough, Saville-Smith, and Pollard 2015	NZ	Mostly ductless	94%	125	Users would recommend a heat pump to friends or family.
Caird, Roy, and Porter 2012	UK	Air and ground source	73–83%	74	Respondents were asked about meeting room heating requirements, warmth and comfort, and system reliability.
Frontier Economics and Element Energy 2013	UK	Air and ground source			Concerns were expressed about noise, visual appearance, vulnerability of outside unit to tampering, and system's ability to provide sufficient heat on cold days.
Lazzarin 2007	Switzer-land	Air and water source	95%	237	
Lowe et al. 2017	UK	Mostly air source	86%	21	Of 21 cases, 10 experienced significant problems after installation.

* Combines ratings of 4 and 5 on a five-point scale

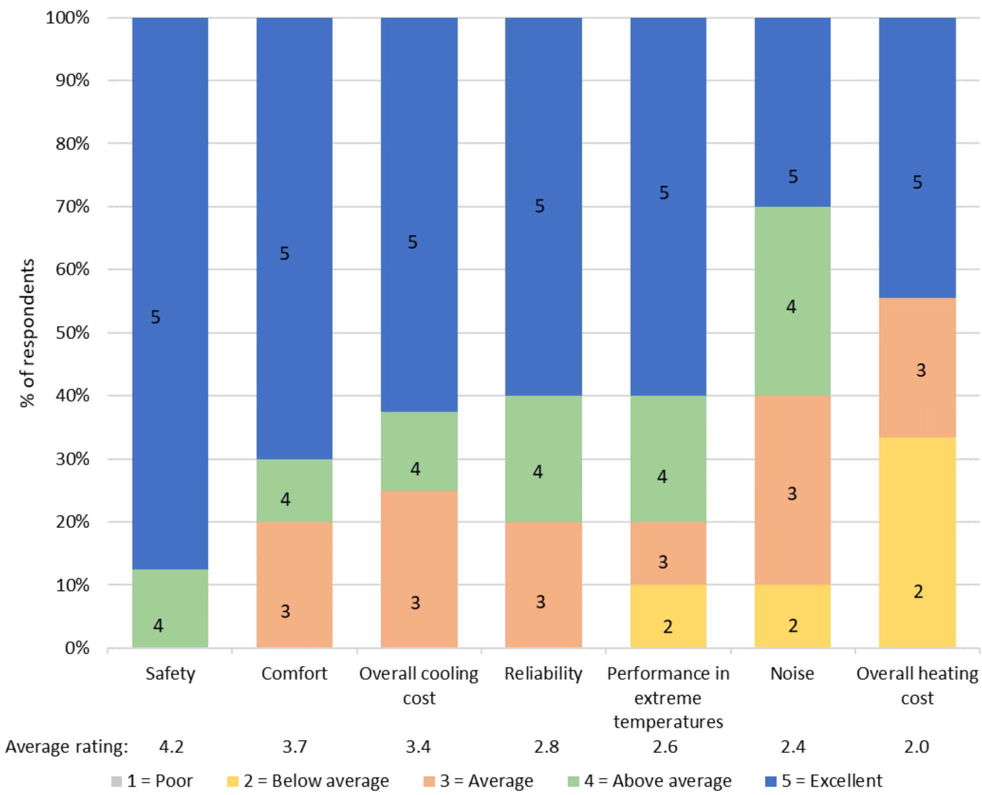

Figure 26. Respondent ratings about various aspects of heat pump systems on a 1–5 scale. *Source:* Brown, Burke-Scoll, and Stebnicki 2011.

In addition, we should note complaints about heat pumps reported on the Internet; these include claims that they blow cold air (the supply air coming out of a heat pump is typically around 90°F, not the 130°F common with furnaces), ice up, and on cold days run all the time without ever quite reaching the desired temperature (see, e.g., Hannabery HVAC 2018). Good system design and consumer education can help address these problems. For example, proper sizing should allow adequate heating on all but the coldest days, systems can be laid out to provide supply air in places where residents do not directly feel this flow of lukewarm air, and consumers can be given information that explains low supply air temperatures and longer run times.

Still, customer concerns about heat pumps could hinder growth in heat pump use. This is illustrated by a consumer survey covering 15 US metropolitan areas. In this survey, 67% and 68% of homeowners said they preferred to use natural gas for space heating and water heating, respectively, while only 25% preferred electricity for these end uses (Scott 2016). Oil and propane were not included in this survey, nor did it differentiate between heat pumps and electric resistance heat; hence, this survey in part captures opinions about electric resistance heat.

Recent and Current Monitoring Studies on Ductless Heat Pumps

Ductless heat pumps are a relatively new type of system, and a variety of recent and ongoing studies are examining their performance in multiple regions of the United States. Some of these studies were discussed earlier: a Building America study on new homes in Massachusetts (Ueno and Loomis 2014) and a Minnesota study on home retrofits using both ducted and ductless cold-climate heat pumps (Schoenbauer, Bohac, and Haynor 2018). Other examples include detailed monitoring of three test homes in California (Proctor and Wilcox 2016), field monitoring of 152 ductless heat pumps in Massachusetts and Rhode Island (Korn et al. 2016), and field monitoring of 77 cold-climate ductless heat pumps in Vermont (Walczyk 2017). These last two studies have led to revisions of energy savings estimates in these states. The Proctor and Wilcox work found that ductless heat pumps saved less energy than expected in a hot part of California (the Central Valley); additional follow-up work is underway. A major study involving about 50 homes with air-source heat pumps (plus another 40 with ground-source heat pumps) is now underway in New York (Smith 2017). These recent and forthcoming studies provide or will provide useful information on the performance of these systems and consumer satisfaction with them, including recommendations on how to best apply these heat pumps in homes and programs.

Experience with Early Programs Promoting Conversions to Heat Pumps

Programs to encourage electrification of space and water heating are still in their infancy, but some initial efforts have started in California and the Northeast. In addition, programs to promote ductless heat pumps in the Northwest are also of interest, even though these programs thus far have targeted homes with electric resistance heat and not homes using fossil fuels for heating. In the following sections we provide brief summaries of major programs in these three regions. For California and the Northeast, we focus on programs that explicitly target electrification, not on those that encourage changing from electric resistance water heaters to heat pumps. For a discussion of exemplary heat pump water heater programs, see York et al. 2015.

CALIFORNIA

In California, as previously noted, the California Public Utilities Commission (CPUC) requires that fuel substitution programs (such as replacing natural gas with electricity) meet a three-pronged test. They must reduce energy use, have a cost–benefit ratio greater than 1 using both the total resource cost (TRC) test and the program administrator cost (PAC) test, and not adversely affect the environment (CPUC 2013). However the mechanics of how to pass the tests lack clarity, and as a result program administrators have largely avoided measures that involve fuel substitution.

Several emerging efforts are worth noting. First, in 2014, the California legislature passed a bill whose goal is to increase access to affordable energy for disadvantaged communities in the San Joaquin Valley, an area where most homes are presently heated with propane and/or wood. In response, there have been several proposals to better serve these communities. Southern California Gas has proposed to extend natural gas lines to these homes so they can be heated with natural gas; other proposals, from Pacific Gas & Electric (PG&E) and Southern California Edison (SCE), would promote high-efficiency heat pumps (CPUC 2018).

Second, SCE has prepared a vision document detailing its thoughts on how California can achieve its climate goals. Under this vision, by 2030 California would use carbon-free energy to meet 80% of its electric needs, more than seven million electric vehicles would be on the state's roads, and nearly one-third of homes would use electricity for space and water heating (SCE 2017).[43] CPUC has opened a proceeding to review and potentially modify the three-pronged test following a petition on this issue by California environmental groups.

While investor-owned utilities are currently constrained from promoting fuel substitution, California municipal utilities are not subject to CPUC regulation, and two of these utilities have begun electrification programs.

First, the municipal electric and natural gas utility serving the city of Palo Alto offers rebates of $600–800 to encourage installation of heat pump water heaters in new construction. It also offers rebates of $1,200–1,500 to replace existing gas water heaters, thereby essentially competing with its own gas service. Palo Alto gets the majority of its power from carbon-free sources, and this program is part of the city's greenhouse gas reduction efforts. After nearly two years of operation, the program has processed 13 rebates for fuel substitution, and a dozen rebates for new construction are now pending. City staff, recognizing that Palo Alto is just a small part of the local water heater market, are now discussing a potential program to be offered throughout the San Francisco Bay Area (C. Tam, program manager, city of Palo Alto, pers. comm., March 29, 2018).

Second, the Sacramento Municipal Utility District (SMUD), an electric-only utility, has a somewhat similar program to encourage use of heat pump water heaters. It offers $1,000 rebates for heat pumps that replace an electric resistance water heater and $1,500 for replacing a gas water heater. Each year the utility processes about 100 electric water heater replacements and half a dozen gas water heater replacements. It is now planning a much more substantial program to begin in late 2018. The program will buy down the wholesale cost of heat pump water heaters (expected to be primarily replacements for electric resistance water heaters) and will also pay contractors who replace gas water heaters with heat pump water heaters. When a customer's gas water heater fails, he or she can call SMUD and the utility will assign a qualified contractor to do the job, or the customer can select a contractor from a list of qualified providers. Tentatively, a rebate of $3,000 for gas conversions is planned, about equal to the lifetime benefit to the utility of a heat pump water heater. The utility hopes the program gets traction, and if it does, the rebate will likely be reduced over time.

SMUD is also planning to give rebates for new all-electric homes ($5,000 for single-family homes, $1,500 for multifamily) and will provide rebates of $2,500 for installation of a new space-heating heat pump in place of a gas system in an existing single-family home. For these rebates an HSPF of at least 8.5 will be required. For new construction, SMUD is considering a $600 rebate for homes that are electric ready, meaning they have adequate electric service, breakers, wiring, and plugs to be easily converted to all electric, even if some gas appliances are installed at the time of construction. In addition to the space-

[43] As of 2009, 21% of California homes used electricity as their primary form of space heating (EIA 2013).

heating heat pump discussed above, existing homes will be eligible to receive $250 for installing an electric induction range in place of a gas stove, and a $2,500 all-electric bonus is available on top of the product-specific rebates if homeowners convert their water heater, furnace, and range. Thus, under this proposal, an existing home can receive up to $8,250 ($3,000 for a heat pump water heater, $2,500 for a heat pump for space heating, $250 for an induction range, and a $2,500 all-electric bonus). For existing multifamily buildings, the maximum incentive will be $3,000 per apartment (S. Blunk, strategic business planner, SMUD, pers. comm., April 3, 2018).

NORTHEAST

This section draws heavily on a recent summary of electrification programs in the Northeast prepared by the Vermont Energy Investment Corporation (VEIC) (VEIC 2018). Many programs in the Northeast focus on ductless heat pumps since only a few ducted products work well at cold temperatures and many better-performing ductless alternatives are available. Also, the market share of boilers is comparatively high in the Northeast; for these homes ductless products are the primary option.

Connecticut

Some 81% of the housing stock in Connecticut uses natural gas, fuel oil, or propane for space heating (EIA 2018c). In 2018 the Connecticut Department of Energy and Environmental Protection (DEEP) implemented a Comprehensive Energy Strategy calling for residential building electrification (Connecticut DEEP 2018). The strategy calls on utilities to promote the installation of ductless air-source heat pumps (DHP), particularly by leveraging consumer demand for space cooling. The primary method for promoting DHPs is through the Energize Connecticut (CT) program, which is spearheaded by Eversource and the United Illuminating Company.[44]

The Energize CT program provides a $300 incentive for single-zone ENERGY STAR DHPs and a $500 incentive for multizone ENERGY STAR DHPs that meet the program's required SEER, EER, and HSPF levels; the program also offers financing at a 0.99% interest rate for qualifying products. The program employs an upstream approach. Incentives are given to wholesale distributors, who must pass the incentive along to customers. To ensure quality installation, incentives are offered at the distributor point of sale only to licensed contractors with a valid customer installation address. With respect to DHPs, Energize CT has found that upstream programs are more effective than downstream programs for several reasons. The first is that customers automatically see the rebated price and do not have to file paperwork for mail-in rebates. Second, wholesale distributors are motivated to receive and pass along the incentive to remain competitive with their counterparts. The program also provides rebates for commercial customers depending on equipment efficiency and size (VEIC 2018).

Energize CT has seen considerable success. Between 2012 and 2015, Connecticut households installed 6,176 DHPs through the program and financed 545 of them. Going forward,

[44] These utilities work closely with the Connecticut Green Bank and Connecticut Department of Energy and Environment.

program administrators hope to achieve deeper energy savings from program participants. Many participants retain their fuel heaters. This can adversely affect energy savings because often these households will use the fuel heater as the primary heat source and the DHP as a supplemental source. Energize CT is providing education and training materials to encourage these households to use their DHP as the primary heat source and their fuel heater as backup. The state is also proactively encouraging new construction to adopt electric heat pumps for heating by directing utilities to develop an all-electric package for residential new construction (VEIC 2018).

Maine

Maine, which joined the Regional Greenhouse Gas Initiative (RGGI) in 2013, has committed to reducing oil dependence by 50% by 2020. Electrification helps to achieve this goal because 79% of households use oil, natural gas, or propane for heating (EIA 2018d). Efficiency Maine, the state's main efficiency program administrator, is leading a ductless heat pump program for both residential and commercial customers. (VEIC 2018). Residential customers can receive a $500 rebate for the first indoor unit and $250 for a second one. Commercial customers can receive up to $1,250 in rebates for multiple units; the first zone qualifies for a $500 rebate and subsequent zones qualify for $250. The residential program is funded by a systems benefit charge on each kWh of electricity sold in the state, while commercial rebates are funded by RGGI.[45]

Since 2011, more than 25,000 units have been installed through the program. Administrators attribute the high adoption rate to the large cost savings from fuel switching, particularly during years of high oil prices. Additionally, the high rebate amounts have encouraged a substantial number of customers to adopt the technology (VEIC 2018).

Massachusetts

Massachusetts views electrification as a strategy to meet its grid flexibility and modernization goals. Residential heating presents a large opportunity; approximately 82% of households use natural gas, fuel oil, or propane (EIA 2018e). The state has two heat pump programs: Mass Save and the Clean Heating and Cooling program (VEIC 2018).

Mass Save is a collaborative effort led by utilities in the state. It operates many statewide programs, including providing rebates for DHPs as well as central ducted heat pumps. To qualify, households must have the unit installed by a certified contractor. For mini-split heat pumps, any unit rated at 18 SEER/10 HSPF or above qualifies for a rebate of $100 per indoor head.[46] Any unit above 20 SEER/12 HSPF qualifies for a $300 rebate per indoor head. For central heat pumps, any unit at 16 SEER/8.5 HSPF or above qualifies for a $250 rebate, and any unit at 18 SEER/9.6 HSPF or above qualifies for a $500 rebate. An additional $500 is available if customers replace a central heat pump system that is at least 12 years old and still functioning. The program has done on-site monitoring on a sample of more than 100 ductless heat pumps installed in homes and used this monitoring to estimate energy and

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[45] RGGI funds are also used for residential low-income programs.

[46] SEER 18 can often be achieved by heat pumps with an HSPF of 10 or more.

demand savings, in-field efficiency, and equivalent full load operating hours (Korn et al. 2016).

The Massachusetts Clean Energy Center (MassCEC) runs the Clean Heating and Cooling program, which provides heat pump rebates to residential and commercial buildings. MassCEC offers a $625 rebate to customers who install air-source or ground-source heat pumps. Low-income customers are eligible for larger incentives, up to $1,500 per heat pump. Participants must receive an energy audit to qualify for the rebate. Contractors may apply for the rebate but must pass the entire amount to their customers. Customers are able to combine Mass Save and MassCEC rebates.

Both programs have had successful starts. The MassCEC program has incentivized more than 9,000 units since it began in 2015. Mass Save incentivized about 9,000 heat pumps in 2016 alone.

Going forward, the state is implementing additional educational programs for both installers and residents. Program implementers believe it is important that installers properly size and position heat pump units so that no parts of the home are underheated; otherwise, residents may return to using their old and inefficient heating systems. To address this issue, MassCEC is training installers to install the appropriate number and size of ductless systems. Beyond system design, installers will also be trained to teach customers how to optimally heat their entire homes using their thermostats to adjust set points for each heat pump unit. Mass Save is offering a Mini-Split Check training, showing installers how to confirm proper refrigerant charge. The two programs have also collaborated on a customer tip sheet for proper mini-split heat pump usage. These educational programs are expected to increase the actual energy savings from both the MassCEC and Mass Save programs (VEIC 2018).

New York

New York is dedicated to reducing its greenhouse gas emissions. Approximately 85% of homes in New York use natural gas, fuel oil, or propane for heating (EIA 2017c). The Clean Energy Fund (CEF) supports fuel-switching programs if they achieve greater GHG emissions reductions and economic benefits than electric-only approaches (VEIC 2018). Currently, NYSERDA and several utilities offer heat pump programs.

In August 2017, NYSERDA launched a midstream heat pump program providing incentives to enrolled contractors who meet quality assurance and control requirements. Contractors receive $500 for each installed DHP or ducted air-source heat pump. Providing the incentive to contractors encourages them to learn about and promote the technology. In contrast to many other programs, contractors are not required to pass the rebates on to their customers. Contractors must report information about their customers, however, such as the heating system being replaced and the age of the home. NYSERDA will use these data to understand the market and program reach. Based on its findings, NYSERDA may change its incentive structure and targeting efforts.

Early results are promising. NYSERDA began the program August 2017 and expects to install 21,000 air-source heat pumps by December 2020. As of April 2018, 150 installers were participating in the program and had received 2,200 incentives in total. Each installer is limited to 1,000 incentives ($500,000) (VEIC 2018).

In addition to this midstream program, several utilities in New York are offering downstream heat pump programs. For example, Consolidated Edison offers $400 rebates to homeowners who install ductless mini-split heat pump systems. Other utilities in the state with heat pump programs include Public Service Enterprise Group, Orange and Rockland, and Central Hudson. The rebates from these programs can be combined with the NYSERDA incentives.

Rhode Island

State regulators implemented the Power Sector Transformation initiative to modernize Rhode Island's grid and meet long-term greenhouse gas emissions goals. The state recognizes that electrification is necessary to meet these goals because 89% of homes in the state use natural gas, oil, or propane for heating (EIA 2017d). Traditionally, programs to switch from oil, propane, or natural gas to a heat pump were not included in program portfolios because they did not pass the necessary cost–benefit tests. To address this issue, the Rhode Island Public Utilities Commission (PUC) approved a new cost–benefit test, the Rhode Island (RI) Test, which includes social and environmental costs. This has allowed National Grid, the primary state utility, to include fuel-switching programs in its energy efficiency plans (VEIC 2018).

National Grid runs the only heat pump program in the state, providing downstream incentives to customers. Those who install DHPs can receive $100–300, or $250–500 for central ducted heat pumps. Additionally, National Grid offers a loan program at 0% interest. The program, funded through a system benefit charge, began in 2017 and therefore does not have results to report yet. VEIC (2018) predicts that Rhode Island will see a slower heat pump uptake than other Northeast states due to the lack of upstream incentives and low incentive rates.

Vermont

In 2015, a renewable energy standard (RES) became law in Vermont and called for the electrification of buildings (VEIC 2018). Approximately 76% of homes in the state use natural gas, fuel oil, or propane for heating (EIA 2017e). Vermont's 2016 Comprehensive Energy Plan identifies heat pumps as a strategy for meeting its goals for reducing fossil fuel consumption. The Electric Energy Efficiency Initiative is funded and implemented by Efficiency Vermont (EVT) and the Burlington Electric Department (BED).

In 2014, EVT launched a DHP program. The program provides a $600–800 per unit midstream incentive to wholesale distributors, and distributors are required to pass the savings to contractors through an instant discount. EVT sends a letter to contractors' customers explaining that the contractor has received a discount on the equipment, which in turn motivates contractors to pass the incentive to the customer. On top of these payments, customers can receive incentives from their electric utilities.[47]

Homeowners can also rent a DHP through the Cold Climate Heat Pump Program. Monthly rates range from $41.99 to $54.99 depending on the equipment size; agreements run for 15 years. Installation, materials, and maintenance are built into the flat monthly fee. The program began in 2013 and has leased more than 1,000 units (NEEP 2017).

Zero Energy Now is another program encouraging the adoption of cold-climate heat pumps in Vermont. The Building Performance Professionals Association of Vermont, in coordination with Vermont's largest utility, Green Mountain Power (GMP), launched the program to move Vermont homes closer to zero net energy by providing comprehensive retrofit services. Installing cold-climate heat pumps has been a key strategy for minimizing each home's energy consumption (Faesy and Kramer 2016). Between April and December 2016, 22 projects were completed through the program. On average, each home was projected to save 61 MMBtu annually (Amann 2017). The program also encourages the installation of heat pump water heaters to achieve deeper fuel savings.

Vermont also has added an energy transformation section to its utility portfolio requirements, sometimes called Tier 3 (Tier 1 is for all renewables, Tier 2 for distributed renewables under 5 MW of output). Under Tier 3, electric utilities must help their customers reduce their direct consumption of fossil fuels. Such reductions are typically achieved either through increased efficiency of fossil fuel use (e.g., by weatherizing oil-heated homes) or through electrification (of home heating, industrial processes, vehicles, and so on). In 2017, the first year with Tier 3 in effect, the utilities were required to obtain fossil fuel reductions equivalent to 2% of their annual retail electric sales in 2017. The target ramps up by 0.67% per year until it reaches an annual requirement equivalent to 12% of electric sales in 2032 (VPUC 2018). An analysis of utility plans for 2018 found that the most common Tier 3 measures are commercial/industrial (C&I) custom fuel-switching projects, cold-climate residential heat pumps, and electric vehicles and chargers (EFG 2018). A report by Green Mountain Power on its 2017 Tier 3 programs notes that it has proved much easier to obtain energy savings from custom C&I projects than from prescriptive residential programs (because savings from each C&I project are equal to the savings from many residential conversions) and that among residential conversion customers, only about 20% are taking advantage of GMP's installment purchase program (GMP 2017).

Vermont has the highest DHP installation rate (as a percentage of total homes) of any state in the Northeast. To date, EVT has incentivized more than 8,200 heat pumps through the program. VEIC attributes this success largely to the large upstream incentives. EVT is able to provide such large incentives because it uses both electric savings and fossil fuel savings in its cost–benefit calculation (many other programs count only electricity savings). These large incentives, paired with strong supply chain engagement, have driven participation.

[47] Vermont Electric Co-op offers a $150 bill credit, Washington Electric Co-op (WEC) offers a $250 incentive, and BED offers an additional $375-450 incentive for customers who switch from propane or fuel oil.

Going forward, EVT plans to continue providing upstream rebates and promoting educational programs (VEIC 2018).

NORTHWEST

In 2010, the Northwest Energy Efficiency Alliance (NEEA) introduced the Ductless Heat Pump (DHP) Initiative to increase heat pump adoption throughout its region. The program targets three housing types: single-family homes with zoned electric heating, single-family homes with electric forced-air furnaces, and manufactured homes with electric forced-air furnaces. Installing heat pumps in these homes could yield about 1,750 million kWh of savings (Storm et al. 2012).

NEEA worked with utilities to create and market robust rebate programs for DHPs.[48] The association engaged installers to promote DHP technology and programs because installers are able to influence the purchasing decisions of their clients. It also created a Master Installer Certification to ensure high-quality work. Customers must hire a certified installer in order to qualify for a rebate, and both the utilities and NEEA maintain a list of master installers that customers may choose from. For their part, installers are motivated to earn the certification by the free marketing and the additional revenue stream. NEEA also facilitates collaborations between manufacturers and retailers to develop and deploy marketing campaigns (Conzemius and Kahl 2016).

As of 2016, the program has seen DHP market penetration increase from 0% to 13% in the four northwestern states. Going forward, NEEA plans to increase online marketing, particularly through social media (Conzemius and Kahl 2016). NEEA is also working with contractors to decrease markups on DHP installations. Data have shown that the cost of DHP installations is increasing (Lee et al. 2018). NEEA interviewed distributors and installers to understand this trend. Some suggested that since installers already experience low profit margins, they might see the introduction of new and complicated technologies as an opportunity to increase those margins. NEEA is working with manufacturers to potentially provide equipment at lower costs to installers to offset these rising prices (Lee et al. 2018).

Conclusions and Recommendations

Our research (this study and prior studies) finds important market niches that look attractive for heat pumps: as replacements for many oil-fired and electric resistance systems and some propane-fired systems. Research by others has also identified new construction as an attractive opportunity (Deason et al. 2018; Billimoria 2018). Some initial programs show promise in reaching these markets. Policymakers and program implementers in states with substantial use of oil, propane, and electric resistance systems should consider offering programs to promote heat pumps for these applications, building on initial successful programs in the Northeast and Northwest. Such programs should focus on heat pumps that

[48] A full listing of DHP rebates available in NEEA's territory can be found at goingductless.com/participating-utilities/p2.

are at least ENERGY STAR certified, with higher incentives for the highest-efficiency systems, particularly cold-climate heat pumps that can provide heat even at low temperatures. Programs and other development efforts should encourage the commercialization of more cold-climate heat pumps, particularly ducted systems with enough heating capacity to serve a home in cold weather.[49] Continued development of gas-fired heat pumps should also be pursued; a key for this technology will be keeping costs at a level that will permit these systems to compete with advanced electric heat pumps as well as high-efficiency natural gas, propane, and oil systems.

In addition, we note the recent recommendations from the Northeast Energy Efficiency Partnership's *Air Source Heat Pump Market Strategy Report* (NEEP 2017):

- Increase consumer education and awareness.
- Increase installer/builder awareness of, and confidence in, air-source heat pumps through expanded training and education.
- Reduce up-front costs of installed systems through robust and aligned promotional programs and the support of alternative business models.
- Mobilize state and local policymakers to expand support for heat pumps.
- Promote advanced control technologies to allow automated coordination among multiple heating systems, with prioritization of heat pump operation.
- Enable the promotion of climate-appropriate heat pumps through improved performance metrics.
- Develop more accurate tools to predict energy, cost, and greenhouse gas savings associated with heat pump installation through collection and analysis of real-world performance data.

We agree with these recommendations. Building on the last two items in the above list, we recommend more field monitoring of actual heat pump performance to better enumerate savings, identify equipment and applications that perform well, and reveal opportunities for improvement. A particular focus of this work should be research on supplemental heat for heat pump replacements in colder climates that could avoid the need to retain a fossil system for supplemental heat on the coldest days.

The results of our research are based on current conditions. The analysis should be repeated in a few years, as several trends favor heat pumps, including improvements in heat pump efficiencies (e.g., the federal minimum efficiency standard will increase to 8.8 HSPF as of 2023, and the ENERGY STAR standard will also increase), development of more cold-climate heat pumps, possible declines in the cost of heat pump water heaters, increased penetration of low-carbon renewable energy generation, and the fact that oil and propane prices are relatively low at present relative to prior years. Other factors that will affect a future analysis include pending federal furnace standards (which could raise the minimum AFUE in the North), development of gas heat pumps, and improvements in home efficiency

[49] We are heartened by an Electric Power Research Institute project that is working with five major manufacturers to develop and field-test such units (Stankorb 2017).

(for new construction and existing homes) that will lower average space-heating and space-cooling energy use per home.

Through these efforts we can increase the market share of heat pumps in appropriate applications while making greater progress in reducing greenhouse gases and lowering the costs of heating and cooling to a larger number of households.

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Appendix A. Detailed Analysis

Table A1. Energy use of oil furnaces and heat pumps

		West		Midwest				Northeast				South			
Furnace	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	VA
Avg. annual mBtu for an oil furnace	70.3	54.9	58.1	57.5	57.5	73.8	72.7	80.9	81.6	63.9	68.3	59.3	59.3	59.3	55.8
Add system distribution losses	70.8	55.3	58.5	57.9	57.9	74.3	73.2	81.5	82.2	64.3	68.8	59.7	59.7	59.7	56.2
Estimated mBtu for a 83% AFUE furnace	67.8	52.9	56.0	55.4	55.4	71.1	70.1	78.0	78.7	61.6	65.8	57.2	57.2	57.2	53.8
Add system distribution losses	68.2	53.3	56.4	55.8	55.8	71.6	70.6	78.5	79.2	62.0	66.3	57.6	57.6	57.6	54.2
Estimated mBtu for a 95% AFUE furnace	59.2	46.2	48.9	48.4	48.4	62.1	61.2	68.1	68.7	53.8	57.5	49.9	49.9	49.9	47.0
Add system distribution losses	59.6	46.6	49.3	48.8	48.8	62.6	61.6	68.6	69.2	54.2	57.9	50.3	50.3	50.3	47.3
Heat pump															
99% winter design temperature	18	40	24	2	2	6	-6	6	14	10	13	42	26	23	18
HSPF adjment factor for a HSPF 8.2 unit	0.1391	-0.1841	0.0613	0.3088	0.3088	0.2715	0.3731	0.2715	0.1867	0.2308	0.1980	-0.2186	0.0336	0.0748	0.1391
Adjusted HSPF for a nominal 8.2 unit	7.06	9.71	7.70	5.67	5.67	5.97	5.14	5.97	6.67	6.31	6.58	9.99	7.92	7.59	7.06
kWh per year with an HSPF 8.2 unit	7,967	4,523	6,038	8,116	8,116	9,884	11,313	10,835	9,788	8,105	8,309	4,747	5,986	6,253	6,323
Add elec system distribution losses	8,445	4,795	6,400	8,603	8,603	10,477	11,992	11,485	10,375	8,591	8,807	5,032	6,346	6,628	6,703
mBtu gas consumed as a function of heat rate															
4,754	40.1	22.8	30.4	40.9	40.9	49.8	57.0	54.6	49.3	40.8	41.9	23.9	30.2	31.5	31.9
6,096	51.5	29.2	39.0	52.4	52.4	63.9	73.1	70.0	63.2	52.4	53.7	30.7	38.7	40.4	40.9
7,652	64.6	36.7	49.0	65.8	65.8	80.2	91.8	87.9	79.4	65.7	67.4	38.5	48.6	50.7	51.3
10,382	87.7	49.8	66.4	89.3	89.3	108.8	124.5	119.2	107.7	89.2	91.4	52.2	65.9	68.8	69.6
HSPF adjment factor for a HSPF 8.5 unit	0.1467	-0.1954	0.0644	0.3254	0.3254	0.2862	0.3926	0.2862	0.1969	0.2434	0.2089	-0.2320	0.0352	0.0787	0.1467
Adjusted HSPF for a nominal 8.5 unit	7.25	10.16	7.95	5.73	5.73	6.07	5.16	6.07	6.83	6.43	6.72	10.47	8.20	7.83	7.25
kWh per year with an HSPF 8.5 unit	7,754	4,322	5,845	8,022	8,022	9,731	11,264	10,667	9,563	7,949	8,125	4,530	5,785	6,058	6,154
Add elec system distribution losses	8,219	4,582	6,196	8,503	8,503	10,315	11,940	11,307	10,136	8,426	8,613	4,802	6,132	6,422	6,524
mBtu gas consumed as a function of heat rate															
4,754	39.1	21.8	29.5	40.4	40.4	49.0	56.8	53.8	48.2	40.1	40.9	22.8	29.2	30.5	31.0
6,096	50.1	27.9	37.8	51.8	51.8	62.9	72.8	68.9	61.8	51.4	52.5	29.3	37.4	39.1	39.8
7,652	62.9	35.1	47.4	65.1	65.1	78.9	91.4	86.5	77.6	64.5	65.9	36.7	46.9	49.1	49.9
10,382	85.3	47.6	64.3	88.3	88.3	107.1	124.0	117.4	105.2	87.5	89.4	49.9	63.7	66.7	67.7
HSPF adjment factor for a HSPF 10.3 unit	0.1974	-0.1447	0.1152	0.3761	0.3761	0.3369	0.4433	0.3369	0.2476	0.2941	0.2596	-0.1813	0.0859	0.1294	0.1974
Adjusted HSPF for a nominal 10.3 unit	8.27	11.79	9.11	6.43	6.43	6.83	5.73	6.83	7.75	7.27	7.63	12.17	9.42	8.97	8.27
kWh per year with an HSPF 10.3 unit	6,803	3,725	5,100	7,158	7,158	8,645	10,142	9,476	8,423	7,031	7,164	3,899	5,039	5,291	5,400
Add elec system distribution losses	7,211	3,949	5,406	7,587	7,587	9,163	10,751	10,045	8,929	7,453	7,594	4,133	5,341	5,608	5,724
mBtu gas consumed as a function of heat rate															
4,754	34.3	18.8	25.7	36.1	36.1	43.6	51.1	47.8	42.4	35.4	36.1	19.6	25.4	26.7	27.2
6,096	44.0	24.1	33.0	46.3	46.3	55.9	65.5	61.2	54.4	45.4	46.3	25.2	32.6	34.2	34.9
7,652	55.2	30.2	41.4	58.1	58.1	70.1	82.3	76.9	68.3	57.0	58.1	31.6	40.9	42.9	43.8
10,382	74.9	41.0	56.1	78.8	78.8	95.1	111.6	104.3	92.7	77.4	78.8	42.9	55.4	58.2	59.4
Cold-climate heat pump															
Seasonal HSPF				8.60	8.60	9.14	7.67	9.14	10.37	9.73	10.20				
kWh per year with a cold-climate heat pump				5,350	5,350	6,461	7,580	7,082	6,295	5,255	5,355				
Add elec system distribution losses				5,671	5,671	6,849	8,035	7,507	6,673	5,570	5,676				
mBtu gas consumed as a function of heat rate															
4,754				27.0	27.0	32.6	38.2	35.7	31.7	26.5	27.0				
6,096				34.6	34.6	41.7	49.0	45.8	40.7	34.0	34.6				
7,652				43.4	43.4	52.4	61.5	57.4	51.1	42.6	43.4				
10,382				58.9	58.9	71.1	83.4	77.9	69.3	57.8	58.9				

Notes to Table A1

- Oil use by state for homes with oil space heating, as provided in the 2009 RECS (EIA 2013). We estimate that the average existing home in this sample has a furnace that achieves 80% AFUE.
- We estimated oil use for 83% and 95% AFUE furnaces by multiplying oil use for 80% AFUE by 80/83 or 80/95.
- We estimated heat pump seasonal efficiency for 8.2 HSPF units with the following formula from Fairey et al. (2004):
  - Seasonal HSPF = 8.2 * (1 – adjustment factor)
  - Adjustment factor = 0.1392 – 0.00846 * Design T – 0.0001074 * (Design T)^2 + 0.0228 * 8.2
  - Design T is the 99% design temperature and is based on representative values for each state, as we show in table A1.
- We based heat pump seasonal efficiency for 8.5 and 10.3 HSPF units on a slightly different adjustment factor, also from Fairey et al. (2004). For 8.5 HSPF and above:
  - Adjustment factor = 0.1041 – 0.008862 * Design T - 0.0001153 * (Design T)^2 + 0.02817 * 8.5
- To heat pump electricity use we added 6% for distribution system losses; oil and propane distribution losses of 0.7% and 1.6% are also included. All of these loss factors are explained in the text.
- We based energy use to supply this electricity on a power plant heat rate of 6,096, 7,652, 10,362, or 4,754 Btus/kWh, as explained in the text.

Table A2 below shows differences in source energy use by state in millions of Btus. In these comparisons, the shaded cells indicate where oil furnaces use less energy on a source basis, while unshaded cells show where electric heat pumps use less energy. Table A2 is just a simple subtraction between the relevant rows of table A1 for each comparison.

Table A2. Oil furnace and heat pump energy use comparisons by state

		West		Midwest				Northeast				South					
	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
83% furnace vs. 8.2 HSPF heat pump																	
4,754	28.1	30.5	26.0	14.9	14.9	21.8	13.6	23.9	29.9	21.2	24.4	33.6	27.4	26.0	24.2	28.7	22.3
6,096	16.8	24.1	17.4	3.4	3.4	7.8	-2.5	8.5	16.0	9.6	12.6	26.9	18.9	17.2	14.8	20.5	13.3
7,652	3.6	16.6	7.4	-10.0	-10.0	-8.5	-21.2	-9.4	-0.2	-3.7	-1.1	19.0	9.0	6.8	3.8	11.1	2.9
10,382	-19.4	3.5	-10.1	-33.5	-33.5	-37.1	-53.9	-40.7	-28.5	-27.2	-25.1	5.3	-8.3	-11.3	-15.3	-5.5	-15.4
83% furnace vs. 8.5 HSPF heat pump																	
4,754	29.2	31.5	26.9	15.4	15.4	22.6	13.8	24.8	31.0	22.0	25.3	34.7	28.4	27.0	25.1	29.7	23.1
6,096	18.1	25.4	18.6	4.0	4.0	8.8	-2.2	9.6	17.4	10.7	13.8	28.3	20.2	18.4	15.9	21.9	14.4
7,652	5.3	18.2	9.0	-9.3	-9.3	-7.3	-20.8	-8.0	1.6	-2.5	0.4	20.8	10.6	8.4	5.3	12.8	4.2
10,382	-17.1	5.7	-7.9	-32.5	-32.5	-35.5	-53.4	-38.9	-26.0	-25.5	-23.1	7.7	-6.1	-9.1	-13.3	-3.2	-13.6
95% furnace vs. 8.5 HSPF heat pump																	
4,754	20.5	24.8	19.8	8.3	8.3	13.5	4.9	14.8	21.0	14.1	17.0	27.5	21.1	19.8	17.8	22.5	16.3
6,096	9.5	18.6	11.5	-3.1	-3.1	-0.3	-11.1	-0.3	7.4	2.8	5.4	21.0	12.9	11.1	8.7	14.6	7.5
7,652	-3.3	11.5	1.9	-16.3	-16.3	-16.3	-29.7	-17.9	-8.4	-10.3	-8.0	13.5	3.4	1.1	-2.0	5.5	-2.6
10,382	-25.7	-1.0	-15.1	-39.5	-39.5	-44.5	-62.3	-48.8	-36.0	-33.3	-31.5	0.4	-13.4	-16.4	-20.6	-10.5	-20.4
95% furnace vs. 10.3 HSPF heat pump																	
4,754	25.3	27.8	23.6	12.7	12.7	19.0	10.5	20.8	26.7	18.8	21.8	30.6	24.9	23.6	21.8	26.1	20.1
6,096	15.7	22.5	16.3	2.5	2.5	6.7	-3.9	7.4	14.8	8.8	11.6	25.1	17.7	16.1	13.8	19.3	12.4
7,652	4.4	16.3	7.9	-9.3	-9.3	-7.5	-20.6	-8.3	0.9	-2.8	-0.2	18.7	9.4	7.4	4.5	11.4	3.5
10,382	-15.3	5.6	-6.9	-30.0	-30.0	-32.6	-50.0	-35.7	-23.5	-23.2	-20.9	7.4	-5.2	-7.9	-11.8	-2.5	-12.1
95% furnace vs. cold-climate heat pump (tentative and illustrative)																	
4,754				28.9	28.9	39.1	32.4	42.8	47.5	35.5	39.3						
6,096				21.2	21.2	29.9	21.6	32.8	38.5	28.1	31.7						
7,652				12.4	12.4	19.2	9.1	21.1	28.1	19.4	22.9						
10,382				-3.1	-3.1	0.5	-12.9	0.6	9.9	4.2	7.4						

Table A3. Energy use of propane furnaces and heat pumps

		West				Midwest				Northeast				South					
Furnace	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Avg. annual mBtu for a propane furnace	42.9	37.7	30.7	64.1	39.2	57.3	59.8	48.1	66.3	35.7	48.1	50.4	48.0	26.8	29.0	28.4	36.8	26.9	25.1
Add system distribution losses	43.6	38.3	31.2	65.1	39.8	58.2	60.8	48.9	67.4	36.3	48.9	51.2	48.8	27.2	29.5	28.9	37.4	27.3	25.5
Estimated mBtu for a 95% AFUE furnace	36.1	31.7	25.9	54.0	33.0	48.3	50.4	40.5	55.8	30.1	40.5	42.4	40.4	22.6	24.4	23.9	31.0	22.7	21.1
Add system distribution losses	36.7	32.3	26.3	54.8	33.5	49.0	51.2	41.2	56.7	30.5	41.2	43.1	41.1	22.9	24.8	24.3	31.5	23.0	21.5
Estimated mBtu for a 97% AFUE furnace	35.4	31.1	25.3	52.9	32.3	47.3	49.3	39.7	54.7	29.4	39.7	41.6	39.6	22.1	23.9	23.4	30.4	22.2	20.7
Add gas system distribution losses	35.9	31.6	25.7	53.7	32.8	48.0	50.1	40.3	55.6	29.9	40.3	42.2	40.2	22.5	24.3	23.8	30.8	22.5	21.0
Heat pump																			
99% winter design temperature	18	37	40	3	24	2	2	6	-6	6	14	10	13	42	26	23	19	29	18
HSPF adjment factor for a HSPF 8.2 unit	0.1391	-0.1339	-0.1841	0.2998	0.0613	0.3088	0.3088	0.2715	0.3731	0.2715	0.1867	0.2308	0.1980	-0.2186	0.0336	0.0748	0.1266	-0.0095	0.1391
Adjusted HSPF for a nominal 8.2 unit	7.06	9.30	9.71	5.74	7.70	5.67	5.67	5.97	5.14	5.97	6.67	6.31	6.58	9.99	7.92	7.59	7.16	8.28	7.06
kWh per year with an HSPF 8.2 unit	4,862	3,244	2,529	8,931	4,074	8,088	8,441	6,442	10,317	4,781	5,770	6,393	5,839	2,146	2,928	2,995	4,111	2,600	2,844
Add system distribution losses	5,153	3,438	2,681	9,467	4,318	8,573	8,947	6,828	10,936	5,068	6,116	6,776	6,190	2,274	3,103	3,174	4,358	2,756	3,015
mBtu gas consumed as a function of heat rate																			
4,754	24.5	16.3	12.7	45.0	20.5	40.8	42.5	32.5	52.0	24.1	29.1	32.2	29.4	10.8	14.8	15.1	20.7	13.1	14.3
6,096	31.4	21.0	16.3	57.7	26.3	52.3	54.5	41.6	66.7	30.9	37.3	41.3	37.7	13.9	18.9	19.4	26.6	16.8	18.4
7,652	39.4	26.3	20.5	72.4	33.0	65.6	68.5	52.3	83.7	38.8	46.8	51.9	47.4	17.4	23.7	24.3	33.3	21.1	23.1
10,382	53.5	35.7	27.8	98.3	44.8	89.0	92.9	70.9	113.5	52.6	63.5	70.4	64.3	23.6	32.2	33.0	45.2	28.6	31.3
HSPF adjment factor for a HSPF 8.5 unit	0.1467	-0.1422	-0.1954	0.3159	0.0644	0.3254	0.3254	0.2862	0.3926	0.2862	0.1969	0.2434	0.2089	-0.2320	0.0352	0.0787	0.1335	-0.0104	0.1467
Adjusted HSPF for a nominal 8.5 unit	7.25	9.71	10.16	5.81	7.95	5.73	5.73	6.07	5.16	6.07	6.83	6.43	6.72	10.47	8.20	7.83	7.36	8.59	7.25
kWh per year with an HSPF 8.5 unit	4,732	3,107	2,417	8,819	3,944	7,994	8,343	6,342	10,273	4,707	5,637	6,269	5,710	2,047	2,829	2,901	3,997	2,506	2,768
Add electric system distribution losses	5,016	3,293	2,562	9,348	4,180	8,473	8,843	6,723	10,889	4,990	5,975	6,646	6,053	2,170	2,999	3,075	4,237	2,656	2,935
mBtu gas consumed as a function of heat rate																			
4,754	23.8	15.7	12.2	44.4	19.9	40.3	42.0	32.0	51.8	23.7	28.4	31.6	28.8	10.3	14.3	14.6	20.1	12.6	14.0
6,096	30.6	20.1	15.6	57.0	25.5	51.7	53.9	41.0	66.4	30.4	36.4	40.5	36.9	13.2	18.3	18.7	25.8	16.2	17.9
7,652	38.4	25.2	19.6	71.5	32.0	64.8	67.7	51.4	83.3	38.2	45.7	50.9	46.3	16.6	22.9	23.5	32.4	20.3	22.5
10,382	52.1	34.2	26.6	97.1	43.4	88.0	91.8	69.8	113.1	51.8	62.0	69.0	62.8	22.5	31.1	31.9	44.0	27.6	30.5
HSPF adjment factor for a HSPF 10.3 unit	0.1974	-0.0915	-0.1447	0.3666	0.1152	0.3761	0.3761	0.3369	0.4433	0.3369	0.2476	0.2941	0.2596	-0.1813	0.0859	0.1294	0.1842	0.0403	0.1974
Adjusted HSPF for a nominal 10.3 unit	8.27	11.24	11.79	6.52	9.11	6.43	6.43	6.83	5.73	6.83	7.75	7.27	7.63	12.17	9.42	8.97	8.40	9.89	8.27
kWh per year with an HSPF 10.3 unit	4,151	2,683	2,083	7,861	3,441	7,133	7,444	5,634	9,250	4,182	4,965	5,546	5,035	1,762	2,464	2,534	3,504	2,177	2,429
Add system distribution losses	4,401	2,844	2,208	8,332	3,647	7,561	7,891	5,972	9,805	4,433	5,263	5,878	5,337	1,868	2,612	2,686	3,714	2,308	2,575
mBtu gas consumed as a function of heat rate																			
4,754	20.9	13.5	10.5	39.6	17.3	35.9	37.5	28.4	46.6	21.1	25.0	27.9	25.4	8.9	12.4	12.8	17.7	11.0	12.2
6,096	26.8	17.3	13.5	50.8	22.2	46.1	48.1	36.4	59.8	27.0	32.1	35.8	32.5	11.4	15.9	16.4	22.6	14.1	15.7
7,652	33.7	21.8	16.9	63.8	27.9	57.9	60.4	45.7	75.0	33.9	40.3	45.0	40.8	14.3	20.0	20.6	28.4	17.7	19.7
10,382	45.7	29.5	22.9	86.5	37.9	78.5	81.9	62.0	101.8	46.0	54.6	61.0	55.4	19.4	27.1	27.9	38.6	24.0	26.7
Cold-climate heat pump																			
Seasonal HSPF	9.13			8.73		8.60	8.60	9.14	7.67	9.14	10.37	9.73	10.20						
kWh per year with a cold-climate heat pump				5875		5331	5564	4211	6913	3125	3711	4145	3763						
Add system distribution losses				6227		5651	5897	4464	7328	3313	3934	4393	3989						
mBtu gas consumed as a function of heat rate																			
4,754				29.6		26.9	28.0	21.2	34.8	15.7	18.7	20.9	19.0						
6,096				38.0		34.4	36.0	27.2	44.7	20.2	24.0	26.8	24.3						
7,652				47.7		43.2	45.1	34.2	56.1	25.4	30.1	33.6	30.5						
10,382				64.7		58.7	61.2	46.3	76.1	34.4	40.8	45.6	41.4						
Gas-fired heat pump																			
Average winter temperature				34		35	30	37	17	31	38	26	31						
Average COP	1.36			1.37		1.37	1.35	1.38	1.31	1.36	1.38	1.34	1.36						
Avg. annual mBtu for a gas-fired heat pump				37.4		33.5	35.4	27.9	40.5	21.0	27.9	30.1	28.2						
Add system distribution losses				38.2		34.1	36.1	28.4	41.3	21.4	28.4	30.7	28.8						

Notes to Table A3

- Notes to table A1 apply here except substitute "propane" for "oil."
- Cold-climate air-source heat pump analysis is illustrative and is based on a study for DOE that tested one unit and found a seasonal COP of about 2.8 in New Haven, Connecticut, over two heating seasons (Johnson 2013). 2.8 COP * 3.412 = 9.55 HSPF. New Haven has a 99% design temp of 7° F, so a 10.3 HSPF non-cold-climate unit there would have a 7.14 adjusted HSPF; thus the cold-climate unit is 33.8% higher. We used this factor for each city as an order-of-magnitude estimate. The DOE field study looked at a Hallowell International Acadia cold-climate heat pump, a product no longer available as the manufacturer has gone out of business. Mitsubishi produces cold-climate heat pumps, most of which are ductless, but a few can be used in ducted applications (see www.mitsubishicomfort.com/sites/default/files/manual/m-series_hyper-heat_brochure.pdf?fid=1010). These can be linked to an indoor air handler (see www.mitsubishicomfort.com/press/press-releases/mvz-multi-position-air-handler-rounds-out-diamond-comfort-systemtm-for-efficient-whole-home-cooling-heating.
- We also conducted an illustrative analysis for gas-fired heat pumps based on Gas Technology Institute (GTI) projections from its research project with A. O. Smith; see Garrabrant (2014). GTI estimates seasonal COP based on average winter temperature. For each state we used a simple average of monthly temperatures for November–March, taken from www.weatherbase.com/weather/state.php3?c=US.

Table A4 below shows differences in source energy use by state in millions of Btus. In these comparisons, the shaded cells indicate where propane furnaces use less energy on a source basis, while unshaded cells show where electric heat pumps use less energy. Table A4 is just a simple subtraction between the relevant rows of table A3 for each comparison.

Table A4. Propane furnace and heat pump energy use comparisons by state

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
80% furnace vs. 8.2 HSPF heat pump																			
4,754	19.1	22.0	18.4	20.1	19.3	17.5	18.2	16.4	15.4	12.2	19.8	19.0	19.3	16.4	14.7	13.8	16.7	14.2	11.2
6,096	12.2	17.3	14.8	7.4	13.5	6.0	6.2	7.2	0.7	5.4	11.6	9.9	11.0	13.4	10.5	9.5	10.8	10.5	7.1
7,652	4.2	12.0	10.7	-7.3	6.8	-7.4	-7.7	-3.4	-16.3	-2.5	2.1	-0.6	1.4	9.8	5.7	4.6	4.0	6.2	2.4
10,382	-9.9	2.6	3.4	-33.2	-5.0	-30.8	-32.1	-22.0	-46.2	-16.3	-14.6	-19.1	-15.5	3.6	-2.8	-4.1	-7.9	-1.3	-5.8
95% furnace vs. 8.5 HSPF heat pump																			
4,754	12.9	16.6	14.1	10.4	13.7	8.7	9.1	9.2	5.0	6.8	12.7	11.5	12.3	12.6	10.6	9.7	11.3	10.4	7.5
6,096	6.1	12.2	10.6	-2.1	8.1	-2.6	-2.7	0.2	-9.7	0.1	4.7	2.6	4.2	9.7	6.5	5.6	5.7	6.8	3.6
7,652	-1.7	7.1	6.7	-16.7	1.6	-15.8	-16.5	-10.3	-26.6	-7.6	-4.6	-7.7	-5.2	6.3	1.9	0.8	-0.9	2.7	-1.0
10,382	-15.4	-1.9	-0.3	-42.2	-9.9	-38.9	-40.6	-28.6	-56.3	-21.3	-20.9	-25.9	-21.8	0.4	-6.3	-7.6	-12.5	-4.6	-9.0
95% furnace vs. 10.3 HSPF heat pump																			
4,754	15.8	18.7	15.8	15.2	16.2	13.1	13.7	12.8	10.1	9.5	16.1	15.2	15.7	14.1	12.4	11.5	13.8	12.0	9.2
6,096	9.9	14.9	12.8	4.0	11.3	2.9	3.1	4.7	-3.0	3.5	9.1	7.3	8.5	11.5	8.9	7.9	8.8	8.9	5.8
7,652	3.0	10.5	9.4	-8.9	5.6	-8.8	-9.2	-4.5	-18.3	-3.4	0.9	-1.9	0.2	8.6	4.8	3.7	3.1	5.4	1.8
10,382	-9.0	2.7	3.3	-31.7	-4.3	-29.5	-30.8	-20.9	-45.1	-15.5	-13.5	-17.9	-14.3	3.5	-2.3	-3.6	-7.1	-0.9	-5.3
97% furnace vs. 10.3 HSPF heat pump																			
4,754	15.0	18.1	15.2	14.1	15.5	12.1	12.6	11.9	8.9	8.8	15.3	14.3	14.8	13.6	11.9	11.0	13.2	11.6	8.8
6,096	9.1	14.3	12.3	2.9	10.6	1.9	2.0	3.9	-4.2	2.9	8.2	6.4	7.7	11.1	8.4	7.4	8.2	8.5	5.3
7,652	2.3	9.8	8.8	-10.0	4.9	-9.8	-10.3	-5.4	-19.5	-4.0	0.0	-2.7	-0.6	8.2	4.3	3.2	2.4	4.9	1.3
10,382	-9.7	2.1	2.8	-32.8	-5.0	-30.5	-31.8	-21.7	-46.2	-16.1	-14.3	-18.8	-15.2	3.1	-2.8	-4.1	-7.7	-1.4	-5.7
95% furnace vs. cold climate heat pump (tentative and illustrative)																			
4,754				25.2		22.2	23.1	19.9	21.9	14.8	22.5	22.2	22.1						
6,096				16.9		14.6	15.2	13.9	12.1	10.3	17.2	16.3	16.8						
7,652				7.2		5.8	6.0	7.0	0.7	5.2	11.1	9.5	10.5						
10,382				-9.8		-9.6	-10.1	-5.2		-3.9	0.3	-2.5	-0.3						
Gas-fired heat pump vs. cold-climate electric (tentative and illustrative)																			
4,754				8.6		7.3	8.1	7.2	6.5	5.7	9.7	9.8	9.8						
6,096				0.2		-0.3	0.2	1.2	-3.4	1.2	4.5	3.9	4.5						
7,652				-9.5		-9.1	-9.0	-5.7	-14.8	-3.9	-1.7	-2.9	-1.7						
10,382				-26.5		-24.5	-25.1	-17.9	-34.8	-13.0	-12.4	-14.9	-12.6						

Table A5. Energy use of oil and propane boilers and ductless heat pumps

		West				Midwest				Northeast				South					
Oil Boiler	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Avg. annual mBtu for an oil system	70.3	52.1	54.9	52.1	58.1	57.5	57.5	73.8	72.7	80.9	81.6	63.9	68.3	59.3	59.3	59.3	59.3	59.3	55.8
Add system distribution losses	70.8	52.5	55.3	52.5	58.5	57.9	57.9	74.3	73.2	81.5	82.2	64.3	68.8	59.7	59.7	59.7	59.7	59.7	56.2
Estimated mBtu for a 86% AFUE boiler	65.4	48.5	51.1	48.5	54.0	53.5	53.5	68.7	67.6	75.3	75.9	59.4	63.5	55.2	55.2	55.2	55.2	55.2	51.9
Add system distribution losses	65.9	48.8	51.4	48.8	54.4	53.9	53.9	69.1	68.1	75.8	76.4	59.9	64.0	55.5	55.5	55.5	55.5	55.5	52.3
Estimated mBtu for a 91% AFUE boiler	61.8	45.8	48.3	45.8	51.1	50.5	50.5	64.9	63.9	71.1	71.7	56.2	60.0	52.1	52.1	52.1	52.1	52.1	49.1
Add system distribution losses	62.2	46.1	48.6	46.1	51.4	50.9	50.9	65.3	64.4	71.6	72.2	56.6	60.5	52.5	52.5	52.5	52.5	52.5	49.4
Propane Boiler																			
Avg. annual mBtu for an 80% propane system	42.9	37.7	30.7	64.1	39.2	57.3	59.8	48.1	66.3	35.7	48.1	50.4	48.0	26.8	29.0	28.4	36.8	26.9	25.1
Add system distribution losses	43.6	38.3	31.2	65.1	39.8	58.2	60.8	48.9	67.4	36.3	48.9	51.2	48.8	27.2	29.5	28.9	37.4	27.3	25.5
Estimated mBtu for a 84% AFUE boiler	40.9	35.9	29.2	61.0	37.3	54.6	57.0	45.8	63.1	34.0	45.8	48.0	45.7	25.5	27.6	27.0	35.0	25.6	23.9
Add system distribution losses	41.5	36.5	29.7	62.0	37.9	55.4	57.9	46.5	64.2	34.5	46.5	48.8	46.4	25.9	28.1	27.5	35.6	26.0	24.3
Estimated mBtu for a 90% AFUE boiler	38.1	33.5	27.3	57.0	34.8	50.9	53.2	42.8	58.9	31.7	42.8	44.8	42.7	23.8	25.8	25.2	32.7	23.9	22.3
Add system distribution losses	38.7	34.0	27.7	57.9	35.4	51.7	54.0	43.4	59.9	32.2	43.4	45.5	43.3	24.2	26.2	25.6	33.2	24.3	22.7
Heat pump (same load as oil boiler)																			
99% winter design temperature	18	37	40	3	24	2	2	6	-6	6	14	10	13	42	26	23	19	29	18
Average annual heating degree days	3,713	1,614	2,235	6,156	5,496	5,224	5,791	4,137	6,642	5,648	4,719	5,124	5,002	336	2,033	2,456	3,089	1,185	3,531
Seasonal COP	3.42	3.93	3.78	2.83	2.99	3.05	2.91	3.32	2.71	2.95	3.17	3.08	3.11	4.24	3.83	3.72	3.57	4.03	3.46
kWh per year with ductless units	4,822	3,110	3,408	4,324	4,563	4,418	4,627	5,219	6,296	6,433	6,028	4,871	5,157	3,281	3,634	3,734	3,895	3,448	3,779
Add elec system distribution losses	5,111	3,297	3,612	4,583	4,837	4,683	4,904	5,532	6,674	6,819	6,389	5,163	5,466	3,478	3,852	3,958	4,129	3,655	4,005
mBtu consumed as a function of heat rate																			
4,754	24.3	15.7	17.2	21.8	23.0	22.3	23.3	26.3	31.7	32.4	30.4	24.5	26.0	16.5	18.3	18.8	19.6	17.4	19.0
6,096	31.2	20.1	22.0	27.9	29.5	28.5	29.9	33.7	40.7	41.6	38.9	31.5	33.3	21.2	23.5	24.1	25.2	22.3	24.4
7,652	39.1	25.2	27.6	35.1	37.0	35.8	37.5	42.3	51.1	52.2	48.9	39.5	41.8	26.6	29.5	30.3	31.6	28.0	30.6
10,382	53.1	34.2	37.5	47.6	50.2	48.6	50.9	57.4	69.3	70.8	66.3	53.6	56.8	36.1	40.0	41.1	42.9	37.9	41.6

Notes to Table A5

- Notes to table A1 generally apply here.
- Heat pump COP based on a formula derived by Nadel and Kallakari (2016) to correlate heating degree days and heat pump COP in the field. The formula is: Seasonal COP = 4.319641711-0.000242756*HDD. The field data used to derive this formula come from the Northwest, including Idaho, Montana, Oregon, and Washington (Ecotope 2014).

Table A6 below shows differences in source energy use by state in millions of Btus. In these comparisons, the shaded cells indicate where oil or propane boilers use less energy on a source basis, while unshaded cells show where electric heat pumps use less energy. Table A6 is just a simple subtraction between the relevant rows of table A5 for each comparison.

Table A6. Oil and propane boiler and ductless heat pump energy use comparisons by state

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
86% oil boiler vs. ductless heat pump																			
4,754	41.6	33.1	34.3	27.0	31.4	31.6	30.5	42.8	36.4	43.4	46.1	35.3	38.0	39.0	37.2	36.7	35.9	38.2	33.2
6,096	34.7	28.7	29.4	20.9	24.9	25.3	24.0	35.4	27.4	34.2	37.5	28.4	30.7	34.3	32.1	31.4	30.4	33.3	27.9
7,652	26.7	23.6	23.8	13.7	17.4	18.0	16.3	26.8	17.0	23.6	27.5	20.3	22.2	28.9	26.1	25.3	24.0	27.6	21.6
10,382	12.8	14.6	13.9	1.2	4.2	5.2	2.9	11.7	-1.2	5.0	10.1	6.3	7.2	19.4	15.6	14.5	12.7	17.6	10.7
91% oil boiler vs. ductless heat pump																			
4,754	37.9	30.5	31.4	24.3	28.4	28.6	27.6	39.0	32.6	39.2	41.9	32.0	34.5	36.0	34.2	33.7	32.9	35.1	30.4
6,096	31.1	26.0	26.6	18.2	21.9	22.4	21.0	31.6	23.7	30.0	33.3	25.1	27.1	31.3	29.0	28.4	27.3	30.2	25.0
7,652	23.1	20.9	21.0	11.1	14.4	15.1	13.4	23.0	13.3	19.4	23.3	17.1	18.6	25.9	23.0	22.2	20.9	24.5	18.7
10,382	9.2	11.9	11.1	-1.5	1.2	2.3	0.0	7.9	-4.9	0.8	5.9	3.0	3.7	16.4	12.5	11.4	9.6	14.5	7.8
84% propane boiler vs. ductless heat pump																			
4,754	26.7	25.1	20.1	35.2	22.4	33.3	33.6	29.4	35.2	20.2	28.6	29.4	28.2	18.5	19.1	18.5	23.4	18.1	15.7
6,096	22.5	21.9	17.4	27.6	18.0	27.0	26.8	24.6	27.0	16.2	23.6	23.9	23.0	16.4	16.6	15.9	20.0	15.9	13.3
7,652	17.6	18.2	14.2	18.9	13.0	19.7	18.8	19.0	17.6	11.5	17.7	17.6	17.0	13.9	13.6	13.0	16.0	13.3	10.5
10,382	9.1	11.7	8.7	3.5	4.1	7.0	4.9	9.1	1.0	3.3	7.4	6.5	6.6	9.6	8.5	7.8	9.0	8.8	5.6
90% propane boiler vs. ductless heat pump																			
4,754	23.9	22.7	18.1	31.1	19.9	29.6	29.8	26.3	30.9	17.9	25.5	26.2	25.1	16.7	17.2	16.6	21.1	16.4	14.1
6,096	19.7	19.5	15.4	23.5	15.5	23.3	22.9	21.5	22.8	13.9	20.5	20.7	19.9	14.6	14.7	14.1	17.6	14.2	11.7
7,652	14.9	15.8	12.3	14.7	10.4	16.0	15.0	15.8	13.3	9.2	14.6	14.4	14.0	12.2	11.8	11.1	13.6	11.6	8.9
10,382	6.4	9.3	6.8	-0.7	1.5	3.3	1.1	6.0	-3.3	1.0	4.3	3.2	3.5	7.9	6.6	6.0	6.6	7.1	4.0

Table A7. Life-cycle cost analysis comparing oil furnaces to heat pumps

		West		Midwest				Northeast				South			
	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	VA
2016 oil rate ($/gal)	2.27	2.15	2.15	1.94	1.95	1.94	1.94	2.30	2.37	2.56	2.00	2.18	2.18	2.17	2.18
2016 electric rate	0.126	0.174	0.101	0.125	0.152	0.112	0.141	0.190	0.157	0.176	0.139	0.110	0.115	0.118	0.114
2030 oil rate	4.05	3.85	3.85	2.55	2.56	2.55	2.54	4.13	4.29	4.64	3.63	3.92	3.92	3.90	3.92
Winter/average oil ratio	1.00	1.00	1.00	1.26	1.00	1.26	1.00	1.26	1.00	1.26	1.00	1.26	1.00	1.26	1.00
2030 winter oil rate	4.05	3.85	3.85	3.20	2.56	3.20	2.54	5.20	4.29	5.84	3.63	4.94	3.92	4.91	3.92
2030 electric rate	0.138	0.219	0.127	0.142	0.172	0.114	0.159	0.205	0.206	0.230	0.182	0.124	0.130	0.134	0.128
2016-17 winter/average elec ratio	1.002	1.059	0.986	0.990	1.007	0.902	1.004	1.024	0.988	0.986	1.011	1.047	0.959	0.984	0.974
2030 winter electric rate	0.138	0.232	0.125	0.140	0.173	0.103	0.160	0.210	0.203	0.227	0.184	0.130	0.125	0.132	0.125
Annual heating cost (2030 energy prices, 2017 $)															
80% furnace	2,055	1,525	1,614	1,331	1,061	1,708	1,331	3,039	2,528	2,694	1,789	2,116	1,680	2,102	1,581
83% furnace	1,980	1,470	1,555	1,282	1,023	1,646	1,283	2,929	2,437	2,597	1,724	2,039	1,619	2,026	1,523
95% furnace	1,730	1,284	1,359	1,120	894	1,438	1,121	2,559	2,129	2,269	1,507	1,782	1,415	1,770	1,331
8.2 HP	1,102	1,050	755	1,139	1,406	1,019	1,806	2,277	1,991	1,840	1,525	617	746	823	791
8.5 HP	1,073	1,003	731	1,125	1,389	1,004	1,798	2,241	1,946	1,805	1,491	588	721	798	769
10.3 HP	941	864	638	1,004	1,240	892	1,619	1,991	1,714	1,597	1,315	506	628	697	675
Cold-climate HP				750	927	666	1,210	1,488	1,281	1,193	983				
Purchase cost including installation (2017 $)															
80% furnace	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068	3,068
83% furnace	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572	3,572
95% furnace	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927
SEER 14 / 8.2 HP (baseline)	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819
SEER 15 / 8.5 HP	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942
10.3 HP	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358
Cold-climate HP	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720
SEER 14 central AC	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115
SEER 13 central AC (baseline)	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046
Life-cycle cost (21 year life, 5% real discount rate)															
80% furnace	29,410	22,619	23,758	20,128	16,677	24,964	20,136	42,028	35,482	37,614	26,006	30,196	24,611	30,020	23,334
83% furnace	28,961	22,416	23,514	20,015	16,689	24,676	20,023	41,124	34,814	36,869	25,681	29,719	24,336	29,550	23,105
95% furnace	27,109	21,391	22,350	19,293	16,387	23,365	19,300	37,735	32,223	34,018	24,243	27,771	23,068	27,623	21,992
8.2 HP	18,947	18,276	14,504	19,416	22,840	17,888	27,972	34,008	30,352	28,415	24,373	12,726	14,384	15,373	14,955
8.5 HP	18,693	17,801	14,317	19,370	22,754	17,810	27,996	33,680	29,887	28,084	24,065	12,487	14,185	15,168	14,808
10.3 HP	18,423	17,440	14,538	19,232	22,252	17,789	27,116	31,888	28,331	26,828	23,220	12,852	14,409	15,288	15,014
Cold-climate HP				16,342	18,599	15,264	22,234	25,801	23,143	22,019	19,322				
Life-cycle cost if heat pump replaces a central AC unit															
8.2 HP	14,832	14,161	10,457	15,370	18,794	13,842	23,926	29,961	26,306	24,369	20,327	8,611	10,269	11,258	10,840
8.5 HP	14,745	13,858	10,364	15,514	18,792	14,034	24,011	29,720	26,137	24,203	20,227	8,717	10,312	11,240	10,872
10.3 HP	14,750	13,781	10,656	15,522	18,354	14,220	23,178	27,993	24,808	23,074	19,542	9,650	10,935	11,669	11,374
Cold-climate HP				12,632	14,701	11,694	18,297	21,906	19,619	18,265	15,644				
Air conditioning															
Avg kWh/year for central AC 2009	1,980	1,288	557	1,022	371	1,797	296	319	1,094	548	875	4,557	3,056	2,293	2,290
Avg kWh/year for central AC SEER 13	1,523	991	428	786	285	1,382	228	245	842	422	673	3,505	2,351	1,764	1,762
Avg kWh/year for central AC SEER 14	1,414	920	398	730	265	1,284	211	228	781	391	625	3,255	2,183	1,638	1,636
Avg kWh/year for central AC SEER 15	1,320	859	371	681	247	1,198	197	213	729	365	583	3,038	2,037	1,529	1,527
Avg kWh/year for central AC SEER 17	1,165	758	328	601	218	1,057	174	188	644	322	515	2,681	1,798	1,349	1,347
Additional LCC savings for cooling															
HSPF 8.5/SEER 15	167	172	93	190	84	270	62	86	296	166	209	345	242	187	179
HSPF 10.3/SEER 17	442	456	164	336	148	477	109	152	523	293	369	914	642	496	475

Notes to Table A7

- Negative numbers mean gas has lower LCC; these cells are shaded.
- We used 2016 energy costs compiled by EIA:
  - www.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm for oilwww.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm for oil
  - www.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm for propanewww.eia.gov/dnav/pet/pet_pri_wfr_dcus_nus_w.htm for propane
  - www.eia.gov/electricity/sales_revenue_price/pdf/table4.pdf for electricitywww.eia.gov/electricity/sales_revenue_price/pdf/table4.pdf for electricity
- We estimated costs for 2030 from 2016 costs by state and projected national costs for 2030 and 2016, as explained in the text.
- Adjustment for winter electricity and propane prices is explained in the text and compares costs by state in January–March 2016 and November–December 2016 to average costs by state over the entire year. We did not include such an adjustment for oil as a significant majority of residential oil sales are for winter heating.
- The installed cost of different systems comes from DOE TSDs as follows:
  - For furnaces, from DOE 2016a
  - For boilers, from DOE 2015
  - For heat pumps and central air conditioners, from DOE 2016b
  - Derivation of costs for ductless heat pumps is explained in the text.
- Average kWh per year for air-conditioning comes from the 2009 RECS (EIA 2013). We assume these data are for SEER 10 units and adjusted consumption downward based on the SEER of the new unit (SEER 13 for a basic new unit in the North, SEER 14 for a basic new unit in the South, SEER 14.5 for the HSPF 8.5 heat pump [both are ENERGY STAR levels], and SEER 17 for the HSPF 10.3 unit [based on slide 29 in DOE's October 26–27, 2015, presentation to CAC and HP ASRAC Working Group]). This can be found at www.regulations.gov/#!documentDetail;D=EERE-2014-BT-STD-0048-0052.
  For room air conditioners (assumed base-case cooling system for homes with boilers) we assumed an efficiency of SEER 13. Room air conditioners are rated with a different metric—CEER (which is similar to EER). Federal standards require at least CEER 11 for the most common sizes. We estimate this is similar to SEER 13 based on the fact that the DOE minimum standard for central air conditioners includes a 2-point difference between SEER and EER (DOE 2014).

Table A8. Life-cycle cost analysis comparing propane furnaces to heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
2016 propane rate ($/gal)	2.05	1.44	1.73	1.90	1.73	1.38	1.75	1.37	1.26	2.89	3.29	2.57	2.75	4.72	2.01	2.41	3.09	2.15	2.75
2016 electric rate	0.126	0.122	0.174	0.121	0.101	0.125	0.152	0.112	0.141	0.190	0.157	0.176	0.139	0.110	0.115	0.118	0.104	0.110	0.114
2030 propane rate	2.36	1.63	2.22	2.14	2.22	1.56	1.98	1.55	1.42	3.27	3.72	2.91	3.11	5.33	2.28	2.72	3.50	2.43	3.11
Winter/average ratio	1.091	1.161	1.293	1.144	1.293	1.125	1.070	1.126	1.166	1.032	1.053	1.117	1.068	1.035	1.069	1.068	1.075	1.064	1.070
2030 winter propane rate	2.58	1.89	2.87	2.45	2.87	1.76	2.12	1.74	1.66	3.37	3.92	3.25	3.32	5.52	2.43	2.91	3.76	2.58	3.32
2030 electric rate	0.138	0.124	0.219	0.123	0.127	0.142	0.172	0.114	0.159	0.205	0.206	0.230	0.182	0.124	0.130	0.134	0.102	0.113	0.128
Winter/average ratio	1.002	0.948	1.059	0.983	0.986	0.990	1.007	0.902	1.004	1.024	0.988	0.986	1.011	1.047	0.959	0.984	1.023	1.010	0.974
2030 winter electric rate	0.138	0.117	0.232	0.121	0.125	0.140	0.173	0.103	0.160	0.210	0.203	0.227	0.184	0.130	0.125	0.132	0.104	0.114	0.125
Annual heating cost (2030 energy prices, 2017 $)																			
80% furnace	1,230	793	980	1,747	1,251	1,119	1,408	932	1,225	1,339	2,095	1,820	1,773	1,644	785	919	1,538	773	928
95% furnace	1,036	667	825	1,471	1,053	943	1,185	785	1,031	1,128	1,764	1,533	1,493	1,385	661	774	1,295	651	782
97% furnace	1,014	654	808	1,441	1,032	923	1,161	769	1,010	1,105	1,728	1,501	1,462	1,356	647	758	1,268	638	765
8.2 HP	713	404	622	1,146	540	1,203	1,550	704	1,746	1,065	1,244	1,539	1,136	295	387	418	455	315	377
8.5 HP	694	387	595	1,131	523	1,189	1,532	693	1,738	1,048	1,216	1,509	1,111	282	374	405	442	304	367
10.3 HP	609	334	512	1,008	456	1,061	1,367	616	1,565	931	1,071	1,335	980	243	326	354	388	264	322
Cold-climate HP				754		793	1,021	460	1,170	696	800	998	732						
Purchase cost including installation (2017 $)																			
80% furnace	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236	2,236
95% furnace	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885	2,885
97% furnace	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983	2,983
SEER 14/8.2 HP (baseline)	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819	4,819
SEER 15/8.5 HP	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942	4,942
10.3 HP	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358	6,358
Cold-climate HP	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720	6,720
SEER 14 central AC	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115
SEER 13 central AC (baseline)	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046
Life-cycle cost (21 year life, 5% real discount rate)																			
80% furnace	18,004	12,398	14,795	24,635	18,272	16,586	20,285	14,192	17,936	19,409	29,101	25,573	24,964	23,317	12,300	14,018	21,952	12,152	14,135
95% furnace	16,162	11,442	13,460	21,746	16,389	14,969	18,083	12,952	16,105	17,345	25,507	22,536	22,024	20,637	11,360	12,806	19,487	11,235	12,905
97% furnace	15,987	11,364	13,341	21,456	16,209	14,818	17,869	12,843	15,931	17,146	25,139	22,230	21,728	20,370	11,284	12,700	19,243	11,162	12,797
8.2 HP	13,958	9,998	12,796	19,508	11,745	20,238	24,686	13,848	27,201	18,472	20,773	24,547	19,386	8,607	9,777	10,177	10,649	8,858	9,652
8.5 HP	13,837	9,902	12,564	19,447	11,647	20,183	24,578	13,832	27,228	18,385	20,529	24,290	19,187	8,557	9,733	10,133	10,612	8,835	9,646
10.3 HP	14,162	10,642	12,927	19,287	12,208	19,957	23,880	14,255	26,424	18,300	20,088	23,472	18,919	9,469	10,531	10,892	11,328	9,741	10,485
Cold-climate HP				16,383		16,884	19,815	12,623	21,717	15,645	16,981	19,511	16,108						
Life-cycle cost if heat pump replaces a central AC unit																			
8.2 HP	9,843	5,883	8,680	15,462	7,699	16,192	20,639	9,802	23,154	14,426	16,726	20,500	15,340	4,491	5,662	6,061	6,534	4,743	5,537
8.5 HP	9,722	5,787	8,449	15,401	7,601	16,136	20,532	9,786	23,181	14,338	16,482	20,244	15,141	4,441	5,618	6,018	6,496	4,720	5,531
10.3 HP	10,047	6,526	8,812	15,240	8,162	15,911	19,833	10,209	22,378	14,253	16,041	19,425	14,873	5,354	6,416	6,776	7,212	5,625	6,370
Cold-climate HP				12,336		12,838	15,769	8,576	17,671	11,599	12,935	15,464	12,062						
Life-cycle cost if heat pump supplements current system (no AC)																			
8.2 HP + 80% furnace	18,162	13,594	16,243	24,113	16,868	21,595	25,765	16,683	26,480	21,526	26,562	27,634	24,158	16,757	13,418	14,306	17,539	12,785	14,018
8.5 HP + 80% furnace	18,132	13,579	16,143	24,120	16,852	21,605	25,743	16,718	26,543	21,517	26,454	27,518	24,078	16,771	13,437	14,324	17,561	12,816	14,061
10.3 HP + 80% furnace	18,861	14,569	16,895	24,543	17,729	21,987	25,827	17,509	26,561	21,987	26,700	27,526	24,433	17,870	14,463	15,326	18,536	13,910	15,113
Cold-climate HP + 80% furnace				22,847		20,185	23,400	16,614	23,729	20,449	24,877	25,165	22,796						
Air conditioning																			
Avg kWh/year for central AC 2009	1,980	5,205	1,288	503	557	1,022	371	1,797	296	319	1,094	548	875	4,557	3,056	2,293	2,295	4,256	2,290
Avg kWh/year for central AC SEER 13	1,523	4,004	991	387	428	786	285	1,382	228	245	842	422	673	3,505	2,351	1,764	1,765	3,274	1,762
Avg kWh/year for central AC SEER 14	1,414	3,718	920	359	398	730	265	1,284	211	228	781	391	625	3,255	2,183	1,638	1,639	3,040	1,636
Avg kWh/year for central AC SEER 15	1,320	3,470	859	335	371	681	247	1,198	197	213	729	365	583	3,038	2,037	1,529	1,530	2,837	1,527
Avg kWh/year for central AC SEER 17	1,165	3,062	758	296	328	601	218	1,057	174	188	644	322	515	2,681	1,798	1,349	1,350	2,504	1,347
Additional LCC savings for cooling																			
HSPF 8.5/SEER 15	167	394	172	81	93	190	84	270	62	86	296	166	209	345	242	187	143	294	179
HSPF 10.3	442	1042	456	144	164	336	148	477	109	152	523	293	369	914	642	496	378	779	475

Notes to table A7 also apply to this table.

Table A9. Life-cycle cost analysis comparing oil and propane boilers to ductless heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
2016 oil rate ($/gal)	2.27	2.01	2.15	2.01	2.15	1.94	1.95	1.94	1.94	2.30	2.37	2.56	2.00	2.18	2.18	2.17	2.04	1.97	2.18
2030 oil rate	4.05	3.48	3.85	3.48	3.85	2.55	2.56	2.55	2.54	4.13	4.29	4.64	3.63	3.92	3.92	3.90	3.74	3.56	3.92
Winter/average oil ratio	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2030 winter oil rate	4.05	3.48	3.85	3.48	3.85	2.55	2.56	2.55	2.54	4.13	4.29	4.64	3.63	3.92	3.92	3.90	3.74	3.56	3.92
2016 propane rate ($/gal)	2.05	1.44	1.73	1.90	1.73	1.38	1.75	1.37	1.26	2.89	3.29	2.57	2.75	4.72	2.01	2.41	3.09	2.15	2.75
2030 propane rate	2.36	1.63	2.22	2.14	2.22	1.56	1.98	1.55	1.42	3.27	3.72	2.91	3.11	5.33	2.28	2.72	3.50	2.43	3.11
Winter/average propane ratio	1.091	1.161	1.293	1.144	1.293	1.125	1.070	1.126	1.166	1.032	1.053	1.117	1.068	1.035	1.069	1.068	1.075	1.064	1.070
2030 winter propane rate	2.58	1.89	2.87	2.45	2.87	1.76	2.12	1.74	1.66	3.37	3.92	3.25	3.32	5.52	2.43	2.91	3.76	2.58	3.32
2016 electric rate	0.126	0.122	0.174	0.121	0.101	0.125	0.152	0.112	0.141	0.190	0.157	0.176	0.139	0.110	0.115	0.118	0.104	0.110	0.114
2030 electric rate	0.138	0.124	0.219	0.123	0.127	0.142	0.172	0.114	0.159	0.205	0.206	0.230	0.182	0.124	0.130	0.134	0.102	0.113	0.128
2016-17 winter/average elec ratio	1.002	0.948	1.059	0.983	0.986	0.990	1.007	0.902	1.004	1.024	0.988	0.986	1.011	1.047	0.959	0.984	1.023	1.010	0.974
2030 winter electric rate	0.138	0.117	0.232	0.121	0.125	0.140	0.173	0.103	0.160	0.210	0.203	0.227	0.184	0.130	0.125	0.132	0.104	0.114	0.125
Annual heating cost (2030 energy prices, 2017 $)																			
80% oil boiler	2,055	1,308	1,525	1,308	1,614	1,057	1,061	1,356	1,331	2,413	2,528	2,140	1,789	1,680	1,680	1,669	1,602	1,525	1,581
86% oil boiler	1,911	1,217	1,418	1,217	1,501	983	987	1,262	1,238	2,245	2,352	1,990	1,664	1,563	1,563	1,553	1,490	1,418	1,470
91% oil boiler	1,806	1,150	1,341	1,150	1,419	929	933	1,192	1,170	2,121	2,223	1,881	1,573	1,477	1,477	1,468	1,408	1,340	1,390
80% propane boiler	1,210	780	964	1,719	1,231	1,102	1,386	918	1,205	1,318	2,062	1,792	1,745	1,618	773	904	1,514	761	913
84% propane boiler	1,153	743	918	1,638	1,172	1,049	1,320	874	1,148	1,256	1,964	1,706	1,662	1,541	736	861	1,441	725	870
90% propane boiler	1,076	693	857	1,528	1,094	979	1,232	816	1,071	1,172	1,833	1,592	1,551	1,439	687	804	1,345	677	812
Ductless heat pump (avg. oil boiler load)	667	365	791	523	571	620	801	538	1,005	1,352	1,226	1,106	947	426	453	492	406	394	472
Ductless heat pump (avg. propane boiler load)	407	264	442	644	385	618	833	351	917	597	723	872	665	193	221	235	252	179	213
Purchase cost including installation (2017 $)																			
80% oil boiler	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899	7,899
86% oil boiler	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684	8,684
91% oil boiler	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118	11,118
80% propane boiler	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593	6,593
84% propane boiler	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657	6,657
90% propane boiler	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544	7,544
Ductless heat pump	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130	14,130
SEER 13 central AC (North baseline)	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046	4,046
SEER 14 central AC (South baseline)	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115	4,115
Life-cycle cost (20 year life, 5% real discount rate)																			
80% oil boiler	33,503	24,200	26,902	24,200	28,010	21,067	21,127	24,800	24,489	37,972	39,406	34,565	30,195	28,838	28,838	28,703	27,861	26,901	27,597
86% oil boiler	32,502	23,848	26,362	23,848	27,392	20,934	20,989	24,406	24,117	36,659	37,993	33,489	29,425	28,163	28,163	28,036	27,254	26,361	27,008
91% oil boiler	33,627	25,448	27,824	25,448	28,798	22,694	22,746	25,975	25,703	37,555	38,816	34,560	30,718	29,526	29,526	29,406	28,667	27,823	28,435
80% propane boiler	21,677	16,314	18,608	28,022	21,935	20,321	23,860	18,031	21,613	23,022	32,294	28,919	28,337	26,761	16,221	17,865	25,455	16,080	17,977
84% propane boiler	21,024	15,916	18,100	27,066	21,269	19,732	23,102	17,551	20,962	22,304	31,135	27,920	27,366	25,865	15,827	17,393	24,621	15,693	17,499
90% propane boiler	20,953	16,186	18,225	26,592	21,182	19,747	22,893	17,711	20,895	22,148	30,390	27,390	26,872	25,472	16,103	17,564	24,310	15,977	17,663
Ductless heat pump (avg. oil boiler load)	22,442	18,684	23,985	20,651	21,244	21,854	24,116	20,838	26,655	30,976	29,414	27,915	25,927	19,441	19,774	20,257	19,196	19,043	20,018
Ductless heat pump (avg. propane boiler load)	19,203	17,425	19,641	22,153	18,930	21,827	24,516	18,502	25,553	21,564	23,139	25,002	22,421	16,530	16,890	17,064	17,274	16,359	16,778
86% oil boiler & ductless heat pump	29,615	24,969	28,971	26,208	27,515	26,199	27,639	26,473	30,062	36,086	35,453	33,323	31,000	26,582	26,792	27,063	26,188	25,857	26,641
84% propane boiler & ductless heat pump	23,577	21,084	23,067	27,059	23,471	24,883	27,483	22,202	27,561	25,408	28,774	29,084	27,308	23,194	20,723	21,254	23,328	20,352	21,102
Air conditioning																			
Avg kWh/year for AC 2009	1,980	5,205	1,288	503	557	1,022	371	1,797	296	319	1,094	548	875	4,557	3,056	2,293	2,295	4,256	2,290
Avg kWh/year for room AC CEER 11	1,523	4,004	991	387	428	786	285	1,382	228	245	842	422	673	3,505	2,351	1,764	1,765	3,274	1,762
Avg kWh/year for central AC SEER 20	990	2,603	644	252	279	511	186	899	148	160	547	274	438	2,279	1,528	1,147	1,148	2,128	1,145
Additional LCC savings for cooling																			
SEER 20 replacing CEER 11	917	2,164	947	208	237	486	214	689	158	220	756	423	533	1,897	1,332	1,029	786	1,616	986

Notes to table A7 also apply to this table.

Table A10. Life-cycle cost comparisons for heat pumps relative to oil furnaces

		West		Midwest				Northeast				South			
	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	VA
Comparisons with replacing central AC															
83% furnace vs. 8.2 HSPF heat pump	14,129	8,255	13,057	4,645	-2,105	10,834	-3,903	11,163	8,509	12,501	5,354	21,108	14,067	18,292	12,265
83% furnace vs. 8.5 HSPF heat pump	14,383	8,730	13,243	4,691	-2,019	10,913	-3,926	11,490	8,973	12,832	5,663	21,347	14,266	18,497	12,412
83% furnace vs. 10.3 HSPF heat pump	14,654	9,091	13,022	4,829	-1,517	10,933	-3,046	13,283	10,530	14,088	6,508	20,983	14,042	18,377	12,206
95% furnace vs. 8.5 HSPF heat pump	12,531	7,704	12,079	3,969	-2,321	9,602	-4,649	8,101	6,382	9,981	4,225	19,399	12,998	16,571	11,300
95% furnace vs. 10.3 HSPF heat pump	12,801	8,066	11,858	4,107	-1,819	9,622	-3,769	9,894	7,938	11,237	5,070	19,035	12,774	16,450	11,094
95% furnace vs. cold-climate heat pump				6,997	1,834	12,148	1,112	15,981	13,127	16,046	8,967				
Comparisons with replacing a furnace (no AC)															
83% furnace vs. 8.2 HSPF heat pump	10,014	4,140	9,010	598	-6,152	6,788	-7,949	7,116	4,462	8,454	1,307	16,993	9,952	14,176	8,149
83% furnace vs. 8.5 HSPF heat pump	10,268	4,614	9,197	645	-6,066	6,866	-7,973	7,443	4,927	8,785	1,616	17,232	10,151	14,382	8,297
83% furnace vs. 10.3 HSPF heat pump	10,538	4,976	8,976	783	-5,563	6,887	-7,093	9,236	6,483	10,042	2,461	16,867	9,927	14,261	8,091
95% furnace vs. 8.5 HSPF heat pump	8,162	3,114	7,846	-124	-6,454	5,477	-8,672	3,728	1,871	5,603	-130	15,045	8,684	12,250	7,037
95% furnace vs. 10.3 HSPF heat pump	8,416	3,589	8,033	-77	-6,368	5,555	-8,696	4,055	2,336	5,934	178	15,284	8,883	12,455	7,184
95% furnace vs. cold-climate heat pump				60	-5,865	5,576	-7,816	5,848	3,892	7,191	1,023				
Retrofit comparisons (without AC)															
Early replacement															
83% furnace vs. 8.2 HSPF heat pump	9,562	3,605	8,490	33	-6,759	6,282	-8,514	6,818	4,085	8,103	814	16,551	9,441	13,732	7,624
83% furnace vs. 8.5 HSPF heat pump	9,816	4,080	8,676	80	-6,673	6,360	-8,538	7,146	4,549	8,434	1,123	16,790	9,640	13,938	7,771
83% furnace vs. 10.3 HSPF heat pump	10,087	4,441	8,455	218	-6,170	6,381	-7,658	8,938	6,106	9,690	1,968	16,425	9,416	13,817	7,565
95% furnace vs. 8.5 HSPF heat pump	7,417	2,287	7,032	-982	-7,354	4,678	-9,530	3,137	1,200	4,958	-917	14,310	7,880	11,512	6,218
95% furnace vs. 10.3 HSPF heat pump	7,671	2,761	7,219	-936	-7,268	4,756	-9,554	3,464	1,665	5,290	-608	14,549	8,079	11,718	6,365
95% furnace vs. cold-climate heat pump				-798	-6,766	4,777	-8,674	5,257	3,221	6,546	237				
Partial replacement															
8.2 HP + 83% furnace	3,401	-390	2,693	-2,655	-6,954	1,309	-8,040	1,744	-15	2,528	-2,130	7,809	3,298	6,032	2,145
8.5 HP + 83% furnace	3,516	-137	2,765	-2,671	-6,945	1,313	-8,100	1,905	232	2,691	-1,981	7,913	3,377	6,115	2,192
10.3 HP + 83% furnace	3,162	-433	2,102	-3,108	-7,152	802	-8,070	2,510	688	2,959	-1,972	7,160	2,712	5,516	1,539
Cold-climate HP + 83% furnace				-1,422	-4,985	2,259	-5,128	6,211	3,823	5,854	349				

Based on data in table A7. Negative numbers mean oil has lower LCC; these cells are shaded.

Table A11. Life-cycle cost comparisons for heat pumps relative to propane furnaces

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Comparisons with replacing central AC																			
80% furnace vs. 8.2 HSPF heat pump	8,161	6,515	6,115	9,173	10,573	394	-354	4,390	-5,218	4,983	12,374	5,073	9,625	18,826	6,639	7,957	15,418	7,410	8,599
80% furnace vs. 8.5 HSPF heat pump	8,449	7,005	6,518	9,316	10,765	640	-163	4,676	-5,184	5,156	12,915	5,495	10,032	19,221	6,925	8,188	15,598	7,727	8,784
80% furnace vs. 10.3 HSPF heat pump	8,398	6,914	6,440	9,538	10,274	1,011	600	4,459	-4,333	5,307	13,582	6,440	10,460	18,877	6,526	7,738	15,118	7,306	8,240
95% furnace vs. 8.5 HSPF heat pump	6,607	6,049	5,184	6,427	8,881	-977	-2,364	3,437	-7,014	3,093	9,321	2,459	7,092	16,541	5,984	6,976	13,133	6,809	7,553
95% furnace vs. 10.3 HSPF heat pump	6,557	5,958	5,105	6,650	8,391	-606	-1,602	3,220	-6,163	3,244	9,989	3,404	7,520	16,197	5,585	6,526	12,653	6,388	7,010
95% furnace vs. cold-climate heat pump				9,554		2,467	2,463	4,853	-1,456	5,898	13,095	7,365	10,331						
Comparisons with replacing a furnace (no AC)																			
80% furnace vs. 8.2 HSPF heat pump	4,046	2,400	2,000	5,126	6,527	-3,652	-4,401	344	-9,265	936	8,328	1,026	5,578	14,710	2,523	3,842	11,302	3,294	4,483
80% furnace vs. 8.5 HSPF heat pump	4,166	2,496	2,231	5,188	6,625	-3,597	-4,293	360	-9,292	1,024	8,572	1,283	5,777	14,761	2,567	3,885	11,340	3,317	4,489
80% furnace vs. 10.3 HSPF heat pump	3,841	1,756	1,868	5,348	6,064	-3,371	-3,595	-64	-8,488	1,109	9,013	2,101	6,045	13,848	1,769	3,127	10,624	2,412	3,650
95% furnace vs. 8.5 HSPF heat pump	2,204	1,444	665	2,238	4,643	-5,270	-6,602	-896	-11,096	-1,127	4,735	-2,010	2,638	12,030	1,582	2,630	8,838	2,377	3,253
95% furnace vs. 10.3 HSPF heat pump	2,325	1,539	896	2,299	4,741	-5,214	-6,495	-880	-11,123	-1,039	4,979	-1,754	2,837	12,080	1,626	2,673	8,875	2,400	3,259
95% furnace vs. cold-climate heat pump				2,460		-4,989	-5,796	-1,303	-10,319	-955	5,420	-935	3,105						
Retrofit comparisons (without AC)																			
Early replacement																			
80% furnace vs. 8.2 HSPF heat pump	3,562	1,916	1,515	4,642	6,043	-4,137	-4,885	-140	-9,749	452	7,844	542	5,094	14,226	2,039	3,358	10,818	2,810	3,999
80% furnace vs. 8.5 HSPF heat pump	3,682	2,011	1,747	4,704	6,141	-4,081	-4,777	-124	-9,776	540	8,088	799	5,293	14,276	2,083	3,401	10,856	2,833	4,005
80% furnace vs. 10.3 HSPF heat pump	3,357	1,272	1,384	4,864	5,580	-3,855	-4,079	-548	-8,973	624	8,529	1,617	5,561	13,364	1,285	2,643	10,140	1,928	3,166
95% furnace vs. 8.5 HSPF heat pump	1,580	819	40	1,614	4,019	-5,894	-7,227	-1,520	-11,720	-1,751	4,110	-2,635	2,014	11,406	958	2,005	8,213	1,753	2,628
95% furnace vs. 10.3 HSPF heat pump	1,701	915	272	1,675	4,117	-5,838	-7,119	-1,504	-11,747	-1,664	4,354	-2,378	2,212	11,456	1,002	2,049	8,251	1,775	2,634
95% furnace vs. cold-climate heat pump				1,835		-5,613	-6,421	-1,928	-10,943	-1,579	4,795	-1,560	2,481						
Partial replacement																			
80% furnace vs. 8.2 HSPF heat pump	-159	-1,196	-1,448	522	1,404	-5,009	-5,480	-2,491	-8,545	-2,118	2,539	-2,061	807	6,560	-1,118	-287	4,413	-632	117
80% furnace vs. 8.5 HSPF heat pump	-129	-1,181	-1,348	515	1,421	-5,019	-5,458	-2,527	-8,607	-2,108	2,647	-1,945	886	6,546	-1,136	-306	4,391	-664	75
80% furnace vs. 10.3 HSPF heat pump	-857	-2,171	-2,100	92	543	-5,401	-5,542	-3,317	-8,625	-2,579	2,401	-1,954	531	5,447	-2,163	-1,307	3,416	-1,758	-978
80% furnace vs. cold-climate heat pump				1,788		-3,599	-3,115	-2,423	-5,794	-1,040	4,224	408	2,168						

Based on data in table A8. Negative numbers mean oil has lower LCC; these cells are shaded.

Table A12. Life-cycle cost comparisons for ductless heat pumps relative to oil and propane boilers

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
LCC Comparisons with replacing central AC																			
86% oil boiler vs. ductless heat pump	10,977	7,328	3,324	3,404	6,385	-435	-2,913	4,257	-2,380	5,903	9,335	5,998	4,031	10,619	9,721	8,809	8,843	8,934	7,977
91% oil boiler vs. ductless heat pump	12,101	8,929	4,786	5,004	7,791	1,326	-1,156	5,827	-795	6,799	10,158	7,069	5,325	11,982	11,084	10,179	10,256	10,396	9,403
84% propane boiler vs. ductless HP	2,738	655	-594	5,120	2,576	-1,609	-1,199	-262	-4,433	960	8,751	3,342	5,478	11,232	270	1,358	8,133	950	1,707
90% propane boiler vs. ductless HP	2,667	925	-469	4,647	2,489	-1,594	-1,408	-101	-4,499	804	8,007	2,811	4,985	10,838	545	1,529	7,822	1,235	1,871
Comparisons without including AC																			
86% oil boiler vs. ductless heat pump	10,060	5,164	2,377	3,196	6,148	-921	-3,127	3,568	-2,538	5,683	8,579	5,575	3,498	8,721	8,389	7,780	8,058	7,317	6,990
91% oil boiler vs. ductless heat pump	11,184	6,764	3,839	4,797	7,554	840	-1,370	5,137	-953	6,579	9,402	6,645	4,792	10,085	9,752	9,150	9,471	8,780	8,417
84% propane boiler vs. ductless HP	1,821	-1,509	-1,541	4,913	2,339	-2,095	-1,413	-952	-4,591	740	7,996	2,918	4,945	9,335	-1,063	329	7,347	-666	721
90% propane boiler vs. ductless HP	1,750	-1,239	-1,416	4,439	2,252	-2,080	-1,623	-791	-4,657	584	7,251	2,388	4,452	8,941	-787	500	7,037	-382	885
Retrofit comparisons (without AC)																			
Early replacement																			
86% oil boiler vs. ductless heat pump	8,800	3,679	957	1,712	4,756	-2,481	-4,686	2,097	-4,016	4,532	7,463	4,341	2,158	7,349	7,017	6,404	6,662	5,898	5,588
91% oil boiler vs. ductless heat pump	9,853	5,042	2,230	3,075	5,991	-1,014	-3,221	3,440	-2,663	5,435	8,319	5,358	3,321	8,557	8,225	7,617	7,902	7,171	6,838
84% propane boiler vs. ductless HP	629	-2,789	-2,783	3,826	1,151	-3,309	-2,569	-2,204	-5,783	-429	6,980	1,846	3,864	8,227	-2,345	-926	6,218	-1,950	-532
90% propane boiler vs. ductless HP	699	-2,497	-2,586	3,633	1,211	-3,183	-2,589	-1,983	-5,711	-415	6,610	1,616	3,658	8,087	-2,049	-698	6,132	-1,649	-309
Partial replacement																			
86% oil boiler & ductless heat pump	2,887	-1,121	-2,609	-2,361	-123	-5,266	-6,650	-2,068	-5,945	573	2,540	167	-1,576	1,580	1,371	974	1,065	504	367
84% propane boiler & ductless heat pump	-2,553	-5,168	-4,967	7	-2,202	-5,151	-4,380	-4,652	-6,599	-3,104	2,361	-1,163	58	2,671	-4,896	-3,861	1,293	-4,660	-3,603

Based on data in table A9. Negative numbers mean oil has lower LCC; these cells are shaded.

Table A13. Simple payback period analysis for replacement of equipment as end-of-life (payback period in years)

For replacing oil furnaces with heat pumps

		West		Midwest				Northeast				South			
	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	VA
At time furnace needs replacement (does not include AC energy savings)															
83% AFUE furnace to 8.5 HSPF heat pump	1.5	2.9	1.7	NS	NS	2.1	NS	2.0	2.8	1.7	5.9	0.9	1.5	1.1	1.8
95% AFUE furnace to 10.3 HSPF heat pump	1.8	3.4	2.0	NS	NS	2.6	NS	2.5	3.4	2.1	7.5	1.1	1.8	1.3	2.2
95% AFUE furnace to cold-climate heat pump				4.8	NS	2.3	NS	1.7	2.1	1.7	3.4				
At time air conditioner needs replacement (includes AC energy savings)															
83% AFUE furnace to 8.5 HSPF heat pump	0.9	1.7	1.1	NS	NS	1.3	NS	1.3	1.7	1.1	3.6	0.6	0.9	0.7	1.1
95% AFUE furnace to 10.3 HSPF heat pump	2.7	4.9	3.2	NS	NS	4.0	NS	4.0	5.1	3.3	10.5	1.7	2.7	2.0	3.2
95% AFUE furnace to cold-climate heat pump				6.7	NS	3.3	NS	2.5	3.0	2.4	4.8				

For replacing propane furnaces with heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
At time furnace needs replacement (does not include AC energy savings)																			
80% AFUE furnace to 8.5 HSPF heat pump	5.0	6.7	7.0	4.4	3.7	NS	NS	11.3	NS	9.3	3.1	8.7	4.1	2.0	6.6	5.3	2.5	5.8	4.8
95% AFUE furnace to 10.3 HSPF heat pump	8.1	10.4	11.1	7.5	5.8	NS	NS	20.5	NS	17.7	5.0	17.5	6.8	3.0	10.4	8.3	3.8	9.0	7.6
95% AFUE furnace to cold-climate heat pump				5.3		25.6	23.4	11.8	NS	8.9	4.0	7.2	5.0						
At time air conditioner needs replacement (includes AC energy savings)																			
80% AFUE furnace to 8.5 HSPF heat pump	1.5	1.9	2.1	1.4	1.2	NS	NS	3.4	NS	3.0	1.0	2.8	1.3	0.6	1.9	1.6	0.7	1.7	1.4
95% AFUE furnace to 10.3 HSPF heat pump	4.9	5.4	6.4	4.9	3.8	NS	NS	11.2	NS	11.1	3.1	10.5	4.3	1.8	5.8	4.9	2.4	5.0	4.5
95% AFUE furnace to cold-climate heat pump				3.7		15.2	15.2	7.4	NS	6.0	2.7	4.8	3.4						

For replacing oil and propane boilers with ductless heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Replacing a boiler, no AC savings																			
86% AFUE oil boiler vs. ductless heat pump	4.4	6.4	8.7	7.9	5.9	15.0	29.3	7.5	23.3	6.1	4.8	6.2	7.6	4.8	4.9	5.1	5.0	5.3	5.5
91% AFUE oil boiler vs. ductless heat pump	2.6	3.8	5.5	4.8	3.6	9.7	22.9	4.6	18.2	3.9	3.0	3.9	4.8	2.9	2.9	3.1	3.0	3.2	3.3
84% AFUE propane boiler vs. ductless HP	10.0	15.6	15.7	7.5	9.5	17.3	15.4	14.3	32.3	11.3	6.0	9.0	7.5	5.5	14.5	11.9	6.3	13.7	11.4
90% AFUE propane boiler vs. ductless HP	9.8	15.4	15.9	7.4	9.3	18.2	16.5	14.2	42.6	11.4	5.9	9.1	7.4	5.3	14.2	11.6	6.0	13.2	11.0
Replacing a boiler, with AC savings																			
86% AFUE oil boiler vs. ductless heat pump	4.1	5.3	7.7	7.7	5.7	13.5	26.8	7.0	22.1	6.0	4.6	5.9	7.2	4.2	4.5	4.8	4.7	4.7	5.1
91% AFUE oil boiler vs. ductless heat pump	2.5	3.1	4.8	4.7	3.5	8.7	20.2	4.2	16.9	3.8	2.9	3.7	4.5	2.5	2.7	2.8	2.8	2.8	3.0
84% AFUE propane boiler vs. ductless HP	9.1	11.5	13.5	7.4	9.3	15.9	14.8	12.9	30.6	11.0	5.7	8.6	7.2	5.0	12.0	10.5	6.0	11.1	10.1
90% AFUE propane boiler vs. ductless HP	8.9	10.9	13.4	7.3	9.0	16.4	15.9	12.7	39.3	11.1	5.6	8.7	7.1	4.7	11.5	10.1	5.7	10.5	9.7

Based on product costs and average annual energy cost in tables A7, A8, and A9. NS = no savings (heat pump is more expensive to operate).
Cells with no savings or more than a 30-year payback are shaded.

Table A14. Simple payback period analysis for early and partial replacement (payback period in years)

For replacing oil furnaces with heat pumps

		West		Midwest				Northeast				South			
	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	VA
Early replacement (payback relative to existing furnace)															
80% furnace vs. 8.5 HSPF heat pump	5.0	9.5	5.6	24.1	NS	7.0	NS	6.2	8.5	5.6	16.6	3.2	5.2	3.8	6.1
80% furnace vs. 10.3 HSPF heat pump	5.7	9.6	6.5	19.5	NS	7.8	NS	6.1	7.8	5.8	13.4	4.0	6.0	4.5	7.0
80% furnace vs. cold-climate heat pump				11.6	49.8	6.5	55.4	4.3	5.4	4.5	8.3				
Partial replacement (payback for paying back supplemental HP cost relative to annual cost to operate existing furnace)															
80% furnace vs. 8.5 HSPF heat pump	8.0	15.0	8.9	38.2	NS	11.1	NS	9.8	13.5	8.8	26.4	5.1	8.2	6.0	9.7
80% furnace vs. 10.3 HSPF heat pump	9.1	15.3	10.3	30.9	NS	12.4	NS	9.6	12.4	9.2	21.3	6.3	9.6	7.2	11.1
80% furnace vs. cold-climate heat pump				18.4	79.1	10.2	88.0	6.9	8.6	7.1	13.2				

For replacing propane furnaces with heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Early replacement (payback relative to existing furnace)																			
80% furnace vs. 8.5 HSPF heat pump	9.2	12.2	12.8	8.0	6.8	NS	NS	20.7	NS	17.0	5.6	15.9	7.5	3.6	12.0	9.6	4.5	10.5	8.8
80% furnace vs. 10.3 HSPF heat pump	10.2	13.9	13.6	8.6	8.0	108.6	154.6	20.1	NS	15.6	6.2	13.1	8.0	4.5	13.8	11.2	5.5	12.5	10.5
80% furnace vs. cold climate heat pump				6.8		20.6	17.4	14.2	122.7	10.4	5.2	8.2	6.5	4.1	8.6	7.3	4.4	8.7	7.2
Partial replacement (payback for paying back supplemental HP cost relative to annual cost to operate existing furnace)																			
80% furnace vs. 8.5 HSPF heat pump	14.6	19.3	20.4	12.7	10.8	NS	NS	32.8	NS	27.0	8.9	25.2	11.9	5.8	19.1	15.3	7.2	16.7	14.0
80% furnace vs. 10.3 HSPF heat pump	16.2	22.0	21.6	13.7	12.7	172.4	245.4	31.9	NS	24.7	9.9	20.8	12.7	7.2	22.0	17.9	8.8	19.8	16.6
80% furnace vs. cold climate heat pump				10.7		32.7	27.6	22.6	194.7	16.6	8.2	13.0	10.3						

For replacing oil and propane boilers with ductless heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Early replacement																			
Ductless HP vs. 80 AFUE oil boiler	10.2	15.0	19.2	18.0	13.5	32.3	54.3	17.3	43.3	13.3	10.9	13.7	16.8	11.3	11.5	12.0	11.8	12.5	12.8
Ductless HP vs. 80 AFUE propane boiler	17.6	27.4	27.1	13.1	16.7	29.2	25.6	24.9	49.0	19.6	10.5	15.4	13.1	9.9	25.6	21.1	11.2	24.3	32.0
Partial replacement																			
86% oil boiler & ductless heat pump	12.9	19.0	24.4	22.9	17.2	41.1	69.0	21.9	55.0	16.9	13.8	17.4	21.3	14.3	14.6	15.2	15.0	15.9	16.2
84% propane boiler & ductless heat pump	22.3	34.8	34.4	16.7	21.2	37.1	32.5	31.6	62.2	24.9	13.4	19.5	16.6	12.6	32.6	26.8	14.2	30.8	25.6

Based on product costs and average annual energy cost in tables A7, A8, and A9. NS = no savings (heat pump is more expensive to operate).
Cells with no savings or more than a 30-year payback are shaded.

Table A15. National-level comparison of gas and electric heat pump water heaters

	Propane				Oil			Electric heat pump	
	Base	Std	Better	Top-tier	Base	Std	Top-tier	Better	Top-tier
Efficiency	0.59	0.62	0.67	0.80	0.55	0.62	0.85	1.92	2.8
Annual energy use (mBtu)	18.8	17.9	16.6	13.9	18.6	16.5	12.0	NA	NA
Annual energy use (kWh)									
Without T&D losses	NA	NA	NA	NA	NA	NA	NA	1,549	1,062
With 6% T&D losses								1,642	1,126
Electric mBtu by heat rate									
4,754								7.8	5.4
6,096								10.0	6.9
7,652								12.6	8.6
10,382								17.0	11.7
Breakeven heat rate									
Better heat pump	11,448	10,894	10,081	8,443	11,326	10,048	7,329	NA	NA
Top-tier heat pump	16,695	15,887	14,702	12,313	16,518	14,653	10,688	NA	NA
Average energy prices									
Per mBtu	19.05	19.05	19.05	19.05	27.79	27.79	27.79	NA	NA
Per kWh	NA	NA	NA	NA	NA	NA	NA	0.1385	0.1385
Average annual operating cost	$ 358	$ 341	$ 315	$ 264	$ 517	$ 459	$ 334	$ 215	$ 147
Installed cost (2017 $)	$ 1,222	$ 1,325	$ 1,325	$ 2,142	$ 2,212	$ 2,263	$ 2,574	$ 1,781	$ 1,921
Lifecycle cost	$ 4,586	$ 4,526	$ 4,287	$ 4,623	$ 7,068	$ 6,570	$ 5,716	$ 3,796	$ 3,303
Simple payback vs. base (years)									
Ref. case prices, propane base		5.9	2.4	9.8				3.9	3.3
Ref. case prices, oil base						0.9	2.0	Both immediate	
High prices, propane base		4.7	1.9	7.8				2.5	2.4
High prices, oil base						0.1	0.7	Both immediate	
Low prices, propane base		7.5	3.0	12.3				7.0	4.8
Low prices, oil base						1.4	3.2	Both immediate	
Breakeven carbon emissions (g/kWh)									
Better heat pump	0.72	0.69	0.64	0.53	0.83	0.74	0.54		
Top-tier heat pump	1.05	1.00	0.93	0.78	1.21	1.07	0.78		
US electric avg, 2016	0.51								

Notes to Table A15

- NS = no savings (the option has a higher operating cost than the base case)
- Energy prices are residential prices for 2025 from AEO2018.
- Gas and electric water heater costs are from Lekov et al. 2011.
- Cost of base and better oil heaters from DOE TSD 2009. These are in 2008$ so we adjusted to 2017$ using GDP deflator.
- Standard water heater cost from www.homeadvisor.com/cost/heating-and-cooling/install-a-boiler/.
  Life-cycle cost based on a 13-year life and 5% real discount rate. This is probably generous for oil water heaters.
- Sensitivity cases with high and low prices based on AEO2018 scenario estimates for 2025.
- Propane and oil emissions per mBtu from www.eia.gov/environment/emissions/co2_vol_mass.php.
- 2016 US emissions of CO_2 per kWh from www.eia.gov/electricity/state/unitedstates.

Table A16. Break-even power plant emissions rate for the oil or propane system to have the same emissions as a heat pump

For replacing oil furnaces with heat pumps

		West		Midwest				Northeast				South			
	US	CA	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	VA
Kilograms CO2 per mBtu of oil	73.16														
Annual emissions (kg C02)															
83% AFUE furnace	4,992	3,898	4,126	4,083	4,083	5,240	5,162	5,745	5,794	4,537	4,850	4,211	4,211	4,211	3,962
95% AFUE furnace	4,361	3,406	3,605	3,567	3,567	4,579	4,510	5,019	5,062	3,964	4,237	3,679	3,679	3,679	3,462
Breakeven emissions rate (kg per kWh) relative to an 83% AFUE furnace															
8.2 HSPF heat pump	0.59	0.81	0.64	0.47	0.47	0.50	0.43	0.50	0.56	0.53	0.55	0.84	0.66	0.64	0.59
8.5 HSPF heat pump	0.61	0.85	0.67	0.48	0.48	0.51	0.43	0.51	0.57	0.54	0.56	0.88	0.69	0.66	0.61
10.3 HSPF heat pump	0.69	0.99	0.76	0.54	0.54	0.57	0.48	0.57	0.65	0.61	0.64	1.02	0.79	0.75	0.69
Cold-climate heat pump				0.72	0.72	0.77	0.64	0.77	0.87	0.81	0.85				
Breakeven emissions rate (kg per kWh) relative to a 95% AFUE furnace															
8.2 HSPF heat pump	0.52	0.71	0.56	0.41	0.41	0.44	0.38	0.44	0.49	0.46	0.48	0.73	0.58	0.56	0.52
8.5 HSPF heat pump	0.53	0.74	0.58	0.42	0.42	0.44	0.38	0.44	0.50	0.47	0.49	0.77	0.60	0.57	0.53
10.3 HSPF heat pump	0.60	0.86	0.67	0.47	0.47	0.50	0.42	0.50	0.57	0.53	0.56	0.89	0.69	0.66	0.60
Cold-climate heat pump				0.63	0.63	0.67	0.56	0.67	0.76	0.71	0.75				
2016 average emissions	0.51	0.18	0.14	0.51	0.56	0.80	0.59	0.24	0.26	0.28	0.59	0.47	0.44	0.37	0.32

For replacing propane furnaces with heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Kilograms CO2 per mBtu of propane	63.07																		
Annual emissions (kg C02)																			
80% AFUE furnace	2,749	2,416	1,967	4,107	2,512	3,672	3,832	3,082	4,248	2,288	3,082	3,230	3,076	1,717	1,858	1,820	2,358	1,724	1,608
95% AFUE furnace	2,315	2,034	1,657	3,459	2,115	3,092	3,227	2,596	3,578	1,926	2,596	2,720	2,590	1,446	1,565	1,533	1,986	1,452	1,354
Breakeven emissions rate (kg per kWh) relative to an 80% AFUE furnace																			
8.2 HSPF heat pump	0.53	0.70	0.73	0.43	0.58	0.43	0.43	0.45	0.39	0.45	0.50	0.48	0.50	0.76	0.60	0.57	0.54	0.63	0.53
8.5 HSPF heat pump	0.55	0.73	0.77	0.44	0.60	0.43	0.43	0.46	0.39	0.46	0.52	0.49	0.51	0.79	0.62	0.59	0.56	0.65	0.55
10.3 HSPF heat pump	0.62	0.85	0.89	0.49	0.69	0.49	0.49	0.52	0.43	0.52	0.59	0.55	0.58	0.92	0.71	0.68	0.63	0.75	0.62
Cold-climate heat pump				0.66		0.65	0.65	0.69	0.58	0.69	0.78	0.74	0.77						
Breakeven emissions rate (kg per kWh) relative to a 95% AFUE furnace																			
8.2 HSPF heat pump	0.45	0.59	0.62	0.37	0.49	0.36	0.36	0.38	0.33	0.38	0.42	0.40	0.42	0.64	0.50	0.48	0.46	0.53	0.45
8.5 HSPF heat pump	0.46	0.62	0.65	0.37	0.51	0.36	0.36	0.39	0.33	0.39	0.43	0.41	0.43	0.67	0.52	0.50	0.47	0.55	0.46
10.3 HSPF heat pump	0.53	0.72	0.75	0.42	0.58	0.41	0.41	0.43	0.36	0.43	0.49	0.46	0.49	0.77	0.60	0.57	0.53	0.63	0.53
Cold-climate heat pump				0.56		0.55	0.55	0.58	0.49	0.58	0.66	0.62	0.65						
2016 average emissions	0.51	0.57	0.18	0.66	0.14	0.51	0.56	0.80	0.59	0.24	0.26	0.28	0.59	0.47	0.44	0.37	0.40	0.59	0.32

For replacing oil and propane boilers with ductless heat pumps

		West				Midwest				Northeast				South					
	US	AZ	CA	CO	OR-WA	IL	MI	MO	WI	MA	NJ	NY	PA	FL	GA	NC-SC	TN	TX	VA
Kilograms CO2 per mBtu of oil	73.16																		
Kilograms CO2 per mBtu of propane	63.07																		
Annual emissions (kg CO2)																			
86% AFUE oil boiler	4,818	3,571	3,762	3,571	3,982	3,941	3,941	5,058	4,982	5,544	5,592	4,379	4,681	4,064	4,064	4,064	4,064	4,064	3,824
91% AFUE oil boiler	4,553	3,374	3,556	3,374	3,763	3,724	3,724	4,780	4,709	5,240	5,285	4,139	4,424	3,841	3,841	3,841	3,841	3,841	3,614
84% AFUE propane boiler	3,037	2,669	2,173	4,538	2,775	4,056	4,233	3,405	4,693	2,527	3,405	3,568	3,398	1,897	2,053	2,010	2,605	1,904	1,777
90% AFUE propane boiler	2,834	2,491	2,028	4,235	2,590	3,786	3,951	3,178	4,381	2,359	3,178	3,330	3,171	1,771	1,916	1,876	2,431	1,777	1,658
Breakeven emissions rate (kg per kWh) for a ductless HP relative to																			
86% AFUE oil boiler	0.94	1.08	1.04	0.78	0.82	0.84	0.80	0.91	0.75	0.81	0.88	0.85	0.86	1.17	1.06	1.03	0.98	1.11	0.95
91% AFUE oil boiler	0.89	1.02	0.98	0.74	0.78	0.80	0.76	0.86	0.71	0.77	0.83	0.80	0.81	1.10	1.00	0.97	0.93	1.05	0.90
84% AFUE propane boiler	0.59	0.81	0.60	0.99	0.57	0.87	0.86	0.62	0.70	0.37	0.53	0.69	0.62	0.55	0.53	0.51	0.63	0.52	0.44
90% AFUE propane boiler	0.55	0.76	0.56	0.92	0.54	0.81	0.81	0.57	0.66	0.35	0.50	0.64	0.58	0.51	0.50	0.47	0.59	0.49	0.41
2016 average emissions	0.51	0.57	0.18	0.66	0.14	0.51	0.56	0.80	0.59	0.24	0.26	0.28	0.59	0.47	0.44	0.37	0.40	0.59	0.32

Notes to Table A16

- Emissions rates for oil and propane from EIA at www.eia.gov/environment/emissions/co2_vol_mass.php.www.eia.gov/environment/emissions/co2_vol_mass.php.
- Annual emissions are based on average annual energy use in tables A7, A8, and A9 times the emission rate for oil and propane.

- Break-even emission rate calculated by taking the annual emissions of the oil or propane unit being displaced from this table and dividing by the annual Btu of the heat pump from tables A1, A3, and A5.
- 2016 average emissions per state derived by ACEEE from EIA data available at www.eia.gov/electricity/state/unitedstates. Cells shaded in green mean that average emissions are lower than the break-even rate and therefore the heat pump is cleaner. Cells shaded in red mean that average emissions are higher than the break-even rate and therefore the oil or propane system is cleaner. Cells shaded in yellow mean that sometimes the heat pump is above the break-even rate and sometimes below.

Table A17. Comparison of carbon dioxide emissions in kilograms per million Btu of space-heating need for gas-fired heat pumps and cold-climate electric heat pumps operating under average US conditions

	Power plant heat rate in Btu/kWh			
	4,754	6,096	7,652	10,382
	CO2 emissions			
Propane heat pump	46.5	46.5	46.5	46.5
Electric heat pumps				
8.2 HSPF	37.9	48.6	61.0	82.7
8.5 HSPF	36.9	47.3	59.3	80.5
10.3 HSPF	32.3	41.5	52.1	70.6
Cold-climate	29.3	37.6	47.1	64.0

Notes to Table A17

- Shaded cells mean the electric heat pump has lower emissions.
- Emissions of 63.07 kG/million Btu for propane and 53.07 for natural gas from EIA: www.eia.gov/environment/emissions/co2_vol_mass.php.www.eia.gov/environment/emissions/co2_vol_mass.php.
- Electric emissions of 0.3656 kG/kWh are for a natural gas combined-cycle power plant with a heat rate of 6,500 Btu/kWh and factoring 6% electric T&D losses (as discussed in the text) and 2% natural gas T&D losses (from Nadel 2016).
- Based on HSPF and COP for the average of the United States in tables A1, A3, and A5. Where an average for the United States is not provided in these tables we calculated a simple average of the figures from each of the listed states. COPs for electric heat pumps = HSPF/3.412 (the Btu in a watt-hour of electricity).
- Propane heat pump emissions per million Btu = 63.07 kG/million Btu for propane/1.36 gas heat pump COP (from table A3).
- Natural gas heat pump emissions per million Btu = 53.07 kG/million Btu for natural gas/1.36 gas heat pump COP *1.02 (2% T&D losses).
  Electric heat pump emissions per million Btu = 53.07 kG/million Btu for natural gas/heat pump COP (from table A3) * power plant heat rate/3412 Btu/kWh * 1.06 (for T&D losses).

Appendix B. Additional Figures

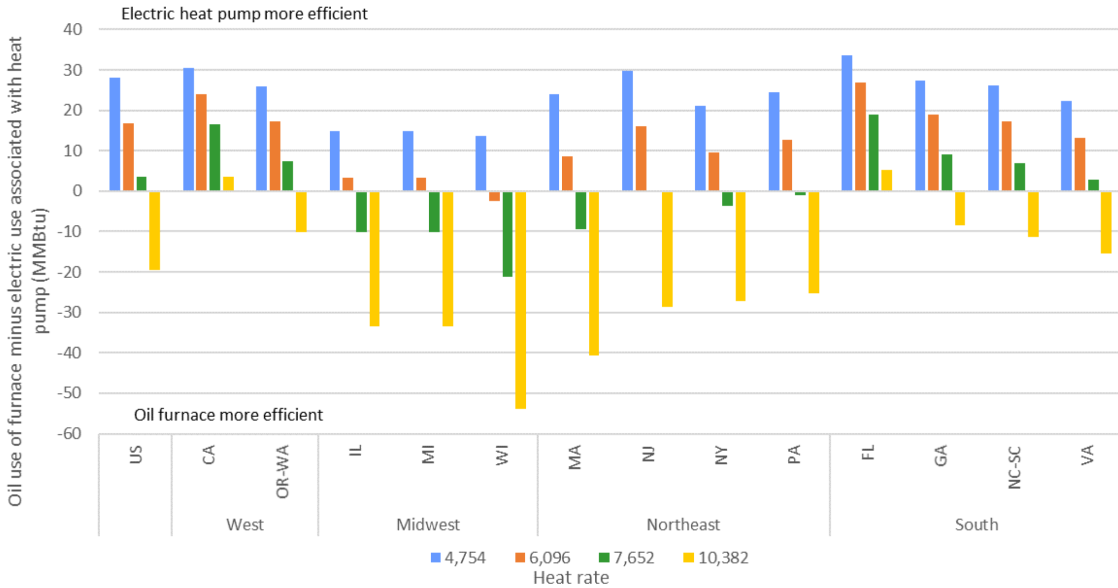

Figure B1. Comparison of annual energy use of an 83% AFUE oil furnace and an 8.2 HSPF electric heat pump

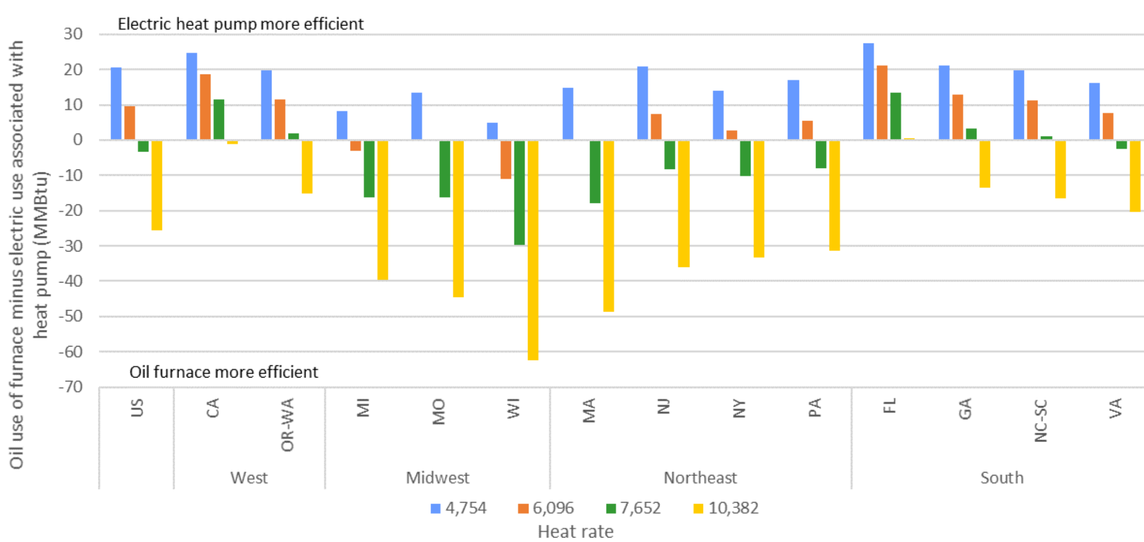

Figure B2. Comparison of annual energy use of a 95% AFUE oil furnace and an 8.5 HSPF electric heat pump

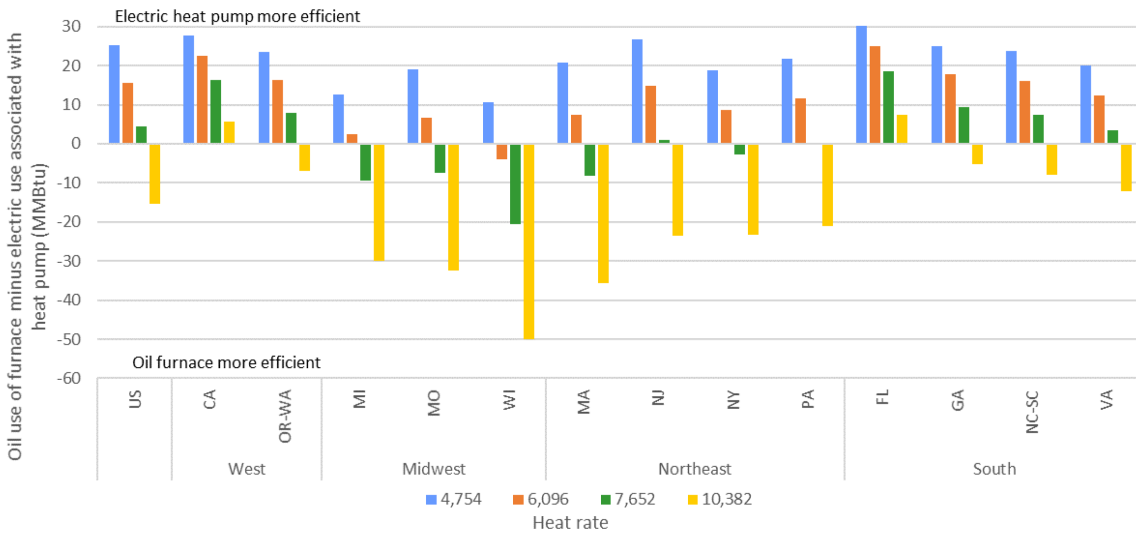

Figure B3. Comparison of annual energy use of a 95% AFUE oil furnace and a 10.3 HSPF heat pump

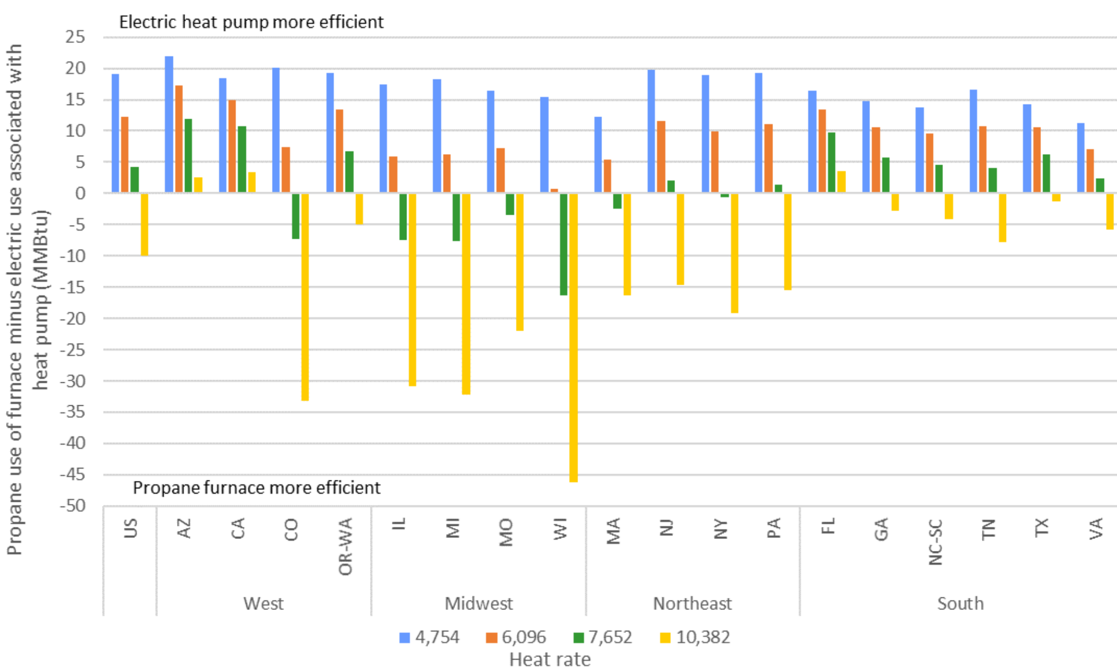

Figure B4. Comparison of annual energy use of an 80% AFUE propane furnace and an 8.2 HSPF heat pump

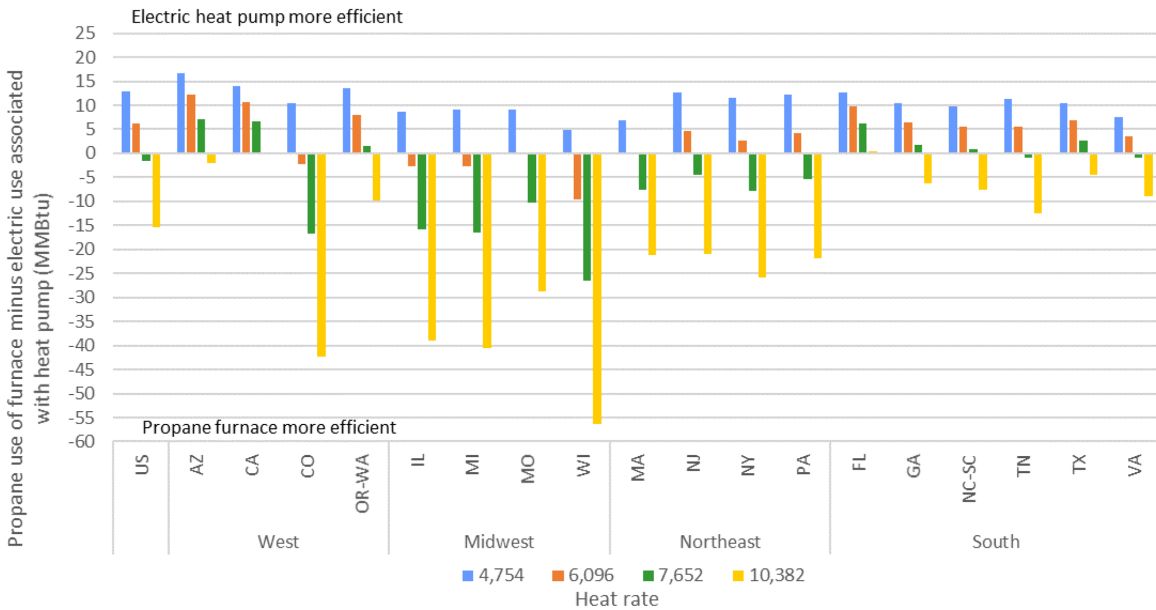

Figure B5. Comparison of annual energy use of a 95% AFUE propane furnace and an 8.5 HSPF heat pump

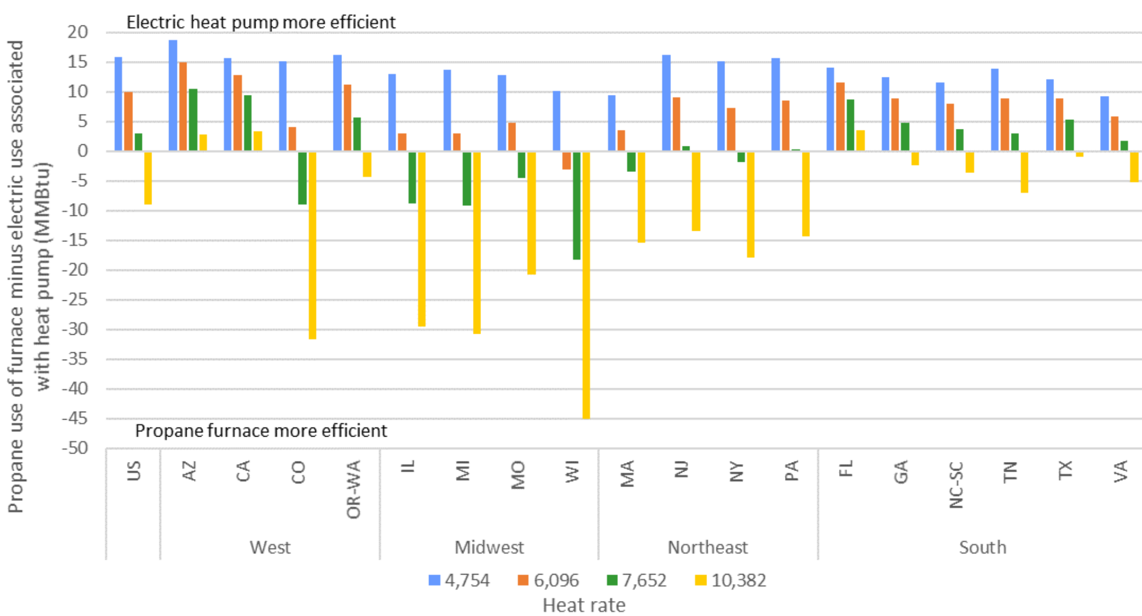

Figure B6. Comparison of annual energy use of a 95% AFUE propane furnace and a 10.3 HSPF heat pump

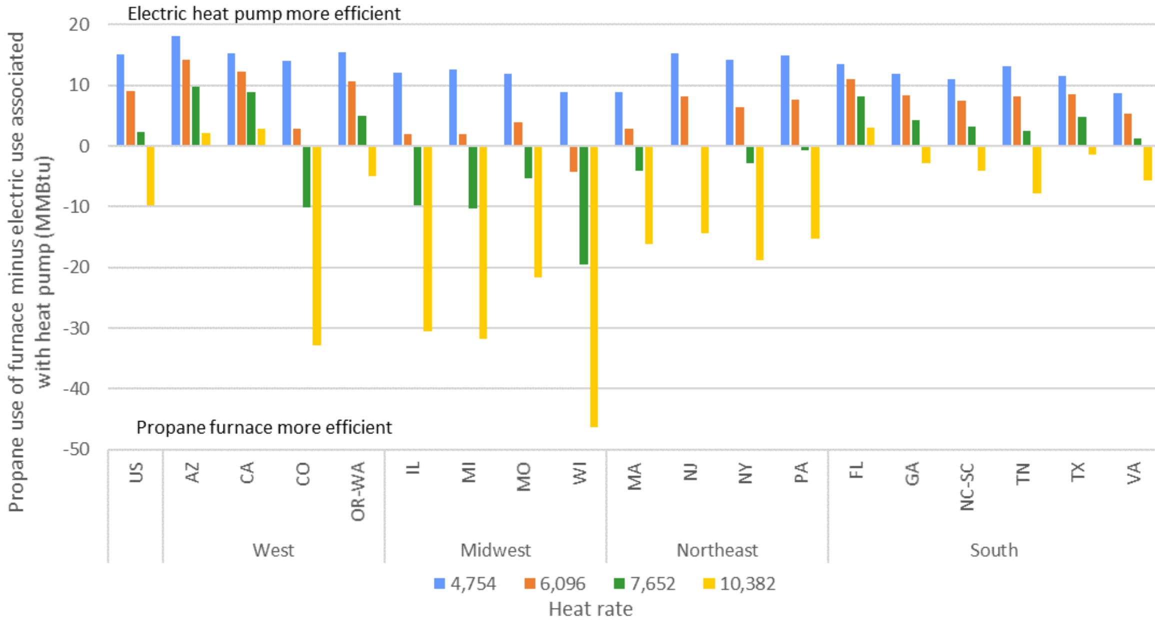

Figure B7. Comparison of annual energy use of a 97% AFUE propane furnace and a 10.3 HSPF heat pump

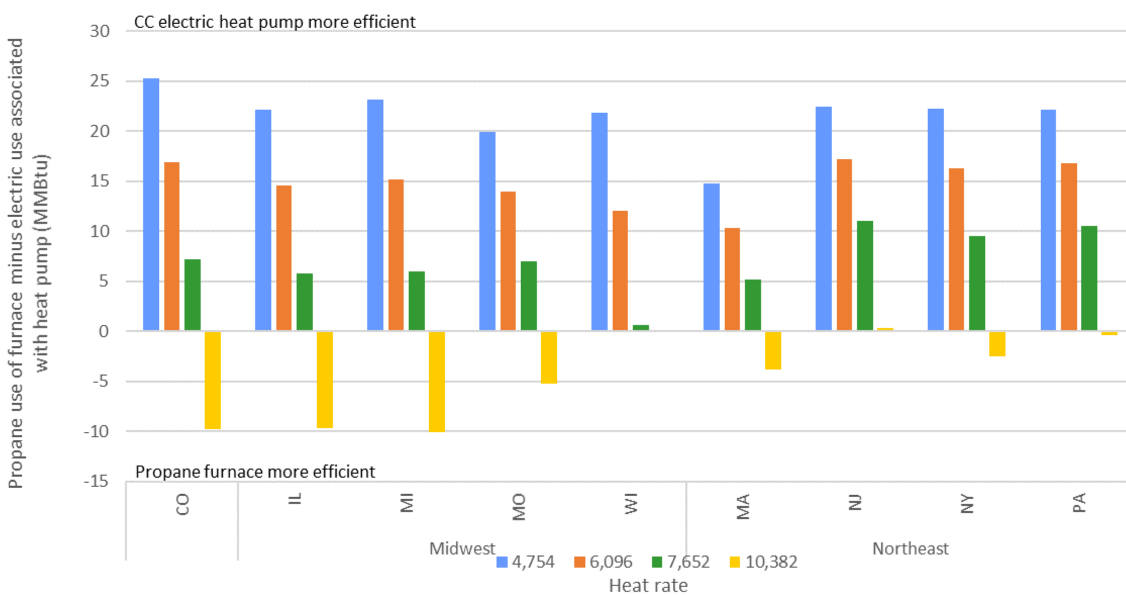

Figure B8. Comparison of annual energy use of a 95% AFUE propane furnace and a cold-climate HSPF heat pump

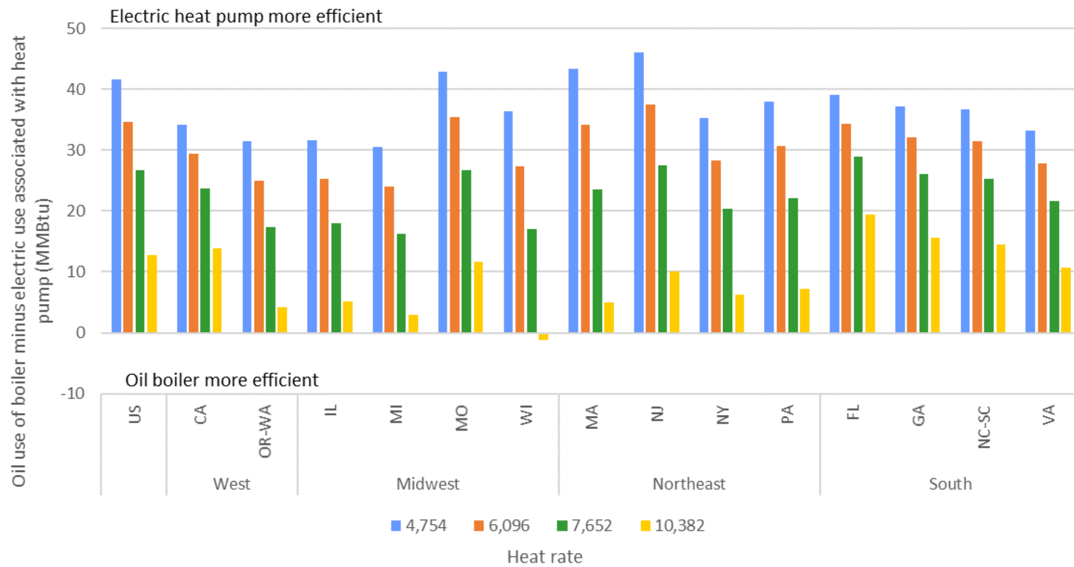

Figure B9. Comparison of annual energy use of an 86% AFUE oil boiler and a ductless heat pump

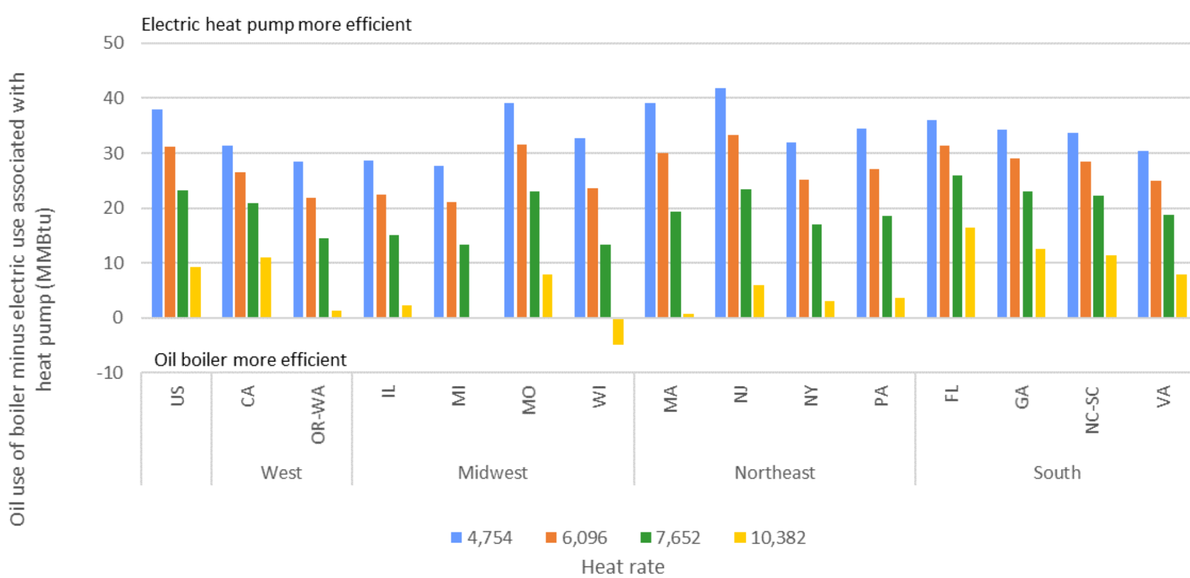

Figure B10. Comparison of annual energy use of a 91% AFUE oil boiler and a ductless heat pump

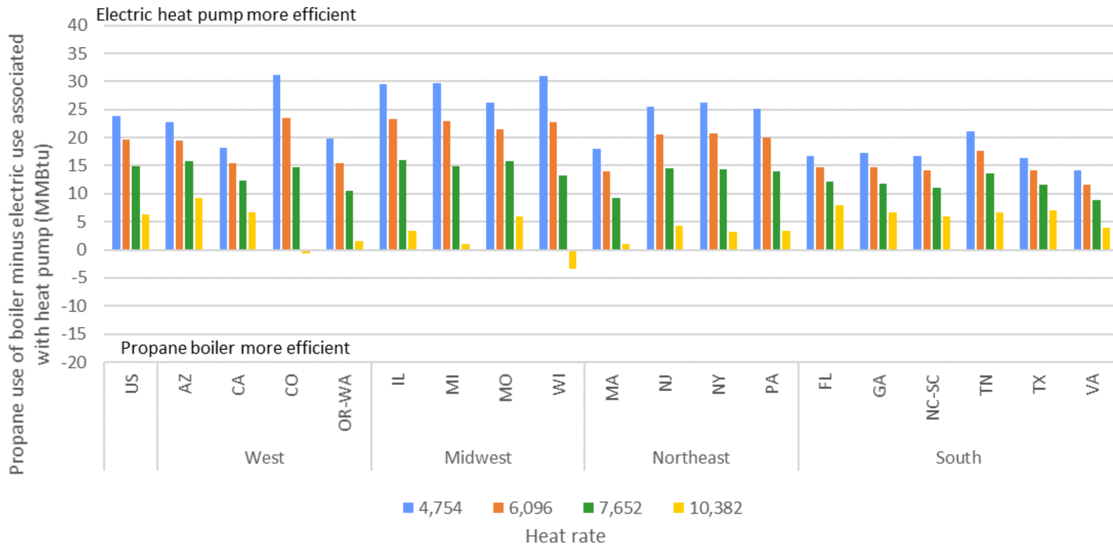

Figure B11. Comparison of annual energy use of a 90% AFUE propane boiler and a ductless heat pump

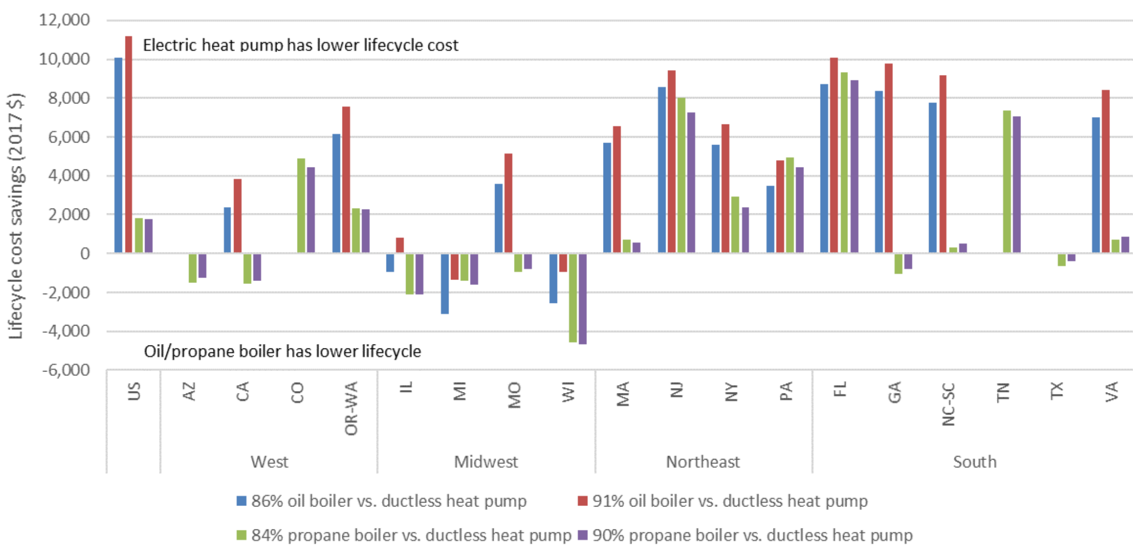

Figure B12. Life-cycle cost savings from replacing an oil furnace with a heat pump; does not include air-conditioning savings.

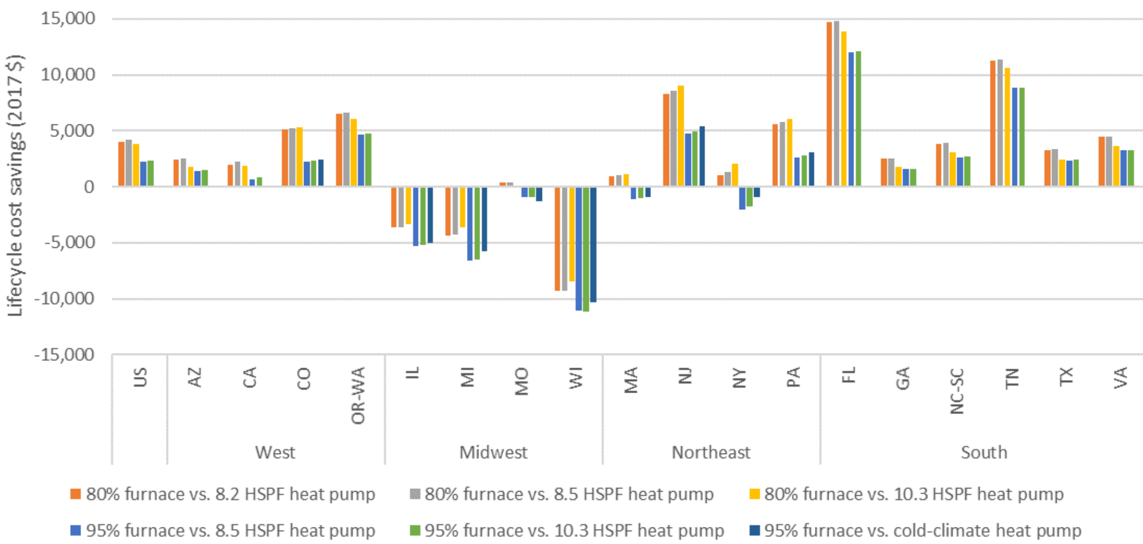

Figure B13. Life-cycle cost savings from replacing a propane furnace with a heat pump; does not include air-conditioning savings.

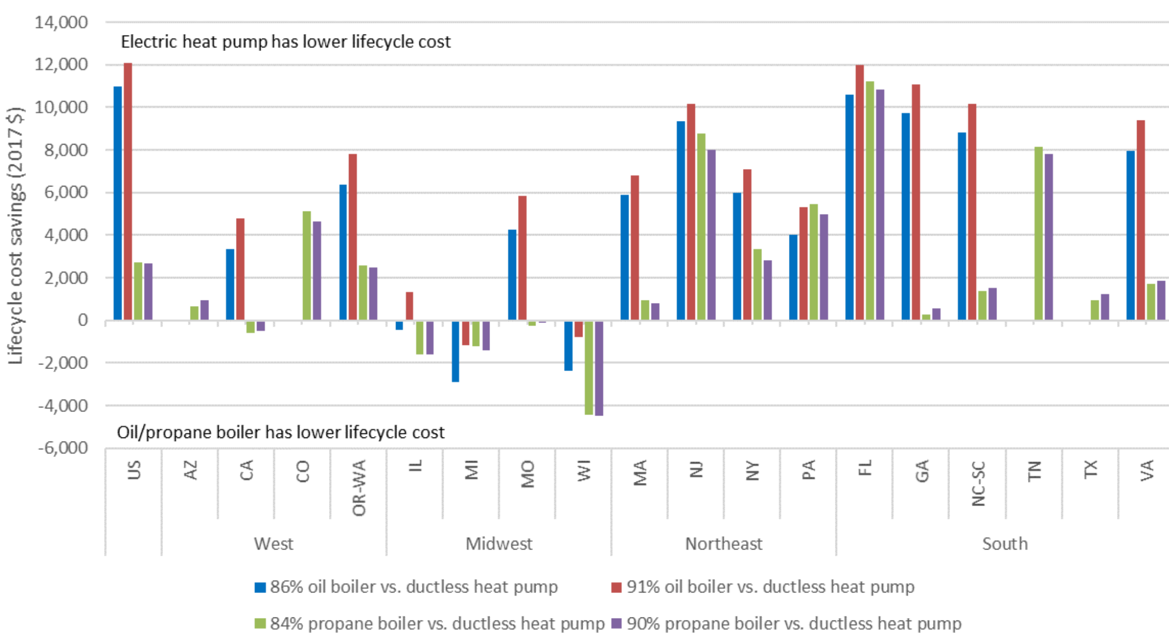

Figure B14. Life-cycle cost savings from replacing an oil or propane boiler with a heat pump; includes air-conditioning savings.

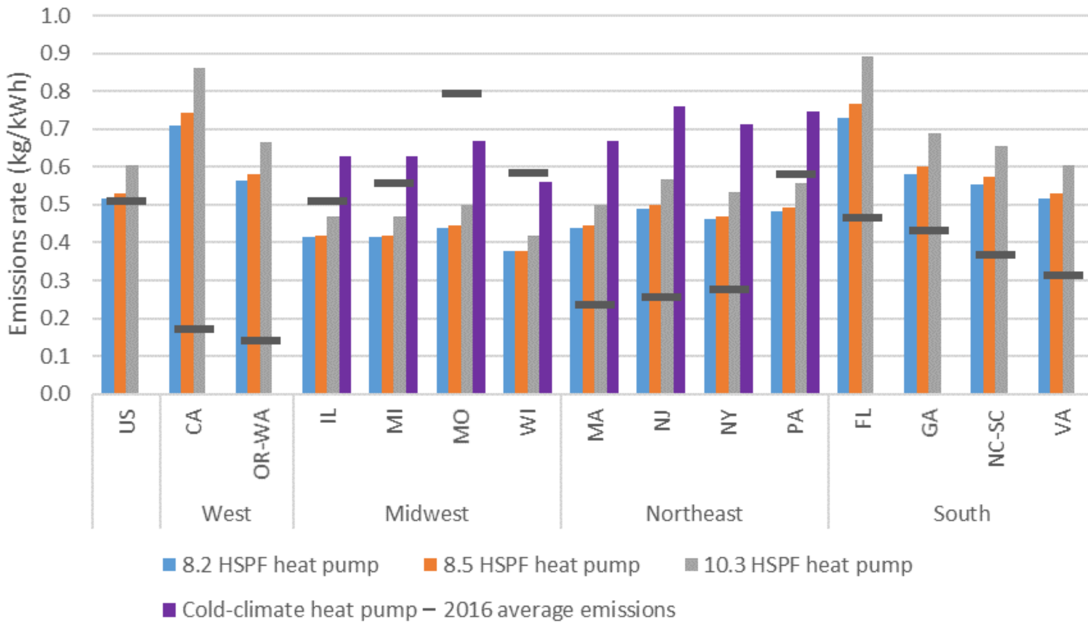

Figure B15. Break-even emissions rate for ducted heat pumps relative to a 95% AFUE oil furnace. If the line showing 2016 average emissions is in the middle of the bars, then heat pumps will on average reduce emissions in 2016. If the line for 2016 emissions is above the bars, then emissions from heat pumps will be higher than emissions from oil or propane heating systems.

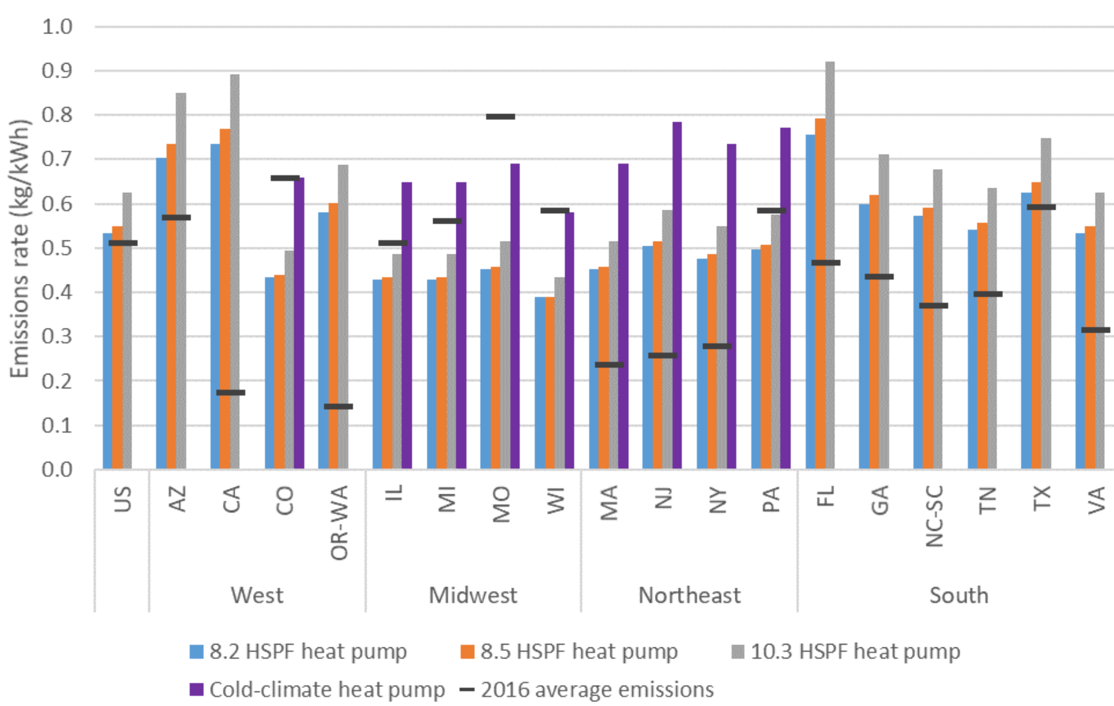

Figure B16. Break-even emissions rate for ducted heat pumps relative to an 80% AFUE propane. If the line showing 2016 average emissions is in the middle of the bars, then heat pumps will on average reduce emissions in 2016. If the line for 2016 emissions is above the bars, then emissions from heat pumps will be higher than emissions from oil or propane heating systems.