Analysis of Electric and Gas Decarbonization Options for Homes and Apartments

Steven Nadel and
Lyla Fadali

N

July 2022
ACEEE Report

ACEEE
American Council for an Energy-Efficient Economy

Contents

About ACEEE ... ii

About the Authors ... ii

Acknowledgments ... ii

Suggested Citation ... iii

Executive Summary ... iv

Introduction ... 1

Analysis Approach ... 2

- The Cost of Decarbonized Electricity and Fuel ... 6
- Heating Degree Days ... 8

Results ... 9

- Space Conditioning ... 11
- Water Heating ... 40
- Summary of Analysis Results ... 42

Extrapolating to the Entire National Housing Stock ... 43

- Results ... 45

Next Steps ... 46

Conclusions ... 52

References ... 54

Appendix A. Methodology ... 63

Appendix B. Analysis of Energy Efficiency Economics for Additional System Types ... 77

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

About the Authors

Steven Nadel has been ACEEE's executive director since 2001. He has worked in the energy efficiency field for more than 40 years and has over 200 publications. His current research interests include energy and climate change policy; strategies to decarbonize the buildings, transportation, and industrial sectors; utility sector energy efficiency programs and policies; and appliance and equipment efficiency standards. 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.

Lyla Fadali is a senior researcher in ACEEE's buildings program. Prior to joining ACEEE, Lyla was an AAAS Science & Technology Policy Fellow in the Building Technologies Office at the U.S. Department of Energy, where she worked on life-cycle carbon of buildings, energy-efficient manufactured housing, and data visualization and analysis. Lyla earned a doctor of philosophy and a master of arts in mathematics from the University of California, San Diego, and bachelor of science in mathematics from the University of Nevada, Reno. Her areas of expertise include manufactured housing and life-cycle carbon in buildings.

Acknowledgments

This report was funded by Commonwealth Edison, Eversource, Los Angeles Department of Water and Power, National Grid, Northwest Energy Efficiency Alliance, Southern California Gas, United Illuminating, and the U.S. Department of Energy (DOE). The authors gratefully acknowledge external reviewers, internal reviewers, colleagues, and sponsors who supported this report. External expert reviewers included Rick Murphy and Sapna Gheewala, American Gas Association; Dan Aas, E3; Peter Klint and Alexandra Abbruscalo, Eversource; Steve Menges, National Grid; Mark Kresowik, Lacey Tan, Edie Taylor, Mohammad Fathollahzadeh, and Talor Gruenwald, RMI; Carlo Cavina, Southern California Gas; Adam Hinge, Sustainable Energy Partnerships; and Billierae Engelman, DOE. External review and support do not imply affiliation or endorsement. Internal reviewers included Nora Wang Esram, Michael Waite, and Amber Wood. External review and support do not imply affiliation or endorsement. Last, we would like to thank Mary Robert Carter and Mariel Wolfson for managing the editing process, Keri Schreiner for copy editing, Roxanna Usher for proofreading, Kate Doughty for graphics design, and Nick Roper, Wendy Koch, and Ben Somberg for their help in launching this report.

This version, which was published in June 2023, includes corrections to several figures and associated text in the report, particularly figures 13–16 and B1–B5.

Suggested Citation

Nadel, S., and L. Fadali. 2022. *Analysis of Electric and Gas Decarbonization Options for Homes and Apartments*. Washington, DC: ACEEE. www.aceee.org/research-report/b2205.

Executive Summary

KEY FINDINGS

This paper reports on the results of a home-by-home analysis we conducted on several thousand homes across the United States. We examined a variety of decarbonization options for space and water heating beginning in 2030, under a scenario in which the electric grid and fuels are largely decarbonized:

- For homes (detached and attached) with one to four units, electric heat pumps generally minimize average life-cycle equipment and energy costs for heating and cooling in places with fewer than 6,000 heating degree days (HDDs), such as south of Detroit. In colder climates, electric heat pumps with an alternative fuel backup below 5°F generally minimize these costs.
- These results assume use of cold-climate electric heat pumps in places with more than 4,000 HDDs (the recent climate in Maryland and points north). These cold-climate models represent an advance in heat pump technology and can provide heat at temperatures down to about 5°F. Our analysis suggests we may best minimize life-cycle costs by popularizing cold-climate models in places that are both cold (4,000 HDD to 6,000 HDD) and super cold (6,000-plus HDD).
- For multifamily buildings with five or more units, energy use per housing unit is generally low and the costs of electrification are currently high. Based on limited data, we find that using alternative fuels in condensing boilers and furnaces often minimizes life-cycle costs. This finding should be considered preliminary, with more data and analysis needed.
- For water heating in one- to four-family homes, electric heat pump water heaters (HPWHs) have the lowest life-cycle costs in all parts of the United. States, followed by gas-driven HPWHs and then gas condensing tankless water heaters.
- Energy efficiency whole-home retrofit packages often reduce life-cycle costs. For many homes, a moderately sized energy efficiency package (based on Home Performance with ENERGY STAR®) has the lowest life-cycle costs, but for some system types and homes, a deep retrofit at the time of building renovation often reduces life-cycle costs, particularly for homes with above-average energy bills and homes in cold climates.
- The above results change modestly when we use higher and lower equipment costs and energy prices. Looking at results by region, electric heat pumps are more likely to minimize life-cycle costs for homes in the South and along the Pacific coast and least likely in the Midwest, with other regions in between.
- As we transition to decarbonized homes, electrification will be needed in most places and alternative fuels in very cold places. As long as inexpensive fossil fuels are available, this transition will proceed slowly. Multiple policies—including research and development, minimum efficiency standards, incentives and grants, restructuring electric (and perhaps gas) rates, clean heat standards, and a price on carbon—will help accelerate this transition.

Many states and utilities are making long-term commitments to decarbonization. With buildings responsible for about one-third of U.S. greenhouse gas emissions, some stakeholders believe this means full electrification of homes. Others tout opportunities to use clean fuels, such as biogas and hydrogen, while also noting opportunities for gas-driven heat pumps. We analyzed several thousand homes across the United States, looking at multiple decarbonization options for space and water heating.

Our analysis focused on the approximately 5,000 homes in the 2015 Residential Energy Consumption Survey (RECS) compiled by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). RECS contains detailed data on the building characteristics and energy use of a national sample chosen to represent the U.S. housing stock across regions and building types (EIA 2018a). For each of the approximately 3,000 homes and apartments in RECS using natural gas,[1] propane, or fuel oil furnaces or boilers in 2015, we analyzed several decarbonization options, including electric and gas heat pump options and alternative fuel options (as we describe in the body of the report). Our analysis assumes that equipment is installed in 2030 at the end of the service life of the existing equipment.[2]

We look at both space heat and water heat. In homes with central air conditioners, we look at installing an electric heat pump when the air conditioner needs replacement. In other homes, we look at installing heat pumps when the existing furnace or boiler needs replacement. For heat pumps, we consider air-source heat pumps that produce warm air, except in homes that have hot-water distribution systems, where we look at air-to-water heat pumps that provide hot water. For water heating, we look at electric and gas options when the existing equipment needs to be replaced. For both space and water heating, this new equipment will typically operate until nearly 2050. We use estimated electricity and fuel prices that assume nearly decarbonized electricity and fuel (details in the main report). In this way, we are able to compare decarbonization options using nearly decarbonized electricity and/or alternative fuels. In 2040, in our medium-cost case, the retail cost of decarbonized fuel will be more than triple EIA's projection of 2040 fossil gas prices. And we project that electricity prices in our medium-cost case will increase by 30% relative to EIA's reference case in Minnesota (less to the south, more to the north), due to the impact of electrification on winter peak demand.

[1] We use the term *natural gas* because it is widely used, including by the U.S. Department of Energy's Energy Information Administration. However, some groups consider *natural* to be a marketing term in this context and prefer to label the fuel *fossil gas*. We elected to stick with *natural gas* here but note the alternative term.

[2] We assume all replacements are in 2030, but, in actuality, the replacements will gradually occur as the existing equipment needs replacement. We do not model any early replacement (before the end of service life).

We find that for homes with up to four units in places with fewer than about 6,000 heating degree days (HDD; the recent climate in Detroit[3]), life-cycle costs are generally lowest for homes using electric heat pumps under our medium-cost assumptions.[4] These findings assume use of cold-climate heat pumps in places with more than 4,000 HDD (e.g., Maryland). These cold-climate models represent an advance in heat pump technology and can provide heat at temperatures down to about 5°F due to use of high-efficiency variable-speed compressors. Above approximately 6,000 HDD, hybrid systems (electric heat pump with a fuel backup) often minimize life-cycle costs. We note that as the climate continues to warm, the 4,000 and 6,000 HDD lines will tend to move north and fewer places will have more than 6,000 HDD. Instead, cooling needs will increase. Electric heat pumps can efficiently cool spaces in all climate regions.

For apartments served by central boilers, based on limited cost data, use of alternative fuels generally has the lowest life-cycle costs. Electrifying these apartments is expensive and their energy needs are generally modest, so it is hard to recoup the cost of electrification investments. The economics of electric heat pumps in multifamily buildings would improve if the installed costs of mini-split heat pumps in multifamily buildings were reduced to the costs that now apply in single-family homes.

Energy efficiency often—but not always—reduces life-cycle costs as homes are decarbonized. For many homes, the moderate energy efficiency package we modeled (based on Home Performance with ENERGY STAR) has the lowest life-cycle costs, but for some system types, a deep retrofit at the time of building renovation often reduces life-cycle costs, particularly for homes with above-average energy use and homes in cold climates.

The above results are based on our medium price assumptions for equipment cost and energy prices, but the results differ only modestly at higher and lower prices. For example, where the above conclusion discusses 6,000 HDDs, other cost and price scenarios may change the pivot point to 5,500 or 5,000 HDDs.

When we look at variation in results by region, household income, and building age, interesting patterns emerge. Electric heat pumps are more likely to reduce life-cycle costs for decarbonizing in the South and West than in the North Central region, with costs in other regions in between. As income increases and building age decreases, electric heat pumps are more likely to decrease life-cycle costs due to correlations with the presence of central air-conditioning (reducing the incremental cost of a heat pump at the time the air conditioner needs to be replaced), improved energy efficiency, and the increased prevalence

[3] Based on average HDD over the 2006–2020 period (NCEI 2021).

[4] For simplicity, we refer to reducing life-cycle costs but we also note that with decarbonization, life-cycle cost "parity" is also useful as it delivers significant greenhouse gas savings/benefits at an equivalent cost.

of single-family (versus multifamily) homes. Given these financial realities, policymakers should prioritize assistance to low- and moderate-income households, whose homes are often the most challenging to decarbonize.

For water heating, electric heat pump water heaters (HPWHs) have the lowest life-cycle costs in every home analyzed, followed by gas HPWHs and gas condensing tankless water heaters.

We also conducted a national analysis on all U.S. homes using the weighting factors EIA assigns to homes in RECS to make them represent the national housing stock. We find that, as a nation, electric heat pumps, supplemented with a backup fuel heating in climates of 6,000 HDDs or more, minimize life-cycle costs. The package with the lowest life-cycle costs generally includes moderate energy efficiency (based on Home Performance with ENERGY STAR), particularly if the energy efficiency helps reduce system costs and hence rates. Results vary slightly at high and low energy prices.

While we need to fully decarbonize buildings, as long as inexpensive fossil fuels are available, market adoption of electric space and water heating will proceed slowly. Policies—including research and development, education and marketing, minimum efficiency standards, incentives and grants, restructuring electric (and perhaps gas) rates, clean heat standards, and a price on carbon—will all be needed to accelerate this transition.

Introduction

Many states and utilities are making long-term decarbonization commitments. In the buildings sector, some stakeholders believe this means fully electrifying buildings and generating power only from clean energy (renewables, nuclear, and fuels with carbon capture, utilization, and storage). Others, including many involved with the natural gas industry, tout opportunities to use clean fuels such as biogas and hydrogen; they also note opportunities for gas-driven heat pumps and heat pump water heaters (HPWHs) to use these fuels efficiently.

Many prior studies have compared fossil fuel heat furnaces and boilers to electric heat pumps, but these analyses generally assume current availability and current prices of natural gas, propane, fuel oil, and electricity (e.g., Nadel 2016, 2018; Bilimoria et al. 2018). However, if we are truly going to reach zero net emissions from buildings by 2050, we will no longer be able to use fossil fuels; instead, we must use fuels and electricity that are fully or nearly carbon free.

Various issues will determine how to best decarbonize the buildings sector. For example, the best solution may vary with climate—it is easier to get heat from heat pumps in Florida than in Alaska. Fuel availability and costs are also issues. While electricity is widely available, how will costs change if vehicles and homes are electrified? Meeting winter peak electricity demand during polar vortex events may be particularly challenging. Efforts to reduce loads through energy efficiency and to control loads through storage and demand flexibility will also affect electricity peaks and economics. Biofuels and hydrogen are more expensive than natural gas; this is particularly true of "green" hydrogen, which is made from carbon-free electricity. If many customers are electrified, what will that mean for how we allocate the costs of maintaining a gas distribution network? There are also important differences between new construction and existing buildings, as well as regional differences in energy prices, how clean the electric grid is, and the potential availability of biofuels and hydrogen.

Given these many uncertainties and in an effort to help policymakers, utilities, and other interested parties to understand appropriate building decarbonization strategies for different building types and regions, ACEEE analyzed the emissions and economic implications of different decarbonization scenarios. To avert the worst impacts of global climate change, the Intergovernmental Panel on Climate Change, the International Energy Agency, and other organizations have determined that power grids and buildings need to be decarbonized by 2050 (IPCC 2022; IEA 2021). Our analysis evaluates strategies to be applied starting in 2030. At that point, gas heat pumps will have been commercially available for at least five years[5] and strategies to decarbonize both the electric grid and gas network will be more established and having an impact on electricity and gas prices. Decisions made in the 2030s will affect equipment operating in 2050 and therefore efforts to fully decarbonize buildings by 2050.

The goal of our research is to assist policymakers and other stakeholders to objectively assess and compare different decarbonization options for buildings in the medium and long terms, helping to inform discussions on near- and mid-term steps.

Of course, low-carbon investments pre-2030 will be crucial to stay on the narrow path to 1.5°C. The "Next Steps" section later in this report discusses policy strategies that can be established in the 2020s to lay a foundation for the 2030 decisions we analyze.

Our research addresses five specific research questions:

- Which building decarbonization options appear to make the most sense in different situations (regions, building types, and system types)?
- How do these options differ by geography and building type, and based on key assumptions such as the future cost of biofuels and green hydrogen?
- What is a reasonable range for key assumptions such as the cost of gas heat pumps, biofuels, green hydrogen, and growth in peak electrical demand?
- What are the options for providing alternative fuels at the home and building level (e.g., existing pipes, new pipes, or by truck)?
- Which policies could we implement in the near term to make the most promising future scenarios a reality?

Analysis Approach

Our basic approach was to analyze many of the approximately 5,000 homes in the 2015 Residential Energy Consumption Survey (RECS) compiled by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE). RECS contains detailed data on the characteristics and energy use of a national sample representing the U.S. housing stock across regions and building types.[6] For each of the relevant homes and apartments in RECS,

[5] Current estimates are that residential gas heat pumps will become commercially available in 2023–2024, depending on the product.

[6] The homes in our analysis cover all the states and climate zones. However, to be a truly nationally representative sample, the weighting factors associated with each home need to be employed. We do this for a national analysis toward the end of this report but do not do this for the analyses that graph and discuss individual homes.

we analyzed several decarbonization options; we describe these below, including one or more heat pump options and one or more alternative fuel options. Our analysis assumes that this new equipment is installed in 2030 and replaces existing equipment that is at the end of its service life. We also assume that the new equipment will operate until nearly 2050 (varying with the life of the equipment). We look at both space and water heating. And we include the cost of space cooling in homes that currently have air-conditioning.[7] We estimate electricity and fuel prices assuming nearly decarbonized electricity and fuel. This allows us to compare decarbonization options using decarbonized electricity and/or alternative fuels.

Specifically, we conducted a complex modeling analysis on decarbonization options using many alternative assumptions.[8] We look at single-family homes and multifamily buildings of various ages, examining both space and water heat. We look at different climates and equipment types, as well as a variety of projections for future power and fuel prices. Our analysis considers energy efficiency options as well as hybrid options that combine use of electricity with a backup fuel-based system. Our analysis shows which decarbonization options may have the lowest life-cycle costs in different building types and climates under the most likely conditions; it also explores how changes in key assumptions will affect the results.

For the electric options, we examine various heat pumps:

- Ducted heat pumps for homes and buildings that already have warm-air ducts
- Air-to-water heat pumps for homes and buildings that circulate hot water to radiators or baseboard heating units
- Ductless mini-split systems for other homes and buildings, such as those now served with steam radiators
- In cold and temperate climates (those with 4,000 HDDs or more),[9] we apply heat pumps designed for use in cold climates (i.e., cold-climate heat pumps)

[7] For homes that do not have air-conditioning, when heat pumps are installed, air-conditioning becomes available. This air-conditioning has an operating cost but also provides comfort and sometimes health benefits. We did not include either these costs or these benefits in our analysis.

[8] The analysis was performed using the R statistical programming language and involved the types of calculations that can also be done with a complex spreadsheet analysis.

[9] Our HDD figures come from the RECS data for each home and are multiyear averages through about 2015. As the climate gets warmer, HDDs will gradually decline. Our analysis does not allow for this effect, which on a national basis has averaged roughly 2% per decade since 1970 (EPA 2021).

- In climates where the temperature (99% design temperature[10]) can get below 5°F for a significant amount of time, we apply cold-climate heat pumps and consider a backup fuel system (i.e., hybrid heat pumps)[11]
- HPWHs for water heating

Ground-source heat pumps are another option, but we did not include them because their costs are highly site specific and we do not have sufficient information on each site to estimate these costs.

For the alternative fuel scenarios we include the following:

- Condensing gas furnaces and boilers for homes currently heated with natural gas or propane[12]
- Gas-fired heat pumps for homes currently heated with natural gas or propane furnaces
- High-efficiency noncondensing boilers for homes currently heated with fuel oil

Most of the systems we examine are widely available from multiple manufacturers in the U.S. market. However, we do include a few system types that are not currently widely available but should be within the next few years. These include cold-climate heat pumps meeting the technical requirements of the DOE Cold Climate Heat Pump Challenge (DOE 2022b), air-to-water heat pumps now sold in Europe but not yet on the U.S. market (Mitsubishi Electric 2022), and residential gas heat pumps (including engine-driven and thermally driven products) (GTI Energy 2022).

For the alternative fuels burned by the systems listed above, we consider

- biogas (largely from bio-wastes),
- synthetic natural gas made from green hydrogen (the term synthetic natural gas refers to a synthetic fuel that is very similar to natural gas and can be used in existing natural gas equipment and infrastructure)[13] and

[10] This is the temperature that is exceeded only 1% of the hours in an average year.

[11] Specifically, we looked at backup systems for locations that get below 5°F for more than 3% of the hours in a heating season. When the temperature only briefly gets this cold, electric resistance backup will often suffice.

[12] Condensing systems cool the exhaust gases to the point that water vapor in the exhaust gases condenses, recovering more energy from the fuel than in non-condensing systems.

[13] Synthetic natural gas is produced from hydrogen by adding carbon atoms to make it usable in existing natural gas equipment. There are a variety of synthetic gases that can be produced. "Green" hydrogen is produced via electrolysis, with the power coming from renewable energy.

- “renewable” fuel oil (similar to biodiesel) and renewable propane (renewable fuels are generally derived from biomass).

We call these *alternative fuels* as they are not fully carbon-free but rather are largely decarbonized. Some biogas is made from plants that absorb carbon dioxide as they grow; this offsets the emissions when they burn. Other biogas comes from methane landfills—burning this gas has less climate impact than the unburned gas (largely methane) that is gradually leaking into the atmosphere, but there is still some climate impact. Synthetic natural gas likewise releases carbon dioxide when burned, but the carbon comes from carbon capture, offsetting these emissions. However, biogas and synthetic natural gas are largely methane, a potent greenhouse gas, and when leaks occur, it has a global warming effect.[14]

Likewise, our electric grid is not fully decarbonized, as our electric prices are based on EIA estimates that do not presume full decarbonization. The costs of full decarbonization will vary locally based on the balance between low-priced renewable energy (new renewable energy is often less expensive than fossil-fuel generation; see Lazard 2021) and the costs of storage and backup power when intermittent renewable power is unavailable. Some of these costs are included in our winter peak adder, but there will likely be additional costs to fully decarbonize that we have not included. For example, analysis by the National Renewable Energy Laboratory has found that moving to approximately 90% renewable energy will not have large incremental costs, but the last 10% increment will add significant costs that we do not fully include (Cole et al. 2021).

Thus, both our gas and electric analyses might be considered roughly 90%+ decarbonization, but not 100%.

For both electric heat pump and alternative fuel scenarios we include the following:

- Low, medium, and high estimates of future prices of decarbonized electricity and alternative fuels. These prices consider the impacts of growing winter peaks and of reduced gas usage due to electrification (we summarize these prices in the next section). In terms of rate structure, we assume that the rate structure that applied in 2015 when the home-specific data were collected will continue to apply.
- Low-, medium-, and high-cost scenarios for the various types of electric, gas, and oil equipment.

[14] We also note that burning alternative fuels results in other emissions, such as nitrogen oxides (NOx) and particulates that can cause adverse health effects. The health effects of natural gas stoves in particular are being hotly debated (Wetzel 2022; Seals and Krasner 2020; AGA 2020)

- Scenarios with weatherization packages that offer moderate (approximately 25%) or deep (approximately 60%) energy use reduction.

For calculation of life-cycle costs, we include equipment and installation costs as well as annual energy costs over the life of the equipment. We discount energy costs in future years using a 5% real discount rate.[15] Our measure of life-cycle costs is a truncated one and does not include maintenance costs or the many nonenergy benefits (and costs) of decarbonization strategies, such as health and comfort impacts. Such costs and benefits are hard to estimate with any precision on a home-by-home basis, and they are often hotly debated; so, to simplify our analysis, we do not include them.

Appendix A describes our methodology in detail.

After analyzing each relevant home in the data set, we consider the distribution of results by system type, building type, and region, and overall. We also look at the results specifically for low- and moderate-income households and for new construction. As we describe later, our report primarily uses mid-case price estimates, but we also report some results using low and high case estimates. We created an online database that provides the results of all scenarios on each home to permit analysis by others.[16]

THE COST OF DECARBONIZED ELECTRICITY AND FUEL

A key driver of our analysis is the cost of decarbonized electricity and fuels. For electricity, we start with retail electricity prices in 2015 as paid by each home in the RECS data set. This allows us to capture utility-specific and home-specific effects. For our medium case, we then include two multipliers: (1) an adjustment for the average national electricity price in 2040[17] relative to the price in 2015, and (2) an adjustment for increased costs due to higher winter peaks caused by electrification. This second adjustment is based on published studies from several different regions and varies based on climate, with no adjustment in warm climates (the South), a moderate adjustment in climates such as Maryland, and a large adjustment in climates such as Minnesota. As the Electric Power Research Institute (2018) notes, growing winter peaks will drive investment needs in much of the country. We do not include an adjustment for increased electricity sales due to electrification, which can spread fixed costs over a wider base. Figure 1 shows the national average electricity price in 2040, adjusted for winter peaks. We use 2040 energy prices as that year is about midlife for equipment installed in 2030. Appendix A offers further details. For our low and high cases, we reduce and

[15] A 5% real discount rate is commonly used by state utility commissions. Many commissions use the weighted average utility cost of capital. This is presently averaging about 4% (NYU Stern 2022), but given recent inflation, 5% might be a more reasonable number for the future.

[16] This database can be found at: www.aceee.org/lcc-results-data.

[17] We use the year 2040 as it is approximately midway into the life of equipment installed in 2030.

increase the electricity price by 25%.[18] These prices are approximations; more refined analyses are needed to estimate state- and utility-specific prices.

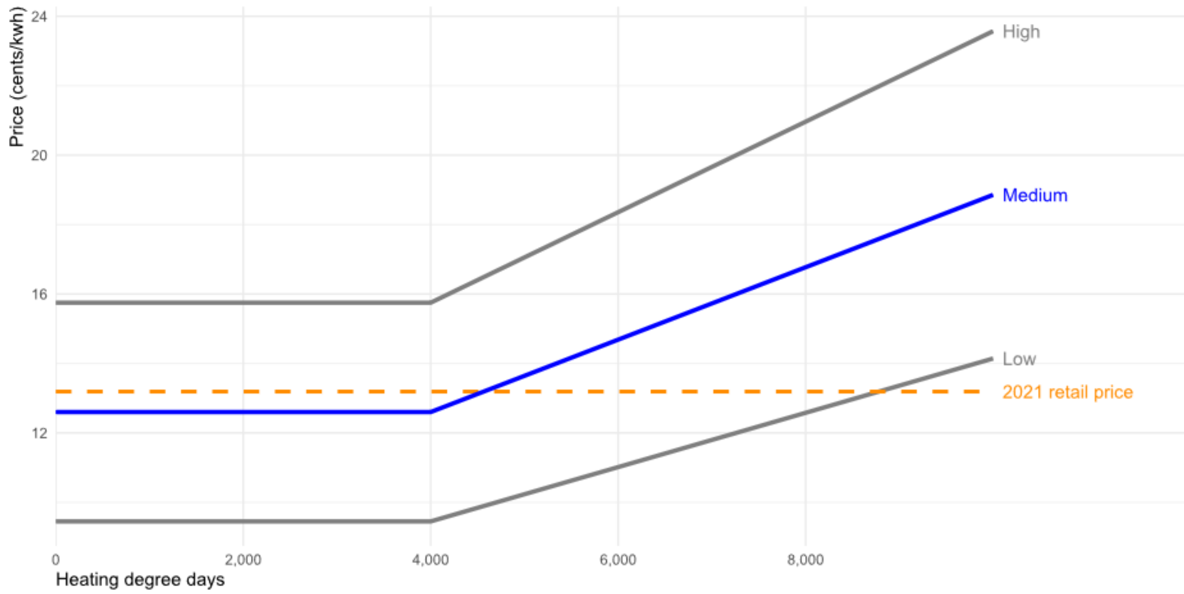


Figure 1. Comparison of different estimates of national electricity price in 2040 relative to the 2021 national average electricity price. The medium estimate for below 4,000 HDD is based on the EIA Reference Case (EIA 2022a). Above 4,000 HDD we incorporate winter peak demand impacts due to electrification of space and water heating (see Appendix A for details). Estimates are in 2020 dollars. Average 2021 price (in 2020$) from EIA 2022b.

For natural gas, we also start with 2015 prices as paid by each home; we then include a multiplier based on the projected increase in the national average natural gas price between 2015 and 2040. Next, we make two adjustments. First, we assume that this fuel will need to be net-zero carbon no later than 2040 and assume a mix of 45% biogas and 55% synthetic natural gas made from green hydrogen. Biogas is in limited supply, hence the need for another gaseous fuel. We assume synthetic natural gas because it can be used in existing distribution pipes and existing residential furnaces, boilers, and water heaters without modification.[19] We use estimates of future wholesale decarbonized gas costs from two consulting firms—ICF (NYC 2021) and E3 (2022)—and then scale these to retail costs using

[18] The lowest and highest cases in EIA's *Annual Energy Outlook* (EIA 2022a) differ by roughly 50% from the reference case. On the other hand, the price range for renewable natural gas estimated by ICF (NYC 2021) is only about 12% from the midpoint. Our plus and minus 25% is in between these extremes.

[19] Hydrogen could be used instead, but burner modifications are required to burn hydrogen instead of natural gas. In addition, depending on the type of pipe used in distribution systems, some locations will require replacement of distribution system gas pipes.

EIA data (see Appendix A for details). The transportation and industrial sectors are likely to drive demand for alternative fuels (Nadel 2022; McKinsey & Company 2022); the buildings sector can benefit from fuel made available by the demand these other sectors create. Second, as gas use declines due to electrification, gas rates will go up in order to recover fixed costs across the lower volume of sales. We use estimates of these effects from Davis and Hausman (2022).[20] Figure 2 summarizes the residential gas prices we use. Again, these prices are approximations; ultimately, further analyses are needed to estimate state- and utility-specific prices.

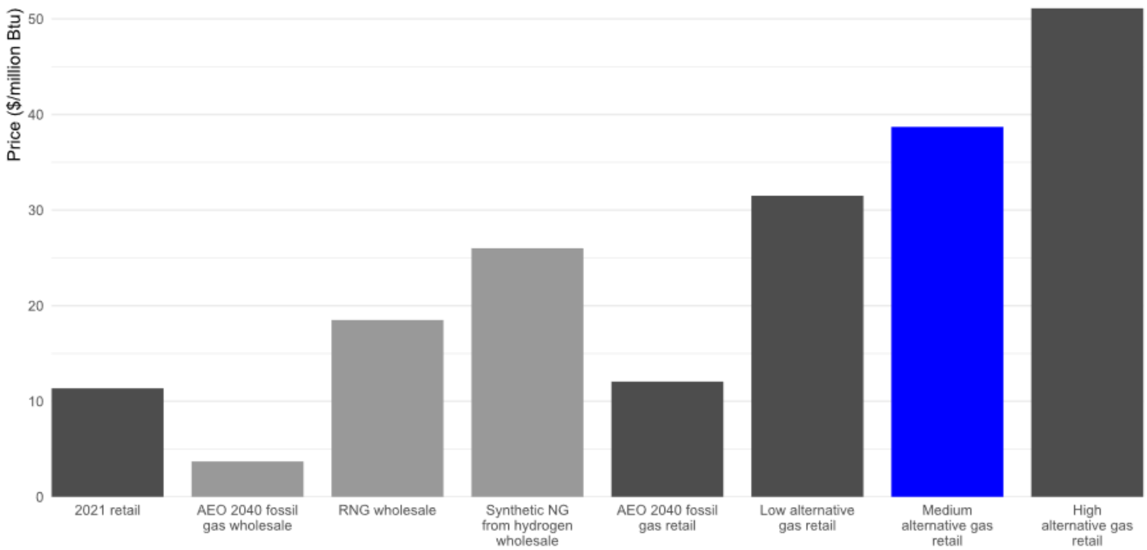


Figure 2. Comparison of 2040 residential gas costs; three are wholesale costs, four are retail. Average 2021 retail price from EIA 2022b. All are in 2020$. Appendix A offers further details.

HEATING DEGREE DAYS

Our analysis adjusts for average heating degree days (HDD) at each home location, using data for each individual home in RECS. HDD measure how cold a climate is over the course of a heating season and are based on the number of hours each winter that the outdoor temperature is below 65°. If on a winter day the average outdoor temperature is 35°F, then 30 HDDs accrue that day (65 minus 35). The HDDs are added for each day of the heating season to produce an annual total. Philadelphia averages about 4,300 HDDs, while northern Alaska often has more than 10,000 HDDs. Figure 3 shows a map of average HDDs for U.S. locations.

[20] Our low and medium estimates are based on Davis and Hausman. Our high estimate was throttled back from the Davis and Hausman estimate as explained in Appendix A.

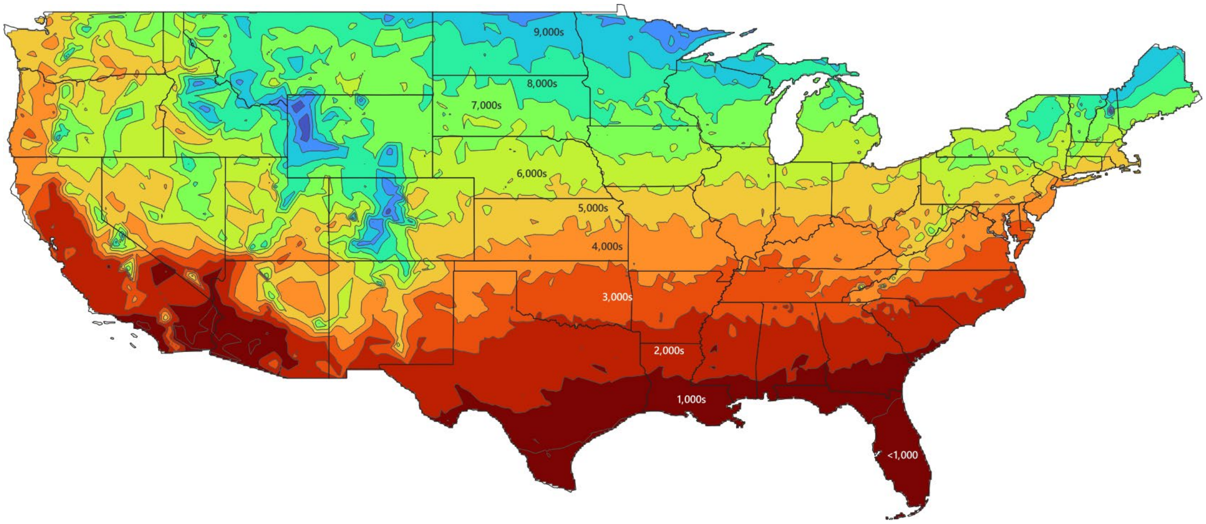


Figure 3. Average heating degree days (HDDs) at various locations in the United States based on averages over the 2006–2020 period. Lines between colors are approximate and not exact. Source: Map created by ACEEE based on data in NCEI 2021.

Please note that the 2015 RECS uses 30-year average HDD from the 1981–2010 period. Due to climate change, most of the U.S. is warming and as a result HDD are declining. Figure 3 and our illustrative cities use 15-year average HDD for 2006–2020. HDDs will continue to decline due to climate change, particularly in the north, but the exact future patterns are unknown and will vary from region to region. We did not attempt to adjust HDDs for future warming. However, we note that the illustrative HDD in figure 3 will gradually decline, and thus the 4,000 and 6,000 HDD inflection points found in our analysis will gradually move north.

Results

Our analysis was conducted for different building types and different base-case equipment types. We also did several special analyses. The subsequent sections present these results:

1. Space conditioning
    a. Single-family homes
        i. Gas furnaces
        ii. Propane and oil furnaces
        iii. Gas, propane, and oil boilers
        iv. Hybrid heating systems (electric heat pump with a fuel backup)
        v. Energy efficiency packages applied to each of the above
    b. Two- to four-unit buildings
    c. Multifamily buildings (five or more units per building)

            i. Furnaces
            ii. Boilers
            iii. Energy efficiency

2. Water heating
3. Overall
    a. Regional differences
    b. Low- and moderate-income households
    c. New construction

Some system types, such as gas furnaces, are very common, while other types are less common. Table 1 shows the number of homes in RECS microdata for different system and building types. These homes and apartments are scattered across all 50 states. In the sections below, we describe the most common system types—such as gas furnaces and boilers—in more detail, both because sample sizes are larger and because these results affect more homes and apartments.

Table 1. Number of units in the RECS database for analysis by building type and current primary heating system

Current primary heating system	Single-family	Two- to four-family buildings	Buildings with five or more units	Total	% of total
Gas furnace	2,063	95	161	2,319	41%
Propane furnace	168	3	4	175	3%
Oil furnace	147	3	7	157	3%
Gas boiler	112	25	107	244	4%
Propane boiler	9	1	NA	10	1%
Oil boiler	40	5	18	63	0%
Electric heat pump	562	21	40	623	11%
Electric resistance	729	100	348	1,177	20%
Other*	687	58	173	918	16%
Total	4,517	311	858	5,686	100%
% of total[21]	79%	5%	15%	100%	

*** Includes built-in floor/wall pipeless furnaces; built-in room heaters burning gas, oil, or kerosene; wood-burning stoves (cordwood or pellets); fireplaces; and portable electric heaters. Source: ACEEE analysis of EIA 2018a.**

Our analysis looked only at homes currently heated with natural gas, oil, or propane. Substantial energy can also be saved by converting homes with electric resistance heat. This was the subject of a prior ACEEE report (Nadel and Kallakuri 2016), and we did not repeat that analysis here.

SPACE CONDITIONING

Single-Family Homes

Single-family homes represent 79% of the homes and apartments in RECS and thus are a particularly important focus for this analysis. Our analysis looks at decarbonization options

[21] By comparison, a study by the Urban Institute (Neil, Goodman, and Young 2020) using the American Community Survey for 2018 estimates 73% single-family, 8% two- to four-unit buildings, and 19% in buildings with five or more units. Thus, the RECS sample may slightly underrepresent multifamily and overrepresent single-family.

for homes now using natural gas, propane, or oil for space and/or water heating. As table 1 shows, of the 2,539 homes in RECS that use fossil fuel furnaces or boilers for space heating (i.e., not including homes that use electricity or "other"), 2,063 use natural gas furnaces for space heating. We discuss these homes in the next section. Subsequent sections deal with propane and oil furnaces and with gas and oil boilers.[22]

Gas Furnaces

For our analysis of gas furnaces, we began by comparing condensing gas furnaces and electric heat pumps using decarbonized electricity and fuels under medium-cost assumptions. As Appendix A describes, these assumptions relate to equipment costs, fuel costs, and electric costs. We compare a condensing gas furnace (95% annual fuel utilization efficiency, or AFUE) with a heat pump. In locations with 4,000 HDDs or more in 2015, we use cold-climate heat pumps (10.5 Heating Seasonal Performance Factor 2, or HSPF2). In warmer climates, we use an ENERGY STAR heat pump (7.8 HSPF2).[23] We included allowances for electric panel upgrades in our medium and high costs for homes that presently do not have central air-conditioning. We did not include maintenance costs for the different systems. Our analysis extends for 18 years due to the 18-year average equipment life for furnaces and heat pumps. Under these assumptions, the electric heat pump usually has lower life-cycle costs, though the condensing gas furnace sometimes has lower life-cycle costs. Figure 4 shows life-cycle costs for the more than 2,000 homes and a best-fit line for the data using each fuel, which shows that under these assumptions, the difference in life-cycle costs decreases as annual HDDs increase. This is due to an increasing need for heat, lower heat pump efficiency at low temperatures, and increasing impact of winter peaks on electricity costs. The electric heat pump has lower life-cycle costs than condensing gas furnaces in 79.7% of the homes we analyzed.

---

[22] Furnaces heat air that is circulated through ducts and blown through registers into the living space. Boilers heat water that is circulated via pipes to radiators or baseboard heating units located in the living space.

[23] HSPF2 is a revised test procedure for HSPF that takes effect in 2023 (AHRI 2020).

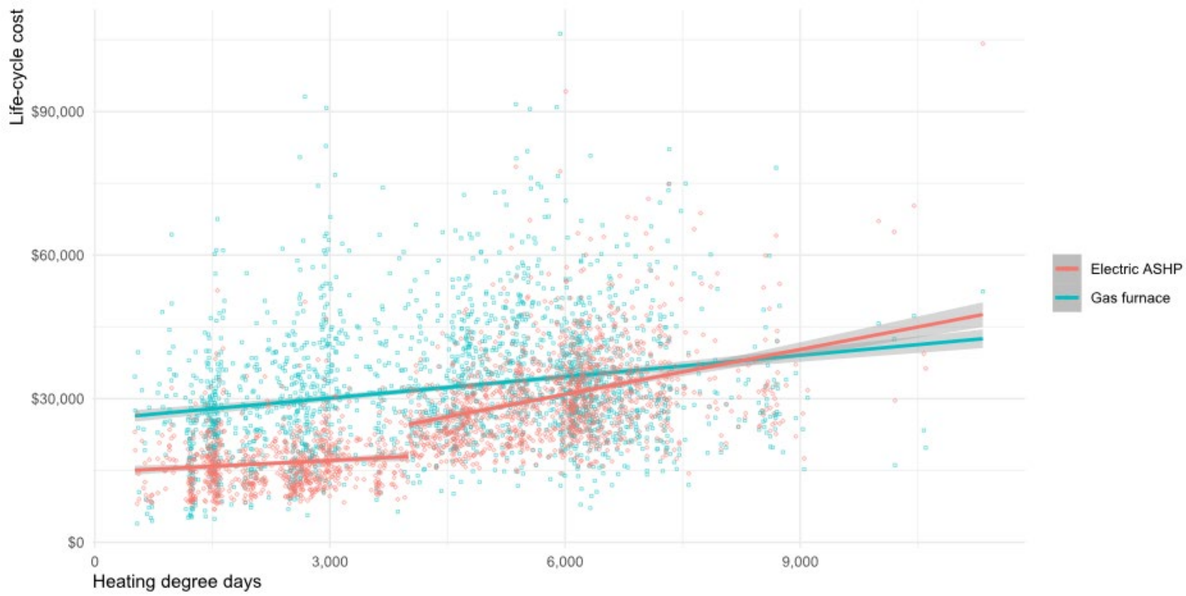


Figure 4. Life-cycle costs for electric heat pumps and condensing gas furnaces using medium-cost assumptions for single-family homes now heated with natural gas. Within a color, each dot represents a different home. The lines are best-fit lines. The gap in the electric heat pump line shows the impact of costs for cold-climate heat pumps for locations with 4,000 HDDs or more. Costs are in 2020$.[24]

We did a similar comparison between electric and gas heat pumps. Gas heat pumps are more efficient than condensing gas furnaces (we used 140% AFUE equivalent for the gas heat pump), but they are also more expensive to purchase. Figure 5 shows this comparison, which repeats the best-fit lines for electric heat pumps and gas furnaces, and adds a best-fit line for gas heat pumps. Under our medium assumptions, the gas heat pump generally has lower life-cycle costs than the condensing gas furnace but higher life-cycle costs than the electric heat pump. The gas and electric heat pump lines meet at roughly 7,300 HDDs, which is the approximate climate in southern Minnesota (we discuss this issue further in the hybrid heating systems section below). Under our medium-cost assumptions, the electric heat pump has lower life-cycle costs than the gas heat pump in 82.6% of the homes we analyzed.

[24] We computed the coefficient of determination R^2 for heating system types with at least 100 homes. For condensing gas furnaces, R^2 is .229; for electric air source heat pumps below 4,000 heating degree days, R^2 is .108, and for electric air source heat pumps 4,000 HDD and above it is .345. These coefficients of determination can be interpreted to indicate the fraction of variation in life-cycle cost that is explained by heating degree days. We expect other variables implicit in our calculation (e.g., square footage of homes) to play a significant role in the life-cycle cost and do not intend our linear regressions to be predictive models but rather an indication of the correlation between life-cycle cost and one important variable. The coefficient of determination is .162 for gas heat pumps and .189 for hybrid electric-gas systems.

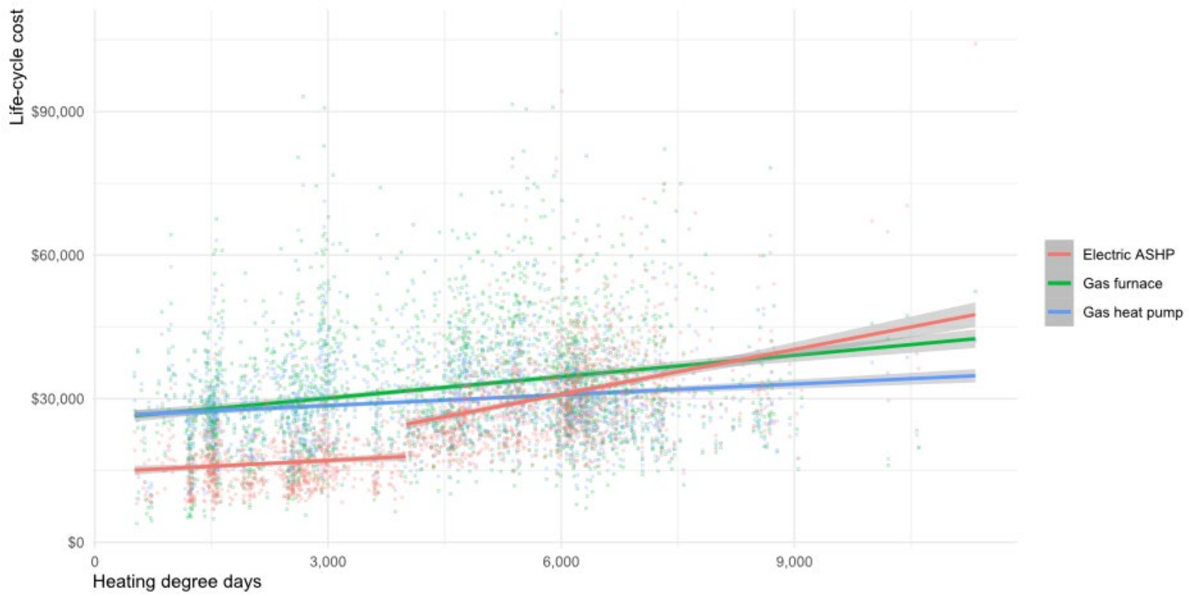


Figure 5. Life-cycle cost for electric heat pumps, condensing gas furnaces, and gas heat pumps using medium-cost assumptions for single-family homes now heated with natural gas. The gap in the electric heat pump line shows the impact of costs for cold-climate heat pumps for locations with 4,000 HDDs or more. Costs are in 2020$.

Relative results were broadly similar when we use our low-cost or high-cost electricity and gas price assumptions. While costs increase for the high-cost assumptions and decrease for the low-cost assumptions, these changes affect both gas and electricity and roughly offset each other.

Looking at figures 4 and 5, a natural gas proponent might argue that the costs of alternative fuel will be lower than our medium case or the price of electricity will be higher than our medium case. To address this concern, figure 6 repeats the analysis in figure 4, but also shows lower and higher electricity and natural gas costs. At a medium electricity cost and a low gas cost, the point at which condensing furnaces on average have lower life-cycle costs than electric heat pumps is above 6,000 HDDs, which is the approximate climate in Detroit (see figure 3). If we use the high electric cost and the low gas cost, condensing gas furnaces have lower average life-cycle costs above roughly 5,000 HDDs, which is the recent climate just south of Boston.

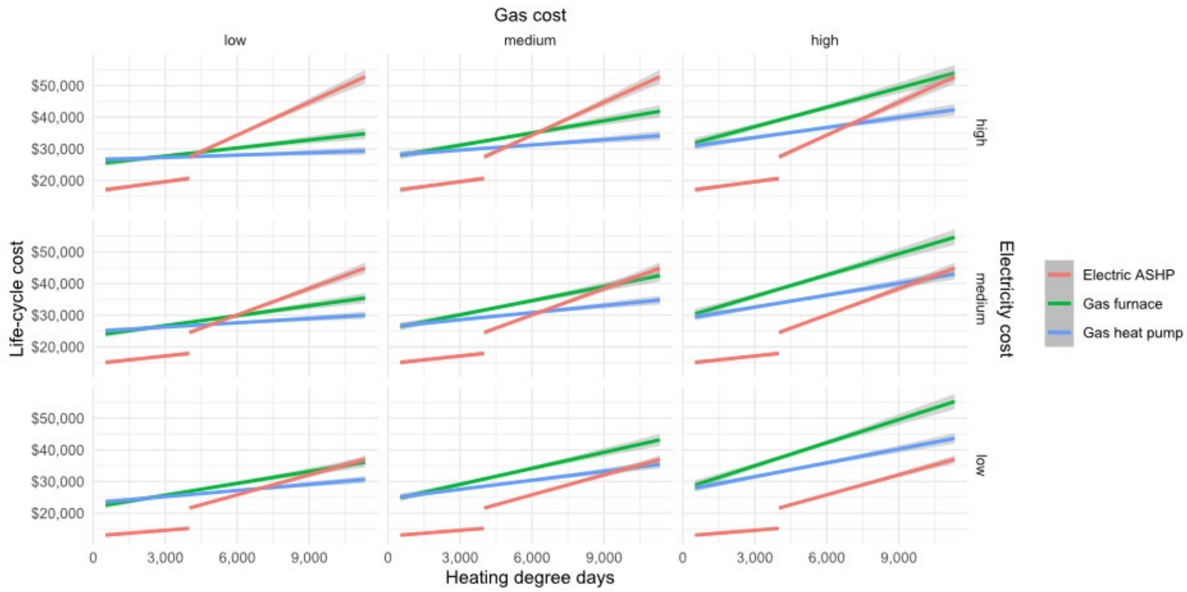


Figure 6. Life-cycle costs for electric and gas heat pumps and condensing gas furnaces for single-family homes now heated with natural gas. This graph shows low, medium, and high costs for both electricity and natural gas. Costs are in 2020$.

We also conducted analyses using lower and higher equipment costs, but while lower equipment costs are favorable to both electric and gas heat pumps and higher equipment costs are unfavorable to them, for the most part these results differ only slightly from the above graphs. When life-cycle costs are in the tens of thousands of dollars, a difference in equipment costs at the levels we modeled generally does not have a large impact on life-cycle cost, unless a high cost for one type of equipment is combined with a low cost for a competing type of equipment.

Propane and Oil Furnaces

Approximately 300 homes in the RECS data set heat with propane or oil furnaces (see table 1). Oil is primarily used in the Northeast and Midwest, while propane is particularly common in rural areas that do not have natural gas service. Some bio-propane is now produced as a byproduct of biodiesel production. Bio-propane can be produced from animal fat, algae, and cooking oil (ROUSH Cleantech 2022). Also, the Gas Technology Institute (GTI) is working to convert bio-derived methane into liquified petroleum gas (LPG) (Littlewood et al. 2022). LPG is the primary way to bring propane into homes. Another option might be to take biogas and compress it, similar to how compressed natural gas (CNG) is now used to power some vehicles. For our analysis, we started with the estimated 2040 price of biogas and then applied a cost multiplier based on the current residential price of LPG to the current residential price of natural gas per million British thermal units (Btu). We look at a condensing gas furnace, but a gas heat pump could also be used. Appendix A offers further details.

For oil-heated homes, we assume use of biodiesel that has been processed to allow use in oil-burners. We estimate prices based on current biodiesel prices and projected 2040 prices for biogas. Because there are relatively few oil-heated homes, we assume there will be sufficient biodiesel for these homes to use without the need to require more expensive synthetic oil made from green hydrogen. We look at a high-efficiency oil furnace that is noncondensing. While a few condensing oil furnaces are on the market, they are from small companies rather than major manufacturers. Appendix A has further details.

Overall, under our medium-cost scenario, the results for propane and oil furnaces are directionally similar to our results for natural gas furnaces—that is, under our medium-cost assumptions, electric heat pumps will generally have lower life-cycle costs than either condensing furnaces burning propane or high-efficiency oil furnaces. Figure 7 shows these results. However, propane furnaces have higher life-cycle costs than natural gas furnaces (due to the higher price of propane), and therefore the savings with electric heat pumps are more pronounced. For oil at very cold temperatures, such as those in Alaska, the oil and electric heat pump lines approach each other. We return to this issue in our discussion of hybrid heating systems later in this report. Electric heat pumps have lower life-cycle costs than propane furnaces in nearly all the homes we analyzed. For homes with oil furnaces, the electric heat pump lowered life-cycle costs in 91.2% of the homes analyzed.

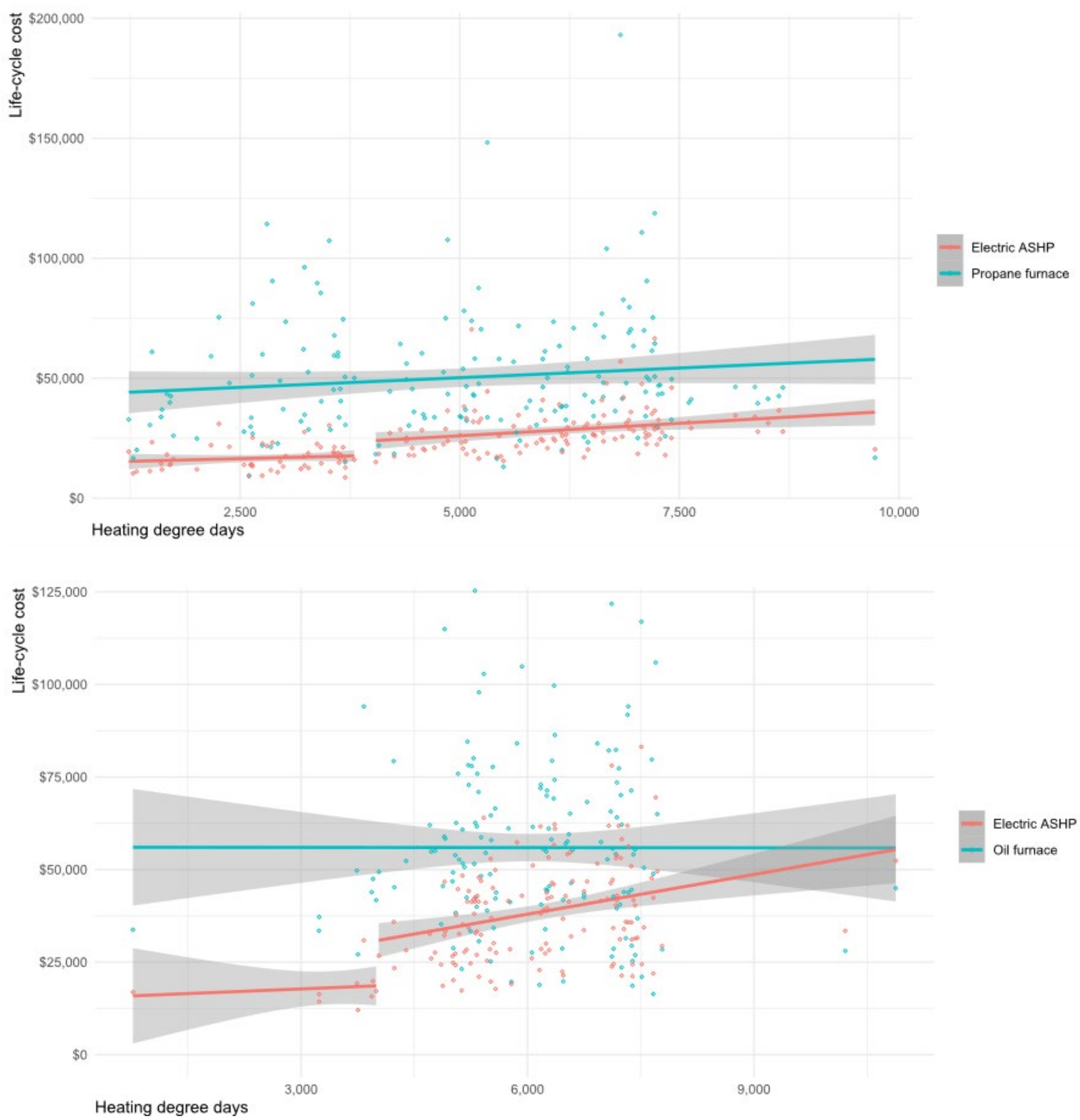


Figure 7. Comparison of electric heat pump with condensing propane furnace (top) and oil furnace (bottom) for single-family homes, using medium-cost assumptions. Costs are in 2020$. The oil furnace line is flat because that is the best-fit line for the approximately 150 sampled homes. We suspect that the homes in the colder climates are more efficient (e.g., more insulated), allowing them on average to have similar life-cycle costs despite the colder climate.[25]

[25] We found no correlation between HDD and the life-cycle cost of oil furnaces (R^2=–.001) Propane heat pumps and furnaces both had R^2 near .1.

Boilers

About 160 homes in the RECS data set are heated with hot water or steam instead of warm air. These systems are more common in older homes (particularly pre-1950) and are primarily in the Northeast and Midwest. The hot water or steam is distributed via pipes to radiators or baseboard heaters in the living space. A potential alternative to a gas, propane or oil-fired boiler is an air-to-water heat pump that takes heat out of the air just like a conventional air-to-air heat pump, but then it uses this heat to produce hot water. Such products are now used extensively in Europe and the United Kingdom. These products are generally variations on ductless heat pumps and are designed to provide substantial heat at cold outdoor temperatures (e.g., Mitsubishi Electric 2022). These products typically heat water to 130°F, but some new products are being developed to heat water to 160°F or above. Manufacturers are planning to bring these products to the United States and Canada soon.[26] Most boiler systems in the United States are designed for hot water of at least 160°F, although many homes can be adequately heated at lower temperatures.[27] Energy efficiency improvements help reduce heating requirements, making lower water temperatures feasible. For system costs and performance, we looked at systems now sold in Europe, converting from Euros to dollars. For the gas systems, we assume use of condensing boilers, while for oil we assume use of a noncondensing high-efficiency boiler. Appendix A provides details.

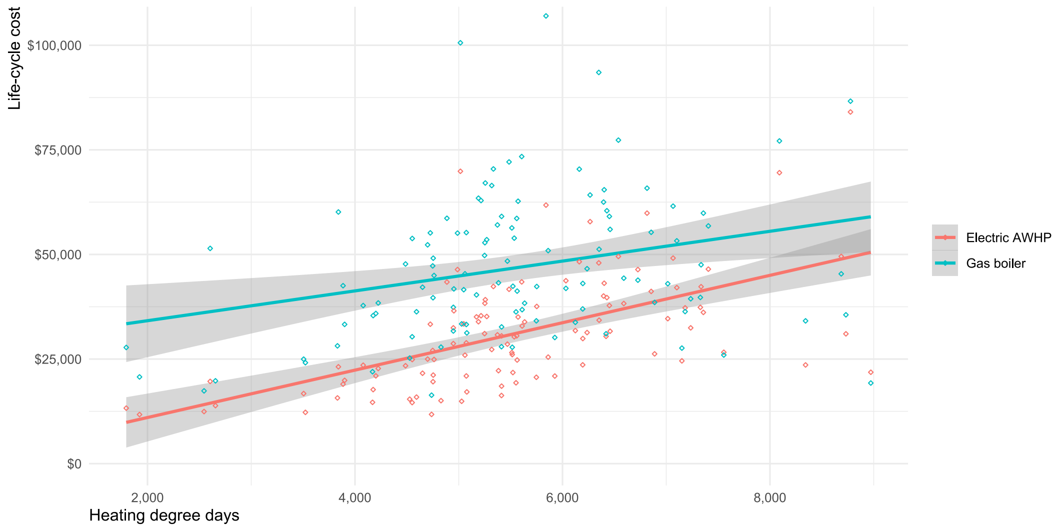
While most boilers provide hot water, some systems produce steam. Residential heat pumps cannot produce steam, so for this analysis, we assume use of multiple ductless heat pumps as the electric option. Another challenge is that RECS does not indicate which homes use hot-water versus steam distribution. To address this, we first analyzed all homes with boilers assuming hot-water distribution and then reexamined homes built before 1950 assuming steam distribution (steam is rare after 1950; before 1950, hot water was more common but steam use was also significant). For the gas and oil steam boilers, we assume noncondensing boilers as condensing steam boilers are not available. Appendix A offers more details.

Figure 8 shows the results of our hot-water analysis, with gas boilers on top and oil boilers on the bottom. The electric heat pumps generally have lower life-cycle costs, except in Alaska (above 9,000 HDDs), where the oil system has lower costs. Across both fuels, electric heat pumps have lower life-cycle costs in 95.4% of the homes analyzed (39 of the 40 oil-

[26] Conversations with several manufacturers; names and details are confidential.

[27] Another option is to replace the baseboard heaters with units designed for lower distribution water temperatures.

heated homes and 106 of the 112 gas-heated homes). We do not include propane boilers as there are only nine such homes in the RECS data set.[28]



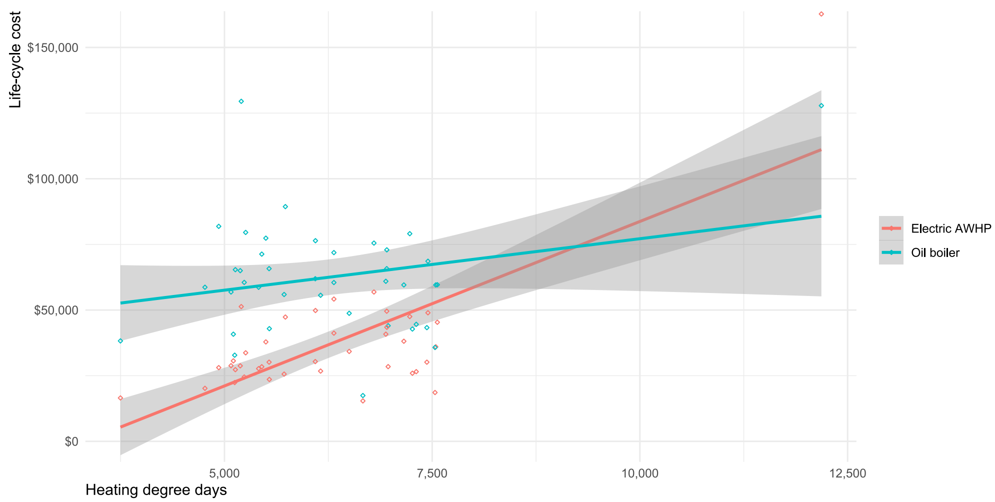


Figure 8. Comparison of electric water-to-air heat pump with condensing gas hot-water boiler (top) and high-efficiency oil hot-water boiler (bottom) for single-family homes, using medium-cost assumptions. Costs are in 2020$.[29]

[28] For this analysis, we used the same 18-year equipment life that we used for furnaces to make comparisons easier. According to ASHRAE (2019), the average life of a boiler is 24–25 years.

[29] Single-family gas boilers and their replacements, air-to-water heat pumps, had higher correlations (R^2=.282, R^2=.579, respectively) than we found above for gas furnaces and their replacements.

Figure 9 shows the results of our steam analysis: electric mini-split heat pumps on average have lower life-cycle costs than steam boilers. Across both fuels, electric heat pumps have lower life-cycle costs in 95.3% of the homes analyzed (100% of the oil boilers and 94.3% of the gas boilers).

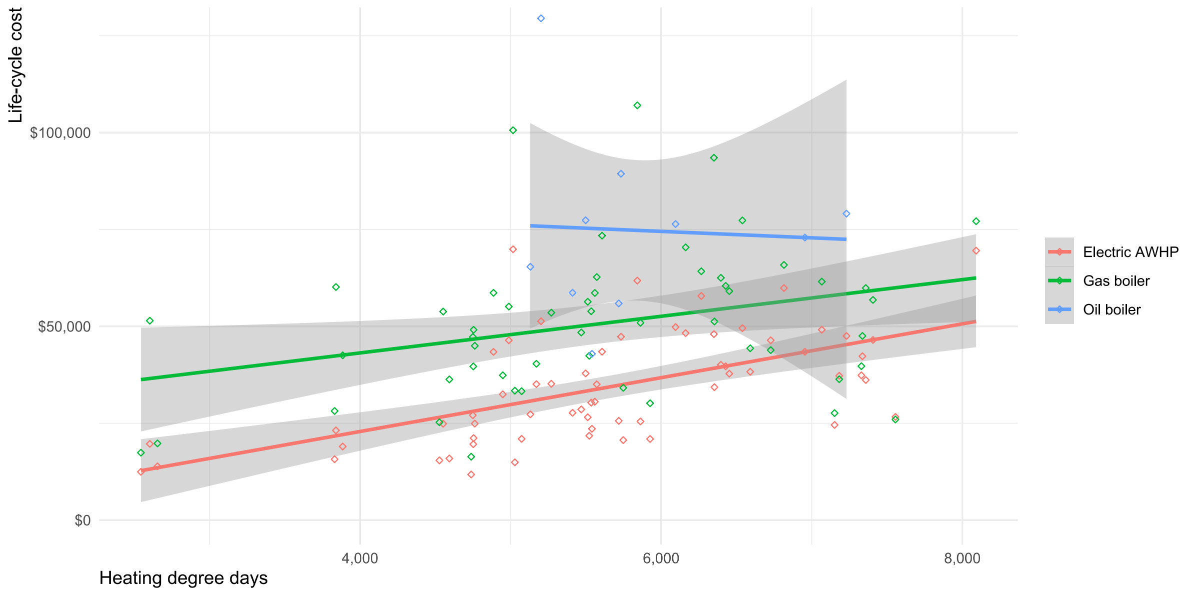


Figure 9. Comparison of electric ductless air-to-air heat pumps with high-efficiency gas and oil steam boilers for single-family homes, using medium-cost assumptions. Because only 10 oil-heated homes were included, the oil line shown is highly approximate. The oil boiler line declines because that is the best-fit line for the 10 sampled homes. We suspect that the homes in the colder climates are more efficient (e.g., more insulated), allowing them to have lower life-cycle costs on average despite the colder climate.

Hybrid Heating Systems

Instead of using either an electric heat pump or a fuel-based system, some homes use both an electric heat pump and a high-efficiency fuel backup system. This arrangement is often called a *hybrid heating system*. Under such an arrangement, the electric heat pump provides most of the heat throughout the full heating season, but the backup system functions when the heat pump cannot provide adequate heat during the coldest outdoor temperatures. This arrangement increases total system costs (a combined system is more expensive than either an electric heat pump or a fuel-based system), but it reduces operating costs because once temperatures dip below the point where heat pumps can provide adequate heat, heat pump systems typically turn on electric resistance coils, which is an expensive form of heat.

Another issue is that if there is extensive use of electric resistance heat, winter peak electric demand increases, which can substantially increase electricity costs. For example, a study in Minnesota estimates future residential electricity prices to average about $0.25/kWh in a high-electrification scenario but only about $0.20/kWh in an electrification plus gas backup scenario (GPI and CEE 2021). The specific impacts on power needs will vary locally. Therefore, a national-level analysis such as ours can offer only an approximate take on these issues.

For our analysis, we looked at systems that combine an electric heat pump with a fuel backup for use in cold climates. We looked at these systems for locations where the outside temperatures go below 5°F for more than 3% of the heating season. This equates to roughly 6,000 annual HDDs, which is approximately the climate in Detroit. The choice of 5°F is driven by technical and peak demand considerations. Cold-climate heat pumps can provide adequate heat down to this temperature, but at lower temperatures the amount of heat provided may not be adequate and a backup heat source may be needed.[30] We did not conduct an economic analysis on whether hybrid systems may be cost effective at somewhat higher temperatures as such an analysis requires more detailed data on utility-specific rates and avoided costs and local temperature profiles (e.g., bin hour data) than we have for the homes in the RECS data set. However, in a Maryland study (Maryland Commission on Climate Change 2021), E3 found that hybrid systems may make sense in some locations with approximately 4,500 HDDs, but the study looked at conventional rather than cold-climate heat pumps. On the other hand, as cold-climate heat pumps improve, they may be able to provide adequate heat down to 0°F or even lower.

The hybrid system includes higher costs than the medium-cost assumptions used in our primary analysis for electric-only and gas-only systems, but we assumed the hybrid system reduces the winter peak multiplier by half (e.g., for Minnesota, instead of a 1.32 multiplier for the impact of winter peaks on electricity prices we used a 1.16 multiplier). This multiplier applies only in locations above 4,000 HDDs; in warmer climates, summer peaks are often higher than winter peaks, even with substantial use of electric heat. For the hybrid case, we also increased the heat pump seasonal efficiency by 13% because electric resistance backup heat is no longer required when temperatures dip below about 5°F (when electric resistance heat is used, this lowers the seasonal coefficient of performance (COP) of the system. The 13% comes from an analysis of hybrid systems in Minnesota; GPI and CEE 2021). Our hybrid system results are summarized in figures 10 (for natural gas), 11 (for propane), and 12 (for oil). For example, figure 10 is the same as figure 5, except we add the hybrid line. As the figure shows, under these assumptions, the hybrid system has lower life-cycle costs, despite the higher initial equipment costs. These results are consistent with the results from the Minnesota and Massachusetts studies referenced above (GPI and CEE 2021; E3 2022).

[30] We chose 5°F because under the DOE Cold Climate Heat Pump Challenge, manufacturers are aiming to provide full heat output down to 5°F. It might be possible to calculate optimal switchover temperatures for each individual home, but that would require dynamic modeling of heat pump performance, which we were not set up to do. Future projects could explore this topic.

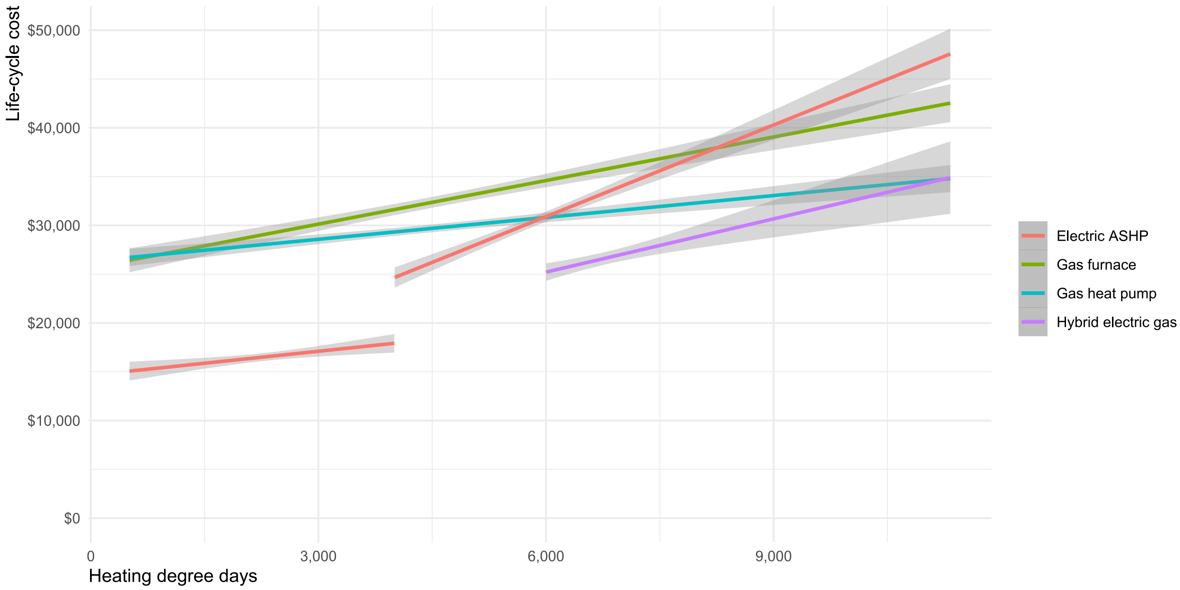


Figure 10. Life-cycle cost best-fit lines for electric heat pumps, condensing gas furnaces, gas heat pumps, and hybrid electric heat pump/condensing gas furnace systems for single-family homes now heated with natural gas. The gap in the electric heat pump line shows the impact of costs for cold-climate heat pumps for locations with 4,000 HDDs or more. Costs are in 2020$.

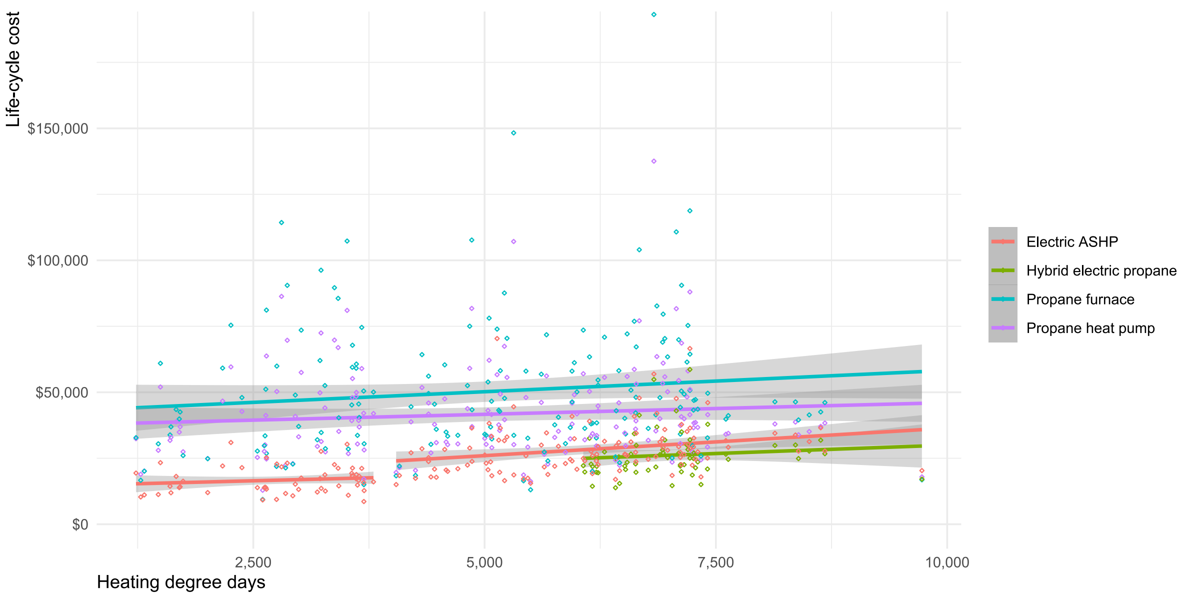


Figure 11. Life-cycle cost best-fit lines for electric heat pumps, condensing propane furnaces, hybrid electric heat pump/condensing propane furnace systems for single-family homes now heated with propane. Costs are in 2020$.

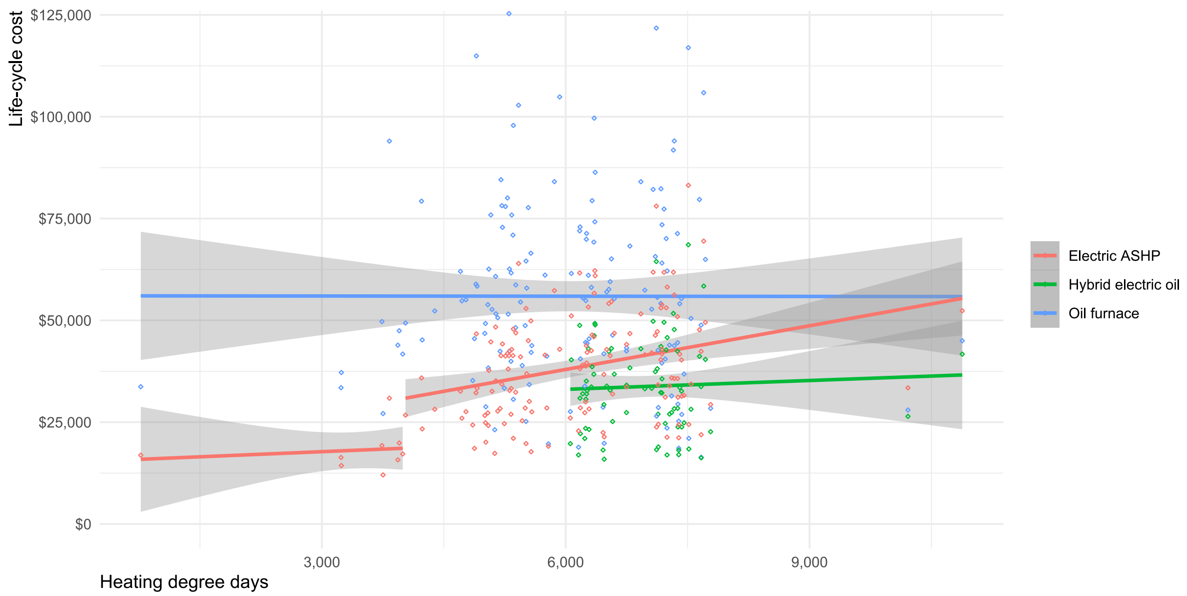


Figure 12. Life-cycle cost best-fit lines for electric heat pumps, high-efficiency oil furnaces, and hybrid electric heat pump/oil furnace systems for single-family homes now heated with oil. Costs are in 2020$.

Energy Efficiency Packages

For our analysis on heating and cooling costs, we also considered a variety of options for improving the energy efficiency of homes to reduce heating and cooling loads and allow modest system downsizing with resulting cost savings. We looked at two levels of retrofits: moderate retrofits and deep retrofits. Moderate retrofits are based on the DOE Home Performance with ENERGY STAR program that has been averaging 25% energy savings at a cost of about $6,000 per home. These retrofits typically include air and duct sealing, insulation upgrades, and lighting improvements, and sometimes a new heating or cooling system. Deep retrofits reduce energy use an average of 60% at a cost of nearly $50,000 per home when including replacement of space conditioning and water heating systems and about $40,000 when we exclude the cost of these equipment replacements to avoid double-counting these costs. These retrofits typically include extensive insulation and air sealing as well as new heating and cooling systems, windows, and other equipment. For deep retrofits, we looked at an energy retrofit on its own, as well as at the time of a major home renovation, which reduces the incremental cost of the deep retrofit by roughly half (Appendix A has details on all these cases). In colder climates, energy efficiency retrofits reduce winter peaks and winter peak costs (e.g., see Hopkins, Takahashi, and Nadel 2020 and GPI and CEE 2021). To model this, we reduced the multiplier for increased winter peak electricity costs by half. This multiplier applies only in locations above 4,000 HDDs. Finally, energy efficiency generally has a better return on investment in homes with higher pre-retrofit energy bills (Less and Walker 2015). We looked at cases in which the energy efficiency packages are applied to all homes and to cases where energy efficiency is applied only to homes with above average heating plus cooling bills.

Impact of Energy Efficiency Packages on Relative Economics of Different Heating Systems

First, we looked at how the efficiency packages affect the life-cycle cost of different heating systems, as shown in figure 13. On the left are best-fit lines without any efficiency, repeating what is shown in figure 10. With the moderate efficiency package (in the middle), the condensing gas furnace line moves closer to the electric heat pump line, but life-cycle costs are still generally lower for electric heat pumps below 6,000 HDDs and lower for hybrid systems in colder climates (above 6,000 HDDs).

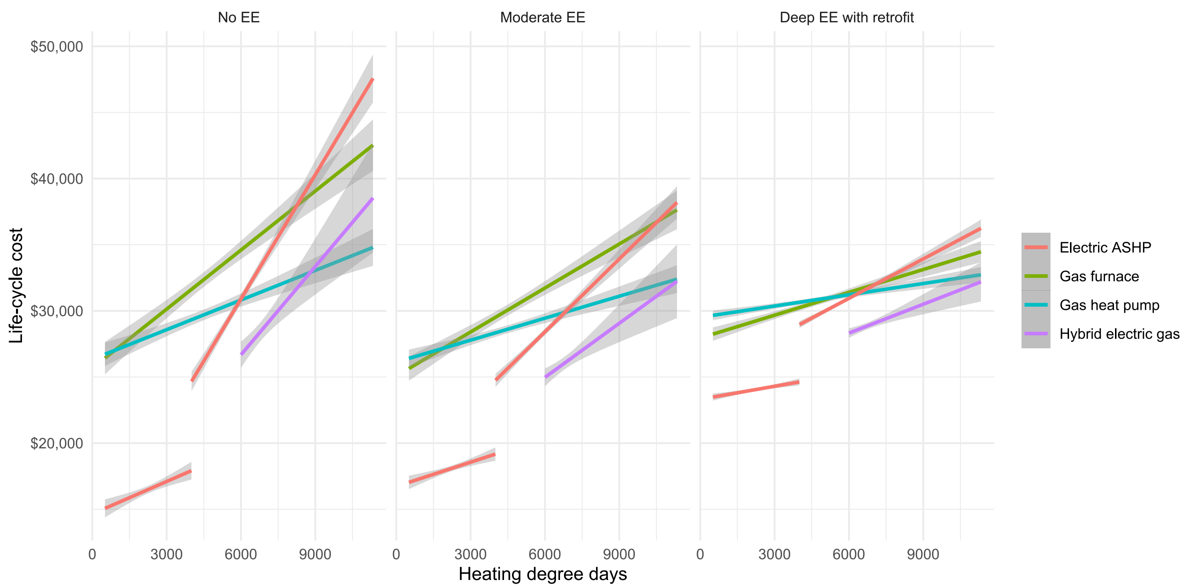


Figure 13. Best-fit lines combining efficiency packages with several different types of heating systems using medium-cost assumptions. Costs are in 2020$.

Impact of Energy Efficiency on Life-Cycle Cost by System Type

Next, we looked at the economics of our efficiency packages separately for each type of heating system. We begin with electric heat pumps using our medium energy price assumptions; figure 14 shows the results. This and subsequent figures have two sets of best-fit lines: one set with all homes, and the other for homes with heating and cooling energy bills above the median in our data sets. For electric heat pumps, the moderate efficiency package on average reduces life-cycle costs above approximately 4,100 HDDs. A deep retrofit package at the time of home renovation often makes sense for homes with above average energy use in climates above approximately 6,500 HDDs (e.g., in Michigan and Minnesota).

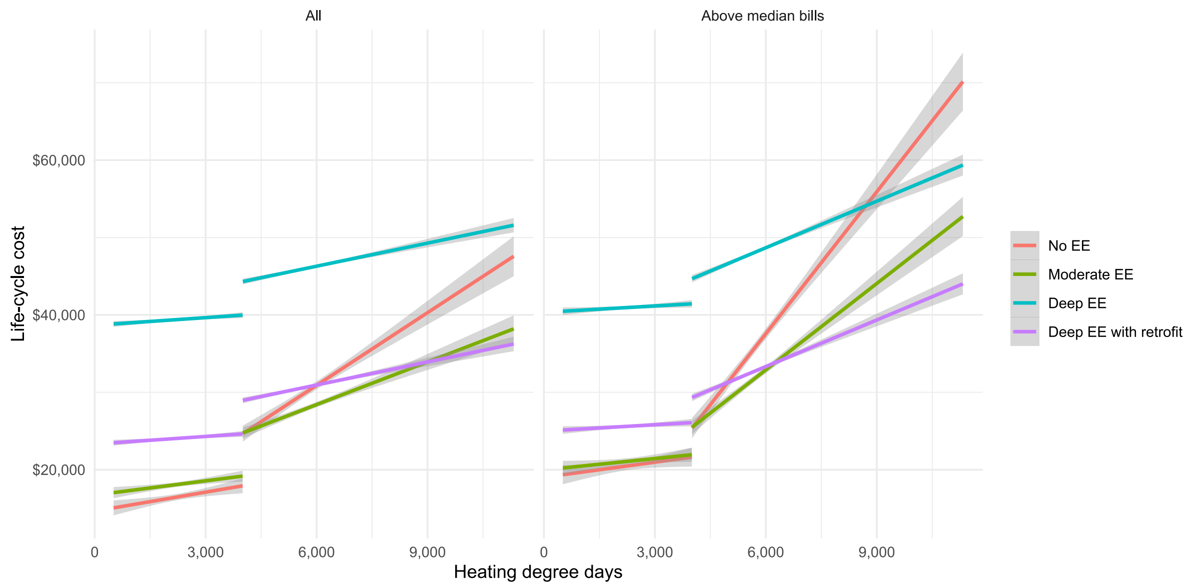


Figure 14. Impact of energy efficiency packages on life-cycle costs for electric heat pumps. Best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions. Costs are in 2020$.

It should be noted that this analysis includes only direct capital and energy costs (heating and cooling) to the homeowner. Additional benefits of energy efficiency such as reduced health costs and improved comfort are not included.[31] Although these other benefits can increase the benefits of energy efficiency by a factor of two or more (Skumatz 2016), they are not shown in these graphs.

Furthermore, energy efficiency can reduce both winter and summer peaks, reducing the impact of electrification on energy bills. Our analysis looks at the impact of these savings on home heating and cooling costs for individual homes, but it does not include the impact of these electricity price changes on other energy uses in these or other homes, such as those that already use electric heat. We return to this issue later in the "Extrapolating to the Entire Housing Stock" section.

As figure 15 shows, for condensing gas furnaces, the moderate efficiency package reduces life-cycle costs on average for most homes. The deep efficiency package, when done at the time of building renovation, may lower life-cycle costs for (1) the average home above approximately 5,000 HDDs and (2) homes with above-average bills regardless of HDDs.

[31] Poorly weatherized homes are more likely to have moisture, mold, insects, and other problems that can trigger health problems such as asthma attacks (e.g., see Hayes and Kubes 2020; Hayes and Densen 2019).

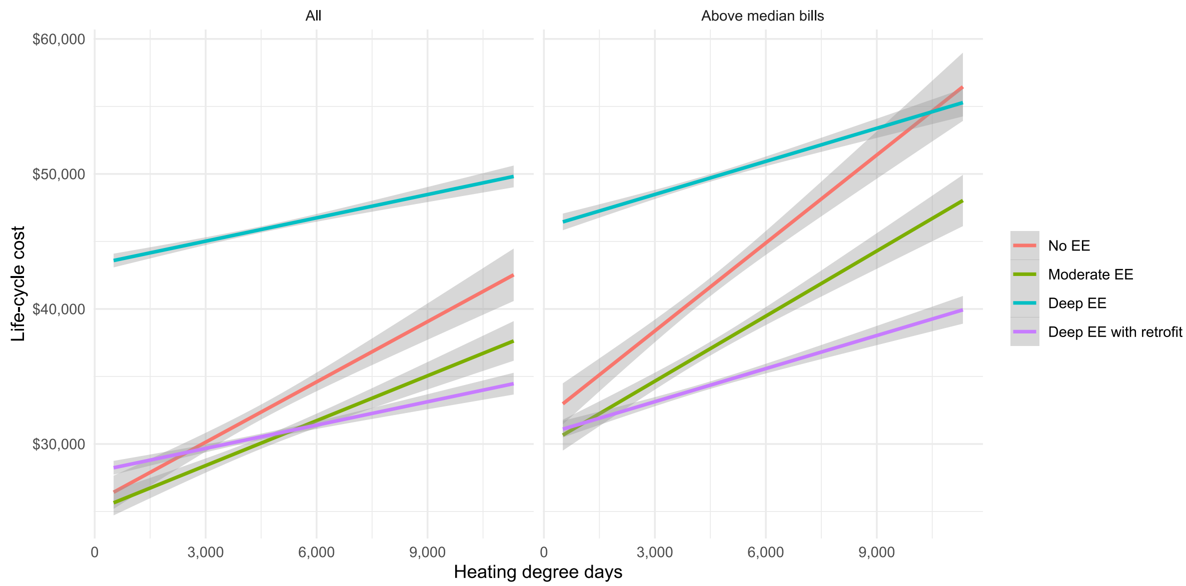


Figure 15. Impact of energy efficiency packages on life-cycle costs for condensing gas furnaces. Best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions in 2020$.

Finally, figure 16 looks at energy efficiency in homes with hybrid systems that combine an electric heat pump with a gas backup. In such cases, we find that the moderate efficiency package often reduces life-cycle costs and that the deep-retrofit package can reduce costs for homes with above-median bills in climates above about 7,000 HDDs.

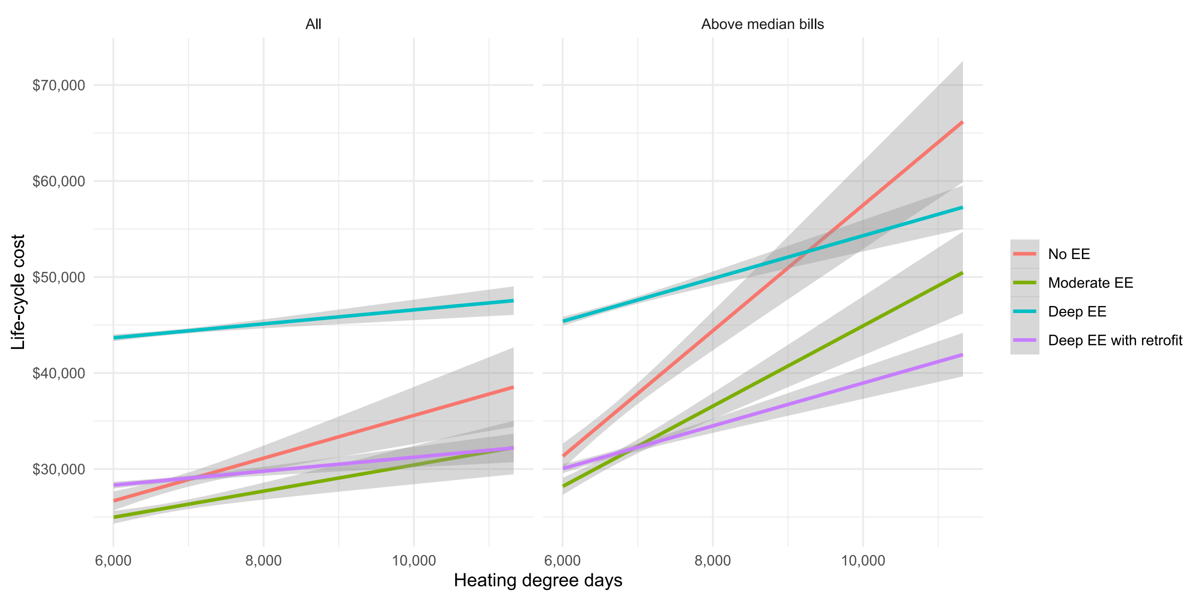


Figure 16. Impact of energy efficiency packages on life-cycle costs for hybrid systems combining electric heat pumps with a gas backup furnace. Best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions in 2020$.

In addition to these three system types, we also examined other system types, including oil and propane furnaces and boilers and gas heat pumps and boilers. These results are presented in Appendix B. In general, they show that moderate efficiency lowers life-cycle costs in most homes and that deep retrofits at the time of building renovation will often lower life-cycle costs, particularly in homes with oil and propane heat, homes with above-average energy use, and homes in cold climates.

Delivering Alternative Fuels to Homes

A big issue is deciding which strategies should be used to deliver alternative fuels to homes. If the fuel is approximately chemically the same as natural gas (e.g., biogas modified to resemble natural gas or synthetic natural gas) it can generally be transported to homes via the existing natural gas distribution system, assuming that the existing system is in good condition and does not need near-term replacement (some old systems will need replacement, which is usually expensive).

Biodiesel and bio-LPG, when treated to resemble heating oil and LPG, can also be distributed via existing fuel oil and LPG systems.

While hydrogen can be converted to synthetic natural gas (at a cost; see figure 2), another option is to directly pipe hydrogen to homes. This would require modifying burners to use pure hydrogen.[32] Some gas distribution pipes and welds could be embrittled with pure hydrogen, but other types of pipes may be able to perform safely (Melaina, Antonia, and Penev 2013). Little is presently known about these issues, but the National Renewable Energy Laboratory is leading a multiyear research initiative to test various piping materials for hydrogen compatibility and for the impact of hydrogen on material life (NREL 2020).

Another potential option might be to deliver compressed natural gas to homes either by delivering full cylinders or perhaps via a truck that would refill in situ tanks. This might be more feasible for use as a backup fuel that is filled a few times per year (at most) than as a primary heating source.

Two- to Four-Family Houses

We compared the energy use of single-family homes and units in two- to four-family buildings (not including what are sometimes called “single-family attached” homes) and found that they differed enough to merit a separate analysis. The RECS database has 132 apartments in two- to four-family buildings that now use fossil fuel heating, including 95 with gas furnaces and 25 with gas boilers. We analyzed only these two system types; sample

[32] Our analysis does not include the cost of such modifications.

sizes for the other system types are too limited for meaningful analysis. We used the same assumptions as for the single-family analysis, but energy use on average is lower due to the smaller unit size and common walls in two- to four-unit buildings.

Figure 17 shows results for gas furnaces. The results are roughly similar to figure 10 for single-family homes, except that the life-cycle costs are lower due to lower heating and cooling energy use, which reduces the difference in life-cycle costs between the different types of systems. On average, life-cycle costs are lowest for electric heat pumps below approximately 5,000 HDDs and are lowest for hybrid systems above 6,000 HDDs. Between 5,000 and 6,000 HDDs, life-cycle costs are similar for electric and the two gas options.

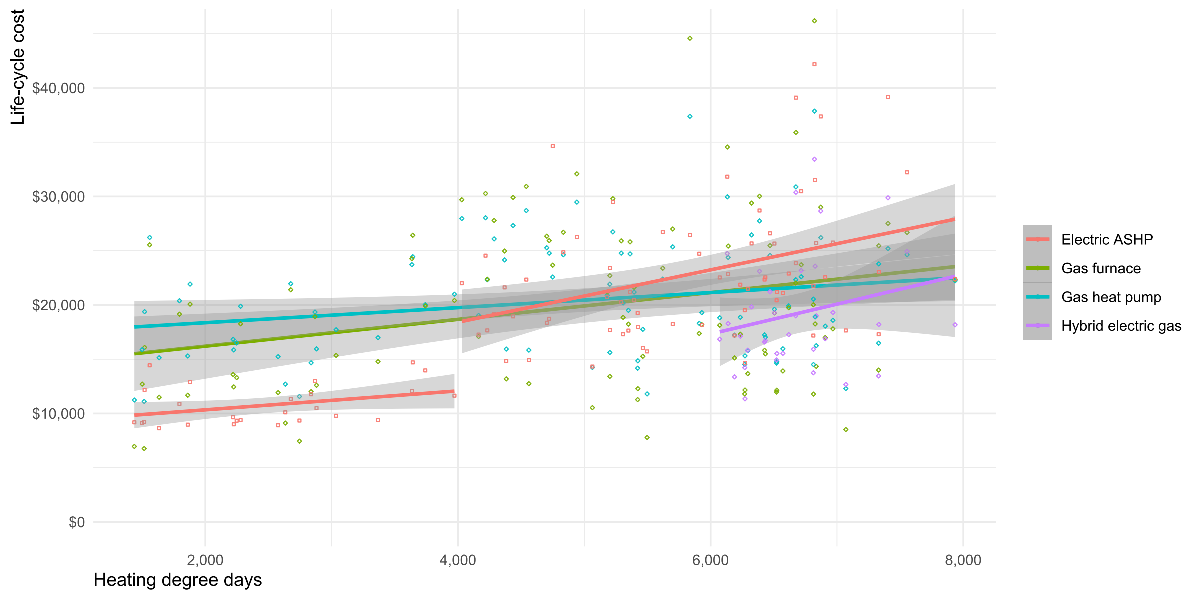


Figure 17. Life-cycle cost and best-fit lines for electric heat pumps, condensing gas furnaces, gas heat pumps, and hybrid systems for apartments in buildings with two to four units now heated with natural gas furnaces. The figures are based on medium-cost assumptions in 2020$.

Figure 18 summarizes our analysis of gas boilers, which finds that average life-cycle costs are lower for the air-to-water electric heat pump.

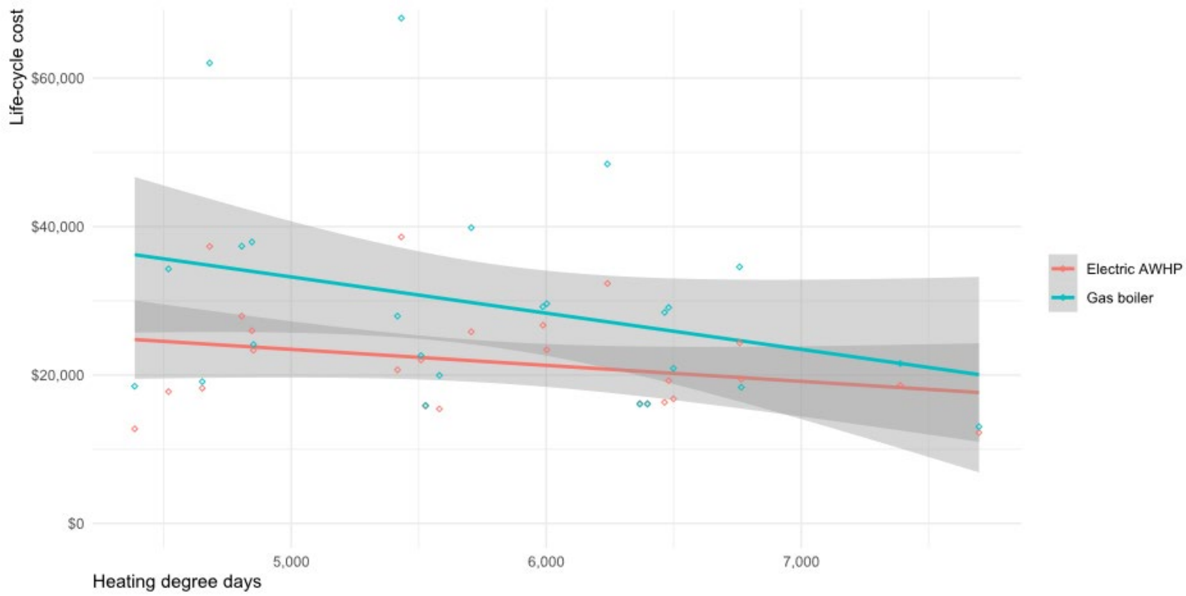


Figure 18. Life-cycle cost and best-fit lines for electric heat pumps and condensing gas boilers for apartments, using medium costs in buidings with two to four units. The sample size is small and the best-fit lines are not well determined. Figures are in 2020$. The lines decline because that is the best-fit line for these homes given the small sample size

MULTIFAMILY (FIVE OR MORE UNITS PER BUILDING)

For buildings with five or more units per building, RECS has data on 856 units (15% of the RECS data set). Of these units, 297 units are now heated with fossil fuels. We analyzed the two most common systems: gas furnaces (161 units) and gas boilers (107 units).

FURNACES

Gas furnaces generally serve individual units, with each unit having its own furnace. We used the same assumptions as for single-family homes. Figure 19 shows the results of our analysis, which are somewhat similar to our results for gas furnaces in two- to four-family houses. On average, life-cycle costs are lowest for electric heat pumps below 4,000 HDDs and are lowest for hybrid systems above 6,000 HDDs.

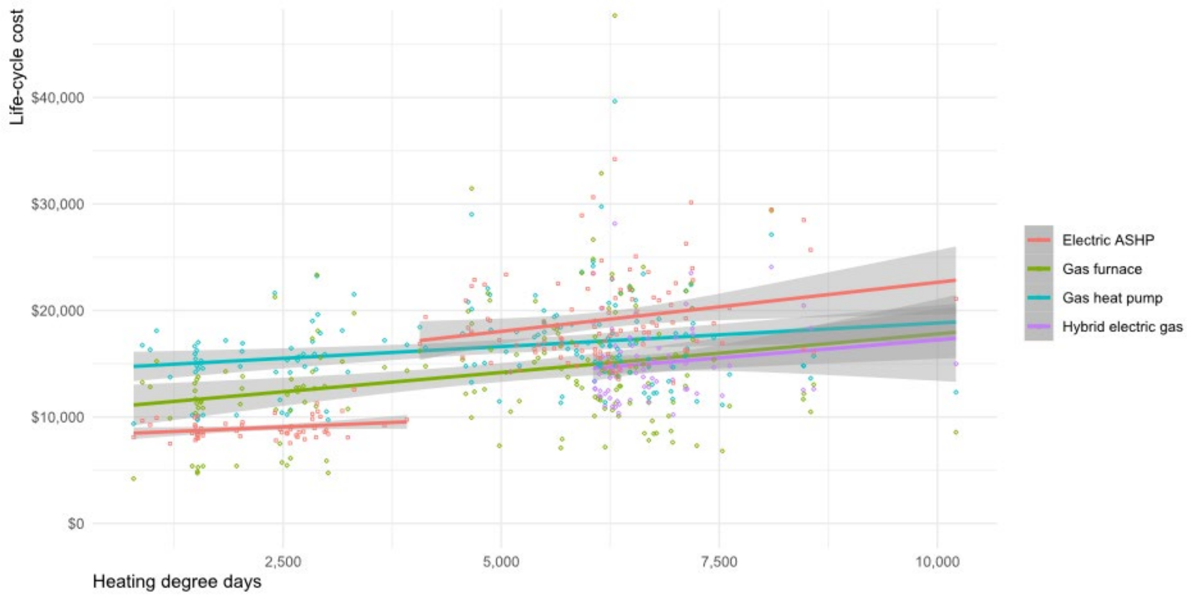


Figure 19. Life-cycle cost and best-fit lines for electric heat pumps, condensing gas furnaces, gas heat pumps, and hybrid systems for apartments in buildings with five or more units now heated with natural gas furnaces. The figures are based on medium-cost assumptions and are in 2020$.

BOILERS

Our multifamily boiler analysis is much cruder than the prior analyses due both to a smaller sample size and limited data on electrification costs. Given this, we consider this a preliminary analysis and recommend further analysis on a larger sample of buildings once more data become available on electrification costs and how these costs vary by building type. We also note that costs can vary by location; our cost data come from New York City, Chicago, and Massachusetts, three high-construction-cost locations.

RECS has data on 125 apartments heated with boilers in buildings with five or more units (see table 1). For central boiler systems, the only source of electrification costs we could find was an Urban Green (2020) study that examined the costs of electrification in 12 buildings in New York City.[33] That study estimated an average cost per apartment of $14,900 for buildings that could be heated using ductless mini-split units and $18,200 for buildings that could use central variable refrigerant flow (VRF) systems. RECS does not provide information on building height and size, so we had no way to estimate which buildings could use mini-splits and which would need VRF systems. Therefore, we examined all units in the data set for both system types. Because recent research indicates that VRF systems cost more for

[33] Costs are fairly similar for several projects in Chicago and Massachusetts.

New York City apartments than Urban Green had estimated, we increased those costs by 25% (this is a preliminary estimate but has not yet been published).

In considering electrification options for these buildings, it is important to note that apartments in these buildings are often smaller than single-family homes and have many shared walls, which reduces heat loss. As a result, energy use in these buildings is often modest. For the multifamily apartments in the RECS data set, 2015 annual energy expenditures for space heating averaged $160 per apartment for buildings heated with natural gas and $333 for buildings heated with oil.[34]

Given the high cost of electrification per apartment and low energy consumption per apartment, it is not surprising that electrification economics are challenging for these buildings. Figure 20 shows the life-cycle costs for the multifamily apartments served by boilers in the RECS data set using our medium-cost assumptions. As the figure shows, for 99.2% of apartments analyzed (i.e., all except one unit), a gas or oil system using alternative fuels has lower life-cycle costs than mini-split electric heat pumps, and much lower life-cycle costs than VRF systems. In this analysis, life-cycle costs are dominated by initial cost, with operating costs lower over the 18-year analysis period.

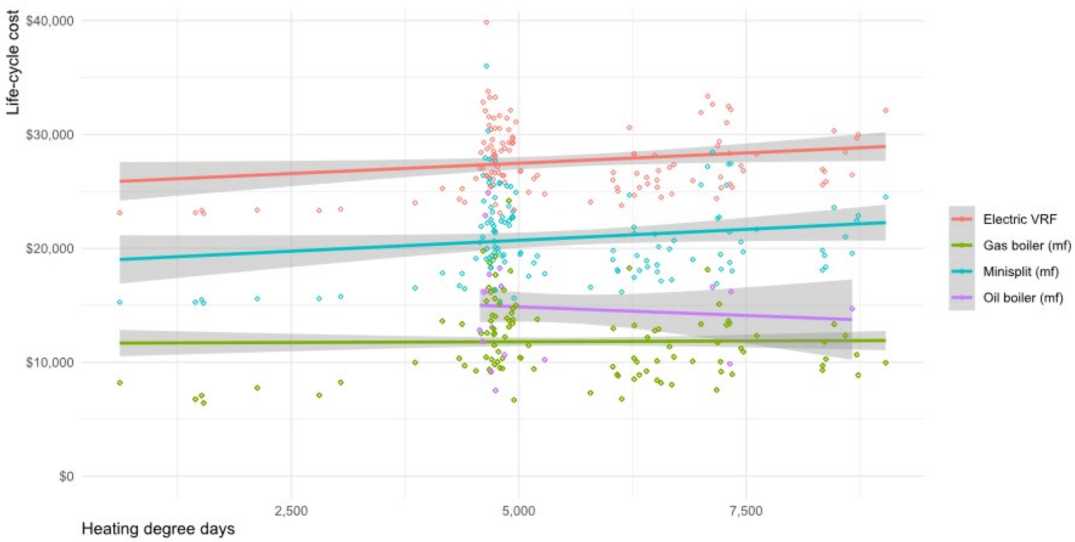


Figure 20. Life-cycle cost and best-fit lines for electric heat pumps (mini-split and VRF) and condensing gas boilers for apartments, using medium costs in buidings with five or more units. Costs are in 2020$.[35]

[34] ACEEE analysis of data in EIA building characteristic and expenditure tables (EIA 2018a).

[35] We found very low correlation between life-cycle costs and HDD for multifamily gas boilers (R^2=.013). Mini-splits in multifamily units had R^2=.201.

Because this analysis is very dependent on our system cost estimates, we also looked at the life-cycle cost economics using the low-cost estimates for electric heat pumps (25% lower than the primary estimates) while keeping the gas and oil boiler replacement costs the same as in the primary analysis. As figure 21 shows, electric heat pumps are somewhat closer to the gas and oil systems, but even still, 96.0% of the apartments examined have lower life-cycle costs using alternative fuels. We also conducted the same analysis using low fuel costs (not shown in any figure), and the results differed only slightly from what figure 20 shows.

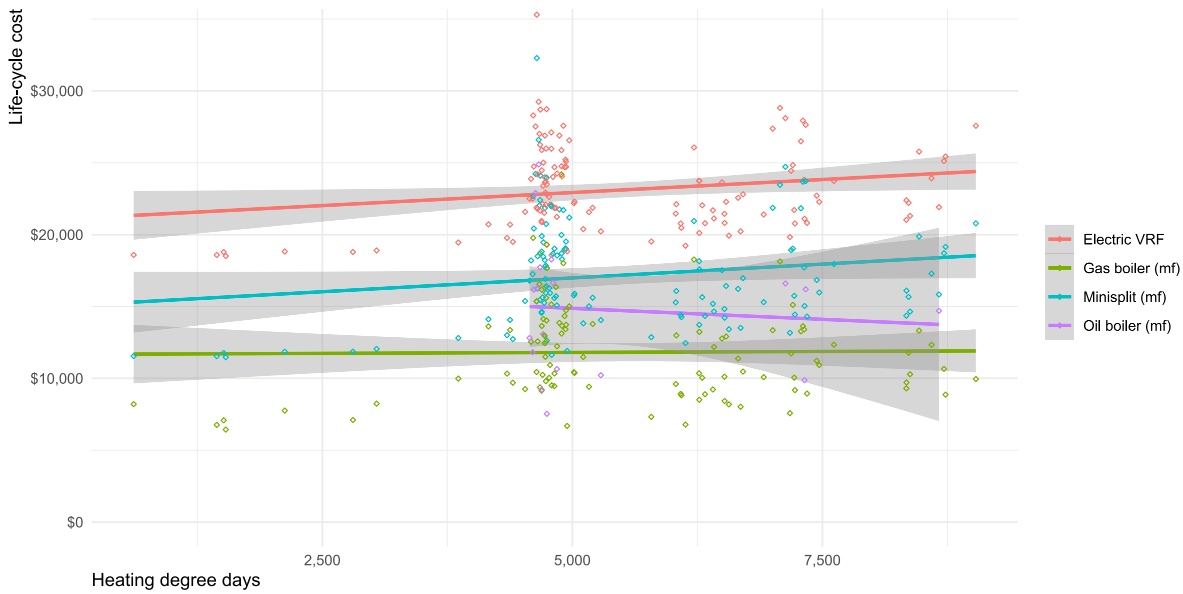


Figure 21. Life-cycle cost and best-fit lines for electric heat pumps (mini-split and VRF) and condensing gas boilers for apartments using low heat pump costs and medium energy costs in buidings with five or more units. Costs are in 2020$.

While these results are not favorable for electrification overall, there will likely be some exceptions to this trend. In Chicago, for example, Elevate has found that electrification often makes sense in local multifamily buildings because the fixed monthly charge for gas service is very high in Chicago, and avoiding that cost can save substantial money (A. Evens, executive director, Elevate Energy, pers. comm., April 12, 2022).

Finally, several reviewers noted that our costs for ductless mini-split heat pumps are much higher for multifamily than for single-family and asked what the impact would be if multifamily costs could be reduced to single-family levels. Figure 22 shows this analysis, which finds that with these lower mini-split costs, electric heat pumps will have similar life-cycle costs to gas boilers and lower costs than oil boilers. Relative to gas boilers, the electric heat pump has, on average, slightly lower life-cycle costs below approximately 5,000 HDDs and slightly higher life-cycle costs above 5,000 HDDs. Achieving single-family costs in multifamily buildings will be challenging, but it could be possible with large-scale installations and improved approaches to installing outdoor units on the exterior of multistory buildings.

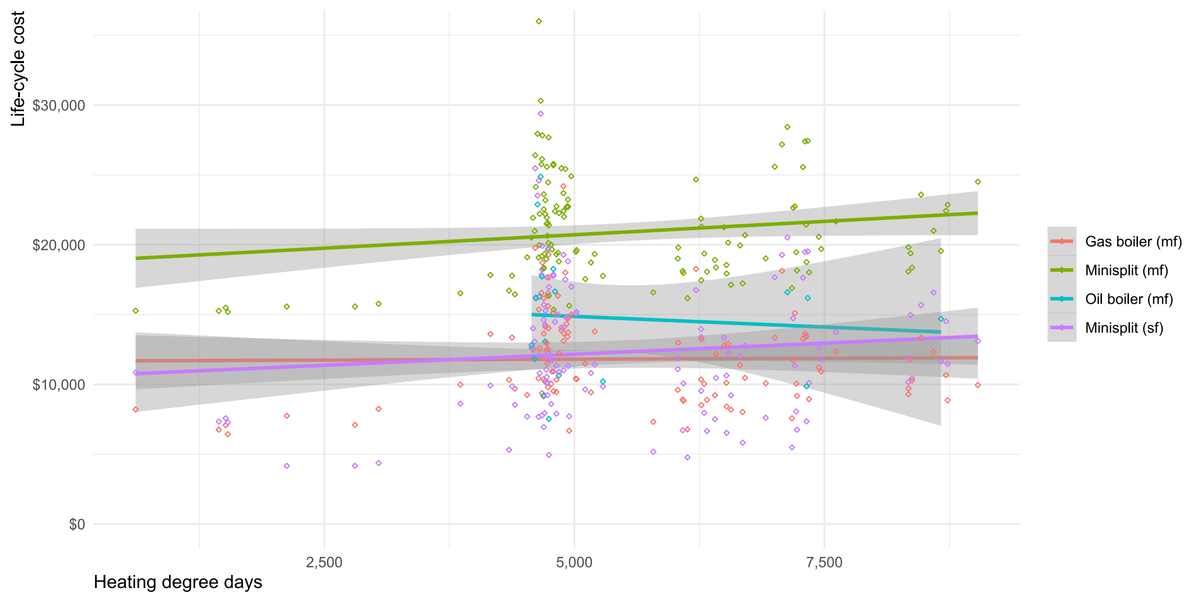


Figure 22. Life-cycle cost and best-fit lines for electric heat pumps (mini-split and VRF) and condensing gas boilers for apartments assuming the medium cost used in our single-family analysis can be achieved in buildings with five or more units. Costs are in 2020$.

ROLE OF ENERGY EFFICIENCY

We looked at a moderate efficiency package based on the Energy Savers program operated by Elevate in Chicago. Typical packages include roof insulation, air sealing, new properly sized boiler and controls, and lighting improvements. More than 11,000 units have received efficiency packages, at an average cost of about $2,200 per apartment (Farley and Ruch 2013), achieving an average of approximately 26% heating season energy savings (Navigant 2013). Most of the buildings in the Energy Savers program use boilers, so we applied these assumptions to the multifamily buildings heated with boilers in our data set. Figure 23 summarizes our results: On average, the moderate energy efficiency package lowers life-cycle costs in buildings with oil boilers; may or may not reduce life-cycle costs with gas boilers (the average with/without efficiency lines are very similar); and reduces life-cycle costs with electric mini-split heat pumps above approximately 5,000 HDDs. When we look at buildings with heating and cooling bills above our sample's median (see figure 24), the moderate efficiency package lowers life-cycle costs on average above approximately 4,750 HDDs for gas boilers and electric mini-splits (the sample size of oil boilers is too small to include).

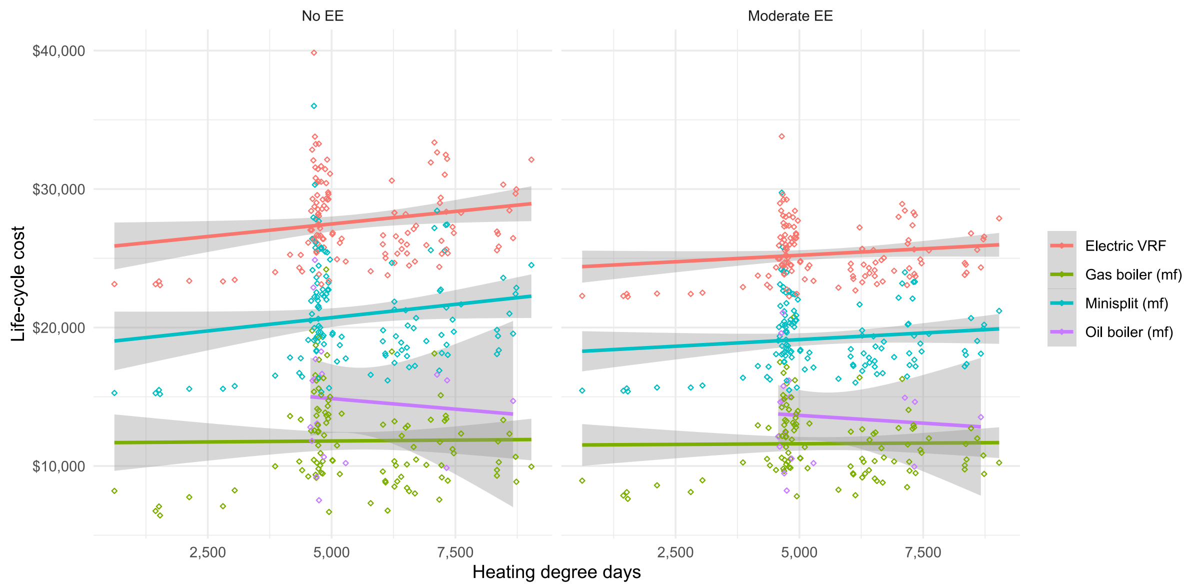


Figure 23. Impact of energy efficiency in all buildings with five or more units that are heated with boilers, using medium-cost assumptions. Costs are in 2020$.

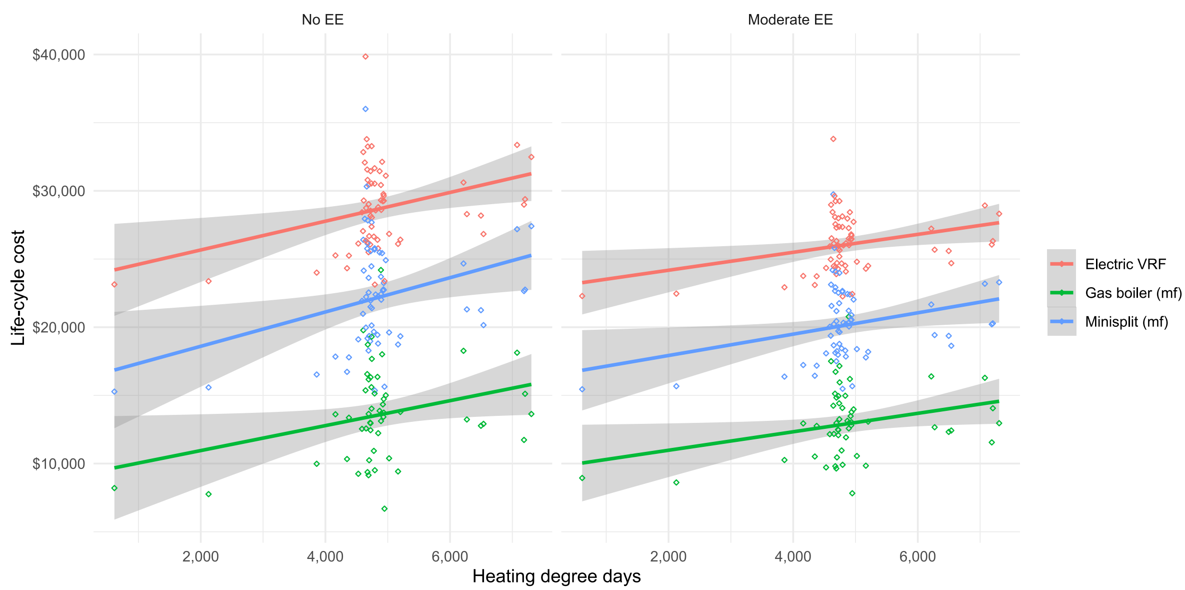


Figure 24. Impact of energy efficiency in multifamily buildings (five or more units per building) heated with boilers that have above-median heating and cooling costs. The figures use medium-cost assumptions. Costs are in 2020$.

We considered analyzing the cost effectiveness of deep retrofits at the time of building renovations, but costs vary widely depending on the building architecture, making it difficult to do a useful analysis.

Analysis of Combined Results

The preceding sections contain many analyses that distinguish between system types and as a function of HDDs. In this section, we combine all the analyses and look at overall trends by fuel, system type, building type, and geography. Specifically, for each of these groupings we look at the percentage of homes in which life-cycle cost is minimized for electric heat pumps, gas heat pumps, fuel-burning furnaces and boilers, and hybrid systems under our medium energy and equipment cost assumptions. Table 2 summarizes our analysis results for most variables, and table 3 summarizes our results for geography. In addition, tables 4 and 5 show a summary of our analysis results by income and building age.

Overall

Overall, life-cycle costs are minimized in our sample for 58% of homes with electric heat pumps and 23% of homes with hybrid systems that combine an electric heat pump with an alternative fuel backup for when temperatures fall below approximately 5° F. Gas heat pumps minimize life-cycle costs for 7% of homes, while other fuel systems minimize costs for 12% of homes.

By Building Type

Electric heat pumps minimize life-cycle costs in 63% of single-family homes and 53% of two- to four-family homes, but only 19% of apartments with five or more units. In the latter, life-cycle costs are minimized with high-efficiency furnaces or boilers in 69% of homes.[36] As noted earlier, in buildings with five or more units, electrification is expensive and energy use is generally too modest to justify this cost. Hybrid systems minimize life-cycle costs in 25% of single-family homes, 15% of two- to four-family homes, and 12% of apartments with five or more units.

By Fuel

For 97% of homes that presently heat with propane, life-cycle costs can be reduced by installing electric heat pumps (61% using only electric heat pumps and 37% using hybrid systems). For oil-heated homes, 84% can benefit from the switch (53% using only electric heat pumps and 38% using hybrid systems), while for natural gas, the total figure is 79% (58% using only electric and 21% hybrid). Of the homes with natural gas heat, gas heat pumps minimize life-cycle costs in 8% of homes, while the other 13% can minimize these costs with a condensing furnace or boiler.

[36] We examined gas heat pumps only for apartments with furnaces. Given the lower energy use of apartments, however, gas heat pumps were generally too expensive to compete, minimizing life-cycle costs in only 2% of the apartments we analyzed.

By System Type

The economics of electric heat pumps vary with system type. Electric heat pumps minimize life-cycle costs relative to propane and oil furnaces and to oil and gas steam boilers in more than 90% of homes in our sample. For propane and oil furnaces, this includes 37% and 57% of homes, respectively, that minimize life-cycle costs with hybrid systems. The figure for oil furnaces is higher as oil furnaces are more likely to be used in cold climates than propane furnaces. For gas furnaces, 59% of homes in our sample minimize life-cycle costs with electric heat pumps and 24% with hybrid systems. For oil hot-water boilers and gas hot-water boilers, 67% and 53% of homes, respectively, minimize life-cycle costs with electric heat pumps (we did not look at hybrid systems for these homes). For boilers, high-efficiency fuel-based equipment minimizes life-cycle costs in the remaining 33% and 47% of homes, respectively. For homes with gas furnaces, the percentage of homes that minimize life-cycle costs with gas heat pumps and condensing furnaces is the same: 9% of homes each.

Electric heat pumps are more cost effective in homes with central air-conditioning than in homes without central air-conditioning. Electric heat pumps and hybrid systems minimize life-cycle costs in 91% of the homes with central air-conditioning but in only 60% of homes without it. Costs of an electric heat pump are lower in the former because ducts are in place, electric capacity is often adequate, and electric heat pumps cost only a little more than a central air conditioner.

Table 2. Distribution of minimum life-cycle cost by type of home, system type, and presence of central air-conditioning

	Percentage of homes with minimum life-cycle cost			
Set of homes	Electric heat pump	Hybrid	Gas heat pump	Furnace or boiler
All homes with fuel furnaces and boilers	58%	23%	7%	12%
By type of home				
Single-family	63%	25%	8%	5%
2–4 units	53%	15%	8%	25%
5 units or more	19%	12%	0%	69%
By current heating fuel				
Natural gas	58%	21%	8%	13%
Oil	53%	38%	NA	9%

	Percentage of homes with minimum life-cycle cost			
Set of homes	Electric heat pump	Hybrid	Gas heat pump	Furnace or boiler
Propane	61%	37%	1%	2%
By system type				
Gas furnace	59%	24%	9%	9%
Propane furnace	61%	37%	1%	2%
Oil furnace	47%	53%	NA	0%
Gas hot-water boiler	53%	NA	NA	47%
Oil hot-water boiler	67%	NA	NA	33%
Gas steam boiler	94%	NA	NA	6%
Oil steam boiler	100%	NA	NA	0%
Central air-conditioning?				
Yes	67%	25%	6%	3%
No	29%	30%	15%	25%

The highest percentage in each row is shaded; darker shading indicates that the percentage is over 80%.

Regional Patterns

The percentage of homes in which electric heat pumps minimize life-cycle costs vary by region, ranging from more than 90% in the South Atlantic and South Central regions (the band from Maryland through to Texas) to only 23% in the East North Central region (bounded by Wisconsin, Michigan, Ohio, and Illinois) and 40% in the West North Central region (bounded by the Dakotas, Minnesota, Missouri, and Kansas). In the latter two regions, hybrid systems minimize life-cycle costs in 49% and 34% of homes, respectively, while gas heat pumps minimize costs in 18% and 13%, respectively. In the Pacific (coastal states, including Alaska and Hawaii) and the Mountain South (Colorado, Utah, New Mexico, Nevada, and Arizona), electric heat pumps minimize life-cycle costs in 82–83% of the homes in our sample. In the Middle Atlantic (New York, New Jersey, and Pennsylvania), electric heat pumps minimize life-cycle costs in 57% of homes, hybrid systems in 13% of homes, and high-efficiency fuel systems (including gas heat pumps) in 30% of homes. In the Mountain North (Wyoming, Montana, and Idaho) and New England, hybrid systems minimize life-cycle costs in 48% and 58% of homes, respectively, followed by electric heat pumps in 31% and 30%, respectively. Table 3 and figure 25 provide more details.

Table 3. Distribution of minimum life-cycle cost by geographic region

	Percentage of homes with minimum life-cycle cost			
Census region	Electric heat pump	Hybrid	Gas heat pump	Furnace or boiler
East North Central	23%	49%	18%	11%
East South Central	98%	0%	0%	2%
Middle Atlantic	57%	13%	8%	22%
Mountain North	31%	48%	3%	18%
Mountain South	83%	3%	6%	8%
New England	30%	58%	3%	9%
Pacific	82%	3%	1%	14%
South Atlantic	96%	0%	0%	4%
West North Central	40%	34%	13%	13%
West South Central	96%	0%	0%	4%

The highest percentage in each row is shaded; darker shading indicates that the percentage is over 80%.

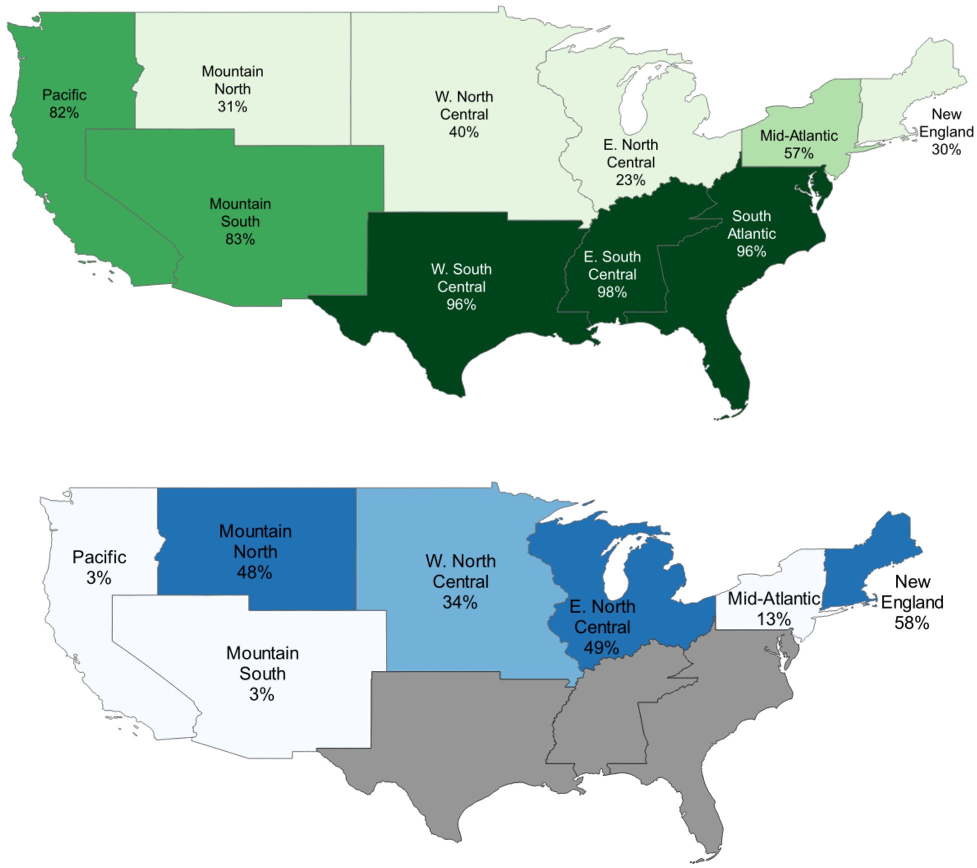


Figure 25. The distribution of minimum life-cycle cost by geographic region. The upper map shows the proportion of homes in which electric heat pumps minimize life-cycle costs. The lower map shows the percentage of homes in which hybrid systems minimize life-cycle costs; regions shaded in gray had no hybrid systems. In both maps, darker shading indicates higher percentages.

HOUSEHOLD INCOME

Table 4 summarizes our results by household income. In general, as income rises, so too does the percentage of homes in which electric heat pumps have the lowest life-cycle costs. Major drivers of this pattern include the higher proportion of single-family homes and homes with central air-conditioning among higher-income households.

Table 4. Distribution of minimum life-cycle cost by household income

	Percentage of homes with minimum life-cycle cost			
Household income	Electric heat pump	Hybrid	Gas heat pump	Furnace or boiler
Under $60,000	50%	24%	8%	19%
$60,001–119,999	59%	25%	7%	9%
$120,000 and up	68%	18%	7%	6%

The highest percentage in each row is shaded.

Building Age, Including New Construction

On average, electric heat pumps are more likely to minimize life-cycle costs in newer homes than older homes; this percentage ranges from 52% for pre-1970 homes (e.g., prior to the 1973 OPEC [Organization of Petroleum Exporting Counties] oil embargo) to 64% for homes built since 2000. We also added a scenario in which the energy efficiency of homes built in the past 15 years is improved by 15%, approximately representing improvements in building codes since 2015. These results are very similar to those for homes built 2000–2015.

Table 5. Distribution of minimum life-cycle cost by building age

	Percentage of homes with minimum life-cycle cost			
Set of homes	Electric heat pump	Hybrid	Gas heat pump	Furnace or boiler
Pre-1970	52%	25%	9%	14%
1970–1999	62%	22%	6%	11%
2000–2015	64%	24%	5%	6%
2000–2015 (15% less energy use)	63%	25%	3%	9%

The highest percentage in each row is shaded.

WATER HEATING

We evaluated the life-cycle cost of water heating for one- to four-family homes not presently using electricity for water heating. For these calculations, we assumed a water heater life of 13 years. This analysis uses the current type of water heater (storage or tankless) as the base system.[37] Appendix A summarizes other assumptions. Figure 26 summarizes the national-level results. Across the many homes analyzed, electric HPWHs have the lowest life-cycle cost, followed by gas HPWHs. Life-cycle costs are highest for oil and propane tankless and tank-type water heaters, with gas tankless and tank-type water heaters falling in-between gas heat pump and propane HPWHs.

Of the homes we analyzed from the RECS database, electric HPWHs had the lowest life-cycle cost in 100% of cases. For homes with gas water heaters, gas HPWHs have the next lowest life-cycle cost for all but two homes. Gas tankless is third best for approximately 62% of homes with gas storage water heaters and for 94% of homes with propane storage water heaters.

Our results showed no regional or building type variation; in all cases, life-cycle costs are lower with electric HPWHs. Gas HPWHs are second lowest on life-cycle costs for all but three homes, in which gas storage has lower costs.

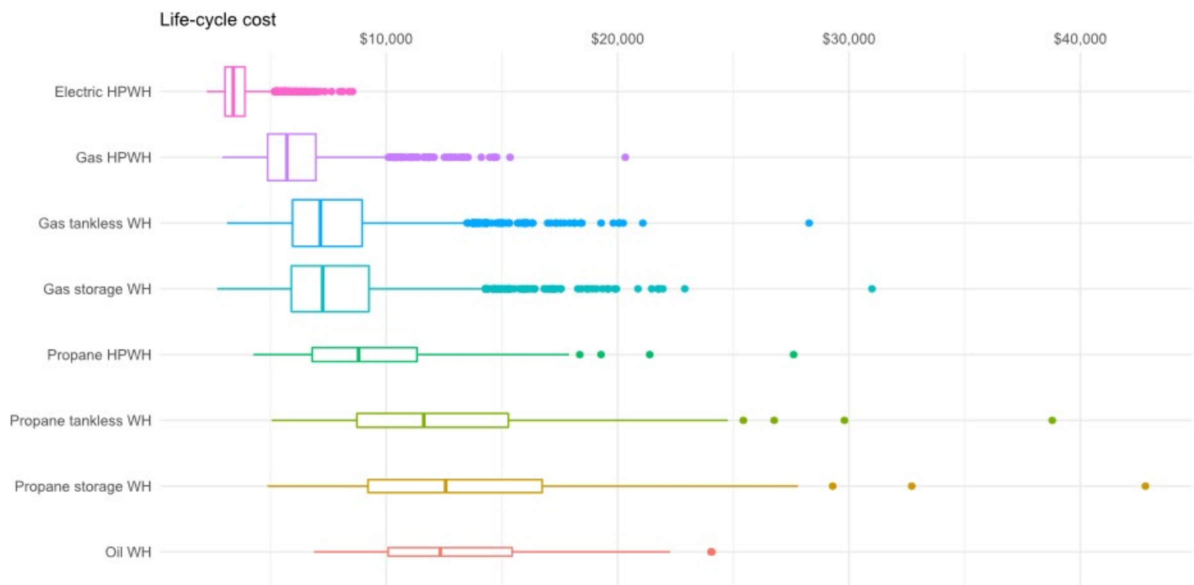


Figure 26. Life-cycle costs for water heating by system type. The lines in the middle of the boxes are the medians, the boxes show the upper and lower quartiles, the whiskers off the boxes show the most extreme data points within 1.5 times the length of the interquartile range, and the dots are individual outliers. Costs are in 2020$.

[37] Some buildings—particularly multifamily buildings—get their hot water from boilers, either the same boiler used for space heating or (in many multifamily buildings) a boiler dedicated to providing service hot water. A 2021 ACEEE study examines electrification options and economics for multifamily hot water (Perry, Khanolkar, and Bastian 2021).

SUMMARY OF ANALYSIS RESULTS

Among the decarbonization options we analyzed, our results show that life-cycle costs are generally lowest for electric heat pumps in one- to four-unit homes below approximately 6,000 HDDs under our medium-cost assumptions. Above 6,000 HDDs, hybrid systems have the lowest life-cycle costs on average under our analytical assumptions. In these colder climates, hybrid systems will reduce winter peak loads caused by use of electric resistance heat at very cold temperatures. This last result is based on an estimate that even with cold-climate heat pumps, supplemental heat will be needed when outdoor temperatures drop below 5°F.

If we use low prices for fuel and medium prices for electricity, electric heat pumps will minimize life-cycle costs below approximately 6,000 HDDs; if we use low prices for fuel and high prices for electricity, electric heat pumps will minimize life-cycle costs below approximately 5,000 HDDs.

These results all assume use of cold-climate heat pumps in locations with 4,000 HDDs or more. Presently, such heat pumps are being promoted in New England and the interior Northwest. Our analysis suggests that we need to popularize cold-climate heat pumps farther south to constrain growth in winter peak demand, and thereby to constrain growth in the price of electricity needed to serve peak demand.

Energy efficiency often reduces life-cycle costs. For many homes, the moderate energy efficiency package (based on Home Performance with ENERGY STAR) has the lowest life-cycle costs. For some system types, however, a deep retrofit at the time of building renovation will often reduce life-cycle costs, particularly in homes with oil or propane heat or above-average energy use, or with homes in cold climates.

Our analysis of apartments in two- to four-unit buildings finds generally the same results as for single-family homes, although energy use is typically less, as are the differences in life-cycle costs between options.

Our analysis of multifamily buildings finds that average life-cycle costs for units using gas furnaces are lowest for electric heat pumps below 4,000 HDDs and lowest for hybrid systems above 6,000 HDDs. Between 4,000 and 6,000 HDDs, life-cycle costs are lowest for condensing gas furnaces due to the higher costs we estimate for cold-climate heat pumps which are used above 4,000 HDD.

For units served by central boilers, use of alternative fuels typically has the lowest life-cycle costs. Electrification of these apartments is expensive, and since energy needs are generally modest, it is often hard to recoup the cost of these investments.

For water heating, electric HPWHs on average have the lowest life-cycle costs, followed by gas HPWHs and gas condensing tankless water heaters. There are no significant differences by geography and building type.

Extrapolating to the Entire National Housing Stock

RECS was designed to be a representative sample of the U.S. housing stock. The EIA provides a weighting factor for each home so that estimates for the entire housing stock can be made. In this section, we use these weighting factors to extrapolate to the entire U.S. housing stock. We look at eight scenarios, each of which builds on the prior scenarios. The scenarios are as follows:

1. All homes now using fossil fuels for space and water heating switch to alternative fuels using gas heat pumps where feasible.
2. All homes now using fossil fuels for space and water heating switch to electric heat pumps.
3. Same as #2, but homes with electric heat are also upgraded to high-efficiency electric heat pumps.
4. Same as #3, except buildings with five or more units use alternative fuels and not heat pumps.
5. Same as #4, except homes in buildings with one to four units use hybrid systems above 6,000 HDDs.
6. Same as #5, but moderate energy efficiency is added above 4,000 HDDs.
7. Same as #6, but moderate energy efficiency is added below 4,000 HDDs for homes with energy bills above the median.
8. Same as #7, but with the further assumption that energy efficiency reduces electric rates 4% relative to business as usual.

Figure 27 illustrates these scenarios graphically.

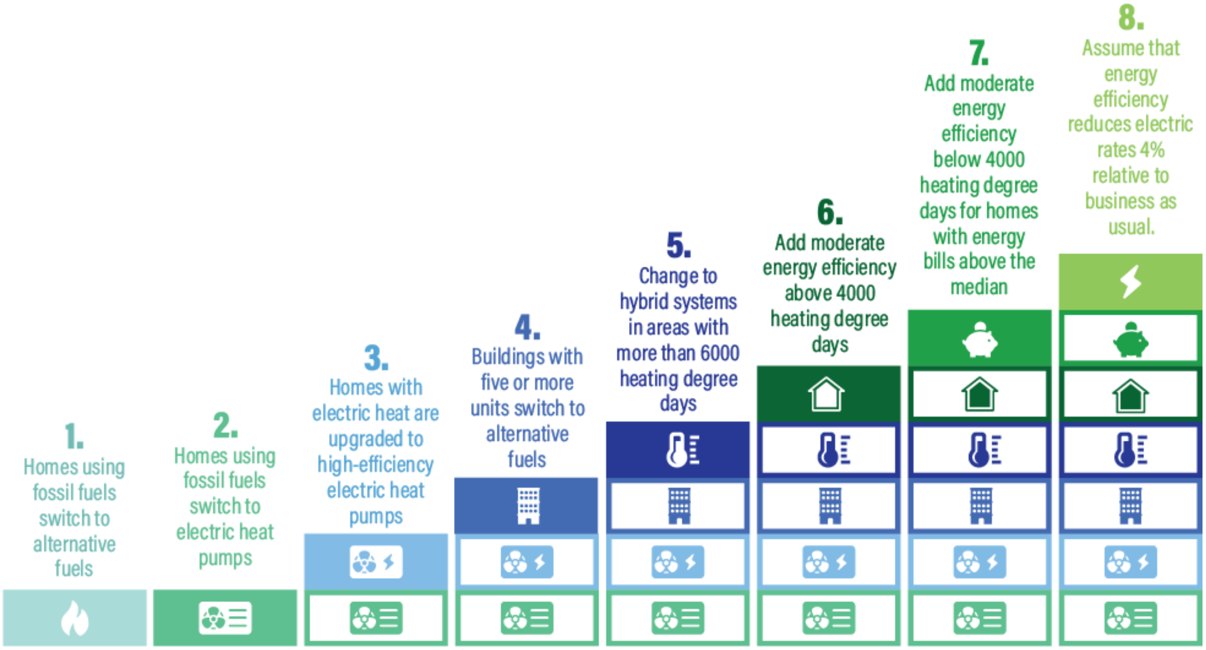


Figure 27. Schematic illustration of scenarios. The height of each box is illustrative and does not reflect the amount each additional box decreases or increases life-cycle costs.

These scenarios build on our prior analyses. For example, in scenario 1, we include gas heat pumps as these on average reduce life-cycle costs relative to condensing gas furnaces. Scenario 4 reflects the fact that our main analysis found that life-cycle costs are generally lower for alternative fuels in multifamily buildings with central boiler systems. Scenario 5 reflects our findings on hybrid systems, while scenarios 6 and 7 reflect our findings on energy efficiency.

Two of these scenarios are entirely new. Scenario 3 includes replacing electric resistance heat and existing heat pumps with high-efficiency heat pumps. In this scenario, we replace electric resistance furnaces with ducted heat pumps and replace electric baseboard heaters with ductless heat pumps (one ductless unit for each 600 sq. ft. of living space). Scenario 8 is an illustrative scenario, reflecting the fact that while energy efficiency programs have costs, such costs are frequently less than the costs of needing to expand generation, transmission, and distribution to serve growing electric loads. The 4% figure we use in scenario 8 comes from an illustrative example by Relf and Baatz (2017) and is only indicative; this price difference will vary from utility to utility.[38]

In conducting our analysis, we include the assumptions and data from our prior analyses, using the medium-cost estimates. Our analysis includes equipment costs for space and water heating as well as electricity and fuel costs for space and water heating and for space cooling in homes that already have air-conditioning.[39] We conduct our analysis for an 18-year period and discount future costs using a 5% real discount rate.[40]

RESULTS

Figure 28 summarizes the results of our eight scenarios with our high-, medium-, and low-cost estimates. Life-cycle costs over our analysis period are in the trillions of dollars. Life-cycle costs are highest for scenario 1 (use of alternative fuels, no electrification) and lower for scenario 5 (shown in orange; it uses electric heat pumps with hybrid systems above 6,000 HDDs, with alternative fuels for buildings of five units and more). Scenario 6 (moderate energy efficiency above 4,000 HDDs) reduces life-cycle costs further. Scenario 8 (bottom) has the lowest life-cycle costs; it includes our moderate energy efficiency package for all homes and a modest rate discount for the role of energy efficiency in reducing power system costs. Scenario 3 includes homes with electric heat that are not included in scenario 2, hence the results of scenarios 1 and 3 cannot be directly compared.

[38] Relf and Baatz (2017) examine the results of capacity auctions in New England and the PJM region and use these findings to illustrate the impact on electric rates for one utility, finding a potential 4% impact on rates. PJM is an electric grid that originally served Pennsylvania, (New) Jersey, and Maryland but now serves multiple additional adjoining states.

[39] We also include air conditioner replacement costs in homes that presently have air conditioners and do not switch to heat pumps in order to include all relevant costs to compare to heat pumps. For homes currently without air-conditioning, we do not include cooling costs—even in homes that install heat pumps—so that we can compare to current costs. These homes will have cooling costs, adding to their life-cycle costs, but they will also benefit from cooling; we implicitly assume that these costs and benefits offset each other.

[40] Explained in footnote 15.

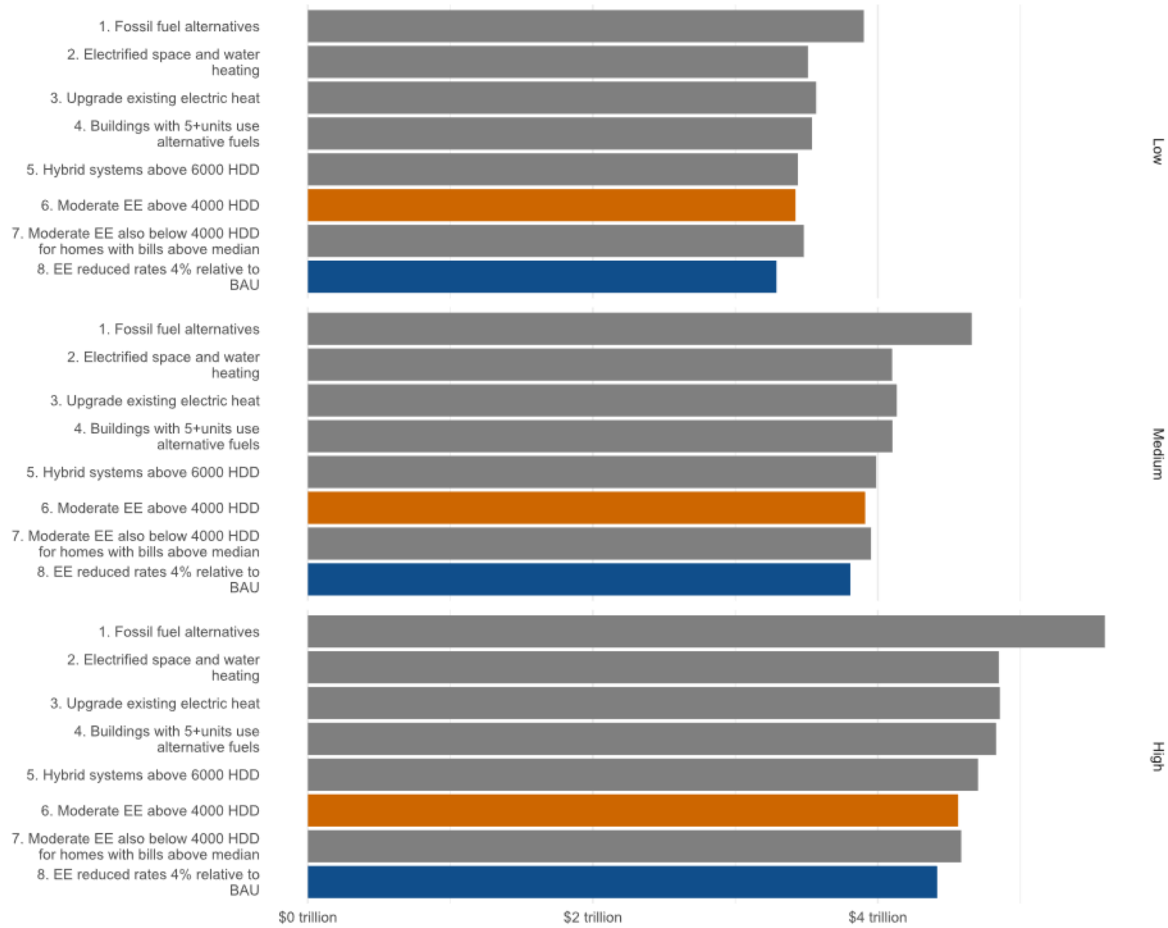


Figure 28. Life-cycle cost of decarbonization scenarios at a national level for the United States. Low, medium, and high refer to the energy cost estimates we used.

Next Steps

Analysis

Our analysis in this report is based on estimates of energy costs and system installation costs at the national level, adjusted for local prices and climate as shown in RECS. The biggest unknowns are the future price of alternative fuels and the impact of electrification on winter peaks as well as the cost to serve these peaks. The latter, in particular, will vary depending on the local distribution system; we therefore suggest additional state- and region-level studies, along the lines of the studies on Maryland, Massachusetts, and Minnesota that we cited earlier. The Massachusetts and Minnesota studies found that hybrid systems make sense for their climates, while the Maryland study found that future peaks could be managed with increased energy efficiency. A study on Rhode Island homes found that for a typical single-family home, either ground-source or electric air-source heat pumps have lower annualized costs than using renewable natural gas; they did not examine gas heat pumps (Murphy and Weiss 2020). A study on British Columbia found that cumulative costs are lower for a strategy that electrifies 25% of homes and uses gas heat pumps in 70% relative to a 100% electrification scenario; both scenarios included extensive building shell improvements (Navigant 2020). The study did not look at hybrid systems that use fuel backup for heat pumps at very cold temperatures. Another study for Puget Sound Energy, a utility in the Seattle area (approximately 4,500 HDDs), found that consumer total cost of ownership will generally be lower for electric heat pumps than hybrid systems (Olson et al. 2021). These results are generally consistent with our findings. Studies on other states would be useful, however, particularly if they examine the full range of options in regions colder than Maryland and Seattle and warmer than Massachusetts. There may also be regional differences in the price of alternative fuels, depending on the regional availability of biogas feedstocks and carbon-free electricity to produce hydrogen via electrolysis.[41]

Another area for further study is multifamily buildings (five or more units) using boilers. Our analysis indicates life-cycle costs are generally lower using alternative fuels, but this is based on electrification costs from New York City. Analysis is needed on buildings and costs from other cities, and, in general, larger samples are needed.

We also note that our assumptions on the impact of reduced gas demand are the same for all homes. We would expect geographic variations—in particular, higher impacts in rural areas and lower impacts in urban areas, with suburban areas in between. Studies are needed on the economics of maintaining gas distribution systems in different density communities.

Policy

Our analyses show that electric heat pumps will often—but not always—have lower life-cycle costs than using alternative fuels. However, as long as fossil gas and fuel oil are readily available to consumers, they will generally choose the fossil fuels and not the substantially more expensive alternative versions of these fuels. Policy measures can begin to address this issue. In the following paragraphs, we discuss seven of these policy options:

- Research and development
- Education and marketing
- Minimum efficiency standards
- Incentives and grants
- Changes to structure of electric rates
- Clean heat standards
- Price on carbon

[41] Fuel availability is discussed by ICF (2019) and Borgeson (2020).

Ultimately, to advance decarbonization, most if not all of these paths will need to be pursued.

Research, Development, and Demonstration

Many of the decarbonization options examined in this report could benefit from additional research, development, and demonstration. Efforts are underway to improve the performance and reduce the cost of electric cold-climate heat pumps and gas heat pumps (e.g., DOE 2022b; GTI Energy 2022). Our analysis indicates that each of these technologies will have a role to play in decarbonization, so improving the technologies and reducing their costs will make decarbonization easier. Some applications will require specialized products, such as lower-cost products for multifamily buildings. As one example, the New York Power Authority (NYPA) is spearheading an effort to develop a cold-climate heat pump that can be installed in the windows of multifamily apartments (Pontecorvo 2022). Further R&D on energy efficiency packages would be useful, particularly on packages that are in-between the "moderate" and "deep" packages we examined. Likewise, significant attention is being paid to reducing the costs of green hydrogen and to technologies to distribute and burn hydrogen (e.g., IEA 2019). Improved methods to deliver and store alternative fuels to homes could be useful for locations where it is not possible or economic to provide piped gas. To expand these efforts, increased funding from federal and state governments—as well as utilities and their associations—would be helpful.

Education and Marketing

Many home and building owners are unfamiliar with heat pumps; if they have heard of them, their knowledge is typically based on moderate-temperature heat pumps that have been on the market for decades and do not work well at temperatures well below freezing. Few people are familiar with new cold-climate heat pumps that can work well at much lower temperatures. This problem also extends to some HVAC contractors. Education and marketing on the performance of the new heat pumps is needed, ideally with testimonials from individuals similar to the targeted audiences (homeowners, landlords, and contractors).

Minimum Efficiency Standards

Minimum efficiency standards require that all equipment meet a specified minimum efficiency level. Furnaces, boilers, water heaters, and heat pumps are all subject to national minimum efficiency standards in the United States. The standards are administered by DOE, which updates the standards approximately every eight years. A new gas furnace standard was proposed in mid-2022 and would take effect in approximately 2030. The proposal calls for a 95% minimum AFUE, up from the 80% AFUE that is now required (DOE 2022c). New water heater standards are also due to be proposed in late 2022 and could take effect in

2028.[42] The present standard requires that water heaters larger than 55 gallons effectively be condensing if they burn gas, and that they use a heat pump if they are electric. A key question will be whether and how much to lower these size thresholds. A new standard for electric central air conditioners and heat pumps is scheduled to be finalized in about 2025, to take effect no sooner than five years later. The most recent standard, to take effect January 1, 2023, requires an HSPF2 of 7.5 for split heat pumps and 6.7 for single-package systems.[43] A future rule will likely raise this requirement, and it could consider separate standards for the north and the south, as is now the case for central air conditioners. These new standards will improve efficiencies, moving all equipment toward the efficiency levels for 2030 that we examined in this report.

Incentives and Grants

Utilities and governments can provide financial incentives to increase uptake of advanced heat pumps and alternative fuels. A recent ACEEE study found 42 programs that offer incentives to encourage electrification, up from 22 programs a year earlier (Cohn and Esram 2022). Many programs also offer incentives for condensing gas furnaces, boilers, and water heaters, and a few programs provide incentives for gas heat pumps. Most of these incentives go to the building owner, but some programs have achieved higher participation by providing the incentive upstream—such as to distributors or even manufacturers (Levin 2018; Hart and Noll 2019). If DOE updates furnace, boiler, and water heater standards to require condensing, then future gas incentives are likely to be limited to gas heat pumps.[44] Incentives that cover part of the cost of decarbonization options can spur middle-class homeowners to make changes, but for low- and moderate-income households and landlords, a combination of outright grants and low-interest loans for remaining costs will be needed. Federal tax incentives for high-efficiency electric heat pumps and HPWHs, and for condensing furnaces and water heaters, are now pending—as is a new federal program to provide incentives for high-efficiency electric equipment. The latter program includes much higher incentives for low- and moderate-income households (House Rules Committee 2022). The tax incentives are scheduled to be in effect for 10 years, and the separate incentive program being proposed has only enough money for a few years of incentives. Depending on how well the program works, additional funding could be provided.

---

[42] For water heaters, the standard takes effect three years after the final rule is published.

[43] This is using a new metric called HSPF2, which modifies the prior HSPF testing procedure. Using the pre-2023 test procedure, the new standard will be approximately 8.8 HSPF for split systems and 8.0 for single-package systems.

[44] Such incentives may be provided in some states and not others, depending on what the state-level policy makers determine is the best role for gas and electric heat pumps in their states.

Incentives can also be provided for the production, distribution, and sale of alternative fuels. The federal government currently has tax incentives for renewable diesel fuel (EIA 2020), and, along with some states, it has incentives for some uses of hydrogen (DOE 2022a). Additional incentives for hydrogen are pending. For example, a large 10-year production tax incentive for hydrogen is included in the pending federal legislation (House Rules Committee 2022).

Changes to Utility Rate Structures

The economics of electric and gas equipment are strongly affected by the retail price of these energy sources, which in turn are affected by both the energy's wholesale price and rate structure. Presently, many electric utilities have a single rate structure for residential customers, ranging from customers that use electricity only for lights and appliances to customers with all-electric homes. Typically, fixed costs are recouped in part through monthly service charges and in part through variable energy charges. In such situations, high users, such as all-electric customers, pay more toward fixed costs. One option might be to establish separate rate classes for customers with electric heat and hot water, which would often reduce the variable cost of electricity for these customers, making electric heat pumps more competitive. Such rates used to be common, and some utilities still have these rate structures. This, in turn, would raise electricity rates for homes now using fossil fuel space and water heating systems, providing them with an incentive to electrify. However, if this is done, care should be taken to find ways to reduce the impact of higher rates on low-income customers.

If electric heat rates are provided, rate designers should consider including time-of-use rates that decrease rates during off-peak times and increase rates during peak times in order to encourage reduced use during peak times. Because winter peaks tend to be early in the morning on cold days, these rates could encourage measures such as preheating hot water outside of peak periods or reducing temperature settings at peak times.

Rates for gas service will also have an impact. For example, some gas utilities have increased their monthly service fees, which can make switching to all-electric more attractive (A. Evens, executive director, Elevate Energy, pers. comm., April 12, 2022). There may also be ways to provide rate discounts for use of alternative fuels.

While cost allocation principles underly both electric and gas rates, these allocations can be made in multiple ways and these choices can be influenced by policy preferences—such as if (and how much) to encourage decarbonization.

Clean Heat Standards

In 2021, the state of Colorado adopted Senate Bill 21-264, which includes a new Clean Heat Standard. Under this new law, Colorado natural gas distribution utilities that serve 90,000 customers or more are required to develop and submit cost-effective plans to the Colorado Public Utilities Commission (PUC) that will reduce emissions that result from delivering fuel to homes and businesses. The bill requires gas distribution utilities to cut emissions by 4% by 2025 and by 22% by 2030. The legislation directs the PUC to set standards for 2035 by 2025, and to set standards for 2040, 2045, and 2050 by 2032. The bill identifies several "clean heat resources" that can be used to achieve the targets, such as efficiency, electrification, green hydrogen, and recovered methane. This last item includes non-fossil sources of methane, such as biogas from agricultural facilities and coal mine methane, and this item also includes reducing leaks of conventional fossil gas (Henchen and Overturf 2021; Colorado General Assembly 2021).

The Minnesota legislature enacted a similar but less aggressive program in 2021. The Natural Gas Innovation Act encourages (but does not require) gas companies to file with regulators "innovation plans" that decarbonize their operations. Utilities can recover costs of pilot projects and use results to meet their goals in the state's Conservation Improvement Program. The legislation is aimed at helping gas utilities introduce renewable natural gas; develop hydrogen-based fuels from renewables; fund energy efficiency projects; and encourage district energy, carbon capture, and geothermal heating (Jossi 2021).

Similar legislation was also passed by the Vermont legislature, but the governor vetoed it (Cotton 2022; Vermont Business Magazine 2022). A revised proposal may be negotiated for 2023.

It is unclear how far clean heat standards can go. Colorado's 22% by 2030 standard was developed via negotiation as aggressive but feasible. Higher standards will be possible in the future, but how far they can ultimately go is an open question.

Price on Carbon

Putting a price on carbon can aid fuel decarbonization in two ways. First, a price on carbon would increase the cost of fossil fuels, making decarbonized electricity and fuels more competitive. Second, a price on carbon could raise funds that could be used for R&D, incentives, and other strategies. Carbon pricing can be a specified carbon fee or a cap-and-trade program in which emissions limits are set and carbon emissions allowances are auctioned, with the market setting the carbon price. The World Bank notes that 65 carbon pricing initiatives are now being implemented around the world, including 45 national programs and 34 at the subnational level (e.g., state or province) (World Bank 2022). In North America, carbon pricing is now in effect in Canada and California, and will soon take effect in Washington State. Electricity in many Northeast and Mid-Atlantic states is subject to the cap-and-trade program administered by the Regional Greenhouse Gas initiative (Nadel, Gaede and Haley 2021; Washington Department of Ecology 2021).

There have been numerous proposals for a U.S. federal price on carbon, but given political divides in Congress, none of these proposals have advanced. While the situation could change in the future, at present, carbon pricing policies in additional states are more likely than federal legislation.

Conclusions

In general, our analysis finds that for one- to four-unit homes (detached and attached), average life-cycle costs for decarbonization will be minimized using electric heat pumps below approximately 6,000 HDDs (the climate in Detroit), and using hybrid systems (electric heat pump with an alternative fuel backup) above this threshold to reduce winter peak loads at very cold temperatures and thereby reduce electric grid update costs. These results all assume use of cold-climate heat pumps in locations with at least 4,000 HDDs (the recent climate in Maryland). Presently, such heat pumps are becoming more common in New England and the interior Northwest. Our analysis suggests that we need to popularize cold-climate heat pumps farther south to constrain growth in winter peak demand and thereby constrain growth in the price of electricity needed to serve the peak demand.

For multifamily buildings (five units or more per building), energy use per unit is generally low and the costs of electrification high. Use of alternative fuels in condensing boilers will often minimize life-cycle costs. However, for apartments served by furnaces, electric heat pumps will minimize life-cycle costs on average below 4,000 HDDs, while hybrid systems minimize costs above roughly 6,000 HDDs. The economics of electric heat pumps could improve if ways are found to reduce the installed costs of ductless mini-split heat pumps in multifamily buildings to the costs that now apply in single-family homes.

For decarbonized water heating, electric HPWHs have the lowest life-cycle costs in all the homes we examined, followed closely by gas condensing tankless water heaters and gas HPWHs using alternative fuels.

Energy efficiency can often reduce life-cycle costs as homes are decarbonized. For many homes, the moderate energy efficiency package (based on Home Performance with ENERGY STAR) has the lowest life-cycle costs, but for some system types, a deep retrofit at time of building renovation will often reduce life-cycle costs further, particularly for homes heated with oil or propane, with above-average energy use or for homes in cold climates.

Our analysis on all U.S. homes using the RECS weighting factors finds that nationally, the lowest life-cycle costs often include a moderate energy efficiency package, particularly if the energy efficiency helps reduce system costs—and hence rates.

When we look at how results vary by region, household income, and building age, interesting patterns emerge. Electric heat pumps are more likely to reduce life-cycle costs for decarbonizing in the South and West than in the North Central region, with other regions falling in between. As income increases and building age decreases, electric heat pumps are more likely to decrease life-cycle costs due to correlations with the presence of central air-conditioning, improved energy efficiency, and an increased number of single-family (vs. multifamily) homes. Given these tendencies, special attention must be paid to assisting low- and moderate-income households to decarbonize, as these households often live in home types that are the most challenging to decarbonize.

While both electrification and alternative fuels will be needed, as long as inexpensive fossil fuels are available, the transition to these systems and fuels will proceed slowly. To accelerate this transition, new policies are needed, including those focused on research and development, minimum efficiency standards, incentives, restructuring electric (and perhaps gas) rates, clean heat standards, and a price on carbon.

References

AGA (American Gas Association). 2020. "AGA Response to *The Atlantic* Article about Natural Gas Cooking." www.aga.org/research/fact-sheets/aga-response-to-the-atlantic-kill-your-gas-stove/.

______. 2022. *Net-Zero Emissions Opportunities for Gas Utilities*. Prepared by ICF. Washington, DC: AGA. www.aga.org/research/reports/net-zero-emissions-opportunities-for-gas-utilities/.

AHRI (Air-Conditioning Heating and Refrigeration Institute). 2020. *AHRI Standard 210/240: 2023 Standard for Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment.* Arlington, VA: AHRI. www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_210-240_2023.pdf.

Amann, J., R. Srivastava, and N. Henner. 2021. *Pathways for Deep Energy Use Reductions and Decarbonization in Homes*. Washington, DC: ACEEE. www.aceee.org/sites/default/files/pdfs/b2103.pdf.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2019. *2019 ASHRAE Handbook—HVAC Applications.* Atlanta: ASHRAE. www.ashrae.org/about/news/2019/ashrae-releases-new-hvac-applications-handbook.

Billimoria, S., L. Guccione, M. Henchen, and L. Louis-Prescott. 2018. *The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings*. Boulder: RMI (Rocky Mountain Institute). rmi.org/wp-content/uploads/2018/06/RMI_Economics_of_Electrifying_Buildings_2018.pdf.

Borgeson, M. 2020. *A Pipe Dream or Climate Solution?* New York: NRDC. www.nrdc.org/resources/pipe-dream-or-climate-solution.

Ciampoli, P. "NYPA Launches Challenge for Innovative Heat Pump." *American Public Power Association*, December 21. www.publicpower.org/periodical/article/nypa-launches-challenge-innovative-heat-pump.

Cohn, C., and N. Esram. 2022. *Building Electrification: Programs and Best Practices*. Washington, DC: ACEEE. www.aceee.org/research-report/b2201.

Cole, W., D. Greer, P. Denholm, A. Frazier, S. Machen, T. Mai, N. Vincent, and S. Baldwin. 2021. "Quantifying the Challenge of Reaching a 100% Renewable Energy Power System for the United States." *Joule* 5 (7): 1732–48. www.sciencedirect.com/science/article/abs/pii/S2542435121002464.

Colorado General Assembly. 2021. *Senate Bill 21-264, An Act Concerning the Adoption of Programs by Gas Utilities to Reduce Greenhouse Gas Emissions, and, in Connection*

Therewith, Making an Appropriation. Denver: Colorado General Assembly. www.leg.colorado.gov/sites/default/files/2021a_264_signed.pdf.

Cotton, E. 2022. "Senate Votes to Support the Clean Heat Standard." *VTDigger*, April 28. www.vtdigger.org/2022/04/28/senate-votes-to-support-the-clean-heat-standard/.

Davis, L., and C. Hausman. 2022. *Who Will Pay for Legacy Utility Costs?* Berkeley: Energy Institute at Haas. www.haas.berkeley.edu/wp-content/uploads/WP317.pdf.

DOE (Department of Energy). 2010. "Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Water Heaters, Direct Heating Equipment, and Pool Heaters." *Federal Register* 75 (73): 20112–236. www.federalregister.gov/documents/2010/04/16/2010-7611/energy-conservation-program-energy-conservation-standards-for-residential-water-heaters-direct.

______. 2011. "Energy Conservation Program: Energy Conservation Standards for Residential Furnaces and Residential Central Air Conditioners and Heat Pumps; Final Rule and Proposed Rule." *Federal Register* 76 (123): 37408–548. www.govinfo.gov/content/pkg/FR-2011-06-27/pdf/2011-14557.pdf.

______. 2015. *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Residential Boilers*. Washington, DC: DOE. www.regulations.gov/document?D=EERE-2012-BT-STD-0047-0070.

______. 2016a. *SNOPR Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Residential Furnaces*. Washington, DC: DOE. www.regulations.gov/document?D=EERE-2014-BT-STD-0031-0217.

______. 2016b. *Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners and Heat Pumps*. Washington, DC: DOE. www.regulations.gov/document/EERE-2014-BT-STD-0048-0098.

______. 2022a. "Hydrogen Laws and Incentives." Accessed June. www.afdc.energy.gov/fuels/laws/HY.

______. 2022b. *Residential Cold-Climate Heat Pump Technology Challenge*. Washington, DC: DOE. www.energy.gov/sites/default/files/2022-02/bto-cchp-fact-sheet-021822.pdf.

_______. 2022c. "Energy Conservation Program: Energy Conservation Standards for Consumer Furnaces, Notice of proposed rulemaking and request for comment." Washington, DC: DOE Office of Energy Efficiency and Renewable Energy. www.energy.gov/sites/default/files/2022-06/res-furnaces-ecs-nopr.pdf.

Dunn, S. 2019. *Home Performance with ENERGY STAR: Program Overview and Progress Update*. Washington, DC: DOE.

www.energystar.gov/sites/default/files/asset/document/HPwES_2018_progress_update_0.pdf.

E3 (Energy+Environmental Economics). 2022. *The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals*. Boston: Massachusetts DPU. www.thefutureofgas.com/sep.

EIA (Energy Information Administration). 2018a. "Residential Energy Consumption Survey: 2015 RECS Survey Data." www.eia.gov/consumption/residential/data/2015/.

______. 2018b. *Updated Buildings Sector Appliance and Equipment Costs and Efficiencies*. Washington, DC: EIA. www.eia.gov/analysis/studies/buildings/equipcosts/.

______. 2020. "U.S. Biomass-Based Diesel Tax Credit Renewed through 2022 in Government Spending Bill." *Today in Energy*, January 28. www.eia.gov/todayinenergy/detail.php?id=42616.

______. 2022a. *Annual Energy Outlook 2022*. Washington, DC: EIA. www.eia.gov/outlooks/aeo/.

______. 2022b. *Monthly Energy Review*. Washington, DC: EIA. www.eia.gov/totalenergy/data/monthly/index.php.

Energiesprong. 2022. "New York State (U.S.)." Accessed March. www.energiesprong.org/?country=new-york.

EPA (Environmental Protection Agency). 2021. "Climate Change Indicators: Heating and Cooling Degree Days." www.epa.gov/climate-indicators/climate-change-indicators-heating-and-cooling-degree-days.

EPRI (Electric Power Research Institute). 2018. *U.S. National Electrification Assessment*. Palo Alto, CA: EPRI. mydocs.epri.com/docs/PublicMeetingMaterials/ee/000000003002013582.pdf.

Fairey, P., D. Parker, B. Wilcox, and M. Lombardi. 2004. *Climate Impacts on Heating Seasonal Performance Factor (HSPF) and Seasonal Energy Efficiency Ratio (SEER) for Air Source Heat Pumps*. Cocoa, FL: Florida Solar Energy Center. http://www.fsec.ucf.edu/en/publications/html/fsec-pf-413-04/.

Farley, J., and R. Ruch. 2013. *Evaluation of CNT Energy Savers Retrofit Packages Implemented in Multifamily Buildings*. Prepared by PARR (Partnership for Advanced Residential Retrofit) and CNT Energy. Washington, DC: DOE. www.elevatenp.org/wp-content/uploads/Evaluation_of_CNT_Energy_Savers_Retrofit_Packages_Implemented_in_Multifamily_Buildings.pdf.

Fixr. 2022. "How Much Does It Cost to Install a Tankless Water Heater?" www.fixr.com/costs/install-tankless-water-heater.

GPI (Great Plains Institute) and CEE (Center for Energy and Environment). 2021. *Decarbonizing Minnesota's Natural Gas End Uses: Stakeholder Process Summary and Consensus Recommendations.* Minneapolis: Great Plains Institute. www.betterenergy.org/blog/report-decarbonizing-minnesotas-natural-gas-end-uses/.

GTI Energy. 2022. "Enhancing Efficiency in Space Conditioning and Water Heating." www.gti.energy/enhancing-efficiency-in-space-conditioning-and-water-heating/.

Hart, D., and E. Noll. 2019. *Less Certain Than Death: Using Tax Incentives to Drive Clean Energy Innovation*. Washington, DC: ITIF (Information Technology & Innovation Foundation). www.itif.org/publications/2019/12/02/less-certain-death-using-tax-incentives-drive-clean-energy-innovation.

Hayes, S., and R. Denson. 2019. *Protecting the Health of Vulnerable Populations with In-Home Energy Efficiency: A Survey of Methods for Demonstrating Health Outcomes*. Washington, DC: ACEEE. www.aceee.org/research-report/h1901.

Hayes, S., and C. Kubes. 2020. *Making Health Count: Monetizing the Health Benefits of In-Home Services Delivered by Energy Efficiency Programs*. Washington, DC: ACEEE. www.aceee.org/research-report/h2001.

Henchen, M., and K. Kroh. 2020. "A New Approach to America's Rapidly Aging Gas Infrastructure." *Rocky Mountain Institute*, January 6. www.rmi.org/a-new-approach-to-americas-rapidly-aging-gas-infrastructure/.

Henchen, M., and E. Overturf. 2021. "Policy Win: Colorado's Innovative Clean Heat Standard Will Force Gas Utilities to Clean Up Their Act." *Canary Media*, August 11. www.canarymedia.com/articles/policy-regulation/policy-win-colorados-innovative-clean-heat-standard.

Home Advisor. 2020. "How Much Does It Cost to Install a Ductless Heating & Cooling System?" www.homeadvisor.com/cost/heating-and-cooling/ductless-heat-pump/.

HomeGuide. 2022. "How Much Will Your Electric Furnace Cost?" Accessed April. www.homeguide.com/costs/electric-furnace-cost.

Hopkins, A., K. Takahashi, and S. Nadel. 2020. "Keep Warm and Carry On: Electrification and Efficiency Meet the 'Polar Vortex.'" *Proceedings of the 2020 ACEEE Summer Study on Energy Efficiency in Buildings* 6: 96–108. Washington, DC: ACEEE. www.aceee.org/files/proceedings/2020/event-data.

House Rules Committee. 2022. *Build Back Better Act — Rules Committee Print, Section-by-Section*. Washington, DC: US House of Representatives Rules Committee. rules.house.gov/sites/democrats.rules.house.gov/files/Section_by_Section_BBB.pdf

ICF. 2019. *Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment*. Washington, DC: AGF (American Gas Foundation). www.gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf.

IEA (International Energy Agency). 2019. *The Future of Hydrogen: Seizing Today's Opportunities*. Paris: IEA. www.iea.org/reports/the-future-of-hydrogen.

______. 2021. *Net Zero by 2050*. Paris: IEA. www.iea.org/reports/net-zero-by-2050.

IPCC (Intergovernmental Panel on Climate Change). 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Geneva: IPCC. www.ipcc.ch/report/ar6/wg2/.

Jossi, F. 2021. "Under New Law, Minnesota Gas Utilities Could Play a Role in Electrification." *Energy News Network*, July 21. www.energynews.us/2021/07/21/under-new-law-minnesota-gas-utilities-could-play-a-role-in-electrification/.

Lazard. 2021. "Lazard's Levelized Cost of Energy Analysis—Version 15.0." New York: Lazard. www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf.

Less, B., and I. Walker. 2015. *Deep Energy Retrofit Guidance for the Building America Solutions Center*. Prepared by Berkeley Lab. Washington, DC: DOE. www.osti.gov/servlets/purl/1248926.

Levin, E. 2018. *Driving the Heat Pump Market: Lessons Learned from the Northeast*. Burlington: VEIC (Vermont Energy Investment Corporation). www.veic.org/resource-library/driving-the-heat-pump-market-lessons-learned-from-the-northeast.

Liss, W., and P. Rowley. 2021. *Assessment of Natural Gas and Electric Decarbonization in State of Colorado Residential Sector*. Prepared by GTI (Gas Technology Institute). Rapid City, SD: Black Hills Energy. www.gti.energy/wp-content/uploads/2021/03/27888-Final-Report-Black-Hills-Energy-CO-GHG-Analysis-w-Appx-A-09-2020_Rev1-03-2021_GTI.pdf.

Littlewood, P., T. Marker, P. Ortiz-Toral, and M. Lesemann. 2022. *Cool LPG: A New Path to Renewable LPG*. Des Plaines, IL: Gas Technology Institute. www.gti.energy/wp-content/uploads/2022/05/05-tcbiomass2022-Presentation-Patrick-Littlewood.pdf .

Maryland Commission on Climate Change. 2021. *Building Energy Transition Plan*. Baltimore: Maryland Department of the Environment. www.mde.maryland.gov/programs/Air/ClimateChange/MCCC/Documents/2021%20Annual%20Report%20Appendices%20FINAL.pdf.

McKinsey & Company. 2022. *Global Energy Perspective 2022.* New York: McKinsey & Company. www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2022.

Melaina, M., O. Antonia, and M. Penev. 2013. *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues.* Prepared by NREL (National Renewable Energy Laboratory). Washington, DC: DOE. www.nrel.gov/docs/fy13osti/51995.pdf.

Mitsubishi Electric. 2022. *2022 Product Catalog*. Uxbridge, UK: Mitsubishi Electric. library.mitsubishielectric.co.uk/pdf/book/2022_LES_Product_Catalogue_-_ME_Edition_-page-.

Murphy, D., and J. Weiss. 2020. *Heating Sector Transformation in Rhode Island, Pathways to Decarbonization by 2050*. Prepared by the Brattle Group. Providence: Rhode Island Division of Public Utilities and Carriers, Rhode Island Office of Energy Resources. energy.ri.gov/HST.

Nadel, S. 2016. *Comparative Energy Use of Residential Furnaces and Heat Pumps*. Washington, DC: ACEEE. www.aceee.org/comparative-energy-use-residential-furnaces-and.

______. 2018. *Energy Savings, Consumer Economics, and Greenhouse Gas Emissions Reductions from Replacing Oil and Propane Furnaces, Boilers, and Water Heaters with Air-Source Heat Pumps*. Washington, DC: ACEEE. www.aceee.org/research-report/a1803.

______. 2022. "What Is the Role of Fuels in a Decarbonized Future? What Is the Potential Role for Gas Utilities?" *Proceedings of the 2022 ACEEE Summer Study on Energy Efficiency in Buildings* (forthcoming). Washington, DC: ACEEE. www.aceee.org/2022-buildings-summer-study.

Nadel, S., and A. deLaski. 2013. *Appliance Standards: Comparing Predicted and Observed Prices.* Washington, DC: ACEEE. www.aceee.org/research-report/e13d.

Nadel, S., and C. Kallakuri. 2016. *Opportunities for Energy and Economic Savings by Replacing Electric Resistance Heat with Higher-Efficiency Heat Pumps*. Washington, DC: ACEEE. www.aceee.org/research-report/a1603.

Nadel, S., and C. Perry. 2020. *Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges*. Washington, DC: ACEEE. www.aceee.org/research-report/b2004.

Nadel, S., J. Gaede, and B. Haley. 2021. *State and Provincial Efforts to Put a Price on Greenhouse Gas Emissions, with Implications for Energy Efficiency*. Washington, DC: ACEEE. www.aceee.org/research-report/i2101.

Navigant. 2013. *Impact Evaluation of the Energy Savers Program for Large Multifamily Buildings*. Chicago: CNT Energy. www.elevatenp.org/wp-content/uploads/Impact_Evaluation_of_the_Energy_Savers_Program_for_Large_Multifamily_Buildings.pdf.

______. 2020. *Pathways for British Columbia to Achieve Its GHG Reduction Goals*. Surrey: FortisBC. www.cdn.fortisbc.com/libraries/docs/default-source/about-us-documents/guidehouse-report.pdf?.

NEEP (Northeast Energy Efficiency Partnerships). 2022. "Cold Climate Air-Source Heat Pump List." www.neep.org/heating-electrification/ccashp-specification-product-list.

Neal, M., L. Goodman, and C. Young. 2020. *Housing Supply Chartbook*. Washington, DC: Urban Institute. www.urban.org/sites/default/files/publication/101553/housing_supply_chartbook_1.pdf.

NREL (National Renewable Energy Laboratory). 2020. "HyBlend Project to Accelerate Potential for Blending Hydrogen in Natural Gas Pipelines." *NREL*, November 18. www.nrel.gov/news/program/2020/hyblend-project-to-accelerate-potential-for-blending-hydrogen-in-natural-gas-pipelines.html.

NYC (New York City). 2021. *Pathways to Carbon-Neutral NYC: Modernize, Reimagine, Reach*. New York: Mayor's Office of Sustainability. www1.nyc.gov/assets/sustainability/downloads/pdf/publications/Carbon-Neutral-NYC.pdf.

NYPA (New York Power Authority). 2021.

NYU Stern (New York University Stern School of Business). 2022. "Cost of Equity and Capital (US)." pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.html.

Olson, A., B. Wheatle, D. Aas, J. Stevens, and J. de Villier. 2021. *E3 PSE Gas Utility Decarbonization: Beyond Net Zero Scenario Analysis, 2021-9-3*. Prepared by E3. Bellevue, WA: Puget Sound Energy. apiproxy.utc.wa.gov/cases/GetDocument?docID=640&year=2022&docketNumber=220067.

Perry, C., A. Khanolkar, and H. Bastian. 2021. *Increasing Sustainability of Multifamily Buildings with Heat Pump Water Heaters*. Washington, DC: ACEEE. www.aceee.org/research-report/b2101.

Pontecorvo, E. 2022. "How NYC's Public Housing Authority Plans to Transform the Market for Clean Heat." *Grist*. Jan. 24. www.grist.org/buildings/how-nycs-public-housing-authority-plans-to-transform-the-market-for-clean-heat/.

PickHVAC. 2021. "Dual Fuel Heat Pump Reviews, Cost and Buying Guide 2021." www.pickhvac.com/dual-fuel-heat-pump/.

Plumbing Products. 2022. "Mitsubishi Ecodan Monobloc Heatpump Kit 5kw." Accessed February. www.plumbingproducts.ie/monobloc/5756-mitsubishi-ecodan-monobloc-heatpump-kit-5kw.html.

Relf, G., and B. Baatz. 2017. *Energy Efficiency in Capacity Auctions: A Historical Review of Value*. Washington, DC: ACEEE. www.aceee.org/research-report/u1714.

ROUSH Cleantech. 2022. "Renewable Propane: The Near-Zero Solution." www.roushcleantech.com/renewable-propane-the-near-zero-solution/.

Seals, B., and A. Krasner. 2020. *Gas Stoves: Health and Air Quality Impacts and Solutions*. Basalt, CO: Rocky Mountain Institute. www.rmi.org/insight/gas-stoves-pollution-health/.

Skumatz, L. 2016. "Non-Energy Benefits / NEBs—Winning at Cost-Effectiveness Dominos: State Progress and TRMs." *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings* 6: 1–13. Washington, DC: ACEEE. www.aceee.org/files/proceedings/2016/data/papers/6_1147.pdf.

Taylor, M., C. Spurlock, and H. Yang. 2015. *Confronting Regulatory Cost and Quality Expectations: An Exploration of Technical Change in Minimum Efficiency Performance Standards*. Washington, DC: Resources for the Future. www.rff.org/publications/working-papers/confronting-regulatory-cost-and-quality-expectations-an-exploration-of-technical-change-in-minimum-efficiency-performance-standards/.

Ungar, L., S. Nadel, and J. Barrett. 2021. *Clean Infrastructure: Efficiency Investments for Jobs, Climate, and Consumers*. Washington, DC: ACEEE. www.aceee.org/white-paper/2021/09/clean-infrastructure-efficiency-investments-jobs-climate-and-consumers.

Urban Green (Urban Green Council). 2020. *Going Electric, Retrofitting NYC's Multifamily Buildings*. New York: Urban Green Council. www.urbangreencouncil.org/content/projects/going-electric-report.

Vermont Business Magazine. 2022. "Scott Vetoes Clean Heat Standard Bill." *Vermont Biz*, May 6. www.vermontbiz.com/news/2022/may/06/scott-vetoes-clean-heat-standard-bill.

Vineyard, E., A. Abu-Heiba, and I. Mahderekal. 2017. "Design and Development of a Residential Gas-Fired Heat Pump." *12th IEA Heat Pump Conference*. Paris: IEA. www.hpc2017.org/wp-content/uploads/2017/05/O.4.7.1-Design-and-Development-of-Residential-Gas-Fired-Heat-Pump.pdf.

Washington Department of Ecology. 2021. "State Begins Work to Implement Climate Commitment Act." Press release, August 6. www.ecology.wa.gov/About-us/Who-we-are/News/2021/Aug-6-State-begins-work-to-implement-Climate-Commi.

Wetzel, C. 2022. "Gas Stoves Are Worse for Climate and Health Than Previously Thought." *Smithsonian Magazine*, February 1. www.smithsonianmag.com/smart-news/gas-stoves-are-worse-for-climate-and-health-than-previously-thought-180979494/.

World Bank. 2022. "Carbon Pricing Dashboard." carbonpricingdashboard.worldbank.org/.

Appendix A. Methodology

The "Analysis Approach" section in the main report describes our general methodology. Here, we provide additional details regarding the following:

- Annual energy use
- Equipment and installation costs
- Equipment performance
- Impact of heat pumps on air-conditioning costs
- Electricity prices
- Fuel prices
- Energy efficiency
- National housing stock analysis

ANNUAL ENERGY USE

For each home and apartment, we adjust its 2015 energy use for the 30-year average heating degree days (HDDs) at its location. This allows us to account for locations with warmer or colder than average heating seasons in 2015. Both 2015 energy use and 30-year average HDDs are included in the 2015 Residential Energy Consumption Survey (RECS) data set and matched with each individual home. The 30-year average in RECS covers the 30 years leading up to 2015.

EQUIPMENT AND INSTALLATION COSTS

We estimated equipment and installation costs from a variety of published sources. The most common source was Technical Support Documents (TSDs) published by the Department of Energy (DOE) as part of rulemakings on minimum efficiency standards for equipment. In these documents, DOE estimates the average installed costs of different types and efficiency levels of equipment. These costs are based on converting all production to at least these levels, and they therefore assume very large volumes. On the other hand, review of actual prices after new standards take effect generally shows that DOE overestimates these costs (Nadel and deLaski 2013; Taylor, Spurlock, and Yang 2015). For our study, we use TSD prices where available, adjusting these to 2020 dollars using the Federal Reserve Bank's Implicit Price Deflator. We use 2020 dollars as a common denominator, adjusting data in 2021 dollars or in pre-2020 dollars to a 2020 basis. Because the TSD prices are for mass markets, we use these for our low-price estimates, with our medium estimates 20% higher, and our high estimates 40% higher. However, for some types of equipment—such as cold-climate electric heat pumps, gas heat pumps, and ductless mini-split heat pumps—and for electrification measures for multifamily buildings, DOE has not published price estimates in TSDs so we rely on other data sources (as explained in the tables below).

Table A-1 summarizes our estimates of equipment and installation costs for space heating equipment used in single-family and two- to four-unit homes.

Table A-1. Costs per home for space heating in one- to four-unit homes (2020$)

	Equipment costs ($)			
Equipment type	Low	Medium	High	Notes
Electric air-source heat pump	5,676	6,811	7,946	For 2023 ENERGY STAR, low costs from DOE TSD (DOE 2016b). If the home has a central air conditioner (AC), the heat pump is installed instead of a replacement AC. If the home does not have central AC, the heat pump is installed instead of a replacement furnace.
Adder for cold-climate heat pump	2,969	5,939	8,908	Medium costs are based on estimates provided to ACEEE by Efficiency Maine and NW Energy Efficiency Alliance for recent installations. For low costs, we take half of this; for high we add 50%.
Adder for electrical work	0	1,250	2,500	Applies to heat pumps installed in homes without central AC.
Central AC	4,585	5,502	6,420	For SEER 16 AC. Low cost from DOE TSD (DOE 2016b). Add 20% for medium and add 40% (to the low) for high.
Hybrid electric heat pump with gas backup	8,015	9,618	11,221	Low from PickHVAC (2021). Add 20% for medium, 40% for high. If the home has a central AC, the hybrid is installed instead of a replacement AC. If the home does not have a central AC, the hybrid is installed instead of a replacement furnace.
Electric air-to-water heat pump	7,146	8,575	10,005	Low of 6,324 Euros (Plumbing Products 2022) with an exchange rate of $1.13/Euro. Add 20% for medium, 40% for high. This heat pump is installed instead of a replacement boiler.
Ductless mini-split heat pump	2,619	3,492	5,675	Medium estimate from Ungar, Nadel, and Barrett (2021); Home Advisor (2020) medium is nearly identical. Home Advisor low and high are fairly extreme, so our low is an average of their low and medium

Equipment type	Equipment costs ($) Low	Medium	High	Notes
				and our high is average of their medium and high.
Gas heat pump	7,500	9,000	10,500	Low from Liss and Rowley (2021); add 20% for medium, 40% for high. This unit is installed instead of a replacement furnace.
Gas furnace	3,051	3,662	4,272	For 95% AFUE. Low from DOE TSD (DOE 2016a); add 20% for medium, 40% for high. For homes with both central AC and a furnace or boiler, we assume the AC is replaced in 2030 and the furnace or boiler is replaced five years later, with the cost of the furnace or boiler discounted at 5% per year for the five years.
Oil furnace	4,388	5,266	6,144	For 85% AFUE. Low from DOE final rule (DOE 2011); add 20% for medium, 40% for high.
Gas boiler	7,261	8,713	10,165	For 84% AFUE. Low from DOE TSD (DOE 2015); add 20% for medium, 40% for high. This applies to both hot water and steam (the costs in the DOE TSD are very similar).
Oil boiler	9,472	11,367	13,261	For 86% AFUE. Low from DOE TSD (DOE 2015); add 20% for medium, 40% for high.

For our analysis of one- to four-unit buildings, we assume a heat pump is installed when an existing central air conditioner needs to be replaced. If the home does not have a central air conditioner, we look at replacement when the existing furnace or boiler needs to be replaced. Likewise, our analysis looks at installing gas heat pumps when an existing gas or propane furnace needs to be replaced. For our boiler analysis, we look at air-to-water heat pumps and ductless mini-split heat pumps that provide only space heating and assume that where there is air-conditioning, it continues to be provided by current systems.

Table A-2 summarizes our cost estimates for multifamily buildings (five or more units). We consider the economics of installing heat pumps at the time an existing boiler needs to be replaced. Costs are per unit, with costs to replace current equipment from EIA (2018b) and costs for electrification from Urban Green (2020). Costs of electrification depend on whether the building can make do with ductless mini-split units or needs a central variable refrigerant flow (VRF) system. All costs are adjusted to 2020$ using the Federal Reserve Bank Implicit Price Deflator. For the fossil fuel equipment we use only a medium-cost estimate as moderate differences in the cost of replacement equipment have only a small impact on the analysis.

The ductless mini-split costs in table A-2 are much higher than the costs in Table A-1, due to factors such as brick walls, multistory construction, and higher labor costs in the large urban areas where multifamily buildings are most common. As one sensitivity case, we looked at the impacts of applying the single-family ductless mini-split costs in multifamily buildings—reducing costs to this level would be challenging, but it could be possible.

Table A-2. Costs for space heating in multifamily apartments (five or more units per building) (2020$, per apartment)

	Equipment costs ($)			
Equipment type	Low	Medium	High	Notes
Replacement gas boiler		5,112		For a condensing boiler (EIA 2018b)
Replacement oil boiler		3,445		For a high-efficiency noncondensing boiler (EIA 2018b)
Electric heat pump, ductless mini-split	11,175	14,900	22,350	Medium cost is from Urban Green (2020); low is 25% less, high is 25% more
Electric heat pump, VRF	18,200	22,750	27,300	Low cost is from Urban Green (2020). Based on preliminary information from recent projects that shows typical costs are about 25% higher (citations not yet available); added 25% for medium estimate and 50% above low for high estimate

Table A-3 summarizes water heater costs. For the gas and oil water heaters, we used estimates from Nadel (2018) for the medium estimate, with the low estimate 20% less and the high estimate 20% more. For the electric heat pump water heater (HPWH), we used the estimate from Nadel (2018) as the low estimate because efficiencies have increased since then and these higher efficiencies add costs. The Nadel estimates are based on DOE TSD costs (DOE 2010), with some adjustments. For the gas heat pump, we used Liss and Riley (2021) as the low based on feedback from some experts that the Liss and Riley costs are probably too low. We examined only homes in buildings with one to four units. Hot water in larger buildings gets very complicated and is the subject of a prior ACEEE study (Perry, Khanolkar, and Bastian 2021), albeit one that does not account for the effect of decarbonization on electricity and fuel prices.

Table A-3. Costs for water heating in one- to four-unit homes (2020$)

	Equipment costs ($)			
Equipment type	Low	Medium	High	Notes
Electric heat pump	2,101	2,225	2,670	Low from Nadel (2018), adjusted for 2020$; add 20% for medium, 40% for high
Gas condensing storage water heater	1,874	2,342	2,811	Medium from Nadel (2018), adjusted for 2020$; subtract 20% for less, add 20% for high
Gas condensing tankless water heater	2,500	2,810	3,500	From Fixr (2022); its high is $4,500, but we reduced it to $3,500 since we are looking for a high average
Gas heat pump	2,250	2,700	3,150	Low from Liss and Riley (2021); add 20% for medium, 40% for high
Oil noncondensing	1,980	2,475	2,970	Medium from Nadel (2018), adjusted for 2020$; subtract 20% for low, add 20% for high
Electric furnace		3,750		Medium from HomeGuide (2022); we use this only for the national extrapolation and not for other analyses

EQUIPMENT PERFORMANCE

For oil and gas space heating systems, we assumed the same efficiency levels nationwide. These assumptions are summarized in table A-4 for equipment used in one- to four-unit buildings.

Table A-4. Assumed efficiency levels for gas and oil space heating equipment for one- to four-unit buildings

Equipment type	Efficiency	Units	Notes
New gas furnace	95%	AFUE	Likely to be required by 2030
Base-case gas furnace	85%	AFUE	Roughly half are 80% and half condensing; in 2015 when RECS was conducted, condensing often meant 90% AFUE
Oil furnace	86%	AFUE	1 percentage point above DOE minimum
Gas hot-water boiler	85%	AFUE	1 percentage point above DOE minimum
Oil hot-water boiler	87%	AFUE	1 percentage point above DOE minimum
Gas steam boiler	83%	AFUE	1 percentage point above DOE minimum

Equipment type	Efficiency	Units	Notes
Oil steam boiler	86%	AFUE	1 percentage point above DOE minimum
Gas heat pump	140%	AFUE equiv.	Liss and Riley 2021

For electric heat pumps, 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 this equipment, we started with the efficiency ratings in table A-5, and then modified them based on the design temperature at each location as reported in the RECS data.

Table A-5. Efficiency levels used for electric heat pumps for space heating in one- to four-unit buildings

Equipment type	Efficiency	Units	Notes
Central ducted air-source	8.5 2.49	HSPF Seasonal COP	2023 ENERGY STAR for split systems
Same as above but cold climate	10.5 3.08	HSPF Seasonal COP	For hybrid systems, estimate 13% higher due to shifting to backup when very cold (GPI and CEE 2021)
Mini-split air-source	10.8 3.17	HSPF Seasonal COP	Multiplied row above by ratio of mini-split to ducted avg HSPF in NEEP cold-climate HP database, January 2022
Air-to-water source	3.33	Seasonal COP	For a Mitsubishi UK system (Mitsubishi Electric 2022)

These are the starting values before adjusting for local design temperature as reported in the RECS data.

For multifamily buildings, we assumed the values shown in table A-6. For the electric mini-split heat pumps, we adjusted performance based on winter design temperature using the same method described above for one- to four-unit buildings. For the VRF systems, we used a regression equation on commercial unitary heat pump performance developed by Nadel and Perry (2020). This varies from a seasonal COP of about 3.5 at roughly 1,000 HDDs to a COP of 1.0 as HDDs approach 11,000.

Table A-6. Efficiency levels used for space heating in multifamily buildings (five or more units per building)

Equipment type	Efficiency	Units	Notes
Gas boiler	95%	Thermal efficiency	Assume condensing system
Oil boiler	85%	Thermal efficiency	From EIA (2018b)
Electric mini-split	3.17	Seasonal COP	Same as for mini-split in one- to four-unit buildings
Electric VRF HP	Varies with HDD	Seasonal COP	Per formula for commercial unitary heat pump derived by Nadel and Perry (2020)

For the electric equipment, these are the starting values before adjusting for local design temperature as reported in the RECS data.

For water heaters, we assumed the same efficiency levels nationwide as shown in table A-7.

Table A-7. Assumed efficiency levels for water heaters used in one- to four-unit buildings

Equipment type	Efficiency	Notes
Electric HPWH	330%	ENERGY STAR 6.0 (units will improve but field performance is a little less than ratings)
Gas condensing storage water heater	80%	Condensing
Gas condensing tankless water heater	90%	Condensing
Gas heat pump water heater	130%	Liss and Riley 2021
Oil water heater	65%	1 percentage point above DOE minimum
Base-case gas water heater	58%	Based on DOE minimum efficiency standard (medium draw, 38 gallons); this is the standard model in the March 2022 DOE Preliminary Technical Support Document
Base-case oil water heater	64%	Based on DOE minimum efficiency standard (high draw, 30 gallons); this is the standard model in the March 2022 DOE PTSD
Base-case electric water heater	92%	From March 2022 DOE PTSD

IMPACT OF HEAT PUMPS ON AIR-CONDITIONING COSTS

Our analysis considers ENERGY STAR and cold-climate electric heat pumps. These are more efficient than the average air conditioner, resulting in modest cooling savings that we incorporated into our analysis. Specifically, ENERGY STAR specifications are generally designed to achieve at least 10% energy savings relative to standard equipment. From this, we subtract 3.6% to allow for air conditioner efficiency improvements since 2015.[45] For cold-climate heat pumps, we assume 5% additional cooling savings beyond ENERGY STAR based on a detailed ACEEE analysis of air conditioner efficiency ratings in the NEEP Cold Climate Air-Source Heat Pump List (NEEP 2022).

For homes that do not have air-conditioning, when heat pumps are installed, air-conditioning becomes available. This air-conditioning has an operating cost, but it also provides comfort and sometimes health benefits. We did not include these costs or these benefits in our analysis.

Gas heat pumps can also provide cooling, but they are not very efficient at cooling.[46] We assumed that when homes have both electric and gas air-conditioning available, they will use the electric air-conditioning.[47]

ELECTRICITY PRICES

For electricity, we start with electricity prices for all end uses in 2015 as paid by each home in the RECS data set. This allows us to capture utility-specific and home-specific effects. For our medium case, we add two multipliers: (1) an adjustment for the average national electricity price in 2040[48] relative to the price in 2015, and (2) an adjustment for increased costs due to higher winter peaks caused by electrification. The first adjustment is based on the Reference Case forecast in EIA's *2022 Annual Energy Outlook* (EIA 2022a). This second adjustment is based on published studies from several different regions and varies based on climate, with no adjustment in the south, a moderate adjustment in climates such as Maryland, and a large adjustment in climates such as Minnesota. Specifically, a study in Vancouver, Canada

---

[45] Federal minimum standard for central air conditioners was SEER 13 in the years leading up to 2015. Add 0.5 for some sales beyond minimum. Since 2015, the standard has been 13 in the North and 14 in the South (an average of ~13.5), plus 0.5 for some sales beyond the minimum.

[46] For example, Vineyard, Abu-Heiba, and Mahderekal (2017) discuss tests on a residential model with a cooling COP of 1.22. The DOE minimum EER for the Southwest is approximately 12, which is a COP of about 3.5 (12/3.412).

[47] A Gas Technology Institute study on decarbonization options for Colorado makes a similar assumption (Liss and Riley 2021).

[48] We use 2040 as it is approximately midway into the life of equipment first installed in 2030.

(roughly 5,000 HDDs) found that an electrification scenario would increase electricity peak demand by 12% (Navigant 2020). For Maryland (roughly 4,500 HDDs), a study found that electrification and efficiency investments would increase residential electricity prices by 21% (Maryland Commission on Climate Change 2021), while a study on Minnesota (roughly 7,300 HDDs) found a 60% increase in electricity price for 100% electrification and a 33% increase for full use of hybrid systems (GPI and CEE 2021). Based on these studies, for our medium scenario, we assumed no increase in electricity price for locations with 4,000 HDDs or less, a 15% increase at 4,500 HDDs, and a 30% increase at 7,000 HDDs, with the ramp-up in costs continuing above 7,000 HDDs. We interpolate for HDDs different from 4,000 and 7,000. For our low and high cases, we reduce and increase the electricity price by 25% relative to the medium scenario.

As we note in the body of the report, our electric prices are for a grid that is nearly—but not fully—decarbonized, as our electric prices are based on EIA estimates that do not presume full decarbonization. The costs of full decarbonization will vary locally based on the balance between low-priced renewable energy (new renewable energy is often less expensive than fossil-fuel generation; Lazard 2021) and costs of storage and backup power for when intermittent renewable power is unavailable. Our winter peak adder includes some of these costs because growing winter peaks will drive investment needs in much of the country (EPRI 2018). We do not include an adjustment for growing electricity sales due to electrification, which can allow fixed costs to be spread over a wider base. Still, there will likely be additional costs to fully decarbonize that we have not included. For example, analysis by the National Renewable Energy Laboratory has found that moving to approximately 90% renewable energy will not have large incremental costs, but the last 10% will add significant costs that we do not fully include (Cole et al. 2021).

FUEL PRICES

For natural gas, we also start with 2015 prices for all end uses as paid by each home; we then add a multiplier based on the projected increase in the national average natural gas price between 2015 and 2040. Next, we make two adjustments. First, we assume that this fuel will need to be net-zero carbon and assume a mix of 45% biogas and 55% synthetic natural gas made from green hydrogen. Biogas is in limited supply, hence the need for another gaseous fuel (Nadel 2022). We explain the 45%/55% mix below. We assume synthetic natural gas as it can be used in existing distribution pipes and existing residential furnaces, boilers, and water heaters without modification.[49] We use ICF estimates of future wholesale biogas costs (NYC 2021) and E3 (2022) estimates of future wholesale hydrogen and scaled these to retail costs using EIA data. Second, as gas use declines due to electrification, gas rates will go up in

[49] Hydrogen could be used instead, but burner modifications will be needed to burn hydrogen instead of natural gas. In addition, depending on the type of pipe used in distribution systems, some (perhaps many) locations will require replacement of distribution system gas pipes.

order to recover fixed costs across the lowered number of sales. We use estimates of these effects from Davis and Hausman (2022).[50] Figure 2 in the main report summarizes residential natural gas prices.

Table A-8 shows the ICF estimates for wholesale alternative fuel costs. We used the 2040 costs as these are midway into the operating life of equipment installed in 2030.

Table A-8. Projections of the wholesale price per million Btu for natural gas and alternative fuels derived from ICF

Fuel	2030	2040	2050
Biogenic renewable natural gas	$14–18	$16–21	$14–19
Hydrogen (green)	$32	$21	$18
Synthetic natural gas	$40	$26	$21

Source: ICF estimates (NYC 2021)

During the review of our draft report, we received several comments stating that the ICF estimates for synthetic natural gas may be optimistic. We therefore compared the ICF hydrogen prices to those from a March 2022 E3 study for Massachusetts. Table A-9 summarizes these prices. To project synthetic natural gas prices, we used the ratio of synthetic natural gas to green hydrogen in table A-8 and applied this to the hydrogen price in table A-9.

[50] Our low and medium estimates are based on Davis and Hausman. Our high estimate was throttled back from the Davis and Hausman estimate as explained in the text on the next page.

Table A-9. Projections of the wholesale price per million Btu for natural gas and alternative fuels derived from E3

Fuel	2030	2040	2050
Hydrogen (green)	$25–30	$20.5–27	$17–23
Synthetic natural gas	$31–38	$25–33	$20–27

Source: E3 (2022) estimates for green hydrogen. We applied the ratio of synthetic to green hydrogen from table A-8 to estimate synthetic natural gas.

Regarding the mix of biogas and synthetic natural gas, a study prepared by ICF for AGA looked at several gas decarbonization scenarios (AGA 2022). These scenarios used an approximately equal mix of biogas and synthetic natural gas. However, the biogas figures include some controversial sources, such as biogas derived from municipal solid waste and from crops and trees explicitly grown to provide biofuel. Due to the controversies around these sources, they may not be fully developed, so we reduced the 50% biogas in the AGA study down to 45%, making up the difference with increased synthetic natural gas.

The ICF and E3 costs are wholesale costs. The majority of residential gas prices are for the cost of the distribution system, not the wholesale commodity cost. We looked at EIA data to compare wholesale natural gas prices (Henry Hub price) to residential natural gas prices and determined that, on average, the wholesale price is 33% of the retail price. We compared the 2040 values in table A-8 for renewable natural gas and table A-9 for synthetic natural gas—assuming 45% and 55%, respectively—to the 2015 average wholesale gas price to figure out the impacts of higher-price alternative gas on the commodity portion of 2040 residential bills relative to the 2015 natural gas bill shown for each home in RECS.

For the distribution portion of future natural gas bills, as Davis and Hausman (2022) show, when customers exit the gas system or substantially scale back their use of gas, fixed costs must be recovered over lower sales, increasing costs to customers.[51] Their results, which figure A-1 illustrates, are based on empirical data on past price responses to changes in gas sales. We used their empirical estimate, assuming 30% of customers exit the gas system in our low-price case and 60% exit in our medium-price case, and 90% exit in our high-price case. However, in discussions with experts. we learned that the Davis and Hausman data does not include distribution cost savings from decommissioning portions of the distribution system. A Massachusetts decarbonization study (E3 2022) does address these cost savings and, based on its data, we reduced the Davis and Hausman data by 25 percentage points for

[51] Low-income customers are more likely to be left on the gas distribution system and will disproportionately feel these impacts (Henchen and Kroh 2020). Any electrification policies should take steps to ameliorate these impacts on low-income customers.

our high-price case. We applied adjustments for declining numbers of customers to the distribution portion of rates, not the wholesale commodity portion. For our multifamily analysis, we looked only at the low and medium impacts, deciding that the high impacts were unlikely in the denser neighborhoods where multifamily housing is often located.

Based on these calculations, for 2040, the national average residential natural gas price is $38.72 per million Btu in the medium case, $31.53 in the low case, and $51.08 in the high case. By way of comparison, in 2021, residential natural gas averaged $11.80 per million Btu (EIA 2022b).

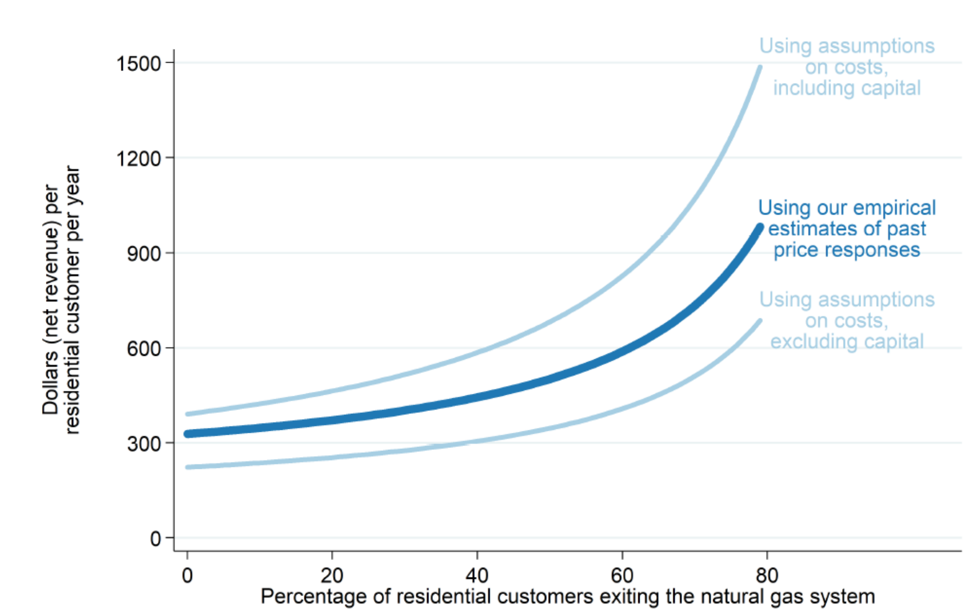


Figure A-1. Impact of the declining number of customers on the remaining customers' gas bills. Source: Davis and Hausman 2022.

ENERGY EFFICIENCY

For one- to four-family homes, we examined three levels of energy efficiency improvements: none, moderate, and deep. Our basic analysis does not include energy efficiency; we add energy efficiency as scenarios later to reduce home energy consumption and system costs (as more-efficient homes need modestly smaller systems), as well as to reduce the impacts of heat pumps on energy demand.

For the moderate efficiency scenario, we used data from DOE (Dunn 2019) on the average cost and energy savings from the Home Performance with ENERGY STAR program in 2018. The program reduced consumption an average of 25%, at an average cost of $5,700 per home. We adjusted this for inflation and for the fact that some of the cost is to reduce hot-water, lighting, and other energy uses—but not space conditioning. Specifically, in the DOE data set reported by Dunn, 70% of the measures were related to space conditioning. We increased this to 80% because space conditioning measures are likely a greater percentage of cost than the number of measures. After adjusting for inflation and this 80%, the average cost per home is $4,857 (2020$). The moderate efficiency package reduces energy use and loads by 25%; we assumed that, on average, system cost will be reduced by half this amount (–12.5%).

For the deep efficiency scenario, we used average costs ($49,665) and savings (60%) across the building types analyzed in a 2021 study (Amann, Srivastava, and Henner 2021). This cost includes a new heat pump and HPWH. To avoid double-counting these costs, we subtracted the heat pump costs (moderate, not cold climate) and the HPWH costs shown in tables A-1 and A-3. As a result, for the medium-cost case, a deep retrofit that costs $49,665 including new heat pumps and HPWHs costs $40,030. We applied the same 80% adjustment for the proportion of costs related to space conditioning. As with the moderate efficiency package, we assumed that, on average, system cost will be reduced by 30%, half of the 60% savings from the deep retrofit.

We looked at deep retrofit costs in two ways: full retrofit cost and incremental retrofit cost at time of home renovation. Less and Walker (2015) find that the latter reduce costs 25–75%. We used their midpoint: –50%.

For apartments in buildings with five units or more, we looked at no efficiency improvements and at a moderate efficiency case based on Elevate Energy's Energy Savers program in Chicago. This program has resulted in 26% average savings during the heating season (Navigant 2013) at a cost of $1,932 per unit in 2013$ (Farley and Ruch 2013). Using the Federal Reserve GDP deflator, this is $2,207 per unit in 2020$. While deep retrofits are possible (see for example Energiesprong 2022), costs are highly site specific and not amenable to an analysis that applies the same cost to all units.

NATIONAL HOUSING STOCK ANALYSIS

For our analysis extrapolating to the national housing stock, we basically used the same assumptions as for prior analyses (discussed above), but we also needed to make additional clarifications as follows:

- The national analysis included all home electricity and fuel costs, not just those for space and water heating and central air-conditioning. We include these other costs for completeness, using the cost of decarbonized electricity and fuel. We did not consider replacement of existing equipment for uses other than space and water heating and central air-conditioning. In contrast with the main analysis, we included air-conditioning for all homes shown as having it in RECS, including multifamily homes, homes with boilers, and homes with only room air conditioners. We did this to permit a better comparisons with homes with electric heat that are included in this analysis but not the earlier analysis.
- For homes with more unusual heating systems (e.g., oil-burning wall furnaces), we use our price assumptions for fuel and electricity to calculate energy costs but assume no equipment costs. We assume these costs are fixed across all scenarios.

- In scenarios 1 and 2, we assume electric resistance heating equipment has an efficiency of 100% and that electric heat pumps have an efficiency of 8.5 Heating Seasonal Performance Factor (HSPF). The cost of an electric central furnace used is $3,750; the costs of other equipment that is not included above is assumed to be fixed across all scenarios.
- To combine our space conditioning analysis (which uses an 18-year equipment life and analysis period) with our water heating analysis (which uses 13 years), we included new replacement water heaters in year 14 of the analysis, discounting these future costs and using 5/13 of replacement equipment costs (to cover five years of use to get to an 18-year analysis period). We assume that homes that already use electric water heaters replace them with an efficient electric HPWH after five years. We assume that the efficiency of existing electric water heaters is 92%.

Appendix B. Analysis of Energy Efficiency Economics for Additional System Types

In the main report, we discuss the impacts of energy efficiency on our overall analysis and on three system types: electric heat pumps, gas furnaces, and hybrid systems. In this appendix, we provide results for other system types.

Figure B-1 shows results for efficiency investments with gas heat pumps. With gas heat pumps, the moderate efficiency package typically reduces life-cycle costs in many homes. The deep retrofit package at time of home renovation is cost effective for many homes with above-median bills in climates with above approximately 4,000 HDDs.

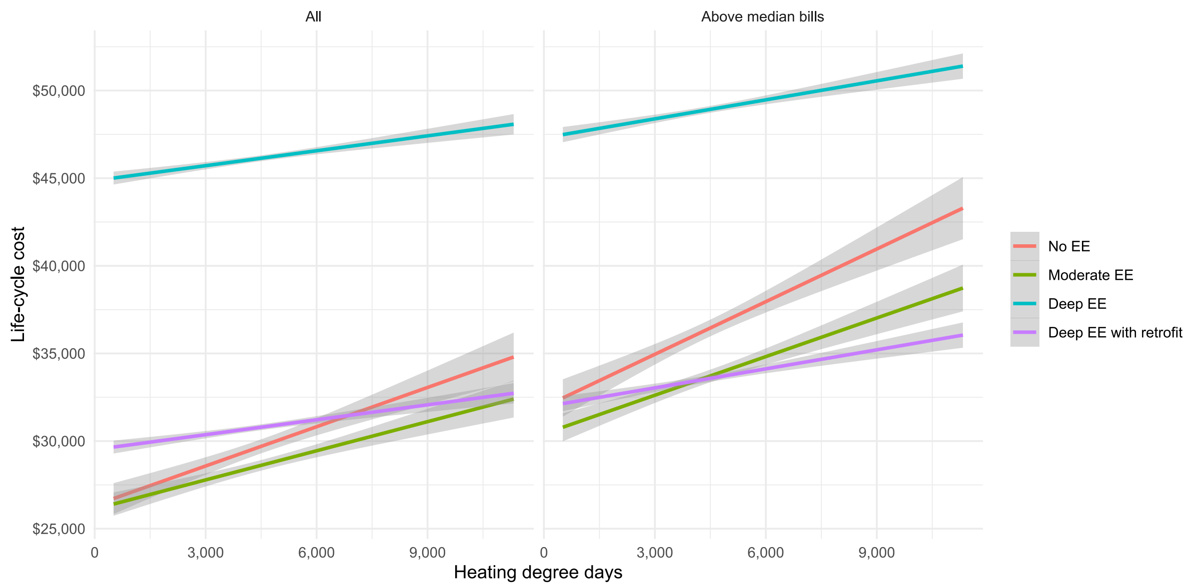


Figure B-1. Impact of energy efficiency packages on life-cycle costs for gas heat pumps. The figure shows the best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions. Costs are in 2020$.

Figure B-2 shows our analysis on efficiency packages for oil furnaces. The deep retrofit package at the time of home renovation is often the lowest cost option, particularly for homes with energy bills above the median.

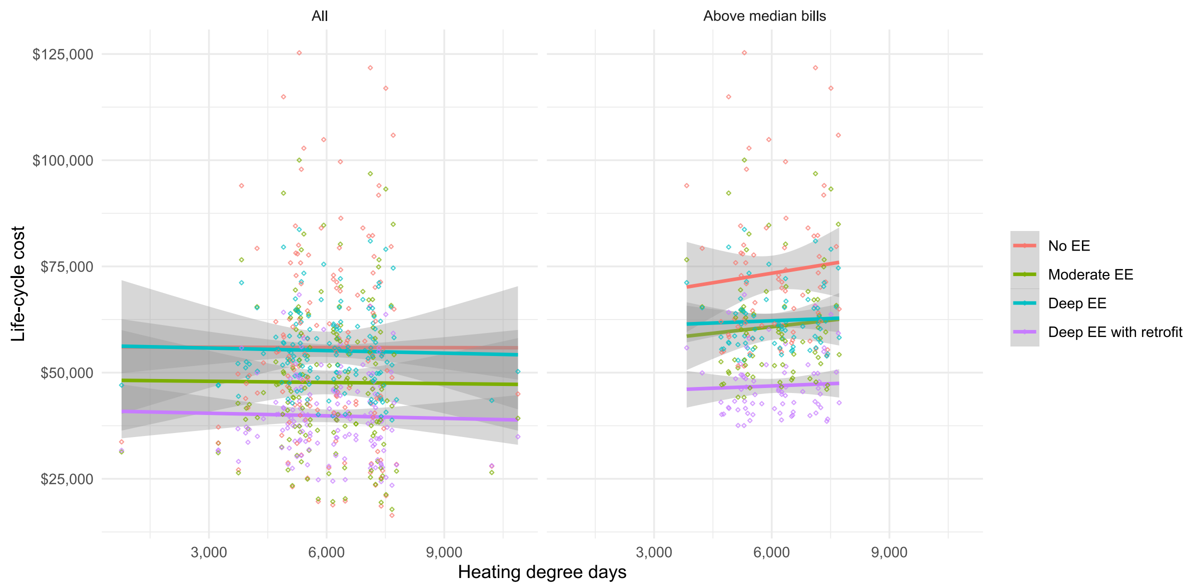


Figure B-2. Impact of energy efficiency packages on life-cycle costs for oil furnaces. The figure shows the best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions. Costs are in 2020$.

Figure B-3 shows our analysis on efficiency packages for propane furnaces. Results are generally similar to our analysis of oil furnaces in figure B-2.

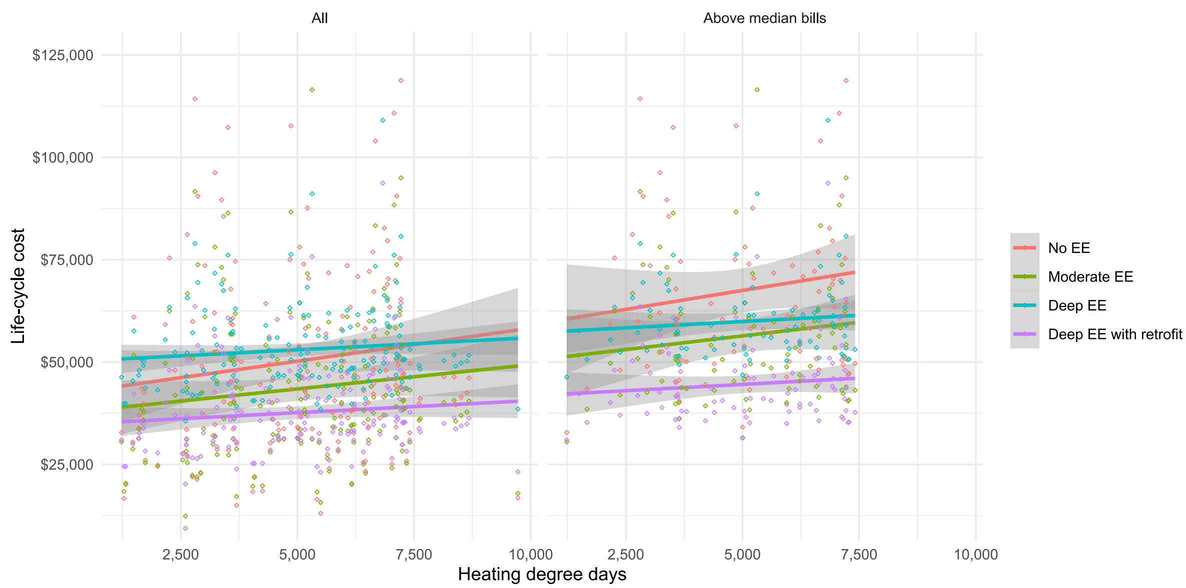


Figure B-3. Impact of energy efficiency packages on life-cycle costs for propane furnaces. The figure shows the best-fit lines for all homes (left) and for homes with energy bills above the median (right), using medium-cost assumptions. Costs are in 2020$. To make the lines clearer, we deleted a few data points with very high life-cycle costs.

Figure B-4 shows our analysis on efficiency packages for gas hot-water boilers. The deep retrofit package at the time of home renovation often makes sense above roughly 2,200 HDDs and for homes with energy bills above the median.

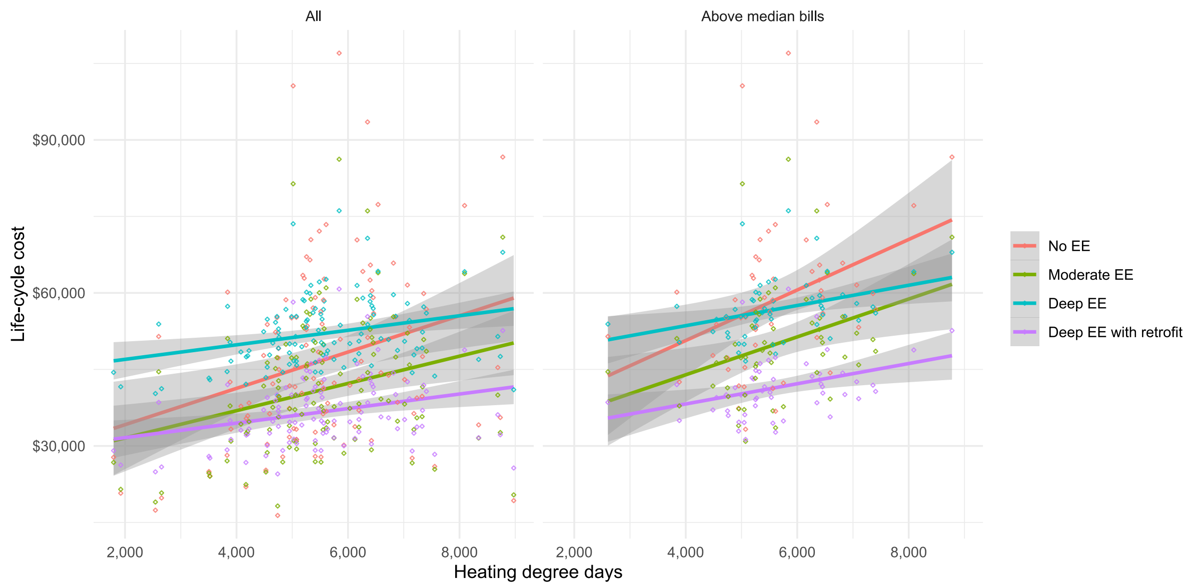


Figure B-4. Impact of energy efficiency packages on life-cycle costs for gas hot-water boilers. The figure shows the best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions. Costs are in 2020$.

Figure B-5 shows our analysis on efficiency packages for oil hot-water boilers. The moderate efficiency package lowers life-cycle costs on most homes, as does the deep retrofit package at the time of home renovation. For homes with energy bills above the median, a deep retrofit may pay off even without the cost savings of incorporating it into home renovation.

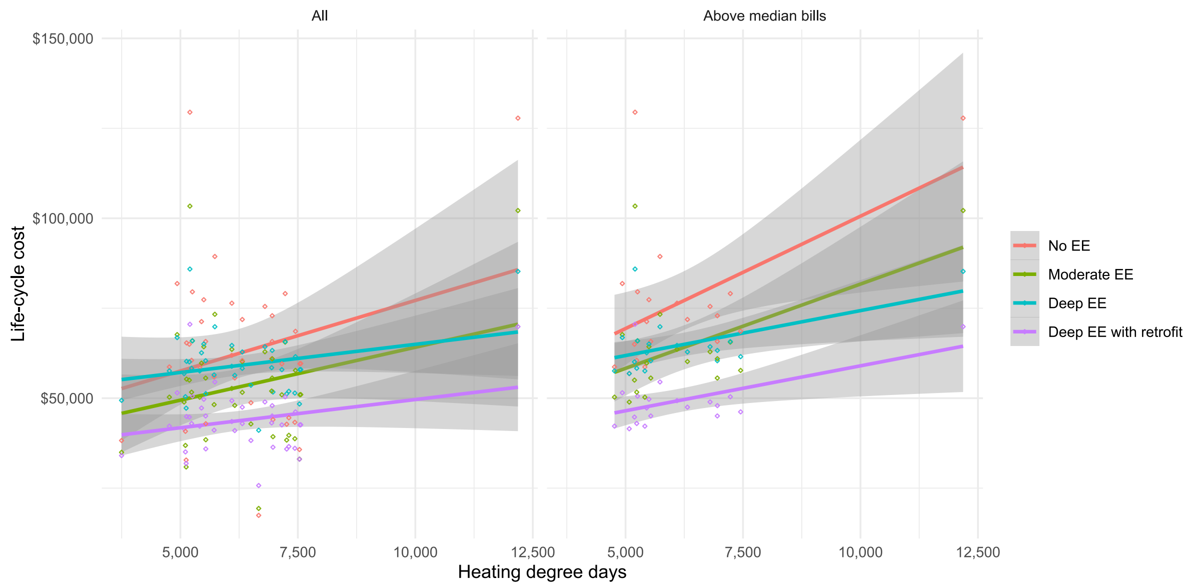


Figure B-5. Impact of energy efficiency packages on life-cycle costs for oil hot-water boilers. The figure shows the best-fit lines for all homes (left) and for homes with energy bills above the median (right) using medium-cost assumptions. Costs are in 2020$.