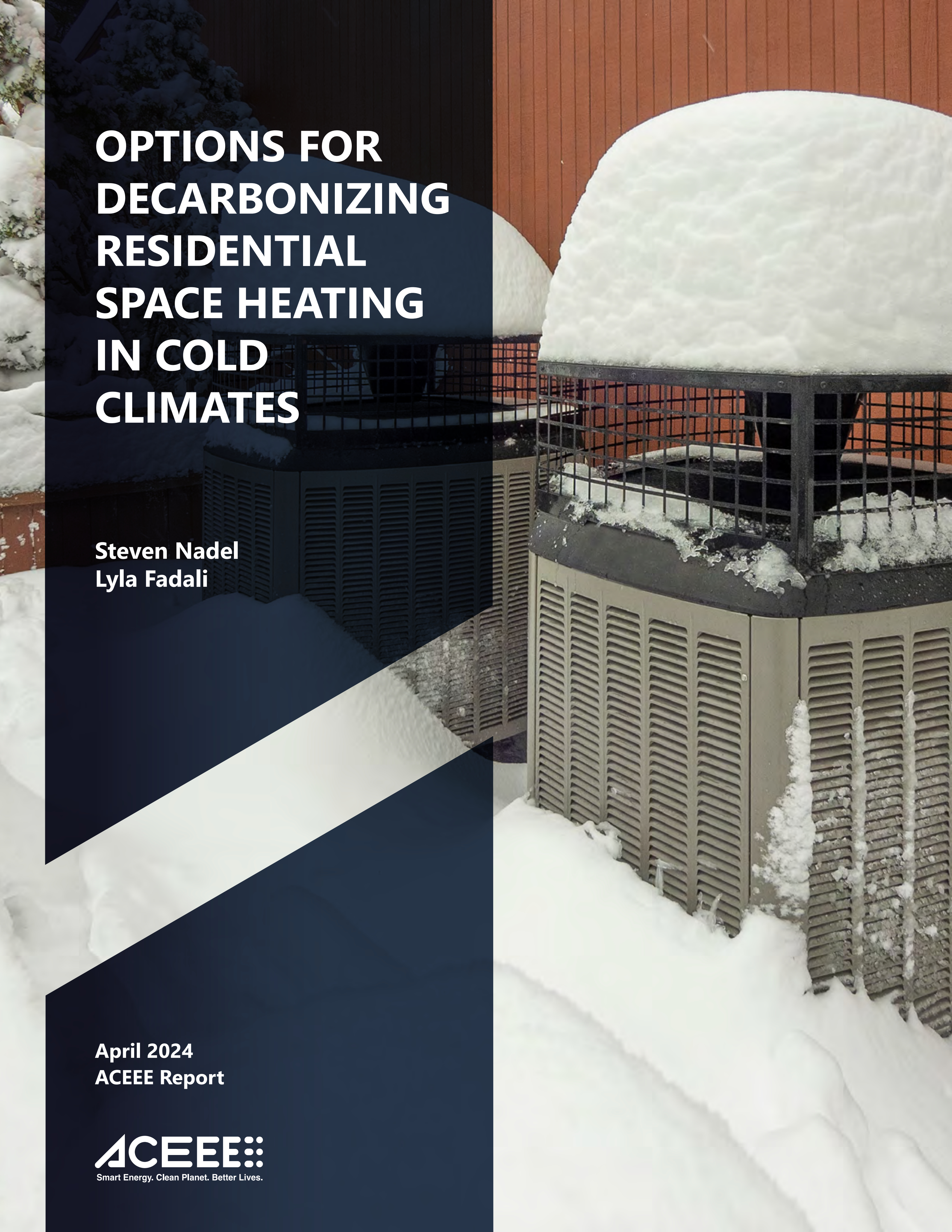

OPTIONS FOR DECARBONIZING RESIDENTIAL SPACE HEATING IN COLD CLIMATES

Steven Nadel
Lyla Fadali

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ACEEE Report

ACEEE
Smart Energy. Clean Planet. Better Lives.

Contents

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.

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Executive Summary

Key Findings

- Even in cold climates, electrification of most space heating is possible and can be cost effective.
- In climates with approximately 7,000 heating degree days or more (e.g., the current climate in Concord, New Hampshire or Madison, Wisconsin), a hybrid system combining a cold climate heat pump and a furnace with a biofuel backup will minimize life-cycle space heating costs compared to using reduced-carbon fuels (e.g., biogas). These findings are affected by the impact of heat pumps on peak winter power demand and hence on electricity prices.
- For homes now heated with gas hot-water boilers, an air-to-water heat pump combined with a moderate weatherization package (such as those promoted via Home Performance with ENERGY STAR®) will typically minimize life-cycle energy costs.
- As a backup fuel for hybrid systems, biogas supplied via existing gas distribution systems generally minimized life-cycle costs—assuming pipes do not need to be replaced and most customers stay on the gas system. If these conditions do not apply then electric resistance as a backup minimizes life-cycle costs, followed closely by propane made from biogas and propane made from ethanol. For a substantial majority of homes, a 100-gallon tank, filled annually by truck, would meet backup needs for an entire winter.
- Using biofuels as a backup energy source is not true decarbonization because biofuels emit greenhouse gas emissions when burned. Only some of those emissions are offset by the carbon captured during growth of the feedstock. Still, while biofuels may not reduce greenhouse gas emissions as much as electric heat pumps powered by low-carbon electricity, they can reduce consumer life-cycle space heating costs when employed as a backup fuel and keep winter peak electric demand from rising too fast.

A previous ACEEE study examined all the individual homes in the 2015 Residential Energy Consumption Survey (RECS) and found that on average for 1–4 family buildings, the lowest-cost decarbonization option was an air-source heat pump powered by a clean electric grid for locations below 6,000 heating degree days (HDD). Above 6,000 HDD, the low-cost option was a hybrid system that combines a cold climate heat pump with a fuel-fired backup system.

Our new study expands this analysis by looking individually at homes in the 2020 RECS data set and adding scenarios that examine the impact of electrification and gas pipe replacement on gas distribution costs, adding ground-source heat pumps, and delving into multiple hybrid heating options for cold climates. We focus on existing homes and assume that they need to install a new heating system in 2030 when their existing heating system reaches end-of-life.

Alternative hybrid-fuel options to backup heat pumps in cold climates include biogas, propane derived from biofuels, and biodiesel;[1] use of these fuels can reduce but not eliminate greenhouse gas emissions. The 2020 RECS contains more than 2,000 gas-heated homes in climates above 6,000 HDD. We analyze each of these homes and summarize how each of the options affects consumer life-cycle energy costs. Our analysis includes the impact of increased electrification on peak winter power demand and hence on electricity prices.

However, we caution that future biofuel prices are subject to substantial uncertainty; we examine alternative prices in the body of the report and an appendix. We also note that these fuels can vary greatly in their greenhouse gas emissions, as well as in local air quality and other impacts. The use of biofuels offers carbon reduction but not true decarbonization as biofuels still emit greenhouse gas emissions when burned, with only some of those emissions offset by accounting for the carbon captured during growth of its feedstock. The reader should not ascribe equivalent greenhouse emissions reductions to these alternative fuel pathways.

LOWER-CARBON ALTERNATIVES TO NATURAL GAS WARM-AIR FURNACES

We examine the life-cycle costs for space heating, comparing several heat pump systems to furnaces that burn lower-carbon alternative fuels such as biogas. We individually examine each cold climate home in the 2020 RECS; for each system type, we then construct best-fit lines. We consider scenarios with no change to gas distribution systems, with fewer gas customers due to electrification, and with higher costs for cold-climate heat pumps. Figure ES-1 shows this approach for a subset of system types and scenarios.

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[1] Wood and hydrogen are other potential options, but we did not examine these for reasons that we explain later in the report.

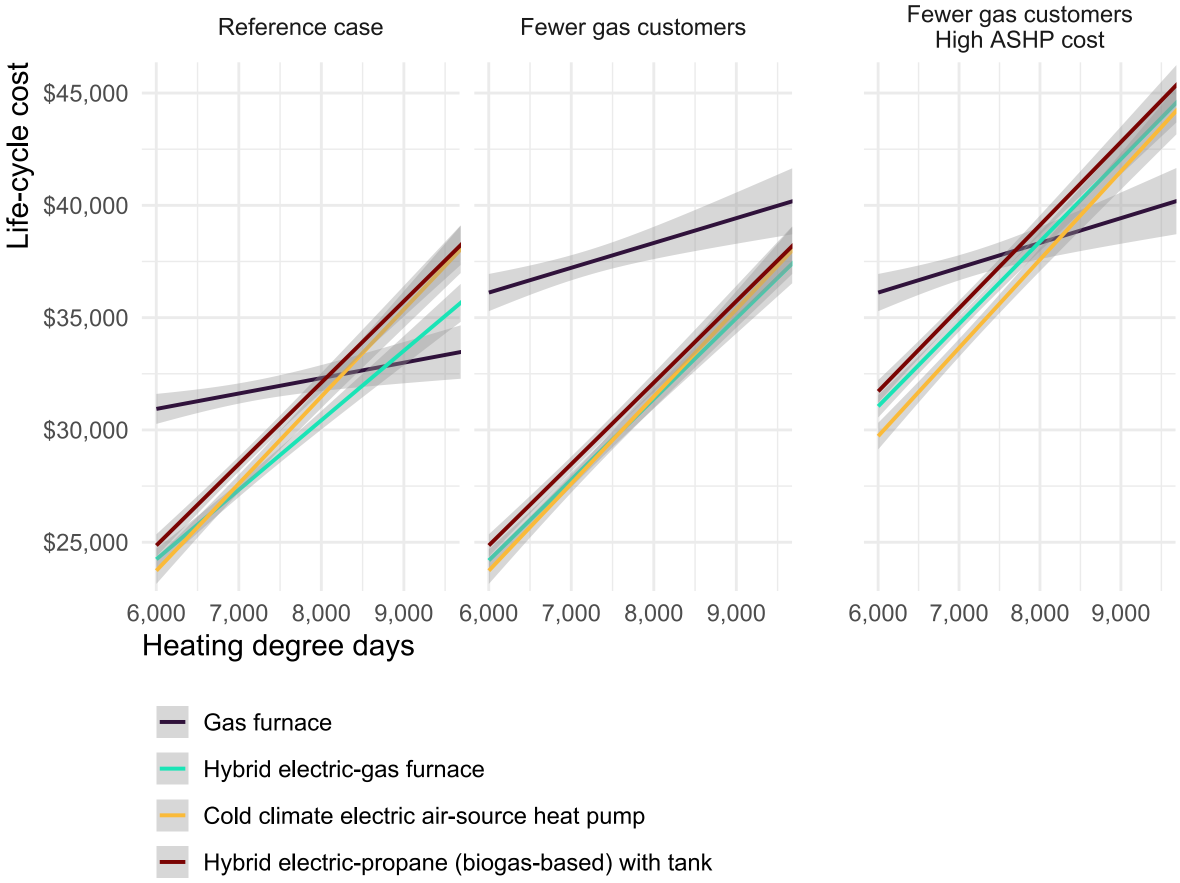

Figure ES-1. Comparison of life-cycle costs for space heating with warm-air distribution for three heating system types and three scenarios. Costs are in 2023 dollars.

As the figure shows, for climates similar to the current climate in Concord, New Hampshire or Madison, Wisconsin (i.e., above approximately 7,000 HDD), under our assumptions, a hybrid cold climate heat pump system with a biogas backup will minimize life-cycle space heating costs. Relative to our prior 2022 study, the dividing line between using only heat pumps and using a hybrid system increases from 6,000 to 7,000 HDD due to use of newer RECS data and to revisions to heating system and biogas costs.

As a reduced carbon backup fuel for hybrid systems, we find that biogas supplied via existing gas distribution systems has the lowest life-cycle costs—assuming pipes do not need to be replaced and most customers stay on the gas system. If these conditions do not apply then propane made from biogas, followed closely by propane made from ethanol, generally has the lowest life-cycle costs, and B100 and renewable diesel are only a little more expensive. For a substantial majority of homes, a 100-gallon tank filled annually by truck would meet backup needs for an entire winter.

Our results indicate that there may be viable routes to decommission gas distribution systems in cold climates and provide backup heat via delivered fuels.

LOWER-CARBON ALTERNATIVES TO NATURAL GAS HOT-WATER BOILERS

For boilers, we find that an air-to-water heat pump combined with a moderate weatherization package (along the lines of Home Performance with ENERGY STAR) will typically minimize life-cycle energy costs. The weatherization both reduces life-cycle costs and helps each room to have adequate heat with lower hot-water temperatures provided by the heat pump. Without weatherization, a backup boiler will often be needed in cold climates to provide adequate heat in each room, raising the hot-water temperature to the 160–180°F for which most hot-water distribution systems are designed. However, for unweatherized homes in climates below 9000 HDD (approx. Duluth), adding a backup boiler will increase life cycle costs compared to installing an air to water heat pump.

ENERGY EFFICIENCY REMAINS CRITICAL

In all of these scenarios, either a moderate energy efficiency package (e.g., a typical Home Performance with ENERGY STAR package) or a deep retrofit at the time of a major remodel will reduce life-cycle space heating costs. These packages also improve resident comfort.

CONCLUSION

Overall, we find that electrification of most space heating is possible and can be cost effective in even cold climates. However, some use of biofuels can be useful as a backup to reduce consumer life-cycle space heating costs and to keep winter peak electric demand from rising too fast. It is essential to note that while useful, biofuels do not reduce greenhouse gas emissions as much as electric heat pumps with a low-carbon electricity supply.

Introduction

Increasingly, governments, utilities, and many businesses and consumers are looking to dramatically reduce carbon emissions in order to protect the climate and deliver benefits to communities and households.

In 2022, ACEEE examined the life-cycle costs of various ways to largely decarbonize home heating for 2,539 homes across the United States that used fossil fuels for space heating. We conducted this examination using detailed data from the Energy Information Administration (EIA) 2015 Residential Energy Consumption Survey (RECS; EIA 2018). In addition to several types of electric air-source heat pumps (ASHPs), we considered several types of gas and oil-fired equipment that use biofuels with lower net emissions than similar fossil fuels. We found, on average, that ENERGY STAR® electric ASHPs will have the lowest life-cycle space heating costs in climates below approximately 4,500 heating degree days (HDD)[2] (about the climate of Baltimore); that cold climate electric ASHPs (designed to deliver full heating capacity down to 5°F and to still continue operating at even colder temperatures) have the lowest life-cycle space heating costs between 4,500 and 6,000 HDD (with 6,000 being the approximate climate of Detroit, Michigan, and Albany, New York); and that above 6,000 HDD, hybrid systems (cold climate heat pumps backed up by fuel-burning systems) have the lowest life-cycle energy costs (Nadel and Fadali 2022). Figure 1 shows a key summary graph from this study.

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[2] Degree days are the difference between the daily temperature mean (high temperature plus low temperature divided by two) and 65°F. If the temperature mean is below 65°F, we subtract the mean from 65 and the result is the heating degree days (NWS 2023). If on a winter day the average outdoor temperature is 35°F, then 30 HDD accrue that day (65 minus 35). The HDD are added for each day of the heating season to produce an annual total.

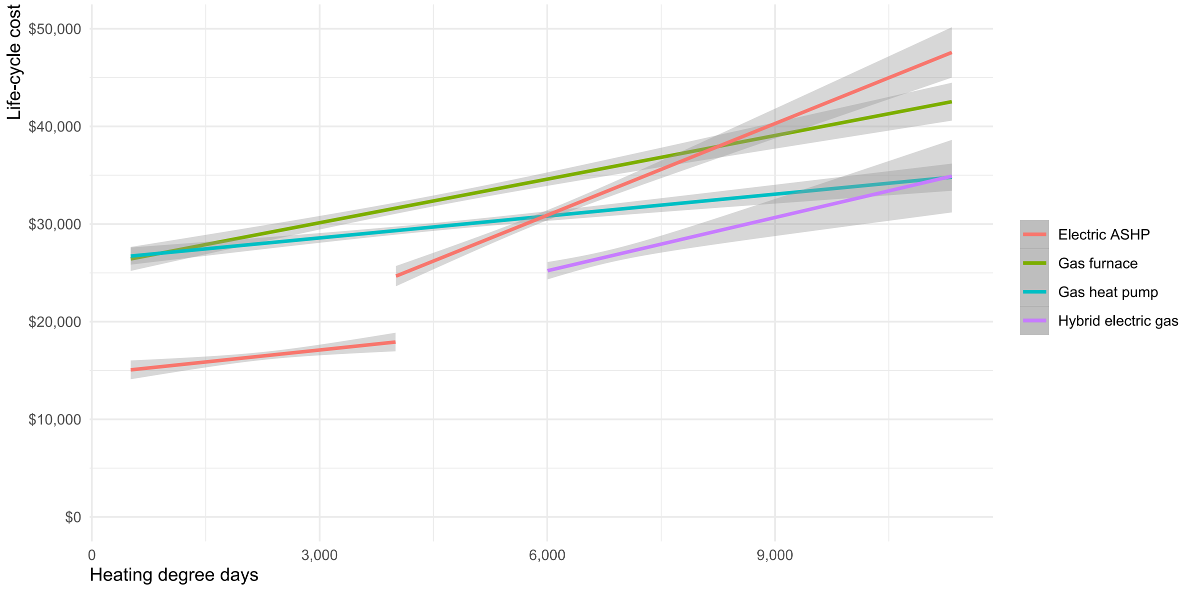

Figure 1. Life-cycle cost best-fit lines for electric air-source heat pumps (ASHP), condensing gas furnaces using biofuels, gas heat pumps using biofuels, and hybrid electric heat pump/condensing gas biofuel furnace systems for single-family homes now heated with natural gas. Data are from our 2022 study. The gap in the electric heat pump line shows the impact of costs for cold climate heat pumps for locations with 4,000 heating degree days (HDD) or more. Costs are in 2020 dollars. In this 2024 report, we update and expand this analysis. Source: Nadel and Fadali 2022.

In 2023, ACEEE looked in more detail at natural gas distribution systems (Nadel 2023a), finding that costs could increase substantially in the future due to three factors:

- Customers electrifying space and water heating as well as other end uses, leaving fewer customers to cover fixed system costs.
- Substantial investments being planned for pipe replacement in some areas, particularly those with aging distribution systems such as along the U.S. east coast.
- The cost of biofuels, which can be substantially more expensive than current fossil fuel costs.

In this new report, we seek to bring these two research streams together. Specifically, we focus here on buildings with 1–4 dwelling units (e.g., single-family homes and duplexes) in cold climates (those with more than 6,000 HDD[3]) that are now heated with natural gas.[4] This report also provides the following:

- We update the 2022 analysis using homes in the EIA's recently released 2020 RECS (EIA 2023a).
- We update our previous analysis to reflect some of the impacts from our 2023 study on gas distribution systems.
- We extend the analysis to include ground-source heat pumps (GSHPs) as an option.[5]
- We focus in particular on backup heat for hybrid systems in cold climates, considering both biogas delivered via gas distribution systems and delivered fuels such as propane biogas and biodiesel.

We focus on homes now heated with natural gas in order to examine situations where these homes could continue to be served by gas distribution systems and where they could be served by delivered fuels. For homes now served by delivered fuels, we assume that they will continue to use these fuels for backup heat but will switch to low-carbon versions of these fuels.

This new report is written for cold climate state officials, utilities, and other people interested in cold climate decarbonization options. Our goal is to inform them about which system types are most likely to minimize life-cycle space heating costs in cold areas, including consideration of options that are not widely discussed, such as GSHPs and use of delivered biofuels.

Methodology

Our detailed analysis looks at each individual dwelling unit in the RECS 2020 dataset that aligns with our study's scope (see below). RECS includes detailed data on a representative sample of homes throughout the United States. We conducted our analysis on each

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[3] Our HDD values come from the RECS data for each home and are 30-year averages for the period 1981–2010. 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).

[4] 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 the label "fossil fuel gas." We elected to stick with natural gas here but note the alternative term.

[5] Ground-source heat pumps (GSHPs) are a heating and cooling system for buildings that use a type of heat pump to transfer heat to or from the ground, taking advantage of the relative constancy of the earth's temperatures across seasons (USDOE 2023a). These pumps are sometimes called geothermal, GeoExchange, or earth-coupled heat pumps.

individual home in the RECS dataset located in a climate of 6,000 HDD or more. Our general approach is to assume that new equipment is installed in 2030 to replace existing equipment that has reached end of life. We use 2030 to allow time for many decarbonization policies to fully take effect and for equipment recently entering the market to become more established. We look at life-cycle costs to homeowners for space heating, including the initial system cost and annual energy costs over the equipment's assumed 18-year life. We do not include tax credits or utility rebates. Costs incurred after 2030 are discounted back to 2030 using a 5% real discount rate. We also factor in reduced air-conditioning costs for cases in which ENERGY STAR heat pumps replace less-efficient central air-conditioning systems. For energy costs, we use projected energy costs in 2040, roughly midway through the life of equipment installed in 2030. Our analysis looks only at direct equipment and energy costs and does not factor in societal costs such as health costs or impacts of climate change. These other costs can be difficult to quantify but should be considered in some fashion.

A total of 2,939 homes are included in our dataset. We examine each home's energy use and costs in 2020 (the latter based on home-specific average gas and electric rates[6]), and then adjust for projected changes in costs between 2020 and 2040 using national projections in the EIA's *2023 Annual Energy Outlook* (EIA 2023b). The costs and performance of the various types of heating systems are generally taken from and documented in a 2023 study prepared for EIA (Guidehouse and Lydos 2023) and our 2022 study (Nadel and Fadali 2022). For this study, we express these costs in 2023 dollars, adjusting for inflation using the implicit price deflator compiled by the Federal Reserve Bank of St. Louis (FRED 2023).

For options added to this study but not included in the 2022 study, we document the assumptions in Appendix A. We also updated the cost of biofuels and necessary electric system upgrades. For biofuels, we offer specifics in the next section and further document our analysis in Appendix A. For electric system upgrades, we used $2,000 as the average cost of an upgrade (IL TRM 2023). Another source (Guidehouse 2022), estimates $2,500, but that analysis doesn't account for the percentage of homes that need upgrades, whereas the Illinois TRM accounts for homes with adequate electrical service. For our analysis we generally use $2,000 for homes without central air conditioning, $1,250 for homes with central air conditioning that electrify without a backup fuel-based system and $0 for homes with central air conditioning and with a backup fuel-based system. We assume less for homes with air conditioning since these homes typically have more electric service and are less likely to need electric upgrades (we effectively assume only half these homes need upgrades). For our high-cost scenario we use $2,500 for homes without central air conditioning and the same assumptions as above for homes with central air conditioning.

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[6] We calculate average energy costs in 2020 for each home using RECS data on energy use and costs. These data do not allow us to separate out the fixed and variable cost portions of rates.

We recognize that there is great uncertainty about 2040 energy prices, hence our results should be considered highly approximate but useful for comparative purposes. In Appendix B, we include a few scenarios in which cost breakthroughs are achieved to reduce some specific energy costs that currently appear high. We also include some higher cost scenarios. Also, results are tightly grouped in terms of life-cycle energy costs for many of our options, so if a few energy sources in this grouping ultimately prove to be more expensive, they will exit this grouping and leave its remaining energy sources more attractive. And if all energy sources are more expensive, the relative results between options will not be substantially different from what we report here.

Energy Sources Examined

For this study, we consider several energy sources that reduce life-cycle greenhouse gas emissions to varying degrees. We include clean electricity, biogas to replace natural gas, propane biogas, biodiesel (B100), and "renewable diesel."

ELECTRICITY

Carbon emissions from electricity generation have been steadily declining (EIA 2022a), and the United States has set a goal to fully decarbonize our economy by 2050 (Department of State and Executive Office of the President 2021). We assume that by the 2040s, electricity will be largely decarbonized in many states and that this trend has affected electricity price projections in EIA's *Annual Energy Outlook* (EIA 2023b). For electricity prices, we start with retail electricity prices in 2020, as paid by each home in the RECS dataset. This allows us to capture utility-specific and home-specific effects. We then include two multipliers: (1) an adjustment for the average national electricity price in 2040 relative to the price in 2020, and (2) an adjustment for increased costs due to higher winter peaks caused by substantial electrification. This second adjustment is based on published studies from several different regions and varies based on climate, with no adjustment in warm climates (e.g., the South[7]), a moderate adjustment in climates such as Maryland, and a large adjustment in climates such as Minnesota. The left side of figure 2 illustrates this adjustment factor.[8]

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[7] In fact, in the South, electric resistance heat is common and heat pumps can reduce wintertime energy use, freeing up electric capacity for electrification of space and water heating and other loads. Nadel, Amann, and Chen (2023) show this in Texas.

[8] We use HDD as our primary climate indicator but note that peak demand and a site's maximum heating load is driven by the coldest temperature (the design temperature) reached at a site. Our previous analysis found that 6,000 HDD on average equates to a design temperature of 5°F, but there are variations.

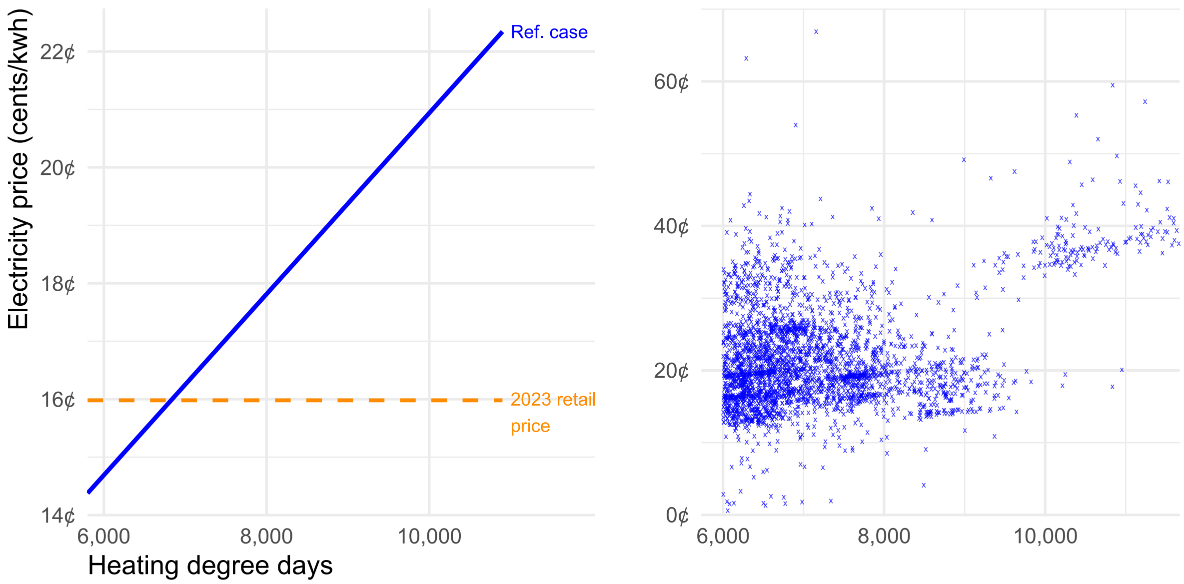

Figure 2. The left-side graph compares different estimates of national electricity price in 2040 relative to the 2023 national average electricity price. This incorporates winter peak demand impacts due to electrification of space and water heating, and hence prices increase as heating degree days (HDD) increase. Estimates are in 2023 dollars; the 2023 average retail price is from EIA 2024. On the right, a plot of the average electricity price used for each of the homes in our sample is expressed in relation to HDD. These electricity prices are based on home-specific prices in 2020, updated to 2040 based on information from the left-side graph.

Details on these adjustments are described by Nadel and Fadali (2022) and include both the cost of some additional power generation as well as programs to reduce winter peak, such as demand response programs. As the Electric Power Research Institute (EPRI 2018) notes, growing winter peaks will drive investment needs in much of the country. U.S. electricity sales are increasing, due in part to electrification, but we do not include an adjustment for these increased electricity sales, which can spread fixed costs over a wider base (Nadel 2024).

The left side of figure 2 shows the national average electricity price in 2040, adjusted for winter peaks. The figure's right side plots the rates used for individual homes based on 2020 rates for each home and adjustments to estimate 2040 rates. We use 2040 energy prices as that year is about midlife for equipment installed in 2030. Appendix A of the 2022 study (Nadel and Fadali 2022) provides further details. We did not include a sensitivity analysis with higher or lower electricity prices because, while there are price uncertainties, in our view these uncertainties are likely to play out differently in different regions, with prices increasing more in some regions (e.g., due to growing winter peaks) and less in others (e.g., due to growing industrial and transportation loads, allowing fixed costs to be spread over larger power sales). We do not expect systematic national trends but instead recommend that future work delve into these issues at a regional level.

Furthermore, these prices are based on 2020 rate classes, which often combine general use and electric heating customers in the same rate class. Some states and utilities are now establishing separate rate classes for electric heating customers. This often increases fixed charges and reduces variable charges, and generally reduces the overall cost of heating with electric heat pumps. The energy prices we use here are approximations; more refined analyses are needed to estimate state- and utility-specific prices in 2040 as well as to potentially break prices down into fixed and variable cost components and consider electric heating rates where applicable.

A NOTE ON PEAK DEMAND IMPACTS OF ELECTRIC HEATING

When temperatures get below 5°F, heat pumps may not be able to fully meet heating loads, and supplemental heating may be needed. If this supplemental heat is from electric resistance coils, it can contribute substantially to winter peak electric demand. To get a handle on what these peaks might be, for each home in our sample we estimated the peak power demand on the coldest day in the winter assuming use of electric resistance heat. This is the maximum demand; heat provided by the heat pump on even those coldest days can reduce this demand substantially. Still, it is useful to know the maximum possible demand. We estimated maximum possible power demand for each home based on winter heating energy use, HDD, and winter design temperature for each site. Across our entire sample, the average maximum heating demand was 5.5 kW of power per home. Figure 3 shows a scatterplot and best-fit line for this demand as a function of HDD.

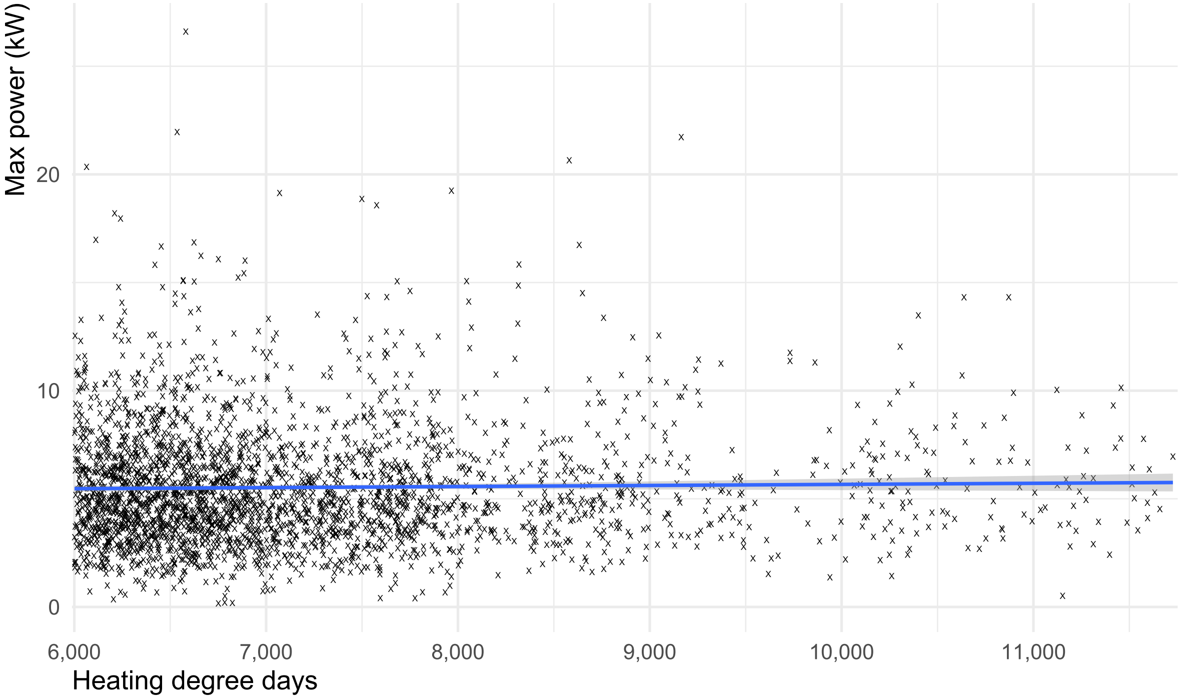

Figure 3. Maximum power demand for space heating for each home in the dataset and a best-fit line. We calculated these figures based on heating fuel consumption, heating degree days, and design temperature for each home in our sample.

CARBON EMISSIONS OF BIOFUELS

Before proceeding to a discussion of individual biofuels, it is important to put carbon emissions from biofuels in context. Biofuels release carbon dioxide when they burn and, they release methane (also a greenhouse gas) when they leak, but some of these emissions can be displaced in their production. For example, biofuels can be made from plants that remove carbon dioxide from the atmosphere as they grow, or they can be made from animal excrement or landfills, which, if not used to produce fuel, would instead release methane into the atmosphere as the waste breaks down in the environment. However, most of these fuels do have some carbon emissions that will need to be offset. To date, biofuels have not been shown to approach the greenhouse gas emissions reduction performance of renewable electricity sources or nuclear power.

For example, the California Low Carbon Fuels Data Dashboard estimates that biodiesel sold in California has about 75% lower greenhouse gas emissions on average than conventional diesel, while bio-LPG fuel (liquified petroleum gas, another name for propane) has roughly 30% lower emissions than propane produced from fossil fuels (CARB 2023). As we discuss below, some new biofuels may do somewhat better, but no such alternative has yet been shown to scale. It is important for readers to understand that low-carbon fuels are nascent technologies and markets in comparison to proven large-scale production from low-carbon electricity sources such as wind, solar, hydropower, and nuclear power. We also note that this discussion applies to fuels with very low emissions; mixing moderate amounts of these low emissions fuels with natural gas or fuel oil will only modestly reduce emissions from natural gas and fuel oil.

Currently, there is also no model for how biofuels can scale dramatically; as we discuss below, supplies are likely to be limited. For this reason, we focus on biofuel as a backup for use when outdoor temperatures plummet, thereby requiring much more limited biofuel quantities.

ACEEE plans to investigate alternative low-emission fuels more thoroughly and publish a report in late 2024.

NATURAL GAS

For natural gas, we also start with 2020 prices as paid by each home; we then include a multiplier based on the projected increase in the national average natural gas price between 2020 and 2040. Next, we make three adjustments. First, we assume that this fuel will need to be low carbon no later than 2040; to address this need, we assume the use of biogas. A 2022 study by the consulting firm ICF for the New York State Energy Research and Development Authority (NYSERDA) estimated 2040 renewable natural gas (RNG) costs for five different production pathways (ICF 2021); we took a simple average of the five pathways—$25.61 per million Btu (2022$)—and adjusted it to 2023 dollars using the Federal Reserve implicit price deflator (FRED 2023). Future biogas costs are much debated, so we also ran sensitivities at costs 25% higher and lower, along with more extreme estimates that 2040 costs would be half or double this amount.[9] 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.[10] In some scenarios we used the 50% electrification scenario from Nadel (2023a), with a gas price increase of 43%. This increase reflects the fact that fixed costs previously paid by leaving customers will now need to be paid by the remaining customers.[11] Third, in some scenarios we applied a 15% adder for gas pipe replacement. This is based on the moderate gas pipe replacement program in Maryland, as discussed by Nadel (2023a). Figure 4 summarizes the residential gas prices we use. Again, these prices are approximations; ultimately, further analyses are needed to estimate state- and utility-specific prices.

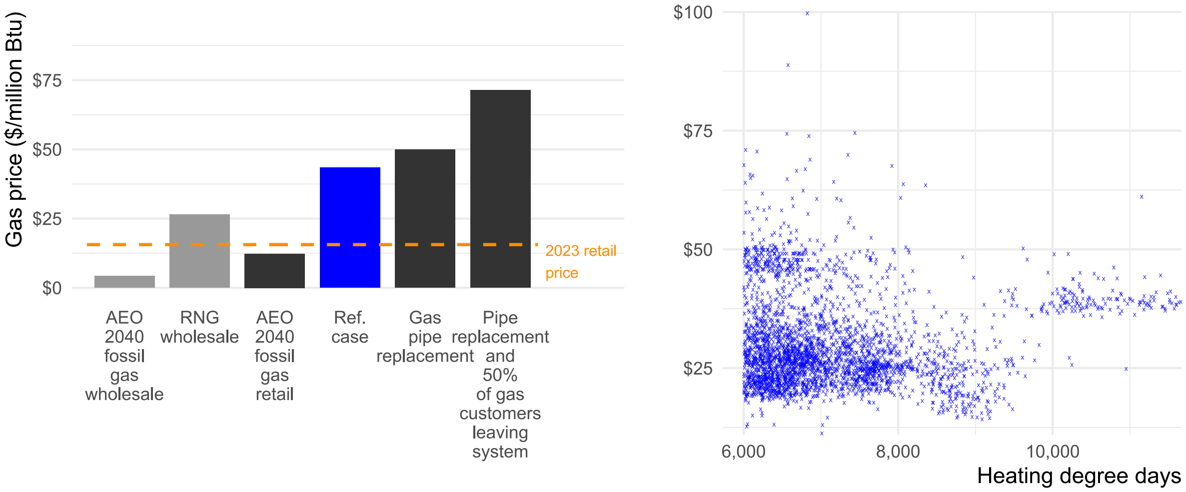

Figure 4. On the left is a comparison of 2040 residential gas costs; the first three are wholesale costs, and the next three are retail. The 2023 retail price is from EIA 2024. All are in 2023 dollars. Appendix A offers further details. On the right, a plot of the average natural gas price employed for each of the homes in our sample is expressed in terms of heating degree days (HDD). These gas prices are based on home-specific prices in 2020, updated to 2040 as shown for the national average with the blue bar.

PROPANE BIOGAS

Small quantities of propane biogas are produced by a process that converts vegetable oils into biodiesel. However, more than 90% of the fuel produced by this process is biodiesel and less than 10% is propane biogas (Dr. P. Littlewood, principal scientist, GTI, pers. comm.,

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[9] Costs could be lower if economies of scale or technical breakthroughs reduce costs. Costs could be higher if demand for biofuels is high enough that expensive biomass sources need to be used (ICF 2019).

[10] These costs can potentially be reduced through techniques such as accelerated depreciation, securitization, and pruning gas lines, but we did not assume use of these techniques.

[11] We are not saying that enough biogas is available to meet 50% of residential space heating needs; we use 50% to provide a midpoint between no customers leaving and all customers leaving.

October 2023). To produce greater quantities of propane biogas, GTI Energy has developed a process to produce synthetic propane, called Cool LPG, from other types of biogas. Biogas can be produced in many ways and is available in much larger quantities than vegetable oils (Kriz 2023). GTI has entered into a partnership with the for-profit firm BioLPG to develop this new technology for developed countries such as the United States and is also partnering with the Global LPG Partnership (a nonprofit organization supported by the United Nations) for markets such as Africa. Plans are to construct pilot-scale plants by 2024 and full-scale plants by the end of the decade (Littlewood et al. 2022; Dr. P. Littlewood, principal scientist, GTI, pers. comm., October 2023).

GTI has also teamed with SHV Energy, a global propane distributor, to produce synthetic propane from ethanol. They are now working on scaling up the catalytic process. This second project is not as far along as the Cool LPG project (Karroum 2023; O. Akpolat, R&D manager, Energy Supply and Conversion, GTI, pers. comm., October 2023). An advantage of it, however, is that ethanol tends to be less expensive per Btu than biogas, particularly as demand for RNG increases while demand for transport fuels declines due to growing electric vehicle sales.

Other efforts are also attempting to derive low-carbon propane from ethanol. For example, UGI Corporation[12] recently signed a 15-year agreement with Vertimass, a California-based technology developer, to use Vertimass-developed catalytic technology to produce propane biogas and sustainable aviation fuel (SAF) from ethanol. The process will allow UGI to vary the mix of propane and SAF based on market demand. UGI anticipates a total investment of $500 million over a 15-year period, targeting total annual production—from multiple facilities—of 1 billion gallons of combined renewable fuels. The goal is to have the first production facility onstream in fiscal year 2024, with an annual production target of approximately 50 million gallons of combined renewable fuels (Biofuels International 2022).

The process was developed by Oak Ridge National Laboratory (ORNL) and licensed to Vertimass. Research by Vertimass, ORNL, and others estimates that the process reduced greenhouse gas emissions anywhere from 40–96% depending on the feedstock and the conversion pathway. Greenhouse gas emissions fell by 40% with corn grain, 70% with sugarcane juice, and 70–96% with cellulosic biomass such as sugarcane straw and corn stover (Hannon et al. 2019).

We estimate the price of propane made from biogas by taking the projected 2040 retail price of propane (from EIA 2023b) and separating it into wholesale and retail components

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[12] UGI Corporation (formerly United Gas Improvement Corp.) is a natural gas and electric power distribution company that provides gas and electric distribution services in portions of Pennsylvania. UGI owns AmeriGas, the largest propane marketer in the United States.

(using data from EIA 2023d). We then increase the wholesale component by a factor of about 10 based on the ratio of wholesale biogas cost (from ICF 2021) to the wholesale natural gas cost at the Henry Hub, plus an additional 10% for the estimated cost of processing biogas into propane. To estimate the price of propane made from ethanol, we also separate the retail price of propane into wholesale and retail components. In this case, however, we based the wholesale component on EIA's projection of the 2040 retail cost of ethanol relative to its 2040 natural gas projection for transportation, plus the cost of converting ethanol into propane from Hannon et al. 2019; Appendix A below offers further details. As with other biogas price estimates, we also include sensitivities with higher and lower costs.

As for the size of long-term supplies, ICF (2019), in a study for the American Gas Association, developed a "high scenario" estimate for biogas fuel availability by 2040, estimating that approximately 4,500 trillion Btu of biogas could be produced annually. This estimate includes some green hydrogen as well as controversial biogas sources such as municipal solid waste and energy crops. Depending on how these controversies are resolved, the available supply may not be as high as these estimates. For example, Borgeson (2020) argues that the ICF estimates are too high. To put the ICF estimate in perspective, its high scenario includes nearly enough gas to serve all current residential demand for natural gas. But much of this gas will be needed in other sectors; the residential sector accounts for only 5% of the total U.S. fuel demand (Nadel 2023a), and it thus might receive only a similar percentage of the available biogas supply. If biogas is sparingly used only as a backup fuel for home heating, there might be sufficient biogas supplies for the residential sector. But if residential demand is higher, then biogas will likely need to be supplemented with substantial amounts of fuel made from green hydrogen (Nadel and Fadali 2022).

If synthetic fuels are produced from ethanol, available feedstock supplies are likely to be substantial. Presently, ethanol is about 10% of the U.S. gasoline volume (EIA 2023c). As liquid fuel demand declines due to vehicle electrification, this fuel could be available for other uses.

BIODIESEL AND RENEWABLE DIESEL

Biodiesel is emerging as a more sustainable alternative to petroleum-based diesel. Biodiesel can be made from vegetable oils, animal fats, and even recycled food waste. Biodiesel can also exist on its own or be combined with petroleum diesel. Such fuels are referred to as "B" followed by the percentage of biodiesel (e.g., B100 contains 100% biodiesel while B20 contains 20% biodiesel). Most biodiesel work focuses on the fuel's potential for powering vehicles, but there are some companies that sell biodiesel for residential heating.

For home heating, it is essential to consider the percentage composition of biodiesel. Some fuel-oil dealers now sell B20 for use in home heating. The 20% mix can be burned in standard oil burners. This represents only a modest reduction in emissions at a time when decarbonizing rapidly is critical, but it does point to a potential path for some end uses. There are some notable requirements, however. For example, to use B5 or above in an existing system, the tank should be emptied and cleaned to remove lingering contaminants.

Also, the manufacturer of existing equipment should be asked if seals and gaskets are compatible with biodiesel percentages above 20% or if they should be replaced (AFDC 2023a). Furthermore, pure biodiesel, or B100, may be difficult to use in cold climates due to its cloud point—that is, the temperature at which crystallization occurs when the fuel systematically cools. Below the cloud point, solid crystals may plug filters or cause other fuel storage problems. The cloud point of B100 can vary, but it is important to store the fuel at least 2.5–5°C (5–10°F) higher than the cloud point. Generally, B100 can be stored underground without major modifications, as underground temperatures are usually higher than the fuel's cloud point (McCormick and Moriarty 2023). Indoor fuel tanks will also generally be acceptable.

Renewable diesel is another diesel-like fuel that is also typically made from vegetable oils (such as soy, corn, and canola). The difference is that renewable diesel is refined to be chemically the same as standard diesel, while biodiesel contains additional compounds not found in standard diesel (EIA 2022b).

Renewable diesel is chemically identical to standard diesel and can be used in existing systems without modification. For a largely decarbonized fuel, we examine 100% renewable diesel. Historically, production of biodiesel has been greater than renewable diesel, but EIA estimates that renewable diesel production passed biodiesel production in 2022 and will remain higher in future years (Shi, Sommer, and Smiddy 2022).

Fuel oil and renewable diesel burn at a higher temperature than natural gas and propane and thus will generally have higher nitrogen oxide emissions. Fuel oil also has higher sulfur dioxide and particulate emissions (EDF and UGC 2009), as figure 5 shows (small homes use #2 oil, while large buildings sometimes use #6). Renewable diesel is chemically identical to #2 oil and hence has the same emissions. NO_x and fine particle pollution can affect the lungs and heart, contributing to respiratory diseases such as asthma and heart problems (EPA 2023a, 2023b). These health problems should be kept in mind when considering the advantages and disadvantages of these fuels.

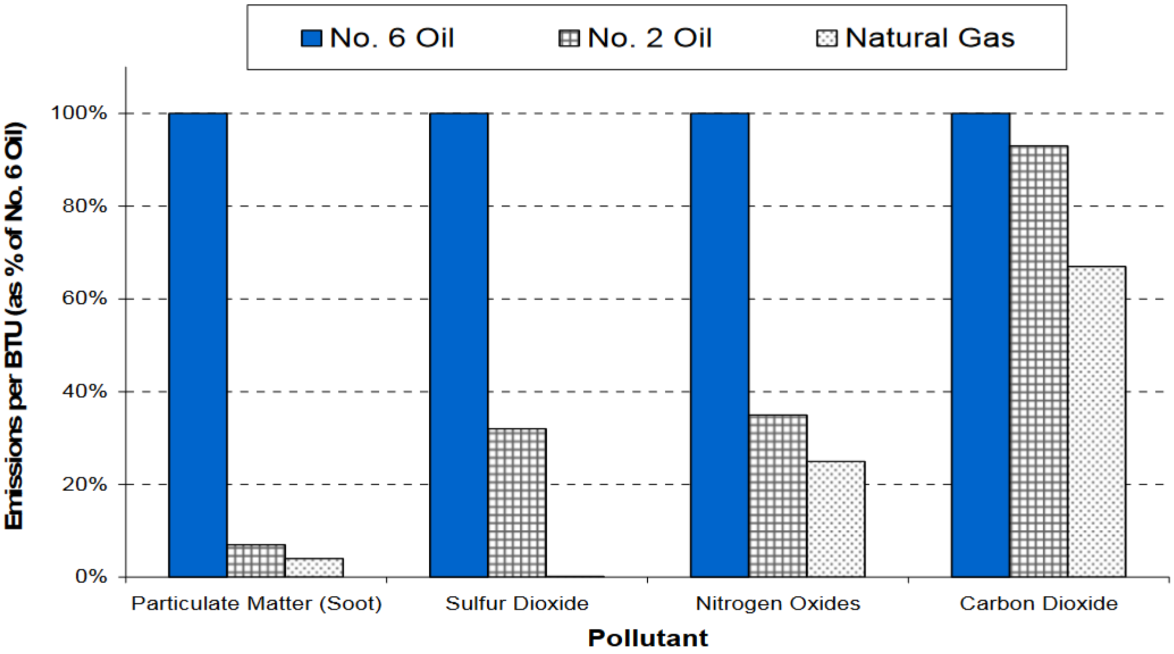

Figure 5. Comparison of emissions from different fossil fuels for home heating. Source: EDF and UGC 2009.

B100 prices are tracked by the DOE Alternative Fuels Data Center. In July 2023, B100 sold for $4.53 per gallon, which is 16.5% more than standard diesel fuel (AFDC 2023b). The Organization for Economic Co-Operation and Development and the UN Food and Agriculture Organization estimate that biodiesel prices will be steady through the 2020s (OECD and FAO 2021). We found no publicly available projections beyond 2030. However, given the level prices projected through 2030 and data from California, which indicate that regular diesel and renewable diesel prices track together (AFDC 2023b), for our 2040 price estimate for B100 we apply the 16.5% adder to EIA's projection of 2040 residential fuel oil prices. We also estimate the price of renewable diesel as 12% higher than B100 based on its higher current production costs (Omidkar et al. 2023).

In terms of availability, biodiesel and renewable diesel production has been growing, using agricultural crops such as soy, corn, and canola. The emissions reductions impact of these fuels is thus far limited, and production represents only a small fraction of the overall use of liquid fuels in the United States. There has been steep growth in biodiesel and renewable diesel production in the 2010–2022 period, primarily to serve the alternative fuel for vehicles market. EIA projects more modest growth in the 2022–2050 period in both fuels (Shi, Sommer, and Smiddy 2022). As electric vehicles grow in market share, this capacity should become increasingly available for other uses.

OTHER FUELS

In addition to the fuels we examined, several other fuels are also options. In forested regions, use of wood stoves, furnaces, and boilers are an option, including as a backup fuel when temperatures get very low or power goes out. We did not examine wood because inexpensive wood is not available everywhere and because the many types of wood heating systems would make the analysis very complicated.

Hydrogen has also been suggested as a residential heating fuel, but hydrogen is expensive and existing natural gas systems would require various modifications in order to transport hydrogen. While hydrogen will likely be used as a fuel for high-temperature industrial applications and for long-distance transport (Nadel 2023b), studies have found that hydrogen is unlikely to make sense as a residential heating fuel (Rosenow 2024).

KEEPING WARM WHEN THE POWER GOES OUT

Heat pumps can work well when power is available. But in cold climates, it is useful to consider how to keep warm when the power goes out, both to maintain comfort and to keep pipes from freezing. To start, a well-weatherized house will help keep the heat in and provide many hours of comfort. But for prolonged outages, some backup heat (gas, oil, propane, or wood) and/or backup power (from a solar system, battery, or portable generator) may be needed. Bear in mind that most gas, oil, and propane systems also need electricity to power fans, pumps, and controls, so backup power may be needed in many cases (NYS Clean Heat 2024). We did not include the cost of backup power in our analysis.

DECARBONIZATION AND EQUITY

While this analysis focuses on all homes, it is important to keep in mind some of the unique challenges that low- and moderate-income homeowners face as they seek to decarbonize. Heat pumps are generally more expensive than furnaces and boilers. In addition, electricity and reduced-carbon fuels are often more expensive than fossil gas. Low- and moderate-income homeowners may not be able to afford cold climate and other advanced heat pumps without grants and/or low-cost financing, such as from government-supported programs. Weatherizing homes can reduce energy use and costs. And good rate design is needed to help customers save money with heat pumps and reduce energy burdens for low- and moderate-income households (Yim and Subramanian 2023). As a society, we can reduce the costs of decarbonization for low- and moderate-income households by investing in decarbonizing their homes. Doing so will reduce inequities and the costs of air pollution and climate impacts on our society. Without this investment, those least able to afford it are likely to be faced with rising gas system costs as wealthier households electrify. A forthcoming report from ACEEE (Fadali, Waite, and Mooney 2024) analyzes these issues in detail.

Analysis Results

In our analysis, we look at 1–4 family homes using gas with either warm-air or hot-water heat distribution that are in climates that currently have more than 6,000 HDD.[13] In the sections below, we first describe our analysis of furnaces that produce warm air that is circulated through ducts; we then discuss boilers that produce hot water that is circulated via pipes to radiators and baseboard heaters. Together, these two system types account for most gas-heated homes in cold climates (EIA 2023a).[14] For both of these system types, we look sequentially at gas-heating options, efficient electric heating options, and hybrid-heating options, and then compare the best options in each category. We also look at home energy efficiency retrofits and how these affect this comparison.

WARM-AIR FURNACES

Gas warm-air furnaces are the most common type of heating system in the United States, accounting for about 85% of gas-heated homes in cold climates (EIA 2023a). In the following sections, we discuss a variety of lower-carbon options for homes with gas warm-air furnaces.

GAS HEATING

For gas heating, we compare a condensing gas furnace (95% efficiency) with a gas heat pump, both using biogas as a fuel. As we explained earlier in the Methodology section, for each option, we look at four scenarios:

1. A reference case based on EIA projections
2. A case with some gas pipe replacement based on plans in Maryland
3. A case with 50% fewer gas customers due to electrification
4. A case with both gas pipe replacement and fewer customers

Scenarios 2 and 3 are based on a mid-2023 ACEEE study that considered various possible changes to gas distribution system costs (Nadel 2023a).

Many older regions of the country have cast iron and unprotected steel pipes that are reaching the end of their service life. Maryland, for example, has a program for pipe replacement. Its Strategic Infrastructure Development and Enhancement Plan (STRIDE) will total $4.764 billion over the 2022–2043 period, which is a 57% increase relative to normal capital spending by Maryland gas utilities (Maryland OPC 2022). Nadel (2023a) estimates

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[13] We did not examine homes that presently heat with propane or fuel oil. The costs we show for propane biogas, B100, and renewable diesel will also approximately apply to these homes.

[14] Cold climate as defined by EIA and DOE's Building America program (www.basc.pnnl.gov/images/building-america-climate-zone-map). Roughly, this is north of the Mason–Dixon line.

that this spending will increase gas bills by about 15%, a figure we apply for scenario 2. Some utilities will spend less, including many gas utilities in the West, where pipes are often only a few decades old (often due to recent growth as well as replacement of old pipes). Other utilities will spend even more as a percentage of gas bills, including utilities in Philadelphia, Massachusetts, and New York State (Nadel 2023a).

Likewise, Nadel (2023a) looked at cases in which 25%, 50%, and 75% of homeowners electrify and leave the gas system, as well as a scenario in which customers use hybrid gas and electric heating and their gas consumption declines. For our analysis, we use the case where 50% electrify and leave the gas system, which increases gas bills for remaining customers by 43% (Nadel 2023a).[15]

Figure 6 illustrates the reference case in two ways. We show individual dots for each home using a gas furnace and for each home using a gas heat pump. In general, gas heat pumps cost more than gas furnaces (with average installed costs of about $16,500 and $4,300, respectively) but operate more efficiently (130% versus 95% AFUE[16]) and hence need less fuel. We present each home in terms of site HDD and life-cycle cost for heating (combining both capital and operating costs over the furnace lifetime). We overlay on this graph best-fit lines for the individual data points. As expected, life-cycle costs increase as HDD increase due to the higher operating costs as outdoor temperatures get colder. In the reference case, the gas furnace has lower life-cycle costs than the gas heat pump at all HDD examined.

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[15] In the long term, more customers may leave the gas system—we use 50% as an illustrative scenario midway between no customers leaving and all customers leaving. We also note that available biogas supplies are limited, and if 50% of current gas customers continue to use gas, some use of more expensive synthetic natural gas will probably be needed (Nadel and Fadali 2022).

[16] Annual fuel utilization efficiency.

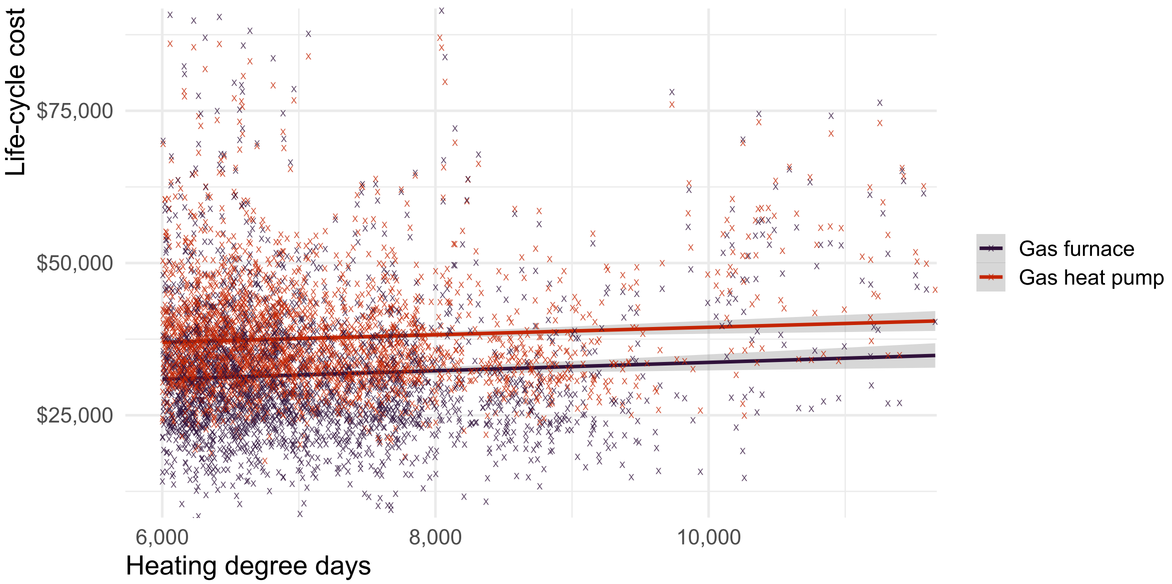

Figure 6. Comparison of life-cycle costs for space heating for a condensing gas furnace and a gas heat pump as a function of heating degree days (HDD). Dots are for individual homes, lines are best-fit regression lines. Note that each home is represented twice, once showing costs using a gas furnace (purple dot) and once showing costs with a gas heat pump (green dot).[17] Costs are in 2023 dollars.

To help interpret HDD numbers, figure 7 shows a map of HDD for the United States using 2006–2020 data. As the climate gets warmer, HDD will gradually decrease in most locations.

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[17] While we include most outliers for our best fit lines, we did exclude about a dozen homes whose standard residuals were above 6 for linear models for gas furnaces, gas heat pumps, electric air-source heat pumps, electric ground-source heat pumps, or hybrid systems, as well as two homes above 12,000 HDD.

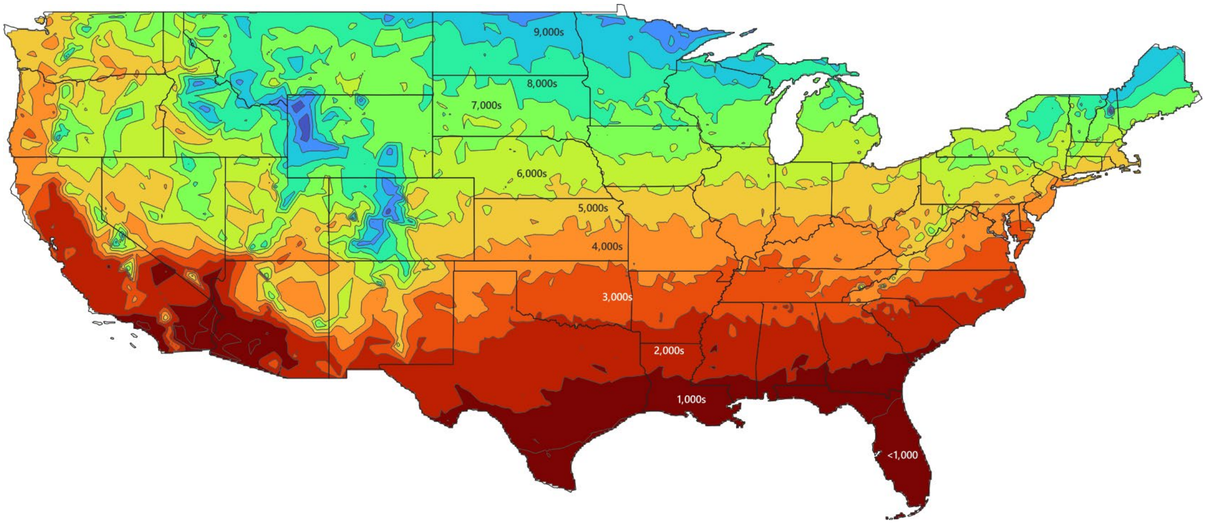

Figure 7. Average heating degree days (HDD) at various locations in the United States based on averages over the 2006–2020 period. Colors represent different numbers of HDD as labeled in the middle of the map. Lines between colors are approximate. Source: Created by ACEEE based on data in NCEI 2021.

Figure 8 contains results of all four scenarios, presented in terms of best-fit lines for the individual data points. In these scenarios, gas furnaces generally have lower life-cycle costs than gas heat pumps, but when we include both pipe replacement costs and the impacts of fewer customers, the lines are closer together. The moderate amount of replacement that we include in the pipe replacement scenario does not have a big impact on our results, but larger amounts of pipe replacement could have more impact.

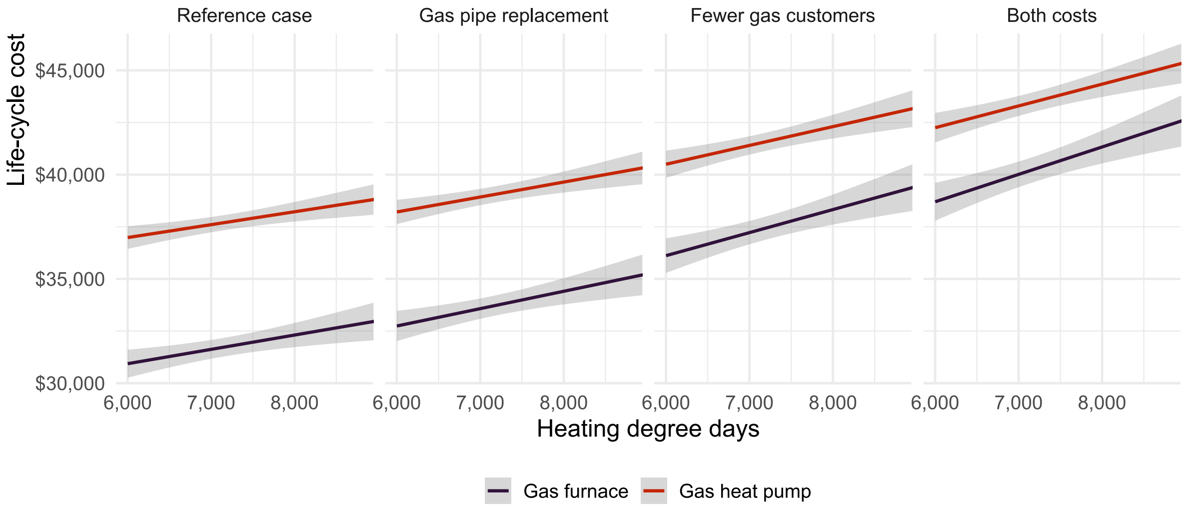

Figure 8. Comparison of life-cycle costs for space heating for a condensing gas furnace and a gas heat pump as a function of heating degree days (HDD) under our four target scenarios. Costs are in 2023 dollars.

ELECTRIC HEATING

For electric heating, we compared a cold-climate-rated ASHP and a GSHP. The cold climate ASHP is rated to provide full heat output down to approximately 5°F and uses supplementary electric resistance heat to complement output from the heat pump at lower temperatures. If a home has central air-conditioning, we assume that the heat pump replaces the air conditioner. If a home does not have a central air conditioner, we assume that the heat pump replaces the furnace and that the electric service must be upgraded to serve the heat pump. Our analysis is based on the current performance of cold climate heat pumps; by 2030, performance is likely to improve, but we did not include performance improvements in our analysis.[18] The GSHP is more expensive but offers higher efficiency, particularly in very cold climates (e.g., one dataset indicates a seasonal coefficient of performance of about 3.2 in Fairbanks, Alaska—a climate with about 10,000 HDD; Garber-Slaght 2021).

Figure 9 shows the best-fit lines for these two systems. As the figure shows, the life-cycle costs are lower for the ASHP. This analysis is based on the GSHP being workable for each specific home in terms of space, geology, and hydrology (USDOE 2023b). Not all sites will be workable.

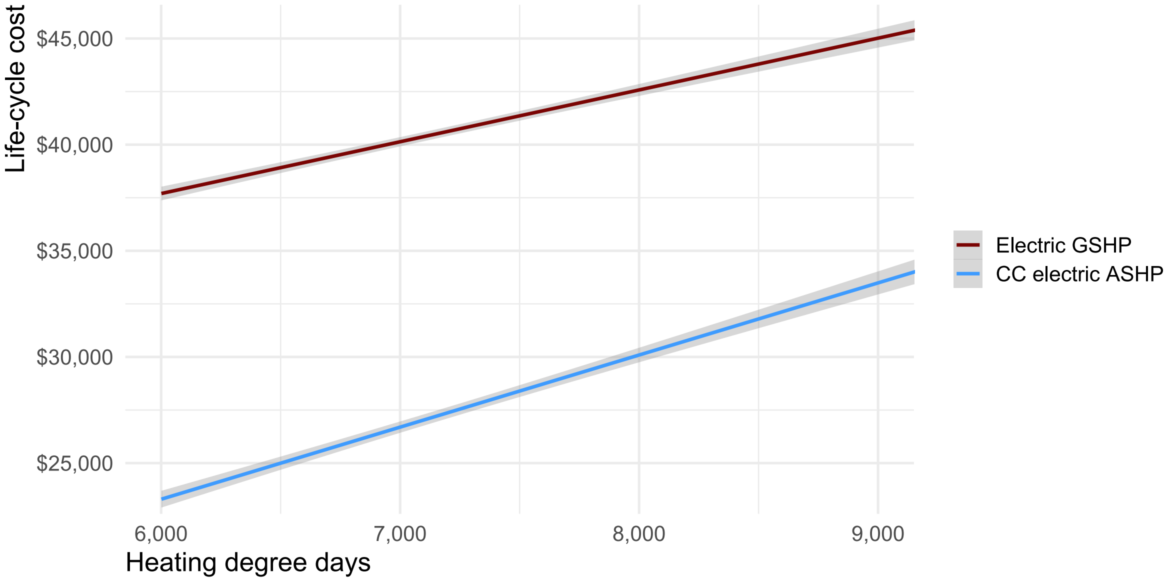

Figure 9. Comparison of life-cycle costs for space heating with warm-air distribution for an air-source and a ground-source heat pump as a function of heating degree days (HDD). Costs are in 2023 dollars.

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[18] While we did not include performance improvements for cold climate heat pumps, we did include a modest price reduction (see Appendix A).

The figure 9 comparison is based on a $25,000 estimate of GSHP average cost (Noel 2023). Other sources indicate higher costs (e.g., about $40,000; E3 2023), but when the federal 30% tax credit and utility rates are applied, the cost may be around $25,000 even with these higher costs, reinforcing this value for our primary value. But since costs could be higher, we reran the analysis with an average GSHP cost of $40,000. We also ran an analysis with cold climate ASHP costs based on current costs—an average of about $15,000 based on data from the Northeast and Northwest (Nadel and Fadali 2022), and then adjusted for recent inflation; this is higher than the $8,920 (from Guidehouse and Lydos 2023) used for our primary analysis. The $8,920 figure may be considered as indicative of less-expensive regions and also of what costs might be in the future as competition increases (e.g., the TECH California program found that project cost decreases logarithmically with the number of enrolled contractors serving a county; Kisch 2024). As shown in figure 10, the ASHP have lower life-cycle costs than the GSHP, even with the higher ASHP and lower GSHP costs.

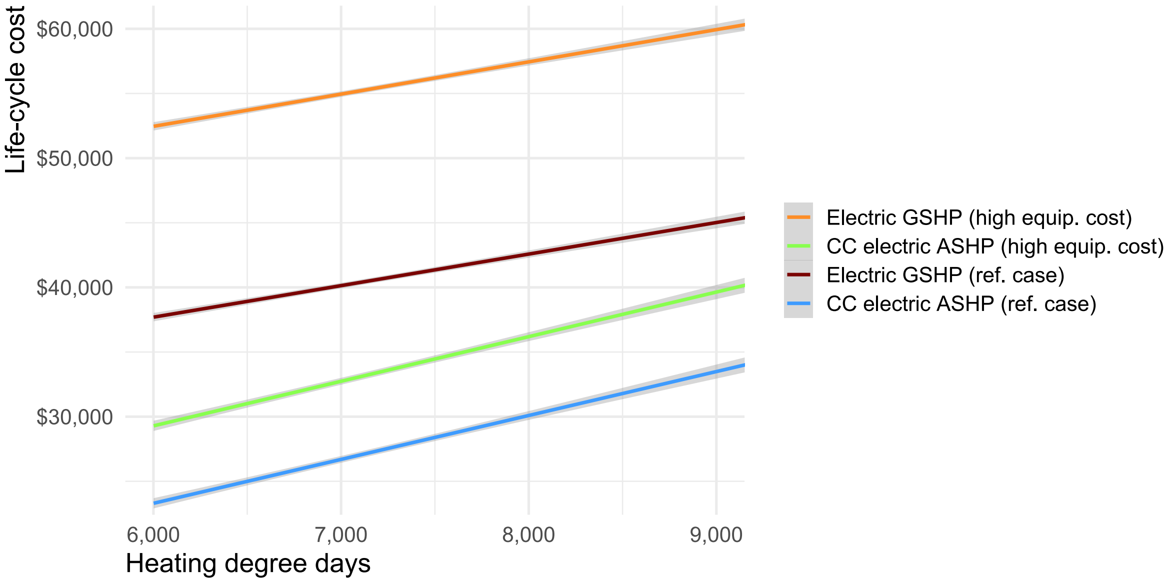

Figure 10. Comparison of life-cycle costs for space heating with warm-air distribution for an air-source and a ground-source heat pump as a function of heating degree days (HDD) using two different estimates of costs for each system. Costs are in 2023 dollars.

HYBRID HEATING

The hybrid warm-air heating system we analyzed uses a cold climate ASHP down to outdoor temperatures of approximately 5°F, and then supplements the heat from the heat pump with a backup fuel-based warm-air furnace at temperatures below 5°F. This avoids the winter peak demands of electric resistance backup heat at temperatures below about 5°F. We examine a central heat pump backed up with a central furnace, but there are alternative system configurations (such as using ductless mini-split heat pumps or fuel-fired space heaters instead of central systems). There are also alternative ways to operate the system (e.g., continuing to operate the heat pump below 5°F, but using the fuel system to provide additional heat[19]). As we discussed earlier, for the fuel-based backup, we assume the use of renewable fuels:

- Biogas using reference case assumptions
- Propane made from biogas
- Propane made from ethanol
- Renewable diesel

The biogas cases assume a 95% efficient furnace, the B100 and renewable diesel cases assume an 86% efficient furnace,[20] and propane assumes a new 95% efficient furnace that replaces an existing gas furnace. The natural gas and biogas are delivered via gas distribution pipes, while propane and oil are delivered via truck and stored on-site in a tank. Below, and also in Appendix B, we look at scenarios in which the biofuels fuels are less expensive and more expensive than our primary assumptions.[21]

We also note that a thermal storage system could be used as a backup to an electric heat pump, but examining such systems is beyond the scope of this paper.

Figure 11 shows best-fit lines for these four cases, plus an additional case for biogas but with 50% fewer gas customers. The hybrid system with biogas as a backup generally has lower life-cycle costs if the number of gas customers does not change. If the number of gas customers declines then the options are closely grouped together, with the biogas backup slightly lower in life-cycle costs. Addition of pipe replacement costs (not shown) would eliminate this difference.

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[19] Cold climate heat pumps will have an efficiency above 100% at temperatures below 5°F but operating two systems simultaneously may require more sophisticated controls. Also, operating the electric heat pump below 5°F will contribute to peak electric demand.

[20] Condensing oil furnaces are expensive and produced only by a few small manufacturers.

[21] We do not look at lower costs for renewable propane from ethanol and for B100, as ethanol and B100 are more established fuels with less opportunity for price reductions.

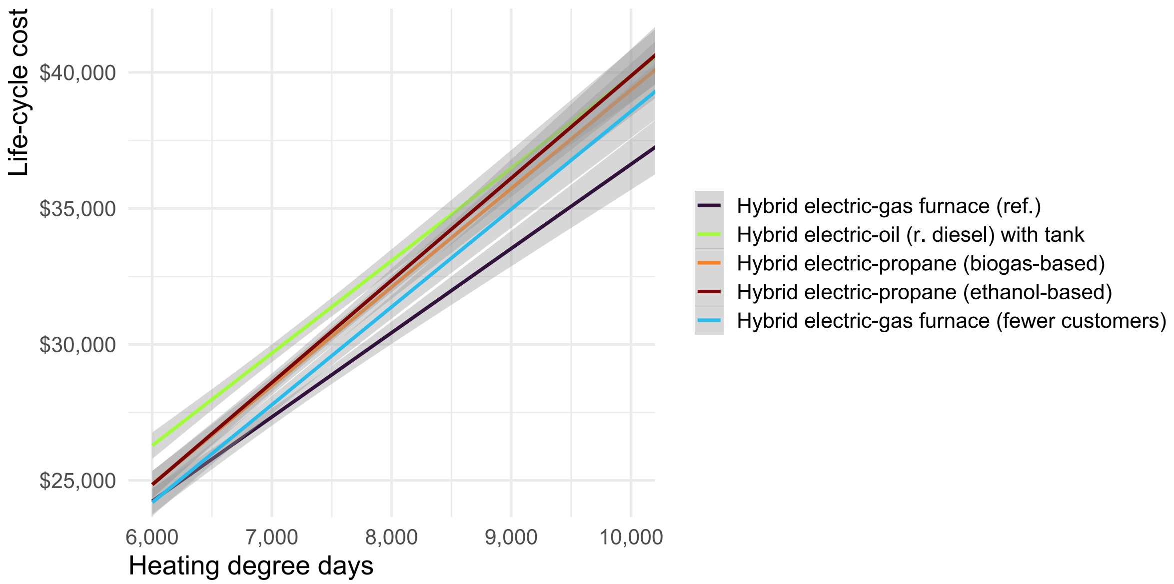

Figure 11. Comparison of life-cycle costs for space heating with warm-air distribution for four hybrid heating options in our reference case. Costs are in 2023 dollars.

In general, this analysis is highly dependent on fuel price assumptions and should be considered highly approximate. The biogas price assumptions are particularly approximate. Fuel costs could be lower than our primary case due to issues such as cost breakthroughs. Costs could be higher than our primary case due to the high costs of obtaining large amounts of biomass (ICF 2019). While there are also uncertainties about costs of renewable diesel and ethanol, the markets for these fuels are much larger and established, reducing uncertainties. Figure 12 shows sensitivities with 25% higher and 25% lower biogas costs (including propane made from biogas). We find that with lower biogas costs, life-cycle costs are somewhat lower for using biogas as the backup fuel and somewhat higher for using renewable diesel as the backup. With higher biogas costs, the same result holds if the number of gas customers does not change, but if there are fewer gas customers, then biogas and propane made from biogas or ethanol have similar life-cycle costs when considering the different backup fuels.

Given how close many of the life-cycle cost lines are, this analysis shows that delivered fuels such as propane made from biogas or ethanol can potentially compete with gas as a backup fuel in the case with fewer gas customers. Because these different fuels are all so close to each other in life-cycle cost, and the analysis is sensitive to relative cost assumptions, the key takeaway is that the best biofuels are those that can scale and approximately achieve the prices assumed. We explore the sensitivities for all fuels in the next section.

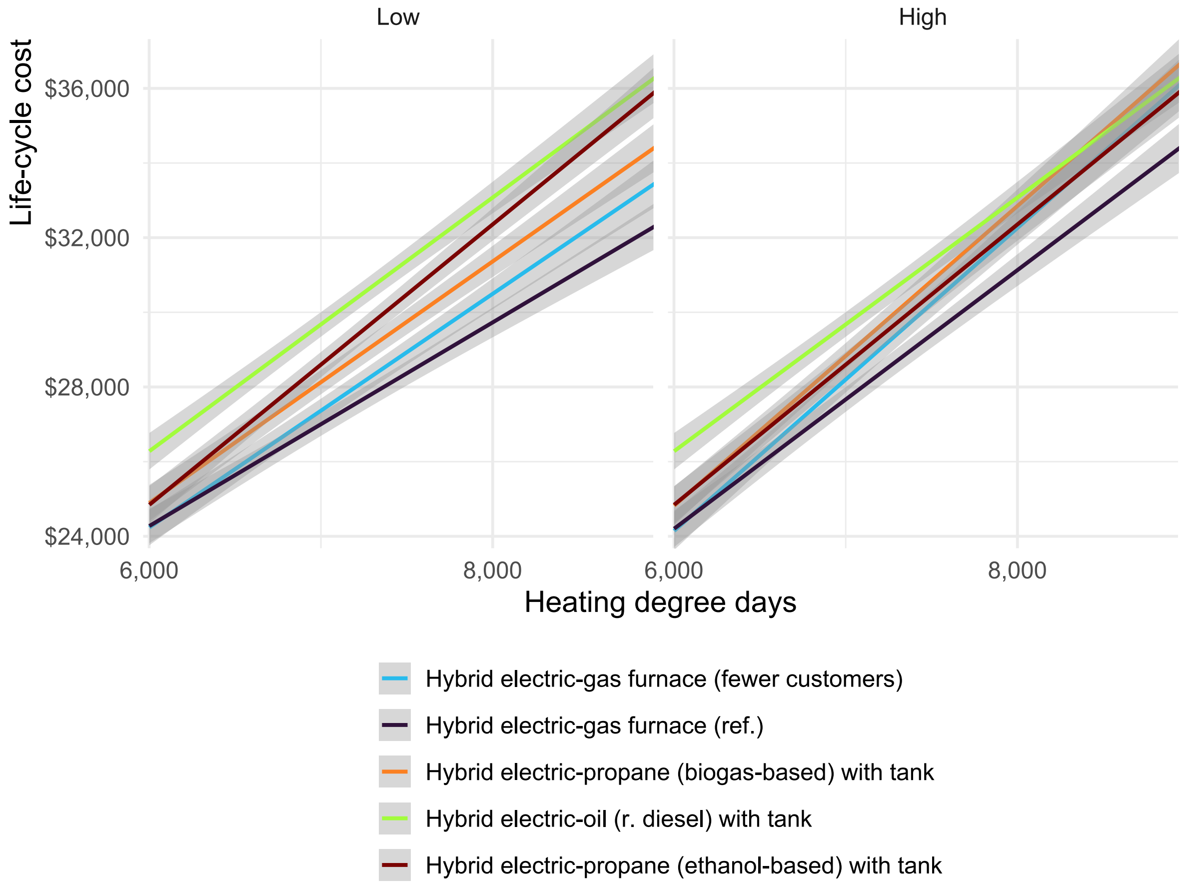

Figure 12. Comparison of life-cycle costs for space heating with warm-air distribution but using 25% lower and 25% higher biogas costs. Costs are in 2023 dollars.

Comparison of Best Options

Up to this point, we have looked at gas, electric, and hybrid options separately. In this section, we compare the best gas, electric, and hybrid options from a life-cycle cost perspective, while noting that these options all have different amounts of associated greenhouse gas emissions.[22] We include the following options:

- Cold climate electric ASHP (reference price)
- Cold climate electric ASHP (higher price)

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[22] We do not examine the relative emissions of carbon dioxide and other pollutants. Relative emissions of the different fuels will be the subject of an ACEEE report to be published in late 2024. As noted earlier, oil has higher NO_x emissions, SO_2, and particulate emissions than the other fuels.

- GSHP
- Gas furnace using biogas
- Hybrid system using an electric ASHP and biogas backup
- Hybrid system using an electric ASHP and B100 backup
- Hybrid system using an electric ASHP and low-carbon propane made from biogas as backup

Appendix A shows the costs and performance of these systems.

For our comparisons, we show two scenarios:

1. No change in gas distribution system costs (the "reference case" in figure 13)
2. 50% fewer gas customers

Figure 13 shows the results. In general, using our reference case assumptions, the electric cold climate ASHP has the lowest life-cycle costs below approximately 7,000 HDD (the current climate in Concord, New Hampshire and Madison, Wisconsin). From about 7,000 HDD) to about 8800 HDD (a little south of Duluth, Minnesota), the hybrid system combining the cold climate heat pump with a biogas-based backup system has the lowest life-cycle cost. And above about 8800 HDD, a gas furnace fueled with biogas has the lowest life-cycle cost assuming that the number of gas customers does not decline. If the number of gas customers declines, then the cold-climate heat pump without backup has the lowest life-cycle costs followed closely by a hybrid system using propane or renewable diesel. In the scenario of fewer customers, life-cycle cost differences between cold climate heat pumps and hybrid systems are fairly small. Among the backup fuels, propane made from biogas has the lowest life-cycle costs under our reference case assumptions, but other backup fuels are only a little higher. If we use the high-cost estimate for cold climate heat pumps (including when used in hybrid systems) and the reference case prices for other systems, the gas furnace has lower life-cycle costs above approximately 6,400 HDD (the current climate in Kalamazoo, Michigan) if no gas customers leave the gas system; if 50% of customers leave the gas system, however, then the cross-over point is approximately 8,300 HDD (the current climate in Bozeman, Montana).

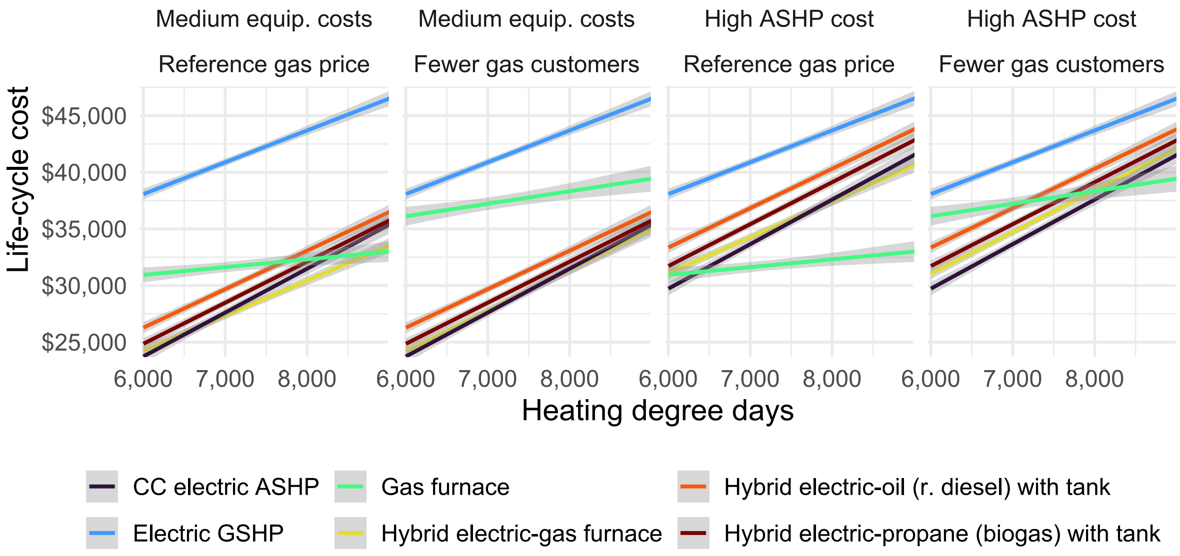

Figure 13. Comparison of life-cycle costs for space heating with warm-air distribution for our seven options and two scenarios. Costs are in 2023 dollars.

Relative to our prior 2022 study (Nadel and Fadali 2022), the dividing line between using only heat pumps and using a hybrid system increases from 6,000 to 7,000 HDD in our medium reference case due to use of newer RECS data and to revisions to heating system and biogas costs.

We also repeated this analysis using 25% lower fuel costs and 25% higher fuel costs, as well as in scenarios with fewer gas customers and combining both fewer gas customers and moderate gas pipe replacement. Fuel costs could be lower than our primary case due to cost breakthroughs for biofuels or to competition among fuel dealers for new customers. Costs could be higher than our primary case due to high costs of obtaining large amounts of biomass (ICF 2019) or due to higher markups by fuel dealers stemming from fewer deliveries per customer (as we discuss below).

Figure 14 shows the results of these analyses. If three criteria are met, namely gas pipes require upgrades, fewer customers are using the gas system, and biogas prices are not lower than our primary case, fully electric heat pumps generally minimize costs, even at high HDD. In most scenarios, the difference in cost between fully electric heat pumps and heat pumps with biogas backup is relatively small.

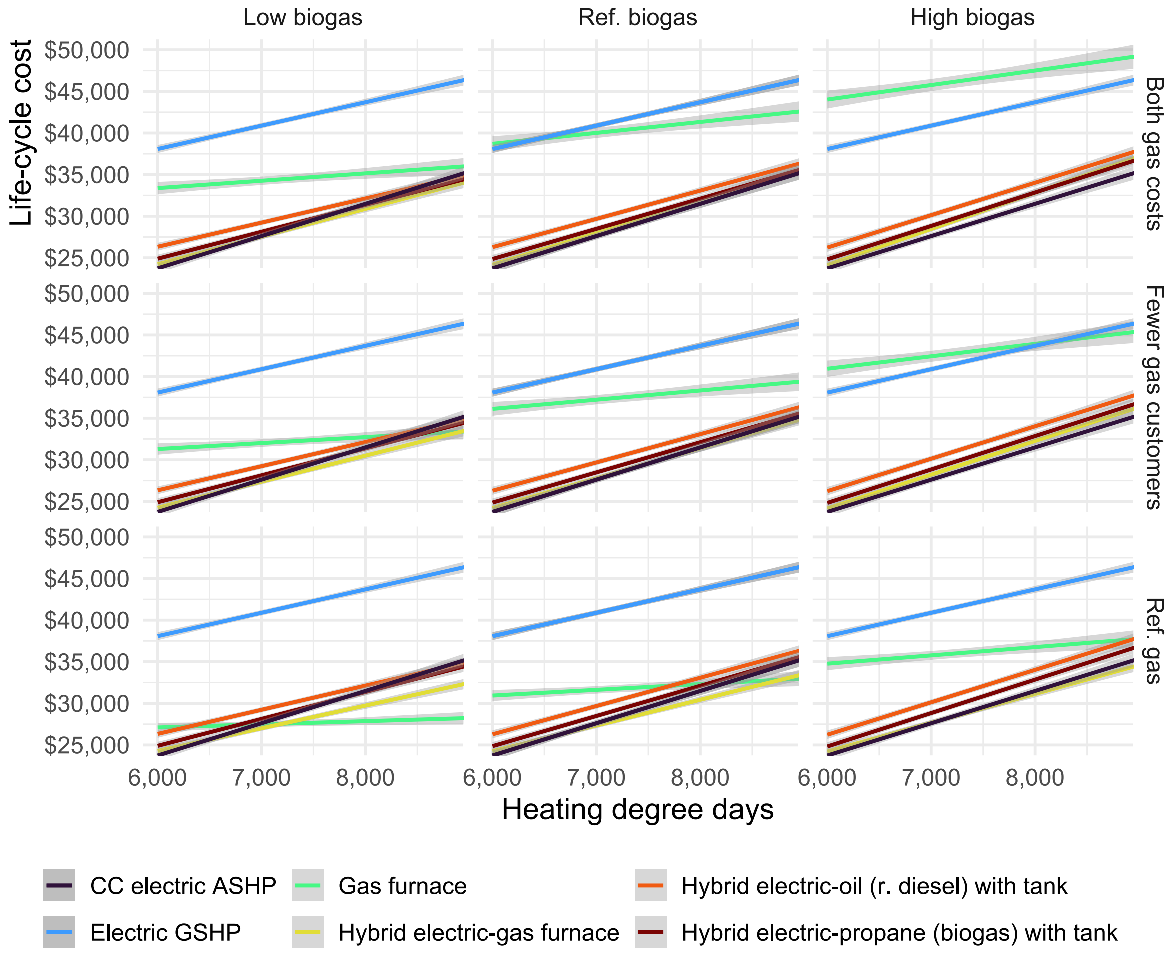

Figure 14. Comparison of life-cycle costs for space heating with warm-air distribution for our six options, three fuel-price cases, and three gas system scenarios. Costs are in 2023 dollars.

In addition to scenarios with 25% lower and higher gas costs, we also developed scenarios with even lower and higher fuel costs (see Appendix B).

AMOUNT OF PROPANE OR OIL USED PER HOME

Our analysis of hybrid systems assumes that the cold climate heat pump is sized to fully heat the home at 5°F, but at colder temperatures the system fires up the fuel backup system to obtain adequate heat and reduce peak winter power demand. Under these assumptions, we examined how much fuel would be needed each winter for the backup fuel. Figure 15 shows our results for propane, and figure 16 shows the results for fuel oil. In a substantial majority of cases, just 100 gallons of fuel will be adequate for the winter and thus only small fuel storage tanks are needed. But in the case of propane, some homes will need either 200-gallon tanks or for homeowners to plan a mid-winter fill-up of smaller tanks.

This raises a question about the business models of fuel oil and propane dealers. Presently, these dealers make multiple deliveries per year to a moderate number of customers. If many current gas customers switch to delivered fuels, the number of their customers would increase, but since these customers would need only backup fuel, the quantity sold per customer would decrease. This new dynamic could affect dealer pricing, either raising prices (due to less-frequent deliveries) or lowering them (due to the greater number of customers and dealer competition to serve them). At a minimum, this issue is a source of price uncertainty and is one reason that we conducted sensitivity analyses with 25% higher and 25% lower prices.

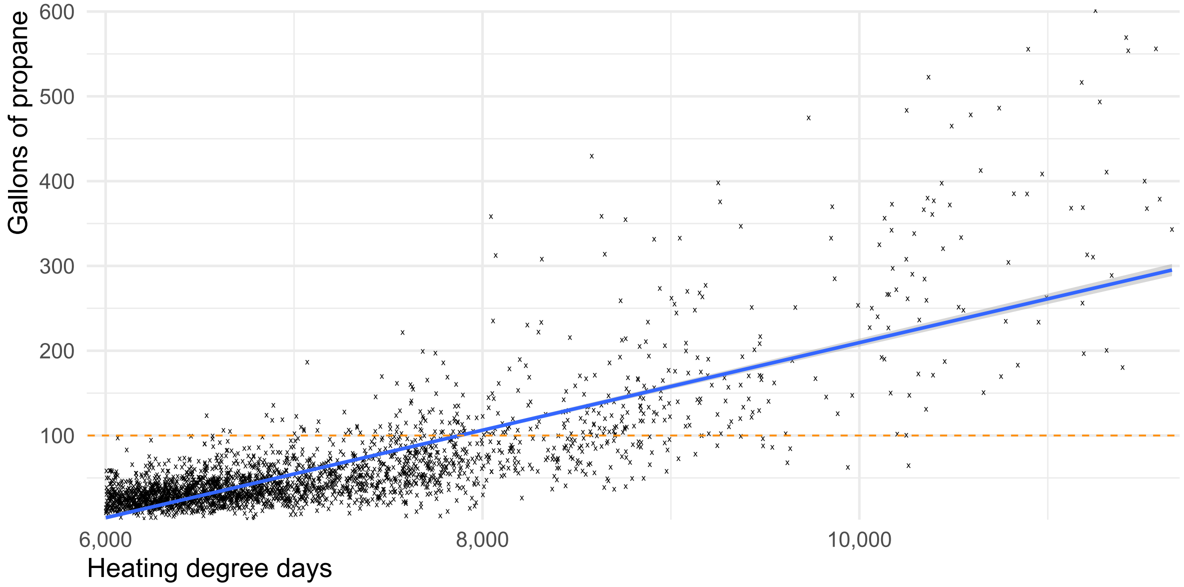

Figure 15. Amount of propane needed per year when used as a backup fuel in hybrid heating systems

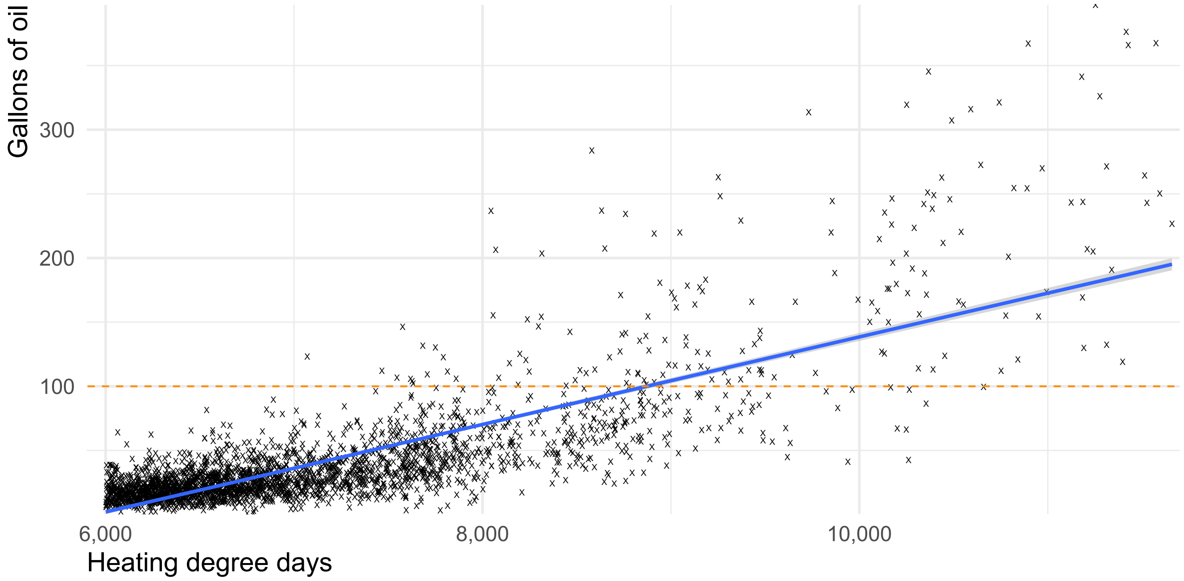

Figure 16. Amount of fuel oil needed per year when used as a backup fuel in hybrid heating systems

ENERGY EFFICIENCY RETROFITS

The above scenarios all are based on the current energy efficiency of each home in our database. Energy efficiency measures, such as building envelope improvements, can play an important role with both electrification and alternative fuels. The more that energy efficiency is employed, the less electricity and alternative fuel that are needed, reducing both operating costs and the amount of capital investment, since a more efficient house can use a smaller heating system. We examined the impact of energy efficiency on our results, considering four energy efficiency cases:

1. No additional energy efficiency
2. A moderate energy efficiency package based on Home Performance with Energy Star (25% energy savings at an average cost of $5,650 in 2023 dollars)
3. A deep energy efficiency package (about 60% savings at an average cost of $46,224 in 2023 dollars)
4. A deep energy efficiency package but at half the cost because the deep retrofit is done at the same time as a major home renovation.

All of our assumptions on costs and savings come from Nadel and Fadali (2022) and include 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.[23] Although these other benefits can increase energy efficiency's benefits by a factor of two or more (Skumatz 2016), they are not shown in our 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.

Figure 17 shows the energy efficiency results. Two trends are noticeable in this analysis. First, across all four scenarios, adding either the moderate energy efficiency package or the deep efficiency package at time of renovation reduces life-cycle costs. In other words, these efficiency retrofits more than pay for themselves. Second, the energy efficiency—particularly with the deep efficiency package—has a larger impact on the life-cycle costs of gas systems, since these systems have lower capital costs but higher operating costs under our

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[23] 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 Denson 2019).

assumptions. By reducing fuel consumption, efficiency reduces the operating cost of all systems, but in dollar terms, these impacts are larger for gas systems.

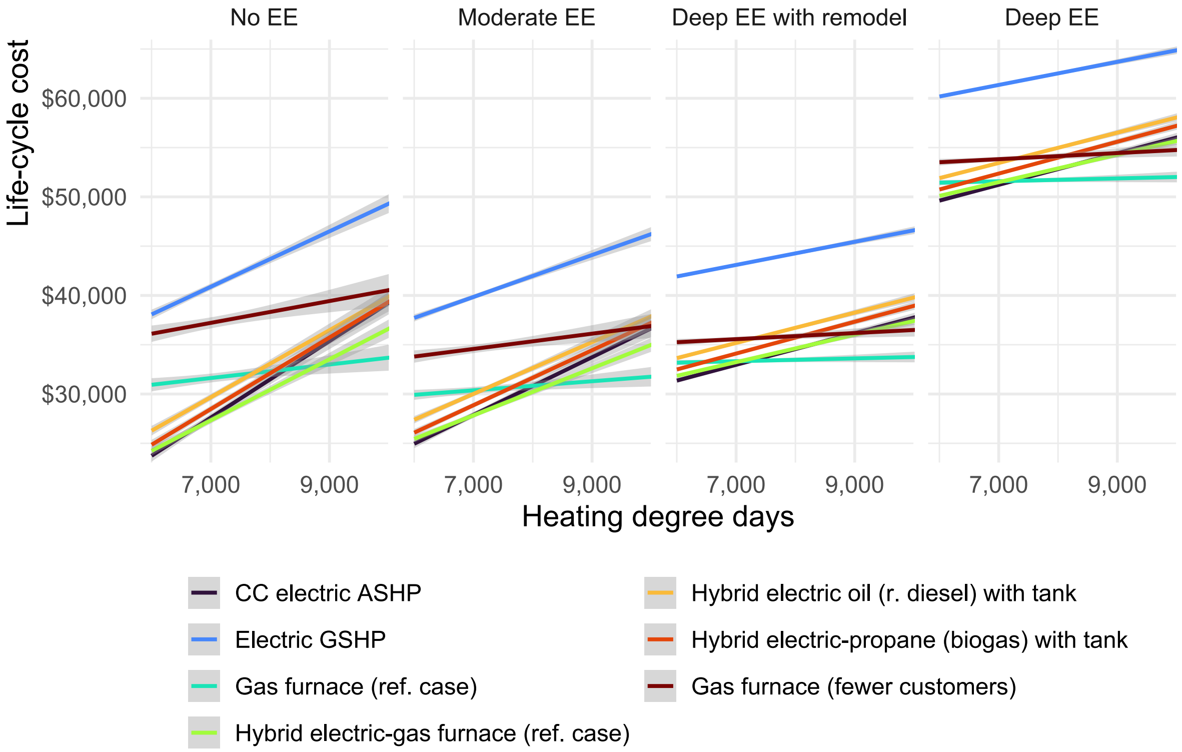

Figure 17. Comparison of life-cycle costs for space heating with warm-air distribution for various system types and energy efficiency packages. Costs are in 2023 dollars.

OTHER OPTIONS

LOWER-EFFICIENCY GAS FURNACES

As noted above, our primary analysis of hybrid gas systems assumes that the existing gas furnace is retained, and that this system has an efficiency of 95% (which is required as of fall 2028 under new DOE minimum efficiency standards). But another option could be to permit less-efficient systems as a backup to a heat pump. Figure 18 compares the life-cycle cost of hybrid systems with 80% and 95% efficiency. As the figure shows, the life-cycle costs of these two systems are very similar, with the 95% system having slightly lower costs above approximately 7,500 HDD (the current climate in Minneapolis[24]) and the 80% being slightly

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[24] ASHRAE 2021.

less expensive below this threshold. Given the small savings, this option does not appear to be worth pursuing.

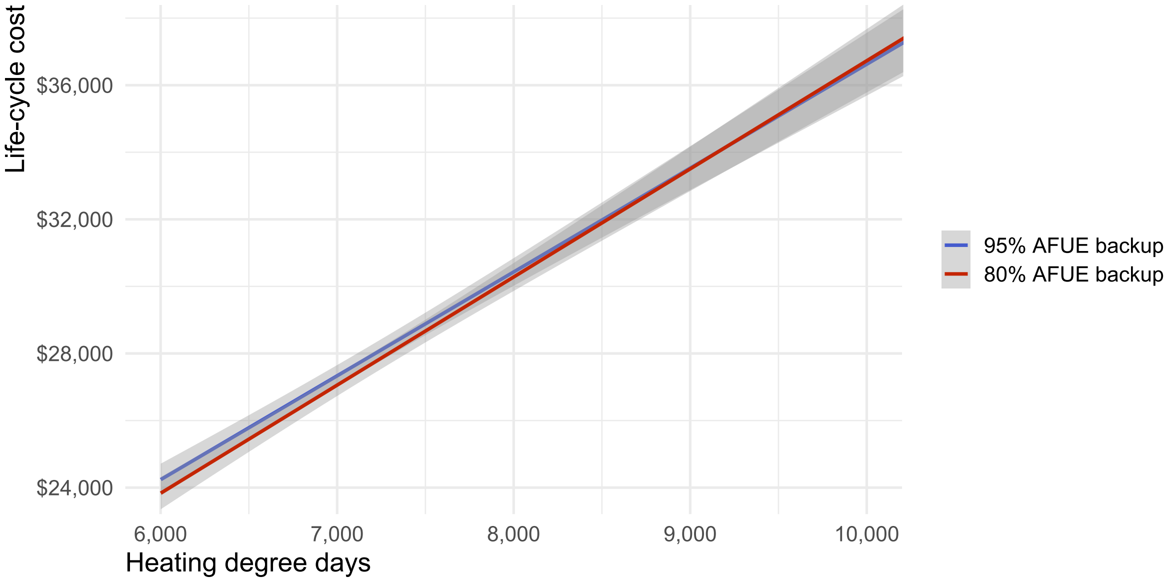

Figure 18. Comparison of life-cycle costs for cold climate heat pumps with two different backup systems, one with an 80% AFUE and one with a 95% AFUE backup.

SPACE HEATERS INSTEAD OF FURNACES

We also considered the option of using a few gas-fired space heaters in the living space as a backup to a cold climate ASHP. However, based on price data we collected, purchasing two space heaters will often be more expensive than replacing a furnace, so we did not look into this further (all but very small houses will need at least two space heaters).

HOT-WATER BOILERS

Hot-water boilers are also a common space heating system, accounting for about 13% of U.S. homes in cold climates with natural gas heating (EIA 2023a).

COMPARISON OF SYSTEM OPTIONS

In this section, we discuss various options to decarbonize gas boilers:

- Gas boiler using biogas as a fuel
- Cold climate electric air-source air-to-water heat pump
- Electric GSHP
- Hybrid system with electric air-to-water heat pump backed up with a gas boiler using biogas
- Hybrid system with electric air-to-water heat pump backed up with a boiler using propane derived from ethanol

- Gas boiler using biogas but with 50% fewer gas customers
- Hybrid system using biogas but with 50% fewer customers

The natural gas and biogas are delivered via gas distribution pipes, while propane and oil are delivered via truck and stored on-site in a tank. Appendix A shows assumptions for each system type. Cold climate air-to-water heat pumps are widely sold in Europe, and several manufacturers have told us that they plan to soon bring these products to the United States. We base our costs on present costs in the United Kingdom. These systems provide hot water of about 130–140°F, a lower temperature than the 160–180°F provided by boilers. To address this lower water temperature, homes need to (a) be weatherized to reduce heat loss so that 130–140°F water provides adequate heat; (b) install additional hot-water baseboard units to increase heat provided to rooms; and/or (c) include a small boiler to raise water temperature to 160–180°F on very cold days. Below we include analysis of options (a) and (c); we did not examine option (b).

Figure 19 summarizes the results of our analysis. In general, the air-to-water heat pump with a moderate efficiency retrofit has the lowest life-cycle costs. Without the efficiency retrofit, hybrid systems may be needed to provide adequate heat to rooms, increasing life-cycle costs a little below approximately 8,800 HDD (a little south of Duluth, Minnesota), but reducing life-cycle costs a little above 8,800 HDD.

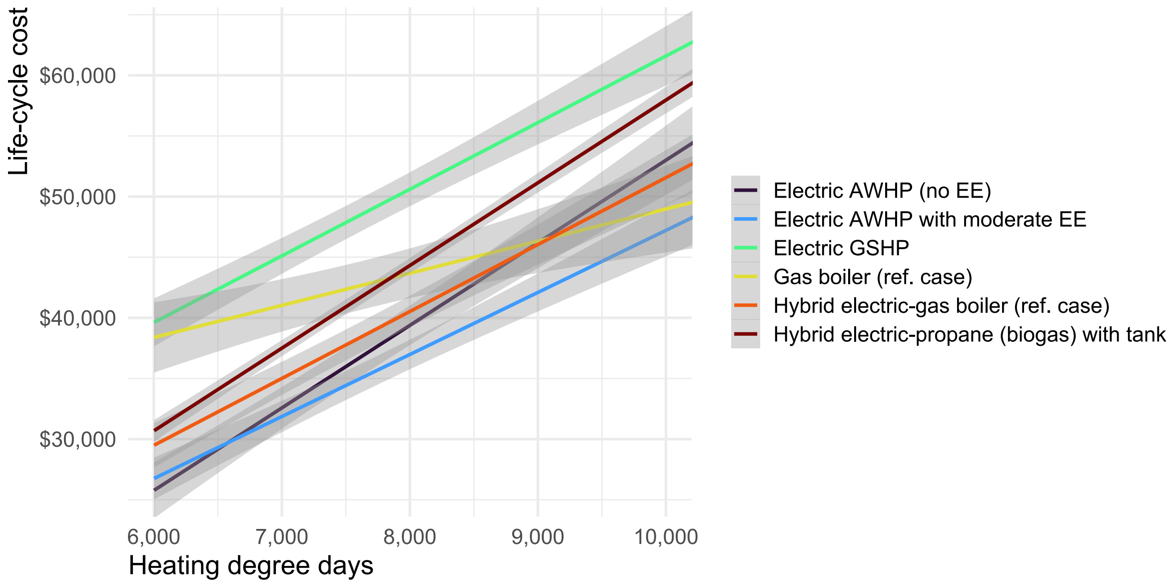

Figure 19. Comparison of life-cycle costs for space heating with hot-water distribution for our six options. Costs are in 2023 dollars.

As figure 20 shows, we also did a similar analysis with 25% lower and higher fuel costs, and with fewer gas customers and both fewer gas customers and gas pipe replacements. Relative to the previous discussion, the one significant change in this case is that the gas boiler has lower life-cycle costs in the low-gas-cost scenario above approximately 8,000 HDD (the current climate in Ottawa, Canada), but only if there are either no gas pipe replacements nor a substantial number of customers leaving the gas system.

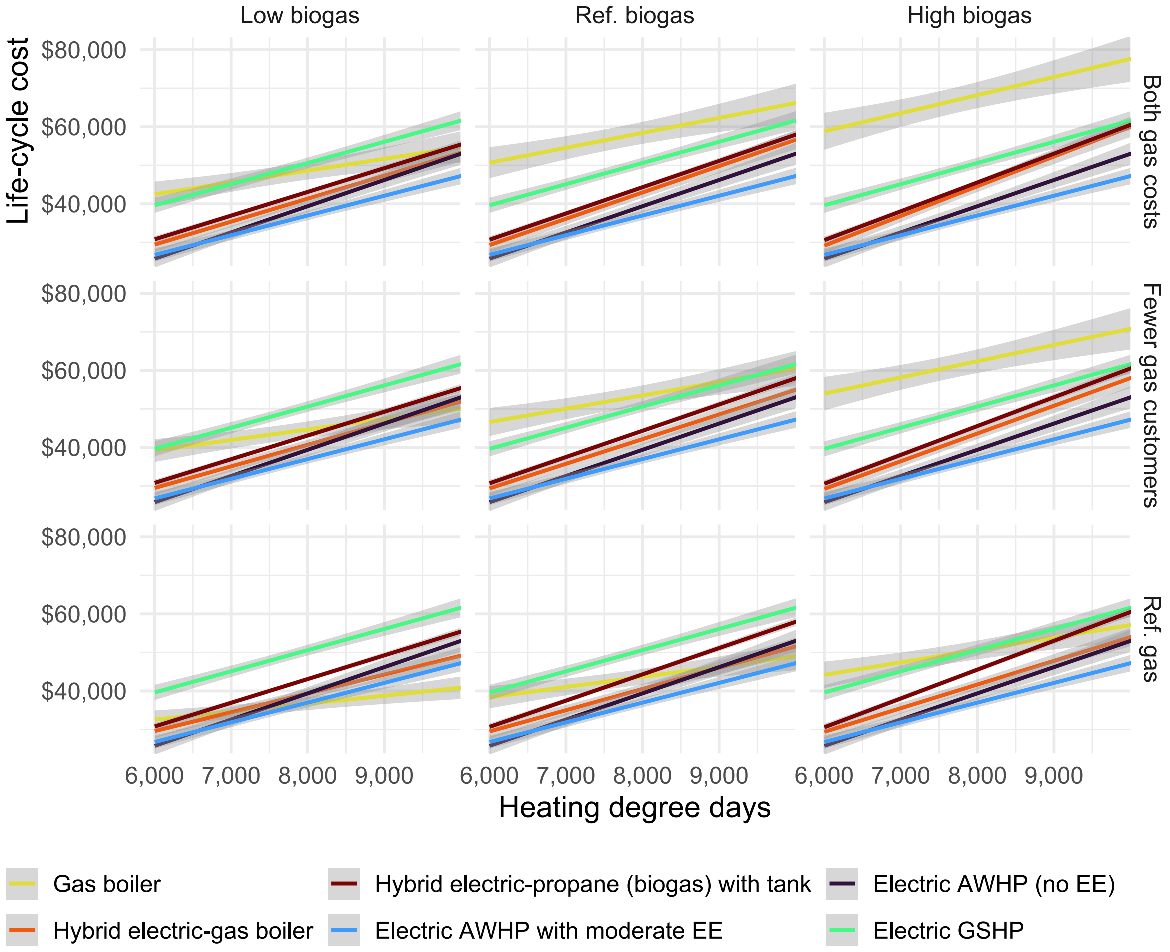

Figure 20. Comparison of life-cycle costs for space heating with hot-water distribution for our six options, three fuel-price cases, and three gas system scenarios. Costs are in 2023 dollars.

In addition to scenarios with 25% lower and higher gas costs, we also developed scenarios with even lower and higher fuel costs, as Appendix B shows.

ENERGY EFFICIENCY RETROFITS

The more that homeowners employ energy efficiency, the less electricity and alternative fuel they need. This reduces both a utility's operating costs and the capital investment needed to supply electricity or alternative fuels since efficient homes can use smaller heating systems. As we did for warm-air furnaces, we examined the impact of energy efficiency on our boiler results, considering four energy efficiency cases:

1. No additional energy efficiency

2. Moderate energy efficiency package based on Home Performance with Energy Star (25% energy savings)
3. Deep energy efficiency package (about 60% savings)
4. Deep energy efficiency package at half the cost because the deep retrofit is done at the same time as a major home retrofit (gut rehabilitation).

Our assumptions on costs and savings are from Nadel and Fadali (2022). Figure 21 shows the results of our analysis. As with our analysis of energy efficiency in homes with furnaces, a few trends are noticeable here and are similar to our findings for furnaces. First, across all scenarios, adding either the moderate energy efficiency package or the deep efficiency package at time of home renovation reduces life-cycle costs. In other words, these efficiency retrofits more than pay for themselves. Second, the energy efficiency package —and particularly the deep efficiency package—improves the relative economic performance of gas boilers, reducing their operating costs and making them more competitive, particularly above approximately 8,500 HDD.

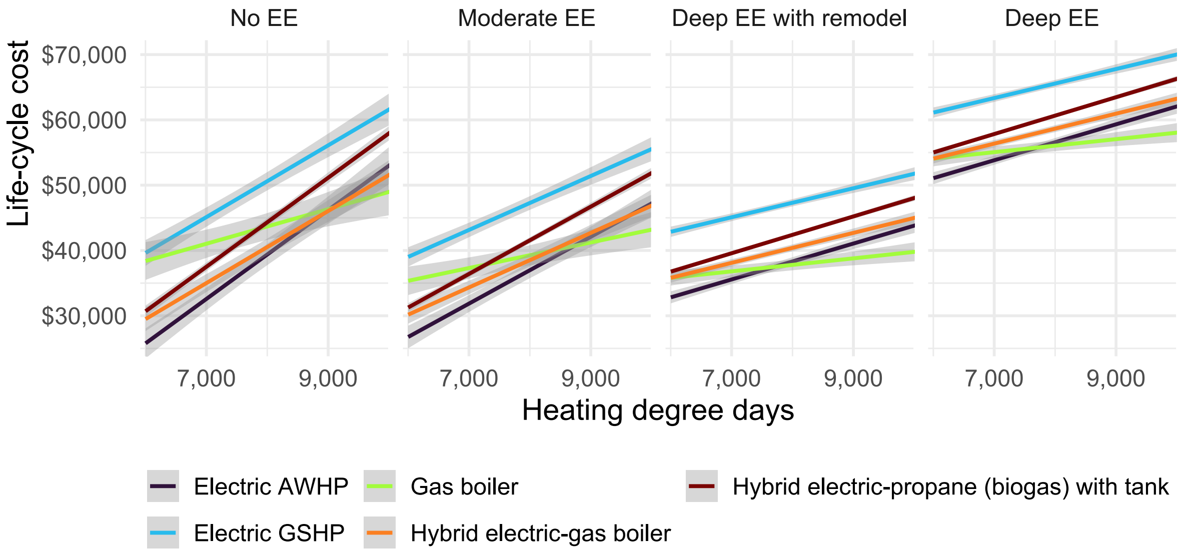

Figure 21. Comparison of life-cycle costs for space heating with hot-water distribution for a variety of system types and energy efficiency packages. Costs are in 2023 dollars.

AMOUNT OF PROPANE OR OIL USED PER HOME

As with our furnace analysis, we also looked at how many gallons of fuel will be needed each year for the options that include delivered fuel as a backup in hybrid heating systems. Figure 22 shows the results: as in our furnaces analysis, in a substantial majority of homes, less than 100 gallons of fuel will be needed annually.

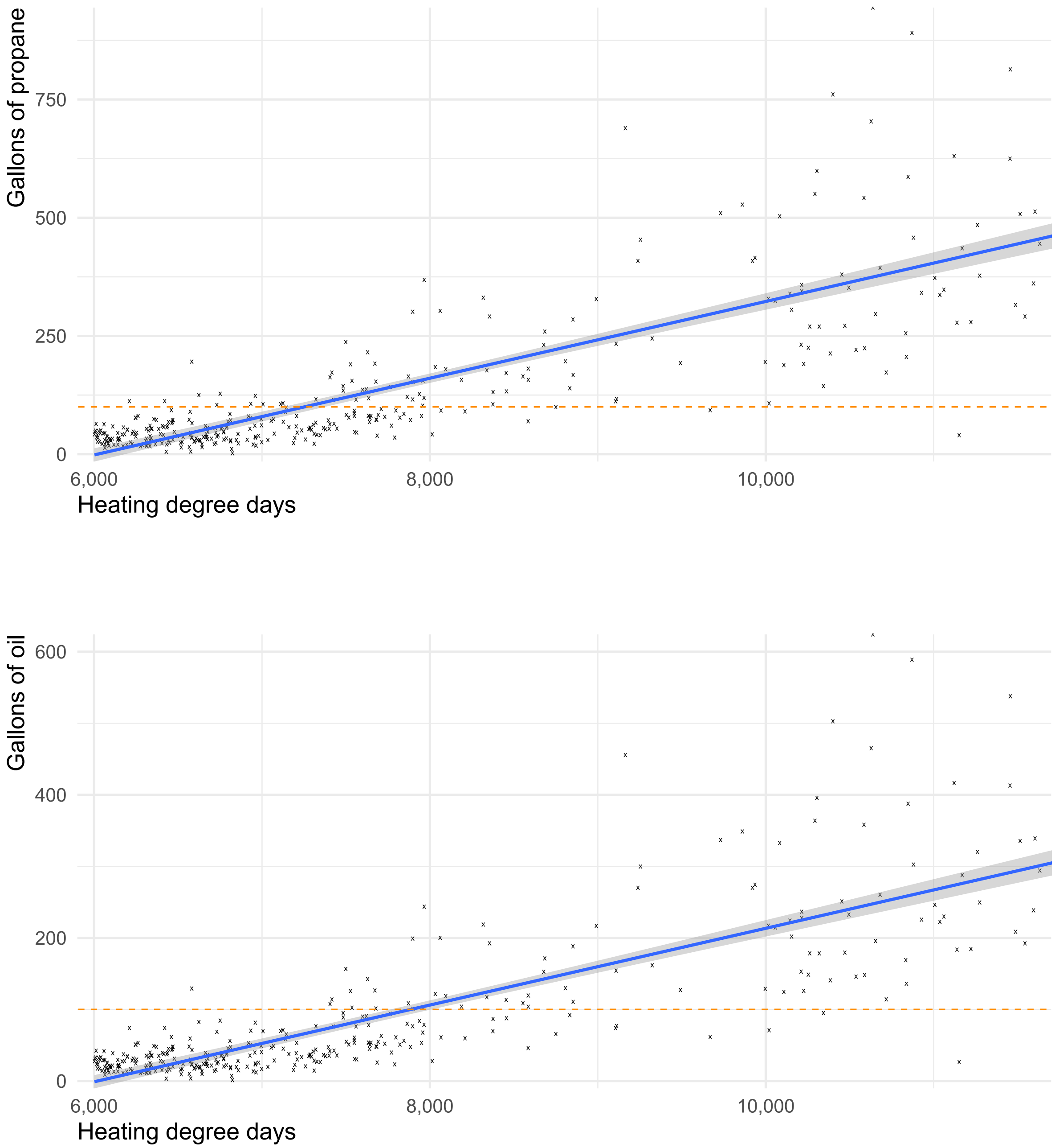

Figure 22. Amount of propane (top) or fuel oil (bottom) needed per year when used as a backup fuel in hybrid heating systems. The dotted line in the upper graph is for 100 gallons of propane.

Discussion and Conclusions

Here, we discuss both the furnace and boiler analyses. For furnaces, our 2022 study found that above approximately 6,000 HDD (the current climate in Detroit), hybrid systems combining a cold climate heat pump with a biogas backup will minimize life-cycle costs for the lower carbon options considered here. Our new analysis, which updates system and biogas costs and uses the 2020 RECS dataset instead of the 2015 RECS dataset, raises this threshold for cold climate heat pumps to approximately 7,000 HDD (the current climate in Minneapolis). For climates above 7,000 HDD, a hybrid system with a biogas backup will minimize life-cycle costs. The same conclusion applies if high costs for cold climate heat pumps are used and 50% of customers leave the gas system, except in this case the cross-over point is approximately 8,300 HDD (the current climate in Bozeman, Montana). These findings are partly driven by the impact of widespread use of heat pumps for space heating on peak winter power demand and hence on electricity prices.

As for the best backup fuel for hybrid systems, our new study uses newer and higher estimates of biogas costs (ICF 2021) and also considers propane and diesel substitutes made from biomass as a backup fuel. Cost estimates for these fuels are imprecise, but at the values we estimate, biogas provided through the gas distribution system has the lowest lifecycle cost assuming pipes do not need to be replaced and most customers stay on the gas system. If these conditions do not apply then propane made from biogas, followed closely by propane made from ethanol, generally has the lowest life-cycle costs, and B100 and renewable diesel are only a little more expensive.

Essentially, our results indicate that there may be viable routes to decommission gas distribution systems in cold climates and provide backup heat via delivered fuels if a substantial number of customers leave the gas system and/or gas pipe replacement costs are high. These delivered fuels could be provided by current propane and fuel oil dealers, or gas utilities could conceivably enter this market to provide conversions and/or on-going fuel deliveries.

For boilers, we find that an air-to-water heat pump combined with a moderate energy efficiency package (along the lines of Home Performance with ENERGY STAR) will typically minimize life-cycle costs. Without the efficiency retrofit, hybrid systems may be needed to provide adequate heat to rooms, increasing life-cycle costs a little below approximately 8,500 HDD (the current climate in Duluth, Minnesota) but reducing those costs a little above 8,500 HDD.

In all of these scenarios, either a moderate energy efficiency package (e.g., a typical Home Performance with Energy Star package) or a deep retrofit at the time of a major home renovation will reduce life-cycle costs.

Estimates of biofuel costs are very imprecise. Further work is needed to develop these fuels and refine cost estimates. If these costs prove to be substantially different from what we estimate, the results of our analysis will change (see Appendix B for a few scenarios). The greenhouse gas emissions of these biofuels vary but are generally substantially higher than emissions associated with a heat pump powered with clean electricity; this issue will be examined in a future ACEEE paper.

Our analysis is based on several thousand homes located throughout the United States, and it uses site-specific energy use and costs. But because our sample sizes are small in most regions, more localized analyses with larger local samples would be useful.

Overall, we find that even in cold climates (above 6,000 HDD), cold climate ASHPs are often the low-cost decarbonization option for space heating 1–4 family homes. In very cold climates (above approximately 7,000 HDD), hybrid systems become a good replacement for furnaces. For homes heated with hot-water boilers, the combination of an efficiency package and an air-to-water heat pump will generally minimize life-cycle costs. Thus, electrification of most space heating is possible even in cold climates, but some use of biofuels can be useful as a backup to reduce consumer life-cycle costs and keep winter peak electric demand from rising too much.

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Appendix A. Fuel and System Costs

In general, we used the same methodology as in Nadel and Fadali (2022). That report, the following describes the methodology and assumptions in detail. Here, provide the updated fuel and heating system costs used in this updated analysis.

Table A1. Fuel and electricity costs

Variable	Value	Notes and source
Multiplier for 2040 site-specific retail electricity price	1.057	For each home, we have the average annual electricity price in 2020. To estimate the site-specific 2040 price, we multiplied the 2020 price by the ratio of national 2040 to 2020 price in real dollars (2020 price is from EIA 2024; 2040 price from EIA 2023b). In addition, we also applied an adjustment for serving winter peak demand (see figure 1).
National average wholesale biogas in 2040 (shown in 2023 dollars)	$26.50/mBtu	ICF 2021 provides seven pathways that average $25.61 in 2022 dollars. We adjust this average to 2023 dollars using the GDP Deflator (FRED 2023).
National average retail biogas price in 2040 (shown in 2023 dollars)	$35.42/mBtu	Based on the wholesale price from the previous row, plus two-thirds of the retail price of natural gas ($12.27 from EIA 2023b, adjusted to 2023 dollars; two-thirds price derived from EIA 2024).
National average retail B100 price in 2040 (shown in 2023 dollars)	$4.81/gal.	$4.26/gallon for fuel oil in 2040 (from EIA 2023b) plus 16.5%, which is how much more B100 cost in 2023 relative to conventional diesel (AFDC 2023b).
National average retail renewable diesel price in 2040 (shown in 2023 dollars)	$5.09/gal.	Derived from previous row assuming that fuel is half the retail cost and that renewable diesel has a production cost of $0.574/kg, while biodiesel is $0.513/kg. Production costs from Omidkar et al. 2023.
National average retail renewable propane derived from biogas price in 2040 (shown in 2023 dollars)	$13.80/gal.	Based on projected retail fossil propane price ($2.91/gal.); an estimate that 37.3% of the retail price is the whole cost (derived from EIA 2023d); and a multiplier for RNG/fossil gas for wholesale portion based on their

Variable	Value	Notes and source
		wholesale prices as noted above, plus an estimated 10% for conversion process.
National average retail renewable propane derived from ethanol price in 2040 (shown in 2023 dollars)	$4.70/gal.	Same as above, but multiplier is based on EIA 2040 projections for retail ethanol per Btu relative to retail natural gas for transportation, plus $1.44/GJ for the conversion in the long term (from Green Car Congress 2019).

For our analysis, we took the national average retail price of each of these alternative fuels, divided by EIA's estimate of the average 2020 retail fossil fuel price for each fuel; we then applied this ratio to the 2020 fuel prices paid by each individual home.

Table A2. Heating equipment costs

	Nadel & Fadali 2022	Guidehouse & Lydos 2023				
Equipment	2020$	2022$	2023$	Efficiency	Units	Notes
	(prior study)					
Gas furnaces		4,130	4,274	90%	AFUE	
	3,662	4,155	4,300	95%	AFUE	Adder for 95% AFUE from USDOE 2023c.
		3,690	3,818	80%	AFUE	Use for lower efficiency furnace scenario
Oil furnace	5,266	5,170	5,350	85%	AFUE	
Central air-to-air HP	6,811	6,880	7,119	8.6	HSPF	
				2.52	COP	From Nadel and Fadali 2022 but adjusted for slightly higher HSPF in row above
Central cold climate air-to-air HP		8,620	8,920	10.6	HSPF	Used cost for high efficiency heat pump

Equipment	Nadel & Fadali 2022 2020$	Guidehouse & Lydos 2023 2022$	2023$	Efficiency	Units	Notes
Higher cost scenario	12,750		14,840			
Adder for electrical -- homes w/o CAC	1,200		2,000			From IL TRM 2023
Central AC	5,502	5,520	5,712	15%	SEER	
GSHP		18,945	25,000	3.6	COP	Cost from Noel 2023
Higher cost scenario	34,100		39,691			Price in first column from E3 2023.
Air-to-water HP	8,575		9,981	3.33	COP	From Nadel and Fadali 2022
Gas HP	9,000	15,995	16,552	130%	AFUE	
Gas boiler	8,713	5,940	6,147	95%	AFUE	20% lower at 6000 HDD, 20% higher at 10000 HDD (based on 60,000 Btu/hr input at 6000 HDD, 120,000 Btu at 8000 HDD; relative costs from Bopray 2023.
Oil boiler	11,367	5,510	5,702	86%	AFUE	Same as row above
Hybrid -- CCHP and gas furnace			11,898			Based on sum of individual equipment prices minus 10% for installing both at same time.
Hybrid -- CCHP and oil furnace			12,843			Same as row above
Hybrid -- CCHP and gas boiler			13,560			Same as row above

	Nadel & Fadali 2022	Guidehouse & Lydos 2023				
Equipment	2020$	2022$	2023$	Efficiency	Units	Notes
Hybrid -- CCHP and oil boiler			13,160			Same as row above

Table A3. Delivered fuel tank costs

Item	Cost	Source
120 gal. propane tank, including installation	$825	This Old House Reviews Team (2023)
Basement tank, including installation	$1,500	Cost Helper (2023)

Appendix B. Additional Alternative Fuel Price Scenarios

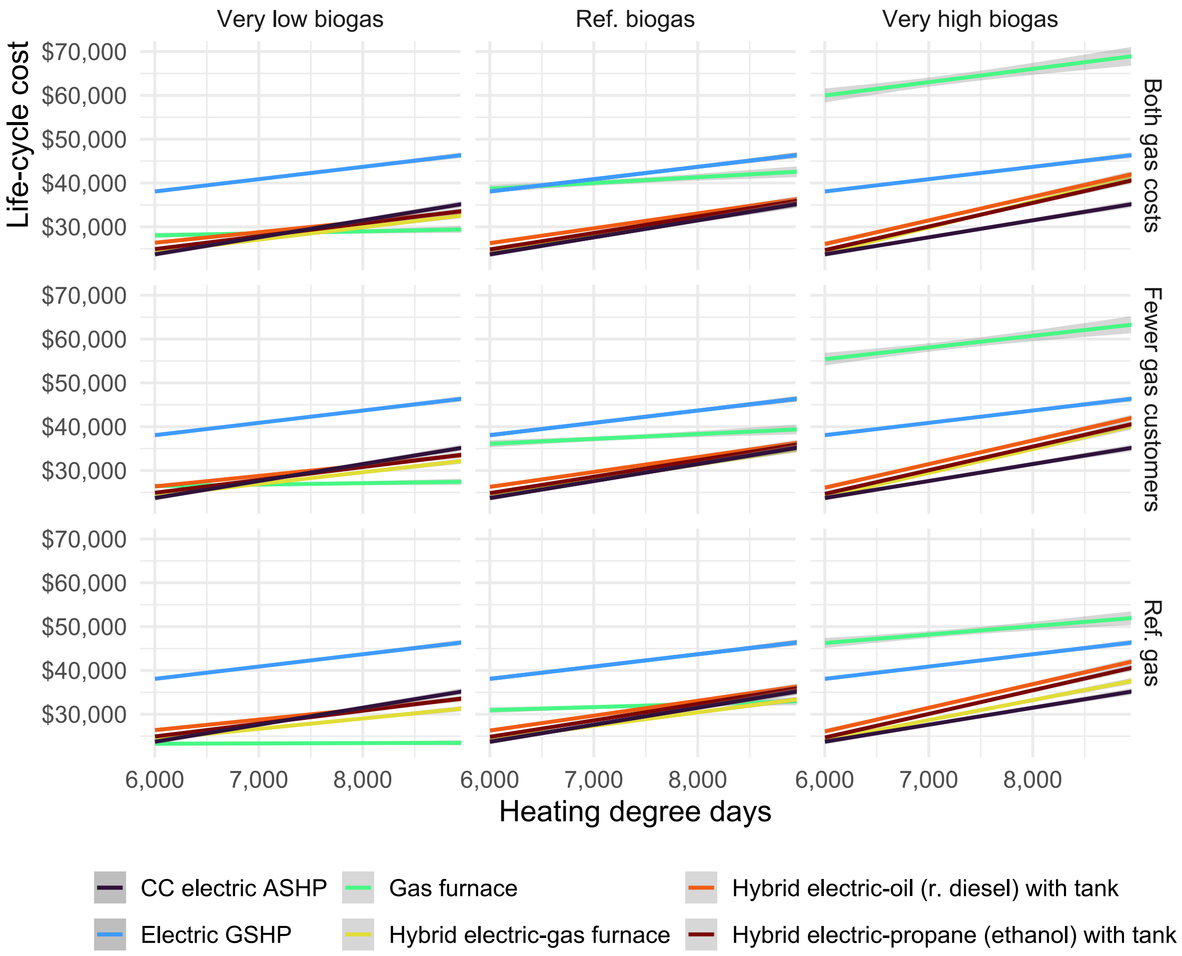

Figure B1. Comparison of life-cycle costs for space heating with warm-air distribution for the six options discussed in main report, but using 50% lower costs and 100% higher costs for fuels. Costs are in 2023 dollars. Except for these lower and higher fuel costs, this figure is the same as figure 14 in the main report.

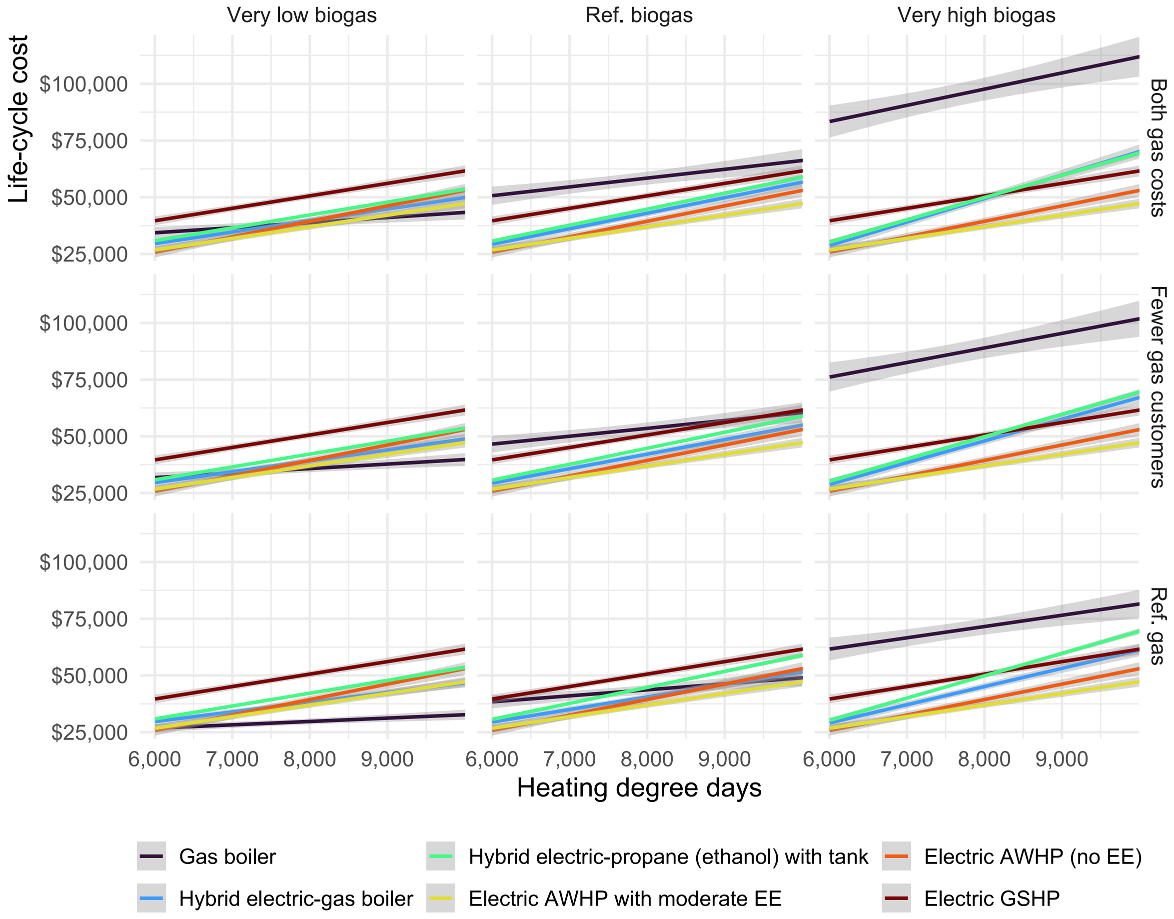

Figure B2. Comparison of life-cycle costs for space heating with hot-water distribution for the six options discussed in the main report, but using 50% lower costs and 100% higher costs for fuels. Costs are in 2023 dollars. Except for these lower and higher fuel costs, this figure is the same as figure 20 in the main report.