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BY NOAH KAUFMAN, DAVID SANDALOW, CLOTILDE ROSSI DI SCHIO AND JAKE HIGDON

DECEMBER 2019

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ACKNOWLEDGMENTS

The authors are grateful for the guidance of experts at the Electric Power Research Institute and National Renewable Energy Laboratory. They would also like to thank three anonymous reviewers who provided helpful comments, Noah Rauschkolb, and colleagues at the Center on Global Energy Policy including Matthew Robinson, Christina Nelson, Anna Gossett, Artealia Gilliard, and Genna Morton.

This policy paper represents the research and views of the authors. It does not necessarily represent the views of the Center on Global Energy Policy. The paper may be subject to further revision.

This work was made possible by support from the Center on Global Energy Policy. More information is available at https://energypolicy.columbia.edu/about/partners.

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EXECUTIVE SUMMARY

In the United States, commercial and residential buildings produce roughly 12 percent of greenhouse gas emissions. Most of these emissions come from burning fossil fuels for space heating. These emissions must be significantly reduced or eliminated for the US to achieve deep decarbonization goals, including net zero emissions by midcentury.

Air source heat pumps (ASHPs) are powered by electricity, using well-established technology to move heat from outdoor air to indoor air. When powered by zero-carbon electricity, ASHPs provide space heating with almost no greenhouse gas emissions. ASHPs are especially effective for space heating in mild climates.

In 2015, roughly 10 percent of US households (mostly in the Southeast) used air source heat pumps as their primary heating source.[1] ASHPs account for roughly one-third of residential space heating in Japan. The world's largest ASHP market is in China, where sales are growing rapidly.

Prominent studies on decarbonization of the US energy system focus on deployment of air source heat pumps as the primary strategy for reducing emissions from space heating.

- Some studies show near-universal electrification of space heating, suggesting that ASHPs (with some backup from electric resistance heaters) can be almost a silver bullet solution for decarbonizing space heating. These studies start with the assumption that fossil fuel furnaces and boilers will be gradually phased out.
- Other studies assume that electric heating technologies such as ASHPs will continue to compete against fossil fuel burning furnaces and boilers in the decades ahead. These studies conclude that furnaces and boilers will retain a significant share in space heating markets, even with technological progress and strong policy support for ASHPs, but often fail to explain why. Do high costs or inferior performance limit market penetration in these studies? Or do other barriers limit ASHP deployment? The answer has important implications for policy makers shaping decarbonization strategies.

To help answer these questions, we built a simple model of ASHP adoption that estimates the lifetime costs of space heating and cooling configurations in three US cities with markedly different climates and energy costs: Atlanta, Georgia; San Diego, California; and Fargo, North Dakota. The model analyzes the choices facing hypothetical consumers installing new heating and cooling equipment in residential buildings. The consumers have the option to purchase an ASHP for heating and cooling (with backup if needed) or a natural gas furnace and air conditioner.

Based on the model results and related research, we conclude:

- Air source heat pumps are cost competitive today in places where electricity is cheap and the climate is mild.

- With climate policies consistent with rapid decarbonization and reasonably foreseeable technological progress, air source heat pumps are the low-cost option for typical residential buildings across much of the US by the mid-2030s. Even in the very cold climate of Fargo, North Dakota, the combination of a price on carbon emissions and steady innovation in ASHPs causes ASHPs (with an electric resistance heater as a backup) to be cost competitive with new natural gas furnaces and air conditioners by the 2030s.

If the United States commits to the rapid decarbonization of space heating by midcentury, the costs and performance of ASHPs are unlikely to be major barriers to deployment. However, other important barriers may persist, including contractors' and homeowners' greater familiarity with incumbent fossil fuel technologies and the slow turnover of the building stock.

As a result of these additional barriers, emissions pricing and technological progress alone may not lead to deployment of air source heat pumps in the United States sufficient to achieve deep decarbonization by midcentury. That would likely require additional policy instruments such as technology standards, emissions caps, or mandates.

Other technologies can also contribute to decarbonizing space heating, including renewable natural gas, hydrogen produced with carbon capture and storage (CCS) or electrolysis, and centralized or district heating. Each of these options comes with challenges that will require policy support to overcome.

This study does not point to a proper balance between ASHPs and other space heating decarbonization technologies. More research is needed to compare different approaches and strategies. In the meantime, our analysis suggests little if any downside to pursuing ambitious policies to promote deployment of ASHPs, prioritizing regions where heat pumps are currently most cost effective. A large-scale increase in ASHP deployments is likely to be an important part of any space heating decarbonization scenario.

1. INTRODUCTION

The Paris Agreement sets a goal of limiting the global average temperature increase to "well below" 2°C (3.6°F) compared to preindustrial levels. It also calls on countries to "pursue efforts" to limit the increase to 1.5°C (2.7°F) and achieve net zero emissions globally by the second half of this century. To accomplish these goals, the global energy system will need to be reshaped to run on mostly carbon-free sources. That transition will involve cutting energy waste, shifting electricity production to carbon-free sources, and using electricity to satisfy a greater share of energy demand, among other strategies.

In the United States, the use of fossil fuels in commercial and residential buildings is currently responsible for roughly 12 percent of greenhouse gas emissions. Despite this significant contribution, the sector has received less attention with respect to decarbonization strategies than either the power sector (28 percent) or the transportation sector (29 percent). Strategies for decarbonizing both the power sector and transportation sector are in general better developed than those for building heating.[2]

In prominent studies of pathways to a low-carbon US energy system, shifting from furnaces and boilers powered by fossil fuels to air source heat pumps (ASHPs) powered by zero-carbon electricity is the primary strategy for decarbonizing space heating. However, these studies show a wide range of outcomes on the potential for ASHPs to contribute to zero emissions space heating in the United States by midcentury. The more optimistic studies show the near-universal electrification of space heating over the next few decades, with ASHPs playing an important role, while the more pessimistic studies show electricity failing to even displace natural gas as the leading space heating fuel. Taken as a whole, this literature leaves policy makers with more questions than answers: What are the largest barriers to the widespread adoption of ASHPs? Are ASHPs the best technology for decarbonizing space heating? Are large investments needed in alternative carbon-free space heating technologies?

This paper is intended for policy makers who wish to make sense of the disparate evidence on the potential for the adoption of air source heat pumps in the United States. It explains that ASHPs are already competitive with fossil fuels in certain regions of the country and that innovation and policy support are likely to make ASHPs more competitive in the years ahead. It also explains the barriers that stand in the way of zero emissions space heating, including costs, performance in cold climates, existing infrastructure, and consumer behavioral tendencies.

Our goal is to provide policy makers with a better understanding of the potential of air source heat pumps and how policies can help realize this potential.

The remainder of the paper proceeds as follows:

- Section 2 describes the market for space heating in the United States today.
- Section 3 introduces the technologies available for decarbonizing space heating, focusing in particular on ASHPs.

- Section 4 summarizes prominent recent studies of the decarbonization and electrification of the US energy system. It highlights the large differences in results of these studies with respect to the penetration of electric ASHPs for space heating, driven primarily by differing modeling assumptions and methods.
- Section 5 introduces a simple model of heat pump adoption that estimates the costs of three space heating and cooling configurations in three US cities. It shows key factors that influence the heat pump adoption decision and describes key factors omitted from the model.
- Section 6 reviews existing policies that promote electric heat pumps and then describes policy options for the future encouragement of heat pump adoption.
- Finally, Section 7 highlights implications for policy makers from the study.

2. SPACE HEATING IN THE UNITED STATES TODAY

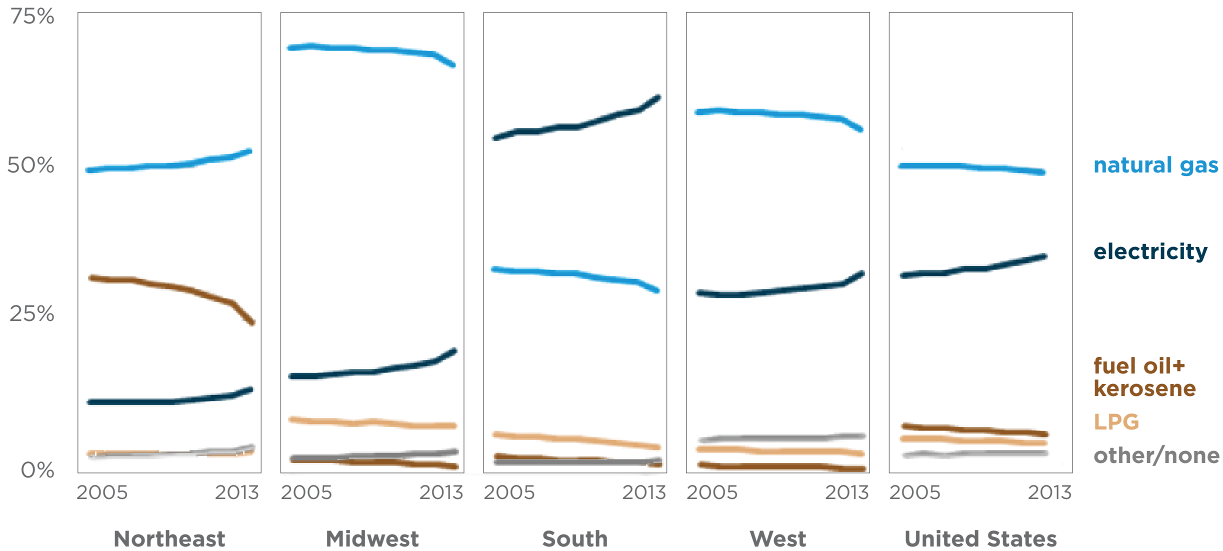
The three leading technologies for space heating in the US today are furnaces, boilers and electric resistance heating:

- **Furnaces** draw in cold air and ignite a burner to heat it, then use fans to distribute the warm air throughout the household through ducts. Most furnaces run on natural gas or fuel oil.
- **Boilers** heat water and distribute hot water or steam through pipes to radiators. This is especially common in apartment buildings in the Northeast. Boilers are almost always fueled by natural gas or fuel oil.[3]
- **Electric resistance heaters** generate heat by passing electricity through resistors. These are commonly used in baseboard heaters and space heaters and are sometimes used in furnaces.[4]

Space heating in US buildings is dominated by fossil fuels. Roughly half of buildings use natural gas for heating. Roughly 10–15 percent use oil or propane. The remainder use electricity. In most parts of the country, electricity is generated primarily using fossil fuels.[5]

Roughly 58 million US homes use natural gas heating. In the Northeast, where fuel oil is still a relatively common heating source, natural gas and fuel oil combine for 77 percent of households' primary heating. In the Midwest, 63 percent of households are heated by natural gas furnaces.[6] About one-third of homes, or around 41 million housing units, used electricity for some portion of their heating, with electric resistance heaters the primary source in this category.[7]

Figure 1: Primary heating fuel choice, 2005-2013



Note: Natural gas is the primary heating fuel by a large margin in most of the United States, yet its market share is declining everywhere but the Northeast, where it is offsetting fuel oil and kerosene.

Source: US Energy Information Administration, based on the Census Bureau American Community Survey

Commercial buildings rely more on electricity for heating. In 2012, at least some portion of about 60 percent of commercial buildings were heated with electricity, 55 percent with natural gas, and 15 percent with fuel oil, propane, solar, or biofuels.[8] A significant percentage of commercial buildings combined fuels. Electricity and natural gas each heated about 50 billion square feet of commercial buildings (about 44 percent of total floor space each).

3. TECHNOLOGIES FOR DECARBONIZING SPACE HEATING

This section describes air source heat pumps and reviews other space heating technologies with the potential to contribute to decarbonization.

3.1. Air Source Heat Pumps

ASHPs use a vapor-compression cycle to move heat from the low-temperature ambient air to the higher-temperature indoor air.

While ASHPs can take many forms, a typical ASHP consists of a closed loop refrigeration system with a compressor and two heat exchangers (one indoors and one outside). In heating mode, the refrigerant evaporates when it flows through the outside heat exchanger and releases heat to the indoor heat exchanger as it condenses back to liquid. A reversing valve can switch the operating mode from heating to cooling as it reverses the thermodynamic cycle.

Heat pumps can be a highly efficient way to satisfy space heating needs.[9] The vapor-compression process allows for a high coefficient of performance (COP) when the desired space temperature is close to the ambient temperature. For example, when the ambient temperature is 60°F (about 15.5°C) and the desired space temperature is 68°F (about 20°C), the COP of an ASHP may be around four, meaning that for every unit of electricity consumed by the heat pump, four units of thermal energy are added to the conditioned space.

A drawback to heat pumps is that their performance degrades as ambient temperatures drop. ASHPs are particularly susceptible to this phenomenon, as they must extract thermal energy from the ambient air. (Ground source heat pumps [GSHPs] extract energy from the soil, which tends to be warmer than the air during the heating season.) However, as the technology has improved in recent years, ASHPs have become viable even in many colder climates.

Today, most heat pumps are equipped with a supplementary electric resistance heater or backup burner that provides additional heat when the building's heating demands exceed the compressor's capabilities.[10] These resistance heaters can provide additional capacity for low capital cost but have a COP of only one.

Figure 2: The heating cycle of an ASHP

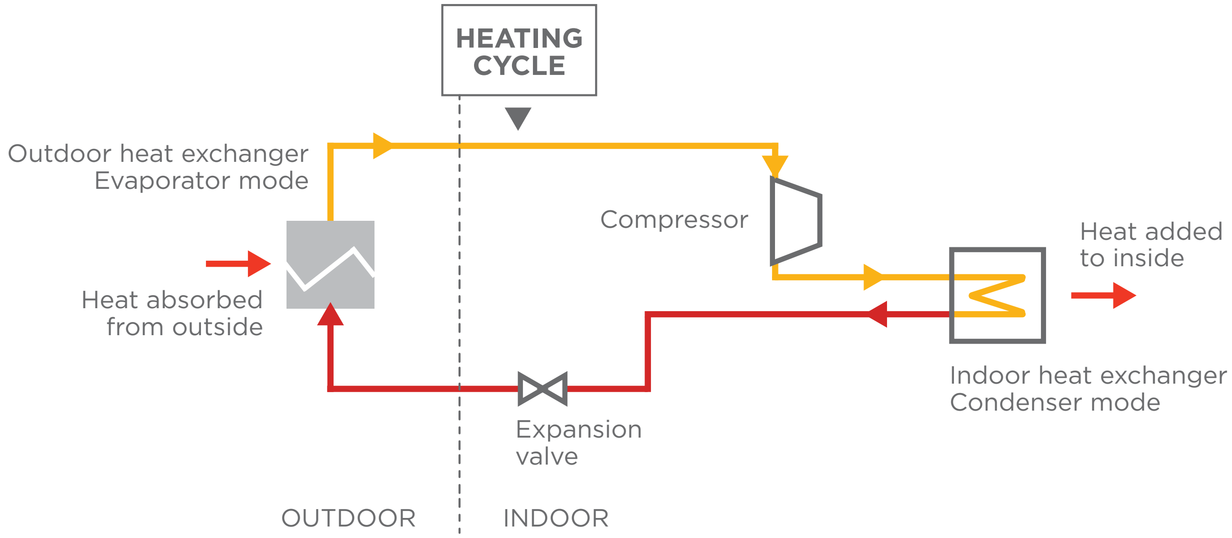
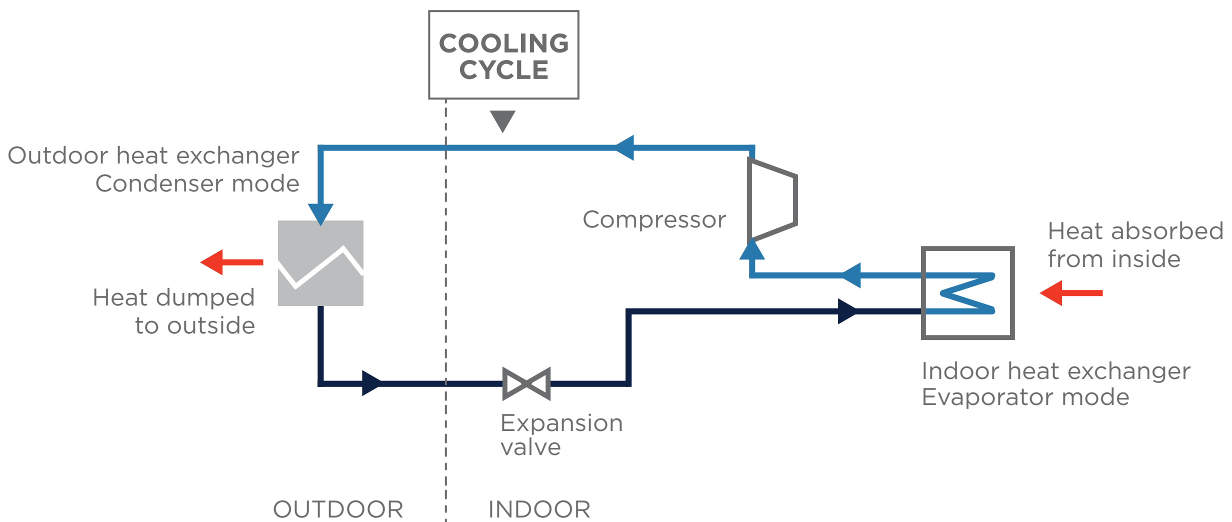


Figure 3: The cooling cycle of an ASHP



In 2015, roughly 10 percent of US households (roughly 12 million homes) used heat pumps as their primary heating source.[11] In 2012, just over 11 percent of US commercial buildings used heat pumps.[12]

- Heat pumps are most commonly found in the southeastern United States, where the climate is hot and humid, winter temperatures are mild and electricity is relatively cheap.

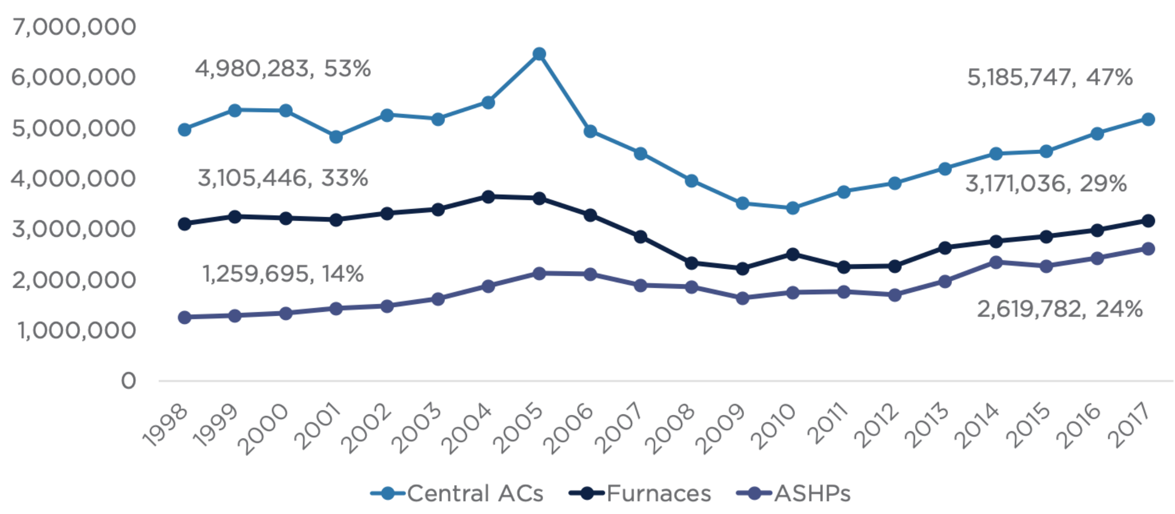
About three-quarters of residential heat pumps installed in the US are in the South (as classified by the US Department of Energy), where ASHP market share is 20 percent.

- The Pacific region is a distant second.[13] However, California has seen particularly strong adoption of heat pumps in commercial buildings, with roughly half of the commercial buildings serviced by San Diego Gas & Electric and 40 percent of commercial Southern California Edison customers using heat pumps.[14]
- Market penetration in the northern United States is low. In the Northeast, for example, the market share of heat pumps in residential households is roughly 3 percent.[15]

The US has seen slow but steady growth in heat pump sales, growing from 14 percent to 24 percent of sector-wide shipments from 1998 to 2017 and cutting into the market shares of both furnaces and central air conditioners.[16]

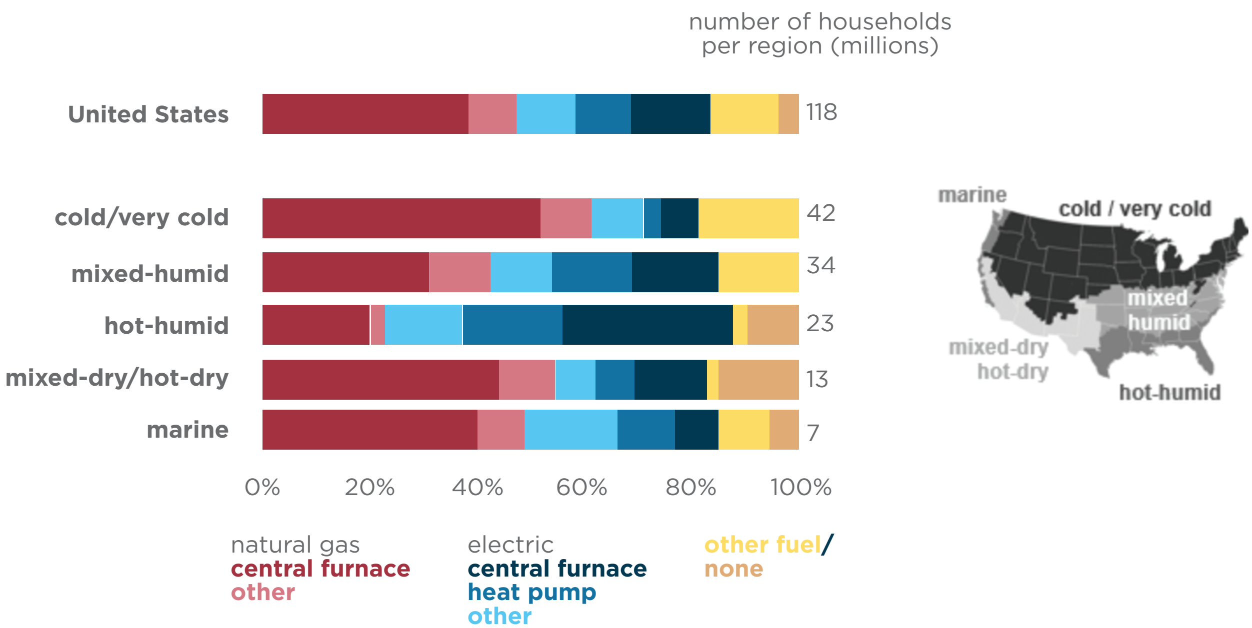
More air source heat pumps are sold in the US than Europe. In 2015, the US saw 2.3 million ASHP shipments, compared with 429,000 ASHPs in Europe. In 2015, heat pumps accounted for 10 percent of the US residential heating market, or about 11.8 million units. Europe has about 9 million heat pumps, about half of which are ASHPs.[17] However, many European countries have faster deployment rates. For instance, in 2018, nearly 5 percent of all households in Norway installed a new ASHP.[18]

Figure 4: US heat pump shipments compared to competing technologies[19]



Source: AHRI

Figure 5: Main heating equipment choice by climate region, 2015



Source: US Energy Information Administration, 2015 Residential Energy Consumption Survey

Note: In the United States, heating equipment still varies significantly along climate lines. Colder and dryer regions tend to use natural gas, while warmer and wetter regions use electricity.

Barriers to ASHP adoption include the following:

- *Costs*. In many climates, ASHPs are more expensive than natural gas furnaces (both in terms of up-front and lifetime costs).
- *Performance*. The COP advantage of ASHPs is reduced in colder climates.
- *Infrastructure*. Many existing buildings were not designed for ASHPs. Installing an ASHP may require costly ductwork or other retrofits.
- *Stock turnover*. Furnaces and boilers can last for decades. Unless furnaces are retired before the end of their useful lives, demand for ASHPs in many existing buildings will be low.
- *Status quo bias*. Consumers are more likely to stick with the equipment they have, and the space heating market is dominated by furnaces. Moreover, most heating systems are replaced only after they have failed, leaving homeowners very little time to shop for a new technology.
- *Short termism*. Consumers place considerable weight on up-front costs, whereas a key advantage of ASHPs is their efficiency, which can reduce long-term costs.
- *Principal-agent problems*. Builders are rarely incentivized to pay higher up-front costs

for energy efficiency, because those costs make homes more expensive. Purchasers heavily weight up-front purchase price over future costs in purchase decisions.

- *Contractor familiarity*. Many contractors and construction managers may not be trained to recommend or install ASHPs, especially in regions with low ASHP penetration.

- *Information*. Consumers may not be aware of emerging technologies or have the most up-to-date information about their costs or performance. ASHPs have a reputation for poor performance in cold climates, despite the fact that hundreds of heat pump models can now operate efficiently in 5°F weather or colder.[20]

3.2. Other Decarbonization Technologies

Other technologies for decarbonizing space heating alternatives fall into four broad categories:

1. **Energy Efficiency.** Efficiency and conservation are critically important strategies for reducing greenhouse gas emissions from space heating. Indeed, improvements to building insulation, architectural design and the efficiency of furnaces and other appliances can often be achieved at a relatively low (and sometimes negative) cost. However, efficiency and conservation on their own cannot achieve net zero emissions, so long as some heating is required.

2. **Ground Source Heat Pumps.** GSHPs are similar to ASHPs, except instead of an air-based heat exchanger, GSHPs have pipe systems in the ground.[21] Due to the relatively moderate and constant temperature of the ground (between 50°F and 60°F) compared to the air, GSHPs are considerably more efficient than ASHPs. However, GSHPs cost significantly more than ASHPs to install—often double or more.[22] GSHPs face almost all the same barriers as ASHPs in displacing incumbent space heating technologies, and these barriers are often magnified by the higher up-front costs.

3. **Low-Carbon Fuels.** The major advantages of low-carbon fuels as an alternative to fossil fuels are that they can be used with existing infrastructure. They also can be stored and perform well in any climate. Two possible low-carbon fuels are biogas and hydrogen. Waste products (e.g., wastewater, food waste, manure) can be processed in a biodigester to create biogas, which can then be upgraded to renewable natural gas (RNG). Hydrogen can be produced without carbon emissions using (i) CCS, or (ii) electrolysis powered by electricity from zero-carbon sources.

   However, the current supply of carbon-free fuels is limited, and there are large barriers to the emergence of low-carbon fuels as a primary space heating decarbonization strategy. In the absence of strong new regulations, biogas from sources other than waste products may not be carbon free (or even low carbon) and could distort markets for other products (e.g., food). Blending too much hydrogen into existing pipelines creates safety concerns. A commitment to carbon-beneficial biomass production or a new pipeline system of hydrogen (or, alternatively, converting the hydrogen to synthetic natural gas) are conceivable but not small undertakings.

4. **District Heating.** Heat can be generated centrally and distributed to individual

buildings. For example, heat can be generated by solar collectors or absorbers, and power plants and industrial plants create waste heat. This centrally generated heat can be stored underground (in hot water tanks, pits, borehole fields, or aquifers) and delivered to consumers when needed via a district heating network.

Perhaps the most prominent existing example of low-carbon district heating in North America is the Drake's Landing community in Alberta, Canada. At Drake's Landing, solar thermal collectors on the roofs of garages through the community collect heat, which is stored in water in short-term storage tanks and distributed as needed via an underground pipe network.[23]

The largest barrier to the widespread adoption of low-carbon district heating networks is the scale and cost of infrastructure projects needed to install them initially or to switch existing steam systems over to low-carbon fuels.

While the remainder of this paper focuses on ASHPs because of their prominence in decarbonization studies, other technologies can contribute to achieving zero emissions space heating as well.

Use of Refrigerants in Air Source Heat Pumps

Refrigerants are a critical component of ASHP technologies. Liquid refrigerants extract heat from the outside air, evaporate into a gas, and release the heat indoors. Historically, most refrigerants used in ASHPs were hydrochlorofluorocarbons (HCFCs) such as R-22 (Freon), which deplete the ozone layer. When the US Environmental Protection Agency (EPA) banned HCFCs, including R-22, in new units as of 2010, hydrofluorocarbons (HFCs) became the most common refrigerant in ASHPs.[24,25] HFCs do not deplete the ozone layer but are powerful greenhouse gases. Some HFCs are thousands of times more potent at trapping heat than carbon dioxide.[26]

HFC emissions are a factor that policy makers should consider in comparing ASHPs to other space heating sources. However, for three reasons, this report focuses on the carbon dioxide emissions from space heating and not HFC emissions.

First, the vast majority of warming from space heating emissions comes from carbon dioxide. In part due to current EPA safeguards on leakage and end-of-life disposal, just 2–5 percent of lifetime total equivalent warming impact of heat pump systems, including end-of-life disposal, is driven by escaped refrigerant gas.[27]

Second, ASHPs provide cooling as well as heating and therefore can displace air conditioners as well as furnaces and boilers. Air conditioners also require the use of refrigerants. Displacing air conditioners with ASHPs may not significantly increase HFC emissions.[28]

Third, under the Kigali Amendment to the Montreal Protocol, 197 countries committed to cut the production and consumption of HFCs by more than 80 percent over the next 30 years. While the US Senate has not yet ratified the agreement, the United States committed to an 85 percent reduction in HFCs by 2035. Alternative refrigerants are already beginning to emerge.[29] Many manufacturers are investing in hydrofluoroolefins (HFOs), developing HFO-based refrigerant blends that are less powerful at trapping heat than HFCs.

4. US DEEP DECARBONIZATION LITERATURE

4.1. Prominent Studies

In recent years, several detailed and comprehensive studies have outlined pathways to deep decarbonization or high levels of electrification of the US energy system. Table 1 provides a summary of prominent national-level studies. In each study, the deployment of ASHPs is a primary strategy used to achieve the electrification and decarbonization of space heating.

Table 1: Studies of the electrification of the US space heating needs

Authors	Year	Study objective or scenario	Electrification of residential space heating demand by 2050	Technology deployment determined by
Williams et al.[30]	2015	80 percent emissions reductions by 2050	About 100 percent	Expert assumption
White House[31]	2016	80 percent emissions reductions by 2050 ("benchmark" scenario)	About 50 percent	Cost minimization
Electric Power Research Institute[32]	2018	"Transformation" electrification scenario	About 40 percent	Cost minimization
US National Renewable Energy Laboratory[33]	2018	"High" electrification scenario	About 60 percent	Expert assumption
Jacobsen et al.[34]	2018	100 percent energy from wind, water, and solar ("Case C")	About 100 percent	Expert assumption

With respect to determining future deployments of ASHPs and other space heating technologies, the studies can be divided into two categories, which we label "expert assumption" and "cost minimization."

In the studies that use expert assumptions to determine the deployment of technologies, the models are used largely as accounting tools, ensuring pathways are technically feasible and that sufficient energy services are available to meet consumer demands under constraints imposed to reflect realistic consumer behavior and stock turnover rates.

For example, Jacobsen et al. (2018) shows that the global energy system can be powered by existing wind, water, and solar energy technologies by 2050, including the United States. To accomplish this goal, the study assumes that nearly all energy uses are electrified by 2050. In one scenario (Case C), all air heating and cooling needs are satisfied by electric heat pumps (both air and ground source). In other words, the elimination of the use of natural gas and other fossil fuels in space heating is not an output of the model, but rather it is assumed to be a policy objective, and thus it is a constraint imposed on the model. A contribution of the study is to show that providing the electricity needed to electrify the energy system by 2050 is technically feasible given a set of assumptions about renewable energy and land resources available and likely demands for energy services, including space heating.

A similar approach is taken by Williams et al. (2015) in the study *Pathways to Deep Decarbonization in the United States*. The purpose of that study is to show multiple technically feasible pathways to 80 percent reductions in US greenhouse gas emissions by 2050 (the group has performed similar studies for the world and many other major economies). The study assumes only existing commercial or near-commercial technologies are available and that equipment is only replaced at the end of its useful life. While achieving 80 percent reductions does not require the full decarbonization of all energy uses, the authors used expert judgment to determine that residential space heating will need to be fully (or near fully) decarbonized by 2050 so that other more-difficult-to-decarbonize sources like heavy-duty transport and certain industrial uses can continue to emit. The results for space heating are therefore similar to the Jacobsen et al. scenario described above, with the complete electrification of space heating by 2050 using high efficiency electric heat pumps and radiators.

In a second category of studies, labeled as "cost minimization" studies in Table 1, technology deployment pathways are model outputs rather than inputs. In these models, it is assumed that energy producers and consumers behave similarly to how they have behaved in the past, favoring less expensive, higher performing, and incumbent technologies. These analyses portray market shares changing in the future based on a set of assumptions about the evolution of technologies and policies. For example, if solar energy becomes less expensive or if a carbon price is imposed, producing electricity using solar energy becomes more attractive, so its market share grows. The preferences of individuals may change over time also, though models rarely depict such changes.

In most cost minimization studies, "extreme" solutions in which new technologies like electric heat pumps dominate a market segment like space heating are extremely difficult, and perhaps impossible, to portray without simply imposing this result as an exogenous assumption. After all, these models are built to portray the energy system as it has existed over a recent historical period.

For example, the *United States Mid-Century Strategy for Deep Decarbonization* (MCS) shows a "benchmark" scenario with greenhouse gas reductions of 80 percent by 2050. The study assumes that the efficiency of heat pumps improves over time and that public policies are imposed to drive down emissions, represented by an increasing carbon price. The market shares of space heating technologies depend on costs, but the Global Change Assessment Model (GCAM) used for the analysis also attempts to proxy for factors that influence consumer decisions aside from costs (including idiosyncratic preferences or circumstances, limitations in availability or information, etc.). Indeed, the model is structured so that technologies that lose their cost advantage do not immediately lose all their market share, because that's not what has occurred in reality. As the GCAM documentation puts it, "For a gradually increasing cost adder, such as a greenhouse gas tax, it can take a long time to push uncompetitive technologies completely out of the market."[35]

The *US National Electrification Assessment*, published in 2018 by the Electric Power Research Institute (EPRI), uses a similar model and methods to the MCS study. In its "transformation" scenario, carbon prices rise to over $300/ton by 2050. EPRI's findings related to the electrification of the residential space heating sector are similar to the MCS study: just under half of energy demand is satisfied with electricity by 2050, with the remainder supplied by natural gas.

Finally, a 2018 study by the US National Renewable Energy Laboratory (NREL)—*Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*—offers a hybrid of the "expert assumption" and "cost minimization" approaches. NREL uses the same model as Williams et al. (2015), with technological deployment determined by expert assumptions and with ASHPs as the primary strategy for electrifying space heating. However, unlike the Williams et al. or Jacobsen et al. studies, NREL did not impose an exogenous constraint on the degree of electrification or decarbonization to achieve by 2050. Like the MCS and EPRI studies, fossil fuel alternatives are assumed to continue competing with electric alternatives through 2050. In addition, NREL's assumptions on technological deployment were based on factors similar to those endogenously modeled with the framework of the MCS and EPRI studies: expected costs, operational characteristics, policies, and reasonable stock turnover rates given preferences for incumbent technologies.

With a hybrid methodology, it is perhaps not surprising that with respect to the electrification of space heating, NREL's results (for its "High" electrification scenario) lay between the two categories of studies described above: about 60 percent of residential space heating energy demand is provided by electricity by 2050.

4.2. Implications

Each of the five studies portrays a massive increase in the deployment of heat pumps. However, policy makers charting a course for a carbon-free energy system could arrive at vastly different conclusions depending on which study they read.

The scenarios that show 100 percent electrification of space heating portray heat pumps as a potential silver bullet solution, implying that policy makers can achieve any space heating decarbonization goal by concentrating on the deployment of this one technology. But these outcomes are contingent on assuming that consumers can no longer use fossil fuels for space heating.

In contrast, the studies that show only moderate electrification by 2050 suggest potential limits to the deployment of heat pump technologies, particularly in cold climates, and imply that near-zero emissions levels will require a focus on additional decarbonization strategies as well. However, the models that produce these results assume that markets will behave in ways that resemble the past—in other words, they assume that unprecedented events will never occur. If large shifts in technologies and consumer preferences are destined to upend the space heating market, energy models are not designed to see this outcome coming in advance.

This literature leaves policy makers with various difficult questions. How can policy be designed to achieve zero emissions space heating in a way that's least burdensome to consumers? Is zero emissions space heating best accomplished through a focus on electric heat pumps, the development of additional strategies, or a more technology neutral approach? The following sections are intended to help policy makers understand the trade-offs associated with these questions.

5. A SIMPLE MODEL OF HEAT PUMP ADOPTION

The detailed models described in the previous section provide important information about possible future energy systems, but these models can be black boxes to nonpractitioners. It can be difficult to isolate factors that lead to specific results in the models.

We built a simple model that compares the costs of installing and operating an ASHP with natural gas furnaces (the current market leader in space heating). The purpose was to help fill an important hole left by the existing literature. As described in the previous section, when fossil fuel options can continue to compete in the market, prominent studies show that the complete decarbonization of space heating is not achieved by midcentury when ASHPs are used as the primary decarbonization tool. However, these studies do not explain why ASHPs are insufficient. Two explanations are plausible:

- First, it may be that ASHP technology is not up to the task, even with technology and policy improvements, because costs are too high or performance is not good enough compared to natural gas furnaces.
- A second possibility is that noncost or performance factors such as lack of information or status quo bias are important barriers.

Policy design may vary significantly depending on the degree to which either of the two explanations is correct.

Our analysis focuses on hypothetical consumers installing new heating and cooling equipment in residential buildings. The consumers have the option to purchase an ASHP for heating and cooling (with backup if needed) or a natural gas furnace and an air conditioner. We examine hypothetical consumers in three US cities—San Diego, California; Atlanta, Georgia; and Fargo, North Dakota—chosen due to the range of climates and energy prices in these cities.

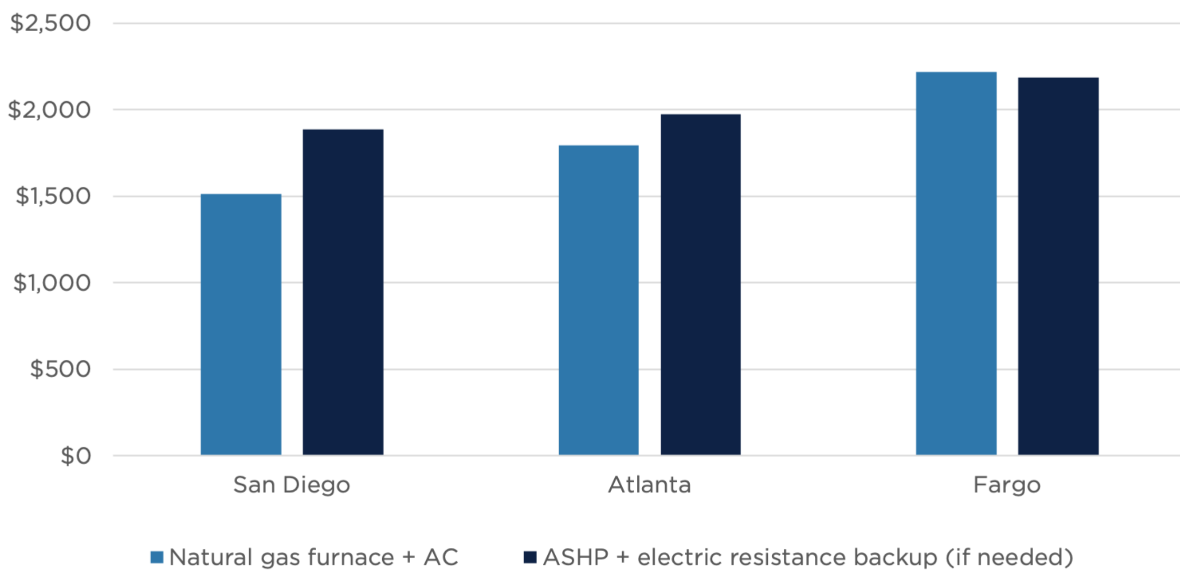
We portray residential consumers making decisions in the early- to mid-2030s and operating the equipment for 15 years, which was chosen so that the equipment's useful life ends around 2050. We start with a base scenario with assumptions on prices, equipment costs, and policies that reflect current or recent historical data. Then we examine three scenarios that reflect changes in technologies and policies over the next decade that may be likely in a jurisdiction that has committed to decarbonization by midcentury.

The uncertainties associated with projecting consumer decisions decades into the future with a simple model are too extensive to name individually. Technologies, economies, and consumer preferences will all change in unexpected ways, and consumer decisions are vastly more complicated than portrayed by a comparison of the costs of installing and operating equipment. However, the simplicity of the analysis enables a straightforward description of the major drivers of the cost differences between ASHPs and natural gas furnaces and how these differences are affected by key uncertainties.

5.1. Results from the Base Scenario

Figure 6 compares the up-front capital costs of (i) a natural gas furnace and air conditioner combination and (ii) an ASHP, with backup if necessary. (In buying an appliance, consumers pay more attention to the up-front capital cost than projected fuel costs over the lifetime of the appliance.) Costs were determined using assumptions on equipment, prices and policies drawn from current or recent historical data. (Sources are described in the Appendix.) Different thermal capacity is appropriate for different climates, so average costs differ by city. The ASHP option is more expensive in San Diego and Atlanta but less expensive in Fargo, although the differences in capital costs are under 20 percent in each city.

Figure 6: Comparison of up-front capital costs of heating and cooling alternatives



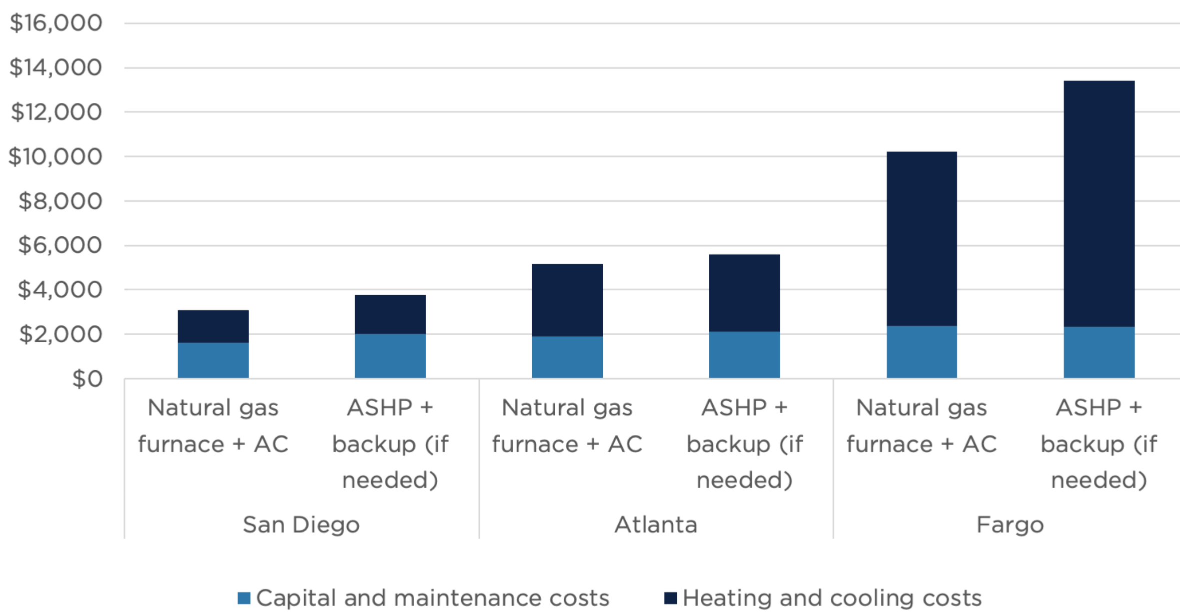
The differences in the costs of heating and cooling are far larger. Figure 7 shows the net present value (NPV)[36] costs of an ASHP (with backup if necessary) compared to a natural gas furnace and air conditioner combination, separating capital and maintenance costs from fuel costs over the lifetime of the equipment.

In Fargo, with its extremely cold climate, lifetime fuel and electricity costs are very high: four to six times the capital cost of the equipment. In San Diego, with its moderate climate, lifetime fuel and electricity costs are low: less than the capital cost of the equipment.

In Atlanta, the NPV costs of the ASHP option is only 8.1 percent (or $416) more than the natural gas furnace option, due to the relatively high costs of natural gas and mild winters in the city. In San Diego, relatively lower natural gas prices and higher electricity prices make natural gas furnaces the cheaper option by $665, or 21.6 percent. A much larger cost difference exists in Fargo, where ASHPs are $3,193 (or 31.3 percent) more expensive than the natural gas furnace option due to the low efficiency of current ASHPs in very cold climates.[37]

The results of the Base Scenario help to explain recent market trends. Because ASHPs are reaching cost competitiveness in certain regions, their penetration has grown considerably in recent years, particularly in the southeastern United States (where Atlanta is located). However, the total market share of ASHPs nationally in the US remains low for various reasons. First, natural gas furnaces remain the cheaper option in many regions. Second, barriers other than cost and performance prevent ASHP adoption, including lack of information, principle-agent problems, and preferences for the status quo.

Figure 7: Comparison of net present value costs of heating and cooling alternatives



5.2. Technology and Policy Progress Scenarios

We also tested scenarios based on the changes in technologies and policies needed to achieve the complete decarbonization of space heating in the United States. The scenarios include the following:

1. **A Strong Technological Progress Scenario:** Capital costs of ASHPs decrease by 30 percent and COP increases by 30 percent between now and the early- to mid-2030s. While some studies suggest that the improvements in heat pump technologies could be even larger in the next couple of decades,[38] we use these assumptions to account for the fact that natural gas furnaces are likely to improve to some extent as well. (Furnaces are a relatively mature technology, so their improvement is likely to be more incremental and less of policy objective than improvement of ASHPs in a jurisdiction committed to decarbonization. But improvements are still likely.)

2. **A Strong Climate Policy Scenario:** Strong policies are implemented to discourage greenhouse gas emissions. While such policies could take many forms, as a proxy, this scenario assumes a price on carbon rises to $150 per metric ton of carbon dioxide emissions by the mid-2030s. This is comparable to the carbon price assumed in the EPRI electrification study[39] and the price on carbon proposed by a bipartisan groups of Senators and House members in legislation introduced in the US Congress in 2018 and 2019.[40] Such a climate policy would significantly decarbonize the US power system by the 2030s. We assume that the carbon intensity of electricity production falls by 75 percent compared to the Base Scenario.[41]

3. **A Moderate Technological Progress and Climate Policy Scenario**: This scenario combines the previous two. It assumes the climate policy is half as stringent as the strong climate policy scenario, with carbon prices rising to $75 per metric ton by the mid-2030s, and it assumes the costs and performance of ASHPs both improve by 15 percent over that period.

Figure 8 shows the difference in NPV of lifetime costs between the ASHPs and natural gas furnace options for the three scenarios and three cities.

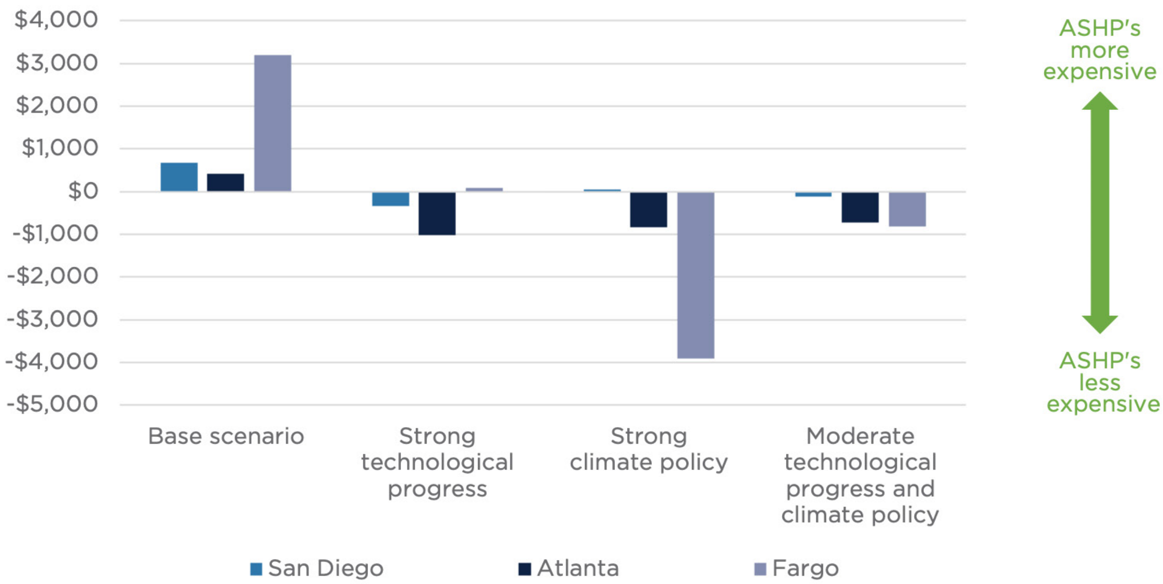
The Base Scenario results are the same as displayed above, with the ASHP option more expensive in each scenario and the magnitude of the cost differences varying widely by city.

The results in the Strong Technological Progress and Strong Climate Policy scenarios tell a different story. With strong technological progress, the ASHP option becomes less expensive than the natural gas furnace and air conditioner combination in San Diego and Atlanta. With strong climate policies, the ASHP option becomes less expensive in Atlanta and Fargo. And with moderate technological progress and moderate climate policies, the ASHP option is less expensive in all three cities. Even in Fargo, where a backup heat source is needed when it gets particularly cold (provided by electric resistance heating in this example), the ASHP option is less expensive under strong climate policies due to the impact of avoiding the extra costs associated with fossil fuel use in these scenarios.

Of course, different assumptions produce different results, including results that flip the low-cost alternative in certain scenarios and cities. But the cost competitiveness of ASHPs in these three regions in the technological progress and climate policy scenarios is robust to a wide range of assumptions in this simplified model.

By looking at only typical residences, this model misses important heterogeneity in needs and preferences that influence the costs and other barriers (referenced in Section 3) to the deployment of ASHPs, so the results should not be interpreted to imply that either option is less costly in all situations.

Figure 8: Lifetime costs of ASHPs as compared to furnace/air conditioner combination



Note: Lifetime cost is calculated as the net present value of the costs over the 15-year life of the appliance using a 10 percent discount rate

5.3. Summing Up

Returning to the question posed at the beginning of this chapter—what are the major barriers inhibiting ASHPs in deep decarbonization scenarios?

The results of this analysis suggest that in a jurisdiction committed to carbon-free space heating in a midcentury time frame, costs and performance of air source heat pumps are unlikely to be major barriers. Even in very cold regions where ASHP deployments are most challenging, a large shift from furnaces to ASHPs (with backup) will not be cost prohibitive and may even result in substantial savings.

Given the simplicity of the model and limited number of situations considered, we do not conclude that ASHPs will be more cost effective than natural gas furnaces in all situations. Moreover, other significant barriers still stand in the way of ASHPs as a primary space heating decarbonization strategy. As discussed in the following section, policy makers committed to zero emissions space heating will need to decide whether to confront the full spectrum of barriers to ASHPs or advance other decarbonization strategies.

6. HEAT PUMP DEPLOYMENT AND POLICIES AROUND THE WORLD

This section provides an overview of heat pump deployment and policies in the United States, the European Union (EU), Japan and China. It then provides an overview of policy options for promoting the deployment of ASHPs.

6.1. Heat Pump Deployment Policies in Major Economies

United States

The US federal government does not offer incentives for deployment of air source heat pumps. Several state governments offer such incentives.

The State of California has several programs to promote ASHPs. In September 2018, California passed Assembly Bill 3232, which assesses the policies needed to enable a 40 percent reduction in greenhouse gases below 1990 levels in the building sector by 2030, as well as Senate Bill 1477, which provides $50 million in annual incentives for low-carbon heating alternatives, including heat pumps.[42] California's Building Energy Efficiency Standards were updated in 2019 to level the playing field between gas and electric heating systems by moving away from the gas efficiency baseline in place today.[43] In addition, some incentives exist at the local level in California. The Sacramento Municipal Utility Division, for example, offers a $5,000 incentive for all-electric households and nearly $14,000 for retrofits.[44]

States in the Northeast also offer incentives for ASHP adoption. Connecticut's 2018 Comprehensive Energy Strategy includes financial incentives for building electrification and partial building use of ASHPs.[45] Maine and Massachusetts offer downstream residential and commercial rebates for ductless heat pumps. New York's heat pump program, which began in 2017, gives a $500 per unit midstream incentive to contractors, contains quality assurance measures, and is administered by the New York State Energy Research and Development Authority and the state's Clean Energy Fund.[46]

European Union

While market share for heat pumps remains low, the EU has seen accelerated deployment of ASHP installations over the past few years. From 2009 to 2018, yearly heat pump sales in Europe grew nearly 50 percent, from 734,000 to 1.3 million units.[47] Much of the groundwork for the rapid growth was laid by policies in the 1980s and 1990s, at a time when consumer awareness was low.[48]

Several European governments offer direct financial incentives for switching to heat pumps. Sweden has used investment subsidies to cover a portion of the cost of heat pump installation for households transitioning from conventional oil or electric heating. Austria subsidizes installations if the unit achieves a mean seasonal COP of 4.0.[49]

Some European countries have also implemented nonfinancial measures to encourage innovation and increase heat pump deployments. In the 1970s and 1980s, test facilities in Switzerland and Sweden improved technical standards, which, in concert with quality labeling, improved trust around the heat pump industry.[50] Building standards have also been implemented at the local, regional, and national levels. In 1997, Zurich implemented an 80 percent cap on nonrenewable energy use for heating new buildings, with the remaining 20 percent allowed to be filled by renewable sources or heat pumps. Germany enacted a 50 percent renewable heat law for new residential buildings in 2009.[51]

Finally, Sweden has used procurement to encourage efficiency gains and industry investment by facilitating purchase agreements between heat pump buyers and manufacturers. In 1993, Sweden launched a competition in partnership with buyers, who agreed to buy heat pumps that were 30 percent cheaper and 30 percent more efficient than existing products.[52] The procurement program led to a doubling in Swedish heat pump sales from 1995 to 1996.[53]

Japan

Japan has the world's most mature heat pump market. Heat pumps account for one-third of the space heating segment and register more than 6 million shipments per year.[54] The country's Top Runner Program, established in 1999, continues to incentivize improvements in energy efficiency for room level appliances, including electric heat pumps.[55] The Japanese government also mandates rigorous labeling and certification for household appliances, leading to greater consumer education, higher product quality, and, as a result, robust deployment.[56]

China

China's heat pump market is estimated at over $18 billion.[57] ASHPs enjoy high market penetration in southern China, but coal-powered furnaces are the dominant heating technology in the colder, northern regions of China.

The Chinese government supports ASHP adoption as part of its program to clean the air across northern China. In many northern Chinese provinces, subsidies for heat pump installation can cover up to 90 percent of unit costs.[58] The Beijing government covers roughly $3,500 per ASHP unit.[59]

6.2. Policy Options for Decarbonizing Space Heating

Existing policies are insufficient to achieve zero emissions from space heating in the United States by midcentury. To achieve that goal, policy makers will need to significantly expand policy support for low-carbon alternatives to fossil fuel powered furnaces and boilers. There are numerous options, each of which has advantages and limitations.

Some policies are focused specifically on encouraging ASHPs. Examples of policies focused on ASHPs include the following:

- *Informational programs*. One barrier to the deployment of emerging products in any market is a lack of information. Governments can fund programs that increase consumer awareness of the existence or the increasing affordability and improving performance of ASHPs.

- *Financial incentives*. Consumers often choose furnaces for space heating due to their lower costs, either up front or throughout the lifetime of the appliances. Targeted financial incentives can include subsidies, tax credits, or rebate programs designed to reduce the costs to consumers of ASHPs and thus make them a more attractive alternative to furnaces and boilers. Well-publicized financial incentives can help address informational barriers as well.

- *Support for technological improvement*. The costs and performance of ASHPs have improved markedly in recent years, and, as described in the previous section, experts believe significant additional improvements can be achieved. Some of these will occur naturally with the acceleration of ASHPs deployments. But other technological improvements will require funding for research and development, which could be carried by the government, the private sector, academia, or partnerships among the groups.

- *Procurement in government buildings*. Federal, state, and local government buildings represent a meaningful portion of the US building market. As of 2012, governments owned or occupied 19.5 billion square feet of commercial floor space, or 22 percent of the nationwide total, across 776,000 buildings.[60] Efforts to install ASHPs in government real estate could increase deployment rates in the near term and lead to technology improvements that can come from increased deployments.

- *Changing utility rate structures*. Public utility commissions could require utilities to develop new service classifications for homes that use ASHPs and charge these households reduced rates.

- *Technology standards that mandate the use of ASHPs*. Policies that mandate improved efficiency of appliances typically do not require the use of specific technologies, but a mandate could gradually require that consumers install ASHPs in certain regions and building types.

Other available policy tools are not focused on ASHPs or any individual technology but rather on the improved efficiency, electrification, or decarbonization of space heating more broadly. Such technology-neutral policies are often more cost effective than technology-specific policies because they can promote technologies that are best suited to accomplish policy objectives without anyone needing to know in advance what these technologies will be. Examples of space heating decarbonization policy options that will encourage the deployment of ASHPs include the following:

- *Energy efficiency programs, incentives and standards*. The US Department of Energy establishes standards that require an increasingly stringent level of energy efficiency, including for space heating appliances. Some states have more stringent requirements. In addition, many public utilities offer financial incentives that reward consumers for purchasing energy efficient appliances. Since ASHPs are highly efficient under typical conditions, these policies often encourage ASHP deployments (along with encouraging more efficient furnaces and boilers).

- *Carbon pricing programs with stringent emissions targets*. Low-carbon prices have a limited impact on ASHP deployments because they do not affect up-front costs or translate into a large portion of the life-cycle costs of a space heating appliance. However, higher carbon prices can have a significant impact on life-cycle costs. And, if combined with a binding emissions target (through a cap-and-trade program or a carbon tax with an emissions target mechanism),[61] a carbon price could ensure that fossil fuel use is phased out over time. Most economists favor a carbon price as a cornerstone of decarbonization policy because it does not dictate where and how emissions reductions must take place.

- *Technology standards that ban the use of fossil fuels*. A middle ground between mandating the use of ASHPs and an economy-wide emissions cap would be technology standards that gradually phase out the use of furnaces and boilers for space heating. This would be more prescriptive than a carbon price, but, unlike a technological mandate, it would encourage both ASHPs and other low-carbon technologies.

This is not an exhaustive list of potential policies for promoting ASHPs. It does not include policies for promoting RNG, hydrogen, or other low-carbon space heating strategies.

Policy makers should not adopt every one of the policies listed above, as some would be redundant with others. And policy makers should not pick just one, since many of these policies would complement one another. For example, an economy-wide carbon price with binding emissions targets combined with support for innovation and a portfolio of energy efficiency incentives and standards could create a cost-effective portfolio of policies that could ensure the decarbonization of space heating in the United States by midcentury.

7. CONCLUSION

The current space heating market is dominated by fossil fuels. For policy makers serious about responding to the risks of climate change, this situation is untenable. To achieve greenhouse gas emissions reductions consistent with international climate change goals, emissions from space heating in the United States need to fall to near zero by midcentury or soon after.

While space heating has received little individualized attention in studies of the decarbonization or electrification of the US energy system, numerous prominent studies have charted a pathway for the decarbonization of the entire energy system, which includes the space heating market. These studies portray the electrification of space heating energy uses, primarily with ASHPs, as a favored pathway to reducing emissions from space heating by 2050.

Indeed, despite minimal policy support, the use of ASHPs is already accelerating rapidly in certain regions of the US, particularly in the Southeast. That is because improvements in the technology, combined with favorable fuel prices, have made ASHPs the low-cost alternative in much of the region. However, throughout most of the country, the market shares of ASHPs remain low, especially in areas with colder climates where ASHPs are less efficient.

The existing decarbonization literature suggests the following two broad conclusions:

- There are no major technological barriers preventing the near-complete electrification of space heating energy uses in US residential and commercial buildings by midcentury, relying primarily on the deployment of ASHPs.
- If consumers behave as they have in the past, fossil fuels will retain a large portion of the market share for building space heating by midcentury, even with strong market-based climate policies (i.e., carbon prices) and technological progress of ASHPs.

Left unanswered by the literature is *why* strong carbon prices and technological progress are insufficient. Is it due to the limitations of the ASHP technology? Or is it due to more general barriers to rapid transformations in energy markets dominated by consumer choice? This study strongly favors the latter explanation.

We built a simple model of building space heating and cooling that estimates the costs of electric versus natural gas space heating and cooling alternatives in a typical household in three representative cities in the United States: San Diego, Atlanta, and Fargo. The model portrayed new equipment installations (not retrofits) in the early 2030s, so that the useful lifetime of the equipment ends around midcentury. The results showed that using ASHPs for heating and cooling is already approaching cost competitiveness in two of the representative cities (Atlanta and San Diego). With climate policies and technological progress that may be expected in a jurisdiction committed to decarbonization by midcentury, by the 2030s ASHPs will be cost-competitive in all three cities (including the very cold climate of Fargo).

Combined with the literature, the results of this analysis point to the following conclusions about how far ASHPs can take the United States on a pathway to the decarbonization of building space heating:

- A large-scale increase in ASHP deployments is likely to be an important part of any space heating decarbonization scenario. Aggressively pursuing the deployment of electric heat pumps in the near term, while prioritizing regions where heat pumps are most cost effective, is a "no regrets" strategy.
- In the longer term, the continued rapid deployment of ASHPs is unlikely to be inhibited by barriers related to their costs or performance. With continued technological improvements and the implementation of climate policies, ASHPs become cost competitive even in cold climates.

These findings suggest that policy makers can be confident in ASHPs as a primary space heating decarbonization strategy. However, to achieve near-zero emissions by midcentury, policy makers need to be prepared to use policy instruments that mandate reductions in emissions from space heating, such as technology standards, emissions caps, or mandates to stop using fossil fuels. Otherwise, the transition to ASHPs is not likely to proceed rapidly enough to be consistent with midcentury emissions goals. Fortunately, the results of this study suggest that such mandates are unlikely to be cost prohibitive for typical households by the 2030s.

Alternatively, there are other options to decarbonizing space heating energy uses: RNG, hydrogen, and centralized or district heating. Each of these options comes with challenges that will require significant government actions to overcome, like the regulatory processes required to ensure carbon-beneficial sources of RNG and the infrastructure projects required to transport low-carbon fuels that cannot be dropped into existing pipelines.

This study does not point to a proper balance between a focus on ASHPs and alternative building space heating decarbonization options, and the broader literature has little to offer policy makers. More research on the opportunities and challenges associated with different building space heating decarbonization alternatives is sorely needed.

APPENDIX: MODEL KEY ASSUMPTIONS

Our goal for the simple model described in Section 5 was to understand whether heat pumps can be competitive under current and potential future market conditions in various regions of the United States.

We did this by estimating and comparing the costs of the following alternatives: (1) natural gas furnaces with central air conditioning; and (2) ASHPs, with backup where needed, in three different locations: San Diego, California; Atlanta, Georgia; and Fargo, North Dakota.

To estimate the costs of a natural gas furnace, we considered housing size, average insulation values, furnace capacity and efficiency values, a reference indoor comfort temperature set equal to 65°F, and historical weather data as reported in the following formula:

Size of gas furnace needed [Btu] = house square footage x shell heating efficiency ÷ furnace capacity x (65°F - region minimum temperature)

The house square footage considered across all three geographies is 1,670 square feet, equal to the median US housing size according to the Electric Power Research Institute.[62]

The furnace capacity used in this formula is 0.5, based on the assumption that the gas furnace is sized so that it runs 50 percent of the time during the coldest hour.[63]

For shell heating efficiency, based on data from EPRI, we assumed 0.20 Btu/sq. ft. for San Diego and Atlanta. Shell heating efficiency was assumed to be 25 percent lower for colder climates, thus we used 0.16 Btu/sq. ft. degree hour for Fargo.[64]

Analogously, for shell cooling efficiency, which was used in the model to size the air conditioner and ASHP (in regions where cooling demand is higher than heating demand only), we assumed 0.29 Btu/sq. ft. for San Diego and Atlanta and 0.23 Btu/sq. ft. for Fargo.[65]

We estimated heating design temperature for each region by calculating the outdoor temperature that each location stayed above for 99 percent of all the hours in the year (i.e., the first percentile), based on 30 years of hourly data.

Similarly, we estimated cooling design temperature for each region, which is used to dimension the air conditioners and ASHPs based on cooling requirements, by calculating the outdoor temperature that each stayed above for only 1 percent of the hours in a year (i.e., the 99th percentile), based on 30 years of data.

The weather data was sourced from the National Climatic Data Center[66] database, hourly information, from January 1, 1987, to December 31, 2016, for each of the three cities.

To estimate the total yearly heating and cooling needs, heating hours and cooling hours were calculated based on temperatures over the same 30-year period. Heating and cooling hours were calculated for each year in the following way: each hour in which the temperature was lower than 60°F was counted as a heating hour, and each hour in which the temperature was higher than 75°F was counted as a cooling hour. The sum of heating and cooling hours was evaluated on a yearly basis, and the average over 30 years was used in the model. ASHP heating and cooling capacity was calculated hourly for temperatures lower than 60°F and higher than 75°F, respectively, to allow the model to account for off-load and partial-load performance. The heating and cooling capacity values shown in table 2 were calculated as the average of these hourly values over 30 years. Heating and cooling hours and region heating and cooling design temperatures are reported in Table 2.

Table 2: Regional heating and cooling hours and design temperatures

	San Diego, CA	Atlanta, GA	Fargo, ND
Heating hours (temperature lower than 60)	2,356 hours	3,699 hours	6,123 hours
Cooling hours (temperature higher than 75)	389 hours	2,166 hours	769 hours
Heating design temperature	47˚F	27˚F	-14˚F
Cooling design temperature	81˚F	92˚F	88˚F
Average COP value (heating)	3.70	3.43	2.86
Average COP value (cooling)	4.49	4.32	4.36
Average ASHP capacity value (heating)	1.050	0.973	0.811
Average ASHP capacity value (cooling)	1.055	1.039	1.043

ASHPs are sized in the model based on the highest load (cooling or heating). In both San Diego and Atlanta, the ASHPs are dimensioned based on cooling needs, with the following formula:

Size of ASHP [Btu] = house square footage x shell cooling efficiency ÷ ASHP capacity x (region maximum temperature - 65°F)

In Fargo, the need for heating is larger than the need for cooling. Therefore, the ASHP was dimensioned based on heating needs to enable a more realistic comparison with the gas furnace. First we considered the heat that needs to be provided by the gas furnace (with the gas furnace dimensioned based on the formula indicated above). Then we assumed the ASHP is sized to cover this heat demand, considering COP and capacity (based on Fargo's average winter temperature). This is a simplification: in reality, this decision would likely be based on an optimization of the size of equipment, based on performance of ASHP, electricity prices, and cost of equipment.

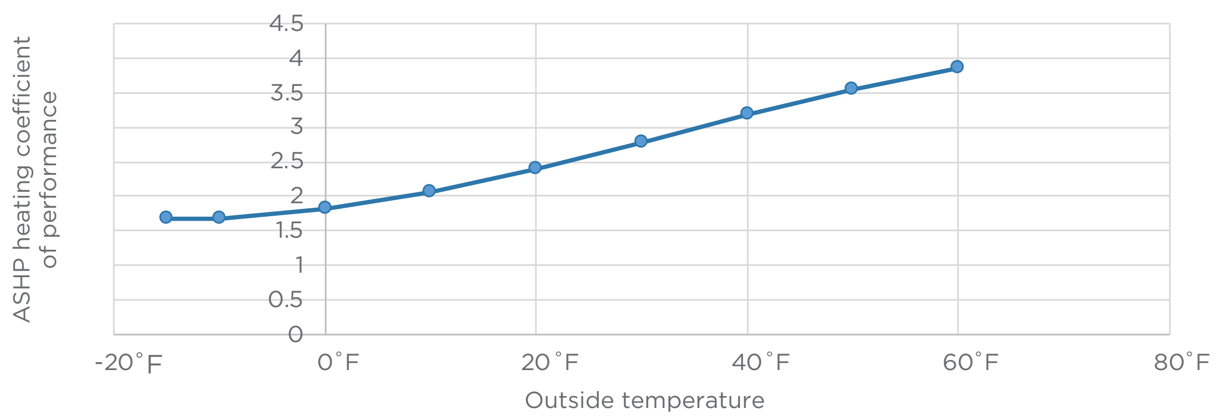
We assumed the size of the backup heater is dependent on the gap between the heat produced by the ASHP at the heating design temperature (-14°F) and the total heating demand. In Fargo, the resistance heater covers 28.4 percent of the total heat at the heating design temperature.

Considering COP and capacity of the ASHP, we evaluated the temperature at which the heat demand can be covered exclusively by the ASHP (3°F in the Base Scenario). Then we calculated the heating hours for which on average (based on 30 years of data) the temperature is lower than 3°F. For these hours, we assumed both ASHP and resistance heater are operating. For the rest of the heating hours, we assumed that only the ASHP is operating. For simplicity, we assumed the same split between ASHP and backup resistance heater in all scenarios, although in reality this split would depend on the COP and other factors.

According to the data from EPRI, we assumed the gas furnace efficiency is 85 percent.[67] Electric resistance efficiency was assumed to be 100 percent.

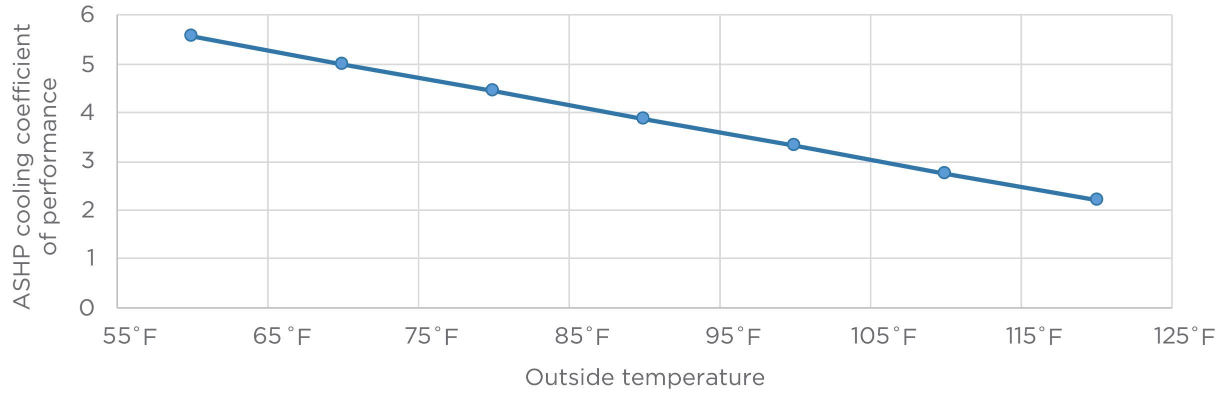
The heat pump COP for heating and cooling are shown below as a function of outside temperature. The values are based on data reported by EPRI.[68]

Figure 9: ASHP heating performance



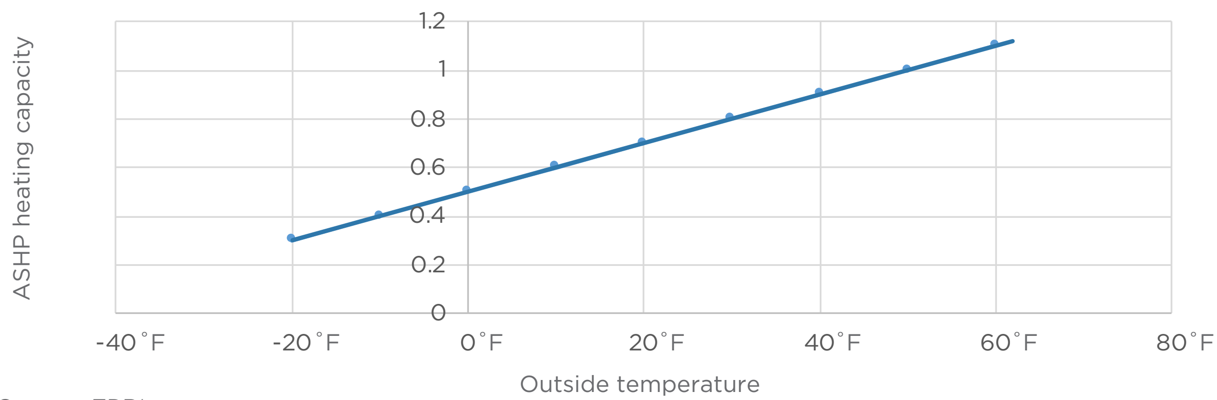
Source: EPRI

Figure 10: ASHP cooling performance



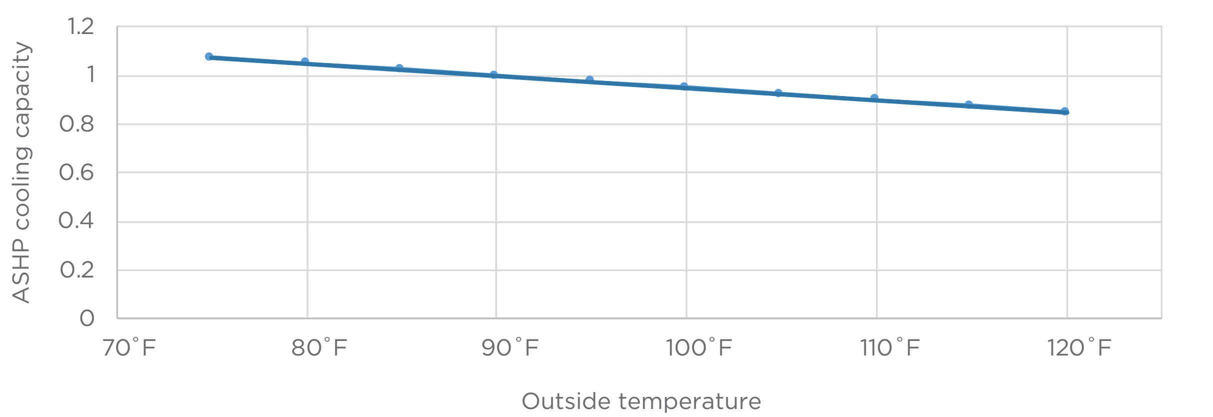
Source: EPRI

Figure 11: ASHP heating capacity



Source: EPRI

Figure 12: ASHP cooling capacity



Source: EPRI

The efficiency of the air conditioner is set to seasonal energy efficiency ratio (SEER) 16, which is our estimate of the SEER of a new air conditioner sold in the 2020s.

The pricing of components is based on cost estimates reported by EPRI (and scaled based on the sizing of the equipment, as described above) and are shown in tables 3 and 4. From the same source, yearly maintenance costs are assumed to be 2 percent of capital expenditure cost.

Table 3: Equipment cost estimates

	San Diego, CA	Atlanta, GA	Fargo, ND
Gas furnace and central air conditioner	$1,961	$2,354	$2,486
ASHP and electric backup			$2,142
ASHP	$1,564	$1,564	

Table 4: Sizing of equipment

	San Diego, CA	Atlanta, GA	Fargo, ND
Gas furnace and central air conditioner	12,024 Btu gas furnace and 2.4 kW air conditioner	25,384 Btu gas furnace and 4 kW air conditioner	42,218 Btu furnace
ASHP and electric backup			5.3 kW + 2.1 kW
ASHP	2.4 kW	4 kW	

We estimated the marginal costs of electricity and natural gas in each of the three locations using 10 years of annual average state-level data, from 2007 to 2016, as reported by the EIA. We considered a 19 percent share of fixed costs for natural gas[69] and a 10 percent fixed cost for electricity.[70] The highest marginal cost for electricity is in California, with 0.1398 USD/kWh, followed by Georgia with 0.0968 USD/kWh and North Dakota with 0.0775 USD/kWh. The highest marginal cost for natural gas is in Georgia, with 12.753[71] USD/1,000 cubic feet, followed by California with 8.699[72] USD/1,000 cubic feet and North Dakota with 6.738[73] USD/1,000 cubic feet.

The NPV cost for the consumers is calculated over a period of 15 years, considering operation and maintenance costs of the unit, the cost of carbon dioxide emissions,[74] and the natural gas and electricity costs. We assume a private discount rate of 10 percent.

The emissions rate for natural gas is 117 lb. of carbon dioxide per million Btu. For the electricity grid, in the Base Scenario, we assumed 0.894933 lb. of carbon dioxide per kWh (which assumes the marginal source of electricity is a natural gas combined cycle (NGCC) plant with a heat rate of 7,649 Btu/kWh).[75] No carbon price is assumed in the Base Scenario. In the strong climate policy scenario, we assumed a carbon price of 150 USD/ton of CO_2 and the decarbonization of the electricity grid of 75 percent relative to the NGCC value provided above. In the Moderate Technological Progress and Climate Policy Scenario, we assumed a carbon price of 75 USD/ton of CO_2 and a decarbonization of the grid of 37.5 percent.

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