# Beneficial Electrification of Space Heating

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Part of the *Electrification in the Public Interest* Series

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# Abbreviations

ACEEE . . . . . American Council for an Energy-Efficient Economy

AHRI . . . . . . . Air-Conditioning, Heating, and Refrigeration Institute

BE . . . . . . . . . beneficial electrification

Btu . . . . . . . . British thermal unit(s)

$CO_2$ . . . . . . . . carbon dioxide

COP . . . . . . . coefficient of performance

HP . . . . . . . . . heat pump

HSPF . . . . . . heating seasonal performance factor

kWh . . . . . . . kilowatt-hour

NREL . . . . . . National Renewable Energy Laboratory

RMI . . . . . . . . Rocky Mountain Institute

RPS . . . . . . . . renewable portfolio standard

SEER . . . . . . seasonal energy efficiency ratio

TOU . . . . . . . time-of-use

Whs . . . . . . . watt-hours

# Figures



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# About This Series

For electrification to be considered beneficial, it must meet one or more of the following conditions without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

The first paper in this series, *Beneficial Electrification: Ensuring Electrification in the Public Interest*, explores policy and regulatory decisions that need to be made to accommodate innovations across the power sector that make it possible to electrify many energy uses currently fueled by oil, propane, and natural gas. The paper makes the case for what RAP calls beneficial electrification—in other words, electrification in the public interest.

The authors offer six principles that will help policymakers and regulators formulate and evaluate their electrification strategies to broadly secure the benefits. Finally, the paper looks at operational elements that states may want to consider as they move ahead with electrification.

This companion paper and two others feature pathways and no-regrets options for regulators to apply these principles specifically to space heating, water heating, and electric vehicles. Each paper lays out initial steps for regulators to establish programs, including standards and metrics to measure success. More specifically, these papers explore issues such as rate design to enable beneficial electrification; program design and implementation; relationships between beneficial electrification and energy efficiency and demand response programs; screening tests for beneficial electrification; and impacts on wholesale markets and vice versa.

Learn more and download the full series at www.raponline.org/BE.

# Executive Summary

RAP has asserted that, for electrification to be considered beneficial, or in the public interest, it must satisfy at least one of the following conditions, without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

Because space heating represents such a sizable proportion of energy use in the average home, it is a key focus for beneficial electrification (BE) efforts. Electric space heating, especially with new heat pump technology, will very often meet one or more of the conditions outlined above. Most space heating currently relies on fossil fuels, such as home heating oil, propane, and natural gas. Beneficial electrification of space heating represents multiple opportunities: for consumers to save on their total energy bills by switching to a more efficient heating technology (depending on the housing type and region, as this paper will explore); for utilities and grid operators to secure valuable grid management benefits; and for significant reduction of greenhouse gas emissions.

This paper examines the variety of technology options for electrification of space heating, considers their applications in various contexts, examines our BE conditions as they apply to space heating, and offers strategies for achieving the benefits we identify.

## Application Considerations for Space Heat Electrification

For the purposes of illustrating BE opportunities, we examine four basic technology options currently available for electrification of space heating: air source heat pumps (HPs), air source HPs in conjunction with other heating sources, ground source HPs, and electric resistance thermal storage heating. All are likely to have a place in a future that includes increased electrification.

Air source heat pumps are a common technology used in every part of the United States.

Air source HPs are a common technology used in every part of the United States. During the heating season, they move heat from outdoors into an interior space; during the cooling season, they move heat from indoors to the outside. They are either ducted or ductless and can be designed for milder environments or colder climates. Ducted systems rely on ductwork to move air evenly around larger houses and are therefore often installed where ductwork is already in place. Ductless systems require less construction and typically have two main components: a condenser outdoors and an air-handling unit indoors connected by conduit.

Ground source heat pumps move warmth to and from the earth (where, several meters below the surface, the temperature is relatively constant) instead of the outside air. Most ground source HPs circulate a liquid through plastic tubing laid out horizontally underground and rely on a heat exchanger to transfer that underground temperature into living spaces.

Electric resistance storage heaters, most commonly with elements encased in heat-storing ceramic, have been around for decades. In the US, however, generally they have been deployed only in rural areas with low-cost off-peak power. These heating technologies can provide beneficial electrification either where the marginal resource in the grid supplying electricity has relatively low carbon emissions or where the use of these units can be concentrated into off-peak hours that offer significantly below-average prices for electricity.

Appropriate space heating options vary by region. The heating capacity and efficiency of air source HPs decrease as outdoor temperatures drop and heating demand increases, although newer systems have improved effectiveness in colder climates. In warmer areas, resistance storage heating is a less attractive option because it does not also provide air conditioning as heat pumps do.

Housing type is another consideration. The number of units served, age of the dwelling unit, and type of building (single family, apartment, mobile home) will all help determine which type of space heating works best.

# Conditions for Beneficial Electrification of Space Heating

## Consumer Economics

Whether electrification will benefit consumers economically depends on several factors, including regional climate variations and building type, as mentioned above. Other economic factors include whether space cooling is being installed simultaneously, the installed cost of the electric appliances themselves, and the relative costs of electricity compared with fossil fuel options. The American Council for an Energy-Efficient Economy published a study of the energy, financial, and emissions impacts of converting existing oil and propane furnaces and boilers to high-efficiency heat pumps. The study concluded that in most of the US, homeowners would benefit from life cycle cost savings by replacing an oil or propane furnace with an air source HP at the time the furnace needs replacing. And the National Renewable Energy Laboratory projects that, on a national average basis, air source heat pump technologies (including cold climate HPs) will be cost-competitive with gas furnaces at the time of replacement by 2050 at the latest. A Rocky Mountain Institute analysis of combined space and water heating electrification found that, for four case study locations, air source HPs are currently more cost-effective on a 15-year net present value basis for new construction. In colder climates, heat pumps can be made a more economical choice by improving building efficiency, relying on a supplemental heat source, or augmenting the system with energy storage.

## Grid Management

The power grid has always needed a certain amount of flexibility because demand for electricity varies on a daily and seasonal basis. The integration of increasing amounts of variable renewable energy into the grid requires even greater flexibility. Grid operators now recognize that demand-side efforts can help meet today's balancing challenges, and BE offers some of the best ways to optimize load shape. Grid operators in warmer climate regions are likely to be able to take advantage of the grid management benefits of air source heat pumps. In colder regions, where customers are more likely to have electric resistance storage heaters or heat pumps with supplemental heating, grid operators can benefit from the management options available from these technologies.

Electric resistance storage heating can provide value to system operators because it can operate as both demand (soaking up energy when it is readily available or inexpensive) and supply (releasing stored energy at times of system stress and higher cost). It also offers a very real economic opportunity in regions with ample wind resources. It is possible to control the heating elements of electric resistance storage heaters on a second-to-second or minute-to-minute basis, making them good candidates for providing ancillary services to the grid, such as frequency regulation and voltage support. Smart technologies can also allow grid operators to use resistance storage heaters to help manage system peaks.

Because heat pumps produce a large quantity of warm heating output rather than a small quantity of high-heat output, they are generally less suitable for overnight charging and subsequent daytime deployment. When connected with smart thermostats, however, heat pumps can help manage system demand by preheating or precooling spaces during the afternoon and running less during early evening peak periods.

## Energy and Emissions Efficiency

Whether electrification of space heating is environmentally beneficial depends on the emissions efficiency of the electric technology and the fossil-fueled option—that is, the emissions per unit of useful energy output. By combining the efficiency of the end-use appliances with the carbon content of their energy supply, we can compare the emissions efficiency of electrification with fossil-fueled alternatives. The calculations shown on pages 44-45 of this paper demonstrate that heat pumps produce higher carbon emissions only when the electricity system has a significant amount of coal-fired generation. In all other systems, heat pumps are more emissions-efficient than their fossil-fueled counterparts. And because the grid is likely to become cleaner over time, electric technologies will become cleaner as well over their useful lifetimes—even where they may not be today.

## Interactions Among the Three Conditions

To meet our definition of beneficial electrification, only one of the three conditions needs to be met while not adversely affecting the other two. However, achievement of each condition will vary depending on the specific circumstances. Those circumstances and the interactions among the three conditions mean that policymakers might need to consider implementation tactics should they wish to promote certain policy objectives or outcomes. For example, if there is a state-level objective to reduce emissions, a policy intervention—such as a rebate program—to reduce the incremental upfront cost of heat pumps might be needed where existing technology does not yet provide economic benefit for consumers.

Potential grid management benefits will vary by region and the type of technologies being used. Capturing these benefits while endeavoring to reduce emissions and customer costs may not happen automatically and may require planning and management on the part of policymakers and grid operators. Space heating load will connect well with wind power, which in many regions is in surplus during overnight hours, but not as well with solar power, which peaks in summer and afternoons.

In many cases, energy-efficient electric technologies like heat pumps are already preferable on an emissions efficiency basis but may not yet be cost-effective for consumers. In addition, even where the emissions of the grid are low enough to create environmental benefit, new electrification load needs to be managed efficiently to keep costs of operating the grid down. These issues likely will become less pronounced as the capabilities of electric heating and storage technologies improve and their costs decline, and as emissions from electricity generation decline. States that adopt climate policies with associated greenhouse gas reduction goals can expect to see opportunities to cut emissions through greater efficiency in the building sector and space heating.

# Putting Beneficial Electrification Into Action for Space Heating

Significant consumer, emissions reduction, and grid management benefits are achievable by changing the way residences are heated. But the appropriate technologies and implementation options will differ by many of the factors discussed above and depend on the policy priorities of the jurisdiction. In this section we discuss potential ideas for operationalizing beneficial electrification of space heating.

1. **Standards for new buildings:** New construction is an ideal opportunity to deploy new technology, because the entire costs of heating and cooling systems, as well as a water heating system, are incremental. Because of the growing cost-competitiveness of air source heat pumps, it may be appropriate for building codes for new construction in most climate zones to require high-efficiency electric space heating and cooling systems. Because of the importance of tight building envelopes to the efficacy of electrified space heating, codes should also require high thermal efficiency for the buildings themselves.
2. **State energy policy:** Current energy efficiency standards and incentives may require energy use reduction for electricity and other fuels separately, or other non-electric fuels may be excluded or exempt from energy efficiency policies. This may discourage electrification. States can address that by including an electrification carve-out in their energy efficiency policies or altering them to focus on reducing primary energy use or greenhouse gas emissions, rather than reducing kilowatt-hours. A carve-out in renewable portfolio standards is another tool to consider. And to mitigate upfront capital costs of heat pumps over fossil-fueled options, states may consider deploying financing programs and assistance to low-income households.
3. **Rate design:** Reforming electric rate design is a critical element of BE. Capturing the emissions reductions and cost savings benefits that occur at certain times of the day (e.g., when the wind is blowing) requires good rate design—incorporating time-varying pricing—to motivate customers to shift their usage of the system.

4. **Incentives:** Financial incentive programs for consumer adoption of various types of end-use technologies are widely used around the country, and the structure of these programs may be an important driver or barrier to beneficial electrification. Incentives can come from utilities (typically through rebates), third-party energy efficiency providers, or governmental agencies or programs (through rebates, loans, or tax incentives). Incentive programs should be evaluated across all fuel types together to ensure they are not operating at cross-purposes.

This paper seeks to stimulate discussion and more detailed thinking about how electrification of space heating can be beneficial. We discuss technology options for a variety of climatic conditions and housing types and conclude that electric space heating can satisfy all three of RAP's conditions for beneficial electrification. As technological improvements continue, particularly for heat pumps and heat storage, more cost-effective electrification opportunities will become available in what are currently more challenging situations, such as very cold climates. Regulatory and policy engagement will be essential to realizing the potential benefits. We suggest examining building codes, state energy efficiency programs, and financial incentives that states and utilities offer. Reviewing electric rate designs is also an important step to ensure that grid management and emissions reduction benefits can be realized. Feasible and generally cost-effective electric space heating options are available today to reduce customer costs, enhance grid flexibility, and dramatically cut carbon pollution, and more are expected to emerge.

# Introduction

In our paper *Beneficial Electrification: Ensuring Electrification in the Public Interest*,[1] we make the case that, for electrification to be considered beneficial, it must satisfy at least one of the following conditions without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

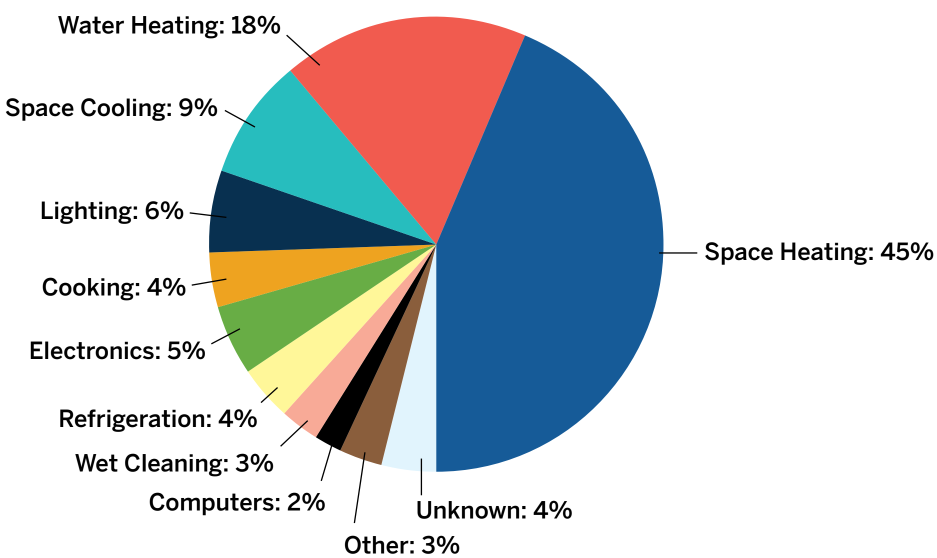
As the largest component of energy use in homes on average, space heating is an important focus for beneficial electrification efforts.

Electric space heating, especially using heat pump (HP) technology, will very often meet one or more of these conditions. As the largest component of energy use in homes on average (see Figure 1),[2] space heating is an important focus for beneficial electrification (BE) efforts.

Most space heating needs are now met with direct use of fossil fuels, largely natural gas. Figure 2 shows that in 2009, about 4.7 quadrillion British thermal units (Btu) of natural gas were used in the residential sector, with the majority occurring in space and water heating.[3] Fuel use by end application varies regionally, and Figure 3 illustrates the sources of energy for space heating in the United States by percent of dwelling units.[4]

Electrification of space heating can represent opportunities for all consumers to save money on their total energy bills by switching from a fossil-fueled technology to a more efficient space heating technology, such as a heat pump. As we discuss below, this is particularly true for certain regions and housing types, and where air conditioning is installed either at the time

**Figure 1. Space Heating is the Largest Component of Home Energy Use**




"Wet cleaning" includes clothes washers and dryers and dishwashers.

Source: US Department of Energy. (2012, March). *2011 Buildings Energy Data Book*.

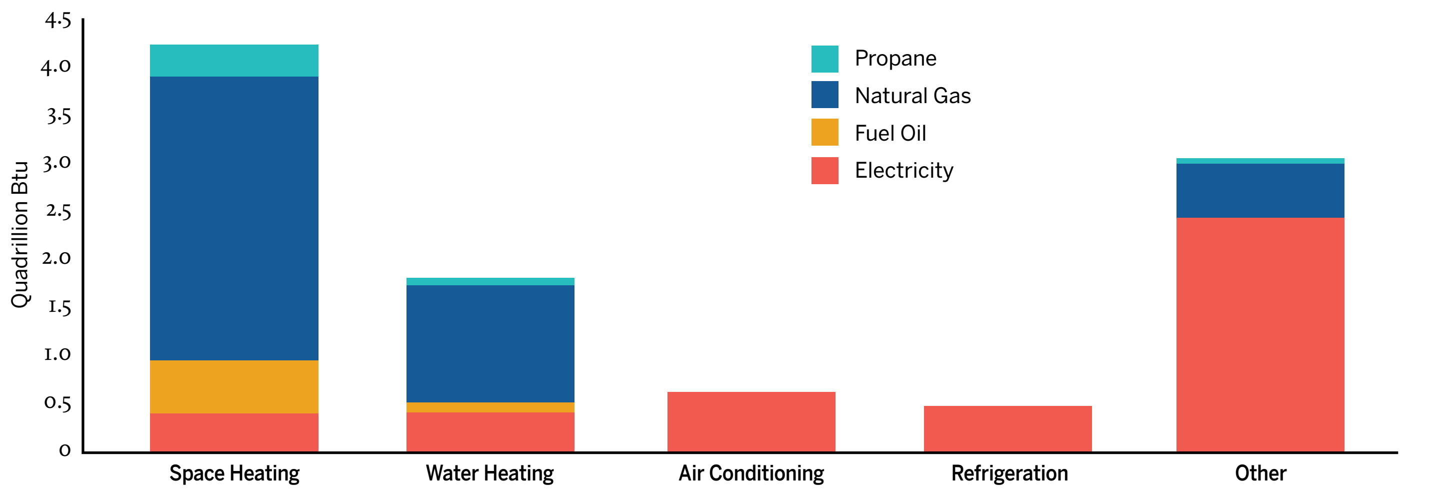
1 Farnsworth, D., Shipley, J., Lazar, J., and Seidman, N. (2018, June). *Beneficial electrification: Ensuring electrification in the public interest.* Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/knowledge-center/beneficial-electrification-ensuring-electrification-public-interest

2 US Department of Energy, Office of Energy Efficiency & Renewable Energy. (2012, March). *2011 buildings energy data book.* Washington, DC: Author. Retrieved from https://openei.org/doe-opendata/dataset/6aaf0248-bc4e-4a33-9735-2babe4aef2a5/resource/3edf59d2-32be-458b-bd4c-796b3e14bc65/download/2011bedb.pdf

3 Steinberg, D., Bielen, D., Eichman, J., Eurek, K., Logan, J., Mai, T., et al. (2017). *Electrification & decarbonization: Exploring U.S. energy use and greenhouse gas emissions in scenarios with widespread electrification and power sector decarbonization.* Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy17osti/68214.pdf. Figure from that report uses data from the US Energy Information Administration 2009 Residential Energy Consumption Survey.

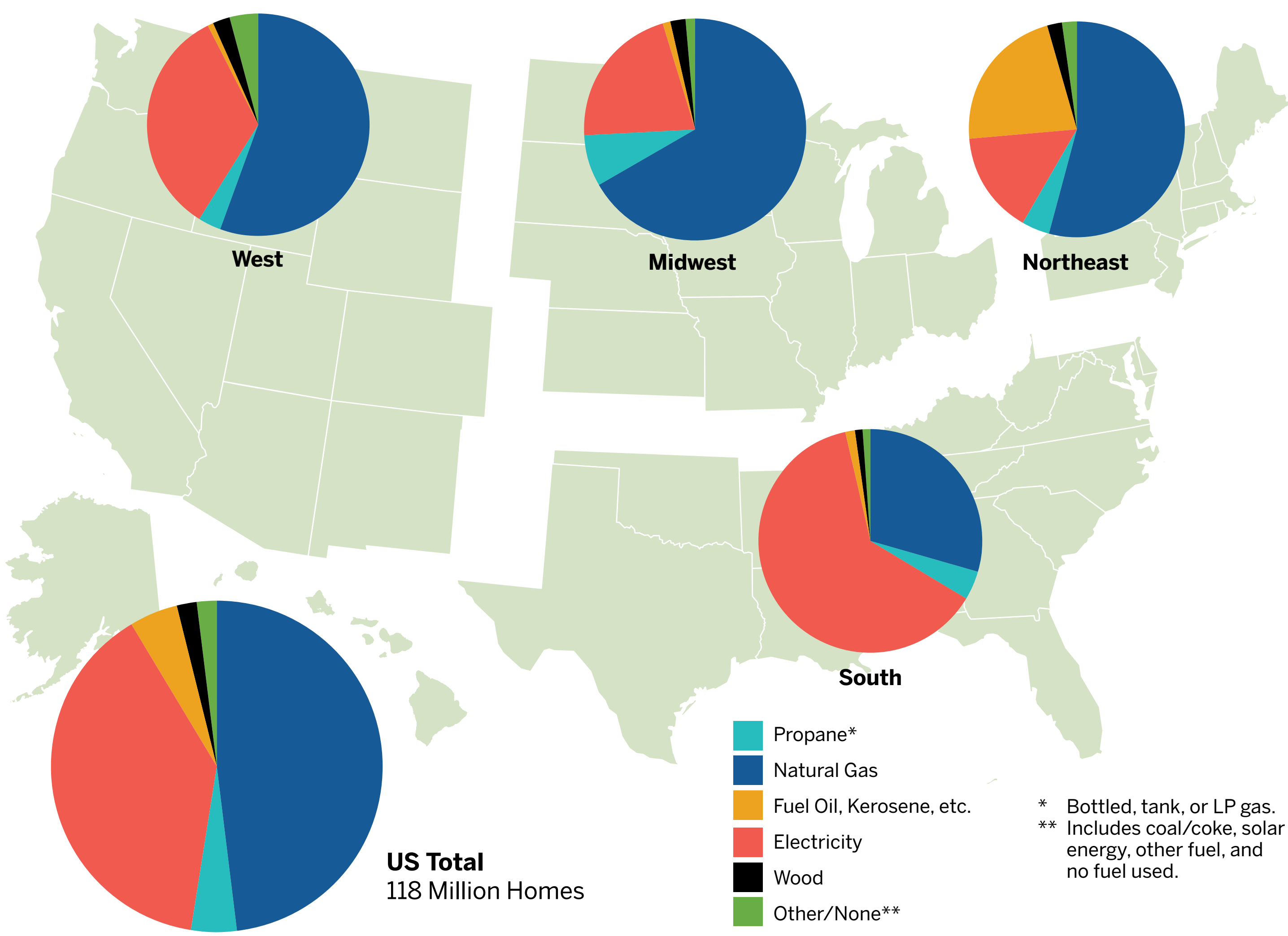
4 US Census Bureau. *2016 American community survey.* Retrieved from https://factfinder.census.gov/bkmk/table/1.0/en/ACS/16_1YR/B25040/0100000US.04000

**Figure 2. Most Space Heating Needs Are Met With Direct Use of Fossil Fuels**




Source: Steinberg, D., Bielen, D., Eichman, J., Eurek, K., Logan, J., Mai, T., et al. (2017). *Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization*, using data from Energy Information Administration 2009 Residential Energy Consumption Survey.

**Figure 3. Share of US Homes by Primary Space Heating Fuel and Census Region**




Source: US Census Bureau. *2016 American Community Survey.*

of construction or added later by the homeowner.

Electric space heating technologies provide valuable grid management benefits through peak load reduction and ancillary services, although they offer less flexibility than electrifying water heating and transportation.[5] However, space heating grid management benefits are particularly valuable when combined with thermal or battery storage. In addition, controlled heat pumps can enable demand response programs whereby a utility can reduce the electric load of a group of HPs by an individually small amount that measurably reduces grid demand when combined. We explore these and other grid management opportunities in this paper.

Electric space heating technologies provide valuable grid management benefits through peak load reduction and ancillary services.

Currently, fuel consumption for residential space heating causes the emission of approximately 270 million metric tons of carbon dioxide ($CO_2$) per year, or about 4 percent of total US $CO_2$ emissions.[6] Electric space heat accounts for roughly a third of emissions from this sector. However, these emissions will fall as more efficient electric heating options are deployed and the grid becomes cleaner.[7] Space heating powered by fossil fuels represents a significant opportunity for emissions reductions through electrification, as we will explore further.

A variety of technology options exist for electrification of space heating, including air source heat pumps, ground source HPs, and electric resistance thermal storage heating. In the following section, we consider a number of them and their applicability in different contexts. We then examine our three criteria for BE as they apply to space heating, and some strategies for achieving the space heating benefits we identify.

5 This is due primarily to the fact that vehicles and water heaters provide thermal or electrical energy storage, which can allow the user to "charge up" at different times than when the energy is being used. We explore the flexibility benefits of other electrified end uses in our companion papers on water heat and transportation.

6 US Energy Information Administration. (2018, May). *2015 Residential energy consumption survey,* Table CE4.1. Retrieved from https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce4.1.pdf; and US Environmental Protection Agency. (2018). *Inventory of U.S. greenhouse gas emissions and sinks, 1990-2016.* (EPA 430-R-18-003). Retrieved from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

7 The authors recognize that the environmental effects of various technology options for space heating are broader than the associated air emissions or, more narrowly, the associated carbon emissions. For example, moving toward electricity and away from natural gas can reduce the risk of gas leaks, explosions and fires, and can improve public health and community safety. However, in this paper we focus more narrowly on $CO_2$ emissions to ensure clarity of exposition and better illustrate these BE principles.

# Application Considerations for Space Heat Electrification

Due to their efficiency, heat pumps can provide equivalent space conditioning for as little as one-quarter the cost of operating conventional heating or cooling appliances.

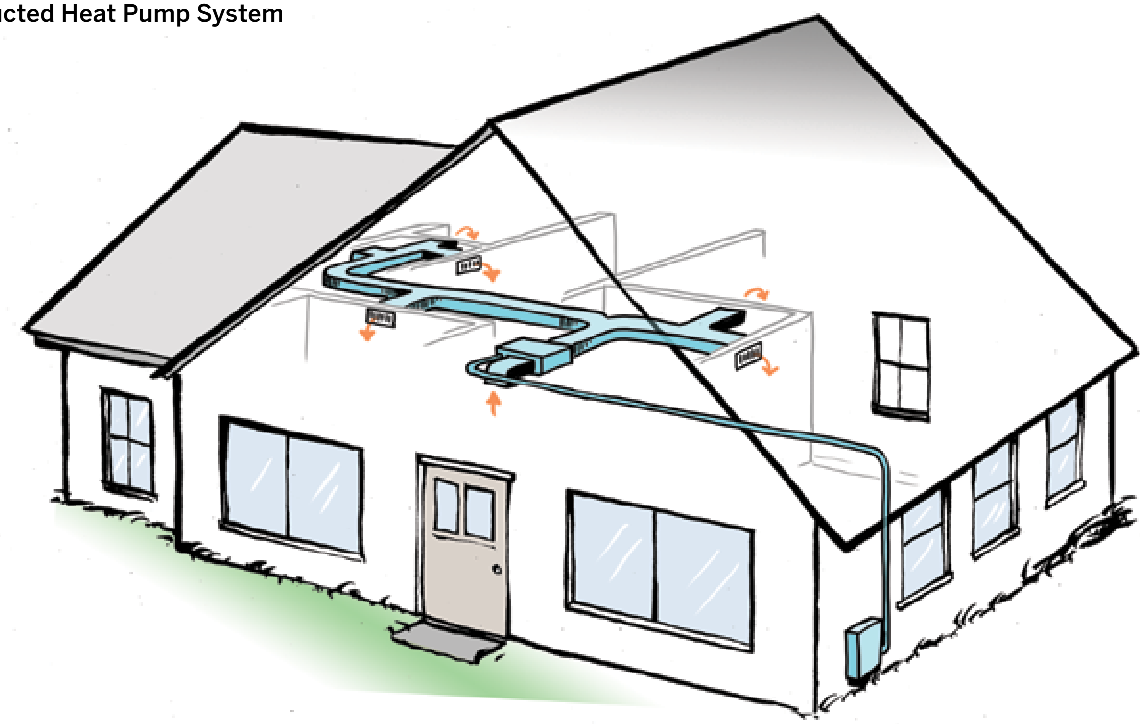
Beneficial electrification seeks to take advantage of technology trends to benefit consumers, grid operations, and the environment. In the case of space heating, this means analyzing the suitability of replacing or partly displacing fossil-fueled heating technologies with such electrical technologies as heat pumps (with or without backup heating) and electric resistance thermal storage heating. This section provides a technology overview and discusses various application considerations, such as housing types and regional variations in weather, that can affect space heating.

## Technology Overview

For the purpose of illustrating BE opportunities, we examine four basic technology options currently available for electrification of space heating loads: air source heat pumps, air source HPs in conjunction with other heating sources, ground source HPs, and electric resistance thermal storage heating.[8] While each has different cost and operating characteristics, all are likely to have a place in a future that includes increased electrification.

Due to their efficiency, heat pumps can provide equivalent space conditioning for as little as one-quarter the cost of operating conventional heating or cooling appliances.[9] Air source HPs are a common heating and cooling technology used in every part of the country.[10] They are typically either ducted or ductless and can be designed for milder environments or colder climates.[11]

**Figure 4. Ducted Heat Pump System**



8 Other forms of electric space heating that are less energy-efficient and unlikely to qualify as BE include electric baseboard heaters, electric wall heaters, electric radiant heat, and electric space heaters.

9 US Department of Energy, Office of Energy Efficiency & Renewable Energy. *Heat pump systems* [Webpage]. Retrieved from https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems

10 During the heating season, heat pumps move heat from outdoors into an interior space to warm it; during the cooling season, they move heat from indoors to the outside to cool the space.

11 Several alternatives to basic ducted and ductless models of space heating exist that still rely on air source HP technology. One, known as a short-run ducted system, uses large ductwork for part of the system in combination with ductless units. Another, called hydronic or radiant heating, uses tubing to run a hot liquid beneath the floor, along the baseboard, or through radiators.

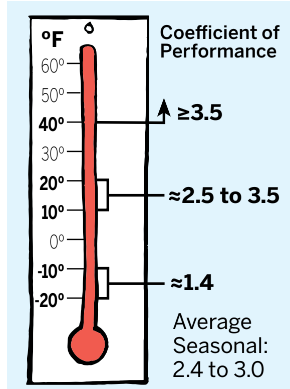
As the name suggests, ducted systems rely on ductwork to move air evenly around larger houses. Figure 4 illustrates such a system. They are often installed in newly constructed homes or homes that have forced-air ventilation systems with ductwork already in place. Installing a ducted system in a home that currently has no ductwork is likely to be more costly and time-consuming than installing a ductless system.

Ductless systems typically have two main components: a condenser outdoors and one or more air-handling units indoors. Ductless systems need only a hole through an outside wall to connect each indoor head unit to the outdoor condenser by conduit.[12] Figure 5 depicts a ductless "mini-split" system.

Northeast Energy Efficiency Partnerships reports that ducted systems require more energy than ductless systems to deliver the same amount of space conditioning, suggesting that ductless systems are roughly 15 to 20 percent more efficient.[13]

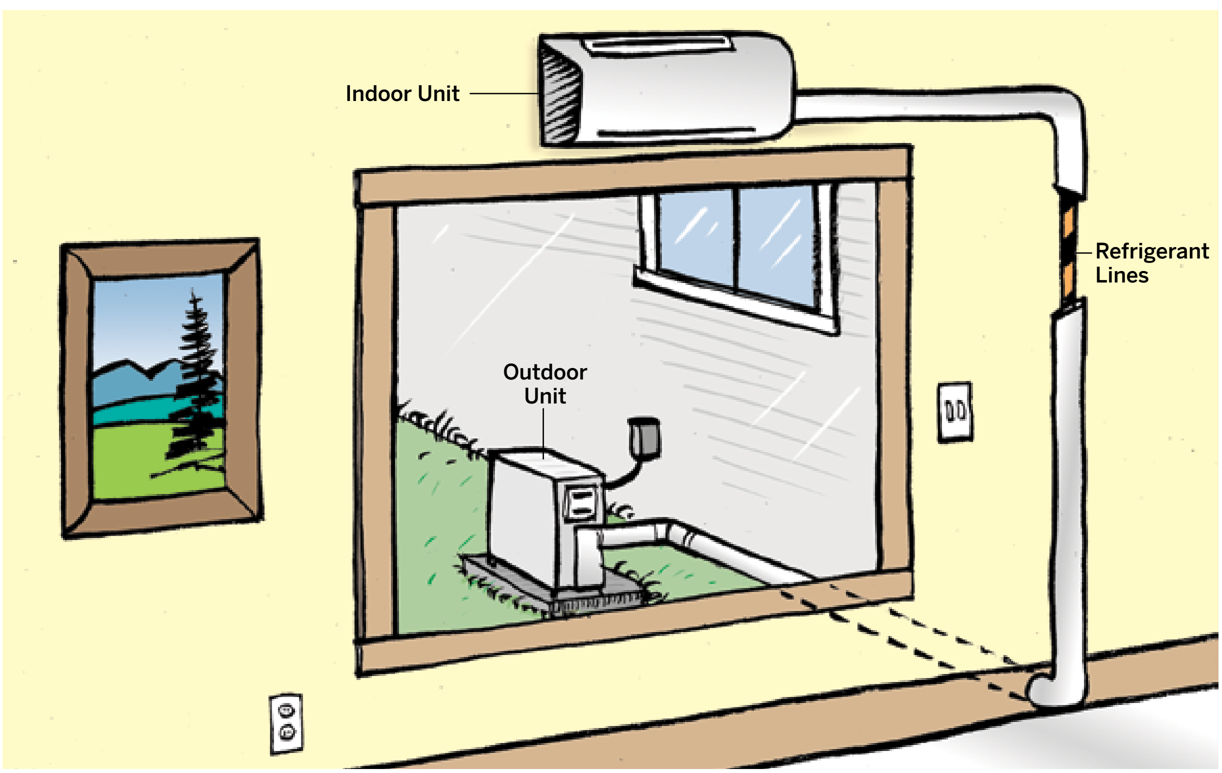
Although standard air source HPs are used around the country even in moderate winter conditions, until recently they have not been used in areas that experience extended periods of subfreezing temperatures. An air source HP's heating capacity and efficiency decrease as outdoor temperatures drop and heating demand increases. Figure 6 illustrates this relationship, although it is important to note that because HP technology continues to improve, this relationship is not fixed.[14] For the purposes of this figure, heat pump efficiency is characterized as the coefficient of performance (COP), which is the percent of input energy

**Figure 6. Cold Climate Heat Pump Performance**




Based on Faesy, R., Grevatt, J., McCowan, B., and Champagne, K. (2014, November 13). *Ductless Heat Pump Meta Study.*

**Figure 5. Ductless Mini-Split Heat Pump**




12 The conduit houses a power cable, refrigerant tubing, suction tubing, and a condensate drain.

13 Northeast Energy Efficiency Partnerships. (2018, September). *Cold climate air source heat pump specification—proposed revisions.* Retrieved from https://neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump

14 Faesy, R., Grevatt, J., McCowan, B., and Champagne, K. (2014, November 13). *Ductless heat pump meta study.* Lexington, MA: Northeast Energy Efficiency Partnerships. Retrieved from https://neep.org/ductless-heat-pump-meta-study-2014

used by the appliance that is ultimately delivered to the end use (heating the building).[15]

In recent years, due largely to design improvements, air source HP technology has advanced to contribute to effective space heating even in colder regions. In 2017, Northeast Energy Efficiency Partnerships reported that:

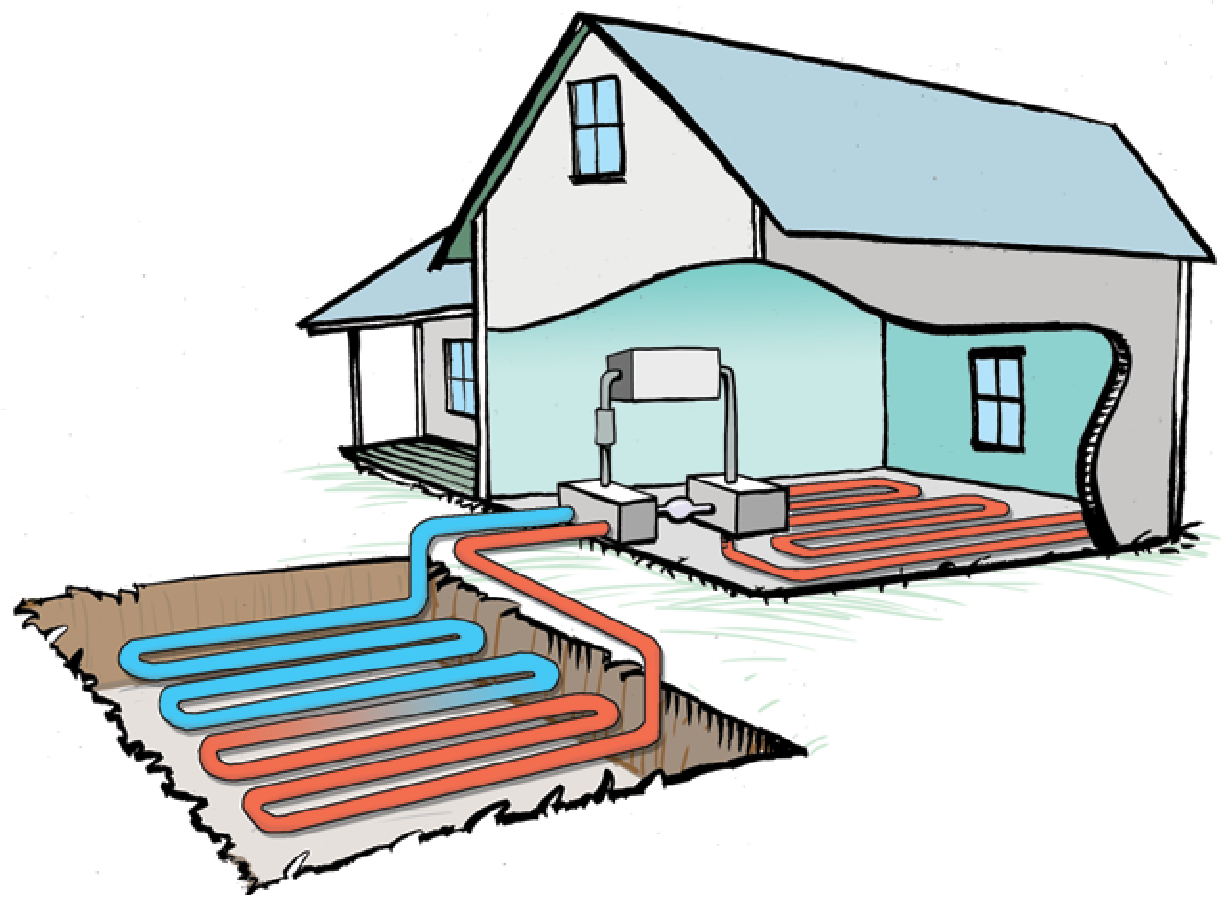
> A new generation of [air source] HPs utilizing inverter-driven, variable-speed compressors has come to market over the past five years. These systems have demonstrated radically improved heating performance under low temperature conditions (near or below 5°F), while continuing to offer highly efficient cooling.[16]

In addition to performance improvements, advances have been made in measuring and characterizing cold climate HP performance.[17]

Ground source HPs rely on the constant temperature of the Earth as the exchange medium, instead of the outside air temperature, and thus can operate in any climate. Despite variations in seasonal temperatures, several meters below ground the temperature remains relatively constant, ranging from 45 degrees Fahrenheit (7 Celsius) to 75 F (21 C).[18]

Most ground source HPs circulate a liquid through plastic tubing laid out horizontally underground and rely on a heat exchanger to transfer that underground temperature into

**Figure 7. Ground Source (Geothermal) Heat Pump**



15 For example, a COP of 1.0 means 100 percent of the input energy delivered to the appliance is ultimately turned into useful space heat within the building. Higher COPs indicate the heat pump delivers far more heat to the home than the energy it uses to do so.

16 Northeast Energy Efficiency Partnerships. (2017, January). *Northeast/Mid-Atlantic air-source heat pump market strategies report 2016 update.* Lexington, MA: Author. Retrieved from https://neep.org/sites/default/files/NEEP_ASHP_2016MTStrategy_Report_FINAL.pdf

17 The status of various specifications for cold climate heat pumps is briefly outlined in Appendix A.

18 US Department of Energy, Office of Energy Efficiency & Renewable Energy. (2017, August 1). *5 things you should know about geothermal heat pumps.* Retrieved from https://www.energy.gov/eere/articles/5-things-you-should-know-about-geothermal-heat-pumps

living spaces. Depending on local conditions, ground source HP loops may also be sunk vertically underground. Figure 7 depicts a standard exterior ground source HP installation being used to provide radiant floor heat inside the home. The technology can also be used with radiators.

Electric resistance storage heaters are another option for space heating. The most common type uses heating elements encased in heat-storing ceramic. Central furnaces incorporating ceramic block are also available, although they are not as common as room heaters.[19]

Electric resistance storage heating has been around for decades, but in the United States it has generally been deployed only in rural areas with low-cost off-peak power.[20] For the most part, this has happened in the service territories of electric cooperatives with a coal-based resource mix, in which available generation and distribution capacity during off-peak hours allowed off-peak electricity prices to be competitive with heating oil and propane. In these areas, natural gas typically is not available due to the rural nature of the service territories and the cost of building natural gas distribution systems.

These four categories of heating technologies, summarized in Table 1, can provide beneficial electrification where:

1. The marginal resource in the grid supplying electricity is relatively low-emitting; or
2. The use of these units can be concentrated into off-peak hours with significantly below-average prices for electricity.

## Optimal Space Heating Options Vary by Region

Geography and related climatic conditions affect the suitability of various space heating technologies. For example, as outdoor temperatures fall, the heating performance of standard air source heat pumps declines. But a simplistic distinction between "cold climate" and "warm climate" is not especially helpful in characterizing the suitability of

**Table 1. Summary of Electric Heating Technologies**

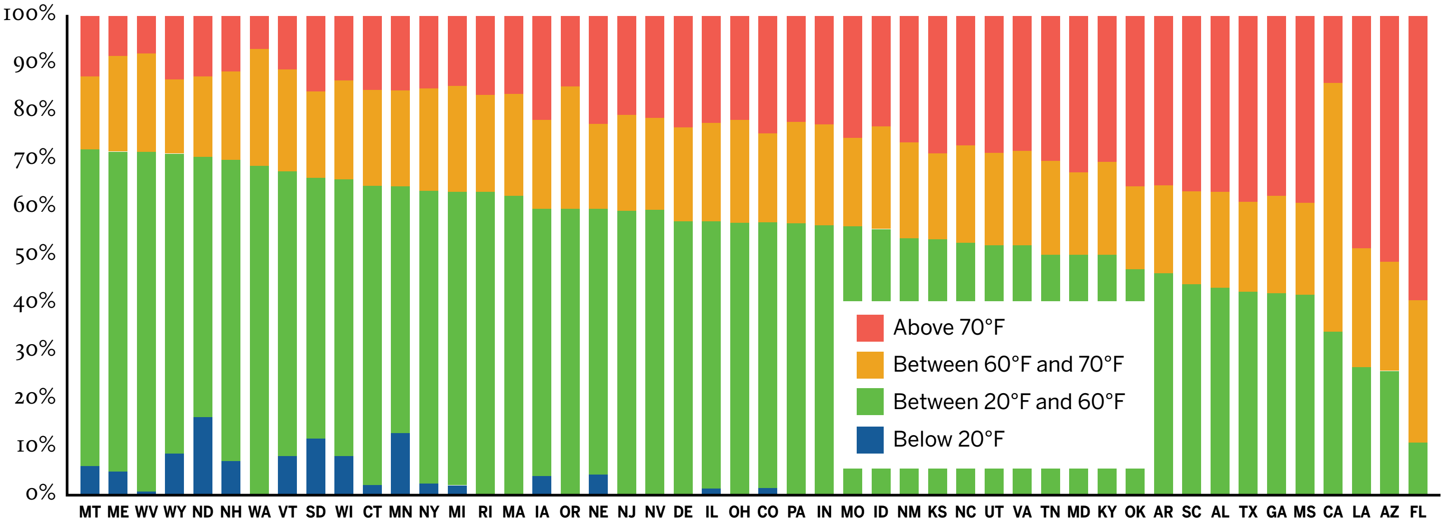
| Air source heat pump: Combined heating and cooling |
| --- |
| **Air source HPs** are a common heating and cooling technology used in every part of the country. These systems are typically either **ducted** or **ductless** and can be designed for standard environment or **cold climate**.<br><br>Ducted systems rely on ductwork to move air evenly around homes and are often installed where a forced-air ventilation system with ductwork is already in place (see Figure 4). **Ductless** systems call for less construction than those that are ducted, needing only a hole through an outside wall to connect each indoor head unit to the outdoor condenser (see Figure 5).<br><br>Several alternatives to basic ducted and ductless models of space heating exist that still rely on air source HP technology. A configuration known as a **short-run ducted** system uses large ductwork for part of the system in combination with ductless units. **Hydronic heating**, also known as radiant heating, uses tubing to run a hot liquid beneath the floor, along baseboards, or through radiators.<br><br>Although standard **air source heat pumps** are used around the country even in moderate winter conditions, their heating capacity and efficiency decrease as outdoor temperatures drop and heating demand increases. **Cold climate HPs** with improved compressor capabilities are now on the market and offer improved heating performance in low temperatures. |
| **Air source heat pump with supplemental heat: Combined heating and cooling** |
| **Air source HPs with supplemental heat**, also known as **dual-fuel** or **hybrid** systems, combine a heat pump with a supplemental heating technology (fossil-fueled or electric resistance) to boost heating performance under very cold conditions. |
| **Ground source or geothermal heat pump: Combined heating and cooling** |
| **Ground source HPs**[21] are heating and cooling systems that rely on the constant temperature of the Earth as the exchange medium instead of the outside air temperature. Most draw the temperature from underground by circulating a liquid through plastic tubing, then through a heat exchanger to transfer that underground temperature into living spaces (see Figure 7). |
| **Electric resistance thermal storage heating: Heating only** |
| A system of this kind uses electric resistance heating elements to store energy in ceramic (brick) blocks, so its electricity consumption can be concentrated into low-cost (and low-carbon) periods of the day. These systems can be combined with heat pumps to provide high-efficiency heating and cooling without requiring an additional energy source to cover very cold periods. |

19 National Renewable Energy Laboratory. (1997). *Saving energy with electric resistance heating*. Golden, CO: Author. Retrieved from https://www.nrel.gov/docs/legosti/fy97/6987.pdf. Holding electrically heated water in an insulated tank is another thermal storage option and will be discussed further in our companion paper on water heating.

20 We are aware of off-peak heating programs, including storage ceramic heaters, provided by several electric cooperatives in the upper Midwest: Eau Claire, Lake Region, Tri-County, Vernon, Polk-Burnett, Traverse, Agralite, Adams, and Beltrami electric cooperatives.

21 For more on ground source heat pumps, see US Department of Energy, Office of Energy Efficiency & Renewable Energy. *Geothermal heat pumps* [Webpage]. Retrieved from https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems/geothermal-heat-pumps

**Figure 8. Percentage of Annual Temperatures Within Selected Ranges**




Source: Synergy Energy Engineering LLC, using state data from usclimatedata.com.

various electric space heating technologies. Figure 8 illustrates the percentage of annual temperatures in the Lower 48 states that fall within different ranges.[22] The vast majority of annual temperatures in the heating season, shown in red, yellow, and green, are much higher than 20 degrees and in a range where standard heat pump performance is generally good.[23] However, one cannot ignore the percentage of time when temperatures are below 20 degrees, shown in blue.

The vast majority of annual temperatures in the heating season are much higher than 20 degrees and in a range where standard heat pump performance is generally good.

The South and Southwest have climates generally favorable to heat pump space conditioning, as does California. In these regions, central air conditioning is almost ubiquitous in new housing and major remodels, so the incremental cost of the heat pump option is a small fraction of the overall system cost,[24] and the efficiency of heat pumps makes them attractive for space heating. Resistance storage heating is less attractive in these climates because it does not provide air conditioning.

The Northern Tier, including the Upper Midwest and New England, is less favorable for standard air source heat pumps. Their performance diminishes in proportion to the drop in outdoor temperatures. Cold climate air source HPs, on the other hand, are improving even in extremely cold regions, and not all HP systems decline in performance in the same way.[25] Furthermore, many systems maintain 100 percent of their rated capacity at 5 degrees Fahrenheit.[26]

New England has a very cold climate and high-cost electricity. Cold climate air source HPs can provide most, but

22 Synergy Energy Engineering LLC developed this figure using state data from usclimatedata.com. Temperature data were collected from 1981-2010 for a selected city in each state.

23 It is important to emphasize that these are averages. For example, according to 2018 US Climate Data version 2.3, Rhode Island's average temperature for January is 21 degrees. This, of course, does not mean temperatures in January don't fall below 21. Knowing the lowest temperatures and the possible duration of those temperatures is important for determining if heat pump technology will meet building heating needs. Also, the authors acknowledge that the ranges of temperatures shown in this figure do not directly correspond with typical HP efficiency ranges and that a detailed analysis of climate and HP efficiency is needed to determine if, and how, a heat pump could be configured to meet space heating needs.

24 Ringo, D., Seiden, K., and Donnell, M. (2015). *Cool Smart incremental cost study: Final report.* The Cadmus Group. Retrieved from http://ma-eeac.org/wordpress/wp-content/uploads/Cool-Smart-Incremental-Cost-Study.pdf

25 Vermont Energy Investment Corp. (2018). *Driving the heat pump market: Lessons learned from the Northeast.* Burlington, VT: Author. Retrieved from https://www.veic.org/documents/default-source/resources/reports/veic-heat-pumps-in-the-northeast.pdf

26 See, for example, the Massachusetts program that requires this level of performance as a condition of receiving program incentives. Massachusetts Clean Energy Center. (2018, July 25). *Residential and small-scale air-source heat pump program: Program manual.* Boston, MA: Author. Retrieved from http://files.masscec.com/get-clean-energy/residential/air-source-heat-pumps/ASHPProgramManualSmallScale.pdf

generally not all, space heating needs. Residences with average thermal efficiency will require supplemental heat (e.g., dual-fuel heat pumps) for air source systems, unless ground source HPs are feasible. However, where homeowners or weatherization programs seal and insulate buildings to lower their heating requirements, cold climate air source HPs may be sufficient.

> Where homeowners or weatherization programs seal and insulate buildings to lower their heating requirements, cold climate air source heat pumps may be sufficient.

In rural areas of the North without access to natural gas service, electric resistance storage heating can compete with more expensive propane and heating oil technologies. Ground source HPs also do not face the same cold climate challenges as air source units, though they do have higher installation costs and aren't familiar to consumers and contractors.

In warmer rural areas, air source heat pumps will be an economic choice as their cooling capabilities will be desirable. In colder rural areas, dual-fuel air source HPs will make sense. No single rule guides deployment across all locations.

## Optimal Space Heating Options Vary by Housing Type

Housing type is another consideration when determining the most appropriate electric space heating applications. Factors such as the number of units served, age of the dwelling unit, and type of building (single family, apartment, mobile home) will affect which type of space heating works best. Table 2 on the following page provides greater detail for major housing types.

**Table 2. Space Heating Considerations for Various Housing Types**

| Existing apartments |
|---|
| Many low-rise apartments in the US have individual electric resistance space heating systems. These units are excellent candidates for installation of ductless air source heat pumps and individual room electric resistance storage heaters.[27] |
| **New apartments** |
| Newly constructed low-rise apartments are good candidates for shared heat pump space heating in appropriate climate zones, particularly California, the desert Southwest, Texas, and the Southeast. Variable refrigerant flow technology may be appropriate for apartments, depending on the size. In such a system, multiple indoor units can heat or cool simultaneously while connected to a single outdoor condenser. In addition, new apartments may be excellent candidates for ground source HP systems installed during initial site development. Changes to building codes may be needed in many areas to enable shared space heating systems, including submetering of heat to equitably allocate energy costs. Alternatively, apartments under construction may be fitted with resistance storage heating units. |
| **Existing single-family homes with natural gas service** |
| Houses with natural gas service will be the least cost-effective to convert to electric space heating in the next 20 years. The economics for switching to air source heat pumps may become favorable over time, however, particularly where there is a desire for central air conditioning, which reduces the incremental cost of heat pump installation. Conversion will be more attractive where a dwelling can also switch to heat pumps for water heating and thereby eliminate the monthly fixed charges for natural gas service, typically $10 to $20. Converting from natural gas represents a major investment for homeowners, so it is less likely without programmatic support. |
| **Existing single-family homes with oil or propane heating** |
| Houses that heat with oil or propane may be good candidates for conversion to air source heat pumps when the existing furnace or boiler needs to be replaced. Homes that heat with these fuels tend to be in colder climates, so the performance of cold climate HPs may be a key factor in the economic calculation. These homes may be more rural and may not have natural gas service available, further improving the economics of switching to heat pumps. Enhancing the thermal efficiency of the building is important for reducing heating needs and enabling the use of heat pumps. |
| **Existing manufactured homes** |
| Most homes of this type have propane or electric resistance space heating. Because propane is more expensive than natural gas, manufactured homes using propane are good candidates for ductless air source HP replacement if there is space for the outside condenser unit. Some manufactured homes are built in a way that will not accommodate a heat pump's airflow requirements. |
| **New manufactured homes** |
| Newly built manufactured homes may be capable of designs that accommodate air source and ground source heat pump systems and often feature ductless air source models. The option of sharing ground source HP systems is also emerging. It may be a fruitful topic for further research and consideration by electric utilities serving areas where many new manufactured homes are going in. |
| **Large multi-family buildings with central heating and cooling** |
| A different approach will be appropriate in high-rise apartment buildings, where natural gas boilers are a common source of both heating energy and hot water, and where central chillers are used for air conditioning. Commercial HP water heating systems (such as variable refrigerant flow) may be applicable, particularly for new construction, to provide hot water for space heating and other uses and chilled water for air conditioning.[28] |

27 This example of moving from less efficient to more efficient electrical space heating is not "electrification" (i.e., moving from a fossil end use to an electrical end use) as we have defined it above. It is important, however, to recognize that electrification-related activities can still produce greater efficiencies, or, as noted above in the context of improving a building's average thermal efficiency, complementary efficiency policies can improve the effects of electrification.

28 These systems are beyond the scope of cost analysis discussed in this paper.

# Conditions for Beneficial Electrification of Space Heating

As noted previously, for electrification to be beneficial, it must satisfy at least one of the following conditions without adversely affecting the other two:

1. Saves consumers money over the long run;
2. Enables better grid management; and
3. Reduces negative environmental impacts.

In this section we look at the ability of electric space heating to satisfy these conditions.

When cooling is also desired, heat pumps are much more cost-effective than separate heating and cooling technologies.

## Consumer Economics

The first condition of BE is that it benefits consumers economically. This means end users will save money over the lifetime of an electric space heating technology as compared to the alternative that would otherwise be used. Determining whether electrification will be cost-effective for consumers is a situation-specific calculation affected by several metrics.

### Factors Affecting Economics

Heat pumps are the most cost-effective electric space heating (and cooling) technology available for most applications, but they are not suitable for all situations. Electric resistance space heating can be cost-effective for consumers under the right conditions, primarily where low-cost energy is available at certain times of the day, enabling the use of stored heat. Here we describe some factors that affect the economics of consumer decisions to switch to electric space heating from a fossil-fueled source, or to have electric space heating installed at the time of new construction.

1. **Regional climatic variations** will determine which space heating technologies are feasible as well as how efficiently they can operate. The efficiency with which space heaters convet input energy (e.g., propane or electricity) into useful heating output is a key factor in determining the operating costs for different technologies.
2. **Building type** significantly affects which technologies can be installed. For example, existing apartments may require ductless heat pumps due to space constraints. Very high-efficiency structures in mild climates have very low heating needs, which could make it difficult to recoup the upfront cost of heat pumps in an acceptable number of years. On the other hand, new buildings that are well-insulated and have low heating needs are good candidates for heat pumps because a fossil-fueled unit might be too large for the heating need. In general, thermally efficient buildings are well-suited for heat pumps. New construction with electric space (and water) heating can also avoid the cost of connecting to the natural gas supply network.
3. Whether **space cooling** is being installed simultaneously with heating or is being added to an existing structure will affect the economics. When cooling is also desired, heat pumps are much more cost-effective than separate heating and cooling technologies, because a heat pump costs less than installing a separate furnace and air conditioner. US Energy Information Administration data show that older US homes are adding window air conditioners or being retrofitted for central air,[29] while 93 percent of new single-family homes in the US are being constructed with air conditioning,[30] making this market segment a prime candidate for the electrification of space conditioning.
4. **Installed cost of the electric appliances** themselves, and specifically the incremental cost above that of alternatives, strongly influences whether consumers adopt technologies. If electric options cost more than fossil-fueled alternatives, consumers able to pay this incremental cost will still need to save on operation and maintenance over the lifetime of the appliance to make the economics attractive.
5. **The cost of energy** for the appliances also affects whether electrification makes sense for consumers. This means comparing fuel costs (e.g., natural gas or fuel oil) with

29 US Energy Information Administration. (2011, August 19). *Air conditioning in nearly 100 million U.S. homes* [Webpage]. Retrieved from https://www.eia.gov/consumption/residential/reports/2009/air-conditioning.php

30 US Census Bureau. *Presence of air-conditioning in new single-family houses completed.* Retrieved from https://www.census.gov/construction/chars/pdf/aircond.pdf

electricity costs for supplying an equivalent amount of useful heat. These costs vary significantly by region. Areas like the Pacific Northwest and the Midwest, with generally low electricity prices,[31] have more favorable conditions for electrification than higher-cost regions like California and the Northeast. In addition to the cost of energy at the time of installation, projected changes in the costs of various fuels over the life of the appliance are useful when considering the total cost of ownership.

In most of the country, homeowners would benefit from life cycle cost savings by switching to an air source heat pump at the time an existing oil or propane furnace needs replacing.

## Current Economics

In 2018, the American Council for an Energy-Efficient Economy (ACEEE) published a study of the energy, financial, and emissions impacts of converting oil and propane furnaces and boilers to high-efficiency heat pumps.[32] It concluded that, in most of the country, homeowners would benefit from life cycle cost savings by switching to an air source heat pump at the time an existing oil or propane furnace needs replacing. Conversion of oil and propane boilers has longer simple payback periods, but the addition of air conditioning to those homes may make them more comfortable to live in. Table 3 shows the high-level findings from this study.[33]

ACEEE analyzed the annual energy use of oil furnaces and air source heat pumps in different states and climates. Using these results and data on fuel costs from the US Energy Information Administration, we can compare the estimated annual fuel costs of the two technologies in different states.[34] The results of this comparison for eight states appear in

**Table 3. Average Years Needed to Recover Higher Costs of Heat Pumps**

| Comparison | US | West | Midwest | Northeast | Southeast |
|---|---|---|---|---|---|
| **Oil furnace vs. heat pump, includes air conditioning savings** | 0.9 | 1.4 | 1.3 in Missouri; no savings in Upper Midwest | 1.9 | 0.8 |
| **Propane furnace vs. heat pump, includes air conditioning savings** | 1.5 | 1.7 | 3.4 in Missouri; no savings in Upper Midwest | 2.0 | 1.3 |
| **Oil boiler vs. ductless heat pump, without air conditioning** | 4.4 | 7.3 | 18.8 | 6.2 | 5.1 |
| **Propane boiler vs. ductless heat pump, without air conditioning** | 16.1 | 12.1 | 19.8 | 8.5 | 9.1 |

Assumes installation is made at the time existing system needs replacement. Comparison based on fossil-fueled options meeting federal minimum efficiency standards and ducted heat pump meeting Energy Star minimum standards.

Source: Nadel, S. (2018). *Energy Savings, Consumer Economics, and Greenhouse Gas Emissions Reductions from Replacing Oil and Propane Furnaces, Boilers, and Water Heaters With Air-Source Heat Pumps.*

31 US Energy Information Administration. (2018, January 25). *State electricity profiles* [Webpage]. Retrieved from https://www.eia.gov/electricity/state/

32 Nadel, S. (2018). *Energy savings, consumer economics, and greenhouse gas emissions reductions from replacing oil and propane furnaces, boilers, and water heaters with air-source heat pumps* (Report No. A1803). Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from https://aceee.org/sites/default/files/publications/researchreports/a1803.pdf

33 The study was for existing homes only. For new construction, the results might be different, as the cost of oil and propane access and oil storage can be saved. In addition, high-performance ductless heat pumps may be an option for new construction.

34 For a table showing the calculations, see Appendix B.

Figure 9.[35] In many states, consumers can save money by switching to an air source heat pump with the technology that exists today. As the efficiency of cold climate HPs improves, so will the economics for heat pumps in states like Massachusetts and Wisconsin.

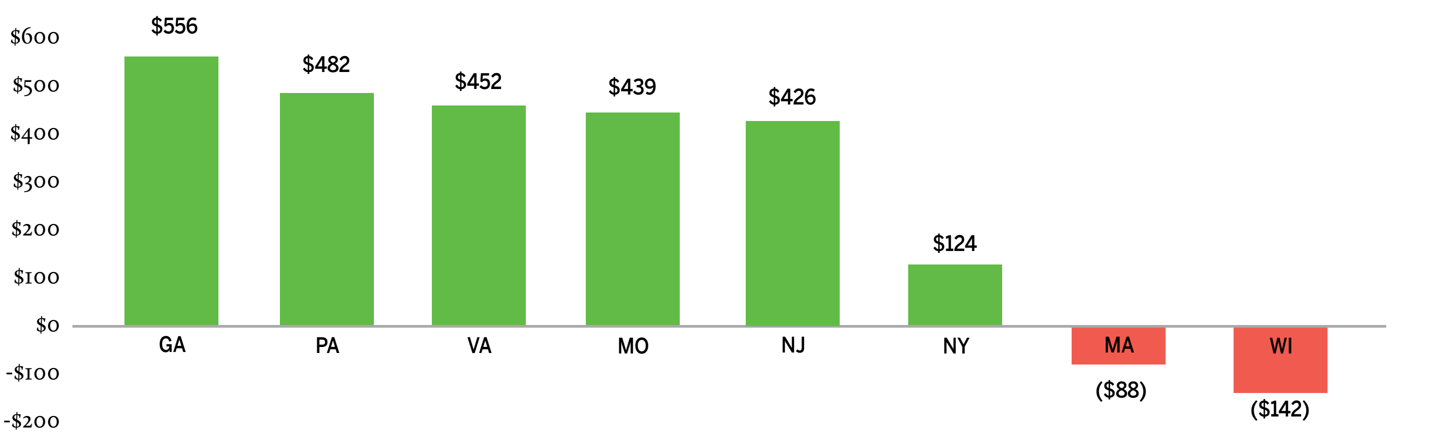
An analysis found that air source heat pump technologies (including cold climate HPs) are projected to be cost-competitive with gas furnaces by 2050.

The ACEEE study discussed above examined the economics of switching to a heat pump when an existing oil or propane furnace or boiler needs to be replaced. A 2018 Rocky Mountain Institute (RMI) analysis examined electrification of both space and water heating for new construction and home retrofits in four locations.[36] For new construction, the RMI analysis found that in all four locations air source heat pumps are currently more cost-effective on a 15-year net present value basis when compared with fossil-fueled options.[37] For many existing homes heated with natural gas, however, electrification is not cost-effective unless a customer needs to replace a furnace and air conditioner simultaneously.

## Future Economics

The National Renewable Energy Laboratory (NREL) published a paper in which it examined the consumer economics of electrification, both at current energy prices and at forecast future prices.[38] As illustrated in Figure 10 on the following page, one of NREL's findings is that air source heat pump technologies (including cold climate HPs) are projected

**Figure 9. Annual Fuel Cost Savings (or Loss) by Switching to Air Source Heat Pump From Oil Furnace**




Source: Compiled with data from American Council for an Energy-Efficient Economy and US Energy Information Administration.

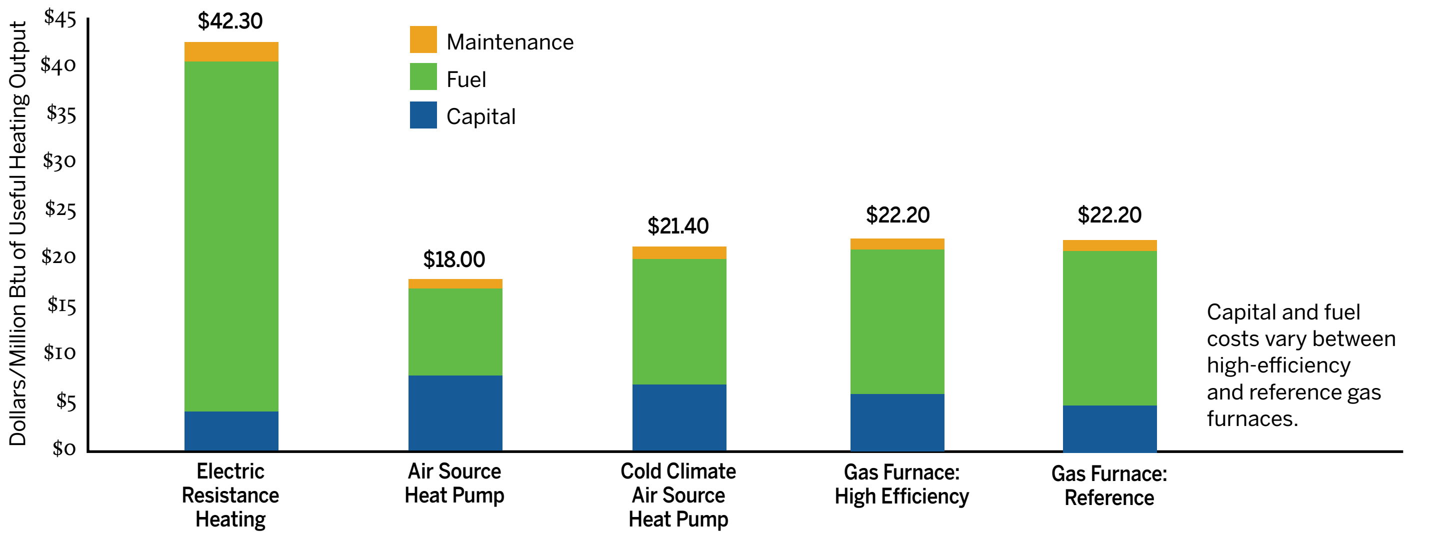
35 Our assumptions about energy use for oil furnaces and heat pumps come from ACEEE, which modeled a standard oil furnace and a heat pump with a COP of 3.02. We converted million Btu of oil usage to gallons using 138,000 Btu per gallon. See Nadel, 2018. Heating oil prices are averages for winter 2017-2018 for the New England, central Atlantic, lower Atlantic, and Midwestern states. US Energy Information Administration. *Weekly heating oil and propane prices* (October-March) [Webpage]. Retrieved from https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPD2F_PRS_dpgal_m.htm. Residential retail prices are 2017 averages by state. US Energy Information Administration. *Electricity data browser* [Webpage]. Retrieved from https://www.eia.gov/electricity/data/browser/

36 Oakland, California; Houston, Texas; Providence, Rhode Island; and Chicago, Illinois.

37 Billimoria, S., Guccione, L., Henchen, M., and Louis-Prescott, L. (2018). *The economics of electrifying buildings.* Boulder, CO: Rocky Mountain Institute. Retrieved from https://www.rmi.org/insights/reports/economics-electrifying-buildings/

38 Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017). *Electrification futures study: End-use electric technology cost and performance projections through 2050* (NREL/TP-6A20-70485). Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy18osti/70485.pdf

**Figure 10. Projected Consumer Economics for Space Heat in 2050**




Source: Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., and Mai, T. (2017). *Electrification Futures Study: End-use Electric Technology Cost and Performance Projections Through 2050.*

to be cost-competitive with gas furnaces by 2050.[39, 40] The results of the study are not regionally differentiated, and it used national averages for fuel prices. This means that regions with lower electricity costs or higher natural gas prices would see more favorable economics than the results show, and vice versa for the opposite fuel price conditions. NREL's findings also imply that electric resistance heat will be cost-effective only if served by very low-cost electricity on systems with sharply defined time-of-use (TOU) or seasonal rates.

NREL's findings demonstrate that at current (or soon expected) cost and performance levels, replacing gas furnaces with air source heat pumps at the time of replacement will be at cost parity with a gas-to-gas replacement in moderate or warm climates. In cold climates, greater technology improvements are needed in order for cost advantages alone to drive adoption of heat pumps in the short to medium term. Accordingly, heat pumps can be readily adopted in regions with above-average natural gas prices or below-average electricity prices, or with seasonal gas price spikes that make the cost of cold climate HPs more favorable. NREL's results also illustrate that the cost-effectiveness of technologies will improve as capabilities and costs change.

There are several ways to address cold-region challenges to make heat pumps more economic for consumers. Improving building envelope efficiency can often make it possible for high-efficiency cold climate HPs to provide all heating needs economically. Air source HP systems relying on supplemental heat provide another solution. In that context, the heat pump serves the majority of the load, and a supplemental heating system is used during periods of extreme low temperature or high electricity cost. The supplemental heat can be from an electric resistance heater, fossil-fueled sources (e.g., oil, propane, or natural gas), or biofuel in the form of wood, wood pellets, or liquid.

Another hybrid approach to enable the use of heat pumps in cold climates is to augment the heating system with energy

39 The study analyzed consumer economics at three discount rates (7, 10, and 13 percent). We are showing the results for a 7 percent discount rate. These results also reflect the "moderate advancement" sensitivity analysis NREL conducted, meaning that a moderate amount of additional research and development and technology innovation, beyond what is assumed in the "slow advancement" case, is assumed to occur. The core components of NREL's analysis include the capital cost, efficiency, and lifetime of a technology; fuel and maintenance costs; the discount rate associated with the individual adopter; and an assumed usage pattern or capacity factor. NREL associated 50 percent of the installed cost of air source heat pumps (and cold climate air source HPs) to the heating service—assuming that approximately half the capital cost is associated with cooling.

40 Commercial HP water heating systems (such as variable refrigerant flow) are beyond the scope of the NREL cost analysis and are appropriate for further inquiry.

storage.[41] Storage can be a thermal mass like ceramic bricks or water, or it can be electric.[42]

Although the NREL data demonstrate that by 2050 heat pumps will be more cost-effective for consumers than gas furnaces, they also show that by 2050 electric resistance space heat will cost consumers about twice as much as natural gas space heat. (The data identify slightly smaller cost premiums over propane and heating oil, which are more expensive than natural gas.) This tells us that unless we can offer consumers about a 50 percent discount below the average national electricity rate—now about 12 cents per kilowatt-hour (kWh)—electric resistance storage heating will not be cost-effective even in regions with a clean electricity supply that would justify its use as a low-emissions option.

## Grid Management

Grid managers use various tools to ensure the electric power system has the flexibility to respond to variations in load. The grid has always needed a certain amount of flexibility because the normal demand for electricity varies on a daily and seasonal basis. The integration of increasing amounts of variable renewable energy requires even more flexibility. A key requirement for grid operators today is meeting net load—the difference between forecast load and the amount of load met by variable resources.[43] Fortunately, many new electric loads are themselves flexible in when they need to use the grid, meaning grid operators have more flexible resources to call upon to ensure stability.

Grid operators now recognize that demand-side efforts can also help meet today's balancing challenges.[44] Specifically, optimizing load shape through a combination of policies, pricing options, and program offerings can make the system more flexible and lower its overall costs. Beneficial electrification provides some of the best ways to optimize load shape. Unlike traditional electricity load, much of the new electrification load is at least somewhat flexible in when it needs to draw grid power.[45] As a result, it can act as either thermal or electrical energy storage and can be served at less expensive times of the day.

Electrifying space heat, and using technologies like controlled electric resistance heaters and heat pumps to do so, can provide increased flexibility to grid operators.[46] These two technologies have different implications for grid management, based on their characteristics and regional climate variations. Heat pumps installed with supplemental heating systems may also offer the ability to shift to the alternative fuel during electric system stress.

Regional climate variations currently dictate the type of technology that grid operators will likely encounter in their specific location. Due to their superior efficiency and low operating costs, heat pump technologies—particularly air source models—have been growing in popularity in the United States. From 1979 to 2012, the share of new US homes built with a heat pump grew from 17 to 49 percent for multi-family homes and from 25 to 38 percent for single-family houses.[47] As of 2015, the share of new single-family homes with a heat pump had risen to 41 percent.[48]

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41 Steffes Corp. produces a ceramic storage add-on to forced-air heat pumps. Steffes ETS. *Owner's and installer's manual for electric thermal storage heat pump boosters.* Retrieved from http://steffes.com/wp-content/uploads/2016/09/HeatPumpBooster_OwnersManual.pdf

42 Electric battery systems are declining sharply in cost, and "(i)ndustry participants expect costs to decrease significantly over the next five years." Lazard. (2017). *Lazard's levelized cost of storage analysis—version 3.0.* Retrieved from https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf

43 Colburn, K. (2017, January 24). Beneficial electrification: A key to better grid management [Blog post]. Regulatory Assistance Project. Retrieved from https://www.raponline.org/blog/beneficial-electrification-a-key-to-better-grid-management/

44 Colburn, K. (2017, February 1). Beneficial electrification: A growth opportunity [Blog post]. Regulatory Assistance Project. Retrieved from https://www.raponline.org/blog/beneficial-electrification-a-growth-opportunity/

45 Like other demand-response resources, managed electrification load has the potential to help utilities keep their systems stable and efficient, to defer upgrades to generation, transmission and distribution systems, and to deliver economic benefits to consumers. See Alstone, P., Potter, J., Piette, M.A., Schwartz, P., Berger, M., Dunn, L.N., et al. (2017). Final report on Phase 2 results: 2025 California demand response potential study. Retrieved from http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442452698

46 Colburn, 2017a.

47 Jadun et al., 2017, citing Lapsa, M., and Khowailed, G. (2014). Recent progress in the residential U.S. heat pump market. *IEA Heat Pump Newsletter* 32(3).

48 Jadun et al., 2017, citing Lapsa, M., Khowailed, G., Sikes, K., and Baxter, V. (2017). The US residential heat pump market, a decade after "the crisis." In Proceedings of the 2017 International Heat Pump Conference. Oak Ridge, TN: Oak Ridge National Laboratory Technologies Research and Integration Center.

However, most of these homes are in warmer climate regions in the United States: Ninety percent of homes that use heat pumps as their primary heating source are in mixed, hot, or marine climates.[49] In these summer-peaking regions (which encompass most of the US at present), a certain amount of generation, transmission, and distribution capacity is available in winter to serve heating loads. As a result, grid operators in warmer climate regions are likely to be able to take advantage of grid management benefits provided by air source heat pumps. Grid operators in colder regions are more likely to encounter resistance storage heaters or heat pumps with supplemental heating on their systems and can benefit from the management options available from these technologies. These distinctions are discussed in more detail below.

As a greater proportion of space heating becomes electrified, many summer-peaking power systems will see peak hours increasing during winter.

As a greater proportion of space heating becomes electrified, many power systems where a majority of peak hours currently occur during summer will see peak hours increasing during winter. According to an NREL study of electrification futures (under its "medium" or "high" electrification scenarios[50]), by 2050 this effect is likely to be particularly pronounced in the Northeast, with a noticeable but less dramatic effect in the Southeast.[51]

A number of issues for grid operators could arise from this shift. There may be implications for resource planning, as different types of resources are available during winter than in summer. Daily load curves in winter tend to have a different shape than in summer, meaning grid managers may need to have a different set of flexible resources available. Load factor—a measure of how continuously utility transmission and distribution investments are utilized—is expected to increase as beneficial electrification of space heating and other end uses increases.[52] However, load shape will become more important than load factor as variable generating resources like wind and solar become more common.

A number of factors will influence the best strategies to manage the potential changes and challenges associated with electrification of space heating, including future electricity rate structures, availability of demand response capabilities in end-use technologies, and the availability of energy storage to help manage system peaks.[53]

## Electric Resistance Storage Heating

Resistance storage heating can provide value to system operators because it can operate as both demand (using energy when it is readily available) and supply (releasing stored energy at times of system stress and higher cost). It also offers a very real economic opportunity for many regions with ample wind resources, which might otherwise risk curtailment. Examples include those regions served by wind resources in the Eastern interconnection (from Oklahoma, Iowa, and offshore New England), in Texas (which is rich in wind resources), and in the Western interconnection (from wind resources in California, New Mexico, Wyoming, and Montana).[54]

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49 Jadun et al., 2017, citing Baechler, M., Gilbride, T., Cole, P., Hefty, M., and Ruiz, K. (2015). *High-performance home technologies: Guide to determining climate regions by country.* Pacific Northwest National Laboratory; and US Energy Information Administration. (2015). *Residential energy consumption survey.* Retrieved from https://www.eia.gov/consumption/residential/

50 NREL's "medium" scenario includes a future with widespread electrification among the "low hanging fruit" opportunities in electric vehicles, heat pumps, and select industrial applications, but one that does not result in transformational change. The "high" scenario is a combination of technology advancements, policy support, and consumer enthusiasm that enables transformational change in electrification. These are compared with a "reference" scenario that serves as a baseline.

51 Mai, T., Jadun, P., Logan, J., McMillan, C., Muratori, M., Steinberg, D., et al. (2018). *Electrification futures study: Scenarios of electric technology adoption and power consumption for the United States* (NREL/TP-6A20-71500), p. 73. Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy18osti/71500.pdf

52 Increasing load factor is generally viewed as a beneficial thing, because utility costs are spread over more hours, ultimately putting downward pressure on costs to all customers. Mai et al., 2018, p. 76.

53 Mai et al., 2018, p. 77.

54 State of Nebraska. *Wind facilities' installed capacity by state* [Webpage]. Retrieved from http://www.neo.ne.gov/statshtml/205.htm

### Ancillary Services

It is possible to control the heating elements of resistance storage heaters on a second-to-second or minute-to-minute basis. Heaters can be charged at any time of day when system conditions are favorable, not just overnight or when customers use the "boost" function.[55] An aggregator could charge up a set of heaters in mid-afternoon if abundant solar or wind energy is available, or switch them off and on for brief periods to provide a fast response to the ancillary services market.[56] Ancillary services include frequency regulation (a transmission-level service) and voltage support (a distribution-level service), and help the grid operate efficiently and reliably.[57, 58]

### Peak Demand Management

Electric resistance storage heating with the aid of smart technology and aggregation can shift charging away from times of system stress and instead charge at other times using abundant wind or solar generation, helping to avoid their curtailment. System balancing can be carried out at different scales, such as at the community level or even within a single building.[59] The extent of possible load shifting for peak demand management will depend on the type and timing of resources available on the grid, how many storage heaters are available to be controlled, and customer demands for heating. Table 4 illustrates the demand response benefits that grid managers could realize when resistance storage heat is combined with smart controls.[60]

## Heat Pumps

Heat pumps provide many opportunities to manage peak demand, even though they cannot provide fast response services (e.g., for ancillary service requests). Because they are mechanical devices, heat pump compressors may suffer unacceptable wear if controlled like electric resistance storage heaters into sub-minute periods.

### Peak Demand Management

We anticipate that the use of thermal storage (typically water or ceramic) with heat pump units would be limited to avoidance of critical peak very high-cost (and high-emissions) hours on a power system. But, because heat pumps typically produce a large quantity of warm heating output rather than a small quantity of high-heat output, they are generally less suitable for overnight charging and daytime deployment like resistance storage heaters.

When connected with smart thermostats, heat pumps can help in managing system demand by preheating or precooling a space during the afternoon and running less during early evening peak periods.[61] Smart thermostats can also enable demand response programs whereby a utility can reduce

**Table 4. Demand Response Benefits of Smart Electric Resistance Storage Heat**

| | |
|---|---|
| **Type of asset** | Distributed, often in clusters (e.g., social housing; rural buildings without access to piped gas). |
| **Notice period required for load shifting** | Notice to aggregator can be very short (even seconds), because customers do not need to know when the appliances are charging provided they have heating when it is wanted. |
| **Duration of load shifting** | Can be as long as is compatible with customers' control settings. |
| **Frequency of load shifting** | As dictated by network and customer constraints. |

55 The boost function refers to times when customers may adjust the controls for extra heat in the course of the day.

56 Darby, S. (2017). Smart electric storage heating and potential for residential demand response. *Energy Efficiency, 11*(1), 67-77. Retrieved from https://link.springer.com/content/pdf/10.1007/s12053-017-9550-3.pdf

57 We address the ancillary services issue in greater detail in a companion paper on water heating.

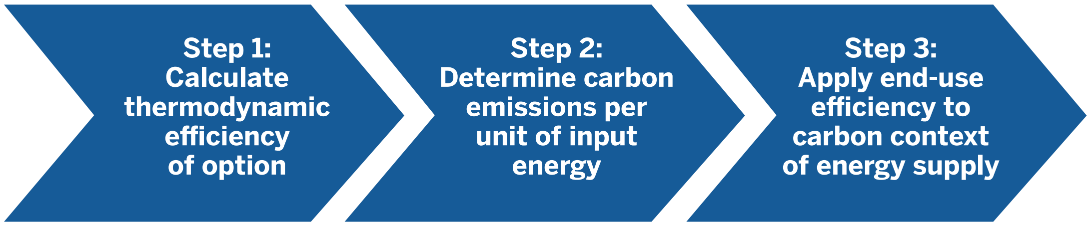
58 Darby, 2017.

59 Darby, 2017.

60 Darby, 2017.

61 "Pre-cooling of buildings refers to shifting the operation of cooling equipment to earlier in the day to make use of more favorable electricity rates and relying on the thermal inertia of the building to provide adequate building comfort in subsequent hours." Deason, J., Wei, M., Leventis, G., Smith, S., and Schwartz, L.C. (2018). *Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches* (LBNL-2001133). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eta-publications.lbl.gov/sites/default/files/electrification_of_buildings_and_industry_final_0.pdf

**Figure 11. Determining Emissions Efficiency of a Space Heating Technology**




the electric load of a group of heat pumps by an individually small amount that cumulatively provides a measurable peak load reduction benefit to the grid and avoids unnecessary air emissions.[62]

## Energy and Emissions Efficiency

To determine whether electrification of space heating applications is beneficial, we need to analyze each technology's emissions efficiency—the emissions per unit of useful heating output. Through beneficial electrification of space heating, consumers can produce less pollution per unit of delivered space heat. Emissions efficiency of various electric options will vary with the characteristics of the utility grid to which they are connected. By combining the efficiency of the end-use appliances with the carbon content of their energy supply, we can compare the emissions efficiency of electrification technologies with fossil-fueled alternatives. The tables in this section summarize the steps, illustrated in Figure 11, in calculating the emissions per million Btu of delivered space heat for various technologies.

The first step is shown on the next page in Table 5 comparing the thermodynamic efficiency of the space heating options.[63] For the electric options, thermodynamic efficiency is determined partly by the efficiency of the generating unit that is assumed to be providing the power.[64] We show different values for the electric options if they are assumed to be powered by a coal-fired or nuclear power plant (both assumed to be 35 percent efficient)[65] or by a natural gas combined-cycle unit (assumed to be 50 percent efficient).

The air source HP with supplemental heat option assumes the heat pump operates when it is at a high COP and that the supplemental heating unit operates when it is very cold and the COP is lower. The supplemental heat could be propane, natural gas, heating oil, or even electric resistance storage heat. The electric options that have higher thermodynamic efficiency than the fossil-fueled alternatives are shaded in green, and those that have lower efficiency are shaded in red.

Although the resistance storage heating unit is the least efficient of the electric options, its thermodynamic efficiency is not the only relevant factor for determining its *emissions*

62 "A future grid system with more electrified end uses, coupled with greater control and automation of end-use operation, can provide grid operators and utilities with greater control over load shapes and aggregated end uses." Deason et al., 2018. See also Nadel, S. (2016). *Comparative energy use of residential furnaces and heat pumps* (Report No. A1602). Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from http://aceee.org/comparative-energy-use-residential-furnaces-and

63 Energy factor (shown as percentages in this table) is the percent of input energy delivered to the appliance that is ultimately delivered to the end use (heating the building). COP represents the same information. A COP of 0.95 is equivalent to an energy factor of 95 percent. Although most older furnaces in existing housing stock will be less efficient than 95 percent, some Energy Star models of oil, propane, and natural gas furnaces in the range of 90 to 95 percent efficient are available. We endeavor to show a conservative assessment of the potential efficiency benefits of heat pumps. As such we are using these Energy Star efficiencies for fossil-fueled furnaces. In this table, COPs are simplified to 3.0 for standard air source heat pumps operating in mild climates and 2.5 for cold climate heat pumps without supplemental heat based on a review of available models using Northeast Energy Efficiency Partnerships specification listings, available here: https://neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump#Listing%20Products. We also note that these efficiencies are with regard to the equipment itself, but that duct leakage can reduce system efficiency. This will affect the efficiency results for ducted versus ductless air source heat pumps, the latter of which do not have such home distribution system losses.

64 Because wind and solar power are not thermodynamic processes, this table does not include them. As we move through the calculation tables, we look at emissions intensity, and wind and solar will come into the calculation.

65 It's important to note that this applies only to the thermodynamic efficiency of these electric generating technologies, not their emissions intensities. Emissions intensity will come into the calculation in the subsequent tables.

efficiency. For the electric heating options, this also requires assessing the carbon intensity of the electricity used to power them. This is what our next calculation shows. Table 6 provides illustrative fuel mixes for electric systems that are assumed to be all coal, half coal/half gas, all gas, half gas/half renewables, and all renewables.[66]

Table 6 shows that after accounting for the generating efficiency and potential line losses, coal-fired power has emissions of 679 pounds of $CO_2$ per million Btu, and gas-fired power has emissions of 260 pounds per million Btu—roughly 60 percent lower than coal. We calculated the "mixed" fuel emissions by averaging the numbers for coal, gas, and non-carbon resources.

Table 5. Comparative Efficiency of Space Heating Technologies

| | Coefficient of performance or energy factor of heating technologies | Coal or nuclear generation efficiency (35%) | Gas combined-cycle generation efficiency (50%) |
|---|---|---|---|
| **Air source heat pump** | | Net thermodynamic efficiency of electric technologies | |
| Mild climate | 3.0 | 105% | 150% |
| Cold climate | 2.5 | 88% | 125% |
| With supplemental heat | 3.0 | 105% | 150% |
| **Ground source heat pump** | 4.0 | 140% | 200% |
| **Electric resistance storage** | 1.0 | 35% | 50% |
| **Natural gas furnace** | 95% | N/A | |
| **Propane furnace** | 95% | | |
| **Oil furnace** | 95% | | |

The third step in determining emissions efficiency is to combine the efficiency of the end-use appliances with the carbon content of the energy supply, to generate the emissions per million Btu of delivered space heat. Calculating the emissions from natural gas, oil, and propane furnaces, at today's best efficiency ratings, establishes a value against which to compare the electric space heating technologies. Table 7 shows calculations for the $CO_2$ emissions per unit of delivered space heat for these fossil-fueled furnaces, using their assumed efficiencies and the carbon content of their fuel.[67]

For our final calculation in this section, we show the emissions associated with electric space heat, using our earlier assumptions about the efficiency of the technologies and what we found in Table 6 for the emissions from

Table 6. Illustrative Electric Sector Carbon Emissions

| | 100% Coal | 50% Coal/ 50% Gas | 100% Gas combined cycle | 50% Gas/ 50% Non-carbon | 100% Non-carbon |
|---|---|---|---|---|---|
| **Fuel source $CO_2$** (pounds/million Btu) | 214 | | 117 | | |
| **Conversion efficiency** | 0.35 | | 0.5 | | |
| **Generated electricity $CO_2$** (pounds/million Btu) | 611 | | 234 | | |
| **Line losses** | 10% | | 10% | | |
| **Delivered electricity $CO_2$** (pounds/million Btu) | 679 | 470 | 260 | 130 | 0 |

66 Nuclear is a relatively low-efficiency resource from a thermodynamic perspective, but we treat it as a non-carbon resource for emissions analysis. Some analysts attribute a carbon impact to nuclear, based on the carbon inputs to the nuclear fuel cycle. For simplicity's sake, we do not do so in this paper.

67 Consumer Reports indicates a few models as high as 97 percent efficiency, but that efficiency will tend to decline over the appliance's lifetime. We use 95 percent as an assumption over the life cycle. See Consumer Reports. (2016, September). *Gas furnace buying guide* [Webpage]. Retrieved from https://www.consumerreports.org/cro/gas-furnaces/buying-guide

**Table 7. Carbon Emissions of Fossil-Fueled Heating Options**

| | Efficiency | Fuel source $CO_2$ (pounds/ million Btu) | Space heat $CO_2$ (pounds/ million Btu) |
|---|---|---|---|
| **Natural gas furnace** | 0.95 | 117 | 123 |
| **Propane furnace** | 0.95 | 139 | 146 |
| **Oil furnace** | 0.95 | 162 | 171 |

generation.[68] The emissions efficiency of electric technologies is calculated by dividing the emissions from various power system mixes, found in Table 6, by the efficiencies of the technologies.

Table 8 illustrates[69] the emissions implications of these technologies compared with the fossil-fueled options shown in Table 7. The green shaded areas are those where the electric option results in lower emissions than fossil-fueled heating systems shown in Table 7. Yellow cells denote an electric option with similar emissions efficiency to one or more of the fossil-fueled options. Red cells denote electric options that are not yet lower-emissions. Note that electric resistance storage heating is advantageous only where the majority of the electricity used is non-carbon-emitting.

Heat pumps, in various climates and with supplemental propane heat, produce higher carbon emissions only when the electricity system has a significant amount of coal-fired generation. In all other systems, heat pumps are more emissions-efficient than their fossil-fueled counterparts. If the electric system is no more carbon-intensive than a gas/non-carbon split, even electric resistance storage heating has lower emissions than fossil-fueled heating. It is worth noting that because the power sector is becoming cleaner, even today's coal-dominated grids will soon become sufficiently less carbon-intensive as to further advantage electrification of space heating.

It is beyond the scope of this paper to do a detailed analysis, region by region, of the emissions reduction potential of converting space heating to electricity. But this section demonstrates that such conversions have the potential to contribute significantly toward emissions reduction goals, particularly as electric generation gets cleaner. The text box on the next page summarizes a simplified calculation of the national potential for emissions reductions from space heat conversions to electricity.

**Table 8. Emissions Efficiency of Electric Heating Options in Various Power System Mixes**

| | Space heat $CO_2$ (pounds/million Btu) | | | | |
|---|---|---|---|---|---|
| | 100% Coal | 50% Gas/ 50% Coal | 100% Gas | 50% Gas/ 50% Non-carbon | 100% Non-carbon |
| **Air source heat pump** | | | | | |
| Mild climate | 226 | 157 | 87 | 43 | 0 |
| Cold climate | 272 | 188 | 104 | 52 | 0 |
| With propane backup 10% of heating | 218 | 156 | 93 | 54 | 15 |
| **Ground source heat pump** | 170 | 117 | 65 | 33 | 0 |
| **Electric resistance storage** | 679 | 470 | 260 | 130 | 0 |

68 Note that the sources of electricity depicted here are illustrative of different background mixes of generation resources. For further discussion of the importance of electric sector emissions for beneficial electrification, see Principle 3 and the Appendix in Farnsworth, D., Shipley, J., Lazar, J., and Seidman, N. (2018). *Beneficial electrification: Ensuring electrification in the public interest.* Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/wp-content/uploads/2018/06/6-19-2018-RAP-BE-Principles2.pdf

69 For purposes of this illustration, we assume that the supplemental heating option to the cold climate heat pump provides 10 percent of the total space heating required, consistent with the data in Figure 6. The storage option is designed to be "charged" during low-cost hours (which, in a system that is more than half non-carbon generation, will likely also be low-emissions hours).

## National Potential for Space Heat Carbon Emissions Reductions

Americans use 187 billion kWh a year for space heat, plus 28 billion therms of natural gas, 2.9 billion gallons of heating oil, and 2.5 billion gallons of propane. Rather than attempt to accurately measure national electrification potential, our goal here is merely to put that potential into perspective. To do that, we make several significant (but reasonable) assumptions about what could be achievable by 2050:

- Fifty percent of existing electric resistance heat, primarily in single-family residences and mobile homes, can be converted to air source heat pumps;
- All existing heat pump installations will be replaced over time with higher-efficiency models;
- Eighty percent of existing natural gas, heating oil, and propane heating energy use can be converted to heat pump use. The remaining 20 percent would remain in climate zones and structures where heat pumps and electric resistance storage heating are inapplicable or uneconomic, and for supplemental heat in air source heat pump systems; and
- Electricity for space heating will transition to a mix of 90 percent non-carbon energy and 10 percent power from efficient natural gas generation to cover the hours when wind, solar, geothermal, biomass, nuclear, and other non-fossil resources are unavailable. This assumes a major growth in renewable energy and an ability to control the charging of many electric loads into hours when non-carbon energy is available.

First, we calculate the current energy consumption of gas, propane, and electric space heaters and the emissions being produced. We juxtapose that against achievement of the assumed targets, with fossil fuel space heating largely retired by 2050. This is an estimate of what could happen, with the necessary codes, standards, pricing, and incentives. It is not an assessment of what will happen without such changes.

Using US Energy Information Administration data on current electricity, natural gas, and propane consumption for residential space heating, and current average efficiencies for fossil-fueled heating systems, we assume that 50 percent of current electric resistance heat can be converted to HP heat and the balance to electric resistance storage heating. We then convert 80 percent of the fossil-fueled space heaters to electric heat pump systems, assuming an average COP of 2.7. We then assume these heating systems would be fueled with 90 percent non-carbon energy and 10 percent power from efficient natural gas generation.

The results are dramatic. Emissions for space heating drop from about 270 million metric tons a year to about 57 million metric tons a year over this period, a decline of about 80 percent. About half the remaining emissions are attributable to natural gas use, with the balance split among propane, heating oil, and electricity generation.

We have no research yet showing that our assumed level of conversion to each technology is economically optimal, or the ability to concentrate 90 percent of the electricity use for space heating into hours when non-carbon resources are the marginal electric generating resources. Technological improvement of heat pumps will be important to the feasibility and cost-effectiveness of this set of strategies. Regulatory engagement on the development of rate design changes and incentive programs will be essential. But we believe this scenario is well within the range of plausibility and that these are available, feasible, and generally cost-effective options to reduce both criteria pollutants and carbon emissions.

## Interactions Among the Three Conditions

To meet our definition of beneficial electrification, only one of the three conditions needs to be met while not adversely affecting the other two. However, consumer costs, effectiveness of grid management tools, and environmental effects will vary depending on the appliances chosen and the circumstances in which they are deployed. Those circumstances and the interactions among the three conditions mean policymakers might need to consider additional interventions or implementation tactics, if they wish to emphasize certain policy objectives or outcomes (e.g., prioritization of emissions reductions). In this section, we consider potential interactions among the three BE conditions.

### Consumer Benefits

In general, conversions to electricity from propane and heating oil at the time consumers need to replace appliances will likely save them money. In the case of conversions where consumers want or need air conditioning, a heat pump is probably a better choice than a discrete air conditioner and can be expected to have a positive effect on the overall economic analysis. But there are plenty of circumstances where complete conversion to a heat pump may not save consumers money with today's technology. For example, in especially cold climates, the analysis should consider the potential need for supplemental heat when the weather is especially cold.[70] Furthermore, converting from propane and heating oil *before* consumers need new appliances may not bring cost savings. Currently, the electric option may be desirable for new construction in mild climates and for multi-family housing. But economical retrofits of existing natural gas heating are a relevant prospect for BE only if the purchase of a new air conditioner is being considered,[71] thereby lowering the incremental cost of conversion.

A challenge for policymakers is that, even in places where the consumer economics are not yet advantageous, emissions benefits could be captured today. Where the power grid is no dirtier than half coal and half gas, conversions from heating oil to electric heat pumps will reduce emissions. Where the power grid is no more carbon-intensive than a system that is entirely natural gas, conversions from natural gas heat to electric heat pumps will reduce emissions. And an analysis of emissions efficiency should take into consideration the fact that, over the lifetime of electric technologies, grids are likely to continue becoming less carbon-intensive.

A challenge for policymakers is that, even in places where the consumer economics are not yet advantageous, emissions benefits could be captured today.

In places where emissions reductions are a policy priority but electrification of space heating is not yet cost-effective for consumers, an intervention may be needed to help reduce the incremental upfront cost of heat pumps. One example of an intervention is a rebate to consumers for purchasing a heat

#### Longer-Term Questions About Energy System Need

In addition to questions associated with enabling electric end uses for heating under various circumstances, decision-makers need to consider consumer benefit questions related to longer-term energy system investments. For example:

- At what point will it no longer be cost-effective to extend natural gas distribution lines to new development where the costs of both the additional infrastructure and new appliances must be incurred?
- What are the appropriate steps when existing gas distribution pipelines need replacement?
- What are the most suitable steps to take with low-income natural gas and delivered fuel consumers and programs, and at what point might they be served at lower cost with electrical end uses?

70 This need could be met by retaining an existing heating source to use periodically, or by acquiring an additional heat source.

71 Billimoria et al., 2018.

pump. In that case, the appropriate level of rebate should be informed by a comparison of the cost of otherwise avoiding the same amount of emissions.[72] As heat pumps become cheaper or more effective or the price of gas increases, this potential need for intervention will become less pronounced.

Capturing grid management benefits while reducing emissions and customer costs may require planning and management by policymakers and grid operators.

This paper has not analyzed the consumer economics that would be required to make resistance storage heating systems attractive, or how that calculation would be affected by TOU rates or utility programs that compensate users for ancillary services. We should note that, in cases where the installed cost of such a system is comparable to that for a fossil-fueled heating system, the NREL analysis suggests that the retail price of power would need to be 30 to 50 percent below the national average residential rate. This is a rate differential that is consistent with best practices for time-varying electricity pricing and implies the potential for consumer benefit.[73] If such time-varying pricing were to match the low-cost hours with the low-emissions hours of the day, these rate structures could also make electric resistance storage heating systems an emissions reduction option.

## Grid Management

Resistance storage heating has the potential to shift peak load and serve as a source of ancillary services like frequency regulation and voltage support due to its ability to quickly turn on and off. Heat pumps, though not well-suited to fast response services, could be used to preheat or precool spaces when connected to smart thermostats, thereby helping avoid system peaks. Heat pumps with supplemental heating may offer the ability to use electricity when the grid has readily available power and switch to other fuels for the limited number of hours when the grid is stressed. The potential grid management benefits vary by geographic region and the type of technologies being used. Capturing these benefits while reducing emissions and customer costs may not happen automatically and may require planning and management by policymakers and grid operators.

Wind power in many regions is surplus during overnight hours. The adoption of managed resistance storage heating and resistance supplemental heating for air source heat pumps could take advantage of this surplus. As variable renewable energy generation expands and becomes cheaper (e.g., wind resources at prices as low as 2 cents per kWh[74]), there will be opportunities to manage loads to connect these resources and supplant fossil fuel space heating. Doing so will require connecting heating loads to smart thermostats and aggregating those loads into valuable system resources. This will enable electric heating technologies to help reduce system peaks and the curtailment of variable resources and turn this grid management benefit into an emissions- and cost-reduction strategy as well.

We do not foresee the same opportunity for connecting space heating load with solar electricity because of the times when solar power is available and abundant. Solar is summer-peaking and—despite being well-matched to air conditioning needs—does not align well with space heating requirements.[75]

72 Air source heat pumps that are Energy Star-certified currently qualify for a $300 federal tax credit.

73 Jadun et al., 2017. See also Faruqui, A., Hledik, R., and Palmer, J. (2012). *Time-varying and dynamic rate design*, p. 29. Regulatory Assistance Project and The Brattle Group. Retrieved from https://www.raponline.org/wp-content/uploads/2016/05/rap-faruquihledikpalmer-timevaryingdynamicratedesign-2012-jul-23.pdf; and Principle 6, in particular Figure 17 and the accompanying discussion of rate design differentials, in Farnsworth et al., 2018.

74 Walton, R. (2018, January 8). Xcel solicitation returns "incredible" renewable energy, storage bids. *Utility Dive*. Retrieved from https://www.utilitydive.com/news/xcel-solicitation-returns-incredible-renewable-energy-storage-bids/514287/

75 See also the discussion of ice and chilled water storage for commercial air conditioning applications in Lazar, J. (2016). *Teaching the "duck" to fly (2nd edition)*. Montpelier, VT: Regulatory Assistance Project. Retrieved from http://www.raponline.org/document/download/id/7956. The limited solar available in the space heating season will likely be devoted to serving other electric loads.

## Environmental Effects

As we have discussed, the environmental benefit of electric space heating will become more significant as the carbon intensity of the power sector decreases and cleaner resources are available to meet more load more often. In many cases, such as retrofits, energy-efficient electric technologies like heat pumps are already preferable on an emissions efficiency basis but may not yet be cost-effective for consumers. In addition, even if the emissions of the grid are low enough to create an environmental benefit, new electrification load needs to be managed efficiently to keep the costs of operating the grid down. These issues can be expected to become less pronounced as the capabilities of electric heating and storage technologies improve and costs decline.

Finally, states that adopt climate policies with associated greenhouse gas reduction goals can expect to see opportunities to cut emissions through greater efficiency in the building sector and space heating.[76] Explicit climate policies will further modify the interactions described here, creating more favorable consumer economics and leading to reduced emissions.

76 California has set targets for the state to double the energy efficiency in the residential, commercial, and industrial sectors while increasing the share of electricity from renewable sources to 50 percent by 2030. See California State Assembly, Chapter 547 [SB 350], 2015. Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB350. SB 758 also requires California's energy and utility commissions to develop a comprehensive program to achieve greater energy efficiency in the state's existing buildings. See California Energy Commission, Docket No. 15-IEPR-05, Existing Buildings Energy Efficiency Action Plan, September 4, 2015, and Docket No. 16-EBP-01, Existing Buildings Energy Efficiency Plan Update December 2016. Retrieved from http://www.energy.ca.gov/ab758/. The plan provides a ten-year roadmap to activate market forces and transform California's existing residential, commercial, and public building stock into high-performing and energy-efficient buildings.

# Putting Beneficial Electrification Into Action for Space Heating

Thus far, this paper has sought to analyze and enumerate the circumstances in which electrification of space heating can be beneficial. We have shown that consumers can save money, the power grid can be managed to reduce costs and integrate more renewable energy, and policy goals like emissions reductions can be achieved. We now turn to a discussion of some of the opportunities for and barriers to beneficial electrification of space heating within policies, programs, and regulations. We identify some ideas for how policymakers might go about putting BE into action for space heating. These ideas fall into four categories: standards for new buildings, state energy policy, rate design, and incentives.

It is important for policymakers, regulators, and utilities to address how new policy initiatives and legacy frameworks may or may not complement one another and to identify existing barriers to economically efficient utility and private investment.

Before turning to these ideas, it is worth reiterating a few of the foundational policy ideas from our companion paper on BE principles. In particular it is useful to develop and prioritize state policy goals (e.g., encouraging innovation and job creation, saving consumers money) before making decisions about specific BE implementation efforts. In addition, as we discuss in several places below, it is important for policymakers, regulators, and utilities to address how new policy initiatives and legacy frameworks may or may not complement one another and to identify existing barriers to economically efficient utility and private investment.

## Standards for New Buildings

Changing our approaches to space heating will be a challenging and long-term task. The transition can be much quicker, however, in new construction. The capital costs of more efficient alternatives are not dramatically higher than those of conventional electric or fossil-fueled heating.

New construction is an ideal opportunity to deploy new technology, because the entire cost of any heating (and cooling) system, as well as a water heating system, is an incremental cost. Installation costs of air source heat pump systems are competitive with conventional heating plus air conditioning in many regions,[77] and data from NREL and RMI indicate these systems will save consumers money even without consideration of emissions.[78] Therefore, we suggest that building codes for new construction in most climate zones require high-efficiency electric space heating and cooling systems. Even before that, however, building codes could begin to mandate that all new residential structures be "all-electric ready." That means the electrical panel and wiring throughout the house are sized to safely handle all-electric heating, cooling, appliances, and electric vehicles.

Building codes should also require a high degree of thermal efficiency for the structures themselves. This makes heat pumps feasible for customers in colder climates and allows the cost of gas hookups or oil tank installation—and, in the case of new development, expanded gas distribution infrastructure—to be avoided. At a minimum, building energy codes should be reviewed to ensure they do not impose barriers to electrification, for example by forbidding resistance thermal storage space heating.[79]

For single-family construction, the option of ground source heat pumps is realistic and may be economic, particularly if the system is configured to provide space heating, space cooling, and water heating. The option of ground source HPs to provide shared thermal energy service to multi-family units is emerging and, where cost-effective, could be included in energy codes.

New manufactured homes are also good candidates for air source heat pumps, including cold climate models.

77 Nadel, 2018, Table A7.

78 Even if a grid is presently 100 percent coal, the emissions efficiency over the lives of these investments has the potential to improve if the generation sector becomes less carbon-intensive.

79 Deason et al., 2018, p. 43.

## State Energy Policy

As with other energy policies, states can expect energy affordability to affect the ability of all customer classes to share the benefits of electric space heating equitably.

State policies can help or hinder BE. Energy efficiency standards and incentives may be set up to require energy use reductions for electricity and other fuels separately, or other fuels may be excluded or exempted from energy efficiency policies. Standards and programs structured this way may hinder electrification because they discourage increases in electricity use even if overall energy use declines. States can address this by including an electrification component, or carve-out, in their energy efficiency policies, or by altering the overarching goals of the policy to reflect reducing primary energy use or greenhouse gas emissions rather than electricity sales. For example, New York state recently adopted a statewide cumulative annual site energy savings target that is delineated in Btu; this will incentivize the most cost-effective efficiency measures across all fuels.[80]

States might also consider using emissions efficiency as a metric when evaluating costs and benefits of programs and policies.[81]

As with installation of energy efficiency measures, upfront costs could present a barrier to replacing existing heating technology with electric heating.[82] States that wish to encourage the development of electrification programs can determine how best to mitigate these costs. Efficiency programs around the country have developed various strategies to address this challenge, many of which could be considered in the context of space heating as well. These include on-bill financing, property tax financing (also known as property assessed clean energy financing, or PACE), performance contracting, and energy efficiency mortgages.[83]

To encourage beneficial electrification of space heating, states can also consider including a carve-out in their renewable portfolio standard (RPS). Utilities could meet part of their obligation by pursuing programs or activities that meet certain criteria for BE. For example, Vermont includes cold climate heat pump installation as one way to meet utility targets for its RPS.[84] A second issue associated with RPS requirements is worth noting. Because most states articulate RPS goals as a percentage of utility load, increased load due to electrification will increase the actual amounts of renewables necessary to comply, unless policymakers intervene.

As with other energy policies, states can expect energy affordability to affect the ability of all customer classes to share the benefits of electric space heating equitably. Low-income households typically have older and less efficient heating and cooling systems and less thermally efficient homes. Without policy intervention, they will likely have less ability than moderate- and higher-income customers to participate in electrification programs. These households often lack the flexibility and resources to consider improving the efficiency of their space heating and cooling options. To ensure that space heating and cooling programs are available to all energy consumers, states will have to recognize these circumstances and determine how best to address the gap in affordability that low-income energy users experience.

## Rate Design

Reforming electric rate design is critical for effective implementation of BE. For electric resistance storage heating to be beneficial, for example, time-varying pricing is needed. Appropriate rate designs can motivate customers to move the

80 New York State Energy Research and Development Authority and Department of Public Service. (2018). *New efficiency: New York*. Retrieved from https://www.nyserda.ny.gov/-/media/Files/Publications/New-Efficiency-New-York.pdf

81 See discussion of emissions efficiency on Pages 31-33 of this paper.

82 See American Council for an Energy-Efficient Economy. *Energy efficiency financing* [Webpage]. Retrieved from http://aceee.org/topics/energy-efficiency-financing

83 See Hayes, S., Nadel, S., Granda, C., and Hottel, K. (2011, September). *What have we learned from energy efficiency financing programs?* (Report No. U115). Washington, DC: American Council for an Energy-Efficient Economy. Retrieved from https://aceee.org/sites/default/files/publications/researchreports/u115.pdf

84 Vermont Department of Public Service. (2016). *Comprehensive energy plan 2016*. Retrieved from https://outside.vermont.gov/sov/webservices/Shared%20Documents/2016CEP_Final.pdf

charging of a storage heating system to off-peak times, which helps with grid management, and to times when it can be most emissions-efficient.

Rate designs that reflect the long-run marginal cost to produce electricity—that is, the cost to produce, transmit, and deliver the next unit of power over the long term—will tend to produce outcomes in the public interest over the long run. TOU pricing, which includes these long-run costs in time-varying energy charges, will tend to encourage customers to adjust their behavior and move their usage to times of day when it is cheaper for the utility to serve. Further, this type of pricing provides an economic incentive to commercialize and adopt technologies that enable demand flexibility, such as thermal storage for all space heating use (thermal mass within the building and electric resistance storage heating) or critical peak use (air source heat pumps).[85]

**Table 9. Illustrative Smart Rate Design**

| Rate element | Based on the cost of: | Illustrative rate |
|---|---|---|
| **Customer charge** | Service drop, billing, and collection only | $4.00/month |
| **Transformer charge** | Final line transformer | $1.00/kilovolt-ampere/month |
| **Off-peak energy** | Baseload resources plus transmission and distribution | $0.07/kWh |
| **Mid-peak energy** | Baseload plus intermediate resources plus T&D | $0.09/kWh |
| **On-peak energy** | Baseload, intermediate, and peaking resources plus T&D | $0.14/kWh |
| **Critical peak energy** | Demand response resources | $0.74/kWh |

The illustrative rate design in Table 9 provides a strong incentive for customers to shift their use away from the higher-cost critical peak, on-peak, and mid-peak times and to take advantage of low-cost off-peak electricity.[86] Instead of paying 18 cents per kWh at peak, for instance, the off-peak rate is 8 cents—less than half. In the RMI scenario analysis discussed earlier in this paper, managing heat pump use for peak load shaving and load shifting (e.g., preheating buildings) to optimize the cost savings of time-varying rates resulted in a lifetime value to individual customers of $2,000 to $4,000.[87]

In addition, where utility peak demands are such that serving space heating load in winter strains the system, a seasonal and time-varying rate will encourage the use of supplemental heat where important for power cost and system stability. With this type of rate design, heat pump heating with sufficient thermal mass storage could carry customers through critical peak periods and be cost-effective in most locations. In addition, the lower off-peak rate will help make electric resistance storage heating cost-competitive with fossil-fueled alternatives.

Of course, not all utility customers will have the ability to shift usage to benefit from off-peak pricing, and it is important to acknowledge that with any change in the structure of rates, not all customers will be affected in the same way. It is appropriate for regulators to examine the likely effects of a shift toward TOU pricing and consider whether certain types of customers (e.g., critical loads or elderly residents) should be treated separately.

## Incentives

Incentive programs are widely used around the country to encourage consumers to adopt various end-use technologies, and the structure of these programs may enable or obstruct BE. For states that wish to accelerate electrification, incentives may be an important driver during the early stages while costs are declining but have not yet reached parity with non-electric technologies. Programs can be run by utilities (typically using rebates), third-party energy efficiency providers, or governments (through rebates, loans, or tax incentives).

Electric utilities have provided incentives to spur innovative technology deployment for more than 30 years.

85 Ellerbrok, C. (2014). Potentials of demand side management using heat pumps with building mass as a thermal storage. *Energy Procedia, 46,* 214-219. Retrieved from https://ac.els-cdn.com/S187661021400191X/1-s2.0-S187661021400191X-main.pdf?_tid=0866a42f-74c1-4663-9641-8a6bfdf02418&acdnat=1531757467_b741f22bc53e7eb1035300429a6a8902

86 See Lazar, J., and Gonzalez, W. (2015). *Smart rate design for a smart future.* Montpelier, VT: Regulatory Assistance Project. Retrieved from https://www.raponline.org/knowledge-center/smart-rate-design-for-a-smart-future

87 These results are 15-year discounted values, and savings of this magnitude require TOU rates with significant cost differentials (e.g., a 3-1 ratio of peak to off-peak pricing). For more see Billimoria et al., 2018.

The Golden Carrot program brought huge improvements in refrigerator efficiency.[88] Window replacement incentives helped move the glazing industry to produce much better products that save energy and improve comfort.[89] Millions of smart thermostats are being deployed with utility financial support.[90] These programs tend to "move the market" over time, so that continued incentives are not required. Utility incentives for purchasing heat pumps are widespread.[91] Some utilities are experimenting with incentives for builders, which can be an effective way to promote electrification in new construction.[92]

For existing buildings, incentive programs could also consider ways to encourage early replacement of equipment based on age and efficiency level to reduce the number of replacements that occur when an existing furnace or heating and air conditioning system fails. Waiting until the existing system needs to be replaced—often during the season in which it is needed most—increases the risk of emergency replacement, which gives customers and contractors little time or opportunity to consider whether a different technology would be better.

Most incentive programs are not directed at electrifying space heating through the replacement of non-electric units. Incentives tend to be either agnostic to the fuel being replaced or exclusively directed at replacing an electric heating unit with a more efficient heat pump.[93] For example, Puget Sound Energy offers incentives of $500 to $800 for high-efficiency ductless heat pumps and up to $1,500 for ground source (geothermal) heat pump conversions and the replacement of electric forced-air furnaces with air source heat pumps.[94] These types of conversions are important and useful because they represent real opportunities to save end-use energy and help build the market infrastructure to deliver air source heat pumps. However, utility and third-party energy efficiency incentive programs that do not allow for or include switching from fossil fuels to cleaner electricity can act as a barrier to achieving the benefits that electrification can provide. States may want to update such programs and policies to take an emissions reduction or primary energy savings approach.

We suggest states take a holistic approach to developing or updating programs to reward installation or replacement of heating equipment. For example, incentives for replacing fossil-fueled equipment that only allow for replacement with the same fuel could neutralize any cost savings consumers might see from switching to electric and thus prevent achievement of emissions reductions and other benefits. In light of the opportunities that BE presents, incentive programs across fuel types should be evaluated together to ensure they are not operating at cross purposes.

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88 Eckert, J., (1995). *The Super Efficiency Refrigerator Program: Case study of a golden carrot program* (NREL/TP-461-7281). Golden, CO: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/legosti/old/7281.pdf

89 Jones, J. (2015, July 21). Efficient window technologies: A history. *EcoBuilding Pulse*. Retrieved from http://www.ecobuildingpulse.com/products/efficient-window-technologies-a-history_s

90 Wilczynski, E. (2017, March 9). Turning up the heat: The rapid surge in smart thermostat programs [Blog post]. Retrieved from https://www.esource.com/Blog/ESource/ES-Blog-3-6-17-Smart-Thermostats

91 North Carolina Clean Energy Technology Center. *Database of state incentives for renewables and efficiency* [Webpage]. Retrieved from http://www.dsireusa.org

92 Deason et al., 2018, citing Mullen-Trento, S., Narayanamurthy, R., Johnson, B., and Zhao, P. (2016, May). *SMUD All-Electric Homes Deep Dive*. Presented at the CA Building Decarbonization Research + Resources Synthesis.

93 In addition to the state- and utility-level considerations discussed here, it is worth noting that current national energy efficiency programs (e.g., Energy Star) categorize equipment based on their fuel, which means it may be difficult to compare the efficiency of a heat pump to a fossil-fueled unit. Indeed, a non-Energy Star heat pump may still be more efficient on a Btu basis than a fossil-fueled unit that does have an Energy Star rating. States and utilities should be aware of this fact when designing their own programs.

94 Puget Sound Energy. *Heating rebates and offers* [Webpage]. Retrieved from https://www.pse.com/rebates/heating

# Conclusion

This paper seeks to stimulate discussion and more detailed thinking about how electrification of space heating can be beneficial. We discuss a number of technology options for a variety of climates and housing types and conclude that electric space heating can satisfy all three of RAP's conditions for beneficial electrification. Some circumstances are more likely to do so in the near term, such as new construction, the replacement of oil or propane heating, or installation in well-insulated buildings or in mild climates where heating needs are lower and air conditioning is desired. As technological improvements continue, particularly for heat pumps and heat storage, more cost-effective electrification opportunities will become available in what are currently more challenging situations, such as very cold climates.

Regulatory and policy engagement will be essential to realize the potential benefits. We recommend examining building codes, state energy efficiency programs, and financial incentives from states and utilities to determine if they pose barriers to BE and whether these policies and programs can be redesigned to encourage the deployment of cost-effective electric technologies. Reviewing electric rate designs is also an important step to ensure that customers can realize the benefits of providing grid services (e.g., load shifting and peak load shaving) and have an incentive to avoid the most costly or dirtiest times of the day.

In conclusion, feasible and generally cost-effective electric space heating options are available to reduce customer costs, enhance grid flexibility, and dramatically cut carbon pollution from the heating sector today. We can expect more options in future years.

# Appendix A: Measuring and Characterizing Heat Pump Performance

To ensure the adoption of appropriate heating technologies, it is important to be able to rely on performance metrics. A brief description of applicable performance metrics and standards follows.[95]

Air source heat pump manufacturers test and rate equipment per the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 210/240: Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment. US Department of Energy minimum efficiency standards found at 10 C.F.R. §430.23(m) also reflect these AHRI procedures.

The AHRI and federal standards rely on two metrics for air source heat pumps: a heating seasonal performance factor (HSPF) and a seasonal energy efficiency ratio (SEER), each of which is briefly described below.

**HSPF**—The HSPF is the total space heating required during the heating season, expressed in British thermal units (Btu), divided by the total electrical energy the heat pump system used during the same season, expressed in watt-hours (Whs).

$$\frac{\text{Total space heating required during the space heating season (Btu)}}{\text{Total electrical energy consumed by the heat pump system during the same season (Whs)}}$$

To determine heating capacity and HSPF of air source heat pumps, systems are tested in four outdoor temperatures: 17, 35, 47, and 62 degrees.[96]

**SEER**—SEER represents the total heat removed from the conditioned space during the annual cooling season, divided by the total electrical energy the heat pump used during the same season.

$$\frac{\text{Total heat removed from the conditioned space during the annual cooling season (Btu)}}{\text{Total electrical energy consumed by the heat pump system during the same season (Whs)}}$$

Establishing cooling capacity and SEER of air source heat pumps requires manufacturers to test performance at four outdoor temperatures: 67, 82, 87, and 95 degrees.

There are several other common performance metrics for air source heat pumps, including an energy efficiency ratio (EER) and coefficient of performance (COP).

**EER**—A ratio of the cooling capacity (Btu/hour) to the total power (watts), expressed in Btu/Whs.[97]

$$\frac{\text{Total heat removed from the conditioned space during } 95^{o} \text{ test (Btu)}}{\text{Total electrical energy consumed by the heat pump system during } 95^{o} \text{ test (Whs)}}$$

95 The following descriptions are largely adopted from Northeast Energy Efficiency Partnerships, 2017. See the discussion there of "Performance, Metrics, Ratings, and Standards."

96 These procedures are outdoor dry bulb tests. In other words, what is called a dry bulb thermometer measures the actual temperature of a location and does not take into account additional cooling that can result from evaporation. On the other hand, "wet bulb" measurement takes that cooling effect into account. The level of evaporation that occurs depends on relative humidity—the amount of water vapor in the air.

97 Air-Conditioning, Heating, and Refrigeration Institute. (2017). *Performance rating of unitary air-conditioning and air-source heat pump equipment* (AHRI Standard 210/240-2017), Section 3.1.16. Retrieved from http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_210-240_2017.pdf

**COP**—For heating, this is the amount of thermal energy delivered (Btu/hour or watts) divided by the electric power consumption (watts). The COP can be examined at any time and any temperature and can vary with temperature.

$$\frac{\text{Total heating capacity delivered (watts)}}{\text{Total electric power consumption (watts)}}$$

The Department of Energy's Appliance and Equipment Standards Program contains standards that set minimum system efficiencies for residential air source heat pumps.[98] The US Environmental Protection Agency manages the voluntary Energy Star program for appliances, including air source heat pumps, which differentiates high-efficiency products from minimally compliant products.[99]

Despite the existence of performance metrics for air source heat pumps in general, there is less clarity with regard to standards for heat pumps designed to operate in colder climates. In its 2017 study of cold climate heat pumps in Vermont, The Cadmus Group noted that a "standard set of criteria to differentiate cold climate from standard mini-split heat pumps does not exist."[100] Still, standards have been established for heat pumps operating at outdoor temperatures ranging from 17 to 47 degrees. Furthermore, manufacturers publish performance data for colder climate heat pumps,[101] and some states maintain lists of cold climate heat pumps that qualify for program incentives.[102]

Recognizing this lack of clarity, Northeast Energy Efficiency Partnerships finalized its Cold Climate Air-Source Heat Pump Specification (Version 2.0) in 2017.[103] Its purpose is to set out performance and reporting requirements for identifying air source heat pumps that are best suited to heat efficiently in cold climates.

98 See 10 C.F.R. §430.32(c)(3).

99 Energy Star. *Air-source heat pumps* [Webpage]. Retrieved from https://www.energystar.gov/products/heating_cooling/heat_pumps_air_source

100 Walczyk, J. (2017, November). *Evaluation of cold climate heat pumps in Vermont.* The Cadmus Group. Retrieved from http://publicservice.vermont.gov/sites/dps/files/documents/Energy_Efficiency/Reports/Evaluation%20of%20Cold%20Climate%20Heat%20Pumps%20in%20Vermont.pdf. In the study, conducted for the Vermont Public Service Department, Cadmus noted that, although it had done metering studies of mini-split heat pumps in Massachusetts, Illinois, New York City, and the Northwest, none of the studies observed usage and performance at temperatures as low as temperatures typically observed in Vermont.

101 Test criteria are discussed in Air-Conditioning, Heating, and Refrigeration Institute, 2017.

102 Efficiency Vermont. *Cold climate heat pumps: Qualifying products.* Retrieved from https://www.efficiencyvermont.com/Media/Default/docs/rebates/qpls/efficiency-vermont-cold-climate-heat-pumps-qualifying-products.pdf

103 Northeast Energy Efficiency Partnerships. (2017, January 1). *Cold climate air-source heat pump specification (version 2.0).* Retrieved from https://neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump

# Appendix B: Comparing Fuel Costs of Technologies

The American Council for an Energy-Efficient Economy (ACEEE) analyzed the annual energy use of oil furnaces and air source heat pumps in different states and climates. Using these results and data on fuel costs from the US Energy Information Administration, we can compare the estimated annual fuel costs of the two technologies in different states. The cost calculations for eight states appear in Table 10.

Our assumptions about energy use for oil furnaces and heat pumps come from ACEEE, which modeled a standard oil furnace and a heat pump with a COP of 3.02. We converted million Btu of oil usage to gallons using 138,000 Btu per gallon.[104] Heating oil prices are averages for winter 2017-2018 for the New England, central Atlantic, lower Atlantic, and Midwestern states.[105] Residential retail prices are 2017 averages by state.[106]

**Table 10. Annual Fuel Cost Savings by Switching to Heat Pump From Oil Furnace for Selected States**

| | Oil furnace | | | Electric heat pump | | | |
|---|---|---|---|---|---|---|---|
| State | Gallons | Cost/gallon | Cost/year | kWh | Cost/kWh | Cost/year | Savings (or loss) |
| **Georgia** | 430 | $2.70 | $1,160 | 5,039 | $0.12 | $605 | $556 |
| **Massachusetts** | 591 | $2.90 | $1,713 | 9,476 | $0.19 | $1,800 | ($88) |
| **Missouri** | 535 | $2.60 | $1,390 | 8,645 | $0.11 | $951 | $439 |
| **New Jersey** | 591 | $3.00 | $1,774 | 8,423 | $0.16 | $1,348 | $426 |
| **New York** | 463 | $3.00 | $1,389 | 7,031 | $0.18 | $1,266 | $124 |
| **Pennsylvania** | 495 | $3.00 | $1,485 | 7,164 | $0.14 | $1,003 | $482 |
| **Virginia** | 407 | $2.70 | $1,100 | 5,400 | $0.12 | $648 | $452 |
| **Wisconsin** | 530 | $2.60 | $1,379 | 10,142 | $0.15 | $1,521 | ($142) |

Amounts used in calculations are rounded.

104 See Nadel, 2018.

105 US Energy Information Administration. *Weekly heating oil and propane prices (October-March).*

106 US Energy Information Administration. *Electricity data browser.*

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