# Equitable Electrification: Making Heat Pumps Work for Everyone

***Paul W. Francisco, Colorado State University***

**ABSTRACT**

Concerns about climate change have resulted in a focus on limiting the use of fossil fuels. In residences, that means a shift away from heating systems, water heaters, and cooking appliances that use natural gas, propane, and oil, to electric appliances. Heat pumps offer the efficiency benefits of the vapor compression cycle and so are touted as a way to achieve "beneficial electrification", meaning that they should both reduce emissions and life cycle costs to consumers. This paper focuses on "equitable" electrification, which we define as also reducing short-term operating costs for consumers. This is especially vital for low-income households, which often cannot afford short-term cost increases even if the life cycle benefits are favorable. We find that heat pumps often do meet this definition of equitable electrification when compared with propane or fuel oil but fall short in most locations when compared to natural gas if no other measures to reduce energy costs are taken. The challenge increases when there are deficiencies. We look at two types of deficiencies: control strategies that reduce the use of the compressor to avoid comfort complaints, and duct leakage and insulation defects that reduce the overall efficiency and cause backup systems to be needed more. Our results point to the need to develop solutions to bridge the operational cost gap so that both climate change and equity can be addressed.

## Introduction

Current concerns about climate change have resulted in a focus on limiting, or eliminating, the use of fossil fuels. In the residential environment, that means a shift away from heating systems, water heaters, and cooking appliances that use natural gas, propane, and oil. In the absence of these fossil fuels, heating needs to be powered by electricity. Electric furnaces and other electric resistance heating devices are very expensive to operate; however, heat pumps get the efficiency benefits of the refrigeration cycle and so are touted as a way to achieve "beneficial electrification", which means that they should reduce both emissions and life-cycle energy costs to consumers.

Heat pumps are essentially air conditioners that can run backwards. There are several types of heat pumps, including ducted split systems which are the most common type, ductless mini-splits which have become common especially in buildings that do not currently have forced-air heating systems, as well as a few others. One can think of heat pumps as moving heat from the outdoor air to the indoor air. At colder outdoor temperatures, a building needs more heat to maintain its temperature. However, at these colder temperatures there is less heat in the outdoor air for the heat pump to extract. This leads to a heat pump "balance point", which is the temperature at which the heat pump can no longer meet the demand of the home based on just the refrigeration cycle. At outdoor temperatures below this balance point, the additional heat required is often provided by electric resistance elements which have much lower efficiency, and this is the assumption made by AHRI Standard 210/240 (AHRI 2023). The balance point in any home will depend on the heat losses of the home and the heat pump that was installed in the home, including its capacity and efficiency profile across temperatures. The additional heat required at low temperatures can be supplied using fossil fuels, and this is common in some locations; however, this works against full electrification.

A major question about electrification using heat pumps is whether they truly deliver reduced costs to users. "Beneficial electrification" usually focuses on life-cycle costs, which also includes assumptions of escalation of energy costs, as well as the actual amount of energy used. Here, we focus here on "equitable electrification", which we define as also reducing short-term costs. This is especially critical for low-income households who do not have the discretionary resources to be able to absorb losses now in exchange for potential benefits in the future.

Determining whether short-term costs are reduced depends on more than the efficiency of the heating system. It also depends greatly on the consumer's costs for delivered energy and the actual installed performance of the system. Propane and fuel oil tend to be expensive fuels on a per unit energy basis; however, natural gas tends to be a lot cheaper, and so there are questions about whether the greater cost for electricity is offset by the greater efficiency of a heat pump. Multiple studies, both in the peer-reviewed literature and in reports or white papers, have explored this question and have generally found that it is often cheaper to heat a home with natural gas than with electric heat pumps. Billimoria et al. (2018) recommended prioritizing electrification in homes using propane or heating oil. A report by Rewiring America (Zurofsky et al. 2021) found that electric heat pumps are cheaper to operate than propane or fuel oil but very slightly more expensive than natural gas, though the authors state that a heat pump "is even cheaper than using natural gas in many localities, depending on prices and climate". Padovani et al. (2021) also found that electrification was economically viable compared to propane. Wilson et al. (2024) found that 62% of homes would have bill savings by installing the minimum-efficiency Energy Star-compliant heat pump but did not distinguish between heating fuels in this overall summary number. Given the fraction of homes that use propane or oil, and their costs relative to natural gas, the majority of the homes that would see savings are likely to use propane, oil, or electric resistance.

Doak et al. (2022) evaluated the economics of heat pumps in the Midwest US, with a focus on the state of Iowa. They found that heat pumps generally are unable to provide first-year bill savings relative to natural gas, and that the required heat pump efficiency to make them cost-neutral is greater than the maximum efficiency using current technologies. Interestingly, they show that electricity costs have tended to increase while natural gas costs have tended to decrease from 2007-2019, yet the Energy Information Agency (2021a) projected that the opposite trend will occur from 2020-2050. It is this assumption that natural gas costs will increase at a greater rate than electricity costs that is often behind projections of life-cycle cost savings for heat pumps.

Another issue is the difference between newer homes that have yet to have natural gas service brought to them vs. existing homes that already have their infrastructure built in. Deason et al. (2018) concluded that electrification will be more effective in new construction. Some jurisdictions, such as Berkeley, California and New York City, have implemented bans on natural gas hookups in new construction (Sierra Club 2021; City of New York 2021), though these have not always withstood legal challenges. Some jurisdictions now require that gas line connection costs be paid up front instead of paid back over time.

This paper explores the comparison between heat pumps and fossil fuel heating systems through three distinct analyses: 1) relative operating costs of the systems; 2) the relative per unit fuel prices required to make heat pumps financially advantageous; and 3) given current costs, what heat pump efficiency would be required to make the heat pump financially advantageous. Layered on top of these analyses are considerations about penalties such as control strategy problems and duct losses due to conduction and leakage outside of the thermal envelope, which are common in homes with ducts in attics or crawl spaces. The general approach provides what we believe to be a framework that is easily understood by contractors who are trusted by residents to recommend systems. We believe that this is the first publication that quantifies the significant impact of control and duct loss penalties.

## Methodology

This analysis focuses specifically on heating systems, i.e. we do not explore water heating or cooking. This is because heating systems are the dominant energy users during the heating season. Further, while minimum efficiencies for gas heating systems have increased substantially in the last 30 years, the most used technologies for gas water heaters and cooking appliances are still those with lower efficiencies. We assume that all installed equipment meets Energy Star requirements, and we base fuel costs on an investigation of published volumetric rates found online at different utilities. These rates include all identified charges that are on a volumetric basis.

### Assumptions

We assume that heat pumps are split systems, which have higher minimum efficiency requirements than unitary systems. We ignore differences in heat pump efficiency due to climate zone; heat pump ratings are based on Climate Zone IV, which can be viewed as similar to Indianapolis, Indiana. Based on an analysis by Francisco et al. (2004a), Climate Zone V (e.g. Minneapolis, Minnesota) could have realized efficiencies of about 10% lower, and Climate Zone II (e.g. Tampa, FL) could have realized efficiencies of up to 20% higher, depending on house heating load and other unit-dependent factors. While these differences do not always change the qualitative assessment of what system is less expensive to operate, it should be considered in locations that diverge from the Climate Zone IV assumptions.

We also assume that the baseline comparison is between appliances that meet U.S. DOE minimum Energy Star efficiency criteria (Energy Star 2021a). For natural gas furnaces, that is 95% efficiency in northern states, and 90% in southern states (defined by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE) as AL, AZ, AR, CA, DC, DE, FL, GA, HI, KY, LA, MD, MS, NV, NM, NC, OK, SC, TN, TX, and VA). For heat pumps, we use the newer HSPF2 (Heating Seasonal Performance Factor v2) from AHRI Standard 210/240 (AHRI 2023), which more closely matches actual performance than the older HSPF and was required starting in 2023. For cold climate heat pumps the minimum HSPF2 is 8.1 BTU/W (Energy Star 2022). For other heat pumps the minimum HSPF2 is 7.8 BTU/W. For simplicity, we assign the cold climate requirement to the northern states that have the minimum 95% efficiency for gas furnaces and the moderate and hot climate designation to the southern states. For reference, the highest efficiency gas furnaces have an efficiency of about 98% and the highest efficiency heat pumps have an HSPF2 of about 13.5.

The HSPF2 rating can be converted to seasonal efficiency by dividing the value by 3.413, which converts between BTU and W. This leads to minimum Energy Star efficiencies of 237%

for northern states and 229% for southern states. This can also be cast as a seasonal Coefficient of Performance (sCOP) which would be written as 2.37 and 2.29, respectively. Heat pumps can have efficiencies greater than 100% because they are using energy to move heat, rather than generating heat.

Initially, we also assume that the heat pump systems were sized and installed properly to take maximum advantage of the compressor, and that there are no efficiency penalties due to duct losses. We then explore the impact of problems with controls and duct losses.

**Fuel Cost Estimation**

Natural gas and electricity costs were obtained for each location via a web search of local utilities to determine their rate structures in January 2022. While prices have fluctuated substantially since then (both up and down), we continue to use this snapshot to avoid the unusual influence of the war in Ukraine that initially resulted in fuel prices rising dramatically. As shown in Figure 1, 2024 Henry Hub prices (EIA 2023) are substantially lower than the January 2022 prices that are indicated by the red arrow, yet we use January 2022 rates so as not to base the analysis on some of the lowest prices over the past quarter century.


Figure 1. Henry Hub Natural Gas Spot Price history, 1997-2024.

Utilities were selected for a range of locations from across the United States, including both northern and southern states. Table 1 identifies the utilities, and the residential retail fuel rates obtained from these sources in January, 2022. Gas costs are per therm[1]. Electricity costs are per kilowatt-hour (kWh). Costs include all volumetric-based charges that we identified in utility published documents, but do not include fixed costs such as monthly connection charges. These fixed charges would only be removed if all appliances using that fuel were removed.

Costs for propane and heating oil were taken from the U.S. Energy Information Administration, as national averages. This was done because costs for these fuels are substantially higher than for natural gas, and so location-specific data are less important for drawing overall conclusions. Concurrent data show costs of $2.70/gallon of propane and

[1] 1 therm = 100,000 BTU = 29.3 kWh.

$3.35/gallon of heating oil (EIA 2021b; EIA 2021c), with heating content of 91,452 BTU and 138,500 BTU, respectively (EIA 2021d). Because a gallon of each of propane and heating oil has different heating content, it can be useful to convert to equivalent bases when comparing costs. On a per therm basis, which is 100,000 BTU, propane and heating oil cost $2.95 and $2.42, respectively. These are both at least twice natural gas prices and so they will be much less competitive against electricity used for heat pumps.

Table 1. Costs for natural gas and electricity

| Location | Natural Gas data source | Natural Gas Cost, $/therm | Electric data source | Electricity Cost, $/kWh |
|---|---|---|---|---|
| Denver, CO | Xcel Energy | $0.81 | Xcel Energy | $0.117 |
| Tampa, FL | TECO People's | $1.40[2] | Tampa Electric | $0.136[3] |
| Atlanta, GA | Georgia Natural Gas | $0.76[4] | Georgia Power | $0.099[5] |
| Chicago, IL | Peoples Gas | $0.84 | Commonwealth Edison | $0.096 |
| Baltimore, MD | Baltimore Gas and Electric | $0.69 | Baltimore Gas and Electric | $0.083 |
| Minneapolis, MN | Xcel Energy | $0.83 | Xcel Energy | $0.060 |
| Albuquerque, NM | New Mexico Gas | $0.35[6] | PNM Resources | $0.101[7] |
| New York[8,9] | NYSERDA | $1.14 | NYSERDA | $0.183 |
| Vermont | Vermont Gas | $1.21 | Green Mountain Power | $0.177 |
| Seattle, WA | Puget Sound Energy | $1.00 | Puget Sound Energy | $0.105[10] |
| Charleston, WV | Mountaineer Gas | $0.99 | Appalachian Power[11] | $0.079 |

**Equating Energy Usage and Costs**

Given an outdoor temperature, homes need a certain amount of heat output, $q_{out}$, to maintain the indoor temperature regardless of the heating system being used. The energy input, $q_{in}$, required to provide that amount of heat can be shown as

$$q_{in} = \frac{q_{out}}{\eta_e} \tag{1}$$

[2] Cost per therm includes the distribution charge of $0.27, recovery factor of $0.096, and the purchased gas adjustment of $1.036

[3] Assumes approval of rate increase request. Without this approval, costs are $0.12/kWh.

[4] Based on the 12-month contract plan.

[5] Weighted average for the first 1000 kWh.

[6] New Mexico Gas was charging an additional fee through December, 2023 to recover costs related to the 2021 winter event. This additional cost is not reflected in the value in Table 1, which is the average of the December 2020-March 2021 costs.

[7] PNM Resources has different rates for the first 450 kWh and the second 450 kWh. The value in Table 1 is the average of the two tiers.

[8] Statewide averages.

[9] NYSERDA's data only went through September 2021 at the time of this analysis. Rates in New York historically increase in the summer. The values in Table 1 are the average for December 2020-March 2021.

[10] Weighted average for the first 1000 kWh.

[11] Appalachian Power has different rates for the first 500 kWh and the usage above 500 kWh. The value in Table 1 is the average of the two tiers.

where $\eta_e$ is the efficiency of the heating system. A heat pump, with efficiencies greater than 100%, requires less input energy to provide the required output, whereas gas furnaces, with efficiencies below 100%, require greater input energy to provide the required output.

To compare costs for a home needing $N$ therms of output, we need to equate energy usage by each technology. Since there are about 29.3 kWh/therm, this leads to:

$$C_{HP} = \frac{N_{kWh} * P_{elec}}{sCOP} = \frac{N_{therm} * 29.3 \frac{kWh}{therm} * P_{elec}}{sCOP} \tag{2a}$$

$$C_{NG} = \frac{N_{therm} * P_{gas}}{\eta_{gas}} \tag{2b}$$

where $C_{HP}$ is the cost for the heat pump to provide $N$ therms of heat
$P_{elec}$ is the cost per kilowatt-hour of electricity, \$
$C_{NG}$ is the cost for the natural gas furnace to provide $N$ therms of heat
$P_{gas}$ is the cost per therm of natural gas, \$
$\eta_{gas}$ is the efficiency of the gas furnace.

## Results

We evaluated the relative costs of gas furnaces vs. electric heat pumps in multiple ways:

- Ratio of per unit fuel costs required for natural gas furnaces to be more expensive to operate than electric heat pumps.
- Compare the costs in Table 1 to these ratio results.
- Given the costs shown in Table 1, what the minimum HSPF2 would be for the electric heat pump to be less expensive to the resident.

### Ratio of Fuel Costs

By setting Equations (2a) and (2b) to be equal and rearranging, the ratio of per-unit-fuel costs to be equal costs can be re-written as

$$\frac{P_{gas}}{P_{elec}} = \frac{29.3 * \eta_{gas}}{sCOP} \tag{3}$$

For northern climates, with $\eta_{gas}$ of 0.95 and $sCOP$ of 2.37, this leads to a cost ratio of 11.7. In other words, if the cost per therm of gas is less than 11.7 times the cost per kWh of electricity, the gas furnace will be less expensive to operate assuming the system choices are the minimum to meet Energy Star requirements. As an example, if electricity was \$0.10/kWh, gas could be up to \$1.17/therm before electricity would be cheaper. We note here that, if the existing furnace was a lower efficiency model – assumed to have an 80% efficiency – and a minimum Energy Star heat pump was being considered, the cost ratio would be 9.9.

For southern climates, with $\eta_{gas}$ of 0.90 and $sCOP$ of 2.29, this leads to a cost ratio of 11.5. In other words, if the cost per therm of gas is less than 11.5 times the cost per kWh of electricity, the gas furnace will be less expensive to operate assuming the system choices are the minimum to meet Energy Star requirements.

Table 2 shows the results of comparing the costs from the evaluated sites to the minimum ratio for electric heat pumps to be less expensive to operate than gas furnaces. The next-to-last column shows the percentage that this cost ratio is above the minimum, with negative numbers meaning that the gas furnace is less expensive to operate. The final column is how much gas prices would need to increase from current rates to make gas furnaces more expensive to operate, assuming electricity costs remain constant. Sites where natural gas furnaces are cheaper to operate are shown in red text.

Table 2 shows that only two evaluated locations – Minneapolis, MN and Charleston, WV – had rates in January 2022 that make electric heat pumps beneficial assuming the minimum efficiency for Energy Star. Tampa, FL was close, with gas prices needing to increase only about 12% more than electricity to make electric heat pumps beneficial from a cost perspective. Other sites show a wide range in the necessary increase in gas prices relative to electricity prices to make gas furnaces more expensive to operate. Most require relative gas prices to less than double, from 23% in Seattle, WA to 88% in New York. Albuquerque, NM would need to see relative gas prices more than triple to make heat pumps the cheaper option.

These results are also depicted in Figure 2. This figure shows that there is a general trend for locations with higher natural gas prices to also have higher electricity prices. The line represents the break-even point for electricity and natural gas operating costs assuming minimum Energy Star appliances.

Table 2. Ratios of fuel costs and comparison to minimum for electric heat pumps to be less expensive to operate.

| Location | Natural Gas Cost, $/therm | Electricity Cost, $/kWh | Cost Ratio | Percent above minimum for heat pump benefit | Necessary percent increase in gas prices |
|---|---|---|---|---|---|
| Northern Sites (minimum ratio of 11.7 for heat pumps to be less expensive to operate) | | | | | |
| Denver, CO | $0.81 | $0.117 | 6.9 | -41% | 69% |
| Chicago, IL | $0.84 | $0.096 | 8.8 | -25% | 34% |
| Baltimore, MD | $0.69 | $0.083 | 8.3 | -29% | 41% |
| Minneapolis, MN | $0.83 | $0.060 | 13.8 | 18% | -- |
| New York | $1.14 | $0.183 | 6.2 | -47% | 88% |
| Montpelier, VT | $1.21 | $0.177 | 6.8 | -42% | 71% |
| Seattle, WA | $1.00 | $0.105 | 9.5 | -19% | 23% |
| Charleston, WV | $0.99 | $0.079 | 12.5 | 7% | -- |
| Southern Sites (minimum ratio of 11.5 for heat pumps to be less expensive to operate) | | | | | |
| Tampa, FL | $1.40 | $0.136 | 10.3 | -10% | 12% |
| Atlanta, GA | $0.76 | $0.099 | 7.7 | -33% | 50% |
| Albuquerque, NM | $0.35 | $0.101 | 3.5 | -70% | 232% |

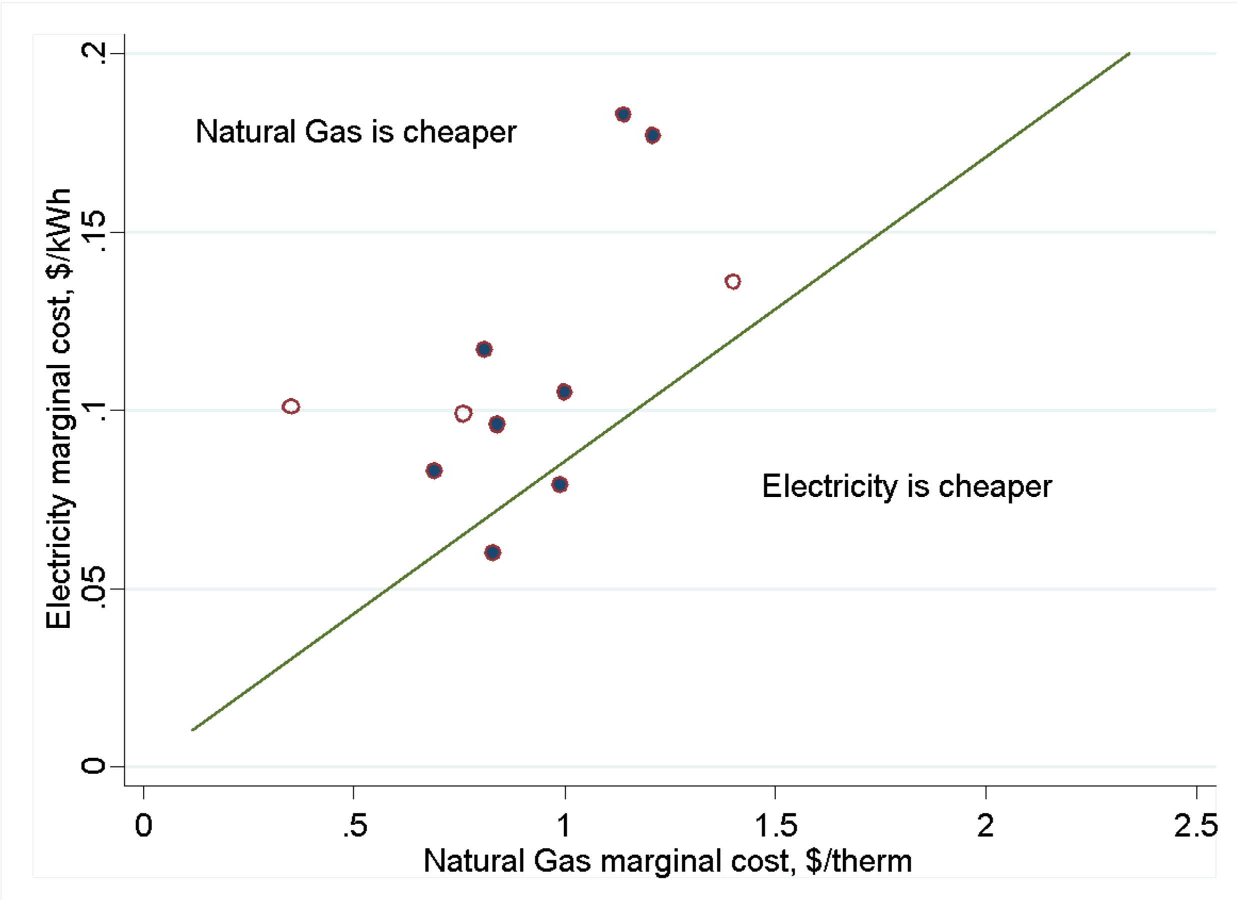


Figure 2. Natural gas vs. electricity costs.

From a policy perspective, one question that could reasonably be asked is whether it would be possible to achieve cost-beneficial electrification by requiring heat pumps that exceed Energy Star minimums. Equation (3) can be rewritten to determine the critical HSPF2 that would be needed to make a heat pump cheaper to operate than a gas furnace:

$$HSPF2_{crit} = 3.413 * sCOP = 3.413 * \frac{29.3 * \eta_{gas} * P_{elec}}{P_{gas}} \quad (4)$$

Table 3 shows the results of applying Equation (4) to the fuel rates for each location. As a reminder, these results are based on assuming that Climate Zone IV efficiencies are appropriate, whereas in reality those efficiencies underestimate likely performance in southern or marine locations such as Atlanta or Seattle and overestimate likely performance in colder climates such as much of Vermont, much of New York, and Minneapolis.

Given that the most efficient heat pumps available are at about HSPF2 of 13, several sites could not make heat pumps less expensive with current technology, including Denver, CO; New York; Vermont; and Albuquerque, NM. Four sites, including Chicago, IL; Baltimore, MD; Seattle, WA; and Tampa, FL could achieve cost-beneficial status with existing heat pump technology, but would need to require heat pumps that are well beyond Energy Star minimums. Even for those sites at which it is feasible with existing technology to achieve cost-beneficial

Table 3. Minimum HSPF2 to make the heat pump less expensive than the gas furnace.

| Location | Natural Gas Cost, $/therm | Electricity Cost, $/kWh | Minimum HSPF2 |
|---|---|---|---|
| Northern Sites (minimum HSPF2 = 8.1 for Energy Star) | | | |
| Denver, CO | $0.81 | $0.117 | 13.7 |
| Chicago, IL | $0.84 | $0.096 | 10.9 |
| Baltimore, MD | $0.69 | $0.083 | 11.4 |
| Minneapolis, MN | $0.83 | $0.060 | 6.9 |
| New York | $1.14 | $0.183 | 15.3 |
| Vermont | $1.21 | $0.177 | 13.9 |
| Seattle, WA | $1.00 | $0.105 | 10.0 |
| Charleston, WV | $0.99 | $0.079 | 7.6 |
| Southern Sites (minimum HSPF2 = 7.8 for Energy Star) | | | |
| Tampa, FL | $1.40 | $0.136 | 8.7 |
| Atlanta, GA | $0.76 | $0.054 | 6.4 |
| Albuquerque, NM | $0.35 | $0.101 | 26.0 |

status for heat pumps, these higher-efficiency units would carry greater first costs which, in the case of low-to-moderate income households, would likely need to be borne by programs.

**Propane and Oil**

Propane furnaces are held to the same efficiency requirements as natural gas furnaces to qualify for Energy Star, and so the same minimum ratios between costs will hold. For oil, Energy Star requires a minimum efficiency of 85% for furnaces (Energy Star 2021a) and 87% for boilers (Energy Star 2021b). Using Equation 3, this leads to necessary cost ratios of 10.0 for furnaces 10.2 for boilers, assuming northern locations where oil is predominantly found.

As stated previously, average U.S. propane and heating oil prices on a per therm basis were about $2.95 and $2.42, respectively, in January 2022. For propane, a necessary cost ratio of 11.7 means that electricity costs can be up to $0.25/kWh to make the minimum Energy Star heat pumps cost beneficial. That is 38% greater than the most expensive electricity rates shown in Table 1, $0.183 in New York. Since propane prices are generally likely to be higher in locations with higher electricity prices, it is also expected that there will be few, if any, locations where heating with propane is cheaper than heating with the electric heat pump, assuming proper installation and low duct losses.

For oil, a necessary cost ratio of about 10 means that electricity costs can be up to $0.24/kWh to make the minimum Energy Star heat pumps cost beneficial. That is 32% greater than the electricity rates in New York. As with propane, it is expected that there will be few, if any, locations where heating with oil is cheaper than heating with the electric heat pump, assuming proper installation and low duct losses.

## Impact of Deficiencies

The prior analyses assumed that the heat pump was installed to optimize its efficiency and that there were no duct losses. This section explores those two issues.

### Installation/Controls Problems

One of the major challenges with heat pumps is the “cold blow” problem. Consumers that are used to furnaces perceive that heat pumps are not providing warm air. For example, the supply air may be 90°F and be able to heat the home, but that is below skin temperature and so feels “cool”. Because consumers may complain to the installers, and installers want to avoid costly callbacks, some installers resort to control strategies that minimize the risk of these complaints. Two of the most common are the “low ambient cutout”, which is a temperature sensor that prevents the use of the compressor below a certain outdoor temperature and wiring the system to bring on backup resistance whenever there is a call for heat. The former usually is set to a temperature between 30-40°F and, if the backup is electric resistance, results in the system effectively being an electric furnace below that setpoint. The latter often means that a 5 kW resistance element is brought on whenever there is a call for heat, such that at mild temperatures most of the heating is provided as though the heat pump was an electric furnace. Both of these compromise the overall efficiency that the consumer is supposed to get from the refrigeration cycle. Baylon et al. (2005) did a survey of 32 contractors in the Pacific Northwest and found that six (19%) often installed a low ambient cutout and that four (13%) often wired a resistance element to come on at first stage heating with another 7 (22%) saying that they seldom followed this practice (but, therefore, did occasionally).

Past work by Francisco et al. (2004b) evaluated the effect of both strategies on the performance of heat pumps for locations in the Pacific Northwest. Spokane is of particular interest as a comparison to large portions of the U.S. as its heating season temperature profile is similar to those of Boston, Philadelphia, and Salt Lake City. Francisco et al. found that the low ambient cutout set to 30°F resulted in about a 30% annual efficiency loss in Spokane, and having a 5 kW element come on at any call for heat resulted in about a 35-40% annual efficiency loss. For a minimum Energy Star unit with an HSPF2 of 8.1, a 30% penalty would effectively reduce the HSPF2 to 5.7.

Looking from the perspective of cost ratios from Equation 3, assuming minimum Energy Star efficiencies, these penalties would change the cost ratio to 16.8 for northern climates, meaning that if electricity was $0.10/kWh then gas could be up to $1.68/therm instead of $1.17/therm for the natural gas to be cheaper. Lastly, if the $HSPF2_{crit}$ from Equation 4 had been 10, then these penalties would increase the necessary HSPF2 to 14.3 which is higher than currently available on the market.

### Duct Losses

Another consideration for the performance of heat pumps is losses from ductwork outside the building envelope. This is common in homes that have ducts in attics, vented crawl spaces, and/or garages. Multiple studies have found that, when ducts are in these spaces, there is an average of about 12% leakage from the supply ducts to outside and a similar amount from outside into the return ducts (Baylon et al. 2005; Francisco et al. 2003).

While duct leakage will negatively impact both heat pumps and furnaces, the impact on heat pumps is more severe. This is for two reasons. First, the equation describing duct efficiency (Palmiter and Francisco 1997), which was the basis for ASHRAE Standard 152 (ASHRAE 2014), includes a dependency on the reciprocal of the temperature rise across the heat exchanger. Since heat pumps typically have a lower temperature rise (usually no more than 20 °F [11 °C]) than gas furnaces (usually 30-70 °F [17-39 °C]), this means that the impact on duct efficiency will be greater for heat pumps.

The second, and more significant reason that duct losses have a larger impact on heat pumps than on furnaces is that duct losses reduce the amount of delivered heating that can be provided by the compressor and therefore increases the degree to which heating relies on supplemental backup heat. In many heat pumps, backup heat is provided by electric resistance, which is of comparable efficiency to Energy Star gas furnaces but with the greater costs of electricity. This phenomenon can be seen in Figure 3, which is taken from Francisco et al. 2004b. In this figure, the line with the solid circles represents the heating load of the example house without any duct losses, and the line with the solid triangles represents the heat pump capacity using only the compressor. Where those two lines cross is considered the compressor "balance point", where the compressor can theoretically meet the entire load of the home without the need for backup. In this example, the compressor balance point is at about 10 °F (-12 °C) when there are no duct losses.

The line with the solid squares represents the required heating for the home with 10% duct leakage on each of the supply and return sides of the system. This shows that the compressor balance point becomes about 22 °F (-6 °C). At all temperatures, there is greater compressor use than without duct losses, represented by the region below the compressor capacity line and between the load lines with and without duct losses. Worse, there is an increase in need for backup heat, represented by the region above the compressor capacity line and the load line with duct losses. Averaging in the increased use of electric resistance backup substantially negatively impacts the overall efficiency of the heat pump.

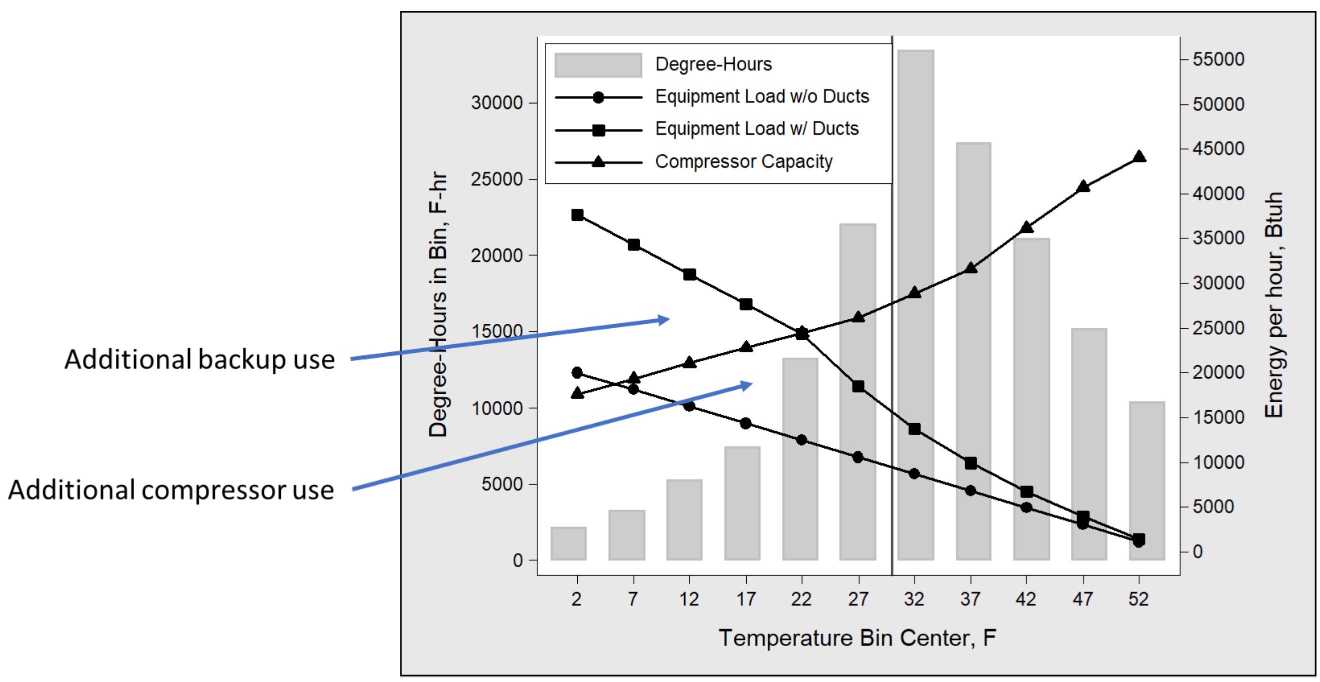


Figure 3. Impact of Duct Losses on Heat Pump Balance Point and Need for Backup Heating

Quantitatively, Palmiter and Francisco (1998) showed that a 10% supply leak to outside in Spokane would convey about a 12% energy penalty for a gas furnace but a 22% energy penalty for the heat pump sized to the house load. This is an 83% greater energy penalty compared to the furnace. For a minimum Energy Star unit with an HSPF2 of 8.1, a 22% penalty would effectively reduce the HSPF2 to 6.3, whereas the 12% penalty on the gas furnace would effectively reduce the furnace efficiency from 95% to 84%. Using Equation 3, this means that the cost ratio for the gas furnace to be more expensive than the heat pump increases from 11.7 to 13.2.

We note that duct losses are not issues for mini-split ductless heat pumps, or for systems where the ducts are all within the thermal boundary of the home.

**Comparison of Impacts from Deficiencies**

Table 4 shows the impacts on the cost ratios for the gas furnace to be more expensive than the Energy Star minimum heat pump considering different scenarios. This includes a combination of controls that reduce compressor use and duct losses.

Table 4. Cost Ratios for Gas Furnace to be Less Expensive than Heat Pump

| | Optimized | Low-Temp Lockout | 5 kW at Stage 1 | 10% supply leak | Low-Temp Lockout + 10% supply leak | 5 kW at Stage 1 + 10% supply leak |
|---|---|---|---|---|---|---|
| Minimum Energy Star HP | 11.7 | 16.8 | 19.5 | 13.2 | 18.9 | 22.1 |
| High-Efficiency HP (HSPF2=13.5) | 7.0 | 10.1 | 11.7 | 7.9 | 11.3 | 13.2 |

The results shown in Table 4 paint a clear picture, when combined with the results shown in Table 2. Either of the two control strategies that reduce the use of the compressor make it so that there will be no locations for which the minimum Energy Star heat pump reduces operating costs, and most locations will see increases in utility bills even with the high-efficiency heat pump. A 10% supply duct leak to outside does not have as drastic effect, but it does make it so that only one location in Table 2 (Minneapolis) would have lower costs with the minimum Energy Star heat pump and five of the locations in Table 2 would see increases in utility bills even with the high-efficiency heat pump. Any additional duct losses would make the economics more challenging. When one of these control strategies is incorporated into a heat pump that is connected to ducts with a 10% supply leak to outside, only two locations in Table 2 would be able to lower costs even with the high-efficiency heat pump.

## Conclusions

The analysis presented here demonstrates that, based on typical prices as of the writing of this article, electrification using heat pumps only reduces short-term operating costs for residential consumers in a few locations based on Energy Star minimum appliance efficiencies, and in several locations it is not possible to achieve short-term cost savings status with even the most efficient heat pump. Differential changes in fuel prices could flip this situation, either if gas prices significantly increased or electricity prices significantly decreased. However, for low-income households already struggling to make ends meet, projections of long-term changes are not key drivers of decisions; further, asking that these families pay more now with the idea that they may pay less in the future raises significant equity questions. Additionally, increases in fuel costs work against equity.

The analysis also shows that common control strategies and duct deficiencies significantly impact heat pump efficiency and make the economics even more challenging. Especially with the control strategies, these impacts can make it so that there is no possibility for the heat pump to save energy, and that even with drastic increases in gas prices relative to electricity prices the operational costs are likely to be greater with the heat pumps. Further, differential penalties for heat pumps compared to furnaces, due to these deficiencies, also means that there will be a greater negative impact on realized carbon reductions from electrification. For example, in the example where duct losses result in an 83% greater energy penalty for heat pumps than gas furnaces, it also means that there will be an 83% greater increase in emissions (if any) from whatever source is being used to generate the electricity used to power the heat pump.

From a policy perspective, this analysis suggests several key policy considerations in order to make electrification with heat pumps equitable:

1. When installing heat pumps in low-income households, additional measures should be explored to ensure that costs do not increase. Examples can include additional energy efficiency measures, site-mounted solar energy with guaranteed maintenance support, and limits to electricity prices for income-eligible consumers. An example of limiting electricity prices is the Percentage of Income Payment Plan (as described in Yim and Subramanian (2023)), which targets a specific percentage of household income as a maximum utility cost. This strategy, however, requires knowing the household income and has a potential side effect of removing the incentive to conserve energy if the household would not be able to avoid the maximum (i.e. additional energy would be "free"). While a fixed maximum per-kWh cost does not index the bills to income, it would preserve the incentive to conserve energy.
2. Rate designs could be modified to reduce electric rates to be closer to their actual marginal costs.
3. Training, quality assurance, and quality control to ensure that control strategies do not limit the useful contribution of the compressor.
4. Duct leakage outside of the conditioned space should be quantified prior to installation of heat pumps, with improvements made as needed.

## References


AHRI. 2023. *Standard 210/240: Standard for Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment*. Air-Conditioning, Heating, and Refrigeration Institute, Arlington, VA.

ASHRAE. 2014. *ANSI/ASHRAE Standard 152: Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems.* ASHRAE. Atlanta, GA.

Baylon, D., S. Strand, B. Davis, D. Robison, and E. Kruse. 2005. *Analysis of Heat Pump Installation Practices and Performance.* Final report. https://ecotope-publications-database.ecotope.com/2005_002_AnalysisHeatPumpInstallation.pdf

Billimoria, S., Henchen, M. Guccione, L. and Louis-Prescott, L. 2018. *The Economics of Electrifying Buildings: How Electric Space and Water Heating Supports Decarbonization of Residential Buildings*. Rocky Mountain Institute, https://rmi.org/insight/the-economics-of-electrifying-buildings/

City of New York. 2021. "Mayor de Blasio Signs Landmark Bill to Ban Combustion of Fossil Fuels in New Buildings". https://www1.nyc.gov/office-of-the-mayor/news/852-21/mayor-de-blasio-signs-landmark-bill-ban-combustion-fossil-fuels-new-buildings, accessed 1/10/22.

Deason, J., M. Wei, G. Leventis, S.J. Smith, and L.C. Schwartz. 2018. *Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches*. Energy Analysis and Environmental Impacts Division Lawrence Berkeley National Laboratory.

Doak, A., C. Stanier, J. Anthony, and H.S. Udaykumar. 2022. "Can Heat-Pumps Provide Routes to Decarbonization of Building Thermal Control in the US Midwest?" *Energy Sci and Eng*. **10**: 2612-2621.

EIA. 2021a. Annual Energy Outlook 2021. U.S. Energy Information Administration.

———. 2021b. U.S. Propane Residential Price. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=M_EPLLPA_PRS_NUS_DPG&f=M, accessed 1/3/22.

———. 2021c. U.S. Weekly Heating Oil and Propane Prices. https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPD2F_PRS_dpgal_m.htm, accessed 1/3/22.

———. 2021d. *Monthly Energy Review, April 2021*. DOE/EIA-0035(2021/4).

———. 2023. https://www.eia.gov/dnav/ng/hist/rngwhhdM.htm.

Energy Star. 2021a. Furnaces Key Product Criteria. Accessed 11/28/24 at https://www.energystar.gov/products/heating_cooling/furnaces/key_product_criteria

———. 2021b. *Boilers*. Accessed 11/28/24 at https://www.energystar.gov/products/boilers

———. 2022. *ENERGYSTAR® Program Requirements for Central Air Conditioner and Heat Pump Equipment, Eligibility Criteria Version 6.1.* Accessed 1/13/2022 at https://www.energystar.gov/sites/default/files/ENERGY%20STAR%20Central%20Air%20Conditioner%20and%20Heat%20Pump%20Version%206.1%20Final%20Specification.pdf

Francisco, P.W., L. Palmiter, and B. Davis. 2003. "Insights into Improved Ways to Measure Residential Duct Leakage." *ASHRAE Transactions*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Francisco, P.W., L. Palmiter, and D. Baylon. 2004a. "Understanding Heating Seasonal Performance Factors for Heat Pumps." Proceedings of the 2004 ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy-Efficient Economy, Washington, DC. https://aceee.org/files/proceedings/2004/data/papers/SS04_Panel1_Paper14.pdf

Francisco, P.W., D. Baylon, B. Davis, and L. Palmiter. 2004b. "Heat Pump System Performance in Northern Climates." *ASHRAE Transactions*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Padovani, F., N. Sommerfeldt, F. Longobardi, and J.M. Pearce. 2021. "Decarbonizing rural residential buildings in cold climates: A techno-economic analysis of heating electrification." Energy & Buildings **250**(1): 11284.

Palmiter, L. and P. Francisco. 1997. *Development of a Practical Method for Estimating the Thermal Efficiency of Residential Forced-Air Distribution Systems.* For the Electric Power

Research Institute, Palo Alto, CA. https://ecotope-publications-database.ecotope.com/1997_007_DevelopmentPracticalMethod.pdf
———. 1998. "Modeled Duct Distribution Efficiency: Insights for Heat Pumps." Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings, ACEEE, Washington, DC. https://aceee.org/files/proceedings/1998/data/papers/0118.PDF
Sierra Club. 2021. "California's Cities Lead the Way to a Gas-Free Future". https://www.sierraclub.org/articles/2021/07/californias-cities-lead-way-gas-free-future, accessed 1/10/22
Wilson, E.J.H., P. Munankarmi, B.D. Less, J.L. Reyna, and S. Rothgeb. 2024. "Heat Pumps for All? Distributions of the Costs and Benefits of Residential Air-Source Heat Pumps in the United States". *Joule* **8**: 1000-1035.
Yim, E. and S. Subramanian. 2023. Equity and Electrification-Driven Rate Policy Options. Report for the American Council for an Energy-Efficient Economy. https://www.aceee.org/sites/default/files/pdfs/equity_and_electrification-driven_rate_policy_options_-_encrypt.pdf.
Zurofsky, A., J. Schub, J. Rhodes, T. Curnes, and S. Calisch. 2021. *Rewiring Communities: A Plan to Accelerate Climate Action and Environmental Justice By Investing in Household Electrification at the Local Level.* Report for Rewiring America and Coalition for Green Capital. https://content.rewiringamerica.org/reports/rewiring-communities-report.pdf