Evaluating Cold Climate Heat Pumps: Understanding How and Where Cold Climate Heat Pumps Can Displace Less Efficient Heating Sources

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ABSTRACT

Among the benefits of ductless mini-split heat pumps (DHPs) is the opportunity for homeowners to reduce the cost of heating their home. However, this application is not suited to all homeowners, and several variables require consideration to identify residences with savings potential. An assessment of two heating alternatives includes the efficiencies of the systems and costs of the resources consumed, and in the case of DHPs, efficiency is temperature dependent and heating can be zonal. Accurately comparing the operation of a DHP and a conventional system requires insight into the number of hours spent in various temperature bins, how spaces in the home are zoned and heated, and the ranges of fuel and electric prices. The use of "cold climate" branding by manufacturers further adds complexity to an evaluation of tradeoffs between systems.

The key component that has been missing from this analysis is an understanding of the relationship between temperature and DHP efficiency that is based on a large sample of *in situ* metering. The difficulty in developing this relationship is the continuous measurement of indoor heating supplied. In a recently published study by the Cadmus Group (Cadmus, 2016), a set of methods for addressing this issue were established, tested, and implemented across 152 homes in Massachusetts and Rhode Island, and from the resulting data several analyses are developed for this paper. In addressing the question of which homeowners benefit from DHP installation, we discuss the importance of measuring supplied heat and the methods it involves, consider characteristics of the observed installations in MA and RI, provide an analysis of tradeoffs with alternative heating systems, and assess the significance of the cold-climate designation.

Introduction

In 2013, program administrators in Massachusetts and Rhode Island commissioned Cadmus to evaluate 152 residences across these states that received incentives for the installation of DHPs. Although the study collected data for the heating and cooling seasons, only heating results are discussed in this paper.

A key element of this study was the logging of the heating provided by the units. This is important because the actual operation of the units and their field efficiency can be calculated using the measured heating. Most studies have simply metered power and attempted to calculate heating using nominal efficiencies. This is problematic because the compressors and outdoor fans are multispeed and the indoor fans have 4 to 5 speeds, yielding many operating points. Therefore, correlating power use with heating output and efficiency can be highly inaccurate. Some manufacturers publish tables of efficiencies with outdoor temperature and compressor speed, but these are limited in their application.

In developing this study, the authors reviewed other DHP studies, including those conducted in the Pacific Northwest (Ecotope, 2014), New York (ERS, 2014), Maine (EMI, 2014), and for the Department of Energy (Williamson, 2015). Of these studies and evaluations, only Ecotope and Williamson attempted to measure heating and cooling delivered by the units, and the number of units monitored in this way was relatively small. This study included some of the methods used in other studies, but modified some of them to either update them to recent thinking, or to make the methods practical for the larger scale of this study. The resulting dataset, which spans two winters, serves as the basis for the following analysis.

This paper's objective is to address how homeowners can better use DHP to displace alternative heating equipment, including fossil-fuel burning systems, while reducing their heating costs. Consideration is given to the methods employed in data collection, the intent of the installation, and tradeoffs between systems in the presence of varied climates and resource pricing. We will also look specifically at DHPs marketed as cold-climate units and conduct similar analyses for this grouping of equipment.

Methods

Figure 1 shows the quantities continuously measured at the residences in the study, with **T** for temperature, **RH** for relative humidity, **P** for total system power, and **i** for indoor fan current.

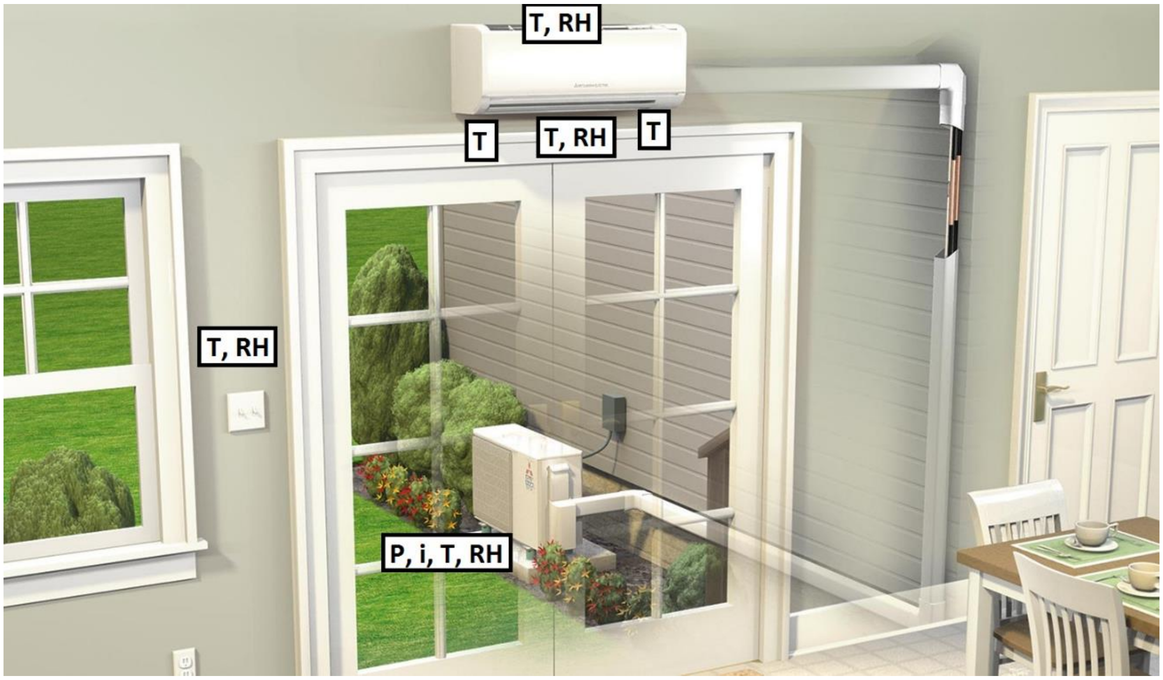

Figure 1. Quantities Measured Continuously On-site. Source of background image: MITSUBISHI ELECTRIC COOLING & HEATING

The reason for metering fan current and supply and return air temperature and relative humidity is to calculate the amount of heating supplied to the space occupied by the indoor unit. This heating is the output of the system, and when combined with the easily-measured input electric power, the ratio of the two values determine system efficiency. Calculating supply heat allows for analyses that are otherwise inaccurate or unattainable, like correlating efficiency and temperature, and avoids falsely attributing energy consumption to certain operations, such as heating instead of defrost cycling. The challenge in determining the provided heat is a reliable and continuous approximation of supply airflow, and this is particularly difficult in the case of an *in situ* evaluation.

We metered indoor unit fan current as a proxy for supply airflow by correlating it with spot measurements of airflow taken on-site and at various fan speed settings (most fans have four or five speeds). The engineering basis for this approach stems from the relationship between the power consumed by the fan, the differential pressure this electric power is converted into, and the airflow resulting from this change in pressure.

These relationships provide the form of the equation for curve fitting, and the constants are determined empirically from spot measurements. Figure 2 shows this correlation, along with the manufacturer's published airflow ratings. One published method (Christensen et. al., 2011) used a digital tachometer and a metal plate retrofitted to the fan to log fan activity. We investigated this method, but found it impractical for use in homes because some units did not allow access to the fan wheel without risking damage to the unit or unbalancing the fan. In discussing our fan amperage method with Winkler, one of the method's authors, he indicated that our fan amperage method was a preferred approach (Winkler, 2016).

Provided these spot measurements, fan current, and supply and return air temperature and relative humidity, the calculation of supply heat becomes straightforward.

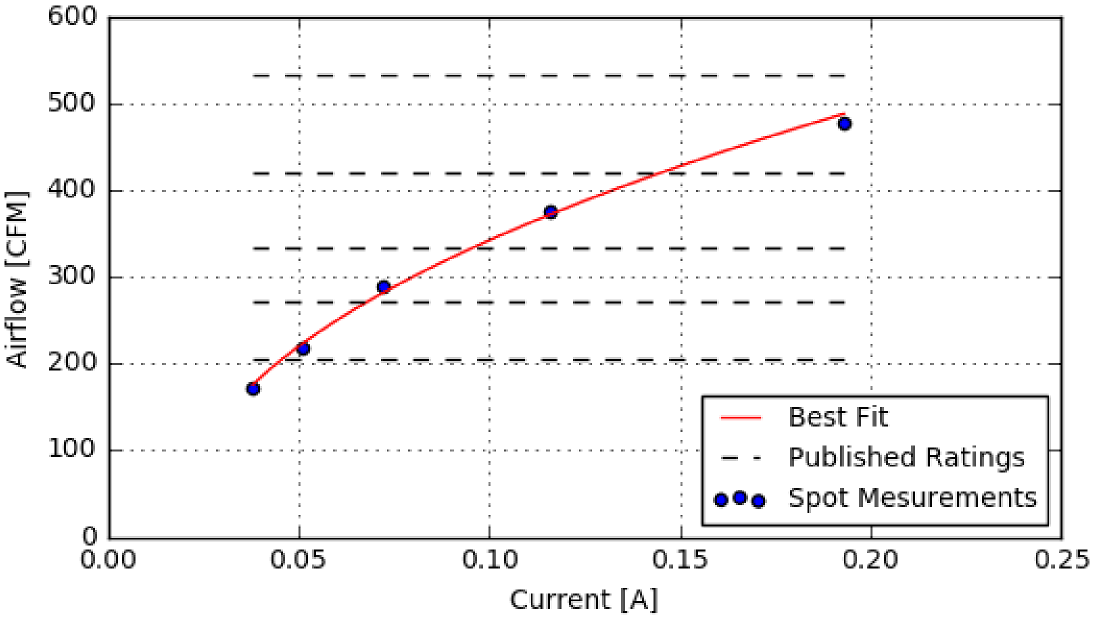

Figure 2. Example Correlation Between Current and Airflow

There is a tradeoff between the convenience (of both the field technician and homeowner) in taking spot measurements of airflow on-site and the accuracy of the devices used. For this study, we used an Alnor/TSI EBT731 balometer, shown in Figure 3. This model of balometer is classified as a non-powered flow hood (Walker, Wray, Dickerhoff, & Sherman, 2010).

Figure 3. DHP Supply Airflow Spot Measurement

There has been some industry skepticism towards these types of flow hoods, but, as presented in a November 2012 publication (Stratton, Turner, Wray, & Walker, 2012) by Lawrence Berkeley National Laboratory and from communications with one of the study's authors (Walker, 2016), these devices, oriented to measure inlet flows (as in Figure 3), produce acceptable accuracy when compared to a laboratory metric. Figure 4 shows the results of this testing with the Alnor measurements within 5% of the reference measurement while above 80 CFM. (Figure 2 shows the typical range of DHP airflows.)

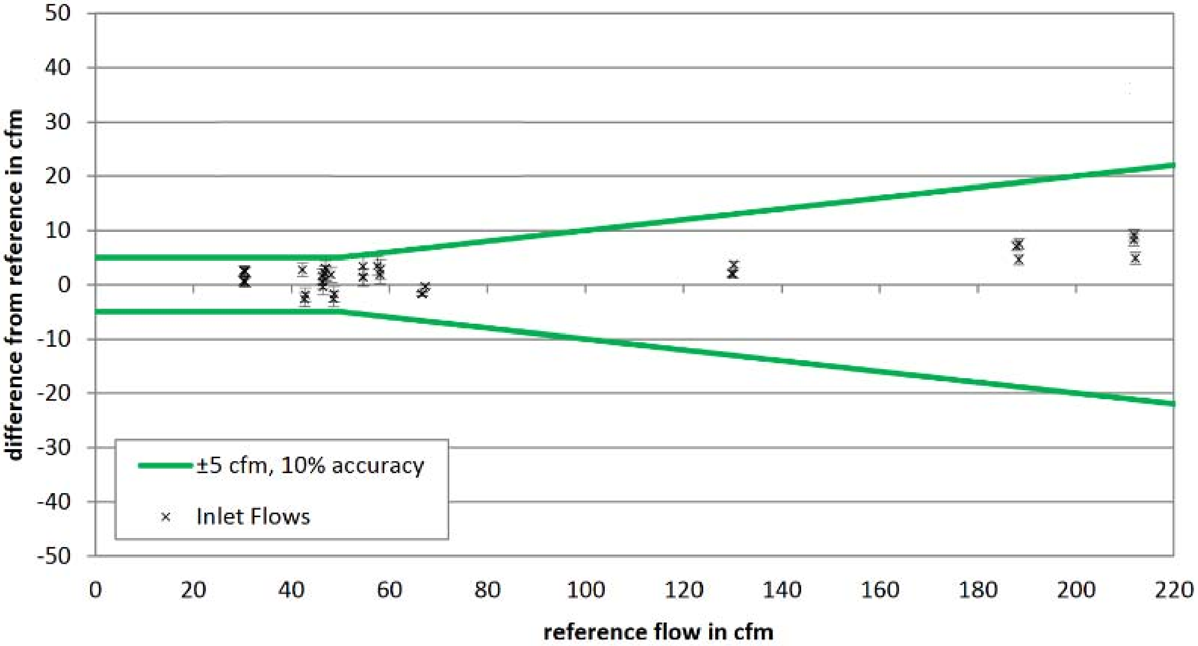

Figure 4. LBNL-5983E Figure 14, Adapted (Stratton et al. 2012)

The data presented in Figure 4 demonstrate that the bounds of uncertainty around further calculated values are tight enough to be actionable. This result, coupled with the ease of using a flow hood, allows reliable measurements for airflow *in situ* and at scale. Additionally, a March 1999 ASHRAE publication supported this method as the most realistic for producing adequate accuracy while measuring airflow (Choat, 1999).

System Sizing and Operation

When identifying homeowners who will benefit from the DHP installations, it is important to understand how the equipment is intended to be used. The cost and ease of installation, ability to provide heating and cooling, and modular configurations of DHPs contribute to the varied ways they are operated, and diminish singular narratives of what consumer behaviors are or should be. The heating capacity of a DHP relative to the thermal load of the space it serves can limit its ability to fully displace alternative conditioning systems and result in different patterns of use. In Figure 5 we calculated the ratio of DHP rated capacity to a Manual J thermal load of the room served for each system studied; in this figure the DHP capacity was rated at 17F, the temperature that AHRI uses to rate capacity, and the Manual J calculation was performed at 6 F based on the location of our study.

The median ratio of capacity to load is close to 1, indicating that contractors are roughly sizing the units to meet heat loads. There is some range around this median where the 25% and 75% values are about 0.85 to 1.6. Strictly speaking, because we are using the rating at 17F, the unit's capacity will be lower at 6F and the median ratio of capacity to design need will be lower than the figure.

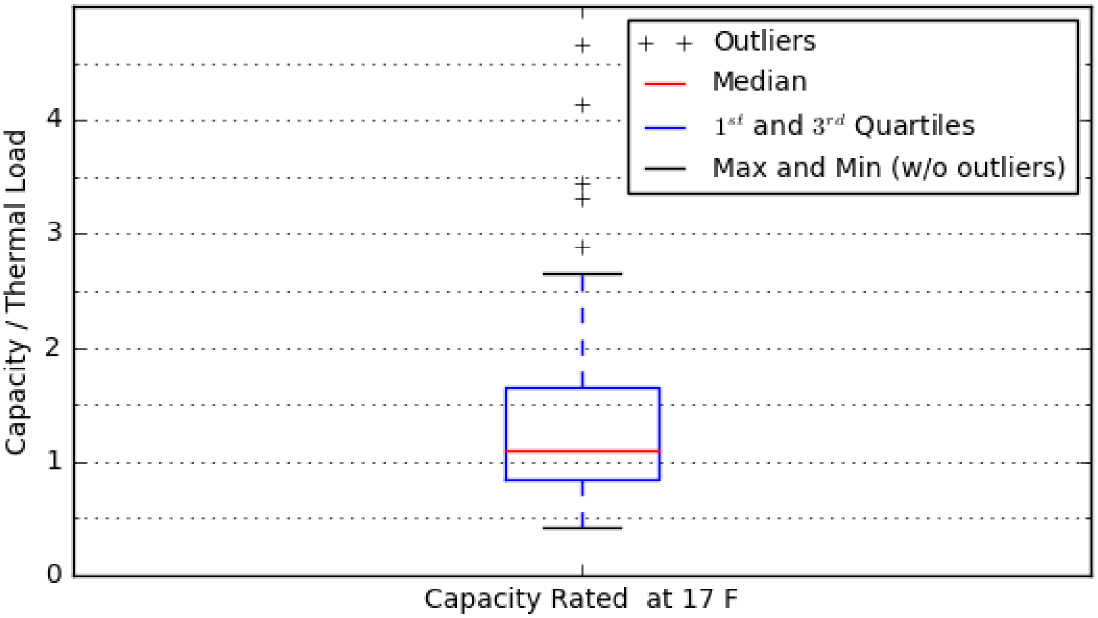

Figure 5. DHP Capacity to Thermal Load of Space Served

Further considering behavior patterns, we suspected the type of room where a DHP was installed might correlate with its use, and, for example, a system installed in a kitchen may on average see more full load hours than one installed in a bedroom. Figures 6 through 8 present some of the varied ways that systems are operated. Each figure is created from the heating supplied by the DHP, the difference in outdoor and indoor temperature, and an assumed linear relationship between outdoor temperature and the Manual J calculated load. The values shown are averages from the winter month of highest DHP energy consumption.

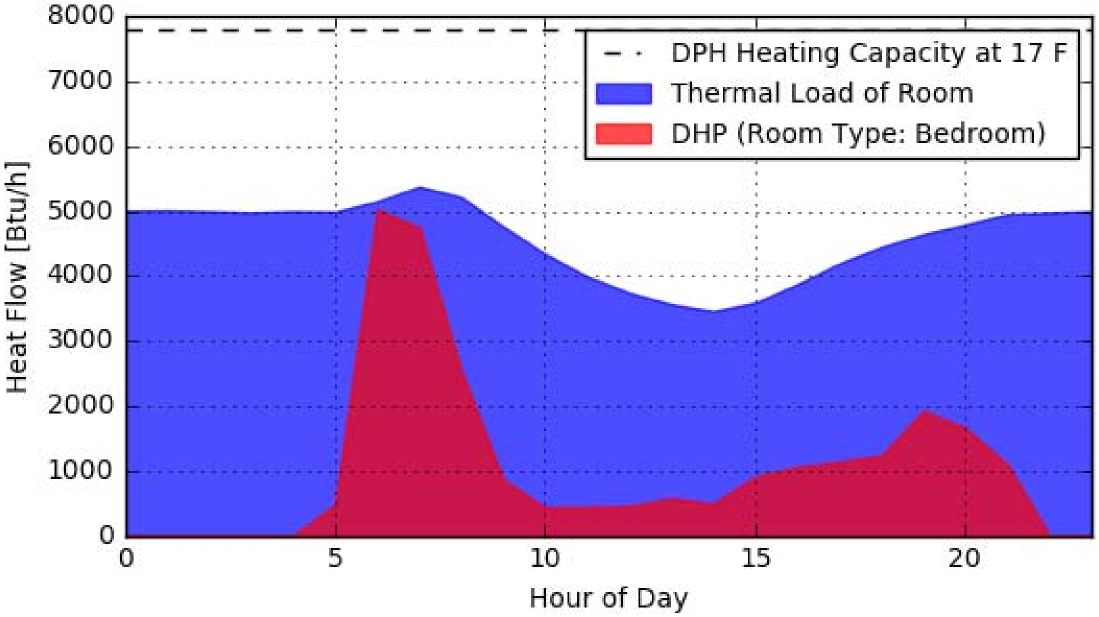

Figure 6. Average DHP Heat Output and Thermal Load (Intermittent Use)

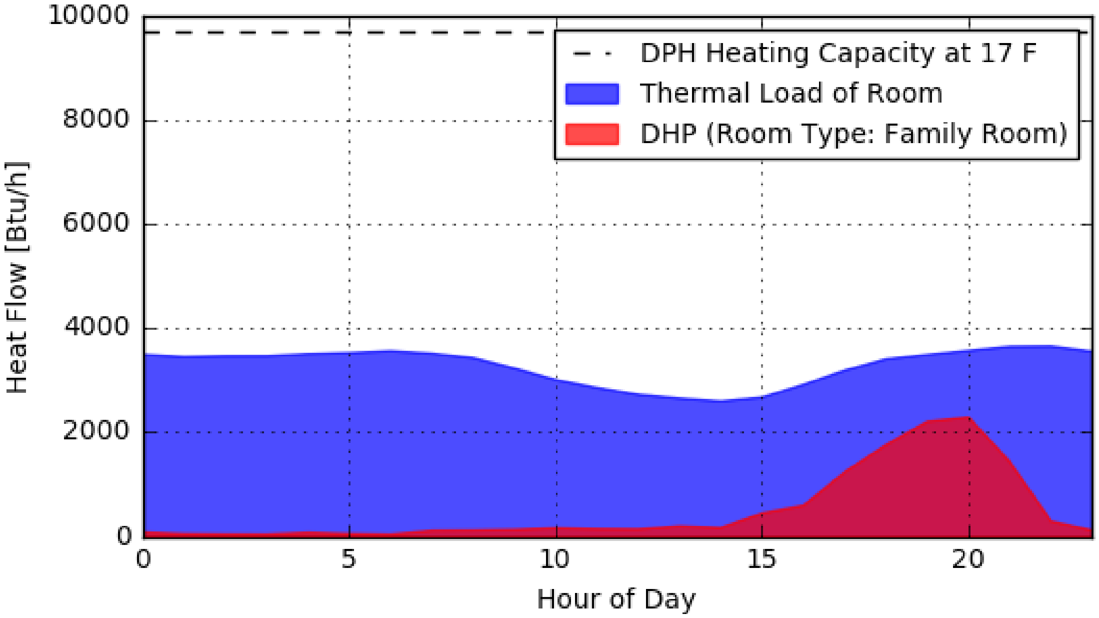

Figure 7. Average DHP Heat Output and Thermal Load (Intermittent Use)

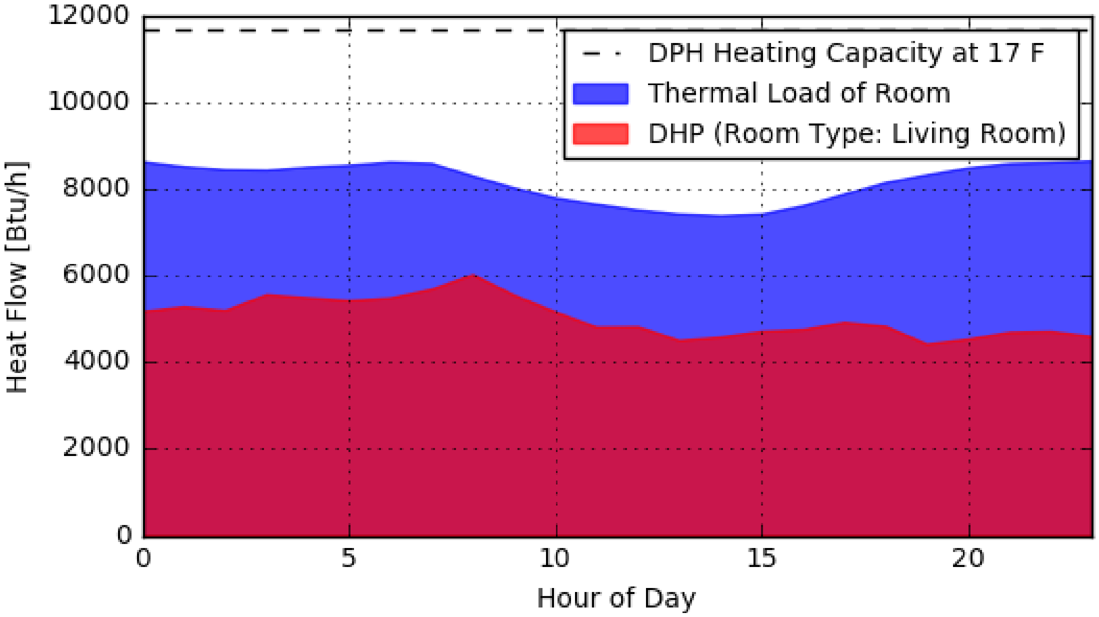

Figure 8. Average DHP Heat Output and Thermal Load (Constant Use)

These three figures alone do not allow for drawing broad conclusions, but instead we have selected them to illustrate typical behaviors observed in the larger sample that can generally be described as constant and intermittent use. Additionally, these patterns are not well correlated with room type.

Economic Operation of DHPs

Although DHPs can operate more efficiently than alternative heating systems, program administrators should also consider the relative costs of operation to the homeowner. The efficiency of a DHP varies with outdoor air temperature, and when compared with a heating system such as a boiler or furnace, with a nearly constant efficiency, there is a temperature at which operating the two systems is equally cost-effective for a homeowner; we refer to this as the breakpoint temperature.

Because a DHP in heating mode has an increasing efficiency with increasing temperature, temperatures above the breakpoint will economically favor DHP operation, and temperatures below will favor the alternative system. This calculation further depends on comparing the prices of the resources consumed by the two systems, and consideration of the number of hours a location expects to experience a range of temperatures is important.

Figures 9, 10, and 11 show breakpoint temperatures between DHPs and natural gas, oil, and propane systems. The assumed alternative system efficiency is 0.8, the DHP efficiency is an average of all systems studied, the electric and fuel prices are averages from Massachusetts during the winters of 2015 and 2016, and the temperature data is TMY3 (Typical Meteorological Year, Version 3) from Logan Airport in Boston. DHPs are more economical to operate than electrical resistance heating for all temperatures, and therefore no temperature breakpoint diagram is shown for this heating alternative.

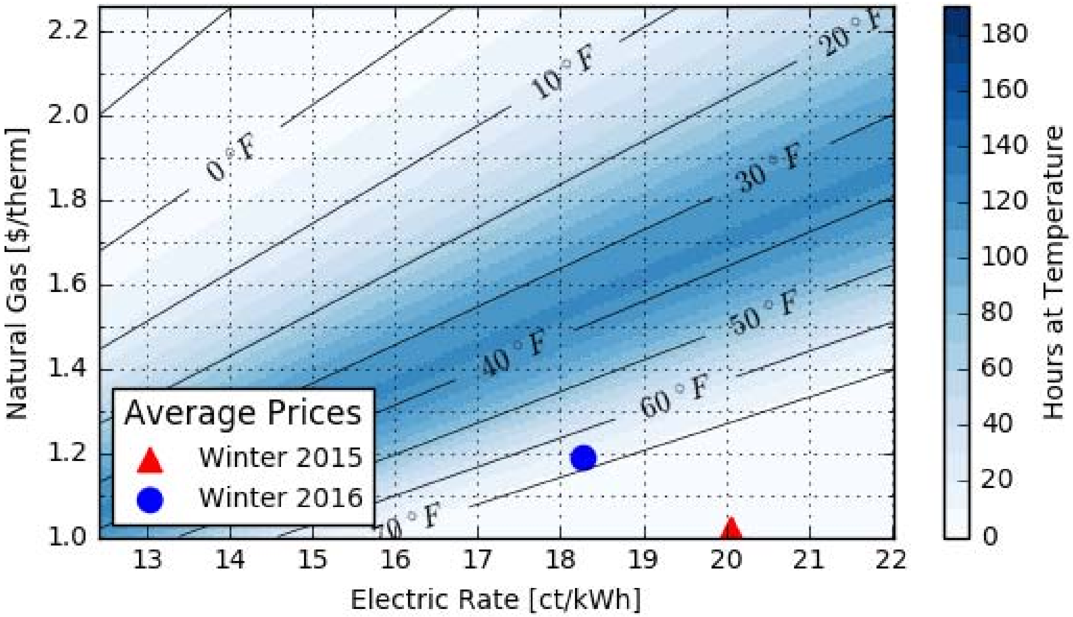

Figure 9. Breakpoint Temperatures of DHPs vs. Natural Gas Systems

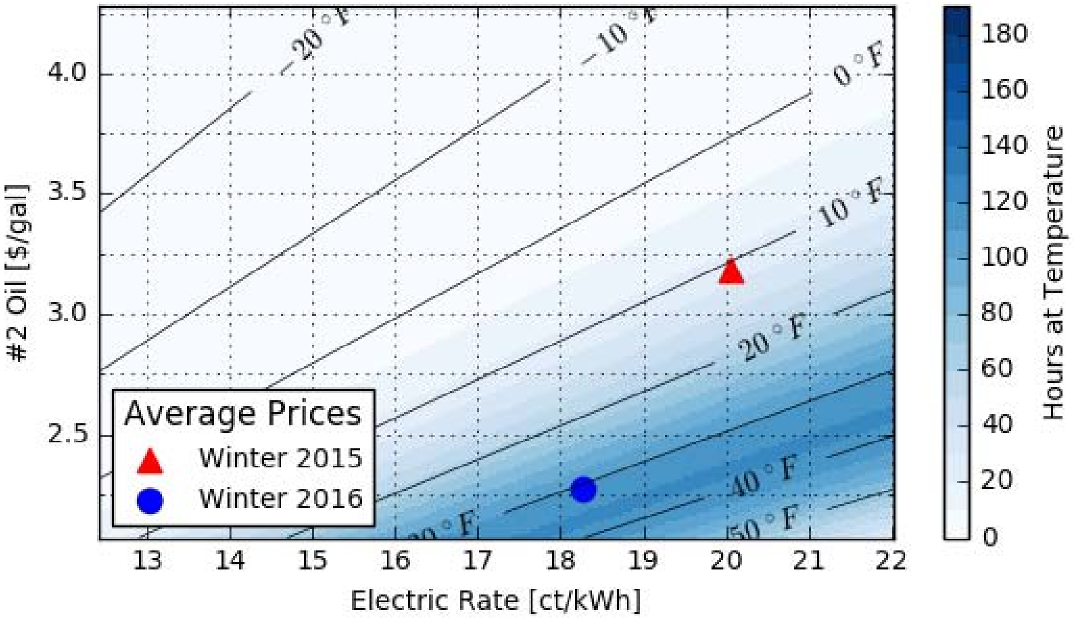

Figure 10. Breakpoint Temperatures of DHPs vs. Oil Systems

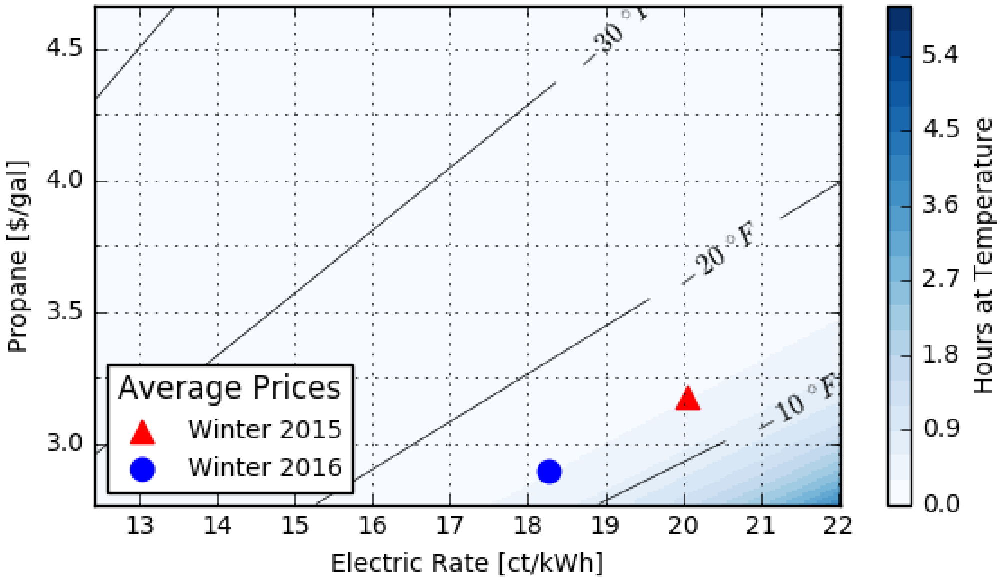

Figure 11. Breakpoint Temperatures of DHPs vs. Propane Systems

These figures are meant to be a quick way of understanding if heating with a DHP is will save money, and possibly convey a simple operation strategy. In Figure 9, heating with a DHP costs more than the alternative gas furnace at nearly all heating temperatures due to the relatively low cost of natural gas. When compared to fuel oil (Figure 10), a typical DHP is more cost-effective down to 10F or 30F, encompassing much of the seasonal heating hours. The breakpoint, however, remains sensitive to variations in electricity and fuel oil prices. In this scenario, a homeowner might consider using a DHP maximally at temperatures higher than 30F, and switching to the oil system when the temperature drops below. In contrast, DHPs fare well against propane systems (shown in Figure 11) for all but the coldest weather.

The assumed DHP efficiencies in the previous figures were taken as the average of all units studied, but selecting a higher heating seasonal performance factor (HSPF) system changes these calculations. Figure 12 specifically examines cold-climate units, which on average achieved a higher efficiency in our sample. Unsurprisingly, a more efficient DHP results in a lower breakpoint temperature, dropping by close to 10F for 2016 winter prices. Another important factor to consider is how the systems being compared are zoned. In the previous figures, it is assumed that both systems are providing an equal amount of heat, but in practice DHPs are often used to heat a smaller portion of a home than boilers or furnaces.

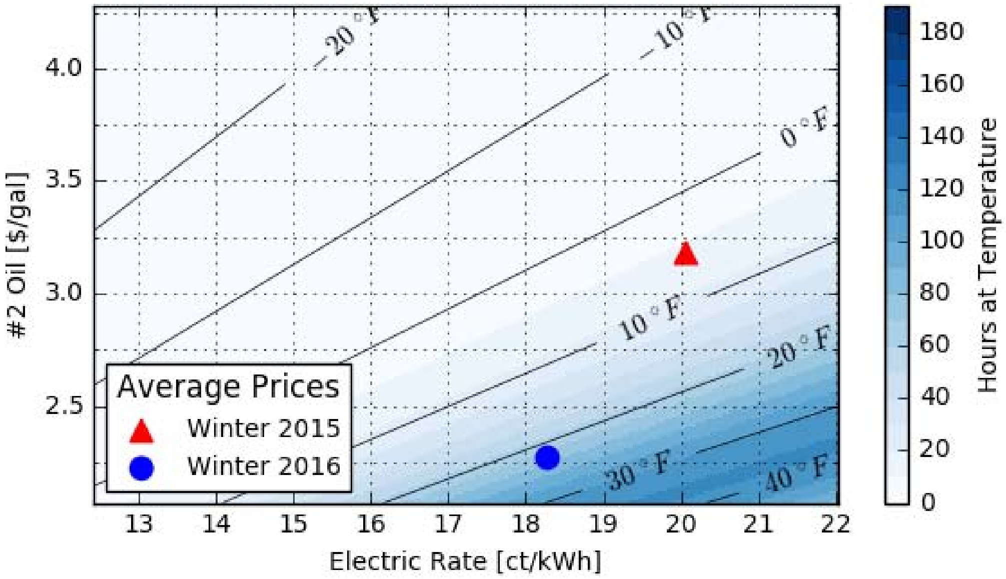

Figure 12. Breakpoint Temperatures of DHPs (Cold Climate Units) vs Oil Systems

In some homes, the zonal nature of the DHP where each heats a single room or zone allows homeowners to heat the portion of the home they are using and allow the remainder of the house to remain cooler. For example, a homeowner might heat their living room until they go to bed and then allow the home's temperature to drift downwards, while heating their bedroom with that room's head. Figure 13 compares a cold-climate DHP to an oil burning system, but sets the DHP output equal to two-thirds of the oil system, effectively simulating zonal savings. The DHP proves more favorable than oil heating, even at 2016's relatively low prices and at temperatures below 0 F. Only a couple of hours fall below the temperature breakpoint, meaning the DHP is nearly always less expensive to operate than a primary oil heat system under this zonal scenario.

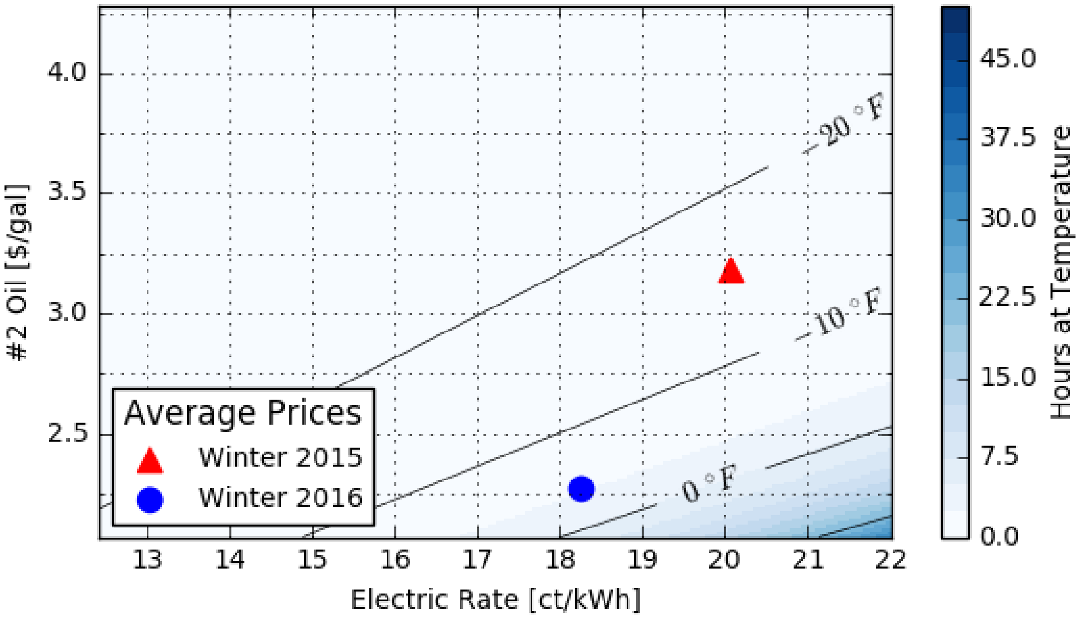

Figure 13. Breakpoint Temperatures of DHP (Cold Climate Units with Zoning) vs. Oil Systems

Cold Climate Systems

Many of the DHPs included in the study were designated as cold climate systems[1], leading to questions of how the performance of "non-cold climate" units compared. Figure 14 shows the average coefficient of performance (CoP) vs. temperature for these two groupings.

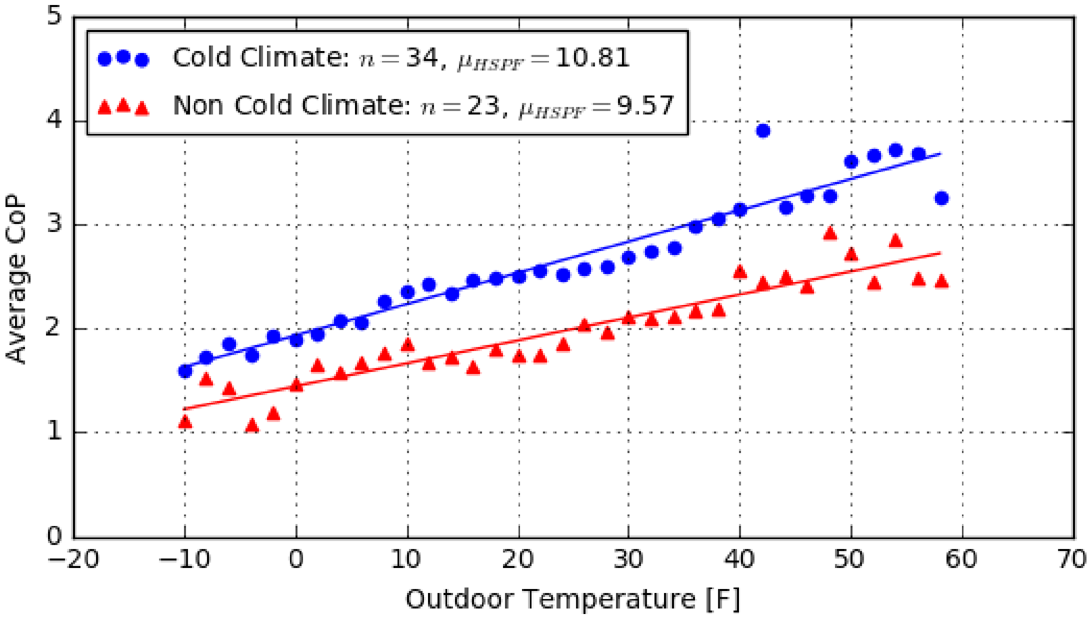

Figure 14. Average DHP Efficiency vs Outdoor Temperature

On average, cold climate units achieved higher efficiencies at all temperatures, but, because of their higher average HSPF ratings, it remains unclear whether cold-climate labeling alone explains the better performance.

Conclusions

We show that the heating output and efficiency of the DHPs can be monitored in situ and that by doing this we can do several things not possible with a power-only metering effort

1. We can observe the heat provided by the unit and compare it to space heating needs to look at unit sizing. We found that in general the units appear to be correctly sized for heating.
2. We can observe how units are used more precisely than a simple power metering effort. We found that use of the units varies greatly, with some used to provide a large portion of the heat load. In other cases, units are used more like an appliance, and are turned on intermittently for morning or evening use.
3. We can observe the actual efficiency of heating provided. This is helpful for examining the use of the heat pumps relative to other heat sources. The relative economics of operating a DHP versus a fossil fueled system depend on electricity pricing, fossil fuel pricing, and on temperature. Based on recent energy pricing, DHPs can compete with oil and propane for most temperatures. They

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[1] Using the Efficiency Vermont Technical Reference Manual current during the study's planning phase.

are not particularly competitive against natural gas however, unless zonal impacts are included. Efficiency of units is discussed at greater length in Cadmus (2016).

4. We can examine the efficiency of units by outdoor air temperature which is useful for examining various HSPF ratings and cold climate labels. Field monitoring confirms that DHPs labeled as cold-climate units provide higher heating efficiencies than non-cold-climate units. In our study, the cold-climate units correlated with higher HSPF ratings and provided higher efficiency for all temperatures. Even for units with similar HSPF ratings, it appears that the cold climate units are more efficient at cold temperatures, though the field data are less conclusive due to smaller sample sizes.

The above observations should be considered in a heating program design and will inform which customers to target (e.g. propane heat), what role customer education will play (likely large in helping them navigate breakpoints), and whether to incentivize multizone systems.

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