Interaction of Cold Weather Ductless Heat Pumps and Primary Fossil Systems

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ABSTRACT

Cold weather ductless heat pumps could displace high-carbon, fuel-oil heating at a lower cost (depending on fuel prices). The cost, energy, and environmental advantages of such displacements depend on achieved efficiencies and on how users set ductless systems to interact with base fossil heating systems. A study of over 100 homes in Massachusetts collected detailed data on 150 ductless mini-split heat pumps (DMSHPs) and on heating systems that had previously fully heated the study homes. This paper examines when residents used ductless systems and base systems and estimates the relative costs of that use. Because the study was conducted after installation, it could not definitively determine savings, but it could identify use factors that impacted savings.

To estimate the heat provided by DMSHPs, the study authors directly monitored temperatures and indirectly metered air flow at the DMSHP indoor head. To estimate space heating provided by primary systems, the authors used run-time meters, gas valve metering, and oil pump run times and installed nozzle sizes. These data provided the information necessary to establish system use across a range of outdoor temperatures.

Mapping heating use enabled the authors to study users' behavior, estimate fuel or electricity offset (heating savings) due to the DMSHP heat provided, and investigate opportunities for savings by better understanding various user behaviors. As cold-weather DMSHPs become increasingly capable and efficient at lower temperatures, this study can be a resource for identifying cost, energy, source, and site energy benefits.

Introduction

The Massachusetts and Rhode Island Program Administrators (PAs) commissioned Cadmus and its subcontractors (the evaluation team) to conduct an *in situ* study of ductless mini-split heat pumps (DMSHPs) in Massachusetts and Rhode Island. This study examined energy use for over 150 DMSHPs and sought to answer these primary research questions:

- How much energy does the installation of a high efficiency[1] DMSHP save compared to a standard efficiency DMSHP or other type of heating and cooling equipment?
- When do DMSHPs run in each season, how much energy do they consume by season (i.e., what are the load shapes), and how much heat do they provide?
- How does DMSHP performance correlate with the units' rated capacity and efficiency and with ambient conditions?

[1] The minimum efficiency requirements of a DMSHP in this study were 18 SEER, 9 HSPF.

To understand performance and efficiency, the evaluation team had to quantify the output or delivered capacity of each indoor unit (or head) for each DMSHP unit. Most previous industry studies logged only the amperage or the total power consumption of DMSHP units then used various published efficiency ratings to roughly calculate their heating and cooling output. Those studies, however, did not factor in that unit capacities can vary greatly at given indoor and outdoor temperatures. Methods using temperatures, power use, and efficiency mapping very much depend on engineering data that often remains unpublished. For this study, the evaluation team directly measured the relevant parameters needed to calculate the heating output, including airflow and temperature differential across the indoor head. Continuously monitoring the heat output allowed the team to compare heat provided by DMSHPs and by primary systems.

Calculation of Heat Provided by DMSHP

Equation 1 and Equation 2 determined the heating amount delivered to a conditioned space. For systems with multiple indoor units (i.e., multi-zone), summing the delivered capacity from each head for every minute produces a system's total delivered capacity (i.e., for each outdoor unit and set of heads).

Equation 1. Heat Transfer Rate Using Mass Flow Rate of Air

$$\dot{Q} = \dot{m} \cdot \Delta h$$

Where:

$\dot{Q} = \ heat\ transfer\ rate\ \left[\frac{Btu}{hr}\right]$

$\dot{m} = mass\ flow\ rate\ of\ air\ \left[\frac{lbm\ of\ dry\ air}{hr}\right]$

$\Delta h = change\ in\ specific\ enthalpy\ of\ airflow\ \left[\frac{Btu}{lbm\ of\ dry\ air}\right]$

Equation 2. Simplified Heat Transfer Rate Using Volumetric Flow Rate of Air

$$\dot{Q} \approx (4.5) \cdot \dot{V} \left[\frac{ft^3}{min}\right] \cdot \Delta h \left[\frac{Btu}{lbm\ of\ dry\ air}\right]$$

Where:

$\dot{Q} = \ heat\ transfer\ rate\ \left[\frac{Btu}{hr}\right]$

$(4.5) = \text{ Unit converstion, from minutes to hours, and from cubic feet of air to pounds of air}$ [2]

$\dot{V} = volumetric\ flow\ rate\ of\ air\ \left[\frac{ft^3}{min}, or\ CFM\right]$

$\Delta h = change\ in\ specific\ enthalpy\ of\ airflow\ \left[\frac{Btu}{lbm\ of\ dry\ air}\right]$

[2] This conversion factor assumes air at standard conditions (70°F and 1 atmosphere).

The evaluation team directly measured the change in enthalpy (produced through Equation 2) using three temperature and humidity sensors on a unit's supply opening and one temperature and humidity sensor at the return air grill.[3] The evaluation team measured airflow using Alnor balometers and collected the corresponding one-minute logged measurements of fan amperage. The team logged fan amperage for the study's duration and then converted the findings to airflow. The Consortium of Advanced Residential Buildings used a similar method for a study of seven DMSHPs (Williamson and Aldrich 2015). The evaluation team considered using a duct blaster-based powered flow hood, as used by Williamson and Aldrich, but that method did not prove practical for the 100 homes included in the study. Instead, the evaluation team compared the airflow measurements produced by the Alnor balometer and an engineered nozzle with a duct blaster-based powered flow hood in six houses. The Alnor consistently read higher than the powered, with values averaging 11% higher than those produced through the flow hood, with the powered flow hood.

Putting Airflow and Current Together

The evaluation team used the airflow and current (amperage) data to create fan performance curves and to convert the logged indoor unit amperage data into functional airflow values for the entire logged period. Figure 1 presents a graph of current spot measurements, plotted against measured airflow at the five available speeds for this head, with the fan current on the x-axis and the airflow on the y-axis. The horizontal, dashed lines indicate published airflow ratings from available manufacturer literature. The evaluation team developed this type of correlation for each type of head in the study. The team then estimated airflow logged metered amperage values.

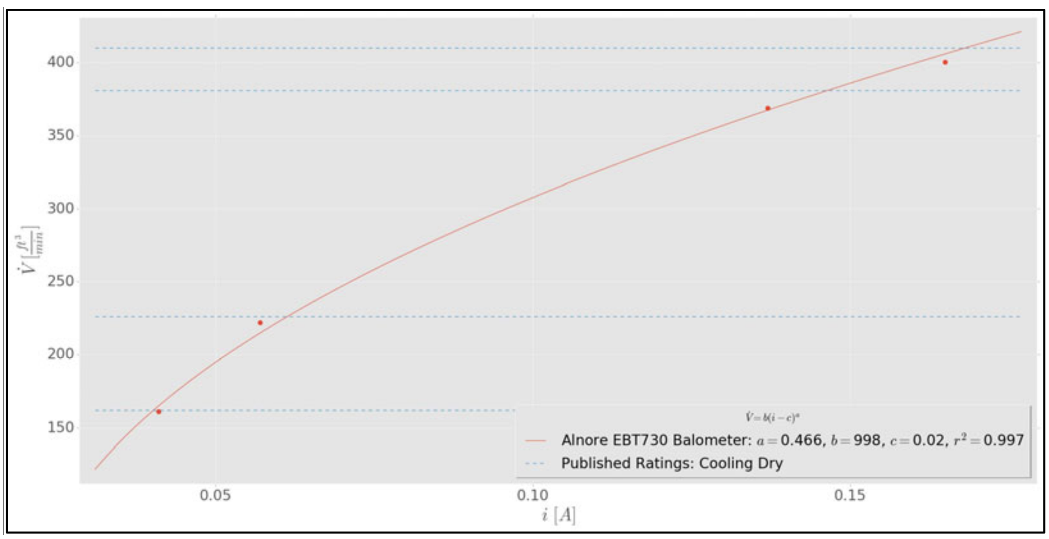

Figure 1. Example Airflow Plot, Maker B, Model 1

[3] Enthalpy is a measure of heat contained per unit of mass, often measured in BTUs per pound. A measurement of the enthalpy of an airstream includes the energy of the dry air (sensible heat) and of the energy contained in the moisture in the air (latent heat).

Equation 3 defines the best fit line for the example in Figure 1. In general, the airflow measurements using balometers and adjusted as discussed above produced airflow estimates roughly 10% lower than manufacturers' published values.

Equation 3. Airflow as a Function of Fan Current

$$\dot{V} = b(i - c)^a$$

Where:

$\dot{V} = volumetric\ flow\ rate\ of\ air\ \left[\frac{ft^3}{min}, or\ CFM\right]$

$i = fan\ current\ [amps, or\ A]$

$a = exponent$

$b = a\ constant$

$c = the\ measured\ current\ draw\ for\ the\ head\ when\ the\ fan\ is\ not\ running$

$r^2 = the\ coefficient\ of\ determination$[4]

Calculation of Heat Provided by Primary Heating Systems

The study focused on metering DMSHPs at a detailed level, as described above. The evaluation team employed a simple method of metering baseline heating systems—including boilers and furnaces—using current transformers (CTs) or motor run-time loggers to meter the gas valve on gas systems and the burner motor on oil-fired systems. Heat output was estimated using the systems' rated output and the run time of the combustion system, as measured at the gas valve or oil burner motor. Where possible the rated output was adjusted based on the nozzle or orifice size using manufacturer's ratings for that specific nozzle or orifice. The actual output may not exactly match the rated output so comparisons of the base systems' output should be considered approximate.

Equation 4. Heating Provided by Primary Heating System

$$\dot{Q} = \text{Rating} \cdot \%\ \text{runtime}$$

Where:

$\dot{Q} =\ average\ heat\ provided\ \left[\frac{Btu}{hr}\right]\ at\ temperature\ t$

$\text{rating} =\ heat\ output\ \left[\frac{Btu}{hr}\right]$

$\%\ \text{run time} = \left[\frac{hours\ runtime}{hours\ in\ temperature\ bin}\right]$

Time Series Analysis of Heat Provided by DMSHP and Primary Heating Systems

The evaluation team calculated the heat that each system provided for each minute and then grouped the data by outdoor air temperature bins.

Figure 2.

[4] Known as the coefficient of determination, r^2 is a metric used to describe how well a dataset fits a given trend line or curve. This value ranges from 0 to 1; a value of 1 indicates a perfect fit of the data to the curve; and a value of 0 represents no fit at all. An r^2 value of 0.9 or higher generally is considered an excellent fit.

Figure 2 shows an example site with the average rate of heat (in BTUh) provided by three house heating systems for a complete heating season. The evaluation team metered all heating systems in the home, which included a gas furnace, an older (installed before 2009) ducted heat pump, and a high efficiency DMSHP capable of operation when outdoor temperature is -5°F. The polynomial regression line (black curve fitted to the sum of average BTUs from all heating systems) represents the average heating signature of the home.

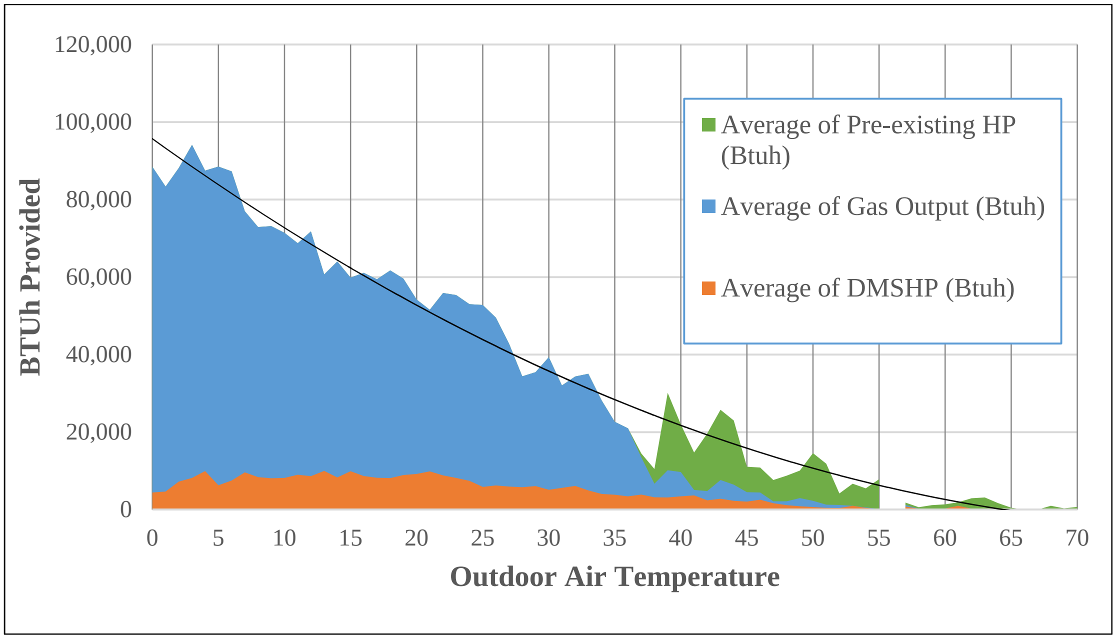

Figure 2. Example Site Heating Plot

Several observations can be drawn from this figure:

- At 0 degrees Fahrenheit (°F), the house load is about 98,000 BTUh.
- The regression line indicates that the house balance point is about 64°F, meaning the homeowners cease using heat at an outdoor air temperature of about 64°F.
- The DMSHP provides heating down to 0°F, with some apparent drop-off below 5°F.
- The DMSHP provides a peak capacity of about 10,000 BTUh, and use tails off as temperatures rise and the heating load drops. This may result from a limited amount of heat needed in the room or may be an artifact of user behavior.
- The existing ducted heat pump is used only during warmer temperatures.
- The DMSHP provides less than 15% of the home's space heating needs.

Figure 3 shows a 9,000 BTUh ductless system operating in a bedroom with an 84,000 BTUh oil furnace, providing primary heating to a 2,300-square-foot home.

Several observations can be drawn from this figure:

- At 0°F, the house load is about 70,000 BTUh (i.e., about 80% of the furnace's capacity).
- A visual inspection indicates that the house balance point is about 61°F.
- The DMSHP provides heating down to 0°F, with a relative peak at about 10°F.

- The DMSHP average capacity never approaches its 9,000 BTUh, probably because this is not needed in the bedroom it serves.

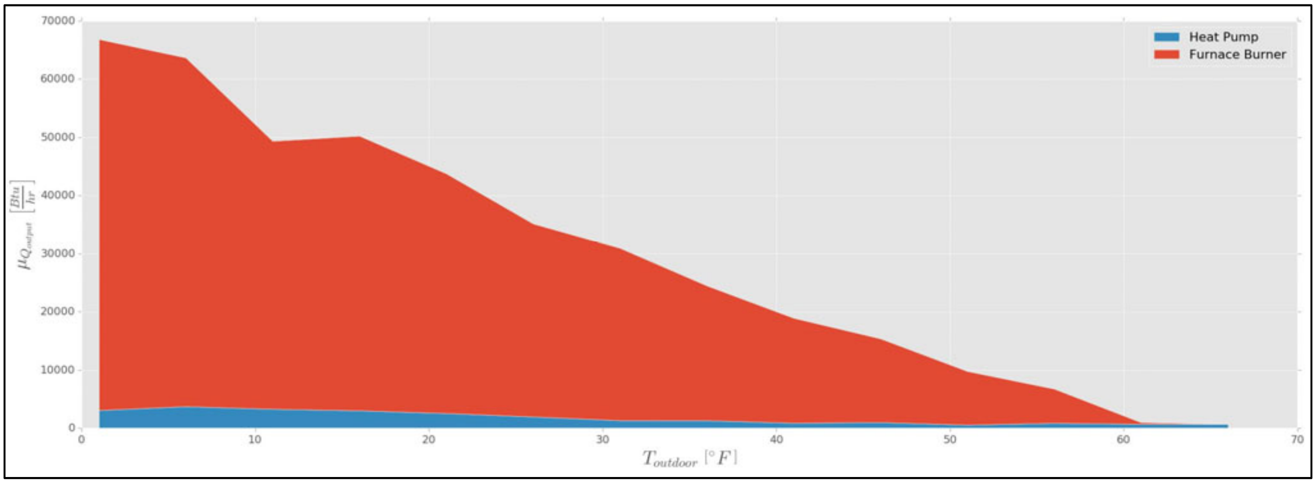

Figure 3. DMSHP and Oil Furnace (Site #036)

Figure 4 shows a 9,000 BTUh ductless system operating in a bedroom with a 77,600 BTUh gas furnace, providing primary heating to the 2,400-square-foot home.

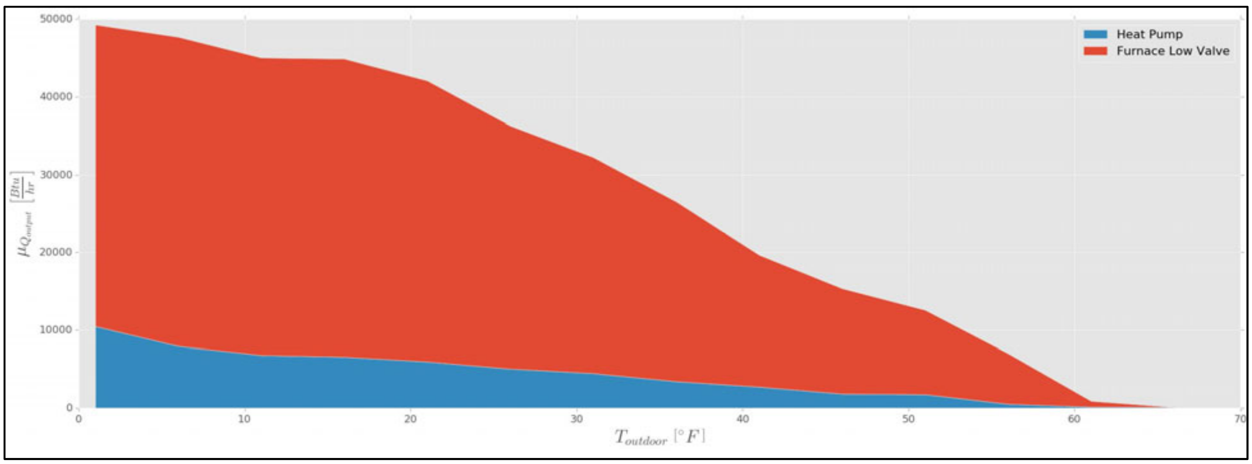

Figure 4. DMSHP and Gas Furnace (Site #021)

Several observations can be drawn from this figure:

- At 0°F, the house load is about 50,000 BTUh (i.e., about 65% of the furnace's capacity).
- The house balance point is slightly higher than 60°F.
- The DMSHP provides heating down to 0°F, with a relative peak at about 0°F.
- The DMSHP provides heat at its capacity of 9,000 BTUh at 0°F; it appears to be used to provide the bulk of heat to the bedroom.

Summary of DMSHP Energy Consumption in the Heating Season

Figure 5 shows the total energy consumed for 150 DMSHPs from November 1, 2014 through April 30, 2015. A common metric of DMSHP size is rated cooling capacity. The average DMSHP size was just over 14,000 BTUs (~1.2 tons). To compare consumption of these DMSHPs, which varied in size from 9,000 – 24,000 BTUs, the authors normalized total energy consumption for each DMSHP by its rated cooling capacity. The energy consumption of each DMSHP in Figure 5 is expressed in kilowatt-hour per rated ton of capacity (kWh/ton).

Clearly, the usage of the DMSHPs in this study varied widely. Median energy consumption was 340 kWh/ton. Half of the DMSHPs consumed on average 121 kWh/ton and the other half consumed over ten times that amount (1,433 kWh/ton).

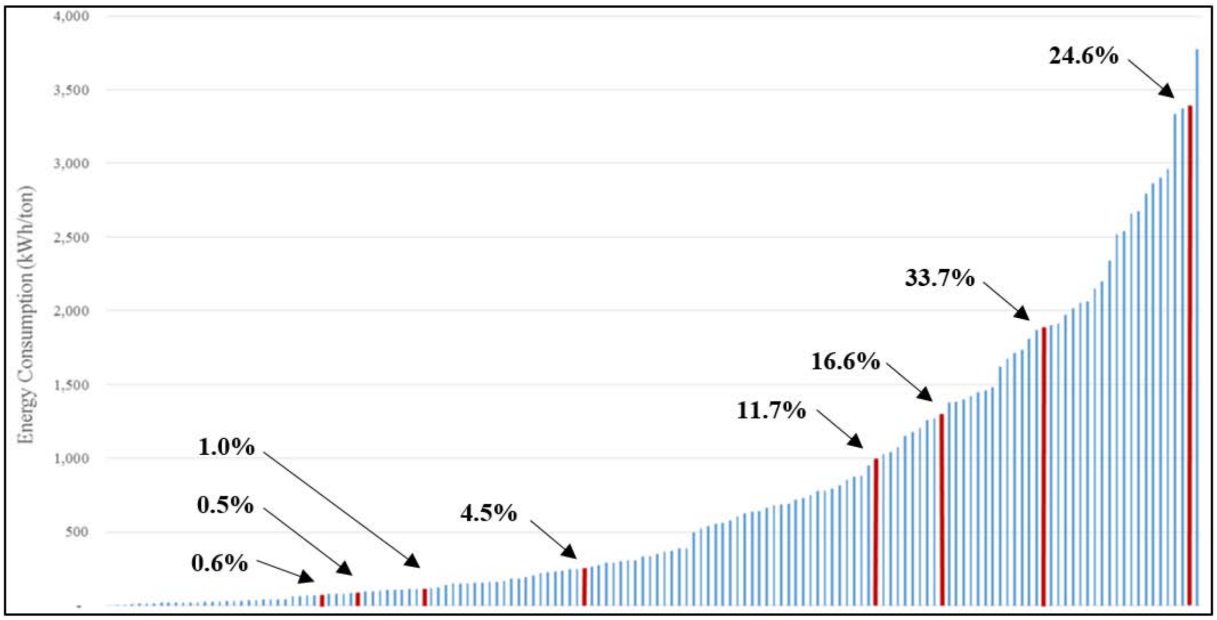

Figure 5. Distribution of Normalized Energy Consumption of 150 DMSHPs

The red lines in Figure 5 highlight eight different sites that the authors randomly chose to further investigate. Table 1 summarizes space heating use at the eight sites. DMSHPs provide from 0.5% to 34.0% of these sites' heating needs. The DMSHP contribution percentages from Table 1 are called out in Figure 5 for each site. The sites' total heat usage also varies greatly, from 34 MMBTU to 109 MMBTU. The primary system heating MMBtu values represent heat output. Thus, depending on the efficiency, actual fuel use may be 10% (e.g. for 90% efficient system) to 25% higher (for a 75% efficient system). In this group, little correlation occurs between the DMSHP indoor heads' capacity, the heads' location, and the proportion of heat provided by the DMSHP.

Table 1. Heat Provided by DMSHP and Primary Heating System for Eight Sites

Site	DMSHP Energy Consumed [kWh/ton]	DMSHP Output [MMBtu]	Primary Heating System Output [MMBtu]	Total Heat [MMBtu]	Portion of Heat Provided by DMSHP	Location of DMSHP Head(s)	Home Size (sq. ft.)
Site #006	110	0.8	76.3	77.0	1.0%	Bedroom	2,300
Site #021 (Figure 4)	1,301	11.4	57.0	68.3	16.6%	Bedroom	2,400
Site #022	98	0.5	108.2	108.8	0.5%	Living Room; Bedroom	1,700
Site #025	1,890	14.6	28.6	43.2	33.7%	Dining Room; Bedroom	1,776
Site #029	3,393	17.7	54.2	71.9	24.6%	Living Room; Dining Room	2,200
Site #036 (Figure 3)	245	1.7	36.2	37.9	4.5%	Living Room	1,100
Site #055	1,001	4.0	30.5	34.5	11.7%	Family Room	2,100
Site #060	90	0.6	44.4	45.0	1.4%	Family Room	1,600

The Relative Economics of DMSHP Use

As outdoor temperature decreases, the efficiency and capacity of most combustion heating systems do not vary significantly. DMSHPs differ from combustion heating systems in that capacity and efficiency decrease as outdoor temperatures decrease. However, the heating need of a home increases as outdoor temperature decreases. Consequently, there is generally a temperature at which DMSHPs are more costly to operate than other heating options. The authors investigated the economics of DMSHP operation and compared operational costs to combustion heating systems. The relative costs of oil heating dropped sharply in 2015 and 2016, with prices just over $2 per gallon. Gas prices were roughly $1.27 per therm (EIA 2015). In Massachusetts, average electricity prices were roughly $0.19/ kWh (EIA 2016).

At warmer temperatures, a DMSHP offers the second-most cost-efficient form of heating, approaching that of a gas furnace (as shown in Table 2). At cold temperatures (17°F), the DMSHP remains less expensive to operate than all sources except a gas furnace. At the coldest temperatures and at the oil prices listed in Table 2, it becomes more economical to operate an oil furnace than a DMSHP when the outdoor temperature drops below 0°F. The table shows the cost to operate an oil furnace at an oil price of $2.19 (EEA 2016) and also for a more typical oil price of $3 per gallon.

Table 2. Relative Cost of Operating a Heating System

	Outdoor Temperature		
Cost per 100,000 BTU	0°F DMSHP COP = 2	17°F DMSHP COP = 3	48°F DMSHP COP = 4
DMSHP[1] (Assumed cost $0.19/kWh)	$2.79	$1.86	$1.40
Oil Furnace; 80% eff[2] (Assumed cost $2.19/gallon)	$2.17	$2.17	$2.17
Oil Furnace; 80% eff[2] (Assumed cost $3.00/gallon)	$2.98	$2.98	$2.98
Gas Furnace; 80% eff[2] (Assumed cost $1.27/therm)	$1.26	$1.26	$1.26
Propane boiler; 80% eff. (Assumed cost $3.00/gallon)	$4.63	$4.63	$4.63
Electric Resistance baseboard heat (Assumed cost $0.19/kWh)	$5.59	$5.59	$5.59

[1]Cost is based on the assumed COP in the column; COP actually varies based on operations and units.
[2]A duct loss of 10% is assumed for the furnaces.

The authors used a standard algorithm (See Equation 5) to determine cost of operation for the heating systems in Table 2. This example equation includes an adjustment for estimated duct losses of 10%:

Equation 5. BTU Cost Estimate for Central Oil Furnace

$$\text{Cost}\ /100{,}000\ \text{BTU} = \frac{\$2.19}{\text{gallon}} * \frac{\text{gallon}}{1.4 * 100{,}000\ BTU} * \frac{1}{80\%\ efficiency} * \frac{1}{90\%\ duct\ eff.} = \$2.17$$

Overall, a DMSHP costs less per delivered BTU than propane or electrical resistance at all temperatures, and it costs less per delivered BTU than oil for all but the coldest temperatures. However, DMSHPs cost more to operate than a gas furnace for all temperatures.

Usage Patterns

DMSHP use greatly varies, with some units operating with increasing frequency in colder periods, much as a central system might operate (Figure 6); others are used episodically to heat a seldom-used space or to add additional heat where wanted (Figure 7).

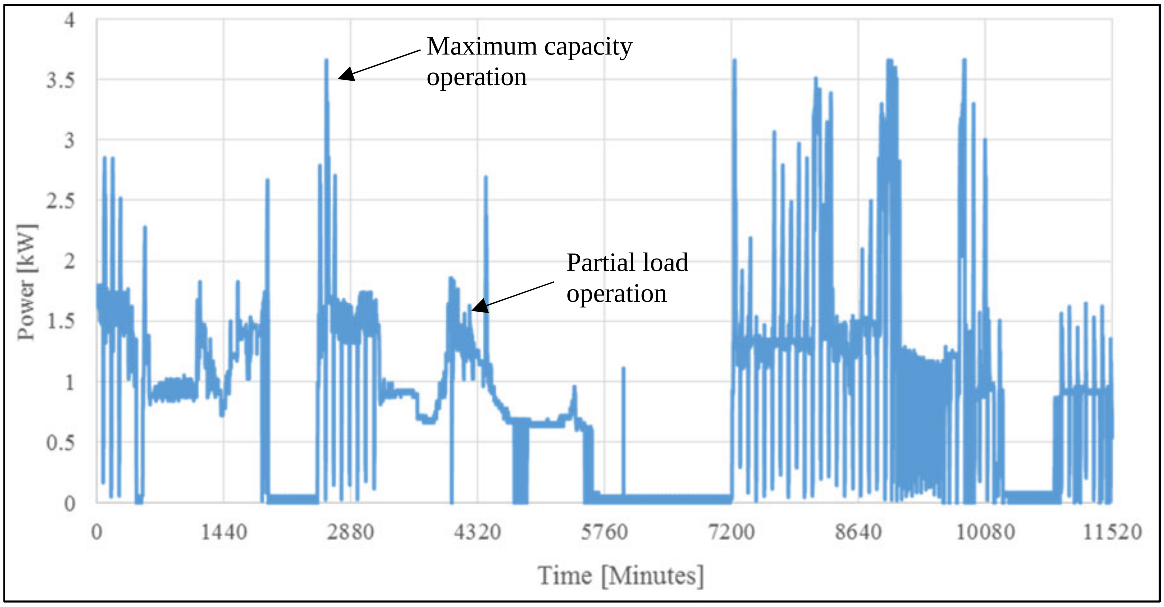

Figure 6. Relatively Continuous Use of a DMSHP

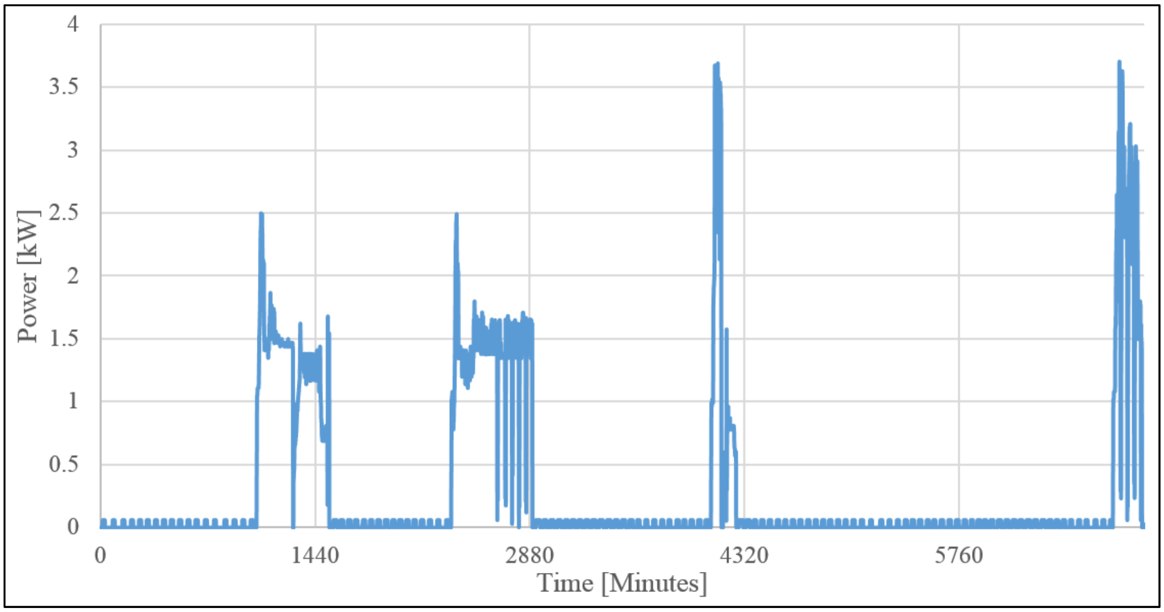

Figure 7. Episodic Use of a DMSHP

Discussion

How a DMSHP is used is one of the largest determiners of fuel savings and cost effectiveness. Table 3 shows the normalized heating energy consumption for 150 DMSHPs metered in Massachusetts and Rhode Island (also see Figure 5). The evaluation team surveyed the metering study participants to understand their motivation to purchase their DMSHP system(s). Most (65%) purchased the DMSHP for both its heating and cooling capability. Some (31%) said they purchased the DMSHP primarily for its cooling capability and were not particularly interested in using it for heat. A small percentage of participants (4%) purchased the DMSHP exclusively for its heating ability. The team found significant differences in DMSHP use between participants who said they purchased it primarily to cool or primarily to heat the space. Those who purchased the DMSHP for cooling did use it for heat, but it provided only about one-fourth the heat of the DMSHPs purchased primarily for that purpose.

Table 3. Normalized DMSHP Energy Consumption for Winter 2014–2015

Stated Purchase Intent	kWh/ton	% of Participants
Purchased for Cooling	349	31%
Purchased for Heating	1,561	4%
Purchased for Heating and Cooling	930	65%
Total	777	100%

Figure 8 shows the distribution of DMSHP heating energy consumption (data also shown in Figure 5) as well as the purchase intent. Though few participants purchased a DMSHP primarily for its heating ability, the two systems with the highest energy consumption fall into this category. This figure also shows that nearly all of the least-used DMSHPs were purchased primarily for cooling.

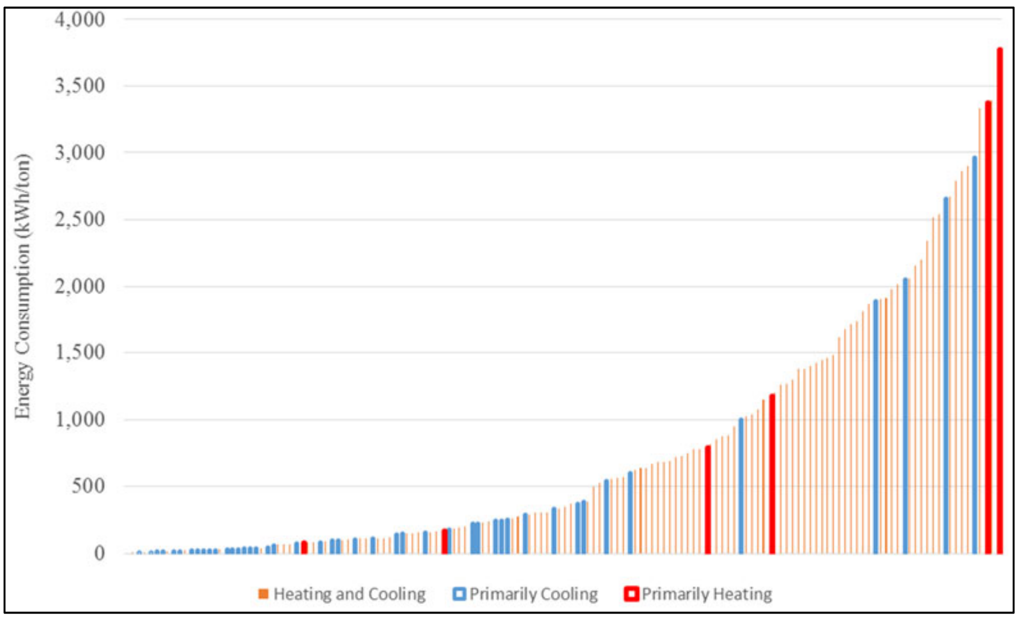

Figure 8. Distribution of Normalized Energy Consumption and Purchase Intent for 150 DMSHPs

Although some DMSHPs operated at maximum capacity (see Figure 4), many did not. Some of the reasons a DMSHPs may not operate at its maximum capacity include:

- ***User choice based on economics.*** A homeowner may fully understand the economics of operation and therefore choose to use the DMSHP minimally as needed, or cease operation when outdoor temperature drops.
- ***User choice based on performance.*** Some homeowners prefer “hot” air that they are accustomed to from more traditional heating systems so when the performance of a DMSHP decreases (generally when outdoor temperature also decreases) they may choose not to operate the DMSHP.

- ***It is located in low-occupancy area.*** If the DMSHP is in a spare room for example, a homeowner may decrease the temperature setpoint of the room.
- ***It is located in zone with coincident heat.*** If primary (e.g. central furnace or boiler) systems are not zoned, users may not be able to turn the temperature setpoint down or off in a space that is also served by a DMSHP. In this common scenario, whenever the primary system operates it adds heat to the space served by the DMSHP. Consequently, the DMSHP does not operate at its maximum capacity or may not operate at all.

If the primary central heating system can be shut off in a zone, the DMSHP would become the primary heat source for the space and its heating capacity would increase.

Conclusions

Although DMSHPs can save homeowners space heating costs compared with oil, propane, and electric-resistance heating sources, they cost more to operate per delivered BTU of heat than do gas-fired sources. They are not used for a great number of hours, partly because of how they interact with primary heating sources and partly because of their sizing in relation to the spaces they serve. Most were installed as secondary system without intention to serve the entire load, and many were installed primarily to provide space cooling. Program planners may want to understand how a potential market intends to use a DMSHP; in Massachusetts and Rhode Island the authors found differences in DMSHP energy consumption for homeowners who were motivated to purchase the DMSHP for cooling (lower usage) compared to heating (higher usage).

The authors continue to examine sizing practices and heat loads for spaces served by the studied DMSHPs.

References

Massachusetts Executive Office of Energy and Environmental Affairs (EEA). 2016. *Heating Oil Price Survey for April 12, 2016* http://www.mass.gov/eea/energy-utilities-clean-tech/home-auto-fuel-price-info/heating-oil-price-surveys.html

U.S. Energy Information Administration (EIA). 2015. *Natural Gas Prices.* https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SMA_m.htm

U.S. Energy Information Administration (EIA). 2016. *Average Price of Electricity to Ultimate Customers by End-Use Sector.* https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a

Williamson, James, Aldrich, Robb. 2015. *Field Performance of Inverter-Driven Heat Pumps in Cold Climates.* http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/inverter-driven-heat-pumps-cold.pdf