Electrification Prognostication: A Data-Driven Approach to Predict Heating Operation of Ductless Mini-Split Heat Pumps

Patrick Hewlett, DNV

ABSTRACT

This paper explores the use of yearlong measurement and verification data on 229 ductless mini-split heat pumps (DMSHPs) installed at 138 residences in the Northeastern U.S. to predict the heating season operation of DMSHPs when sharing the heating load with other systems. Due to their modular design and minimal installation barriers, DMSHPs can be an attractive gateway for customers to high-efficiency, lower-carbon heating alternatives in cold climates. In some cases, their modularity opens the door for partial displacements in which the customer retains their existing fossil fuel heating system to share the building's heating load with the mini-split.

In such scenarios, the DMSHP's heating load share is unknown and can be highly variable. Program administrators have attempted to account for such *partial displacements* through different algorithms and factors in technical reference manuals (TRMs); however, such factors often overestimate the heat pump's heating share and associated impacts.

By leveraging participant characteristics that are typically collected by program administrators—e.g., climate zone, preexisting heating fuel, cooling status—the authors have developed a model to forecast the expected heating output fraction and associated energy and carbon impacts from incented DMSHPs. This paper examines the most predictive indicators of DMSHP operation to assist program administrators in designing and marketing heating electrification measures and incentives to optimize the achieved carbon offset per installation. As the database of heat pump operation grows with remote monitoring capabilities, the authors explore the potential for machine learning-based enhancements to the model.

Introduction

The decarbonization of space heating through electrification has been increasingly emphasized by utility programs, particularly among cold-climate states with aggressive carbon emissions reduction targets. This challenge requires a significant behavioral shift from end-users, who have relied on fossil fuels for generations to keep their homes comfortable during the heating season. Despite targeted incentives and a maturing market of products, uptake in heat pumps has been slower than desired (Nerkar and Ngo 2023).

Ductless mini-split heat pumps (DMSHPs) provide homeowners an opportunity to more gradually move away from fossil fuels. DMSHPs are modular and, if desired by the homeowner, can be installed without significantly reconfiguring the home's existing heating configuration. Such installations, in which the preexisting heating system remains and shares the home's heating load with the DMSHP, are referred to as partial displacements.

Despite slower progress than desired, utility programs process more and more DMSHP installation incentives each year. With the advent of the Inflation Reduction Act, through which homeowners can receive significant federal tax credits for installing heat pumps (ENERGY STAR 2023), adoption is expected to grow further. To measure progress against statewide carbon emissions reduction goals, utility program administrators (PAs) are tasked with estimating the energy impacts from each heat pump installation. Mature programs measure energy impacts by fuel, accounting for the displaced fossil fuel as well as the associated increase in electricity. The most mature programs leverage available site-specific data (e.g., location, dwelling type) or system-specific data (e.g., rated heating and cooling capacities and efficiencies) to customize the heat pump impact predictions. Traditionally, energy impact quantification is guided by savings algorithms and assumptions within state-wide or utility-specific technical reference manuals (TRMs).

Impacts from partial displacement DMSHP installations are particularly challenging to predict. "Partial displacement" spans a broad spectrum, from occasional, on-demand use during the heating season to constant, thermostat-driven operation. Some TRMs therefore reduce the "best-case" DMSHP impacts to more realistically account for load-sharing with other heating systems (NYS 2023). Other TRMs offer deemed savings estimates that reflect load-sharing by a portion of installations presumed to be partial displacements (Maine 2024).

Research Objective

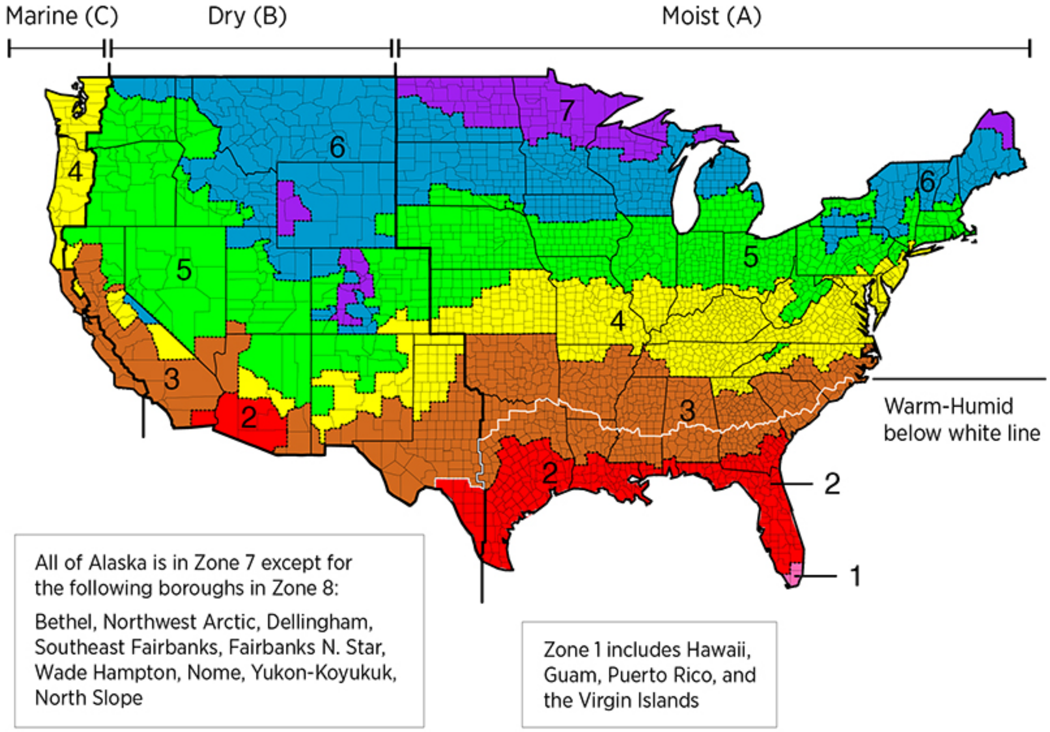
This paper examines results from yearlong measurement and verification (M&V) activities in the Northeastern U.S. to identify possible predictors of DMSHP use during the heating season. The author analyzed annual heating output data from 229 program-incented DMSHPs installed at 138 unique residential dwellings with site- and system-specific data archived through the programs' tracking databases. The objective was to identify which tracked parameters correlated most strongly with DMSHP heating operation. If certain site-specific parameters increase the likelihood that DMSHPs are used for heating, this data could refine the programs' impact predictions for energy and carbon offset per rebated DMSHP installation. Additionally, this information empowers policymakers and program administrators (PAs) to target the "ideal" DMSHP recipient through intelligent incentive designs and marketing to offset the most carbon emissions per dollar spent.

Methodologies

Data Collection

Over the last four years, the research teams deployed data loggers on 229 DMSHPs installed at 138 unique residential dwellings between 2017 and 2021. Each of the DMSHP recipients, the majority of which were homeowners of single-family detached residences, had received incentives from programs specifically targeting decarbonization through heat pumps and heat pump water heaters. Only four of the 138 residential dwellings were classified as multifamily dwellings.

The International Energy Conservation Code categorizes the United States into eight climate zones (CZs) as illustrated in Figure 2 (IECC 2018). The researched DMSHP installations occurred in the Northeastern U.S. among CZs 4, 5, and 6, as summarized in Table 1.



All of Alaska is in Zone 7 except for the following boroughs in Zone 8:

Bethel, Northwest Arctic, Dellingham, Southeast Fairbanks, Fairbanks N. Star, Wade Hampton, Nome, Yukon-Koyukuk, North Slope

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands

Figure 2. IECC climate zone designations. *Source: IECC 2018.*

Table 1. Participant characteristics by climate zone

IECC Climate Zone	Count of Dwellings	Installed DMSHP Quantity
4	40	62
5	78	134
6	21	33

Each of the incented DMSHPs was designated as “cold climate,” meaning they are designed to provide significant heating at very low outside air temperatures, with coefficients of performance exceeding 1.75 at 5°F (ENERGY STAR 2024). Initial outreach to the prior program participants involved a web survey that explored the customer’s satisfaction with the installed DMSHPs, including comfort during winter and summer seasons. Overall, 89% of survey respondents were satisfied with the DMSHPs’ comfort level on extremely cold days. Beyond this qualitative assessment of customer satisfaction with DMSHPs, the research did not quantitatively assess the DMSHPs’ ability to achieve the desired temperature setpoints in cold-climate conditions. Rather, the research focused on the quantification of energy impacts as a result of the DMSHPs’ displacement of fossil fuels and the associated increase in electric consumption.

Field engineers deployed data loggers on DMSHP components of interest, including outdoor units (full-unit power including indoor unit(s) power, fan amperage) and indoor units (supply air temperature) to measure electric input and identify heating and cooling operating modes. Cloud-communicating loggers collected and securely transmitted DMSHP operational data for at least a year in order to capture the systems' full range of operation in winter, summer, and swing seasons.

In parallel with field data collection, research analysts compiled and extracted key information from program tracking databases. The author then compared this data with annualized heating operation per DMSHP as described in the next subsection.

Analysis

Upon retrieving the deployed loggers, research analysts correlated the DMSHP's electrical consumption (in kWh) with hourly outside air temperature (OAT) data from the most proximate National Oceanic and Atmospheric Administration (NOAA) station (NOAA 2024). For each metered DMSHP, kWh vs. OAT correlations during heating and cooling seasons were extrapolated over a full year using typical meteorological year (TMY) data for the same weather station. Weather-normalized kWh consumption was paired with equipment-specific performance ratings, as well as in-field performance monitoring data collected at a subset of twenty high-rigor sites, to derive the annual heating and cooling energy outputs per DMSHP at all sampled sites.

Analysts also established the most appropriate baseline system given the circumstances at each participant site. Baseline selection considered the operability and age of the preexisting equipment, the customer's likelihood of replacing the preexisting system regardless of program intervention, and the customer's preferred alternatives in such a replacement scenario. Typically, if the preexisting equipment was operable, it defined the baseline condition. Otherwise, if the preexisting equipment was inoperable or would have been removed anyway by the customer, or in cases of new construction or major renovation, the baseline was defined by the customer's preferred HVAC alternatives. The scope of the research did not include monitoring of the baseline system. Rather, the heating and cooling loads satisfied by the DMSHP were assumed to be equal to those that would have been satisfied by the baseline system. In other words, the metered heating operation of the DMSHP was presumed to correlate proportionally with energy impacts—the more the DMSHP operates during the heating season, the more the baseline fuel was presumably displaced.

After factoring in the performance efficiencies of the heat pump and baseline systems, the analysts compared each scenario's annual energy consumptions to quantify the gross energy savings achieved by the program per DMSHP. The team also quantified "all-fuels" savings into equivalent energy units, both "at site" (not accounting for energy losses due to generation, transmission, or distribution) and "at source." All-fuels energy impacts provide a consolidated metric that, depending on the mix of displaced fuels, generally correlates with carbon emissions reductions. For consistency, in the remainder of this paper, annual energy is quantified using units of one million British thermal units (Btu), or MMBtu.

Terms and Definitions

Before reviewing the results, it is helpful to define five terms related to the analysis of heating energy.

a) **Rated heating capacity** (Btu per hour) – The amount of energy per hour output by a heating system (in this case, a DMSHP) to achieve its lab-tested efficiency as published by the manufacturer. Capacity decreases with outdoor test temperature, so the temperature associated with the rated capacity must be specified. For this research, analysts used the rated heating capacity at the 47°F test temperature.

b) **Annual heating output** (MMBtu per year) – The amount of energy delivered per year by a heating system, in this case, a DMSHP. For partial displacement DMSHPs, the annual heating output can vary significantly, as explored later in this paper. Annual heating outputs were calculated for each metered DMSHP as described in the prior section.

c) **Annual equivalent full-load hours** (EFLH) (hours per year) – The ratio of the annual heating output (b) to the rated heating capacity (a) at a prescribed test condition. This term quantifies how frequently a system would operate over the course of a year if it operated exclusively at full load. HVAC system operation is typically forecasted in TRM-based savings estimates through the use of predictive EFLHs that vary by region.

d) **Predicted annual heating output** (MMBtu per year) – The product of rated heating capacity (a) and predicted heating EFLH (c), typically derived from a TRM or similar. This value generally represents the best available estimate of heating system operation based on its size and the region in which it is installed.

e) **Heating output fraction** – The ratio of actual annual heating output (b) to predicted annual heating output (d) as illustrated in the formula below. Heating output fraction, which can vary substantially above or below 100%, is the focus of this paper's research.

$$Heating\ output\ fraction = \frac{Annual\ heating\ output\ (Btu)}{Rated\ heating\ capacity\ \times EFLH}$$

Figure 1 illustrates the distribution of annual heating outputs and associated heating output fractions across all DMSHPs researched in this study. Each point along the x-axis represents an individual metered DMSHP. The vertical lines correspond with the left-hand y-axis and represent the annual heating output per metered DMSHP in MMBtu. The light blue dots correspond with the right-hand y-axis and represent the heating output fractions defined above. As TRM-based EFLHs are predictive averages, the annual heating output for some DMSHPs exceeded the predicted heating output—in other words, their heating output fractions (light blue dots) are above 100%. But the majority of DMSHPs fell short of the predicted heating output, resulting in light blue dots below 100%.

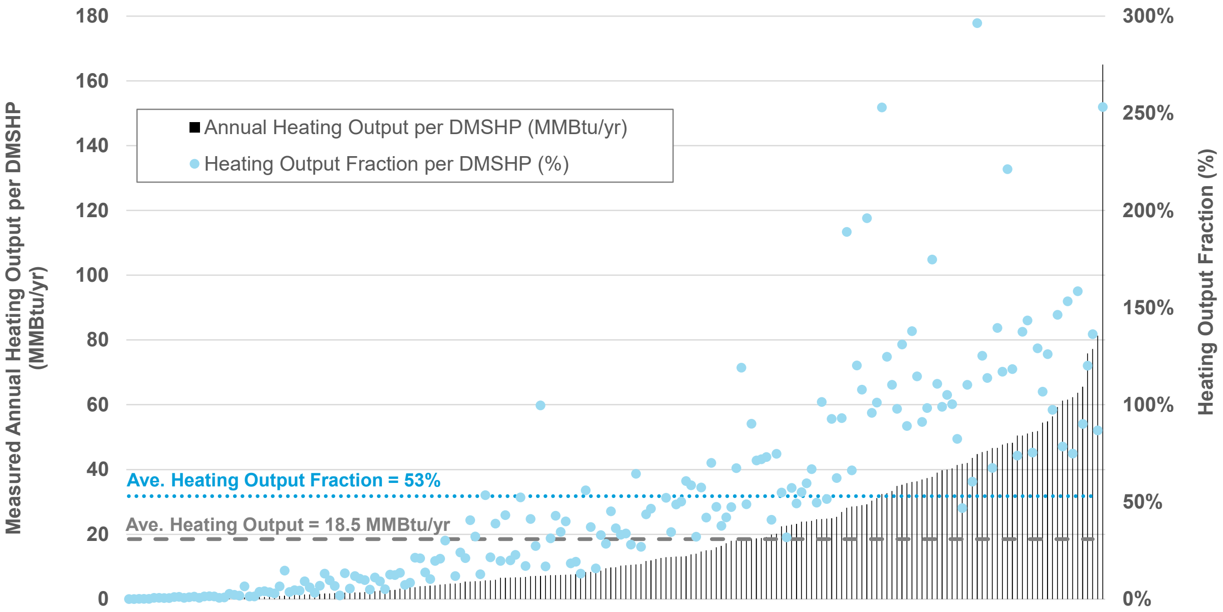


Figure 1. Distribution of annual heating outputs and output fractions among metered DMSHPs.

Analysis of Predictive Parameters

The author examined the effects on DMSHP heating output fraction among various system and customer characteristics known at the time of installation, as presented in the following subsections. Note that, for some metered DMSHPs, the system or customer characteristics were unknown, thereby reducing the sample counts available for analysis.

Climate Zone

Program administrators typically record the installation address of the rebated heat pump. In midstream or upstream programs, which often collect minimal data on the end-user, program administrators typically know the *region* in which the unit is installed. Based on the tracked address or region, the author examined how CZ correlated with DMSHP heating output fraction, as illustrated in Figure 3.

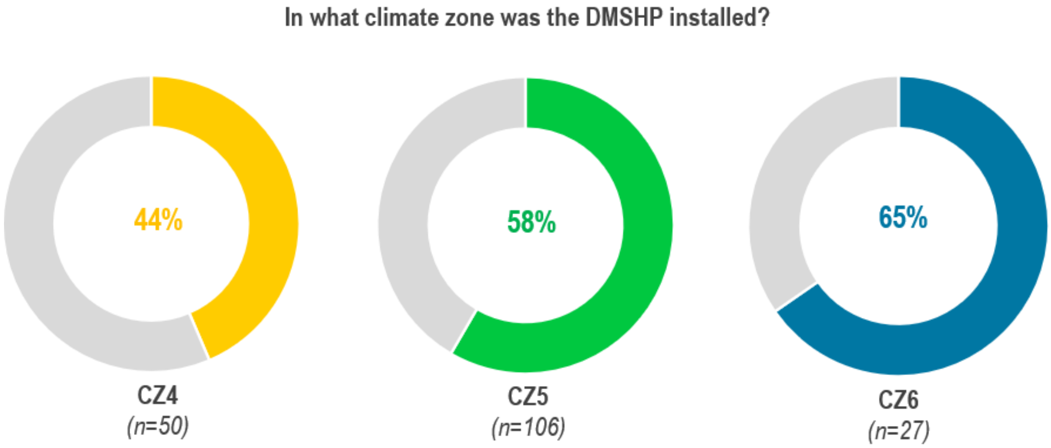


Figure 3. Variation of DMSHP heating output fractions with climate zone.

Heat pumps in colder climates (CZ5, CZ6) not only ran more often than those in warmer areas as might be expected given the longer heating seasons, they ran enough more that they also exhibited significantly higher heating output fractions than milder climates (CZ4). Heating output fractions for CZ4 and CZ6 were statistically significantly different at the 95% confidence interval. These results reinforce that climatological effects should be considered when predicting DMSHP operation. This correlation should not be extrapolated to milder climate regions without testing.

Preexisting Heating Fuel

The author next explored the effects of pre-installation heating fuel on DMSHP heating output fraction, as illustrated in Figure 4. The pre-installation heating fuel was available from utility tracking data, as PAs and contractors typically collect this data for downstream installations. When unknown, this information may be available from tax parcel records or the utilities' customer information databases. The availability and economics of other heating fuel alternatives may influence the homeowner's use of the DMSHP during the heating season.

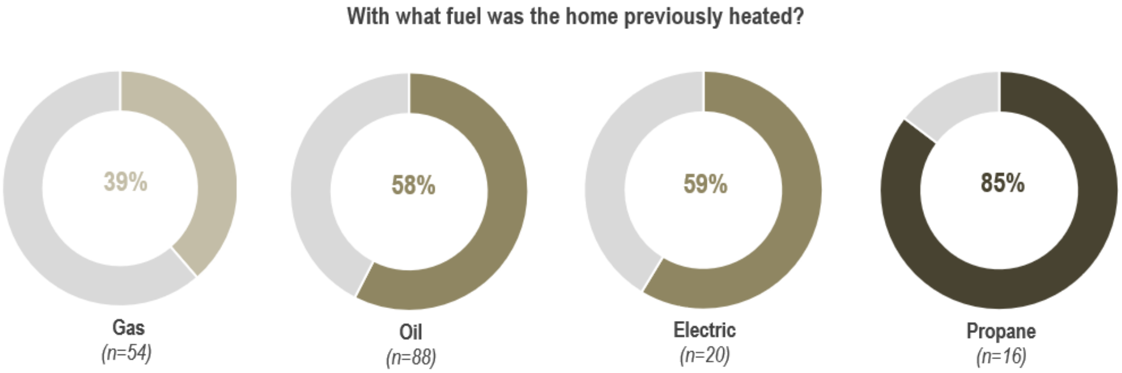


Figure 4. Variation of DMSHP heating output fractions with preexisting heating fuel.

Preexisting heating fuel appears to influence the homeowners' use of the DMSHP. Delivered fuels such as propane and home heating oil, which are more expensive per unit than natural gas, correlated with higher heating output fractions. The two fuels with the most sample points, gas and oil, exhibited heating output fractions statistically significantly different at the 95% confidence interval.

Customers that previously heated the affected space(s) with electricity—mostly through resistance but including a small number of preexisting heat pumps—demonstrated a heating fraction nearly identical to that of oil. Again, the unfavorable economics of electric resistance heating may have influenced the homeowners' use.

Results in Figure 4 do not account for the carbon emissions intensities of the various fuels. If we presume that the offset fuel would have been consumed if not for the installed DMSHP, propane and oil become even more impactful after applying their associated CO_2 equivalent factors.

Preexisting Heating System

Related, the author explored if the system that was the primary source of heat to the space now conditioned by the DMSHP correlated with DMSHP heating season use, as shown in Figure 5. This parameter is less frequently collected by implementers than heating fuel but was collected by the programs associated with the studied DMSHPs.

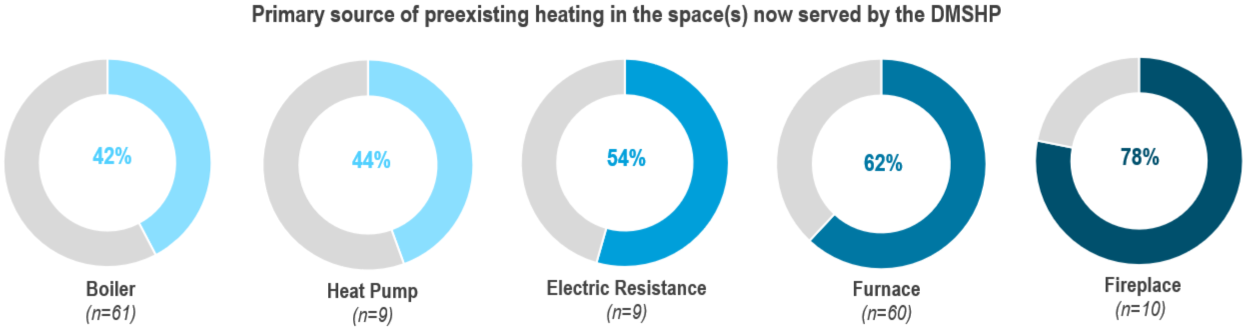


Figure 5. Variation of DMSHP heating output fractions with preexisting heating system type.

DMSHP heating use varies with heating system type, though relatively low sample counts should be considered for three of the five system designations. The two most prominent heating system types—boilers and furnaces—produced heating output fractions statistically significant at the 95% confidence interval. The author speculates that these distinctions may relate to the status of preexisting cooling, as covered in the next subsection. Homes with furnaces (and associated ductwork) may have been more likely to have existing central cooling. On the other hand, homeowners with boilers may have been more likely to install the DMSHP primarily for cooling comfort purposes.

Preexisting Cooling System

According to the 2020 Residential Energy Consumption Survey, 39% of residential dwellings in the Northeastern U.S. are centrally cooled, 42% are cooled with window air conditioners, and 11% are not mechanically cooled (EIA 2020). Homeowners without central cooling may be motivated to install DMSHPs for cooling purposes, either as a replacement for existing window units or to add new cooling to a previously uncooled space.

The author explored the effects of preexisting cooling system classification on DMSHP heating use, as illustrated in Figure 6.

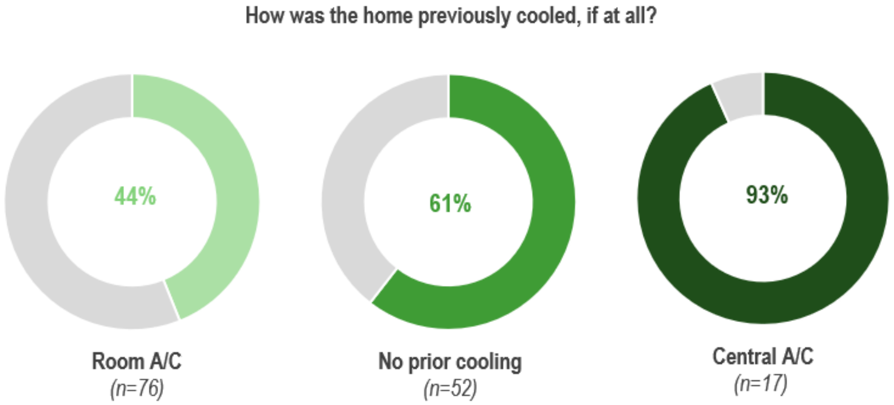


Figure 6. Variation of DMSHP heating output fractions with preexisting cooling classification.

The figure illustrates that cooling system classification affected DMSHP heating use. Customers with preexisting central air conditioners (CACs) exhibited the highest heating output fractions. While this finding is seemingly counterintuitive, the author hypothesizes that such customers were less motivated to install the DMSHP for cooling purposes than in other scenarios, thereby resulting in higher heating use. Consideration should be given to the relatively low sample count of such customers in the research pool.

On the other hand, customers with preexisting room air conditioners (RACs) may have been more likely to install the DMSHP as an RAC replacement, with heating a secondary benefit. DMSHP heating output fractions between customers with CAC and customers with RAC were statistically significantly different at the 95% confidence interval. Customers without preexisting mechanical cooling exhibited a heating output fraction between these two extremes.

Load-Sharing with Other Heating Systems

Some heat pump programs have evolved to encourage the whole-home *replacement* of fossil fuel heating systems with heat pumps through more attractive incentives. Such programs may still allow partial *displacements* in which the legacy fossil fuel system remains in place, but such installations typically correspond to lower incentives. The status of other heating systems operating alongside the DMSHPs is therefore collected by these programs to determine appropriate incentive amounts.

The author explored whether heating load-sharing correlated with DMSHP heating output fraction, as illustrated in Figure 7.

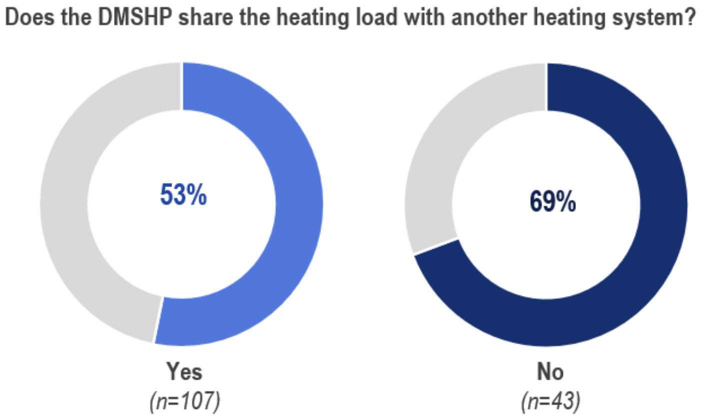


Figure 7. Variation of DMSHP heating output fractions with status of heating load-sharing.

As expected, DMSHPs that solely handle the heating load exhibit a higher heating output fraction on average than DMSHPs that share the heating load with other system(s). Nonetheless, systems that are presumed to solely handle the heating load exhibited only a 69% heating output fraction, indicating the possibility of oversizing.

DMSHP Installation Quantity

The researched heat pump programs allowed participants to install multiple DMSHP systems (i.e., multiple outdoor units), and each eligible system received incentives. The author next examined if single- versus multi-DMSHP installations correlated with heating output fraction, as illustrated in Figure 8. Note: this analysis does not differentiate between single-zone and multi-zone DMSHPs (i.e., indoor heads)—these results are addressed in the next subsection.

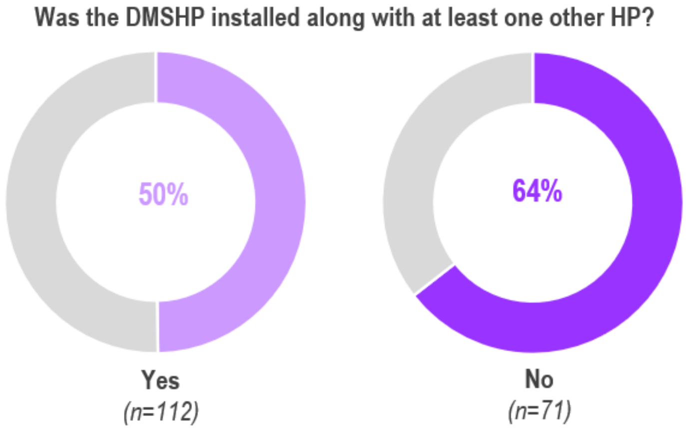


Figure 8. Variation of DMSHP heating output fraction with DMSHP installation quantity.

The figure illustrates that lone DMSHP system installations exhibited a 14% higher heating output fraction than DMSHP systems installed along with at least one other HP. The results suggest slightly diminishing returns in heating season savings when multiple DMSHPs are installed simultaneously.

Other Parameters

The author explored the variation in DMSHP heating output fraction among seven other distinctions of interest; however, the results were inconclusive for the reasons described below.

- **Single- versus multi-zone DMSHPs** – Heating output fractions were nearly identical between these two scenarios. Rated heating capacity—and, by association, the denominator of the heating output fraction— generally correlates with number of indoor heads.
- **Square footage of home** – Programs tracked only the total square footage of the home, not of the conditioned space(s) affected by the DMSHP, resulting in a weak correlation with heating output fraction.
- **Integrated controls** – Some programs incentivize the installation of integrated controls that optimize load-sharing between DMSHPs and other heating systems. However, the participant sample included too few installations with integrated controls for conclusive analysis.
- **Single-family versus multifamily dwellings,**
- **New construction versus existing buildings,**
- **Own versus rent status,**
- **Year-round versus seasonal occupancy** – The above four comparisons produced sample counts too low for conclusive analysis.

Conclusion

The Ideal DMSHP Recipient

Ideally, homeowners are willing to part with their legacy fossil fuel-fired heating systems and fully adopt heat pumps through whole-home replacement. But when homeowners are reluctant to do so, perhaps due to the nascence of cold-climate technology, a partial displacement DMSHP may provide a compromise between the status quo and a cleaner heating alternative. Such customers may learn over time that cold-climate heat pumps are able to meet their comfort needs throughout the winter, resulting in gradually higher heating output fractions and setting the stage for more comprehensive heat pump installations in the future. Based on the variations in heating output fraction examined above, the ideal DMSHP recipient in the residential sector can be profiled as follows:

- The customer resides in a northern climate (CZ5 or higher).
- The customer previously heated their home with a delivered fuel, ideally propane.
- The customer previously heated their home with a furnace.
- The customer's existing ductwork may have also provided central air conditioning.
- The customer has not retained any other heating system that shares the heating load within the zone(s) affected by the DMSHP.

Key Takeaways for Program Administrators

This research empowers program administrators and policymakers to design heat pump offerings that target the most impactful displacements of fossil fuels. Such targeting requires accurate and comprehensive tracking of site-specific information per rebated installation. Results illustrate that preexisting heating system type, fuel, and status, as well as preexisting cooling system type, each influence the operation of the rebated DMSHP during the heating season. Credibly collecting and tracking this data is a crucial first step to the success of a targeted heat pump initiative.

This research provides an opportunity to optimize how heat pump programs allocate funds to optimize carbon emissions reduction per dollar spent. Program marketing initiatives might consider customer characteristics and strategically deploy marketing collateral to ideal candidates based on predicted DMSHP operation. Program policies could allow a "sliding scale" incentive structure, with which incentives would correlate with each DMSHP's predicted fossil fuel displacement. Study results show that certain site-specific parameters, such as preexisting heating fuel and climate zone, could influence the appropriate incentive amounts most impactfully.

Additionally, this research allows program administrators to more accurately track progress versus goals related to energy efficiency and decarbonization. Not all DMSHP installations are equal, and as the body of this research grows, energy savings claims—and associated carbon emissions reduction— should reflect the variations in DMSHP heating operation with key characteristics of the customer and the installed system.

Future Research and Trends

This paper identified shortcomings related to the relatively low sample count of 229 DMSHPs metered through various heat pump program studies in the Northeastern U.S. Insufficient data occasionally limited the author's ability to explore hypothetical drivers such as dwelling type (single- versus multi-family), tenancy (own versus rent), and controls (integrated versus traditional thermostats). Sample counts diminish further when attempting to explore multivariable correlations with DMSHP heating operation: for example, DMSHPs installed in single-family homes with a preexisting propane-fired furnace and central air conditioning. Additionally, this research did not consider socio-economic factors and installation or maintenance costs when profiling the ideal DMSHP recipient—only the energy benefits.

To expand the body of research, program administrators and evaluators should proactively pool together relevant M&V and market research results as available. Organizations such as the Midwest Energy Efficiency Alliance's (MEEA's) Advanced Heat Pump Coalition (AHPC) serve as platforms for cross-jurisdictional sharing and collaboration on heat pump research (MEEA 2024). Consideration should be given to the regions in which the heat pump installations occurred, as there are obvious limitations in applying cold-climate heating results to milder climates, and vice versa.

Emerging industry trends will also unlock predictive analytics capabilities related to heat pump operation. The prevalence of advanced metering infrastructure (AMI) meters continues to expand, with Northeastern states Maine and Vermont nearly fully converted to AMI (EIA 2022). Other nearby states are catching up; for example, the Massachusetts Department of Public Utilities (DPU) recently approved grid modernization plans and AMI infrastructure investments (MA 2023). Depending on various site-specific characteristics, the availability of 15-minute premise-level data will supplement or supersede the need for equipment-specific M&V. Pairing AMI data with tracked customer characteristics will allow program administrators to continuously examine if and how a customer is using their heat pump.

As the breadth and depth of available data exponentially grow, the use of machine learning will unlock more powerful capabilities to recognize trends in heat pump use. Machine learning software can intake continuous streams of AMI data or cloud-communicating M&V data and instantaneously correlate observed system use with an unlimited array of site-specific and system-specific variables. These capabilities will be particularly critical in commercial or industrial sectors in which the heat pump may comprise only a small fraction of the electric meter's total consumption. Machine learning can not only identify the permutations of variables that most strongly correlate with DMSHP use but can provide real-time detection of suboptimal DMSHP use. This data may spur the creation of performance-based heat pump programs, with similar design and oversight as demand response programs, which incentivize the customer to increasingly offset fossil fuel consumption with cleaner heating alternatives.

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