Efficiency Maine Residential Heat Pump Impact Evaluation

Prepared for the Efficiency Maine Trust
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Cover: Installers in action installing a heat pump on a manufactured home in Maine.

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Term	Definition
AHI	The Affordable Heat Initiative (AHI) is a market-based initiative offering enhanced rebates for weatherization and heat pumps for low- and moderate-income homes. Homes qualify for participation based on participation in the Low Income Home Energy Assistance Program (LIHEAP) or ownership of homes with property values less than county-based thresholds established by Efficiency Maine.
AMI	Advanced Metering Infrastructure (AMI) is an integrated system of smart meters, communication networks, and data management systems. In this evaluation, we use the term AMI to refer to the source of 15-minute electrical data that we received.
BTU and BTU/h	British Thermal Units and BTU per Hour. A firing rate or heat delivery rate of 1 BTU per hour. A British Thermal Unit is the energy needed to raise the temperature of 1 pound of water one degree Fahrenheit.
CBAT	Efficiency Maine's cost benefit analysis tool (CBAT)
COP	Coefficient of Performance. This is a unitless ratio of heat added or removed by a heat pump to the energy used to move that heat. For example if 9,000 BTU (2.6Wh) of heat is removed from a home during the cooling season, and this takes 3,000 BTU (0.88kWh) of electrical energy, the COP of the heat pump is (9,000/ 3,000) or 3.0.
CV	Coefficient of variation (CV). A statistical measure of the dispersion of a population of data points relative to the mean. It is calculated by dividing the standard deviation by the mean.
effRT	The Efficiency Maine Reporting and Tracking System (effRT) is a SQL-based database. Efficiency Maine uses the effRT database to manage and track energy efficiency projects.
Free Ridership	A program participant who would have implemented the program measure or practice in the absence of the program. A free rider can be: 1) total, in which the participant's activity would have completely replicated the program measure; 2) partial, in which the participant's activity would have partially replicated the program measure; or 3) deferred, in which the participant's activity would have completely replicated the program measure but at a future time beyond the program's timeframe. (Maine TRM)
HESP	The Home Energy Savings Program (HESP) drives market-based home weatherization and installation of efficient heating systems by offering rebates and loans, providing customer and vendor education, and developing and maintaining a vendor network.
HSPF	Heating Seasonal Performance Factor is a heating efficiency rating for heat pumps that has units of BTU/watt-hours. $HSPF = \frac{Heating\ Delivered\ by\ Heat\ Pump\ \ over\ heating\ season(BTU)}{Energy\ used\ by\ the\ Heat\ Pump\ over\ the\ heating\ season\ (kWh)*1000}$
kW	A kilowatt (kW) is 1,000 Watts of power and is a rate of energy use. This measurement is usually used to show the peak power that a facility or a piece of equipment draws.

Term	Definition
kWh	A kilowatt-hour (kWh) is a measurement of electricity consumption equivalent to one kilowatt of demand for one hour.
LoRa	**LoRa** (from "long range") is a physical proprietary radio communication technique. It is based on spread spectrum modulation techniques derived from chirp spread spectrum (CSS) technology. It was developed by Cycleo.
Lost opportunity	New equipment in a newly constructed building or addition, or a replacement of failed equipment or removed equipment that has reached the end of its effective useful life. The annual savings for such installations reflect the efficiency gain from the rebated system as compared with a code-compliant alternative.
MMBtu	1 million BTUs. This nomenclature derives from the Roman numeral M for 1,000, so: a thousand, thousand BTUs. It is equivalent to the heat provided by about 9 gallons of oil used in an 80% efficient furnace or boiler.
Multi-zone heat pump	A heat pump that matches more than one indoor unit to a single outdoor unit.
Net-to-gross	Net-to-gross – The adjustment of evaluated savings to account for the share of savings attributable to the program. Net-to- gross includes two components (see definitions): free-ridership and spillover.
Realization rate	Realization rate (RR) – The ratio of evaluated impact and reported impact. Calculated as the total evaluated savings divided by the total filed savings, a RR >1.0 means that the program had larger impacts than were reported.
Relative precision	Relative precision – Precision, also termed absolute precision, is a measure of uncertainty or error around an estimate. Relative precision is absolute precision divided by an estimate of a mean.
Single zone heat pump	A heat pump that matches a single indoor unit to a single outdoor unit.
Spill Over	Additional energy efficiency savings due to program influences beyond those directly associated with program participation.
TRM	The Technical Reference Manual (TRM) documents Efficiency Maine's methods, formulas, assumptions, and sources that are used to estimate energy and demand impacts of energy-efficiency measures.

1 EXECUTIVE SUMMARY

This evaluation focuses on the installation of high efficiency heat pumps under the Home Energy Savings Program (HESP) and Affordable Heat Initiative (AHI) for the period from December 2019 through June 30, 2021. The majority of these heat pumps were supplemental heat pumps in that the previous heating system, usually a boiler or a furnace, remained in operation. The primary objectives of this study are to (1) quantify and verify electric energy and demand impacts (increases and decreases), (2) verify non-electric energy impacts (increases and decreases), and (3) analyze program cost-effectiveness.

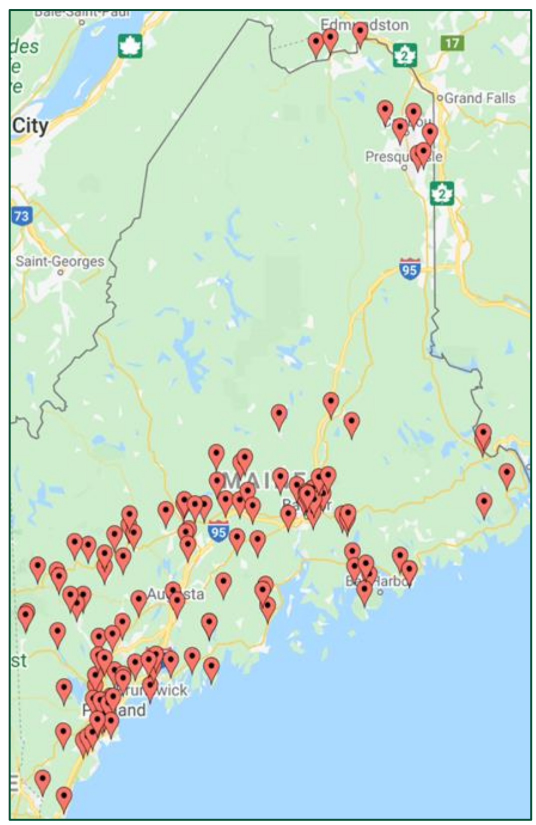
1.1 SAMPLING AND SITES INVESTIGATED

The initial sample design for this study was 92 sites and was expanded to the final sample design by program and strata as shown in Table 1 below. Ultimately, this study included 124 homes across all 16 Maine counties (Figure 1). We wanted to cover at least some homes in far northern Maine to ensure that the metered heat pumps experienced some very cold temperatures. We metered 12 homes north of Lincoln, Maine, of which nine were in one of the coldest regions of Maine: Presque Isle and north.

Table 1. Sample Design

Strata	Population Size (projects)	Coefficient of Variation (CV)	Sample Size (N)
Single Zone, Tier 1	2,497	0.75	20
Single Zone, Tier 2	9,573	0.75	60
Multi-zone	4,732	0.75	25
Property Assessed	1,150	0.75	12
LIHEAP	192	0.75	9
TOTAL	18,144		126

Figure 1. Home Locations



1.2 PARTICIPANT AND TRADE ALLY SURVEYS

Participants are highly satisfied with their program experiences and their heat pumps, rating the comfort of their home 4.7/5 when cooling, and 4.4 and 4.3 for HESP and AHI when heating (Figure 2). These are high ratings with half or more giving the highest category—"5-very satisfied," and most of the others one rating short of this (4).

Participants were asked what influenced their purchase, with 5 linked to the phrase “highly influential”. Figure 3 shows rebates and word-of-mouth from other participants were highly influential or nearly so.

Figure 2. Customer Satisfaction

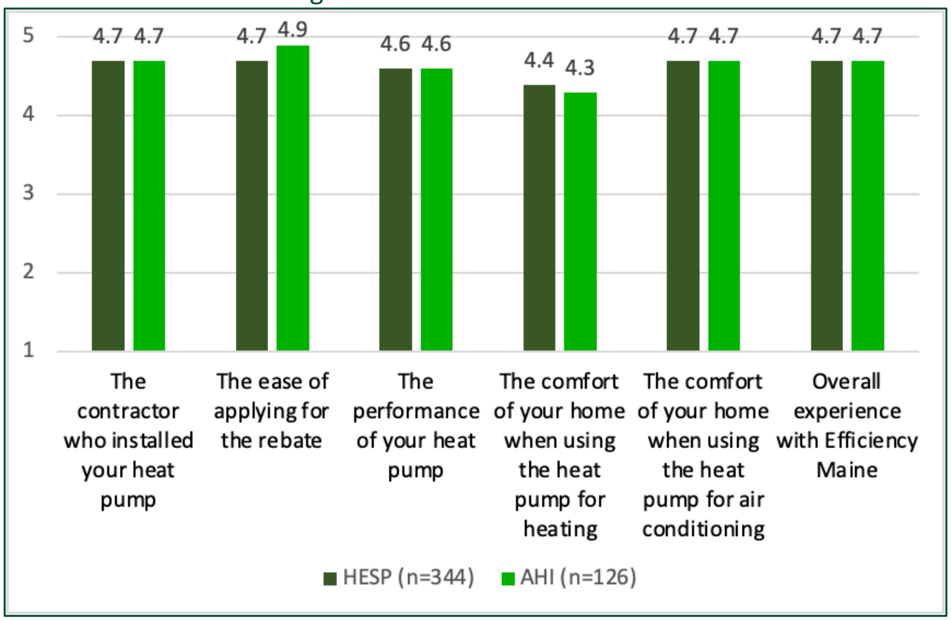
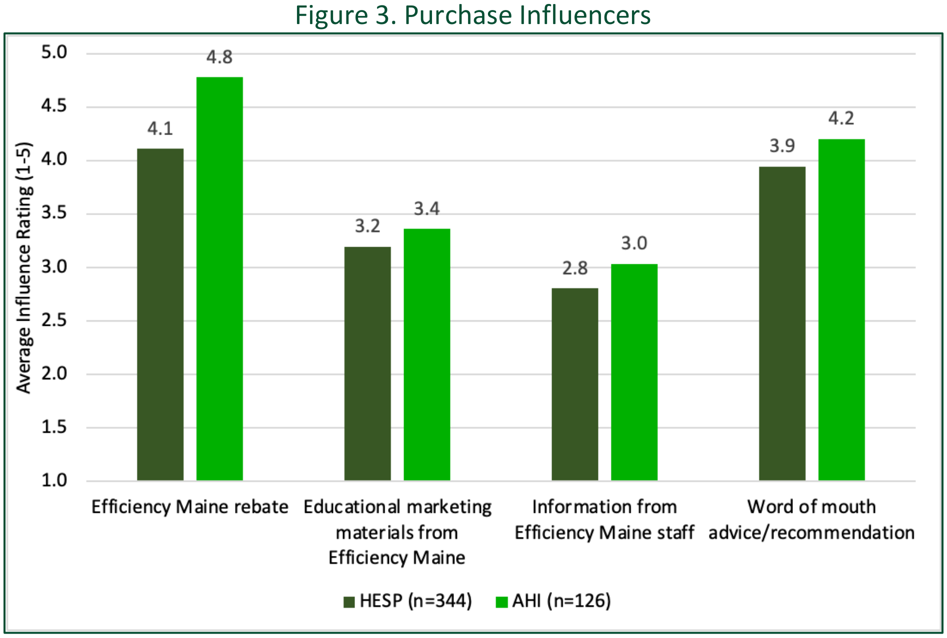


Figure 3. Purchase Influencers



As might be expected, rebates were a higher influence for lower income participants. Figure 4 shows a more detailed view of participants' intentions exploring what they would have done in absence of the program. In this chart, the rebate is again highly influential to lower income participants with very few indicating that they would have bought the same system at the same price without the rebate. Participants in the HESP program indicate that most would not have purchased a heat pump without the rebate, specifically 24% would not have made any purchase at all and 45% would have purchased different equipment.

Figure 4. Participants' Most Likely Purchase in Absence of Program

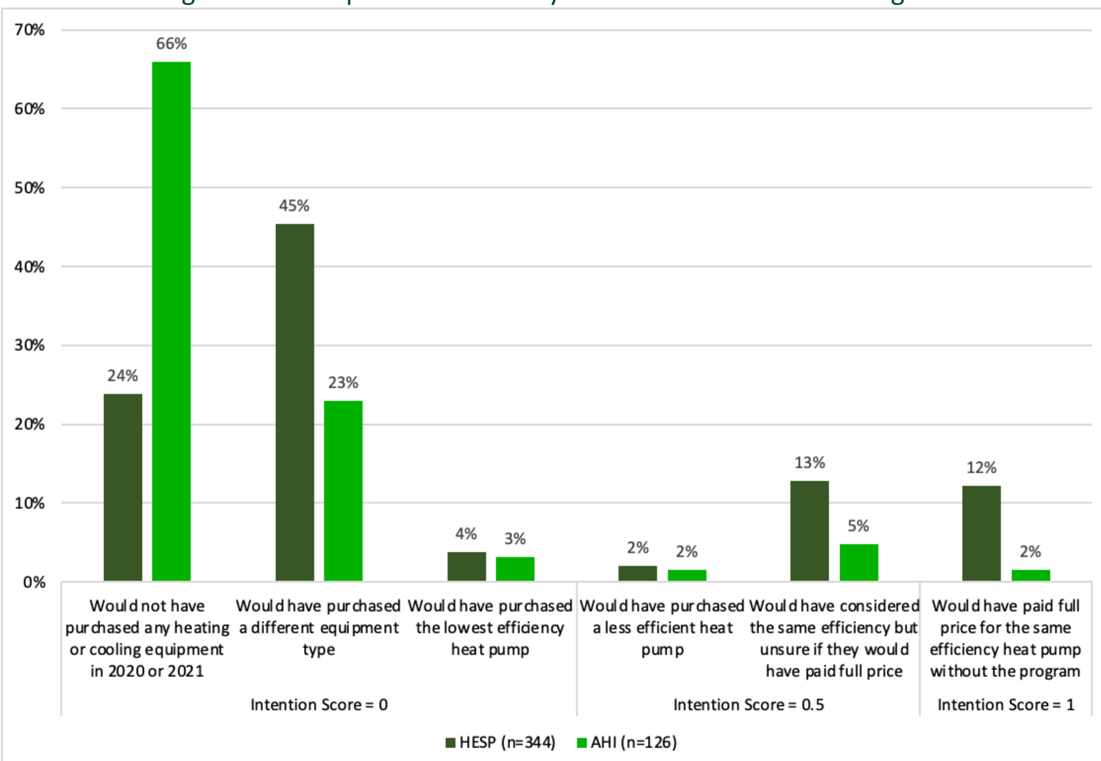


Table 2 calculates the overall net to gross value for each program where 1 – free ridership + spillover = net-to-gross. The value for HESP is 86% and is nearly 100% for the AHI program.

Table 2. Net to Gross Components for the Heat Pump Programs

Program	Free Ridership (FR)	Spillover (SO)	Net-to-Gross (NTG)
HESP	16%	2%	86%
AHI	2%	0%	98%

Participating installers show high satisfaction with the program overall, giving it an average rating of 7.75 out of 10.

1.3 IMPACT

Figure 5 shows heating provided by 140 heat pumps with a mean value of 16.6 MMBtu/year. Nearly 38% of heat pumps provide less than 10 MMBtu per year, and about 30% provide more than 20 MMBtu per year. For reference, 1 MMBtu is equivalent to the heat output of 9 gallons of oil, combusted at 80% effective efficiency.

Figure 54 shows COP for metered heat pumps. COP decreases with decreasing outdoor temperature, primarily due to the difference in outside and desired indoor temperatures. Total measured COP across all heating usage for sampled heat pumps was 2.57, which includes energy used for defrosting.

Figure 5. Heating Provided by Heat Pumps

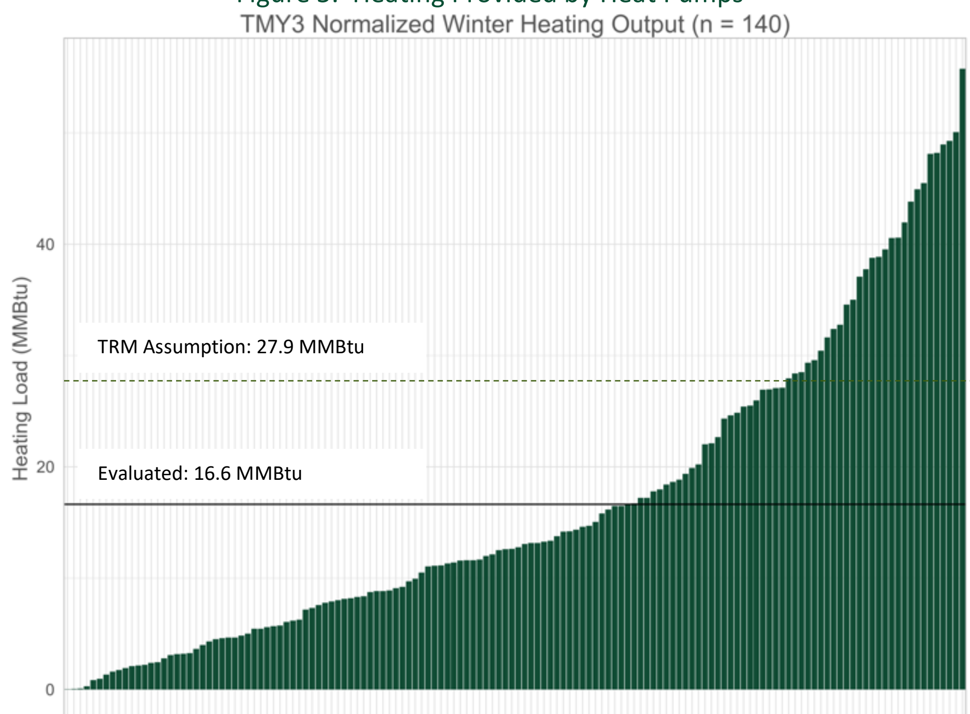


Figure 6. Average Measured COP vs. Outdoor Air Temperature

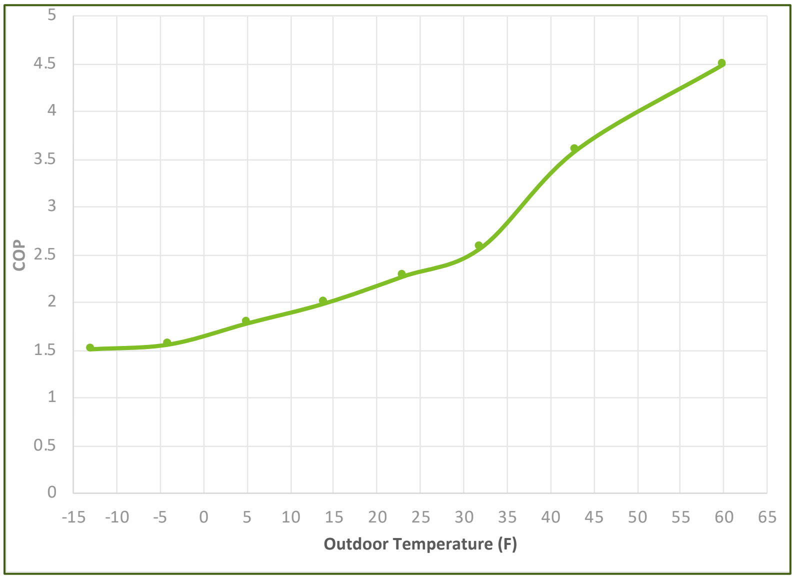
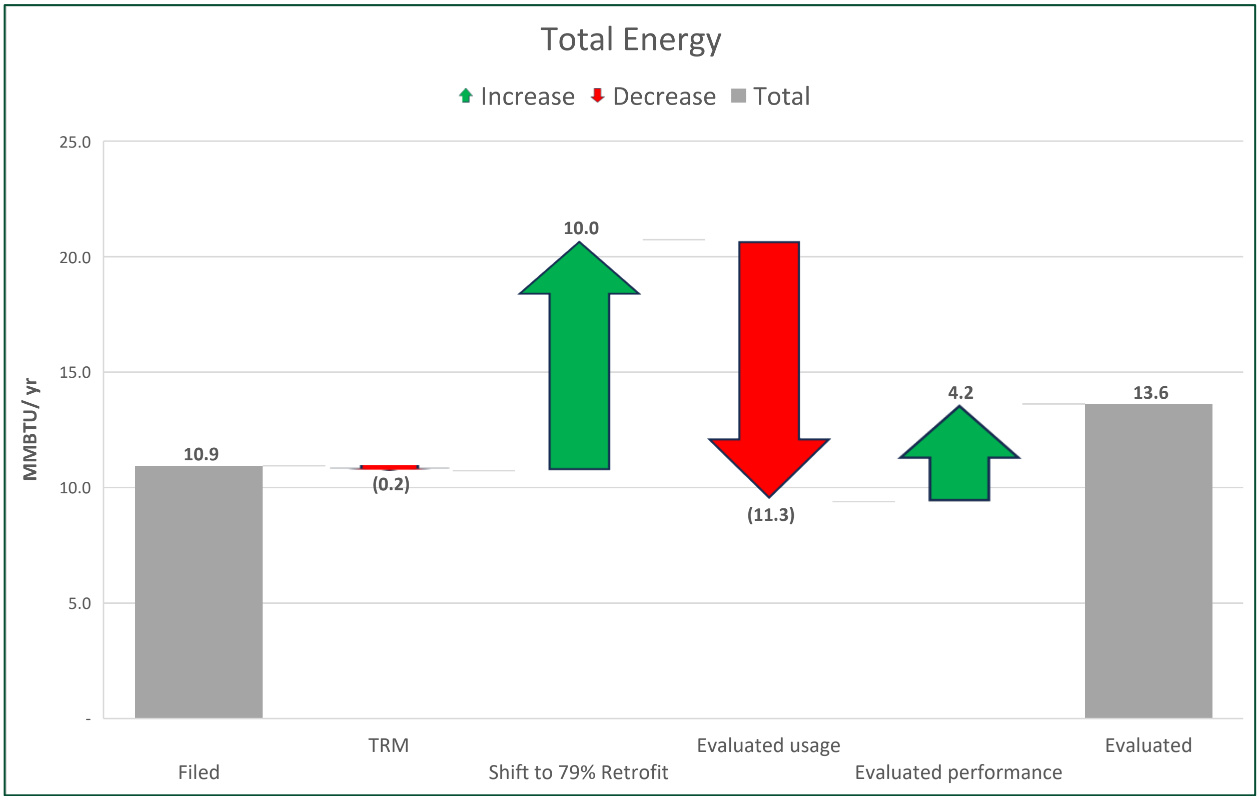


Figure 7 shows the reported (filed) and evaluated values for equivalent MMBtus saved where the kWh and MMBtu impacts are both converted to MMBtus and summed. The largest change in the reported value is shifting from a lower efficiency heat pump baseline to a fossil fuel baseline which nearly doubles the fuel savings. The Technical Reference Manual (TRM) derives fuel savings from the difference between a program-qualifying heat pump and a standard-efficiency heat pump which results in the installed heat pump offsetting more heat from the pre-existing heating system. Lower winter usage on the order of 50% lowers the evaluated value back to a value similar to the reported number.

Figure 7. Waterfall Chart Comparing Reported and Evaluated MMBTU Equivalent Heating and Cooling Energy



The average heat pump used 1,887 kWh per year for heating, had a mean seasonal COP of 2.57, and saved the equivalent of 2,988 kWh versus an electric baseline and 14.4 MMBtu versus an 80% efficient fossil system.

Rebated heat pump installations produced large and widespread annual energy savings. The HESP and AHI programs' heat pumps measures resulted in 57,000 therms of natural gas savings, 325,000 MMBtu (2.3 million gallons) of fuel oil savings, and 44,000 MMBtu (489,000 gallons) of propane savings. Heat pumps also displaced 46,000 MMBtu of pellet and cord wood heat.

2 INTRODUCTION

2.1 BACKGROUND

The Efficiency Maine Trust (Efficiency Maine) administers programs to improve the efficiency of energy use and reduce greenhouse gases in Maine. A primary activity is delivering financial incentives on the purchase of high-efficiency equipment or changes to operations that help customers save electricity, heating oil and other fuels throughout the Maine economy. This evaluation focuses on the installation of high efficiency heat pumps under the Home Energy Savings Program (HESP) and Affordable Heat Initiative (AHI) for the period from December 2019 through June 2021.

The primary objectives of this study are to (1) quantify and verify electric energy and demand impacts (increases and decreases), (2) verify non-electric energy impacts (increases and decreases), and (3) analyze program cost-effectiveness.

2.2 OVERVIEW

The study consisted of these elements:

- A review of program data to understand the populations of installed heat pumps
- A participant survey that included a net-to-gross set of questions
- A survey of contractors and distributors
- A metering study of homes that installed heat pumps across Maine (Impact study)
- A benefit/cost analysis of heat pump installations

2.3 STUDY OBJECTIVES

2.3.1 PARTICIPANT SURVEY OBJECTIVES

The participant survey was administered online from December 20, 2021, through February 20, 2022. 344 HESP participants and 126 AHI participants completed the survey, achieving a response rate of 22% for HESP and 25% for AHI. The survey targeted HESP and AHI participants who received a heat pump rebate between December 2019 and June 2021 and also targeted homes that were metered during this study. Roughly 70 of the 124 metered homes responded. The survey collected information related to:

- demographics
- heat pump operation by season
- control strategies used
- influences on purchase decision and operation
- satisfaction with the equipment, contractor, and the program
- perceptions about energy savings and usage
- critical metrics needed to estimate free ridership and spillover effects, including program influence on purchase decision, installation, and operation
- appropriate baseline

2.3.2 Contractor Survey objectives

Assess the following topics through survey of Residential Registered Venders (RRV):

- Program influence on installation and sales, and distributor's stocking practices
- Percent of sales volume of program-qualifying equipment
- Barriers to program-qualifying HP sales
- Sales influenced by the program
- Customer education on system operation
-

2.3.3 Gross impact evaluation objectives

- Quantify annual energy consumption during heating and cooling seasons by measuring a sample of systems.
- Quantify annual energy impacts (changes in consumption compared to baseline).
- Use advanced metering infrastructure (AMI) meter data to supplement, and to examine the viability of future AMI analyses.
- Quantify peak summer and winter demand impacts by measuring a sample of systems.
- Establish annual load profile, peak coincidence, and energy period factors.
- Quantify annual heat delivered by rebated HPs
- Determine coefficient of performance (COP) of heat pumps through measurement
- Correlate COP with outside air temperature and compare with manufacturers' ratings
- Establish appropriate baseline using information collected through the customer survey and on-site visits.

2.3.4 Cost-Benefit Analysis objectives

Verify benefit/cost calculations using program-provided costs and evaluated savings in Efficiency Maine's cost benefit analysis tool (CBAT). Determine for each measure type incentivized under the program the following:

1. Verified measure costs based on the costs of installed efficiency measures and appropriate baseline costs;
2. Lifetime benefits of verified savings (gross and net);
3. Lifetime costs of fuel use increases (gross and net); and
4. Measure-level benefit/cost ratios (excluding program delivery and marketing costs) using prescribed and alternate methods.

3 METHODS

3.1 OVERVIEW

This section describes methods used for sample design, recruiting, home visits, metering, and analysis. The methods described include pictures to illustrate our approach, and where a procedure needed to change based on issues encountered in the field, that is noted as well.

3.2 SAMPLE DESIGN

The study's objective for statistical precision is to achieve 80% confidence that the actual population value is within 10% of the evaluated value (i.e. 10% relative precision). A key driver of achieved precision is the coefficient of variation (CV) between results for projects in the sample. This coefficient representing the degree of homogeneity in results cannot be determined in advance and therefore the initial sample design must *estimate* the CV based on *expected* results. For results that are expected to follow a perfect bell curve, and that average typical data dispersion, the typical process is to assume a CV of 0.5.

Equation 1 shows the sample size calculated for an 80% two-tailed confidence interval, around 10% relative precision. Assuming the standard default coefficient of variation of 0.5, the equation returns a sample size of 41.

Equation 1: Sample Size Calculation Formula

$$N = \left(\frac{1.282 * \mathrm{CV}}{RP}\right)^2 = \left(\frac{1.282 * 0.5}{0.1}\right)^2 = 41$$

Savings from HVAC equipment are typically much more diverse than a typical "Normal" (bell curve shape) distribution. Weather patterns, regional micro-climates, user preferences, and inconsistency in refrigerant charge are just a few of myriad variables that can cause significantly more or less savings on a unit-by-unit basis. The team estimated a CV of 0.75 in anticipation of the broader than Normal distribution in metered results. The resulting sample size (N) required to achieve 80/10 two-tailed for the combined portfolio is 92 projects. We took this sample size estimate as the initial, minimally viable target for this study.

Equation 2: Sample Size Calculation Formula

$$N = \left(\frac{1.282 * \mathrm{CV}}{RP}\right)^2 = \left(\frac{1.282 * 0.75}{0.1}\right)^2 = 92$$

The study team reviewed Efficiency Maine's program data and statistical needs and initially came up with a sample of 105 homes. After further discussion with Efficiency Maine, we collectively decided to further increase the sample size to 126 sites. The additional sites were to provide a buffer against potential unforeseen issues with data collection and enable alternate segmentations of results. The final sample design by program and strata is shown in Table 3 below.

Table 3. Sample Design

Strata	Program	Population Size (projects)	Coefficient of Variation (CV)	Sample Size (N)
Single Zone, Tier 1	HESP	2,497	0.75	20
Single Zone, Tier 2	HESP	9,573	0.75	60
Multi-zone	HESP	4,732	0.75	25
Property Assessed	AHI	1,150	0.75	12
LIHEAP	AHI	192	0.75	9
TOTAL		18,144		126

The distinction between Tier 1 and Tier 2 is defined by the program as follows:

Tier 1

1. AHRI-rated HSPF 12.0 or greater for systems with single indoor unit
2. AHRI-rated HSPF 10.0 or greater for systems with multiple indoor units

Tier 2

1. AHRI-rated HSPF 12.5 or greater
2. Home does not have a natural gas utility account
3. Each system is a one-to-one single-zone system with a wall mounted indoor unit

AHI

1. AHRI-rated HSPF 13 or greater
2. Home does not have a natural gas utility account
3. Each system is a one-to-one single-zone system with a wall mounted indoor unit

3.2.1 Avoiding Bias and Sample Reprsentitiveness

The evaluation team sought to reduce and mitigate sampling bias wherever possible. The following section provides an overview of some key areas where bias can originate and our process to mitigate those influences.

At the highest level, self-selection bias is introduced into a research project when participants choose whether or not to participate in the project, and the group that chooses to participate is not equivalent (in terms of the research criteria) to the group that opts out. Because we are asking homes to opt into the study, some self-selection bias is unavoidable, however we attempted to limit it in the following ways:

- Recruitment outreach occurred over a broad range of customers across Maine using land lines, cell phones, and email.
- We offered a relatively large incentive, an average of $200 per home, in part to reduce self-selection bias.
    - A more modest incentive risks skewing the sample toward homes on lower incomes and to homes where more occupants are home during the day.
    - The higher incentive was attractive to a larger demographic range.
    - Achieved recruitment rate was materially similar across all income segments.

Non-response is essentially the converse of self-selection bias where a portion of the population may choose to not participate. Our techniques for limiting self-selection also helped correct non-response bias.

Bias can also be introduced once we enter the home. Ridgeline field staff are trained not to offer guidance on system operation or otherwise promote modification to the occupants' existing operation of their HVAC equipment.

We metered all heat pumps in a home, including both program and non-program heat pumps. In this way, we ensured that we didn't inadvertently pick heat pumps that were all low use or all high use.

Additionally, the sample selection was a stratified random sample which promotes sample repetitiveness of the larger population. The resulting sample was also checked to confirm general alignment between the sample's vs population's: program track (HESP vs AHI), measure mix (single zone Tier 1, single zone Tier 2, multi-zone), and geographic distribution.

3.3 RECRUITMENT AND SCHEDULING

Recruitment began in May 2021 and had an early stretch goal of installing data loggers during the summer to capture a portion of the cooling season. Supply chain issues in obtaining meter parts prevented starting logger installation until late July 2021. By mid-August, we had installed meters in nearly half of the 126 homes recruited. Our goal then shifted to recruiting homes and completing site visits by November 2021. We met that goal with nearly all site visits completed by mid-November. We visited a few more sites to fill in gaps in statistical strata in early December.

Overall, we achieved a recruitment rate of about 18% including some over-recruiting to ensure that we could fulfill geographic and program goals. This is in contrast to typical recruitment rate for studies that use simple, mail-based strategies and are typically 0.5%. We mailed the recruiting letters in waves to ensure geographic coverage and to ensure efficiency of field work (Table 4).

Table 4. Recruiting Mail Waves

Wave	County	Mailed	Recruitment Rate
1	Hancock, Washington, Penobscot	July 6, 2021	17%
2	Androscoggin, Cumberland, Knox, Lincoln, Waldo, York,	July 14, 2021	20%
3	Aroostook, Franklin, Kennebec, Oxford, Piscataquis, Sagadahoc, Somerset	August 27, 2021	17%

We recruited using a letter approved by Efficiency Maine, that included Efficiency Maine's letterhead and was signed by Laura Martel, the Efficiency Maine evaluation manager. We made all outbound calls from a (207) area code phone number, leaving the same number for call backs. Homeowners were offered $200 to participate in the study for one year. In general, homeowners had a very positive attitude towards Efficiency Maine, the program and our efforts. We believe that all of these elements contributed to the high recruitment rate.

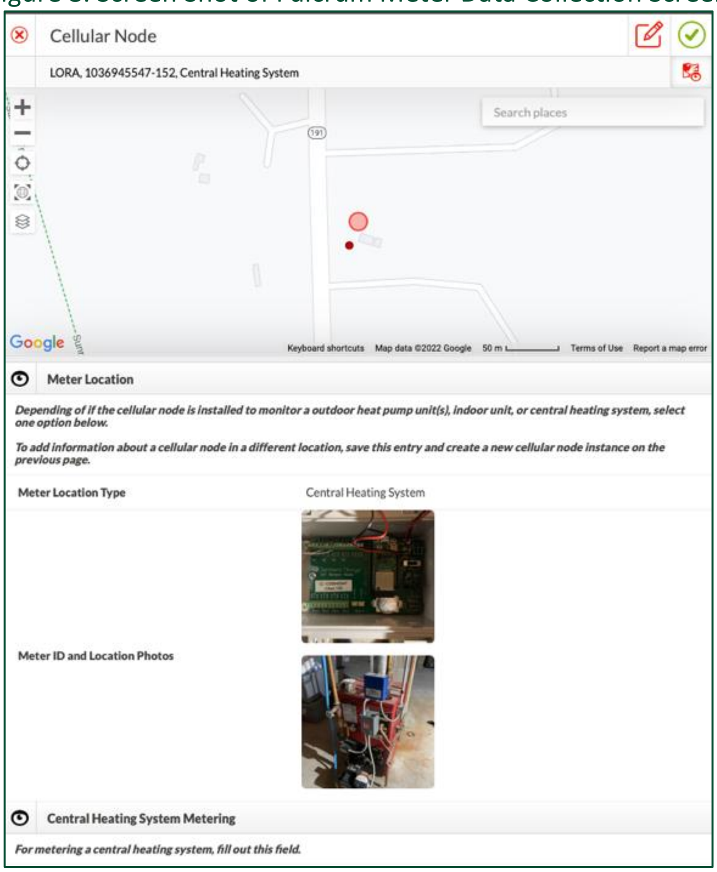
3.4 FIELD DATA COLLECTION

We designed a sample to address program distribution and geographical area, oversampling strata based on an increased sample size of 126 sites. Ultimately, we installed meters in 124 homes by December 2021, of which 5 were manufactured and 119 were site-built. In total, we metered 170 outdoor heat pumps serving 210 indoor (fan coil) units. We used photos and tablet-based data collection tools to document the home and its heating system.

3.4.1 Data Collection Tool

Ridgeline wrote a custom field data collection form based on Fulcrum[1], a tablet-based data collection software authoring tool that we had used on previous projects including a study of residential loads in Massachusetts. An example screen from the tool customized for this project is shown in Figure 8. Our system allowed field engineers to enter home and heat pump characteristics directly into a database while on the site. Engineers also entered detailed metering data including meter type, meter serial number, sensor type and current transformer (CT) size.

Figure 8. Screen Shot of Fulcrum Meter Data Collection Screen



To aid in meter removal, help with QA, and to understand the heating zoning of each home, field engineers produced a plan view of each home roughly to scale with heat pump locations noted. Because we metered every indoor and outdoor unit encountered, locating heat pumps is identical to

[1] https://www.fulcrumapp.com

locating metering equipment. Figure 9 shows an example of one of these drawings of a manufactured home. Here the heat pump can contribute heat to the main space. However, to the extent that the heat pump influences the single primary thermostat, the added room and the bedroom will remain cold.

Figure 9. Example of Technician Site Map of Manufactured Home with Single Zone

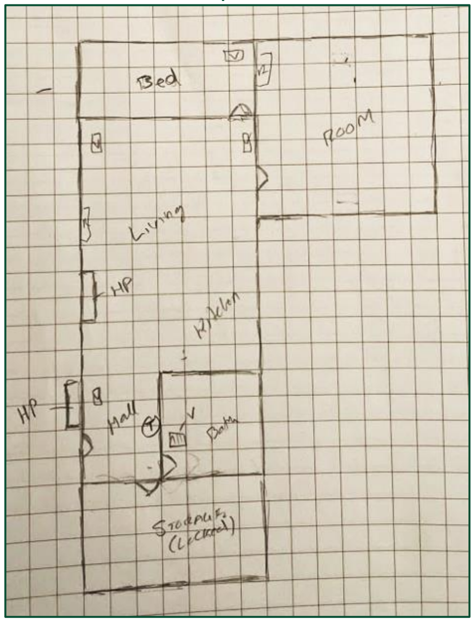
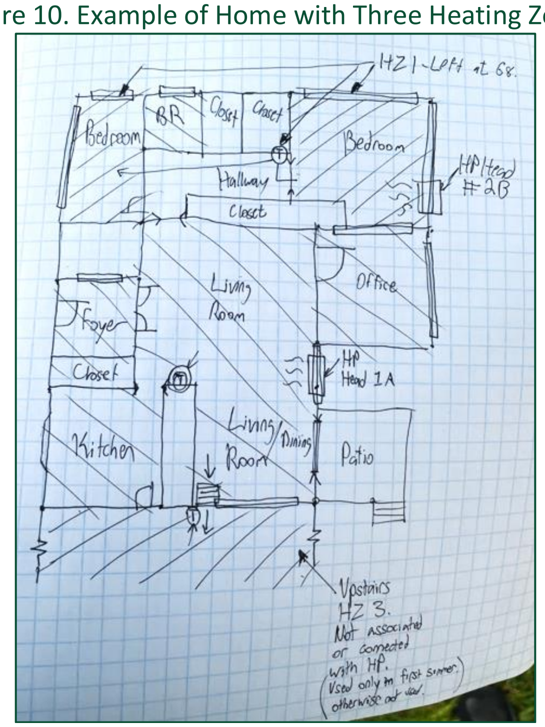


Figure 10 shows another home where the home has three heating zones, and two heat pump indoor units can potentially displace the heat source for the zone.

Figure 10. Example of Home with Three Heating Zones



3.4.2 Homeowner Discussions

Part of the data collection effort discussed in the previous section included developing a plan view of heating zones including location of thermostats for pre-existing heating systems and location of heat pumps. To supplement this physical knowledge, we also discussed the use of heat pumps with each homeowner. The level of detail in these discussions and therefore usefulness in assessing usage varied with homeowner's knowledge, specificity, and the interplay of other household members.

For most homeowners, we could discern if their intention was to use the heat pump a low amount. Indicators of this intention include statements that they used the heat pump primarily for cooling, that they were away in the winter, or that they turned the heat pump on to take the chill off but relied on their other system. Indicators of high use would be statements that they set the heat pump to a comfortable temperature and set the other system to well below this setting, that they sought to use the heat pump as much as possible, and that they had either no other heating system or a seldom used system. Indicators of moderate usage fell in between these extremes where the homeowner attempted to use the heat pump for most heating but was unclear on exactly how to do that, or that they primarily used the heat pump down to a certain outdoor temperature.

3.5 METERING AND MEASUREMENT

3.5.1 Loggers

For this study, Ridgeline's metering systems consisted of web-connected Gateways made by Sentient Things (Figure 11) that can collect up to two temperatures and four pulse inputs. The Gateways send data to the Web. The Gateways also communicate wirelessly with up to 30 LORA nodes that can each collect up to 3 temperatures, 1 humidity, and 2 pulse inputs. For this project, each home had one Gateway installed (Figure 12). LORA nodes were installed on each indoor unit, and on one pre-existing heating system. Where there was more than one outdoor unit, a LORA node was installed on the additional heat pumps, and the LORA node collected power and fan current as described in the following sections.

3.5.2 Power

The team installed a power meter to measure each site's heat pump's energy consumption. The metering setup consisted of a Watt Node alternating-current watt-hour transducer, two 20 Amp current transformers (CTs), sized for the heat pump's full-load operating current, and two voltage taps that allow the transducer to measure real power and energy. The Watt Node sends out a pulse signal proportional to the energy used (Watt-hours). A Watt Node is shown in Figure 13. The pulse signal is logged by a Sentient Things Gateway that directly sends the data to the Web. Where there is more than one heat pump, the additional heat pumps are logged using a LORA-based node that sends signals to the Gateway and that data is relayed to the Web.

Figure 11. Cellular Gateway

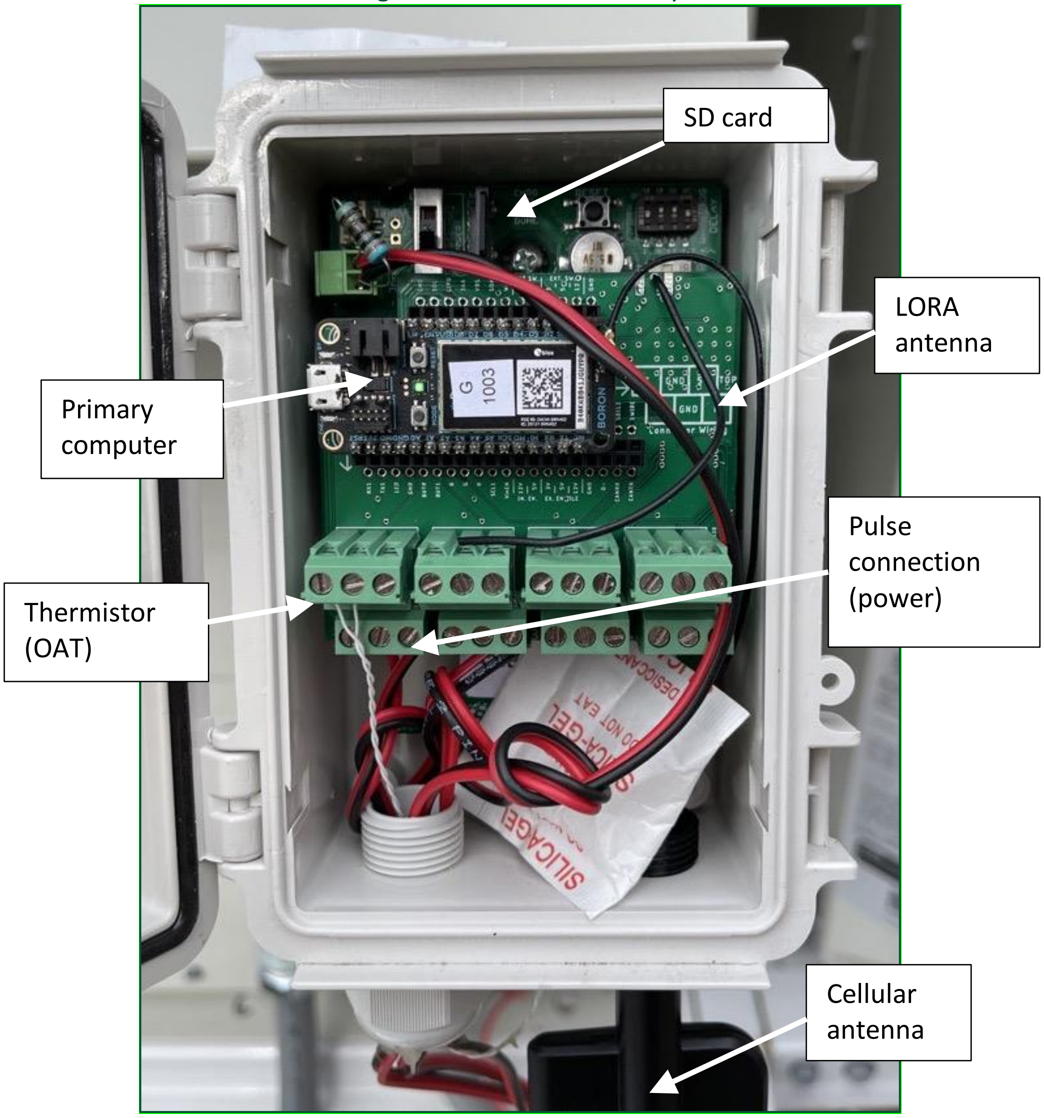
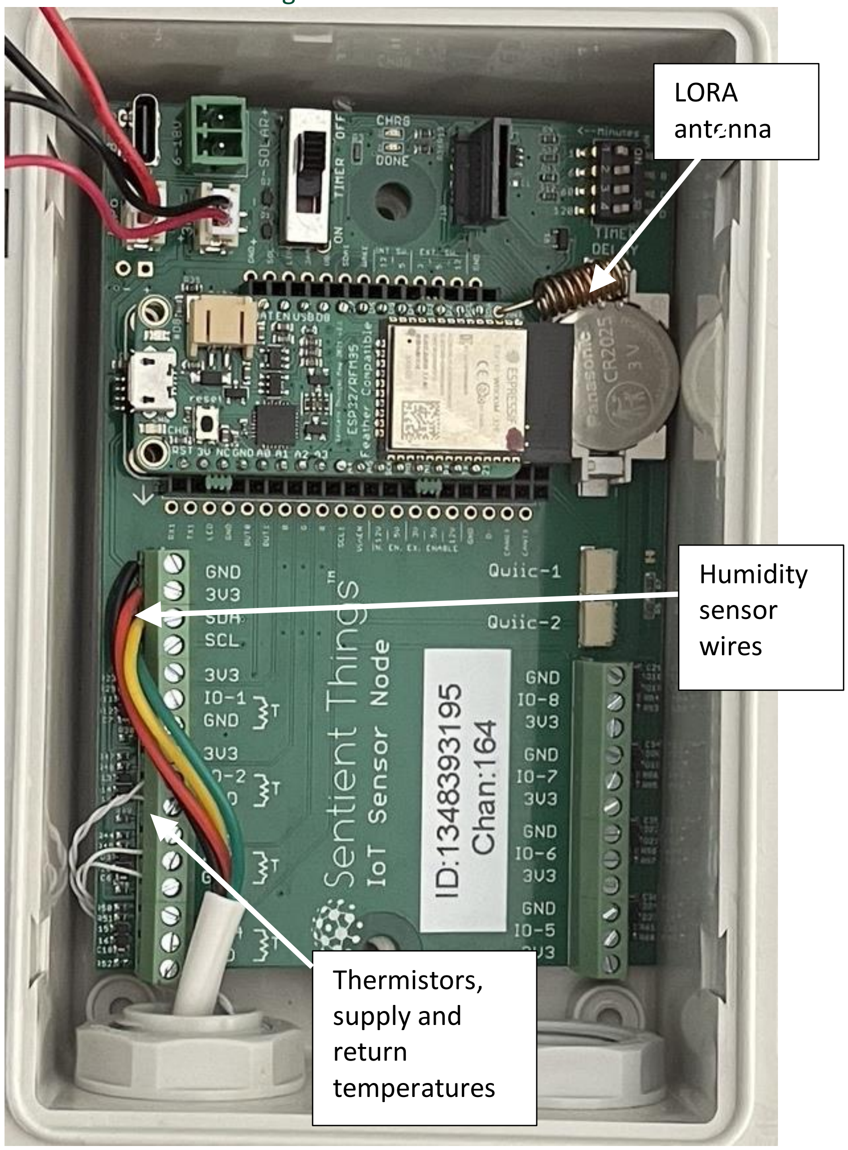
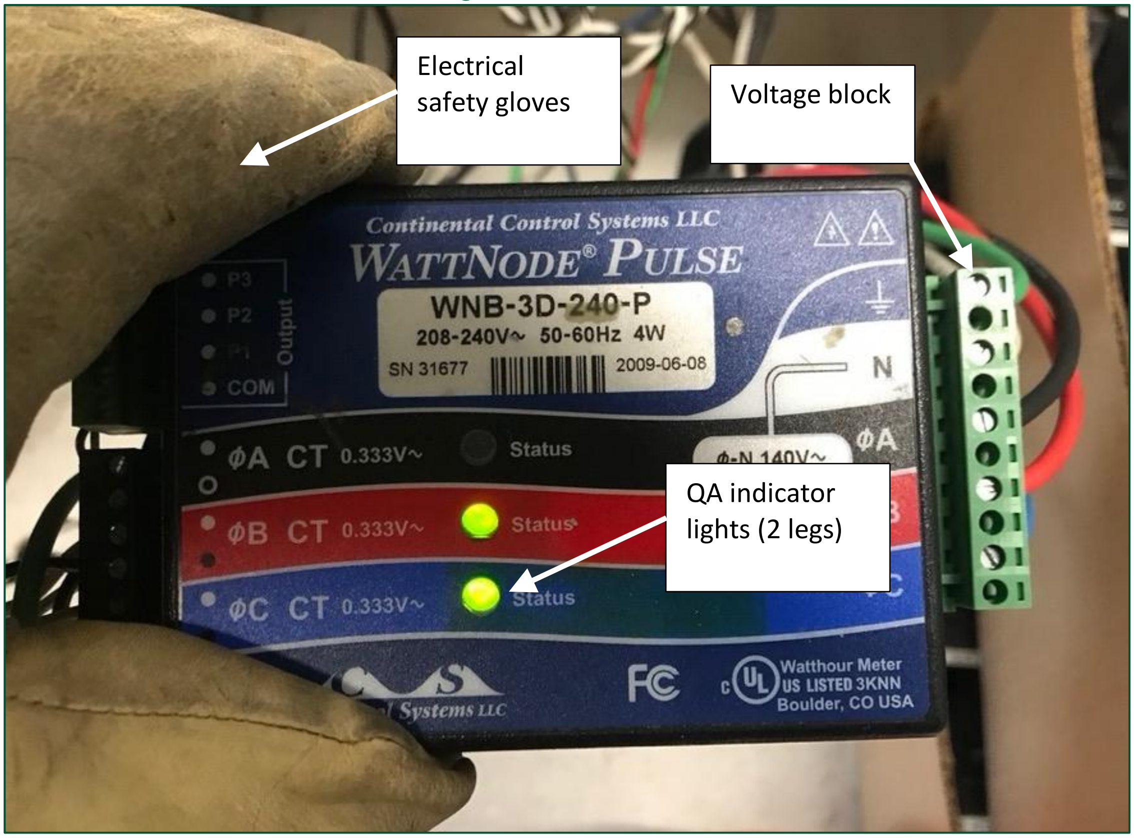


Figure 12. LORA Node



The team then accesses data from ThingSpeak and converts the pulses to watt-hours and using the logging interval, derives average power and energy consumed over that time period. The power data was rolled up into 2-minute intervals.

Figure 13. Watt Node



3.5.3 Airflow

The team used balometers (Model Alnor EBT731) to collect volumetric airflow in fan only mode for each of the speed settings for each of the six makes and 62 models of indoor units (Figure 14). Coincidental with the airflow measurement the team also collected the amperage of the fan to establish an airflow amperage curve. The reason the evaluation team used the fan only setting was that in this and previous studies, the team found that in heating and cooling mode, the units often have an automatic fan setting that overrides manual settings making it very difficult to run the test. While airflow volumes can vary between fan only, and heating and cooling settings, the fan will follow the same airflow/amperage curve. By establishing this curve, then monitoring amperage, the evaluation team can monitor airflow whether it is in heating, cooling, or fan only mode.

3.5.4 Fan Current

For each unit studied, the evaluation team installed 1 Ampere (A) current transformers (CT) on the wire powering the heat pump's indoor units (

Figure 15). The CTs out put a signal of 0 – 333 mV proportional to their 0 – 1A scale. Typical readings of the fan are 0.01 – 0.02 amps at off, 0.03 – 0.05A at low speed, and 0.1 to 0.15A at high speeds. The Voltage signal was transformed to pulses[2] a format that the data loggers could read.

Figure 14. Technician Preparing to Collect Airflow Measurement

Figure 15. 1A CT Placed on Wire Powering Indoor Fan

[2] Some meters send information in pulses where circuits turn a voltage on and off and each pulse is equivalent to a known parameter. In this case a pulse was equivalent to a reading of 1 mV.

3.5.5 Temperature andf Relative Humidity

The team installed loggers to measure temperature of outdoor air, supply air from the indoor unit, and return air to the indoor unit. At the outdoor unit, the team installed a thermistor, logging outdoor air temperatures at one-minute intervals. At the indoor fan units, the team installed a thermistor each in the supply and return air streams (Figure 16), and an additional humidity sensor in the supply air to measure relative humidity (Figure 16).

Figure 16. LORA Node Humidity Sensor and Thermistor on an Indoor Unit

3.5.6 Combustion Heating systems

To measure other heating systems' operating times, the evaluation team placed temperature probes on the flue duct or where that was impractical, on the supply water pipe (Figure 17). The team collected nameplate data from all relevant heating system equipment and used these data for various baseline and coincident-heat calculations.

Figure 17. Cell Phone Meter on a Smith Boiler

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3.6 DATA SYSTEM

Ridgeline's Sentient Things meters are based on the Particle[3] chip and collect data roughly 60 times per hour, and send data to ThingSpeak[4], an Internet of Things Platform operated by MathWorks. Data is also stored locally on SD cards that hold several years' worth of data as needed.

3.7 ANALYSIS

The team analyzed the power usage by each heat pump versus time of day and versus outdoor temperature. To examine the heating provided by each indoor unit, we use fan amperage as an analog for airflow. Airflow times the difference between supply and return air temperatures yields heat added. For the cooling season, we also measured humidity to capture removal of moisture (latent heat).

3.7.1 LOGGER DATA PROCESSING

Each site has the following set of data collected roughly 1x/minute (Table 5). These seven data streams (plus three for each additional indoor unit) must be aligned for analysis at each site. Ridgeline wrote Python code to pull data from the ThingSpeak platform and process it for analysis.

Table 5. Data Collected at Each Site

Location or Unit	Parameter	Data stored
Outdoor unit	Power	Pulses - kWh
	Fan current	Pulses - Amps
	Outdoor air	Temperature (F)
Indoor unit	Return air	Temperature (F)
	Supply air	Temperature (F)
	Supply air	Relative humidity (RH)
Furnace/ boiler/ wood stove	Temperature adjacent to flue or wood stove indicating operation	Temperature (F)

3.7.2 AIRFLOW VS CURRENT

The analysis team grouped indoor units by manufacturer, capacity, and motor similarity. The team then created scatterplots of airflow versus fan amperage. The best-fit curve for these plots was a natural logarithmic curve of the format:

$$Airflow\ (cfm) = a * \ln(fan\ amperage) + b$$

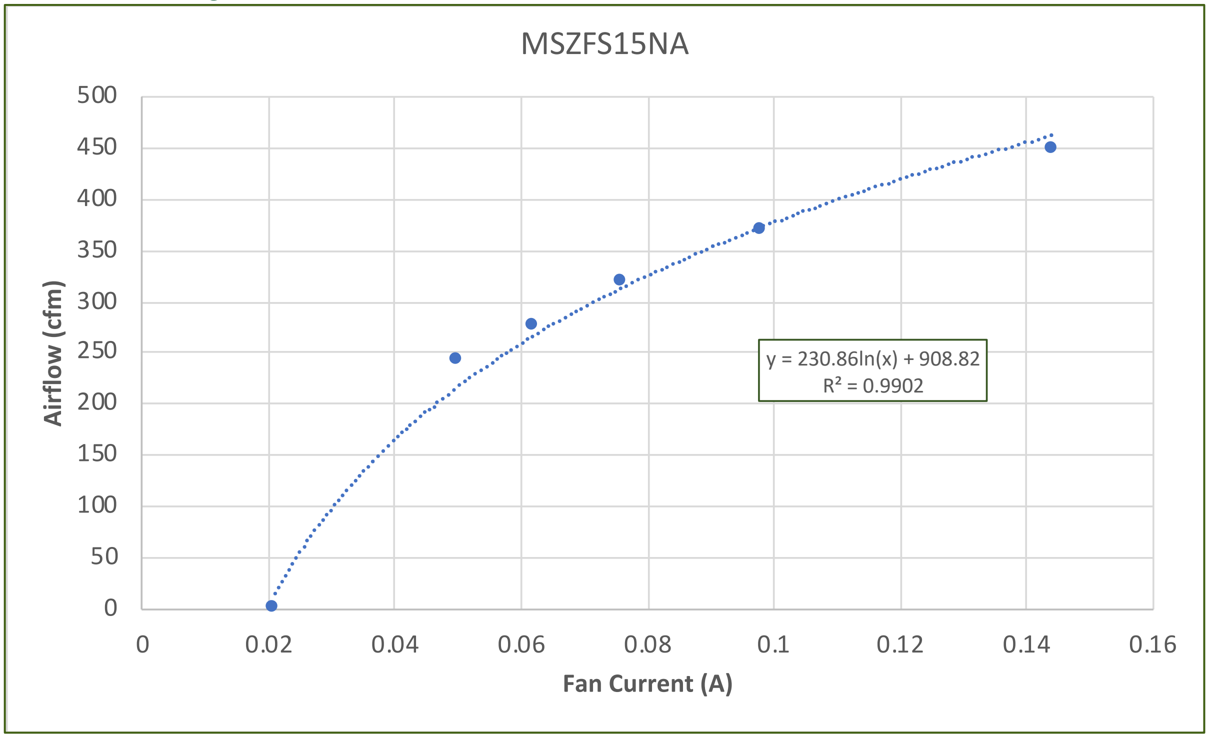
Where:

a = constant multiplied by the natural log of the fam amperage and
b = constant added to previous term in the equation

An example curve for a 15,000 BTU/h Mitsubishi unit is shown in Figure 18. The R^2 of 0.99 indicates a close fit for this curve. The team took repeat measurements for some units and found that the curves were repeatable.

[3] https://www.particle.io
[4] https://thingspeak.com/pages/energy_monitoring

Figure 18. Airflow vs. Fan Current Curve for 15 kBTU/h Mitsubishi Unit



In this equation a = 230.86 and b = 908.82.
Where the fan amperage is 0.1A, cfm = 230.86 * ln(0.1) + 908.82 = 230.86 * -2.303 +908.82 = 377 cfm.

3.7.3 Performance

The measurements collected in the study were used to calculate the coefficient of performance (COP) for the heat pumps installed in the 124 sites. The COP is the ratio of the heat delivered or removed from a space divided to the energy consumed by the system. The energy consumed by the system was directly metered as a part of our data collection process described in section 3.5.2.

The energy delivered or removed by the system is calculated using an energy balance analysis. Previous sections describe how the team installed meters to collect key measurements to calculate the energy output of the system; the fan current, supply temperature and return temperature, and humidity.[5] The energy provided or removed by the system is equal to the difference between the energy state of the air leaving and entering the system. The equation used to calculate the change in energy is shown below:

$$\Delta E = \Delta h_s = V \cdot \rho \cdot c_p \cdot (T_s - T_r)$$

Where ΔE is the energy removed or provided, Δh_s is the change in sensible heat, V is the volumetric flowrate, ρ is the density of air, c_p is the specific heat of air, T_s is the supply temperature and T_r is the return temperature. In cases where there were multiple indoor units, the team added the energy delivered or removed by all of the indoor units and divided by the energy consumed by the respective outdoor unit. This equation simplifies to

[5] Only the sensible heat was considered for the winter analysis. In the cooling season we account for latent heat using humidity measurements.

$$\Delta(BTUH) = 1.08 * V\ (cfm) \cdot (T_s - T_r)$$

The team made a couple of assumptions to identify the operating modes for the system. First, the team assumed that the system was operating when the energy input to the system was greater than 100W. If there was a fan operating during times when the power input was below 100W, it was assumed the system was in fan only mode and not heating or cooling the space. Temperature sensors had an accuracy of about ± 0.5°F. There are times when heating and cooling by other systems in the house and stratification can cause slight differences in temperature readings. To account for this, the team only calculated the energy into the system if the temperature differential between the return and supply temperature were greater than 2°F.

Energy benefit provided by the heat pump is converted into BTUs and divided by the electricity used, also converted into BTUs.

$$\text{COP} = \frac{\Delta E}{kWh\ x\ 3.412}$$

For cooling, the equation is slightly more complex. It includes calculated latent heat, which is added to sensible heat calculated above:

$$\Delta E = \Delta h_l = 0.68 \cdot V \cdot \rho \cdot c_p \cdot dw_{gr}$$

Where ΔE is the energy removed or provided, Δh_l is the change in latent heat, V is the volumetric flowrate, ρ is the density of air, c_p is the specific heat of air, dw_{gr} is the humidity ratio difference (*grains water/lb. dry air*).

3.8 PARTICIPANT SURVEY

This section describes the methods used for survey design, sample design, survey recruiting, and analysis of the participant web survey.

3.8.1 SURVEY INSTRUMENT

The evaluation team designed the survey instrument in collaboration with Efficiency Maine before fielding the survey. The survey was administered online via the Qualtrics platform from December 20, 2021, through February 20, 2022.

3.8.2 SAMPLE DESIGN, RECRUITING AND REPRESENTATIVENESS

The sample was developed from the population of HESP and AHI participants who received rebates between December 2019 and June 2021. Due to the smaller population of AHI participants, Guidehouse, part of the Ridgeline evaluation team, sent survey invitations to all 566 AHI participants with email addresses. Guidehouse drew a random sample of 1,620 HESP participants and added to that sample a census of the on-site participants, to provide additional insight and context to the findings from the corresponding impact analysis.

Guidehouse recruited for the survey via email, starting with initial email invitations on December 20, 2021, for the soft launch population, followed by a full launch and an additional wave of on-site customers. All surveyed participants who had not yet completed the survey within two weeks received at least one reminder; on-site participants received two reminders. The survey remained open through February 20, 2022.

Participants who completed the survey received a $10 incentive via electronic gift card. Guidehouse used incentives and reminders to maximize response rates, which helps mitigate the risk of non-response bias and ensure that the results are representative of the population. Ultimately, 344 HESP participants and 126 AHI participants completed the survey, providing an achieved response rate of 22% for HESP and 25% for AHI. Table 6 shows the survey approach and completion rate by program.

Table 6. Participant Survey Characteristics

Survey Characteristic	HESP	AHI
Implementation Method	Online	
Incentive	$10	
Frequency/Timing	Initial email, one reminder for non-site visit customers, two reminders for stie visit customers	
Sample Design	Census of 93 site visit customers; random sample of 1,620 remaining participants (1,713 total contacted)	Census of 566 participants with email addresses
Number of Valid Emails Sent	1,575	508
Number of Completes	344	126
Response Rate	22%	25%

Source: Guidehouse, 2022

3.8.3 Question Format

Most questions were asked as direct choices. Where the respondent was asked to rate a situation, the scales in Table 7 were used.

Table 7. Participant Survey Rating Choices

	Categories					
	1	2	3	4	5	NA
Influence	Not at all influential	2	3	4	Very influential	Not applicable
Satisfaction	Very dissatisfied	2	3	4	Very satisfied	

3.9 CONTRACTOR AND DISTRIBUTOR SURVEY

In June and July 2022, Guidehouse conducted a survey of trade allies, including installers and distributors serving the HESP and AHI programs to obtain information related to the influence of the program, partner experience with the program, and installation and maintenance practices. The survey targeted installers who were active in the program between January 1, 2020, and June 30, 2021 (as well as active distributors).

The trade ally survey sample was developed from several sources, including Efficiency Maine's qualified heat pump installer list. The distributor sample included 16 individuals at 6 unique distributors selling heat pumps in Maine and was a compilation of contacts from Efficiency Maine (6), contacts provided by installers who took the survey (8), and the evaluation team's contacts (2).

Guidehouse recruited for the survey via email, starting with initial email invitations in May 2022. Distributors were also contacted by Efficiency Maine call center representatives to encourage survey participation. The survey remained open through August 3, 2022. Ultimately, 10 installers and 6 distributors completed the survey, providing an achieved response rate of 19% for installers and 38% for distributors.

3.10 ANALYSIS OF PRE- AND POST-INSTALLATION ELECTRICAL DATA

Maine has a high saturation of Advanced Metering Infrastructure (AMI) meters that collect and store high frequency electrical consumption data. The evaluation team obtained 15-minute electrical consumption data for homes for periods before and after the heat pump installation, with these limitations.

- Municipal utilities did not offer AMI data
- Northern sites in Versant territory did not have AMI data
- Some sites had little AMI data prior to the installation of the heat pump

These data are highly variable as would be expected and correlating each data point to outside air temperature does not yield a clear pattern. The team resolved the electrical data to daily electricity use (kWh/day) and regressed it on average outdoor temperature. The team followed these steps:

- Convert 15-minute consumption data into daily consumption (kWh/day)
- Use site specific outdoor temperature data or local weather data to develop average daily temperature values
- Regress pre-installation data on average outdoor temperature
- Regress post-installation data on average outdoor temperature
- View and compare pre- and post-linear regression lines
- Where appropriate, subtract the two regression lines to develop a line representing the difference in temperature dependent electrical use
- Where patterns were not well captured by linear regression but where clear patterns exist, graphical techniques were used to develop a linear model of heat pump use
- Where patterns were unclear, or where pre- and post-data were indistinguishable, no attempt was made to model heat pump use.
- The temperature-dependent linear models were used to develop annual heating season use based on TMY3 data.
- For sites with a clear model for temperature-dependent electrical usage, and that site had metering data, the AMI derived model and the heat pump metered data were compared.

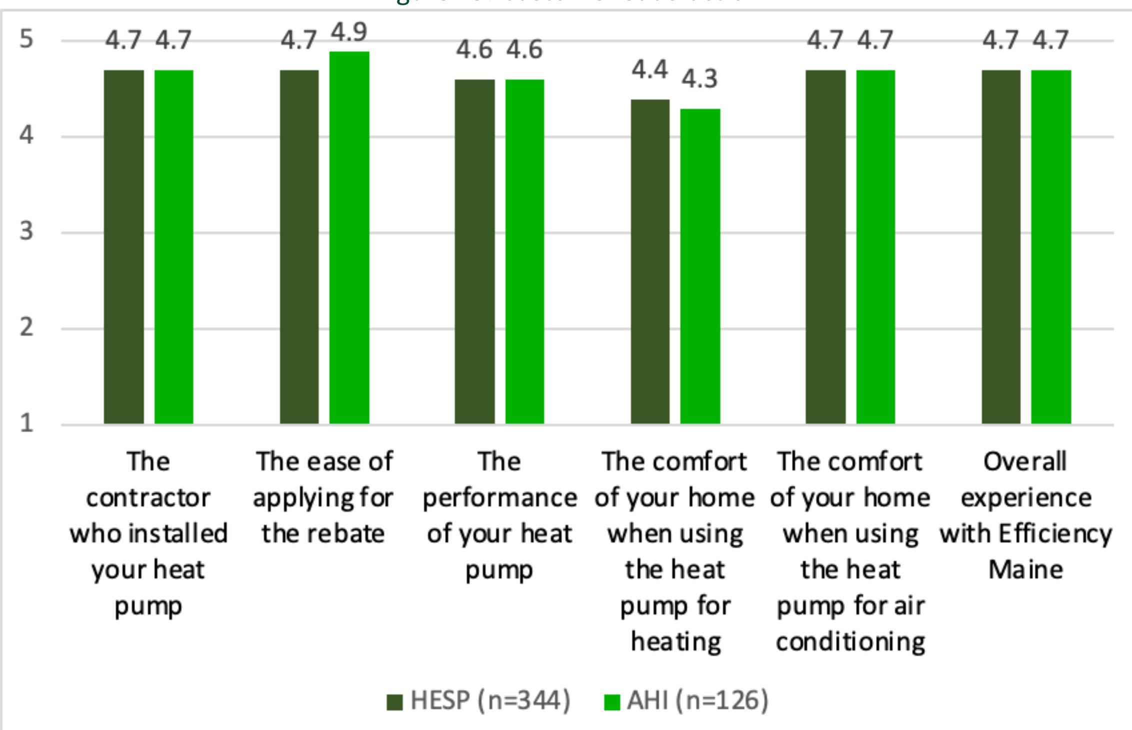
4 PARTICIPANT SURVEY

Guidehouse recruited for the survey starting December 20, 2021, and the survey remained open through February 20, 2022. Ultimately, 344 HESP participants and 126 AHI participants completed the survey, a response rate of 22% for HESP and 25% for AHI, and 470 responses overall. Because not all respondents answered every question, responses for individual questions are lower.

4.1 OVERALL SATISFACTION

Participants are highly satisfied with their program experiences and their heat pumps, rating the comfort of their home 4.7/5 when cooling, and 4.4 and 4.3 for HESP and AHI when heating (Figure 19). These are very high ratings with half or more giving the highest category—"very satisfied," and most one rating short of this.

Figure 19. Customer Satisfaction



4.2 PURCHASE INFLUENCE

Participants were asked what influenced their purchase, with 5 linked to the phrase "highly influential." Figure 20 shows rebates and word-of-mouth from other participants were highly influential or nearly so.

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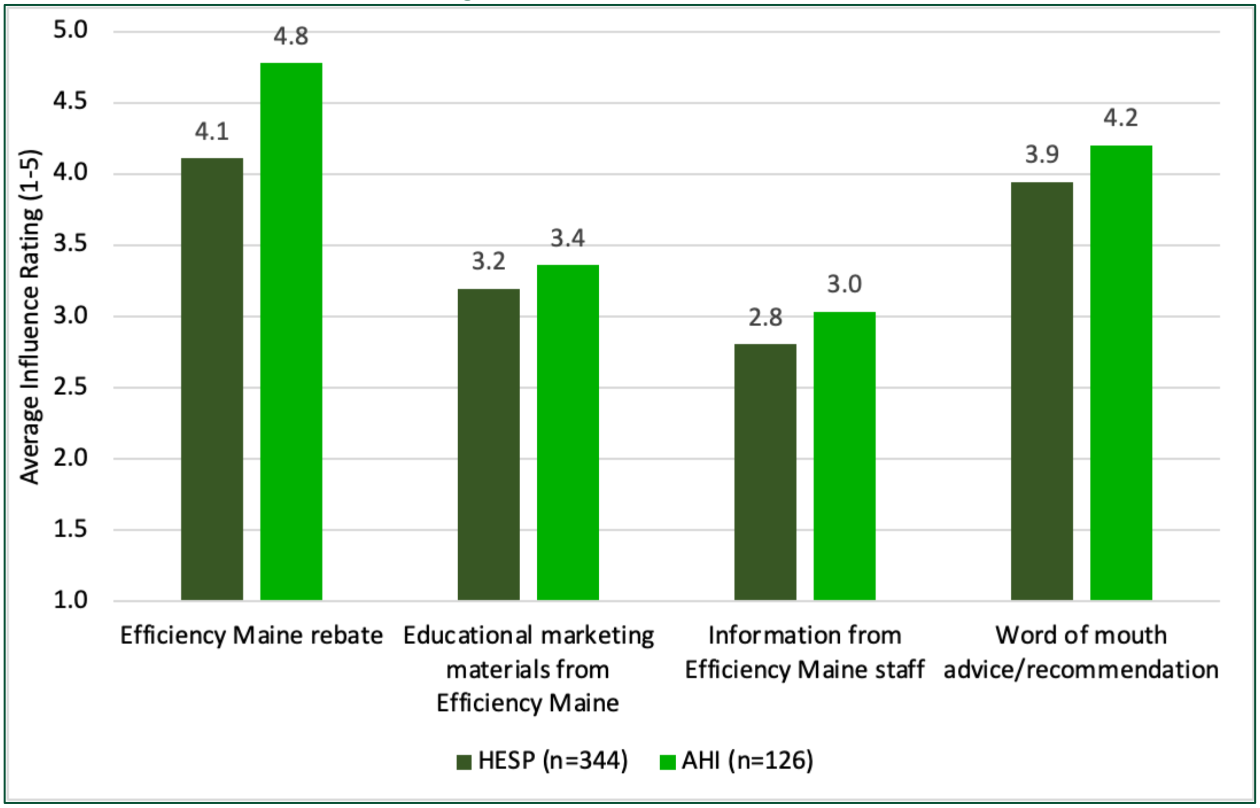
Figure 20. Purchase Influencers



As expected, rebates had a relatively higher influence for lower income participants. Figure 21 shows a more detailed view of participants' intentions exploring what they would have done in absence of the program. The intention score is a translation of their responses into a free ridership score where 0 equates to no free ridership and 1 equates to complete free ridership.

In this chart, the rebate is again highly influential to lower income participants, with few indicating that they would have bought the same system at the same price without the rebate. Participants in the HESP program indicate that the majority would not have purchased a heat pump without the rebate.

Figure 21. Participants' Most Likely Purchase in Absence of Program

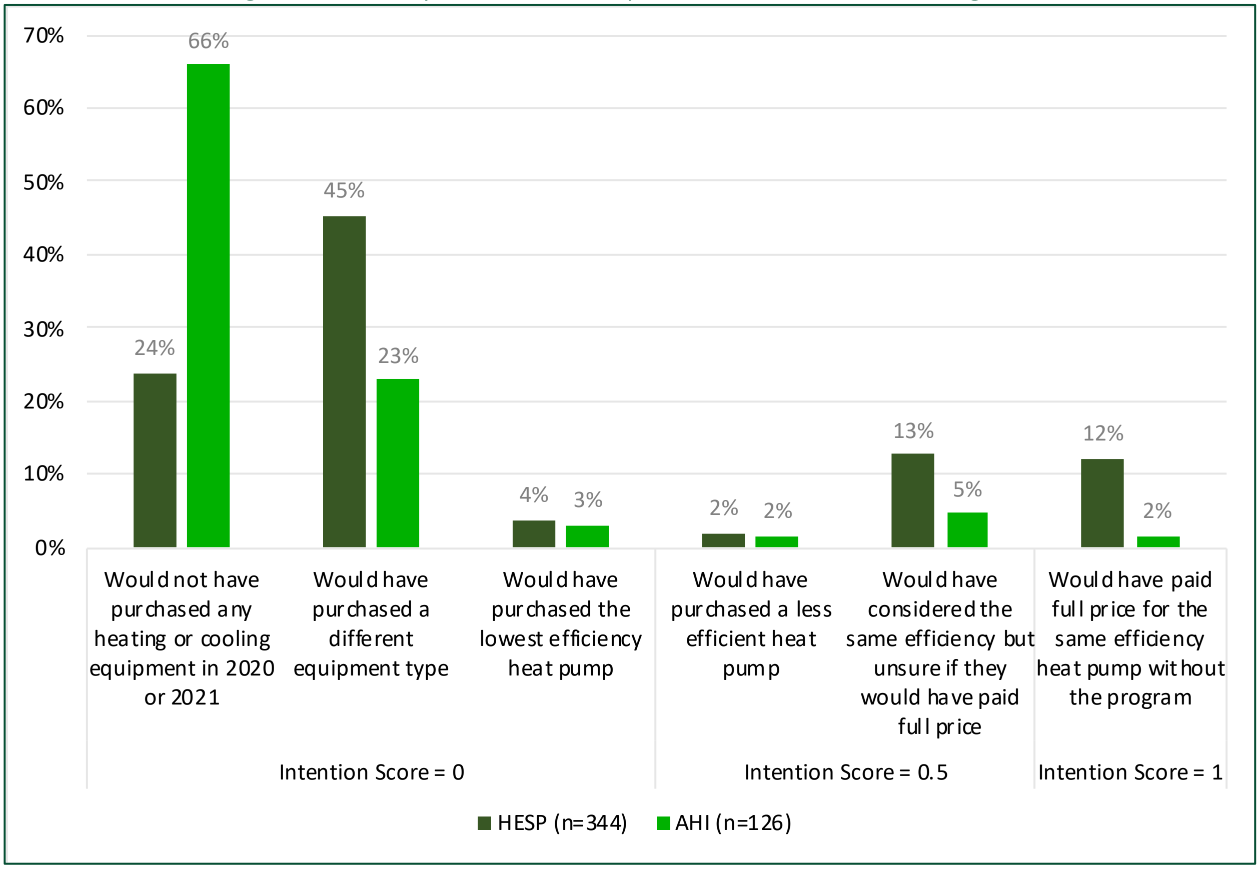


Table 8 calculates the overall net to gross value for each program where 1 – free ridership + spillover = net-to-gross. The value for HESP is 86% and is nearly 100% for the AHI program type.

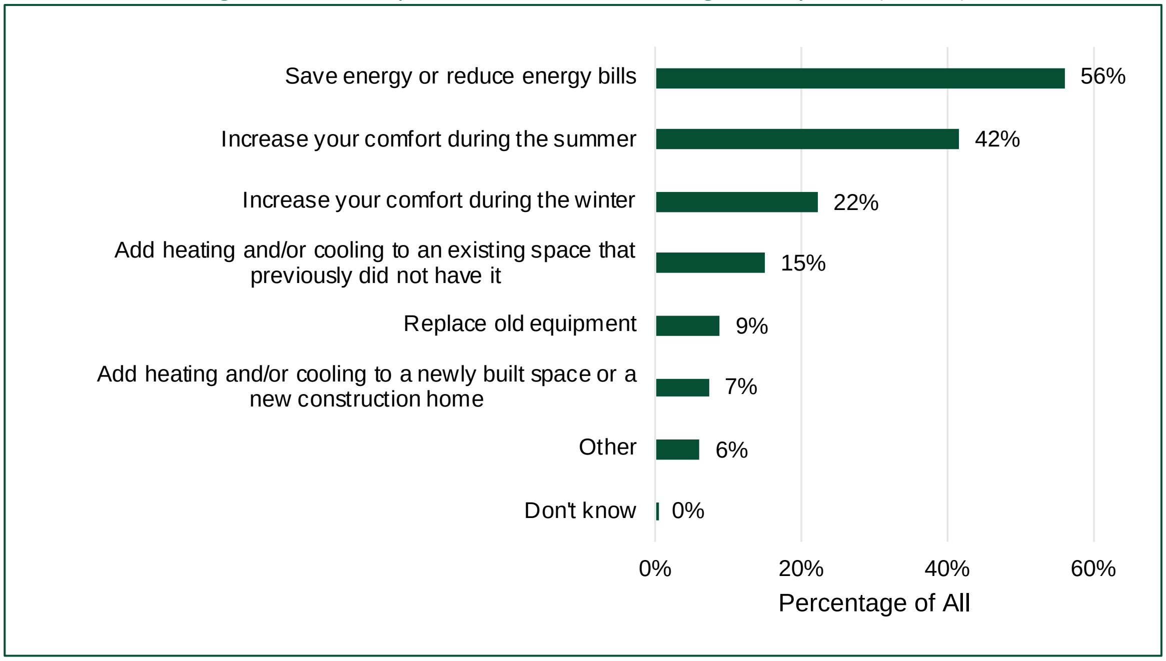
Table 8. Participant Survey Rating Choices

Program	Free Ridership (FR)	Spillover (SO)	Net-to-Gross (NTG)
HESP	16%	2%	86%
AHI	2%	0%	98%

4.3 HOMEOWNER INTENT AND OPERATION OF HEAT PUMPS

Roughly 20% of participants in the regular income HESP program bought their heat pumps for cooling, while only 13% of lower income participants had the same intent. Examining reasons for purchase more closely, 42% mentioned summer comfort although not as an exclusive reason (Figure 22). It was the second highest reason for purchasing a heat pump. While a portion of these participants ultimately heated at least somewhat with their units, this original purchase intent could reduce the use of installed heat pumps.

Figure 22. Participants' Reasons for Seeking New System (n=470)



How homeowners indicate they use their heat pumps can help inform how much heat pumps are used. Later in this evaluation we show how a combination of intent, operation and zoning can determine how much heat pumps are used.

Figure 23 shows four operating strategies that classify homeowners' use.

1. About half of users set the heat pump to a desired temperature and leave it to operate, the preferred strategy from an operational and efficiency perspective.
2. About a quarter of users change the temperature setpoint throughout the day, which can work well, but in some cases, this could lead to the base fuel system operating more. We have seen some homeowners set their heat pump to the same as the pre-existing heating system thermostat in the mistaken belief that this leads to heat pump use, and we have seen other homeowners understand the droop strategy perfectly setting the heat pump to warmer than their pre-existing heating system.
3. About a fifth of homeowners turn the heat pump on and off manually as needed. We have seen homeowners turn the heat pump on in the morning and achieve a moderate amount of usage this way, and others turn the heat pump on, say at dinner to bring a bit of extra heat during mealtime, but don't use the heat pump that much.
4. The remaining 8% of respondents use a programmable controller or another strategy.

The evaluators asked participants if they shut their heat pumps off at a particular temperature because we had heard about this behavior anecdotally. It turns out that most homeowners shut their heat pumps off or choose not to turn them on at some minimum temperature. Reasons given included making sure that the heat pumps weren't working too hard, implying an effort to either prevent damage, save money since efficiencies decline at cooler temperatures, or an observation or belief that heat pumps could not heat a space below a temperature—a capacity issue.

Figure 23. Typical Heat Pump Operational Strategy (n=470)

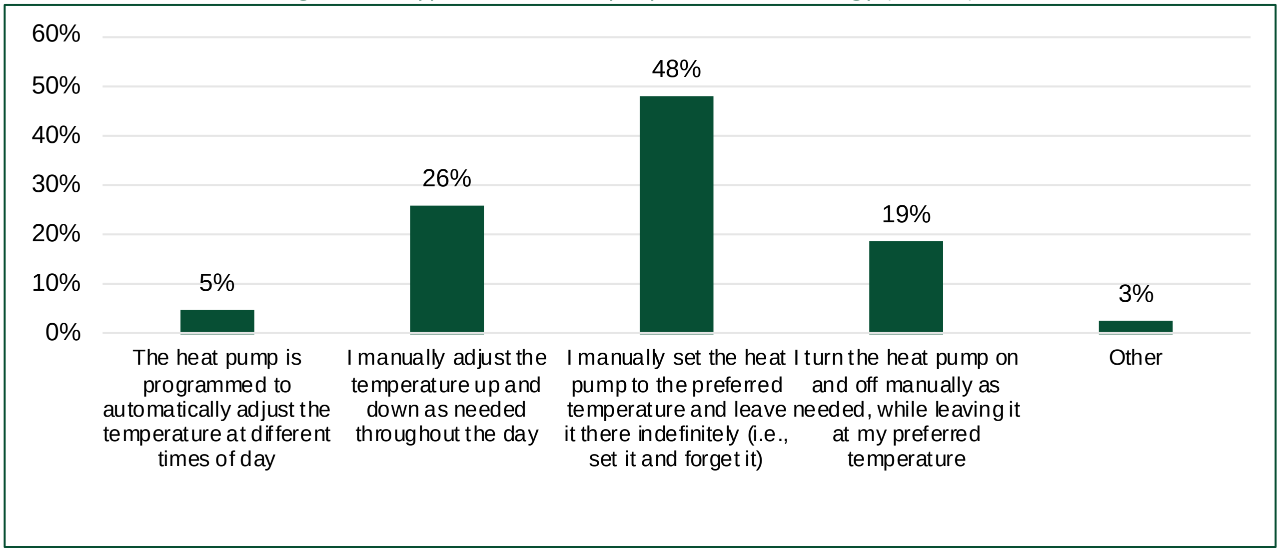


Figure 24 shows that about half of all heat pumps are shut off when temperatures drop to 15°F, and by around 1°F, 70% of heat pumps were shut off. Below this temperature, given the few hours that occur in most parts of Maine below 0°F, it is unclear whether the last 15% are shut off or if other systems are simply turned on. Given that 22% of heat pumps are shut off above 20°F, there is opportunity to increase the use of installed heat pumps.

Figure 24. Outdoor Temperature Where Users Report Shutting Off Heat Pumps (n=112)

5 CONTRACTOR SURVEY

In June and July 2022, Guidehouse conducted a survey of trade allies, including installers and distributors serving the HESP and AHI programs. The survey gathered information related to the influence of the program, partner experience with the program, and installation and maintenance practices.

Participating installers show high satisfaction with the program overall, giving it an average rating of 7.75 out of 10 (Figure 25). Recommendations for improvement included (1) increasing rebate levels, (2) adjusting the AHI eligibility criteria to allow more customers to qualify, and (3) reducing rebate turnaround time. Higher rebates and faster payment are typical suggestions received in this type of survey, and in the opinion of the evaluator, are not indicative of a problem. Given that AHI rebate levels were significantly higher than HESP rebate levels, the suggestion regarding AHI eligibility is equivalent to raising rebate levels.

Figure 25. Installer Satisfaction with Program

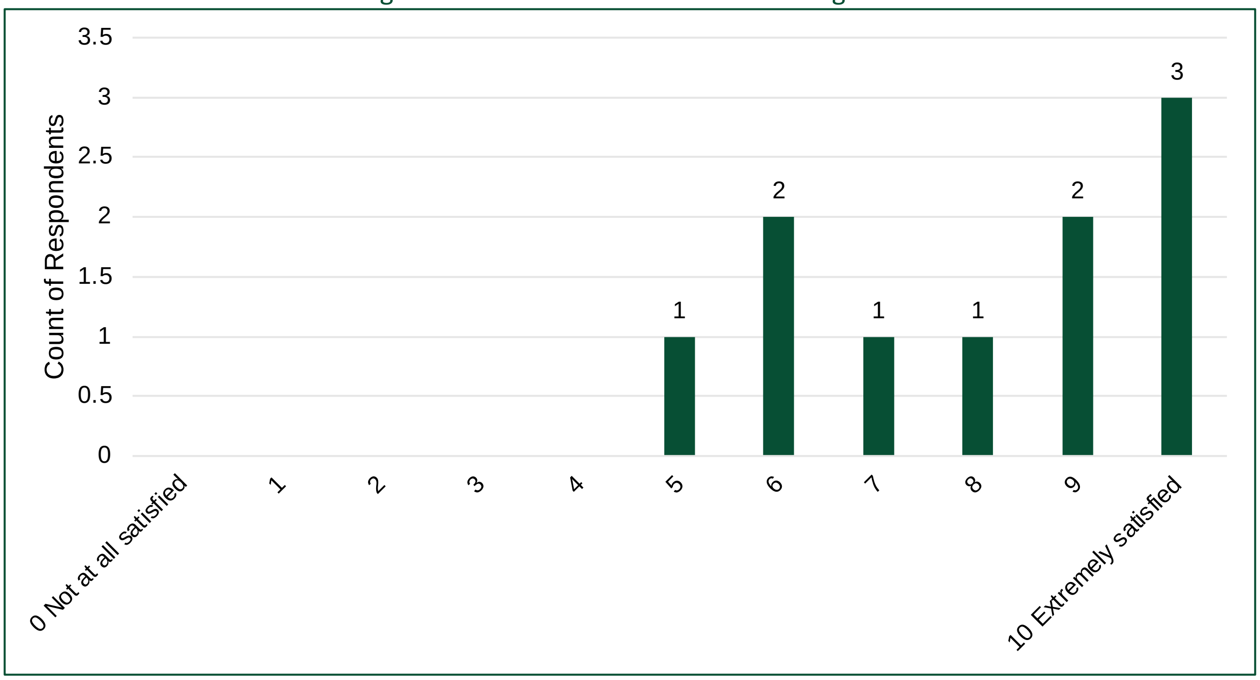


Figure 26 summarizes the reported percentage of heat pump types comprising respondents' heat pump sales. Single-zone heat pumps are the most popular by a wide margin, accounting for 67% for installers and 56% for distributors. Multi-zone heat pumps account for, on average, about 30% of heat pump sales for both market actor types. Ducted units are a small fraction of sales. The evaluation team spoke with multiple contractors in the field that prefer not to install multi-zone system for the following reasons:

1. They view multi-zone systems as less efficient and are concerned about limited turndown ratios.
2. They see costs savings as proportionally small compared with the equipment reduction of a multi-zone versus multiple single-zone heat pumps.
3. They prefer the redundancy of a multiple single-zone heat pump configuration.

Figure 26. Average Percentage of Heat Pumps Sold by Type

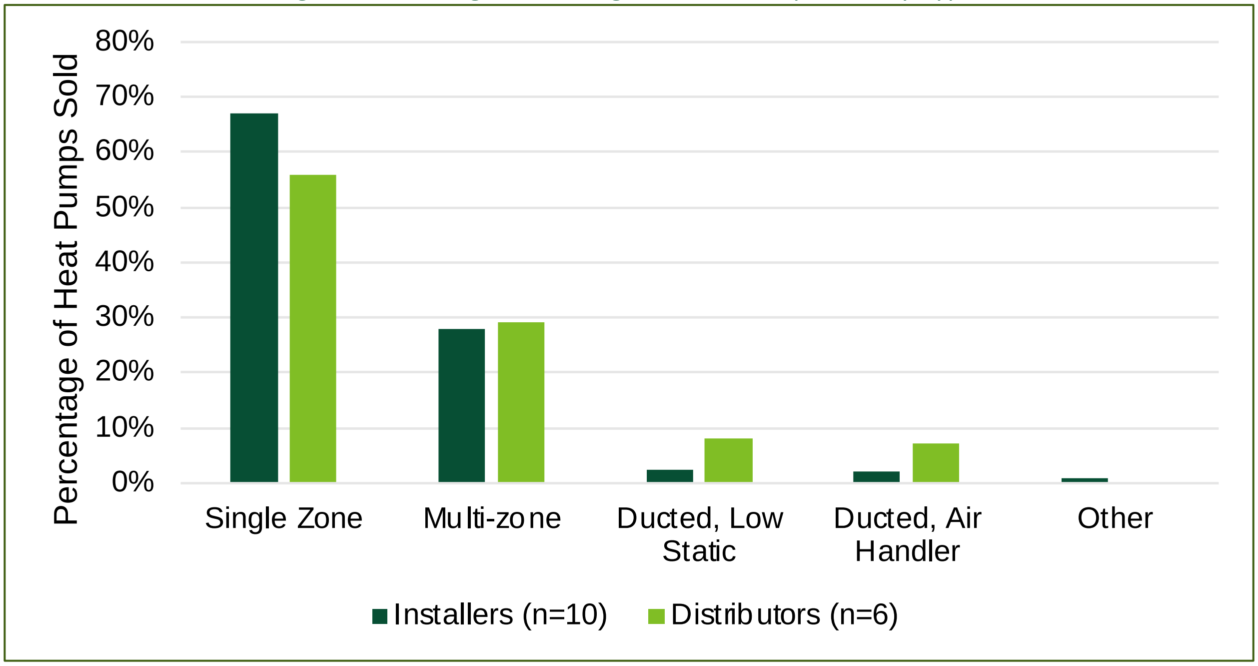


Figure 27 summarizes the changes to business practices trade allies attribute to Efficiency Maine's heat pump rebate program. Using Efficiency Maine's heat pump tips to train customers (8) and recommending qualified heat pumps (7) are the most common changes trade allies made.

Six distributors were also surveyed about the changes to business practices as a result of the rebate program. Each distributor indicated that it recommend that installers join Efficiency Maine's Residential Registered Vendor network, that it stocks more qualifying heat pumps, and that it works with more installers because of their participation in the program (Figure 28).

Two-thirds of distributors (4 of 6 respondents) reported selling more heat pumps that qualify for Efficiency Maine's rebate since participating in the program. Similarly, 5 of 6 installers report selling more heat pumps that qualify for the rebate since participating in the program. Another three distributors started selling heat pumps coincident with the intiation of rebates, illustrating the effect of Efficiency Maine's rebate program in growing the heat pump market in Maine (Figure 29).

Figure 27. Installer Changes to Business Practices (n=10)

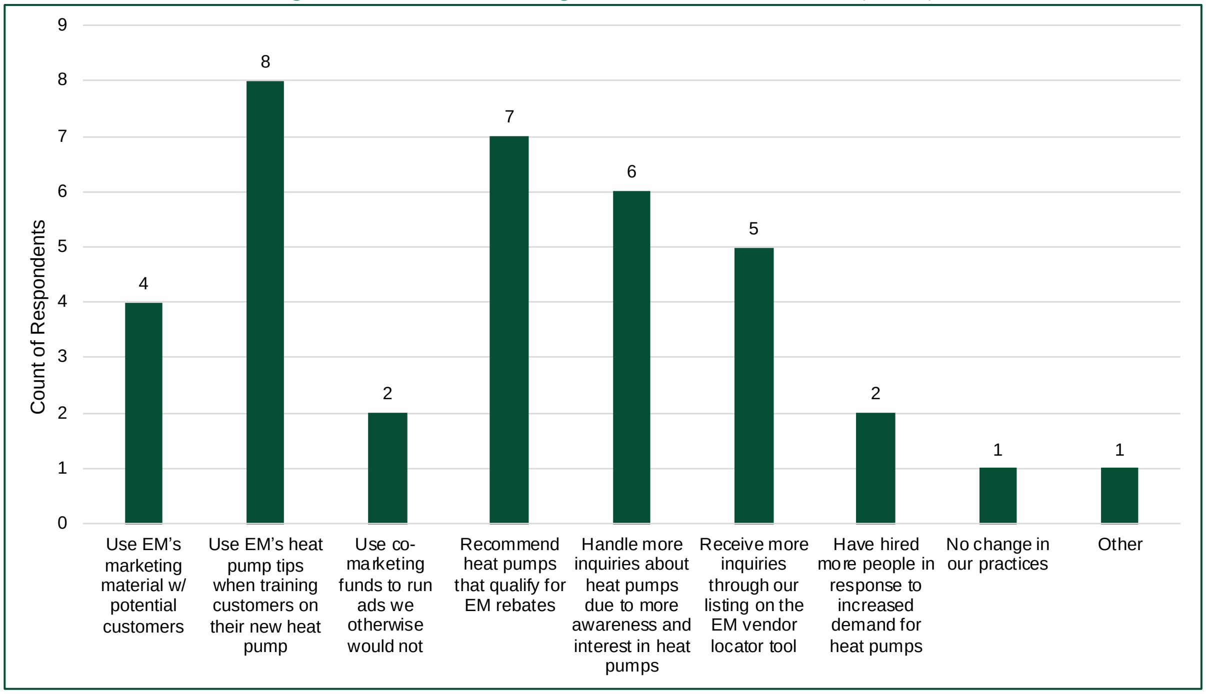


Figure 28. Distributor Changes to Business Practices (n=6)

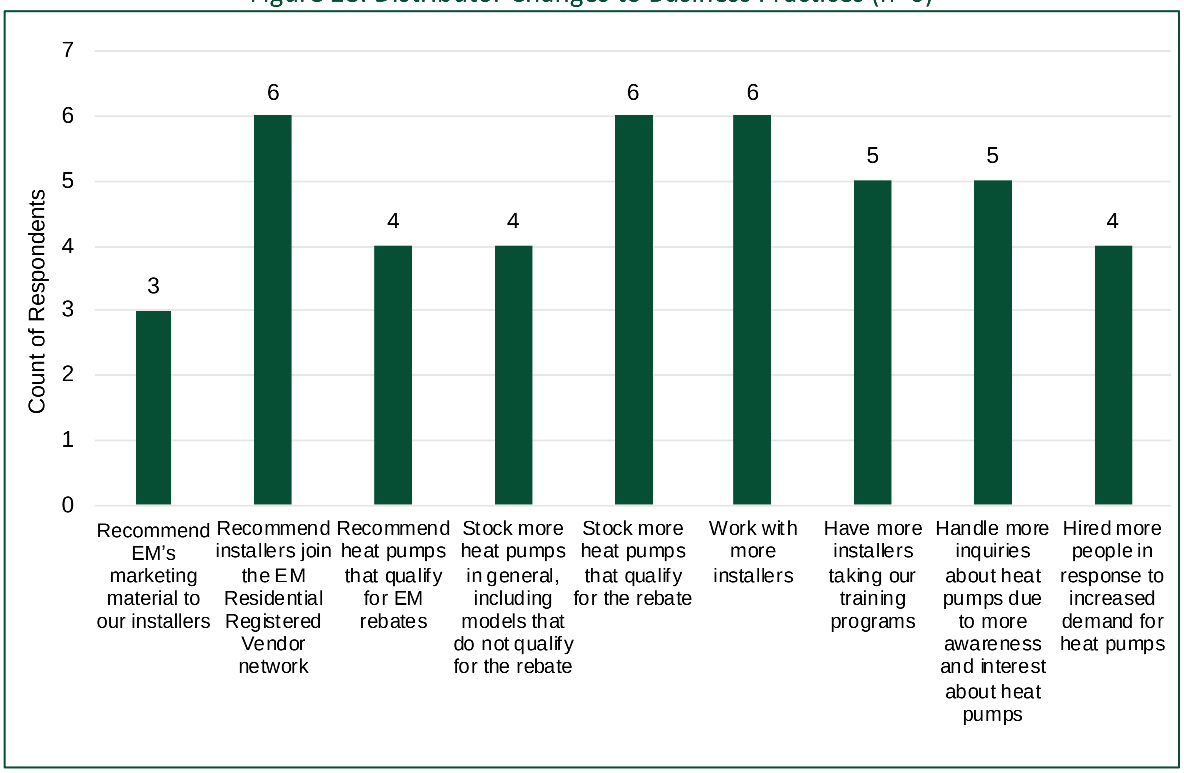
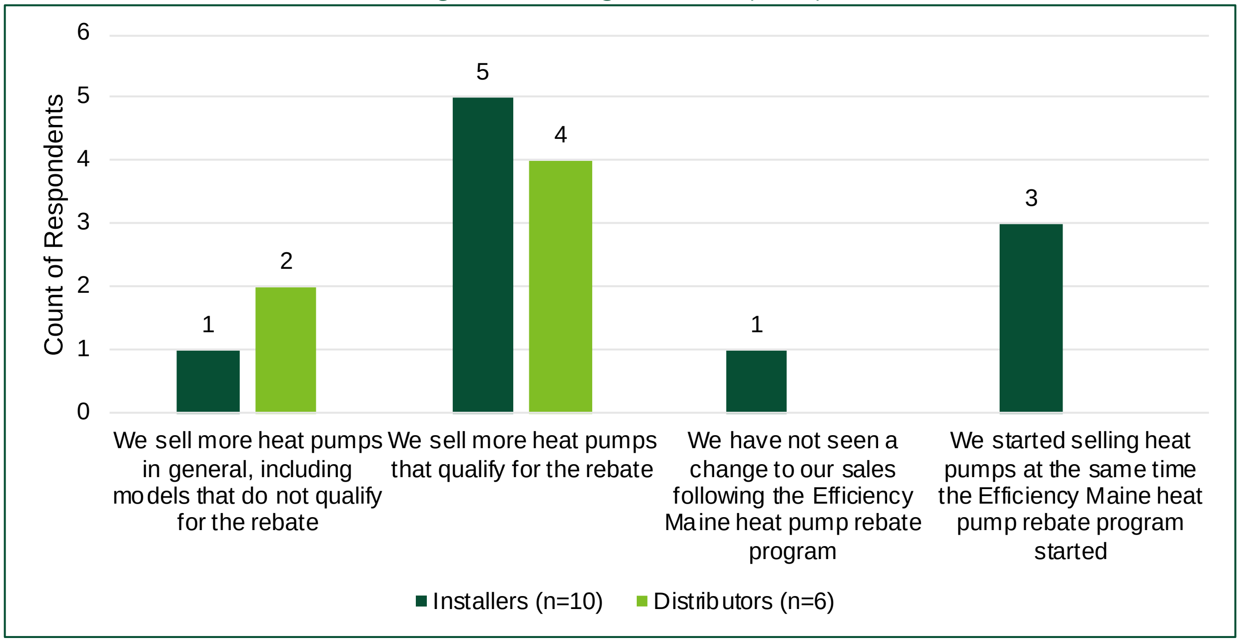


Figure 29. Changes to Sales (n=16)



When asked how beneficial each element of the Efficiency Maine Heat Pump Program is, installers responses were varied. Installers rated rebate impact on customer's total cost as the most beneficial element of the program, with an average score of 8.6 out of 10 (Figure 30). Vendor listing on the Efficiency Maine website was rated the second most beneficial (8.1). The program elements reported as the least beneficial by installers were Efficiency Maine's required training (5.6) and program materials such as printed brochure and heat pump user tips (5.8).

Installer respondents were asked about the motivations for heat pump installations (Figure 31). Installers indicated that 45% of heat pump installations were focused on adding heating and cooling to offset other heating and cooling systems (i.e., use less of the other heating and cooling systems). Replacing other heating and cooling systems (12%), adding heating and cooling to a newly built space or a new construction home (11%), and adding heating and cooling to an underserved area (9%) were the second, third, and fourth greatest motivations for heat pump installations. In total, about 15% of systems are installed to replace a heating or heating and cooling system. This leaves the possibility that a large portion of the 85% of remaining systems will compete with an existing heating system.

Figure 30. Contractor Rating of Program Elements (n=10)

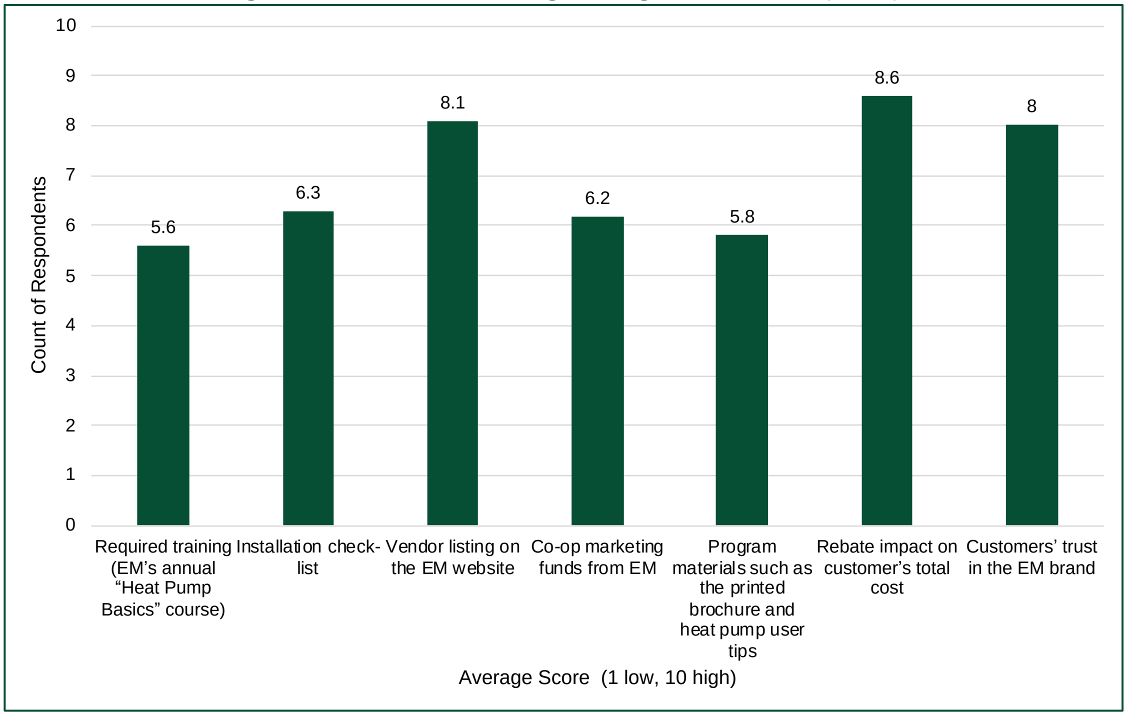
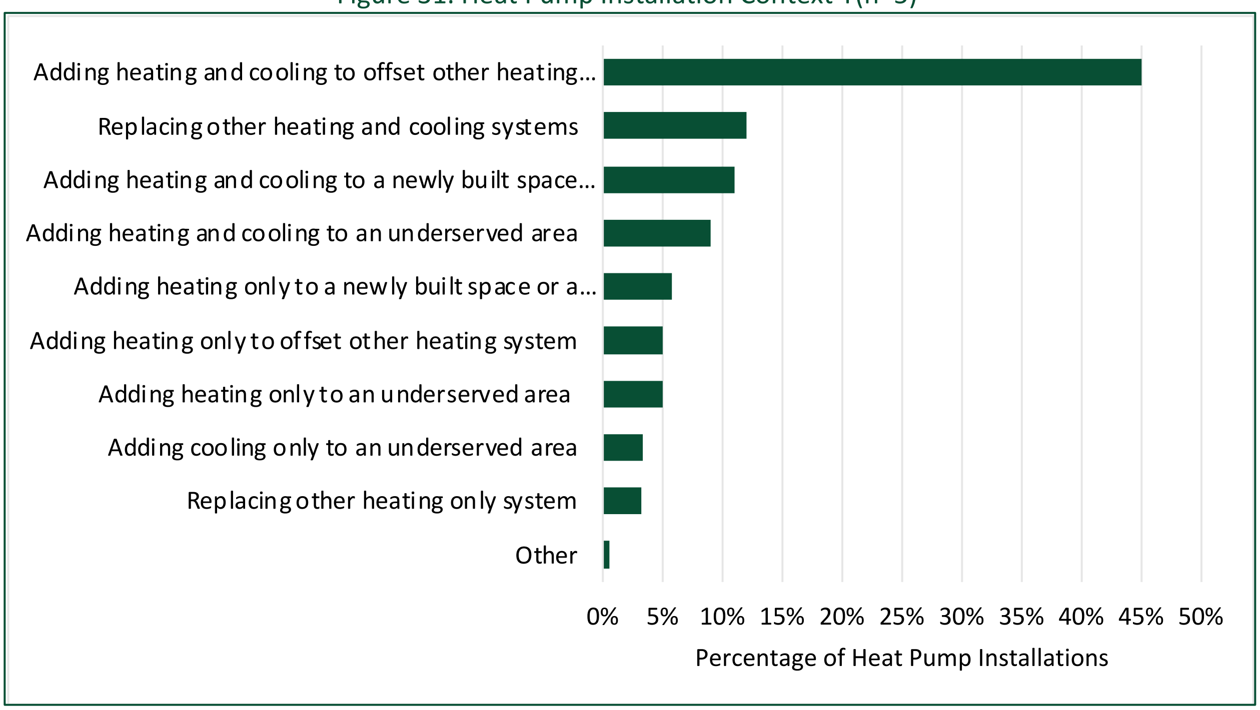


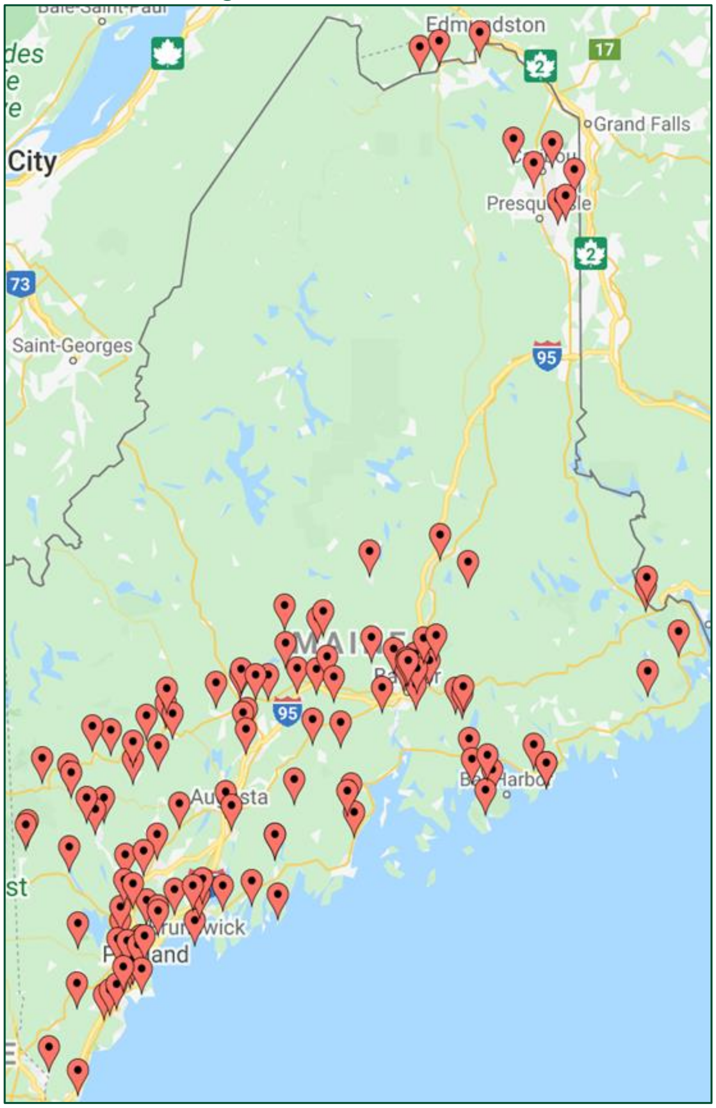
Figure 31. Heat Pump Installation Context T(n=5)



6 SITE AND HEAT PUMP CHARACTERISTICS

We studied 124 homes across 16 Maine counties (Figure 32). We wanted to cover at least some homes in far northern Maine to ensure that the metered heat pumps experienced some very cold temperatures. We metered 12 homes north of Lincoln Maine, of which nine were in one of the coldest regions of Maine-- Presque Isle and north.

Figure 32. Home Locations



Examining a USDA map of minimum expected temperatures that was available at the time of the study, we can see that we have groups of sites in 4a and 3b with minimum expected temperatures of -25°F to -35°F (Figure 33). During the study, we saw some homes with temperatures in this range, albeit for brief periods. The majority of the sites were in zones 5b to 4b with minimum expected temperatures of -10°F to -25°F. A few sites were in the relatively warmer coastal sites with minimum expected temperatures in the -5°F to -10°F range. During the study, nearly every site experienced -10°F or colder, but again for brief periods. On February 4th, 2023, even coastal sites saw temperatures of -10°F or colder. A newer version has been recently released by USDA after this study was completed. Climate zones have shifted northward, that is areas have gotten warmer.

Figure 33. Regions of Sites on Map of Climate Zones based on Minimum Temperatures

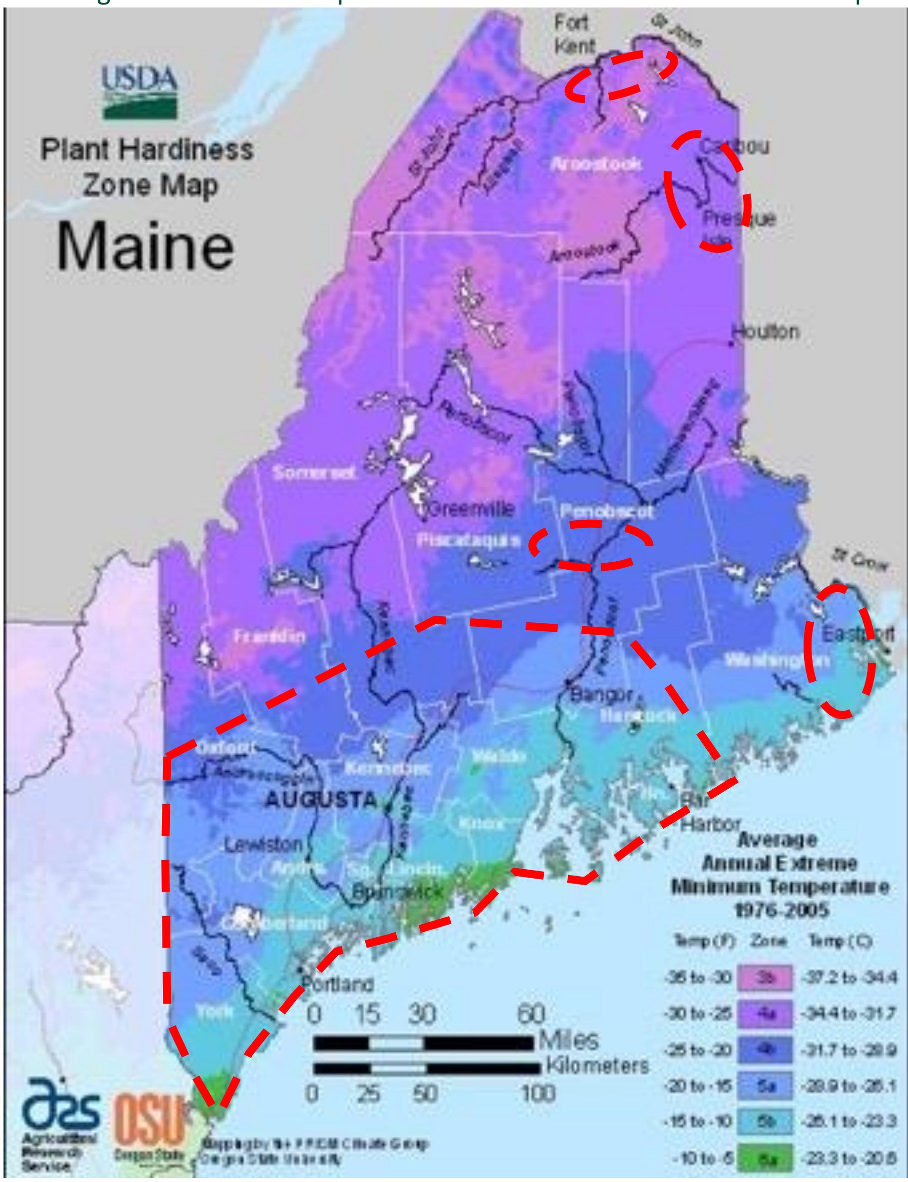
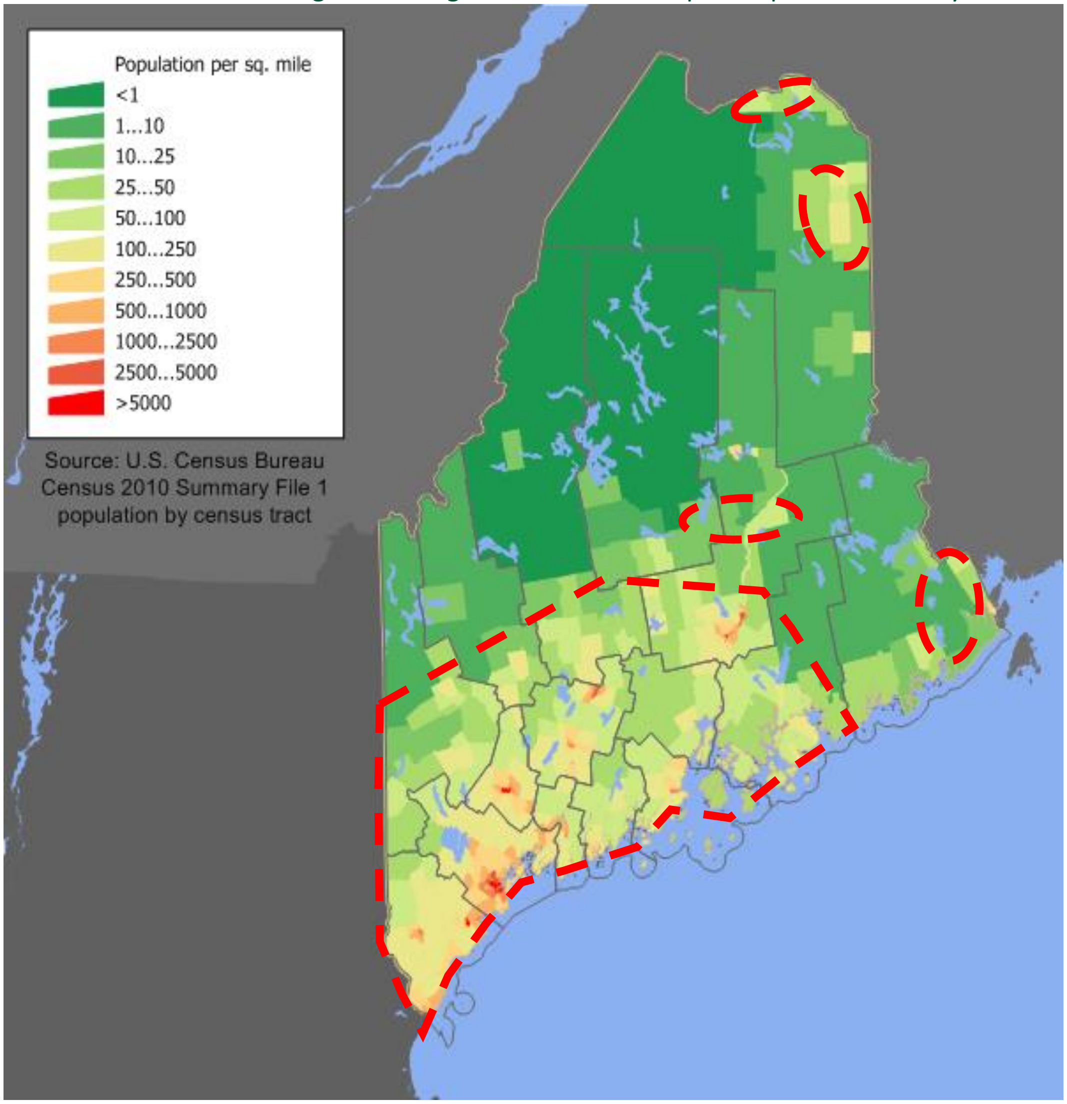


Figure 34 shows the regions with site visits laid over a population map. The sampled sites cover all of the high density and most of the moderate density portions of the state.

Figure 34. Regions of Sites on Map of Population density



Ridgeline studied 124 homes of which most were single-zone heat pumps with one outdoor unit connected to one indoor unit. In all, the homes contained 170 outdoor units and 210 indoor units (Table 10). Of the 170 heat pumps, 135 were single zone units, and 35 were multi-zone units, that is, outdoor units with more than one indoor unit each. While we observed 6 brands of heat pump, 98% were Mitsubishi, Daikin, or Fujitsu (Table 11).

Table 9 shows the proportion of measures in the program population and in the study. The TRM assumes different savings for the first and second units installed, but the evaluation did not make that distinction because there was no systematic, consistent way to determine which was considered first versus second. For this reason, percentages of first and second units are combined. The study sites had 18% Tier 1 single-zone HPs, 46% Tier 2 single-zone HPs, 19% multi-zone HPs, and 17% property assessed and LIHEAP measures. The sample follows the population generally, but Efficiency Maine and the evaluators sought a larger sample (than 6.5%) of the property assessed and LIHEAP categories, and shifted some of the sample accordingly. There was also expected variability due to recruiting by category and climate and Tier 1 units were sampled at a slightly higher rate than the population and multi-zone systems a bit lower.

Ridgeline studied 124 homes of which most were single-zone heat pumps. In all, the homes contained 170 outdoor units and 210 indoor units (Table 10). Of the 170 heat pumps, 135 were single zone units, and 35 were multi-zone units. While we observed 6 brands of heat pump, 98% were Mitsubishi, Daikin, or Fujitsu (

Table 11).

Table 9. Sites Investigated by Program Subcategory

Program Category	Sample	Percent	Population	Percent
Heat Pump Single Zone 1st Unit Tier 1	17	17.7	2,162	13.4
Heat Pump Single Zone 2nd Unit Tier 1	5		740	
Heat Pump Single Zone 1st Unit Tier 2	50	45.9	9,639	56.3
Heat Pump Single Zone 2nd Unit Tier 2	7		2,495	
Heat Pump Multi-zone 2 or more zones	23	19.3	4,525	23.8
Heat Pump Multi-zone add on	1		610	
Mini Split HP Property Assessed	12	9.7	1,216	5.6
MiniSplit HP LIHEAP	9	7.3	199	0.9
Total	124	100%	21,586	100%

Table 10. Sites Investigated by Number of Heat Pumps (Outdoor Units) and Indoor Units

Count	Outdoor	Indoor	Multi-zone
62	1	1	N
17	1	2	Y
5	1	3	Y
2	1	4	Y
28	2	2	N
2	2	3	Mixed
2	2	4	Mixed
3	3	3	N
1	3	4	Mixed
2	4	4	N
124	**170**	**210**	

Table 11. Heat Pumps by Make and Size of Outdoor Unit

	Size range					
(counts)	<=9,000	12,000	12,001 – 15,000	>15,001 BTU/h	Total	%
Mitsubishi	15	13	19	27	74	**44%**
Daikin	1	6	8	8	23	**14%**
Fujitsu	12	13	37	8	70	**41%**
Haier	0	1	0	0	1	**1%**
Samsung	0	0	0	1	1	**1%**
Boreal	0	0	0	1	1	**1%**
	28	33	64	45	170	**100%**
		19%	38%	26%	100%	

Mitsubishi and Fujitsu were the most numerous brands (Figure 35). The Fujitsu units tended to be a bit smaller, but examining brand by capacity did not shift the proportions by much (Figure 36).

Figure 35. Brand of Heat Pumps by Count

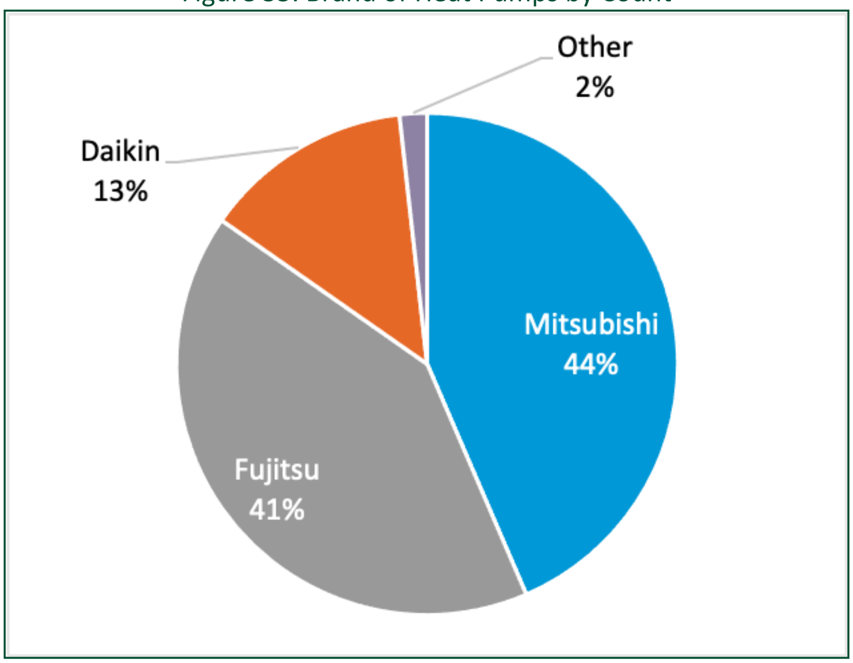
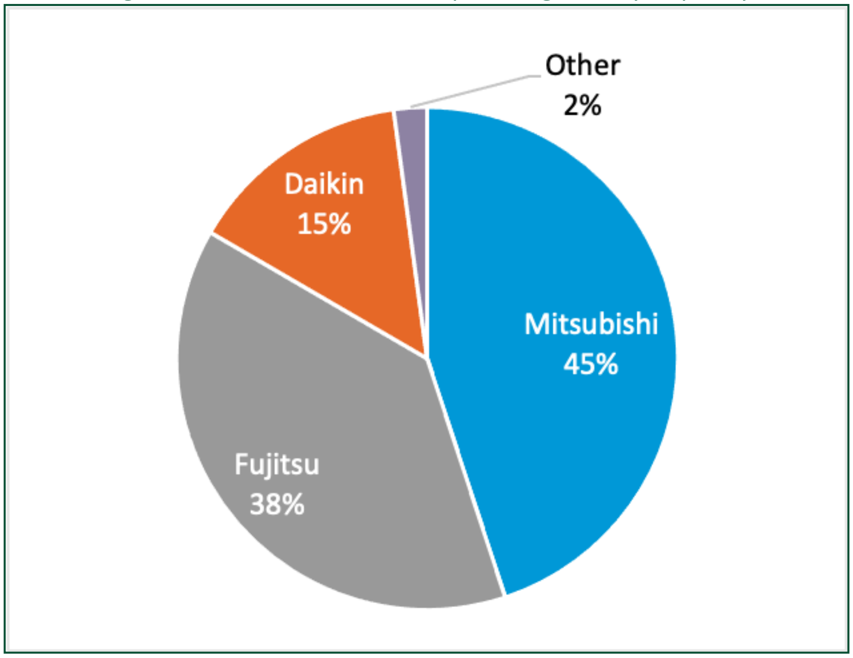


Figure 36. Brand of Heat Pumps, Weighted by Capacity



It is interesting to note that brands are not distributed evenly across programs. Fujitsu units make up nearly the entirety of the AHI program, while the three major brands are more evenly split in the HESP program (Figure 37). Sizes ranged widely but the majority (57%) of heat pumps were 9,000 – 15,000 BTU/h (Figure 38).

Figure 37. Brand of Heat Pumps, Rebated by Program and Year

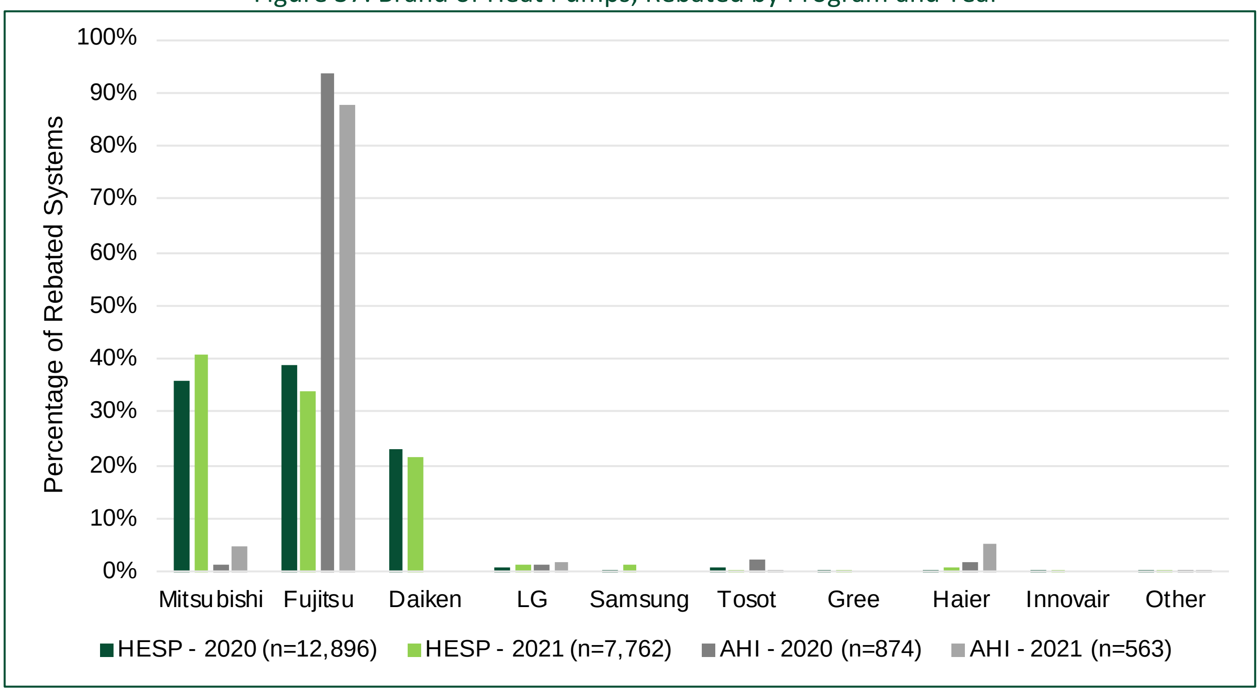
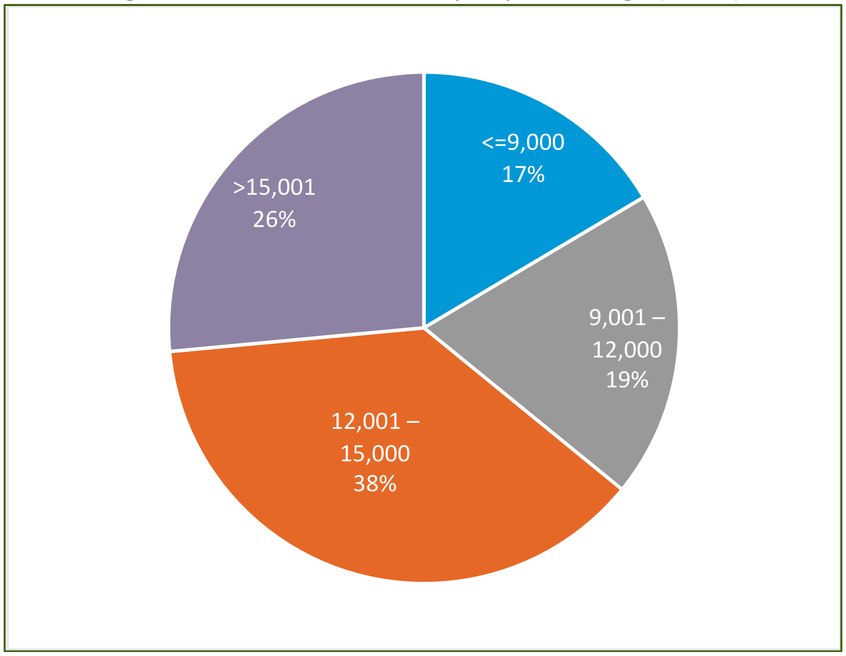


Figure 38. Count of Heat Pumps by Size Range (Btu/h)



7 HEATING

7.1 ELECTRICAL USAGE

This section presents the electrical usage of heat pumps metered during the period October 2021 to April 2023.

Figure 39 shows annual electricity consumption per heat pump. Usage averages 1,887 kWh per year and varies widely with nearly 40% of heat pumps using less than 1,000 kWh per year, and nearly 25% using more than 3,000 kWh per year. We discuss reasons for variation in usage later in the report and reasons include homes using heat pumps for cooling only, homeowners leaving for several months in the winter, and heat pumps overlapped by whole home fossil fuel or wood heating.

Figure 39. TMY Normalized Winter Heating Electricity Usage (n = 140)

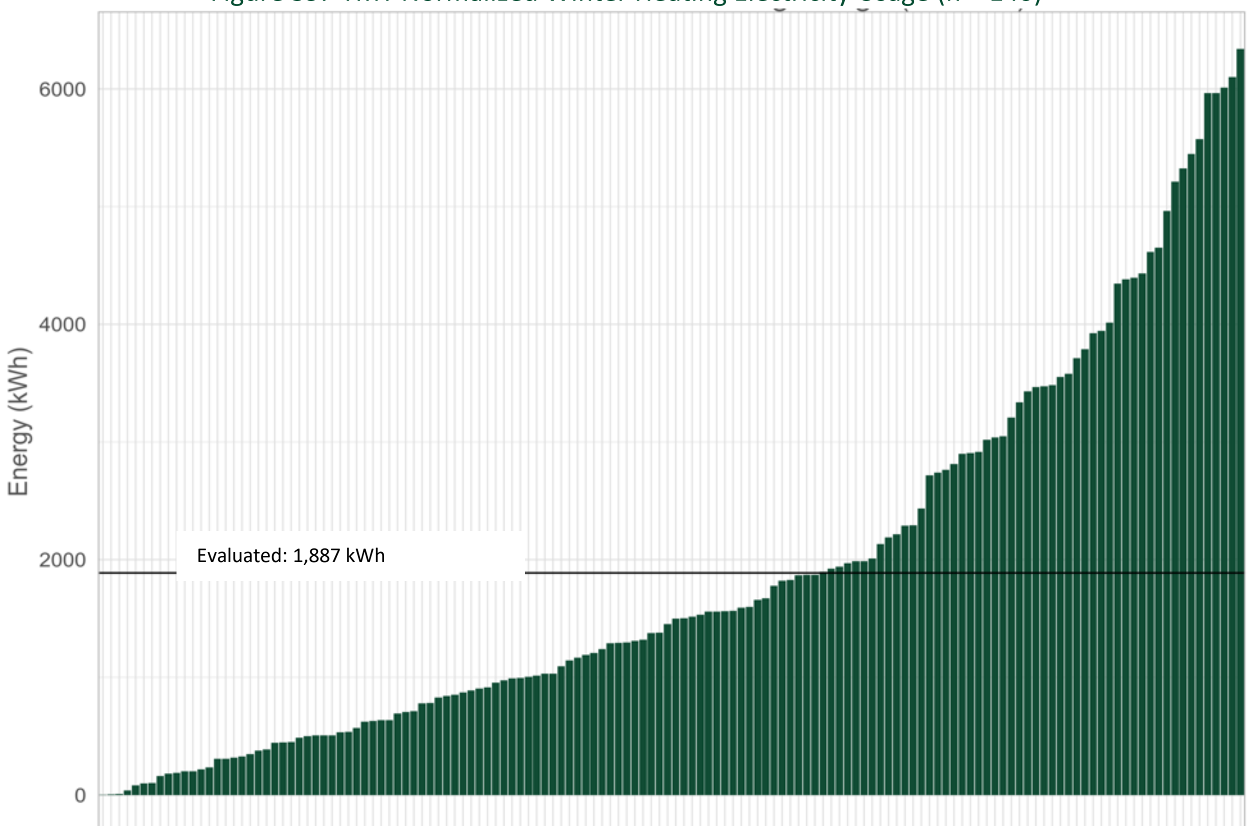


Figure 40 presents average power usage of metered units versus outdoor air temperatures. The power usage peaked at 0.8 kW/unit, when the outside ambient temperature was 2°F. On average, the heat pumps metered in this sample saw reduced average usage at temperatures below 0°F. This pattern is reflected in manufacturer's data where peak power occurs between 0°F and 17°F depending on brand and model and decreases below these temperatures. See Table 12.

Figure 40. Average Electrical usage with Outdoor Air temperature (n=119 outdoor units)

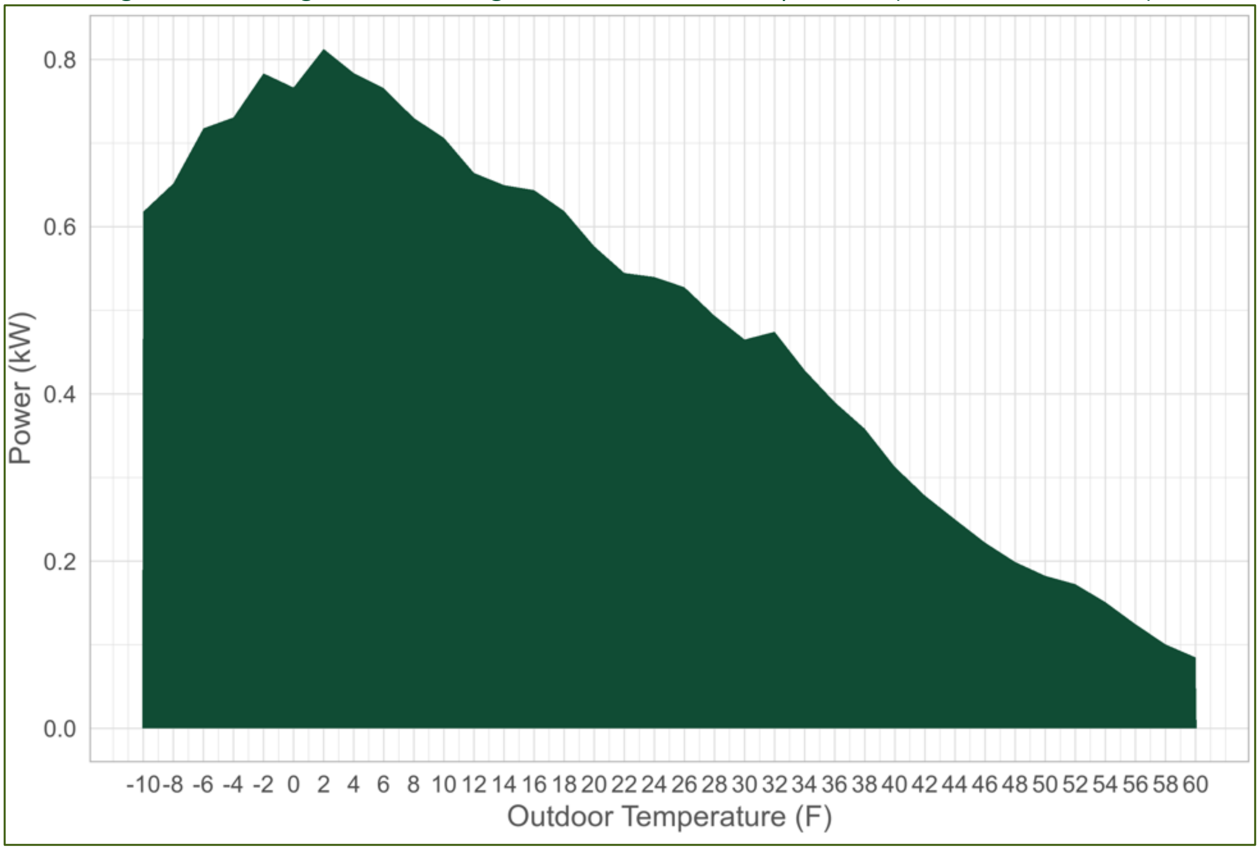


Figure 41 shows metered units' average winter power usage for winter by time of day. Average heating demand ranges from about 0.33 to 0.45 kW. It appears that the coldest portion of the day (around dawn), and when many families wake up, combine to produce the peak load on heat pumps. The minimum load occurs in early afternoon, around 2:00PM, when many occupants are away from home and outdoor temperatures rise.

Figure 42 shows the same information, split between weekday and weekend. There is little change in the load shape.

RIDGELINE energy analytics

Figure 41. Average Power Consumption vs. Time of Day, Day Type, (n = 119 outdoor units)

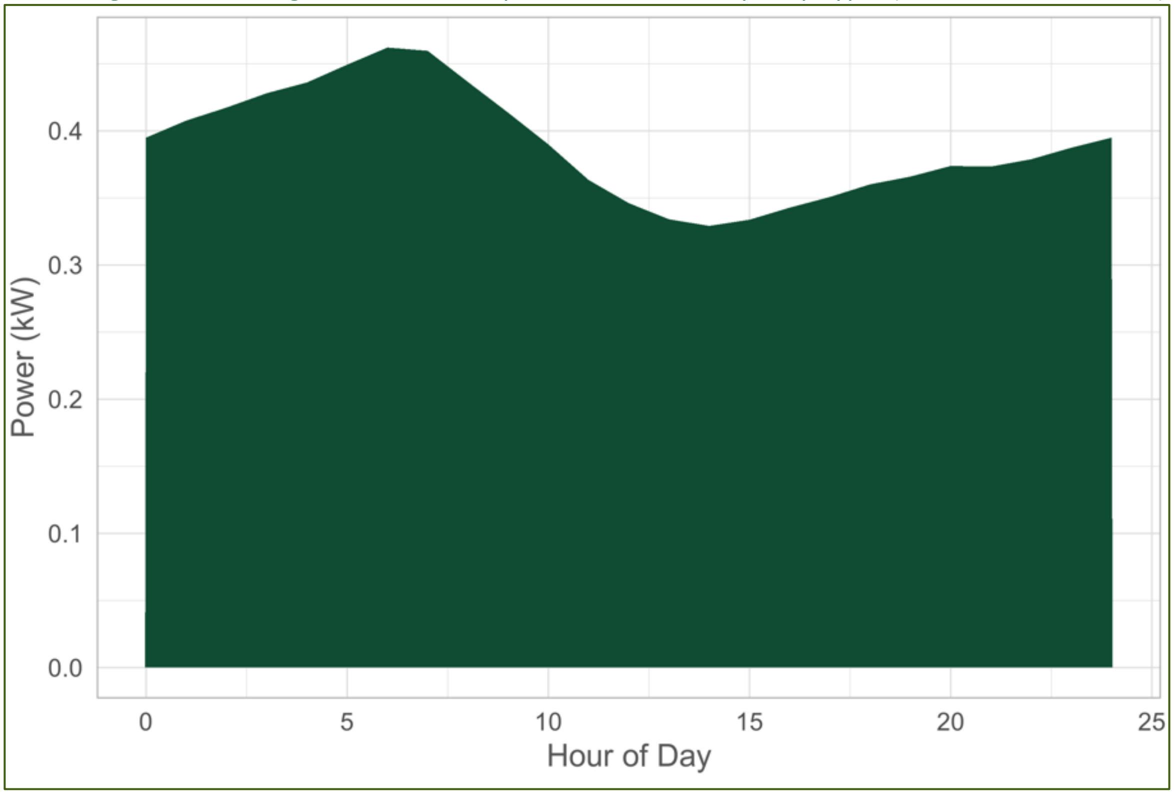
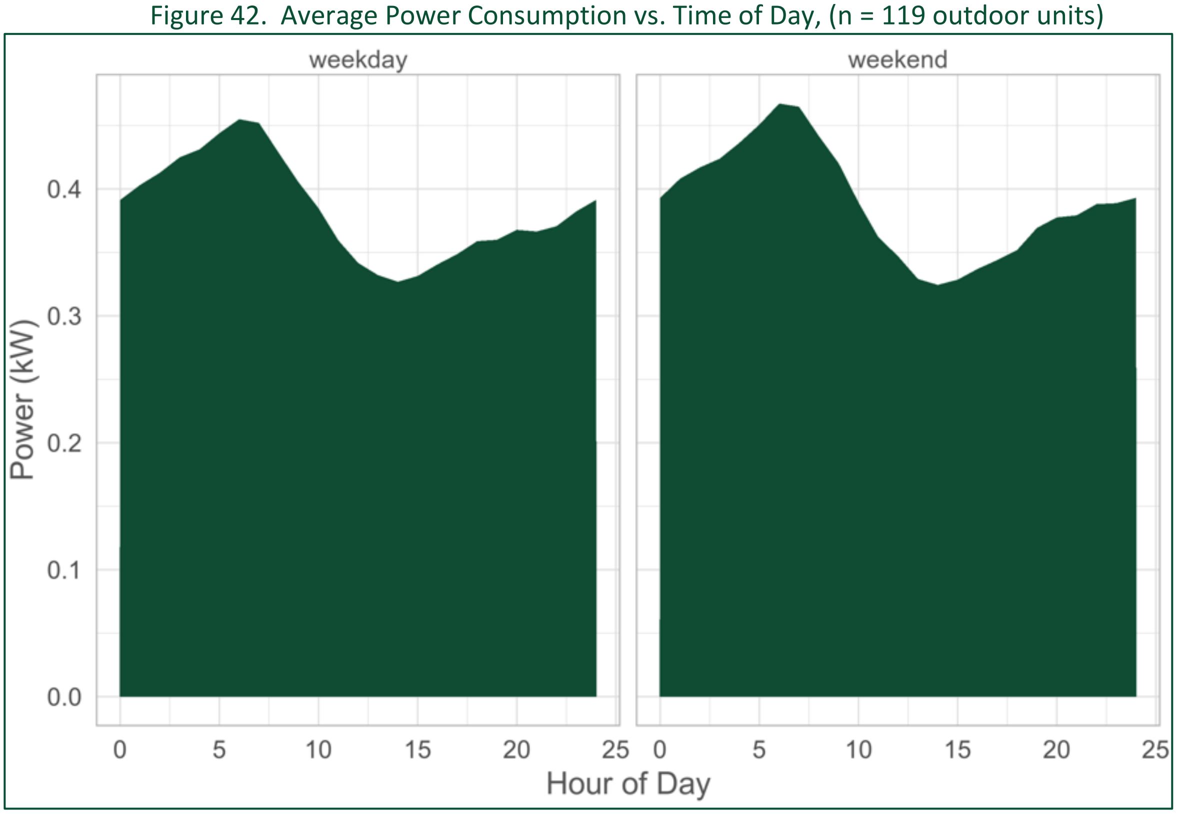
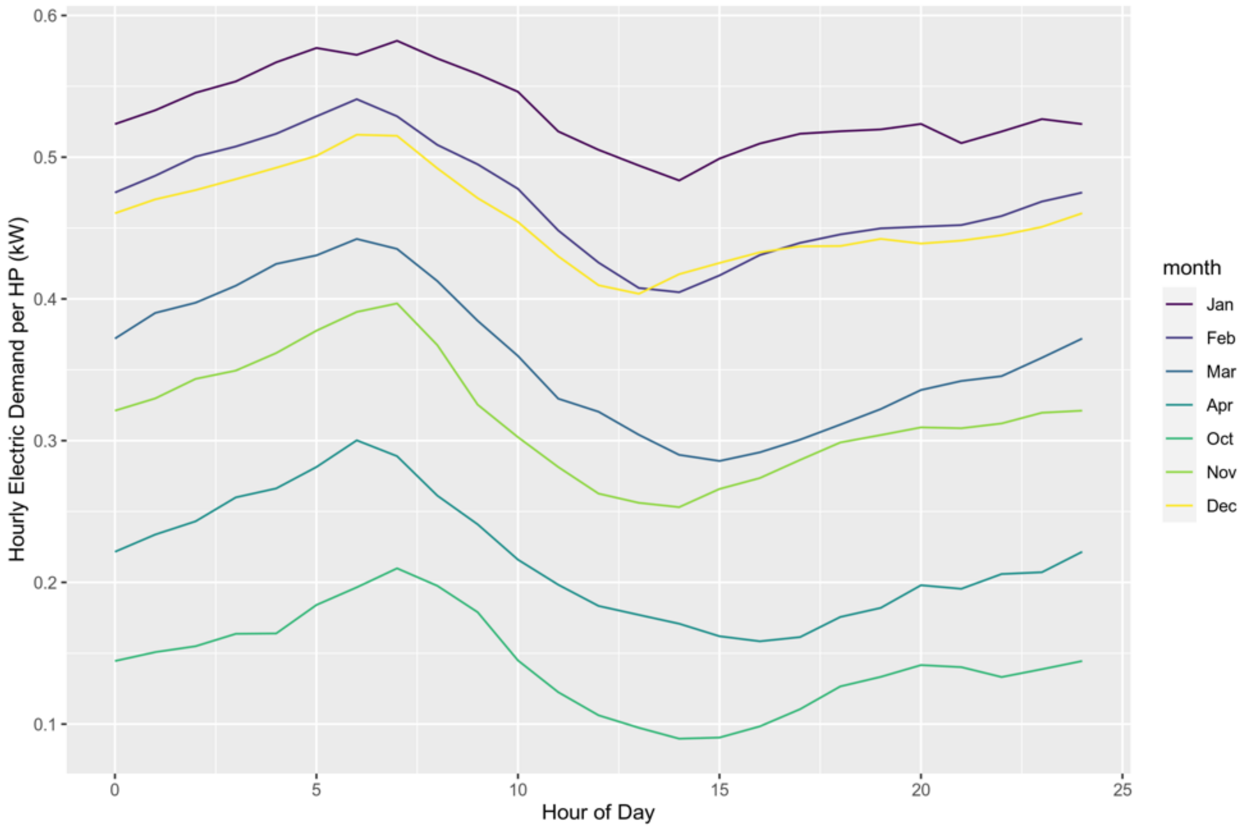


Figure 42. Average Power Consumption vs. Time of Day, (n = 119 outdoor units)



Looking at the daily variation in heating electricity use by month, Figure 43 shows the change in the magnitude of use and the change in daily pattern during the heating season by month.

Figure 43. Average Power Consumption vs. Time of Day, for 7 Months



7.2 HEATING PROVIDED

Figure 44 shows heating provided by 140 heat pumps with a mean value of 16.6 MMBtu/year. Nearly 38% of heat pumps provided less than 10 MMBtu per year, and about 30% provided more than 20 MMBtu per year. For reference, one MMBtu is equivalent to the heat output of 9 gallons of oil, combusted at 80%[6] effective efficiency. The heating outputs normalized by heat pump capacity is shown in Figure 45. The pattern of the curve is similar.

[6] While nominal combustion efficiencies can be higher than this, heat is lost in piping, duct leakage, and at the furnace or boiler. An effective efficiency is how much heat enters the occupied space.

Figure 44. Heating Provided by Heat Pumps

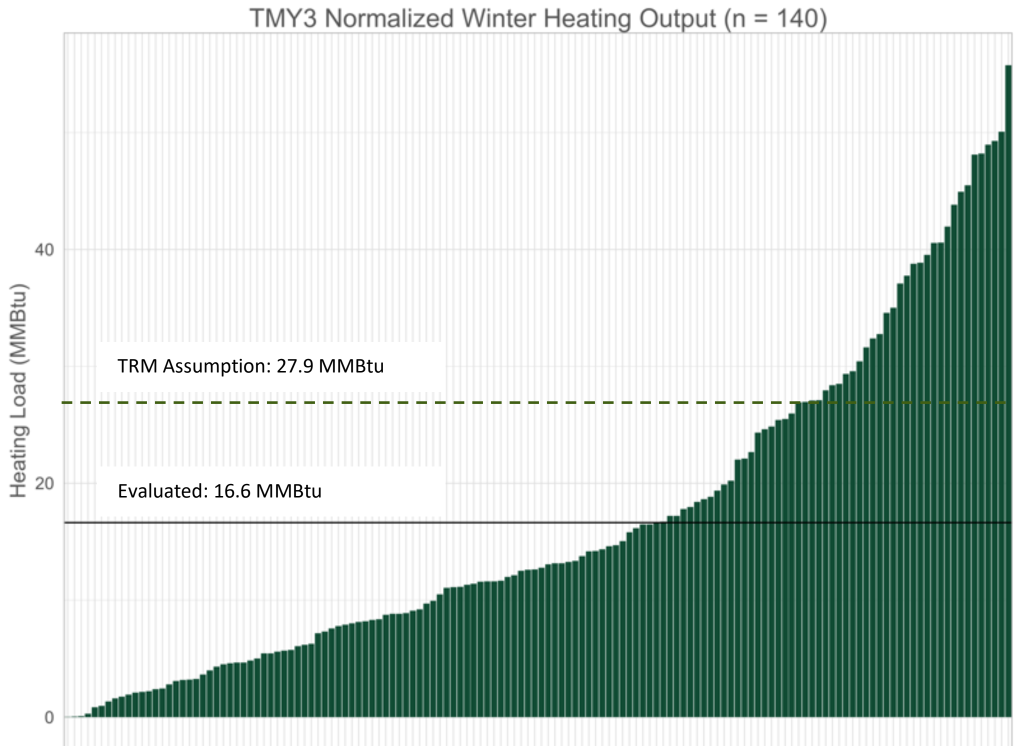
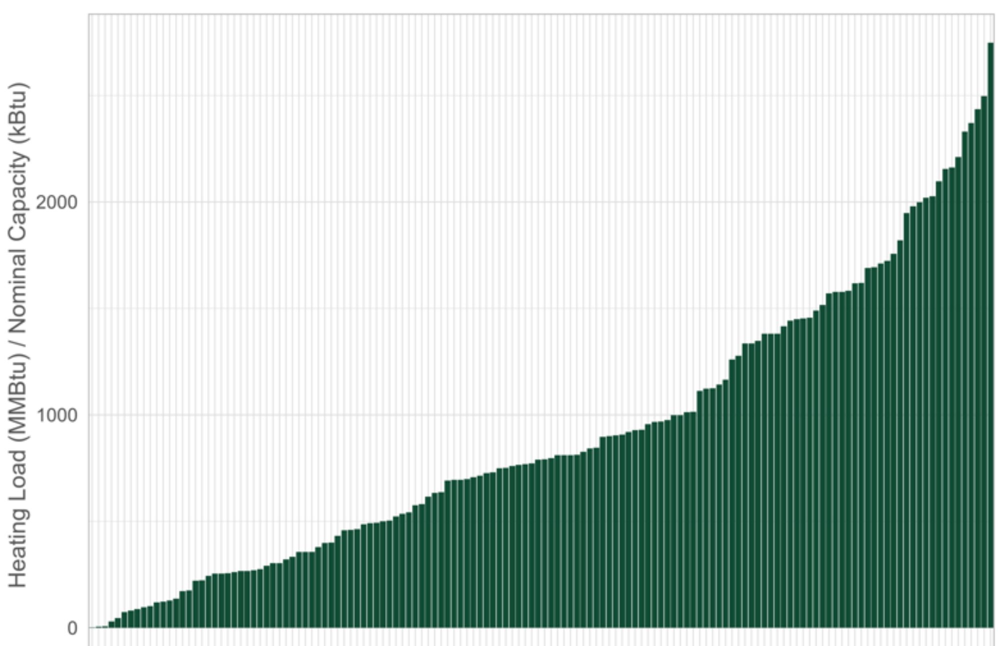


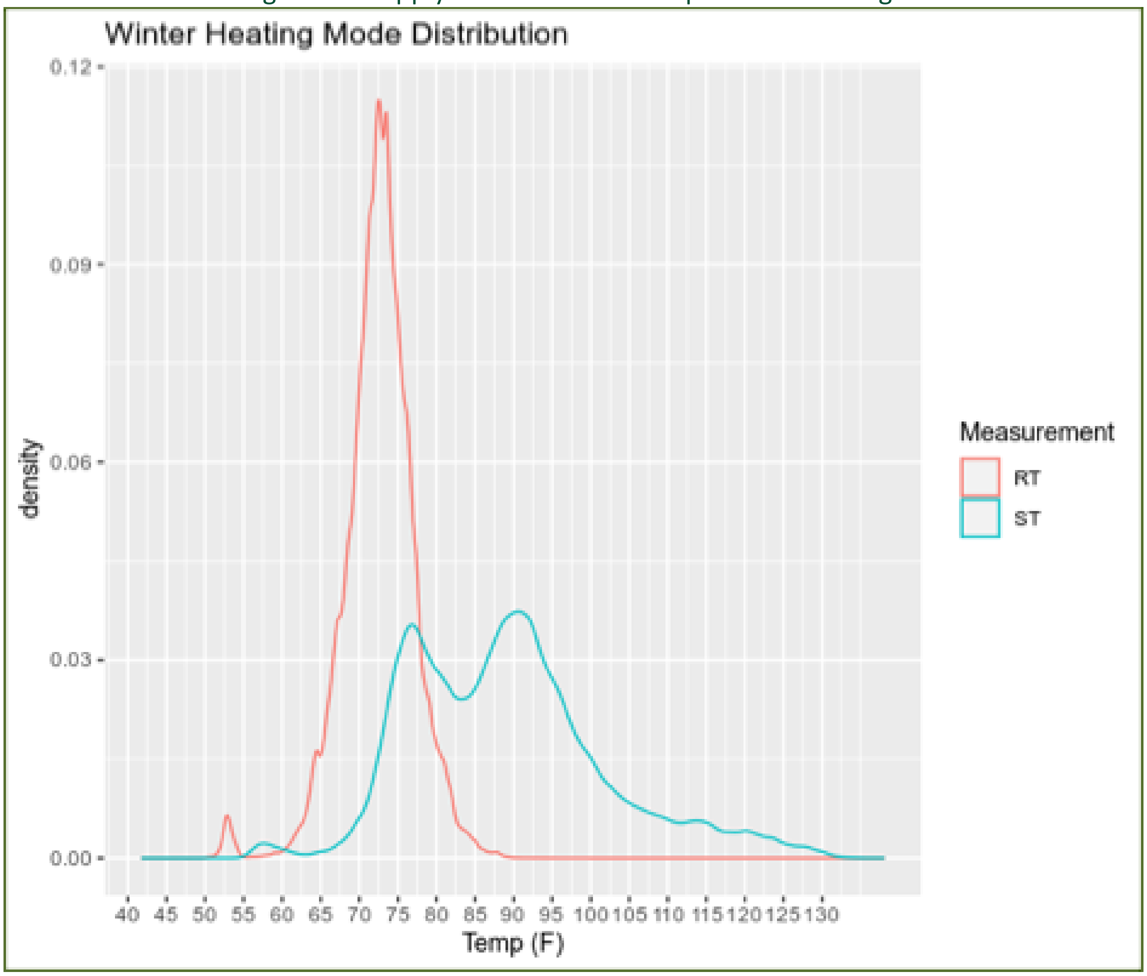
Figure 45. Heating Provided by Heat Pumps Normalized by Capacity (n=140 outdoor units)



7.3 SUPPLY AND RETURN TEMPERATURES

We graphed the supply and return temperatures at each indoor unit when the unit was operating in heating mode. Figure 46 is a histogram that shows the frequency of temperature readings. The most frequent return temperature is 72.5°F, with most readings occurring from 70°F to 75°F. Nearly all readings (well over 90%) occur from 65°F to 80°F. While the return temperature is indicative of the temperature of the heated space, it is generally higher than the experienced temperature by occupants. This is because all but a few of the units are wall-mounted and many of these are near the ceiling. Stratification of room temperatures caused the return temp to be higher than the set point and experienced temperatures.

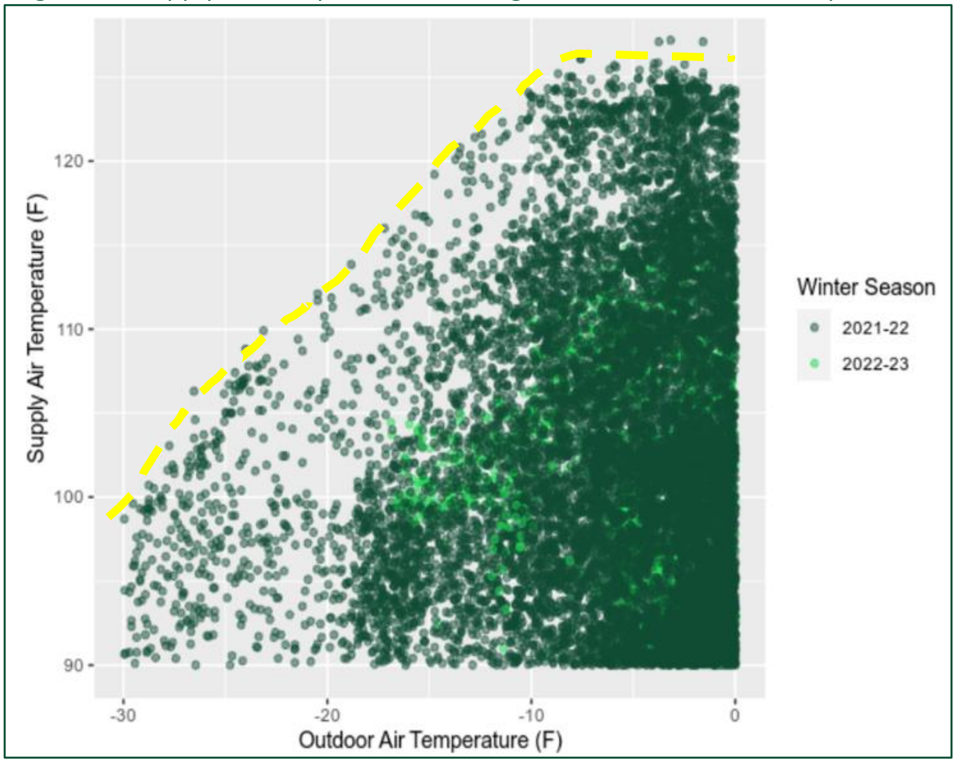
Figure 46. Supply Air and Return Temperature Readings



The supply (heating) air temperature is a broad peak between 75°F and 90°F, and warmer temperatures in the 90°F to 130°F range. The heating temperature will depend on internal algorithms of the heat pump, and outdoor temperature, where at very cold temperatures, supply temperatures drop with capacity.

We graphed the supply temperature versus outdoor air temperature for temperatures below 0°F in Figure 47. Each dot represents a two-minute data point. Overall, the readings vary because heat pumps have variable speed compressors and fans and may ramp temperatures down when setpoints are nearly met. The upper region of the curve (yellow dashed line) is interesting in that it shows that readings above 120°F supply air occur down to -10°F, near the minimum rated temperature for most heat pumps. There are numerous data points above 100°F supply air down to -20°F and even at -30°F heat pumps are producing air that is warmer than 90°F. Because each dot is one site for two minutes, the total readings below -30F are therefore about 5 site-hours, and only a few sites had readings this low. We checked at northern weather stations and saw temperatures of around -30°F at Presque Isle and one small station recorded a reading of -39°F in late January 2023.

Figure 47. Supply Air Temperature Readings at Low Outdoor Air Temperatures



8 COOLING

8.1 ELECTRICAL USAGE

This section presents the cooling-related electrical usage of heat pumps metered during the period August 2021 to April 2023[7]. Figure 48 shows cooling related electricity consumption per heat pump. Usage averages 252 kWh per year, and varies widely from 0 to about 1,000 kWh, with one system at about 1,150 kWh. Usage is low, as expected, given Maine's short summers and cool evenings.

Figure 48. TMY Normalized Summer Cooling Electricity Usage

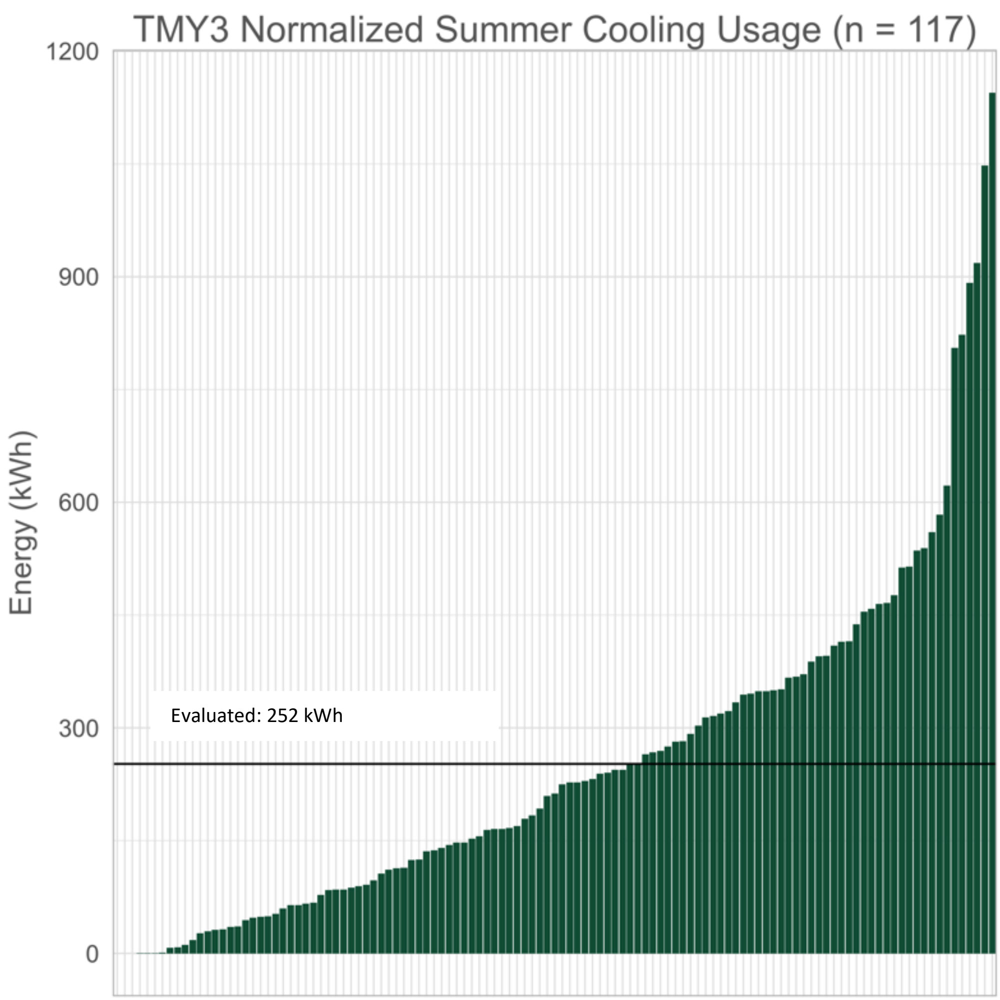


Figure 49 shows metered units' average cooling power usage by time of day. Average cooling demand ranges from 0.067 to 0.12 kW (0.16 kW on weekend). Peak load is about 4:30-5:00PM. The minimum load occurs around 3:00AM but is fairly flat from about midnight to 4:00AM.

[7] Cooling energy use and cooling provided is limited to the period May 1 to September 30 in our analysis.

Figure 49. Average Cooling Power Consumption vs. Time of Day, (n = 117 outdoor units)

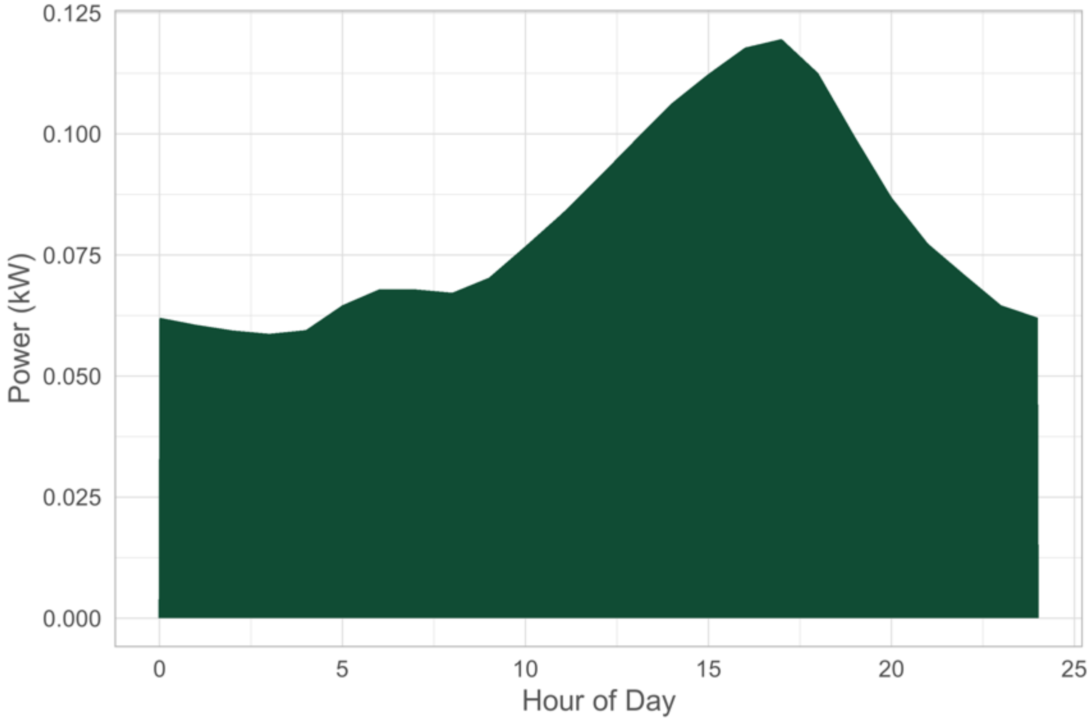
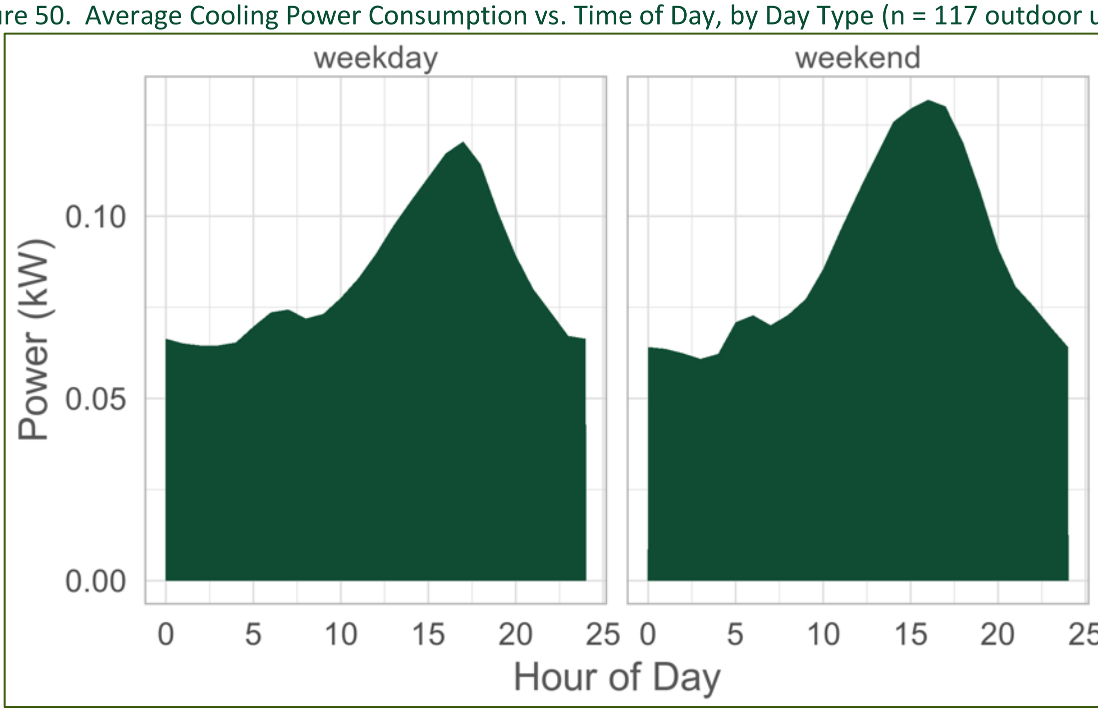


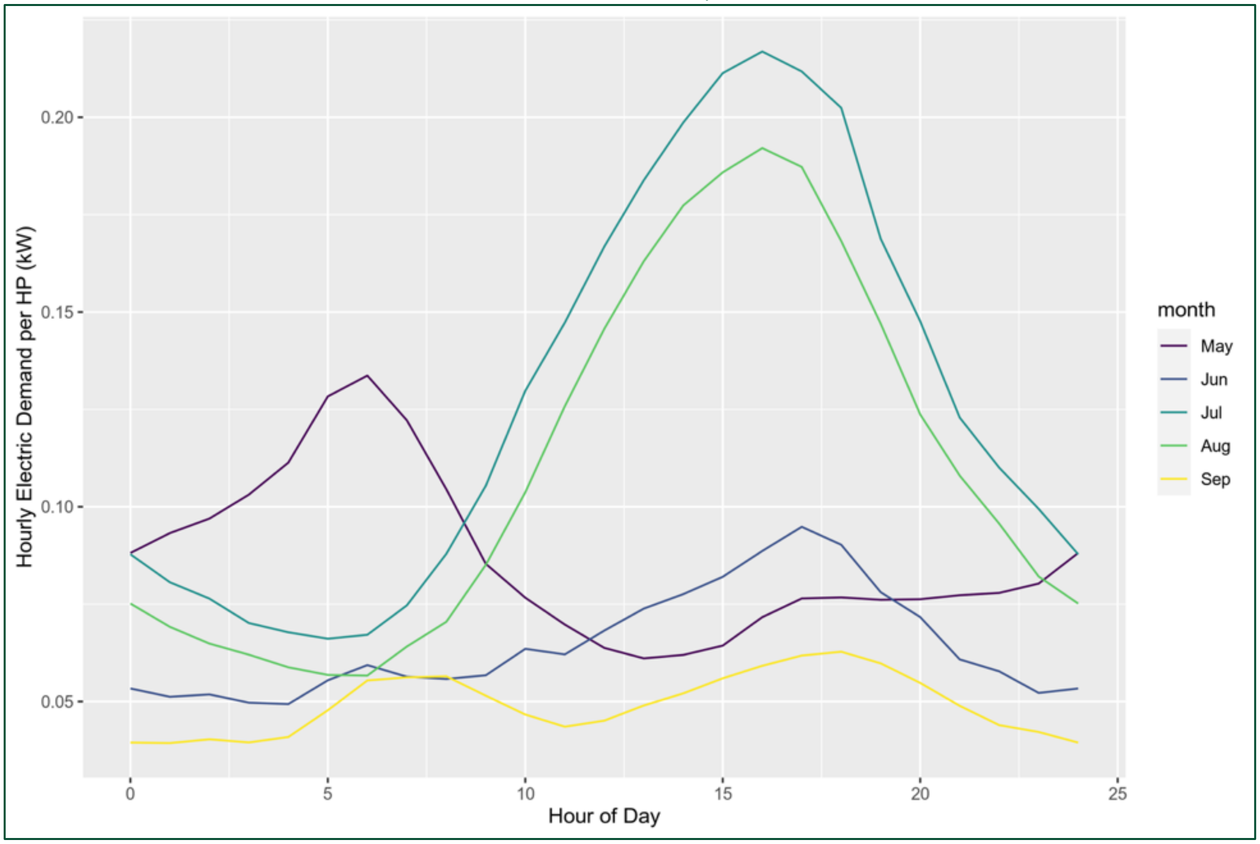
Figure 50 shows metered units' average cooling power usage by time of day for weekday and weekend. Average cooling demand ranges from 0.07 to 0.12 kW (0.13 kW on weekends). Peak load is about 4:30PM on weekdays and 3:30PM on weekends.

Figure 50. Average Cooling Power Consumption vs. Time of Day, by Day Type (n = 117 outdoor units)



Looking again at the daily variation in power use by month, Figure 51 shows May with mild heating in the early morning, June and September with flat energy use with time of day and July and August with later afternoon peaks characteristic of cooling activity.

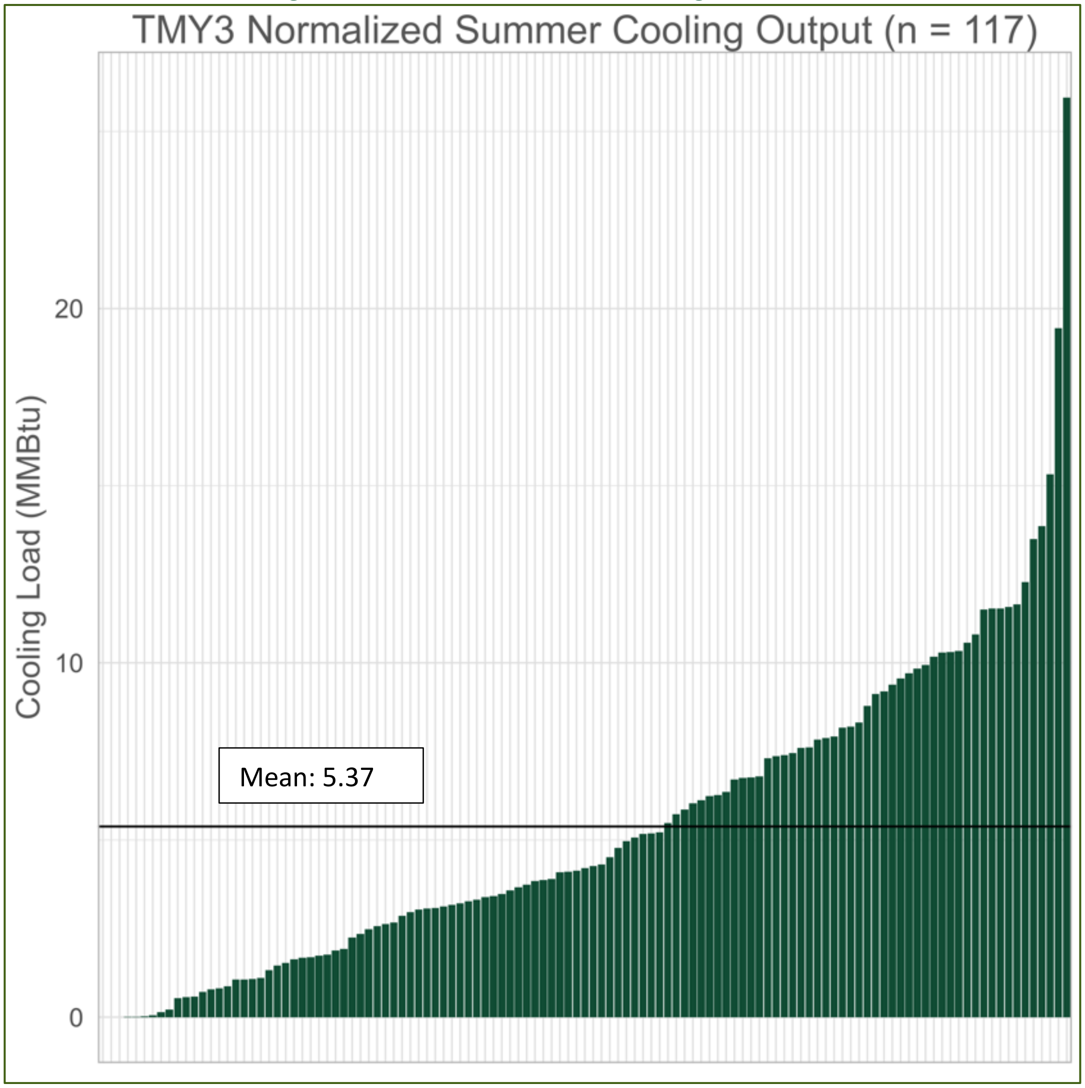
Figure 51. Average Power Consumption vs. Time of Day, for Shoulder and Cooling Months (n = 117 outdoor units)



8.2 COOLING PROVIDED

Figure 52 shows the estimated cooling (heat removed) from 107 units. It ranges from less than one MMBtu up to about 25 MMBtu. The mean value is about 5 MMBtu/year. Nearly all of the units provided less than 15 MMBtu per year. The two largest units ran nearly continuously and one of the units had a SEER higher than the average of the units.

Figure 52. TMY3 Normalized Cooling Provided

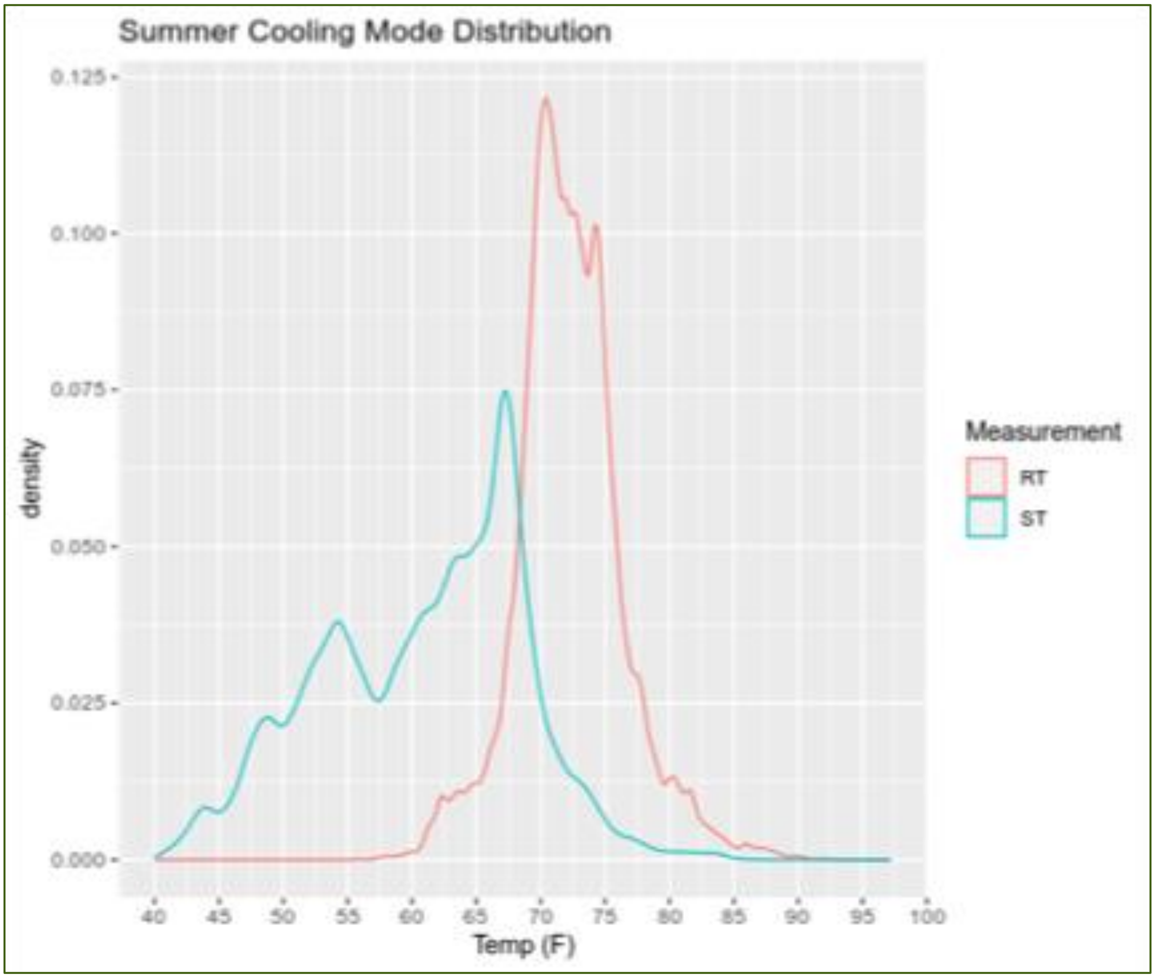


8.3 SUPPLY AND RETURN TEMPERATURES

We graphed the supply and return temperatures at each indoor unit when the unit was operating in cooling mode. Figure 53 is a histogram that shows the frequency of temperature readings. The most frequent return temperature is 70°F to 75°F as expected. Nearly all readings (well over 90%) occur from 65°F to 80°F, again as expected. Cooler temperatures could be cooler setpoints and warmer temperatures could be at startup. While the return temperature is indicative of the temperature of the cooled space, it is not necessarily the same temperature experienced by occupants. Most units are wall-mounted and many of these are near the ceiling, so there could be some stratification.

The supply temperatures can be as low as 40°F to 45°F, which is not unexpected, but the most common supply temperature is 65°F, a bit warmer than expected. This could be due to operating the unit in dry mode or due to modulation of the unit. Temperatures from 72°F upwards may indicate dry mode and not full cooling mode, although temperatures were only recorded for this graph when there was a delta T of at least 2.5°F, indicating some cooling.

Figure 53. Cooling Supply and Return Temperatures, (n = 119 outdoor units)



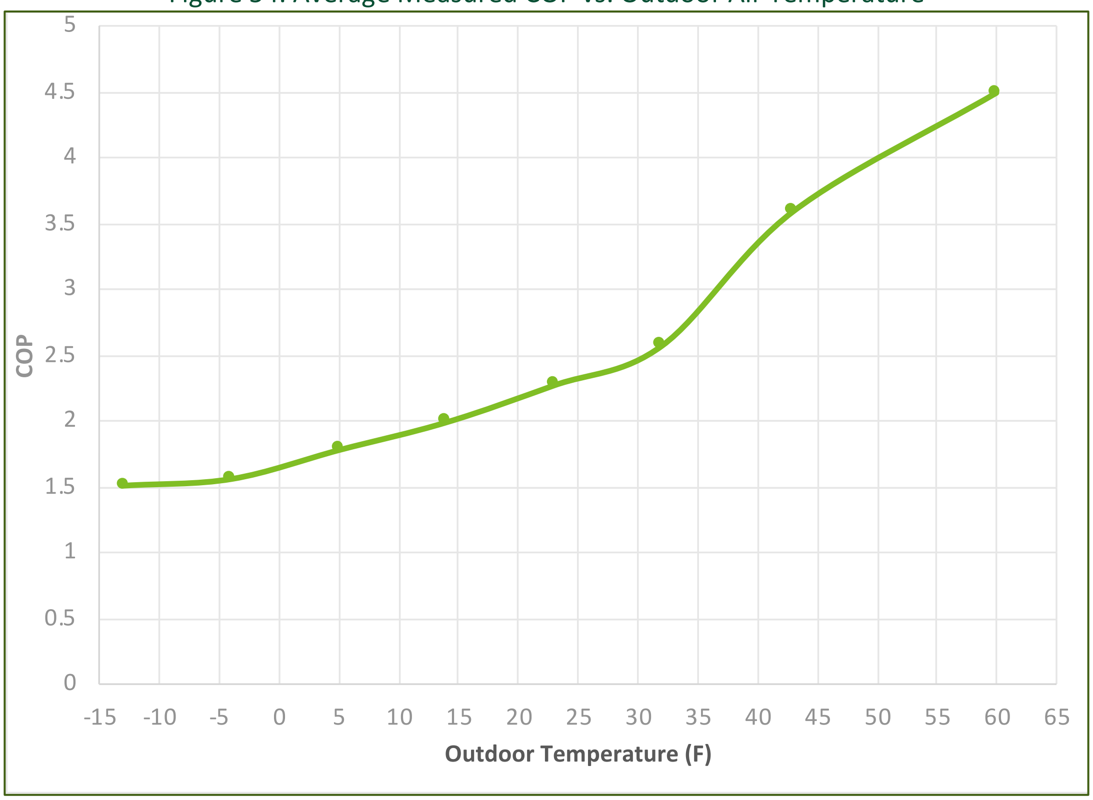
9 OPERATING EFFICIENCY

9.1 COEFFICIENT OF PERFORMANCE (COP)

The Coefficient of Performance (COP) is the simplest measurement of a heat pump's performance and is equal to the ratio of the energy of heat delivered to the energy of electricity required to achieve this heat transfer measured in the same units. COP values typically range from 2 to 4, indicating that they can deliver two to four units of heat for every unit of energy consumed.

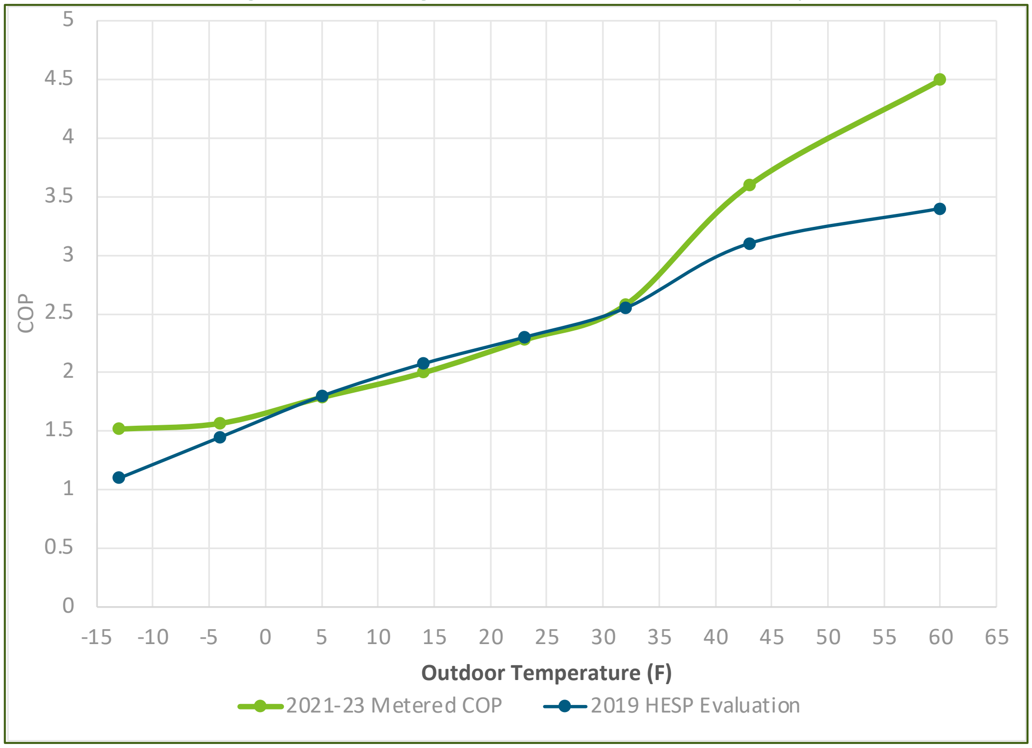
Figure 54 shows COP for metered heat pumps. Heating COP decreases with decreasing evaporating (outdoor) temperature, primarily due to the increased difference in outside and desired indoor temperatures. Observed heat pumps averaged a COP of 1.6 from -10°F to 5°F. This means that even for the coldest temperatures, heat pumps offer effective heating efficiencies 60% higher than electrical resistance heating. The data point at -13°F generates less confidence, because there were few measurements at this temperature. Total measured heating COP across all outdoor temperatures was 2.57, which includes energy used for defrosting.

Figure 54. Average Measured COP vs. Outdoor Air Temperature



The evaluation team compared these findings to the last evaluation of residential heat pumps in Maine, an evaluation of heat pumps installed under HESP and published in 2019 (Figure 55). The curves are nearly identical up to about 32°F. While the earlier evaluation saw a slight increase in the slope of the COP line above 32°F, this study saw a larger increase in COP at higher temperatures. One possible reason is that some heat pumps with higher HSPF values now available, have higher COPs at warmer temperatures. The other is that the current study had more data points at warmer weather and may be showing a more accurate picture of warm weather performance.

Figure 55. Average 2023 COP vs 2019 HESP Study



9.2 MEASURED VERSUS RATED COP

Heat pumps are rated several ways. Manufacturers publish a single seasonal factor, the heating season performance factor of HSPF. They also publish engineering tables that show maximum heating capacity and electricity input versus outdoor temperature.[8] Table 12 shows an example of one of these tables for a 12,000 BTU/h, 12 HSPF unit.

Table 12. Heat Pump Engineering Data

INDOOR	OUTDOOR TEMPERATURE (°FWB)															
EDB	−13		−4		5		14		23		32		43		60	
°F	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI	TC	PI
59.0	9.73	1.65	12.55	1.68	15.27	1.72	16.23	1.68	17.21	1.63	18.22	1.58	19.45	1.53	23.48	1.65
70.0	8.72	1.70	11.58	1.73	14.33	1.77	15.39	1.72	16.46	1.67	17.52	1.62	18.80	1.56	22.83	1.68
71.6	7.88	1.58	10.93	1.68	13.95	1.79	15.06	1.74	16.16	1.69	17.24	1.64	18.54	1.58	21.97	1.63
75.2	6.55	1.29	9.60	1.46	12.65	1.61	14.73	1.76	15.85	1.70	16.96	1.65	18.28	1.59	20.64	1.51
77.0	5.88	1.15	8.93	1.35	11.98	1.52	14.56	1.77	15.70	1.71	16.82	1.66	18.15	1.60	19.97	1.46
80.6	4.55	0.88	7.60	1.14	10.65	1.33	13.32	1.60	15.40	1.73	16.54	1.68	17.89	1.61	18.64	1.34

[8] The table shows maximum heating capacity, and the actual operation will follow this table when full capacity is used at colder temperatures. At temperatures above freezing for example, the capacity is not fully used, and one would expect higher efficiencies. Some manufacturers publish a second table showing rated inputs at partial load capacities.

In the table at the highlighted heat output of 18,800 BTU at 43°F, the COP can be calculated by the equation.

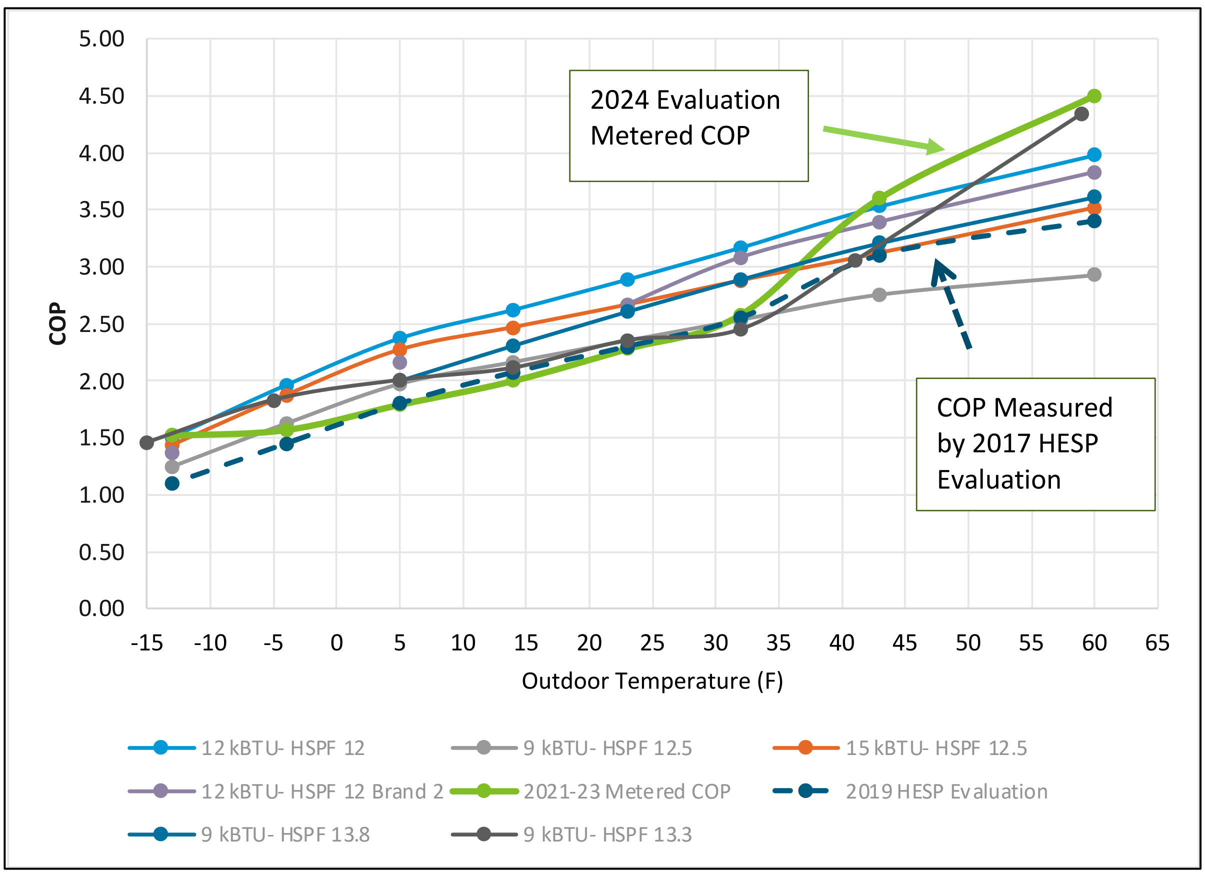
$$COP = \frac{TC}{PI\ x\ 3.412} = \frac{18{,}800}{1{,}560\ x\ 3.412} = 3.53$$

Where:
TC = Total capacity in kBTU/h
PI = Power in kW

It is interesting to note that given the nominal size of the heat pump (12,000 BTU/h), only a fraction of the 18,800 BTU that the heat pump could provide at 43°F would be needed. More precisely, if the heat pump were sized to just meet needs at -4°F, then at 43°F, the heat pump would only need to provide (70-43)/(70-(-4))*11,580 = 4,225 BTU/h, or about 22% of the heat capacity at 43°F.

The evaluators graphed six heat pumps using engineering data, an example of which is shown in Table 12. These graphs along with measured in-situ COPs from 2019 and 2023 are shown in Figure 56.

Figure 56. Average Metered and Rated COPs vs. Outdoor Air Temperature

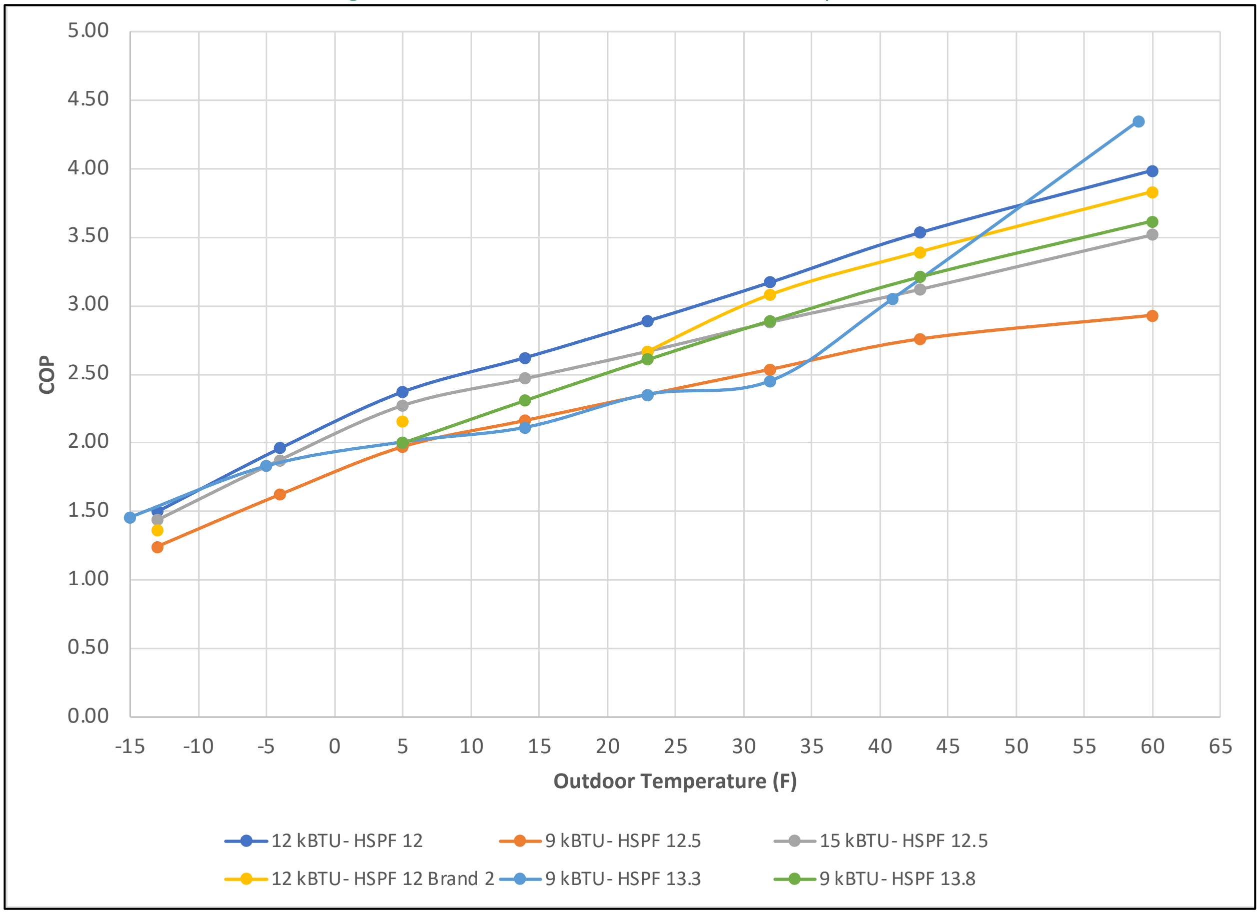


The COPs at maximum capacity vary by about 0.5 between heat pumps at a given colder temperature, but at warmer temperatures, efficiency starts to vary more with a gap of 0.75. The measured COPs track along the lower range of the rated efficiencies until about 32°F. Above that, the 2019 study COP increases to the middle of the rating curves and the 2023 COP climbs to the top of the ratings at about 40°F, and at very warm temperatures, albeit when less heat is needed, the measured COP is above the rating at capacity. This is because the graphed ratings are at maximum capacity, and at warmer temperatures the heat pump is likely operating at partial capacity.

9.3 HSPF VERSUS COP

Rated HSPFs are calculated using complex formulas and laboratory data. They won't match actual seasonal efficiency because field conditions are less controlled than a laboratory and because the heat needs and temperatures do not match the assumptions built into the HSPF calculation. Because HSPF is calculated using very specific, albeit, limited conditions, the relationship between COP versus temperature and HSPF ratings is not proportional. Figure 57 shows that the heat pump with the highest HSPF at 13.8 does not have the highest COPs across all temperatures. Similarly, the heat pump with the second highest HSPF (13.3) has the lowest COP from 5°F to 32°F.

Figure 57. Rated COP vs. Outdoor Air Temperature



The actual seasonal efficiency is determined by the temperatures it is used at, and the heating provided at each temperature. For example, there are about 800 hours at 45°F in Portland and the rated COP is nearly 3.5, but only 30% of design load is needed at that temperature, so the impact to the true seasonal efficiency is modest.

The evaluation team performed a bin analysis on the rated heat pumps shown in the preceding figures. We first took the COP at each temperature and multiplied it by observed hours in Portland to develop a simple seasonal weighted COP not related to heat produced. We then added in heating produced with the simplifying assumption that the heat pump just met heat load at design conditions. To illustrate, a 15 kBTU/h HSPF 12.5 heat pump has an equivalent COP of 3.66 (12.5/3.412 = 3.66) under the HSPF test conditions. The calculated seasonal COP for this unit is 3.07, weighted for observed hours in Portland. Weighting further for heat expected to be delivered, the COP drops to 2.85. Again, this is using performance factors from laboratory tested units applied to expected temperatures in Portland. Field-measured COP is expected to be lower than this value.

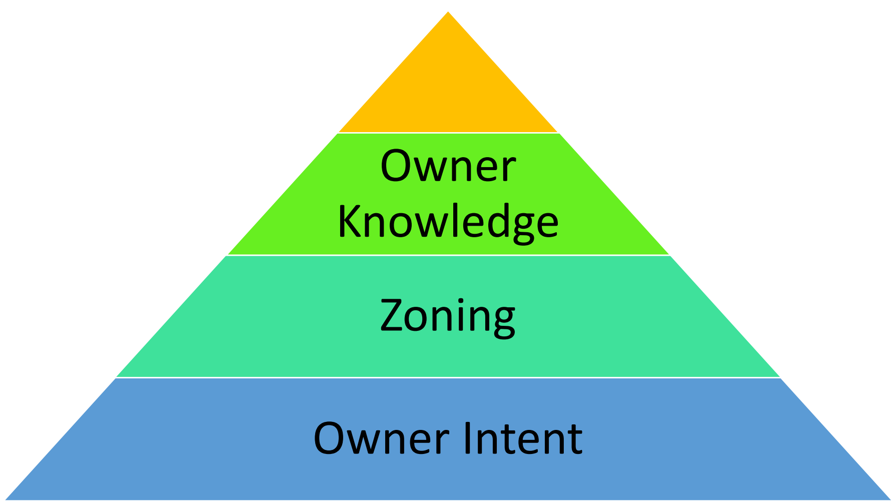
10 HEAT PUMP OPERATION AND PREDICTING USAGE

Heat pumps have the potential to provide significant home heating. The reported savings anticipated moderate heating use of the heat pumps. This evaluation found that heat pumps are not being used to their full potential and not as much as anticipated by Efficiency Maine due to a variety of reasons.

Figure 58 shows a hierarchy of elements that determine the heating usage of a heat pump. If all of the elements are optimal, then the heat pump will be used throughout the winter, and it will fully displace other heat sources for the areas that it serves. If any of the elements is lacking however, usage will be reduced, sometimes substantially.

- The owner's intent is primary. If the owner intends to use the heat pump mostly for cooling, for a small space, or to take the chill off at certain moments, the heat pump will be used little, regardless of the design of the heating systems, their placement, or the knowledge of the owner.
- Next in importance is zoning. This concept includes several elements that include the level of overlap between the zone of the heat pump and a zone of the pre-existing heating system, and the capacity of the heat pump compared with the zone's heating needs.
- Last in the set of elements is owner knowledge. Even if the owner intends to use the heat pump and it is zoned optimally, a lack of knowledge can reduce use of the heat pump.

Figure 58. Hierarchy of Elements that Determine Usage of Heat Pumps



10.1 OWNER INTENT

Initially, the participant survey would have indicated very high heat pump use. Only 1% of survey respondents claim to only cool with the HP, but field discussions point to 5% or higher that do not heat. Looking deeper into survey results, other elements that will reduce heat pump use that the evaluators noted include:

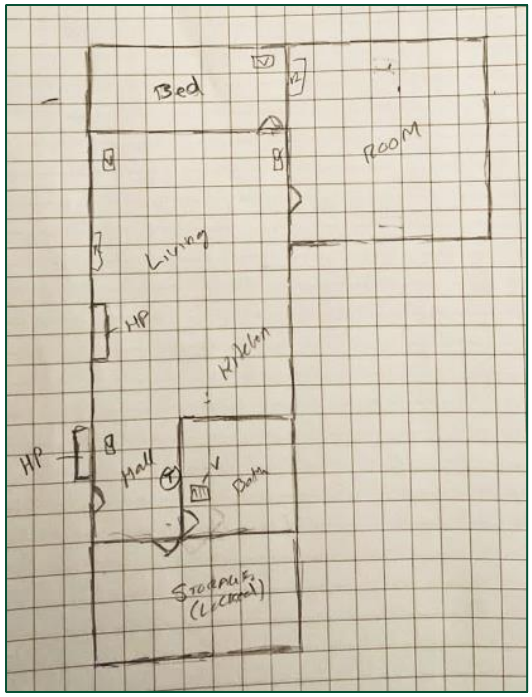
- 19% turn the heat pump on and off as needed, pointing to the heat pump's use as supplemental heating. Several homeowners indicated during site visits that they turned the heat pump on in the morning to take the chill off, indicating its being turned off at night.
- One third of homeowners shut off their heat pumps at ~20°F. One homeowner noted that they turn their heat pump off at around 20°F because they thought its declining capacity would make it cost more (than delivered oil) below that temperature.
- Wood heat is very common as a supplement (31% of homes), and owners like it for reasons including low cost and ambiance. One homeowner had a central pellet furnace that they used for most heating. Others had wood stoves that were used for various amounts of heating.
- Based on site interviews, some homeowners leave Maine for three or more winter months (~5-10%) and most use fuel to maintain home temperatures while away.
- Some homeowners preferred their other heating system as did one owner of a kerosene monitor, while another had a central pellet stove and saw no reason to heat with the heat pump due to both zoning and cost.

10.2 ZONING

An optimally zoned heat pump will run continuously all winter, will provide a zone's heat at design heat load (coldest temperatures) and will displace other heating systems all winter. There are multiple factors that will reduce the use of the heat pump from this optimal situation:

- Where a heat pump serves one space, and that space is overlapped by a pre-existing heating system that serves a broader zone, the heat pump will be superseded by the other system whenever other overlapping zones need heat. A classic example is a furnace heated home with a single zone (1 thermostat) and a heat pump that heats one room. Even if the heat pump were perfectly sized to heat that room, the furnace will need to operate to heat the rest of the home and when it does, it will heat the room served by the heat pump, reducing the use of the heat pump, often substantially. This is a common situation in furnace heated homes, and 31% of participant respondents had furnace homes, all of which would be single zone. Figure 59 shows a sketch of a home with this situation. The supply registers are indicated with a box with a 'V'. The heat pump serves the living room and kitchen of a furnace heated manufactured home. This is a good placement of the heat pump, and the heat pump will heat the furnace thermostat reducing the furnace's use. The heat pump's heat does not reach the room at the ell or the bedroom, or the locked storage room. If any of those rooms become too cold, the homeowner would turn up the furnace thermostat to push heat to the outer rooms. A home with a multi-zone boiler can allow for better matching of heat pumps to zones.
- Where a heat pump serves a room and its capacity is greater than the room's heat needs, the heat pump's usage will be limited. This is common where a heat pump is placed in a small bedroom (120 ft^2, for example). The smallest indoor units made by some makers are as large as 9,000 BTU/h, meaning that the bedroom heat pump is providing 75 $BTU/h/ft^2$. If the room is well insulated, this could be 2 to 3 times the capacity needed. The outcome would be that the heat pump runs at low capacity at the coldest temperatures and would cycle for most other temperatures. In this circumstance the heat pump would sufficiently heat the space and likely satisfy the occupant's comfort without the need for any other heat source, but the total heat produced by the heat pump would still be lower than its potential.

Figure 59. Site Plan of Manufactured Home with Single Zone Furnace and Heat Pump



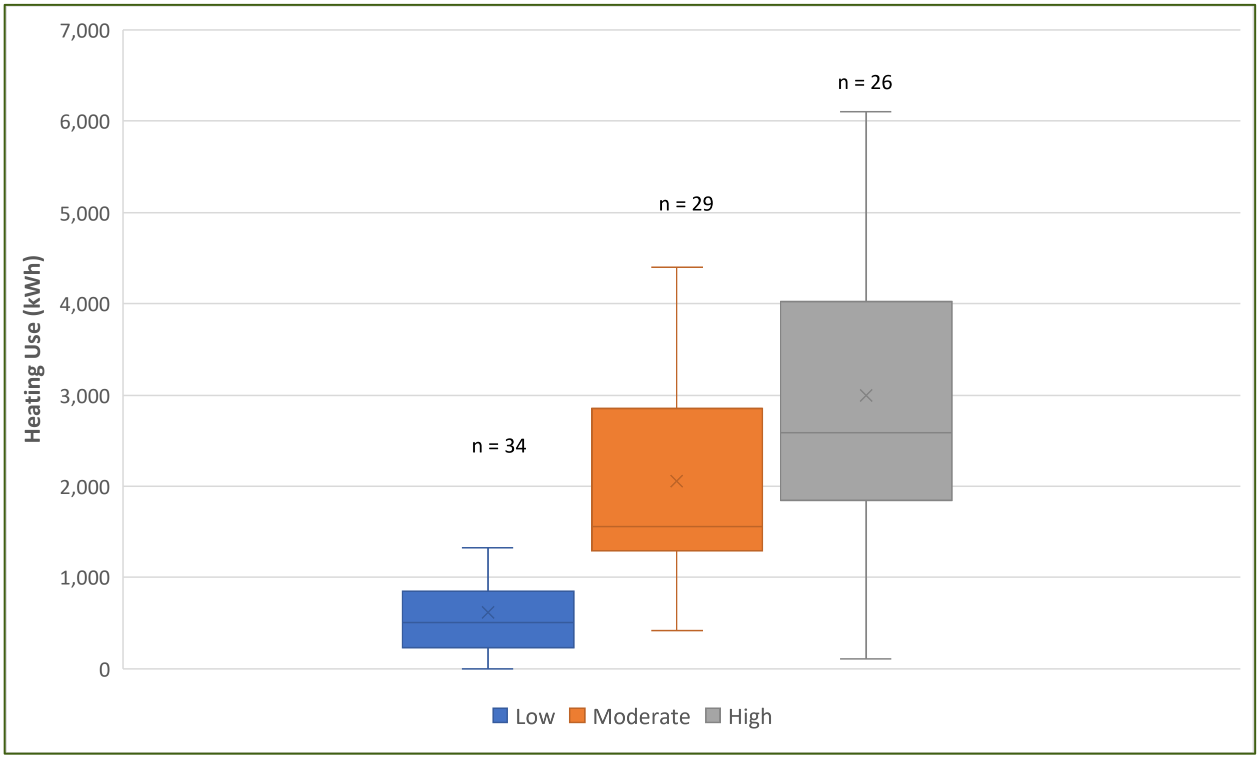
10.3 OWNER KNOWLEDGE

Owner knowledge can be important to ensure that an optimally zoned heat pump is operated correctly. Some homeowners seemed to understand that setting a thermostat droop where the pre-existing heating system is set 3-5 degrees below the desired temperature, with heat pump set to the desired temperature, gives the heat pump the best chance to carry the heat load, (where zoning allows). Others were confused and either set the temperatures the same, or turned the heat pump on and off, not realizing they were decreasing the heat pump's effectiveness.

10.4 PREDICTING HEAT PUMP USAGE

One question that arose during the evaluation was why heat pump use seemed to lag behind expected use, particularly since survey respondents generally indicated that they viewed the heat pump as a primary heating system. The evaluators used a combination of sketched zone plans for each home and discussions with owners to rate the likely use of the heat pump as low, moderate, or high. This was done before examining metered data. Low users were a combination of intent (use if mostly for cooling) and zoning, (the heat pump serves one room in a single thermostat zone home). High usage was predicted for homes where the user's intention was clear, and where zoning would allow heating by the heat pump. Moderate usage was predicted for homes where the owner generally intended to heat with the heat pump, but some factor reduced potential usage such as zoning, or a wood stove that was used in tandem. The ranking was not meant to be strictly quantitative but to see whether an owner's intent, knowledge and zoning could help predict usage. Of the 124 sites, we had enough information to predict usage by 71 sites, comprising 89 of 172 heat pumps, with the remaining having no clear characteristics to predict usage. Figure 60 shows a box and whisker graph of the results. Sites predicted to have low usage had low metered usage. So low that the 25-75 percentile box does not overlap with the other categories. The mean metered usage for these sites was 618 kWh. The sites predicted to have moderate or high usage were less distinct with some overlap and average metered usage of 2,055 and 2,992 respectively. The reason for the lower than anticipated usage was not so much the homes where user intent and zoning lined up, it was the homes where usage was not likely to be high from the beginning. 34 of the 89 homes rated (38%) were predicted to and actually had low usage. These homes pulled down the average heating use of the studied heat pumps. For the 89 heat pumps with predicted use, the mean metered use was 1,790 kWh/y. If the low use heat pumps are removed, the average electricity use is about 40% higher at 2,498 kWh/y.

Figure 60. Metered Heating Use Versus Category of Predicted Use



11 IMPACT ANALYSIS

11.1 OVERVIEW

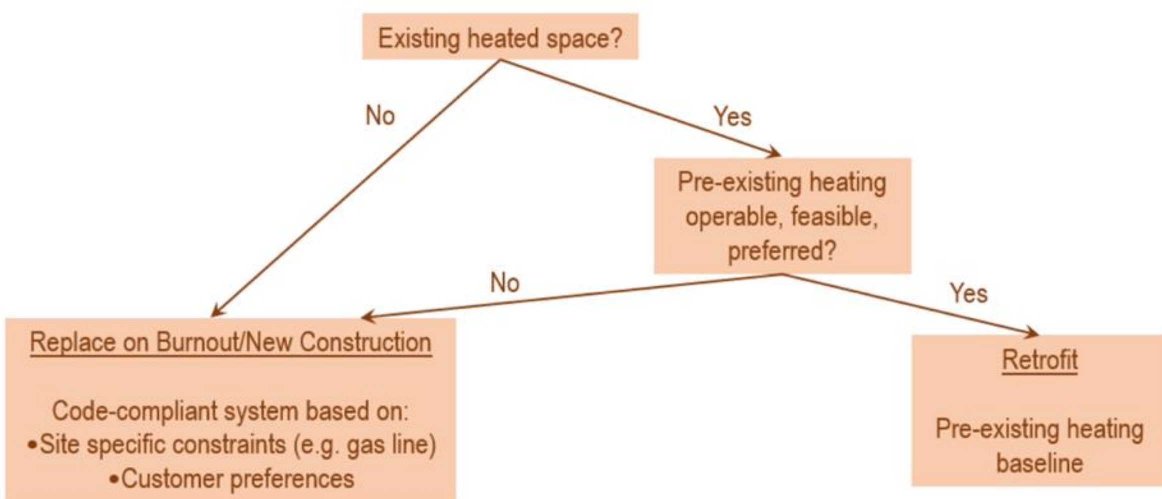
This section develops a baseline, then uses the baselines in the TRM and in the evaluated sample to compare the reported with evaluated savings and the reasons for any differences discovered.

11.2 ESTABLISHING BASELINES

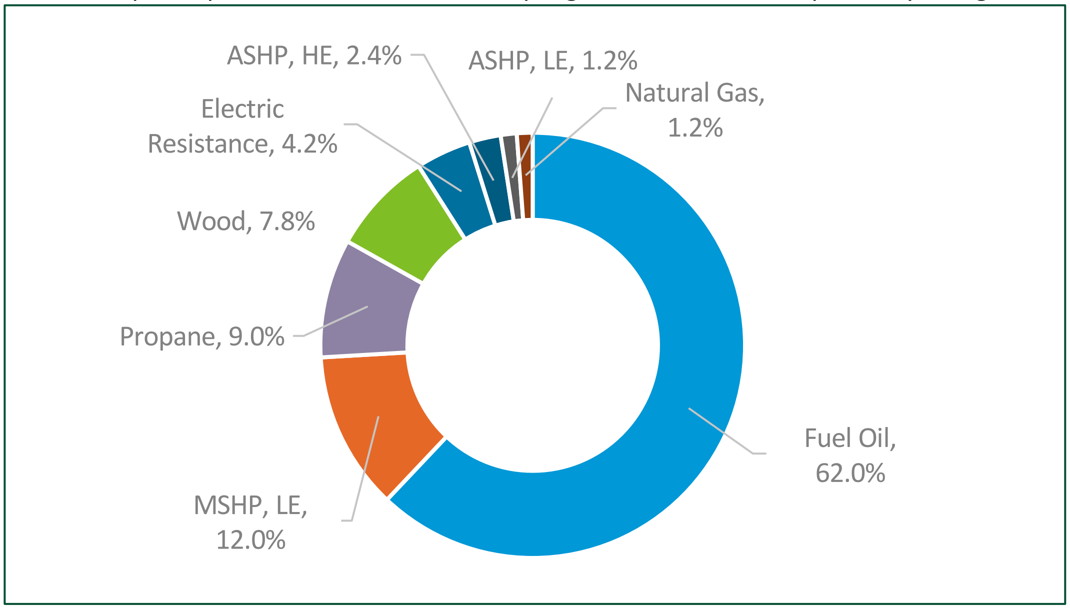
Inherent in determining the impact of the heat pump program is determining a baseline, more specifically what would have happened in absence of a program. This is, by its nature, a difficult and inexact effort. There are multiple reasons for this. In particular, what happened during the evaluation period is a product of both the program incentives that year and the long-term efforts of Efficiency Maine in building a market for heat pumps in Maine. Also, it is difficult for a homeowner to exactly determine what course they would have taken if a rebate or set of education materials were not available.

Determining the heating baseline for this evaluation is a two-step process. First, we establish the heating system that would have been used in absence of the heat pump purchase. Then, we establish the ratio of projects that are retrofit (where the pre-existing heating system still operates) against replacement on burnout/new construction (a category termed “Lost Opportunity” in Efficiency Maine’s TRM) (Figure 61).

Figure 61. Logic for Determining Heating Systems Baseline



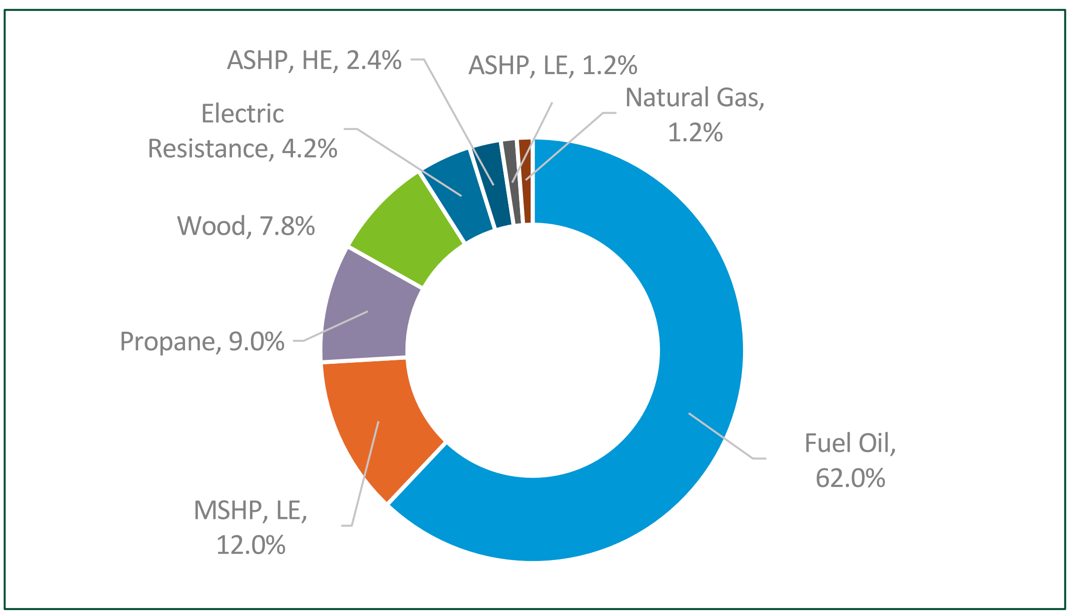
The evaluators determined the heating baseline for heat pumps using a survey of 470 respondents. The results for participants in the HESP and AHI programs are shown respectively in Figure 62



MSHP = mini-split heat pump; LE = low or standard efficiency; ASHP = ducted air source heat pump; HE = high efficiency; Fuel Oil = oil and kerosene.

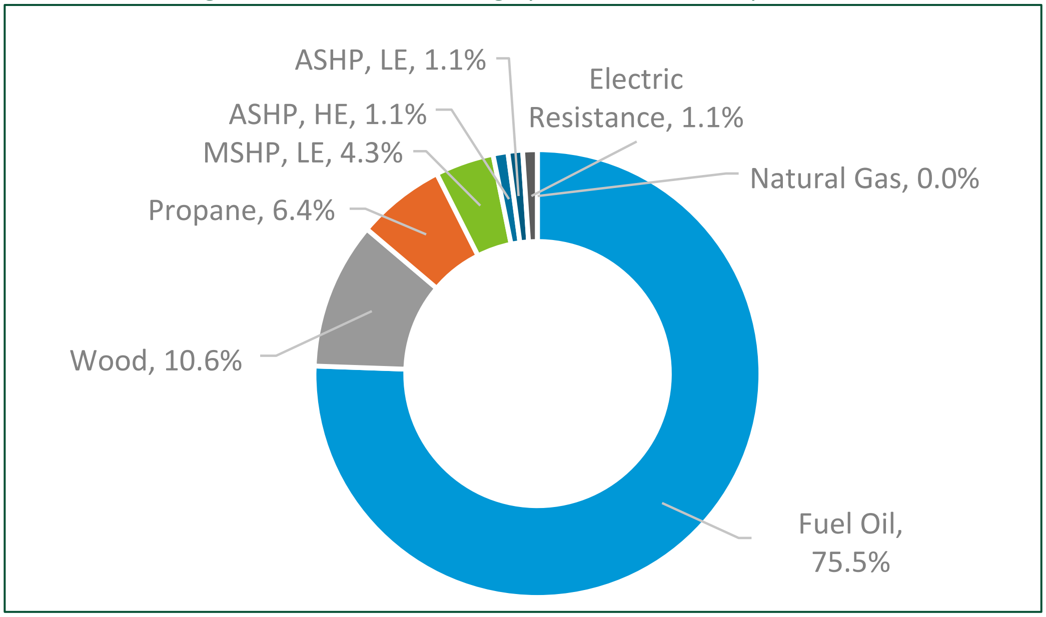
(LE = low [standard] efficiency, HE = high efficiency, ASHP = central ducted heat pump). The primary difference between the two is that the AHI respondents had a higher proportion of oil as a baseline.

Figure 62. Baseline Heating Systems for HESP Respondents



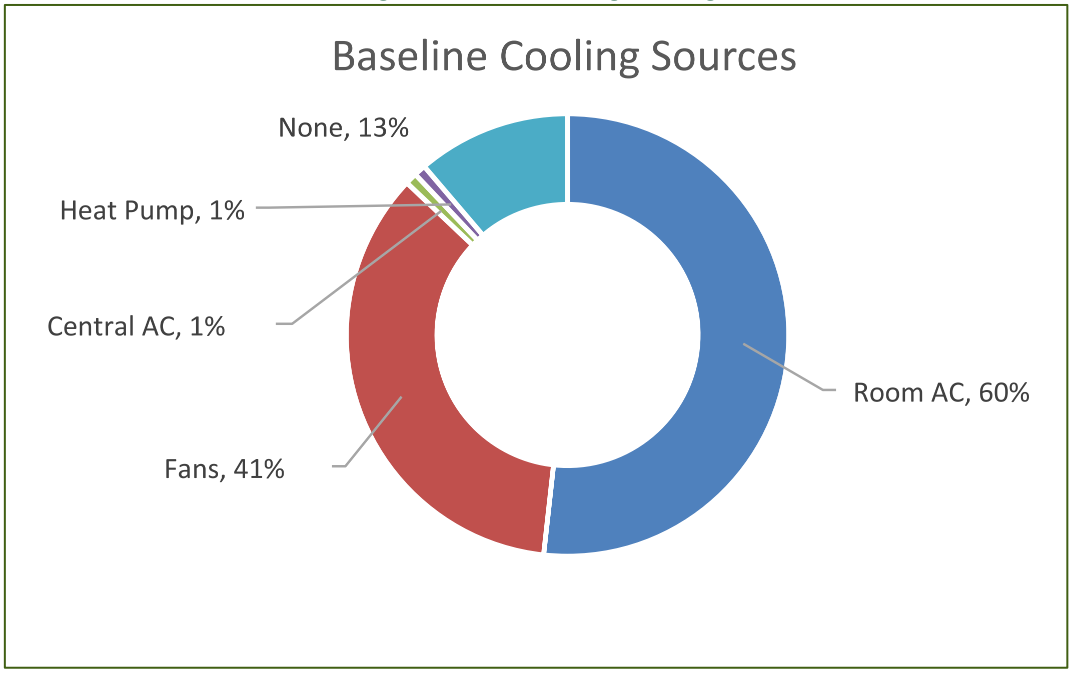
MSHP = mini-split heat pump; LE = low or standard efficiency; ASHP = ducted air source heat pump; HE = high efficiency; Fuel Oil = oil and kerosene.

Figure 63. Baseline Heating Systems for AHI Respondents



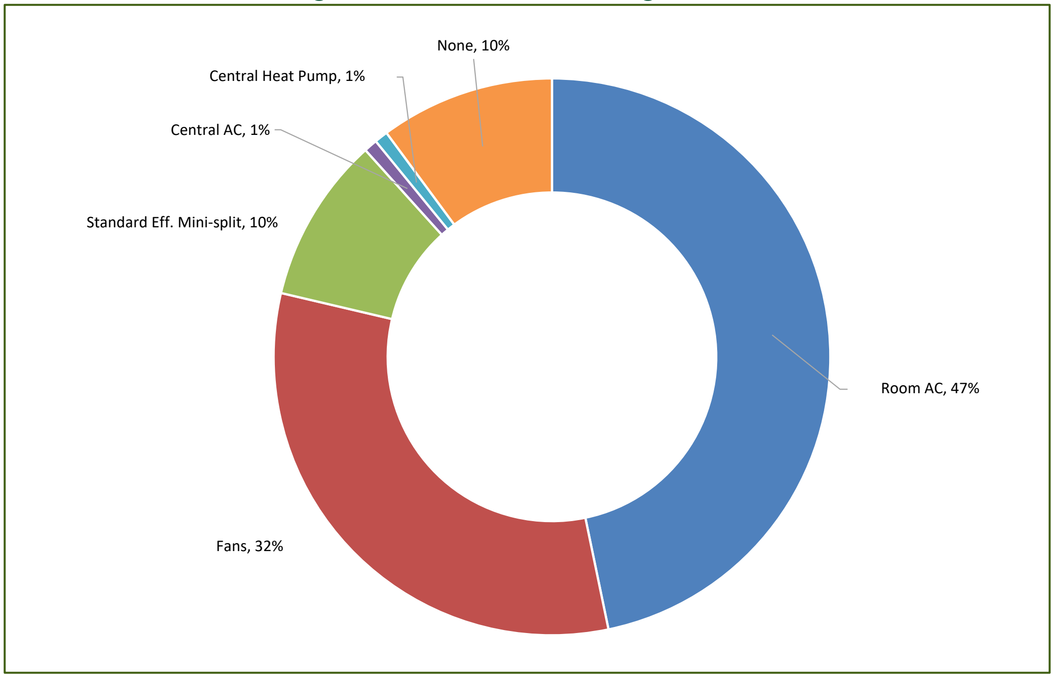
For the cooling baseline, we asked a multi-response question about the existing cooling systems a home used (Figure 64). We then asked what cooling strategy they would have employed in the absence of an incentive. 11% of HESP participants indicated that they would have cooled with a lower efficiency heat pump in absence of the program and 4% of AHI participants indicated that they would have cooled with a lower efficiency heat pump in absence of the program. The net percent of sites that would not have installed cooling without the program is 42% (Figure 65). While this may appear high, it is consistent with Massachusetts (a warmer climate), where similar work found non-cooling proportions of 30% to 37% depending on type of heating system in the home.

Figure 64. Pre-Existing Cooling



Considering both responses, the evaluators constructed a combined baseline for cooling (Figure 65).

Figure 65. Determined Cooling Baseline



11.3 ELECTRICAL IMPACT

In Table 13, the reported and evaluated summer on-peak demand[9] impact values are shown across six categories of HESP measures. The reported values were found by reviewing the roughly 20,000 projects in the effRT database. In this table and following tables, we compare the reported values with the TRM values. We then adjust for baselines (in this case the number of non-cooled homes), and differences in evaluated performance and usage.

Table 13. Reported and Evaluated Summer On-Peak Demand Impact (kW)

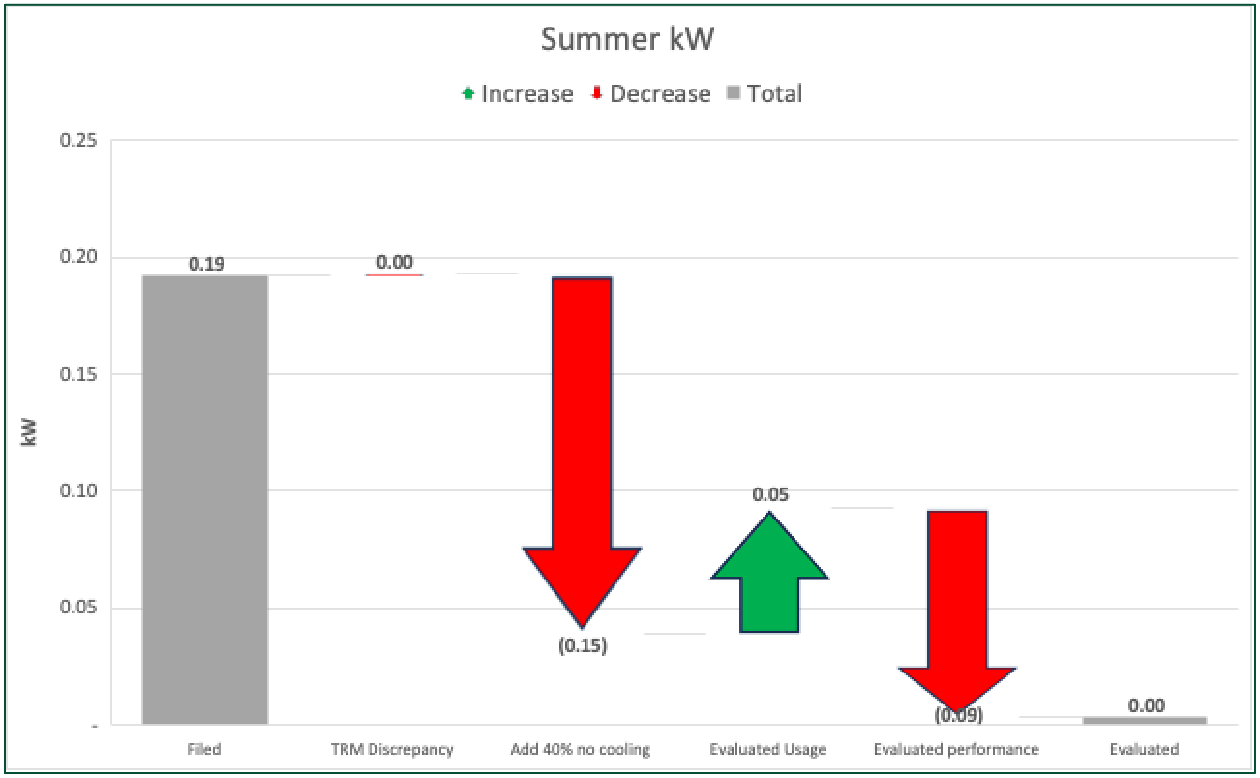
Program	Measure Name	Count	Reported kW	TRM	42% no cooling	Evaluated Usage	Evaluated	RR
HESP	Heat Pump Single Zone 1st Unit Tier 2	9,639	0.17	0.17	0.04	0.08	0.02	0.13
HESP	Heat Pump Single Zone 2nd Unit Tier 2	2,495	0.08	0.08	0.02	0.04	0.02	0.22
HESP	Heat Pump Single Zone 1st Unit Tier 1	2,162	0.22	0.22	0.05	0.11	0.02	0.10
HESP	Heat Pump Single Zone 2nd Unit Tier 1	740	0.09	0.09	0.02	0.04	0.02	0.18
HESP	Heat Pump Multi-zone 2 or more zones	4,525	0.31	0.31	0.06	0.15	(0.05)	(0.16)
HESP	Heat Pump Multi-zone add on	610	0.09	0.09	0.02	0.04	(0.05)	(0.56)
HESP	All	20,171	0.19	0.19	0.04	0.09	0.00	0.02
	Change			0.00	(0.15)	0.05	(0.09)	

Figure 66 compares the weighted average for each column showing the causes of any difference between the Reported and evaluated numbers. For summer on-peak, the largest adjustment was adding in 42% of homes that build demand by adding cooling compared to the 21% assumed by the TRM. Evaluated usage was higher leading to more cooling savings. All other factors including a decrease in average SEER from the 25.5 assumed in the TRM to 21.3 for installed units and in-situ performance are included in the Evaluated Performance category (the difference between the evaluated impact and

[9] Summer on-peak is 1:00 PM - 5:00 PM on non-holiday weekdays in June, July and August.

the impact adjusted for evaluated usage). All of the difference categories combined result in a smaller summer on-peak demand impact leading to a realization rate of 0.02.

Figure 66. Waterfall Chart Comparing Reported and Evaluated Summer On-Peak Demand Impact



Similarly, Table 14 and Figure 67 show an evaluation of winter on-peak[10] demand impact, which builds electrical demand shown as negative values. The largest change which increases the negative value (demand building) is shifting from the TRM baseline that is predominantly a lower efficiency heat pump to a baseline of fossil fuel heating. The evaluated baseline results in the entire heat demand resulting in demand building rather than a fraction from a mostly heat pump baseline. Other effects including a lower COP, but also a lower usage decrease the demand increase by about 0.1 kW. Lastly, Table 15 and Figure 68 show an evaluation of annual electric energy impact, which combines load building in the winter and savings in the summer. The largest change is shifting from a lower efficiency heat pump baseline to a fossil fuel baseline. Lower winter usage lowers the negative value.

[10] Winter on-peak is 5:00 PM to 7:00 PM on non-holiday weekdays in December and January.

Table 14. Reported and Evaluated Winter On-Peak Demand Impact (kW)

Program	Measure Name	Count	Reported	TRM	Convert COP from 2.48 to 2.57	Shift to 79% Retrofit	Evaluated	RR
HESP	Heat Pump Single Zone 1st Unit Tier 2	9,639	(0.29)	(0.32)	(0.30)	(0.55)	(0.40)	1.38
HESP	Heat Pump Single Zone 2nd Unit Tier 2	2,495	(0.17)	(0.18)	(0.18)	(0.34)	(0.16)	0.97
HESP	Heat Pump Single Zone 1st Unit Tier 1	2,162	(0.12)	(0.13)	(0.12)	(0.53)	(0.40)	3.43
HESP	Heat Pump Single Zone 2nd Unit Tier 1	740	(0.12)	(0.13)	(0.12)	(0.35)	(0.16)	1.39
HESP	Heat Pump Multi-zone 2 or more zones	4,525	(0.24)	(0.25)	(0.25)	(0.38)	(0.65)	2.76
HESP	Heat Pump Multi-zone add on	610	(0.12)	(0.13)	(0.12)	(0.68)	(0.65)	5.41
HESP	All	20,171	(0.23)	(0.25)	(0.24)	(0.48)	(0.43)	1.83
	Change			(0.02)	0.01	(0.24)	0.05	

Figure 67. Waterfall Chart Comparing Reported and Evaluated Winter On-Peak Demand Impact

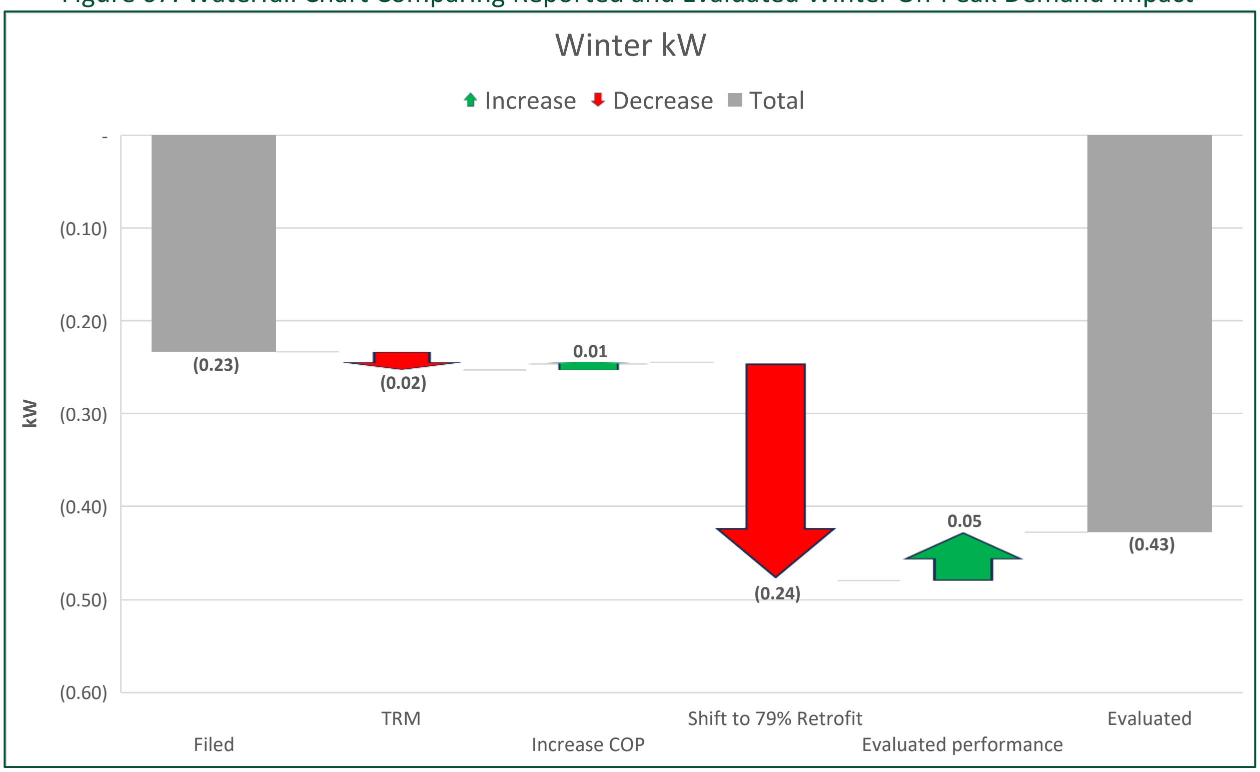


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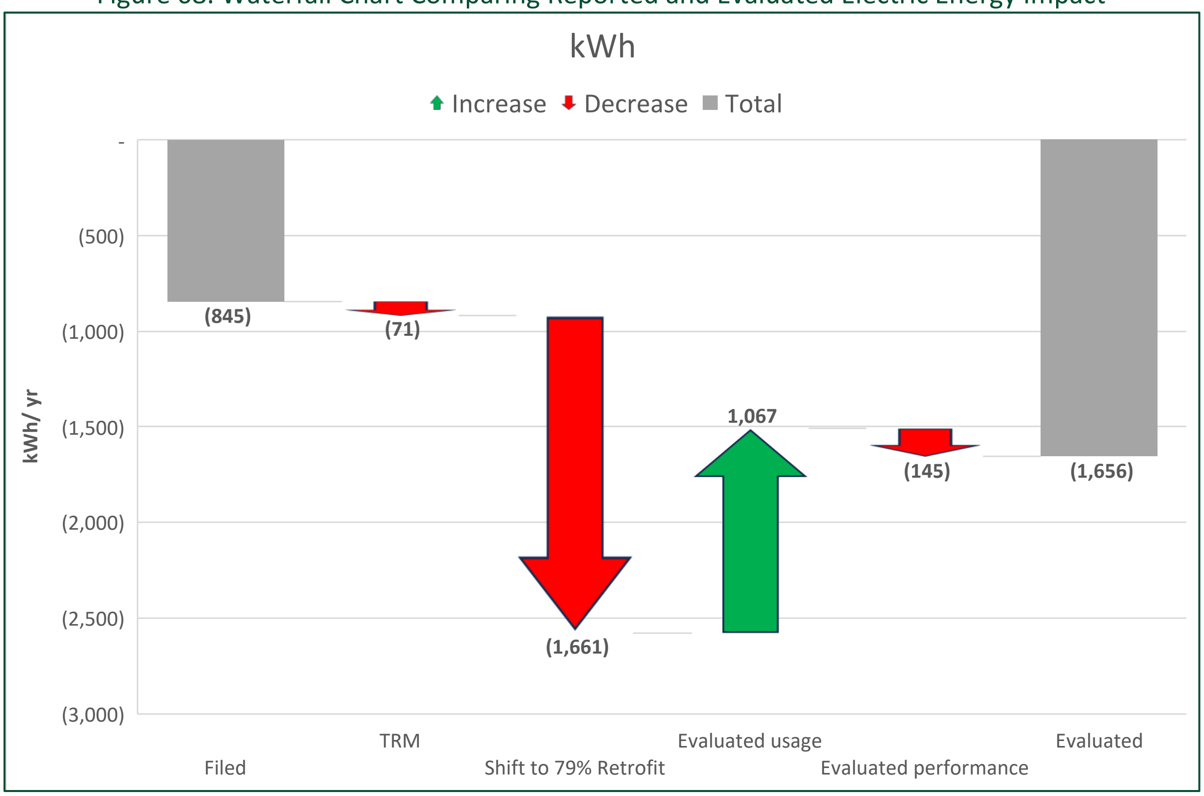
Table 15. Reported and Evaluated Electric Energy Impact (kWh/y)

Program	Measure Name	Count	Reported	TRM	Shift to 79% Retrofit	Evaluated usage	Evaluated	RR
HESP	Heat Pump Single Zone 1st Unit Tier 2	9,639	(1,152)	(1,252)	(2,426)	(1,422)	(1,467)	1.27
HESP	Heat Pump Single Zone 2nd Unit Tier 2	2,495	(569)	(614)	(1,372)	(804)	(779)	1.37
HESP	Heat Pump Single Zone 1st Unit Tier 1	2,162	(386)	(417)	(2,437)	(1,428)	(1,467)	3.80
HESP	Heat Pump Single Zone 2nd Unit Tier 1	740	(330)	(356)	(1,512)	(886)	(779)	2.36
HESP	Heat Pump Multi-zone 2 or more zones	4,525	(716)	(773)	(3,949)	(2,314)	(2,642)	3.69
HESP	Heat Pump Multi-zone add on	610	(337)	(356)	(1,512)	(886)	(2,642)	7.85
HESP	All	20,171	(845)	(916)	(2577)	(1,510)	(1656)	1.96
	Change			(71)	(1661)	1067	(145)	

Figure 68. Waterfall Chart Comparing Reported and Evaluated Electric Energy Impact



11.4 FUEL IMPACT

In Table 16, the reported and evaluated fuel impact values are shown across six categories of HESP measures. Figure 69 compares the weighted average for each column showing the causes of differences between the reported and evaluated numbers. By far, the largest change is shifting from a lower efficiency heat pump baseline to a fossil fuel baseline, which nearly doubles the fuel savings. Lower winter usage on the order of 50% lowers the evaluated value back to a value similar to the reported number.

Table 16. Reported and Evaluated Fuel Impact (MMBTU/y)

Program	Measure Name	Count	Reported	TRM	Shift to 79% Retrofit	Evaluated usage	Evaluated	RR
HESP	Heat Pump Single Zone 1st Unit Tier 2	9,639	18.5	18.5	29.5	14.6	19.8	1.1
HESP	Heat Pump Single Zone 2nd Unit Tier 2	2,495	9.2	9.2	16.5	8.1	10.5	1.1
HESP	Heat Pump Single Zone 1st Unit Tier 1	2,162	7.3	7.4	26.2	12.9	19.8	2.7
HESP	Heat Pump Single Zone 2nd Unit Tier 1	740	4.9	4.9	16.1	7.9	10.5	2.1
HESP	Heat Pump Multi-zone 2 or more zones	4,525	12.3	12.3	42.2	20.8	23.6	1.9
HESP	Heat Pump Multi-zone add on	610	4.9	4.9	16.1	7.9	23.6	4.8
HESP	All	20,171	13.8	13.8	29.5	14.5	19.3	1.4
	Change			(0.0)	15.7	(15.0)	4.7	

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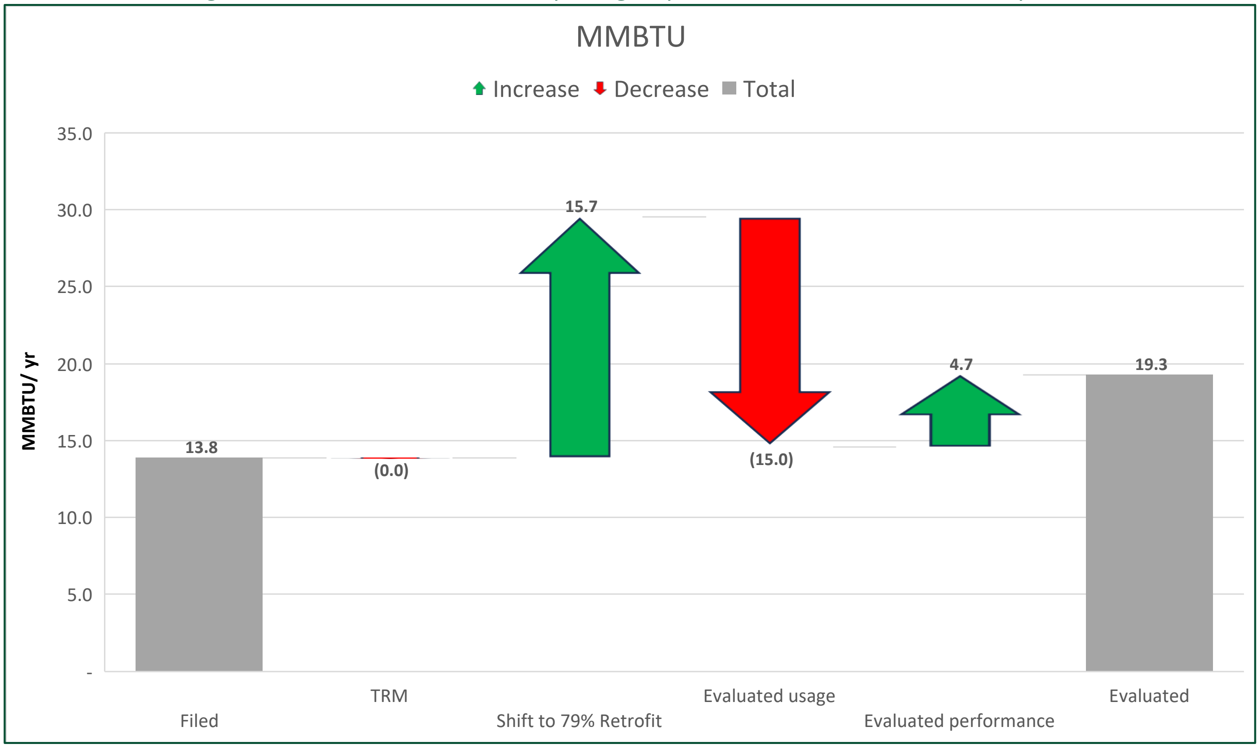
Figure 69. Waterfall Chart Comparing Reported and Evaluated Fuel Impact



11.5 OVERALL IMPACT

Similarly, Table 17 and Figure 70 show the reported and evaluated values for equivalent energy impacts where the negative electric impacts and positive fuel impacts are both converted to MMBtu/y and summed. The data are very similar directionally to the fuel impact, but the magnitude is lower accounting for increased use of electricity.

Table 17. Reported and Evaluated Total Heating and Cooling Energy (MMBTU/y)

Program	Measure Name	Count	Reported	TRM	Shift to 79% Retrofit	Evaluated usage	Evaluated	RR
HESP	Heat Pump Single Zone 1st Unit Tier 2	9,639	14.5	14.2	21.3	9.7	14.78	1.0
HESP	Heat Pump Single Zone 2nd Unit Tier 2	2,495	7.2	7.1	11.8	5.4	7.82	1.1
HESP	Heat Pump Single Zone 1st Unit Tier 1	2,162	6.0	5.9	17.9	8.0	14.78	2.4
HESP	Heat Pump Single Zone 2nd Unit Tier 1	740	3.8	3.7	10.9	4.9	7.82	2.1
HESP	Heat Pump Multi-zone 2 or more zones	4,525	9.8	9.6	28.8	12.9	14.58	1.5
HESP	Heat Pump Multi-zone add on	610	3.8	3.7	10.9	4.9	14.58	3.9
HESP	All	20,171	10.9	10.7	20.7	9.4	13.6	1.2
	Change			(0.02)	10.0	(11.3)	4.2	

Table 18 shows energy use and savings for example systems based on average heat pump performance. While the site energy savings are least for electrical resistance, the cost savings would be highest based on current electrical rates. Table 19 shows energy use and savings for example systems based on average heat pump performance.

Figure 70. Waterfall Chart Comparing Reported and Evaluated Total Heating and Cooling Energy (MMBTU/y)

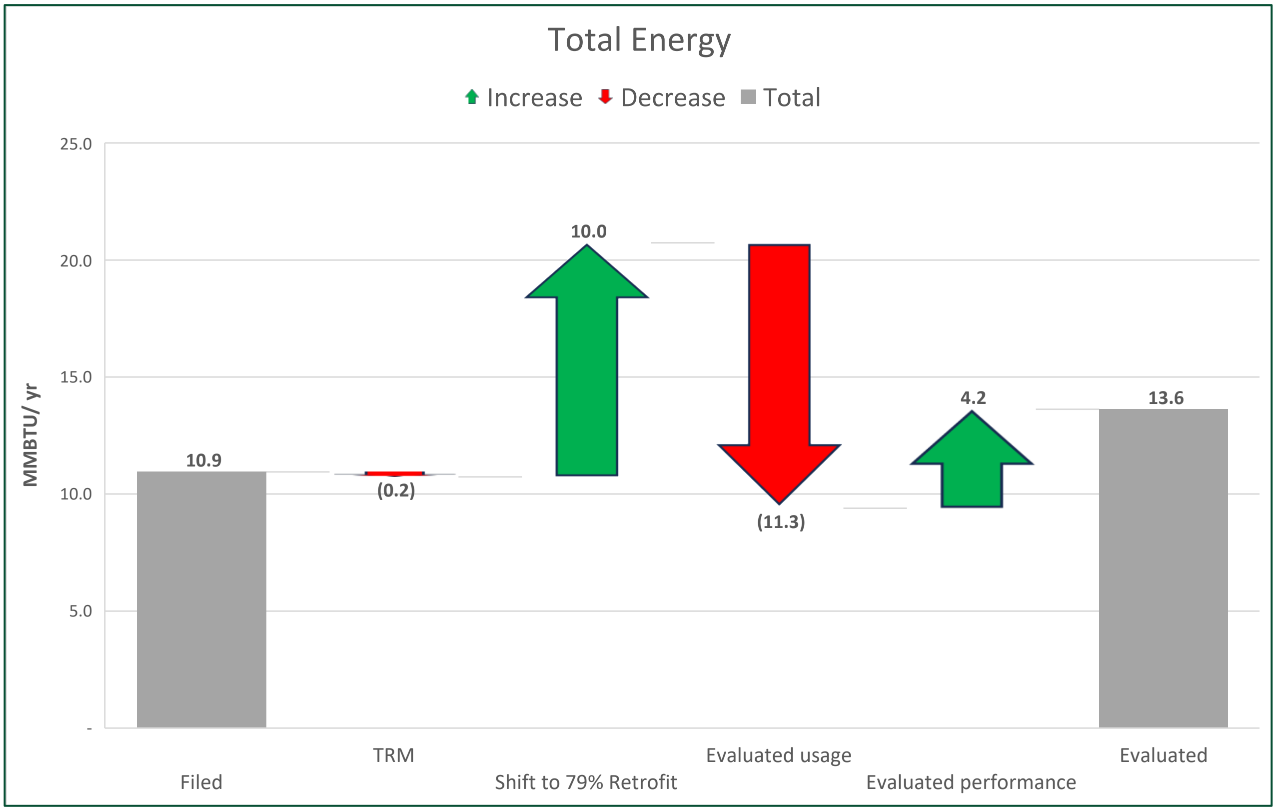


Table 18. Savings Estimates for Example Heating Systems

Baseline System	Electric Usage of Heat Pump (kWh/y)	Baseline System Energy Usage (MMBtu/y)	Winter Season Savings (MMBtu/y)
90% AFUE Boiler/Furnace	1,887	18.5	12.0
80% AFUE Boiler/Furnace	1,887	20.8	14.4
Electric Resistance	1,887	16.6 (4,870 kWh)	10.2 (2,990 kWh)

Table 19. Savings Estimates for Example Cooling Systems

Baseline System	Electric Usage of Heat Pump (kWh/y)	Baseline System Energy Usage (kWh/y)	Summer Season Savings (kWh/y)
Low Efficiency Heat Pump	252	528	276
Room Air Conditioner	252	544	292

11.6 REALIZATION RATE

Table 20 shows realization rates by measure type and by program and all heat pumps. As shown in previous sections, the realization rate for kWh is high but this means that a negative number is more negative, and the evaluated increased kWh use is higher than reported. Conversely, the saved fuel in MMBtu is slightly higher than the reported value by about 12%. Combining the higher electrical use and the higher savings, the evaluated equivalent MMBtu savings are similar to the reported number.

Table 20. Realization Rates for Measures and Programs

			Realization Rate									
Program	**Measure Name**	**Quantity**	**kWh**	**Winter kW**	**Summer kW**	**Natural Gas**	**Propane**	**Heating Oil**	**Kerosene**	**Wood**	**MMBtu Total**	**Fuel + kWh**
HESP	Heat Pump Single Zone 1st Unit Tier 2	9,639	1.27	1.38	0.13	n.a	0.62	1.10	0.00	2.08	1.07	1.02
HESP	Heat Pump Single Zone 2nd Unit Tier 2	2,495	1.37	0.97	0.22	n.a	0.66	1.18	0.00	2.22	1.14	1.08
HESP	Heat Pump Single Zone 1st Unit Tier 1	2,162	3.80	3.43	0.10	n.a	1.56	2.77	0.00	5.19	2.69	2.45
HESP	Heat Pump Single Zone 2nd Unit Tier 1	740	2.36	1.39	0.18	n.a	1.23	2.19	0.00	4.12	2.13	2.06
HESP	Heat Pump Multi-zone 2 or more zones	4,525	3.69	2.76	(0.16)	n.a	1.11	1.98	0.00	3.72	1.92	1.48
HESP	Heat Pump Multi-zone add on	610	7.85	5.41	(0.56)	n.a	2.77	4.94	0.00	9.28	4.79	3.86
AHI	MiniSplit HP Property Assessed	1,216	0.53	0.63	0.53	n.a	0.40	0.63	0.00	1.22	0.61	0.65
AHI	MiniSplit HP LIHEAP	199	0.34	0.43	(0.00)	n.a	0.16	0.39	0.00	0.61	0.34	0.34
HESP	**All**	**20,171**	**1.96**	**1.83**	**0.02**	**n.a**	**0.81**	**1.43**	**-**	**2.70**	**1.39**	**1.24**
AHI	**All**	**1,415**	**0.50**	**0.60**	**0.45**	**n.a**	**0.35**	**0.59**	**-**	**1.13**	**0.57**	**0.61**
Both	**All Heat Pumps**	**21,586**	**1.69**	**1.64**	**0.03**	**n.a**	**0.77**	**1.33**	**-**	**2.48**	**1.29**	**1.18**

11.7 PEAK IMPACTS

The TRM identifies six periods of interest as follows:

Demand On-Peaks as defined by the ISO-NE Forward Capacity Market (FCM).

- Summer On-Peak: 1:00 PM to 5:00 PM on non-holiday weekdays in June, July and August.
- Winter On-Peak: 5:00 PM to 7:00 PM on non-holiday weekdays in December and January.

And these energy period factors:

- Winter Peak: 7:00 AM to 11:00 PM on non-holiday weekdays during October through May (8 months).
- Winter Off-Peak: 11:00 PM to 7:00 AM on non-holiday weekdays and all hours on weekends and holidays during October through May (8 months).

- Summer Peak: 7:00 AM to 11:00 PM on non-holiday weekdays during June through September (4 months).
- Summer Off Peak: 11:00 PM to 7:00 AM on non-holiday weekdays and all hours on weekends and holidays during June through September (4 months).

The evaluators cover the ISO New England on-peak demand periods in section 11.3. Table 21 shows the winter and summer peak and off-peak energy period factors. The values are similar across categories.

Table 21. Peak Energy Period Factor Values

Strata	Population Size (projects)	Winter Peak EPF	Winter Off Peak EPF	Summer Peak EPF	Summer Off Peak EPF
Single Zone, Tier 2	12,134	0.35	0.51	0.08	0.06
Single Zone, Tier 1	2,902	0.35	0.52	0.07	0.07
Multi-zone	5,135	0.37	0.52	0.06	0.05
Property Assessed	1,216	0.37	0.52	0.07	0.05
LIHEAP	199	0.32	0.39	0.17	0.12
Total/ average	21,586	0.36	0.51	0.07	0.06

12 BENEFIT COST ANALYSIS

The evaluation team processed the gross and net savings from this study in Efficiency Maine's Cost Benefit Analysis Tool (CBAT) to assess the cost-effectiveness of HP measures. Table 22 shows the benefit/cost ratio (BCR) for the prescriptive HP measures offered by the program over the evaluation timeframe. The evaluation team ran several iterations of CBAT using the avoided cost values in effect during the evaluated period (AESC 2018, updated to reflect 2020 dollars) and using the avoided cost values approved for Triennial Plan V that started July 1, 2022 (AESC 2021). Values in green indicate BCRs that pass the cost-effectiveness threshold of 1, values in yellow indicate BCRs just below 1, and values in red indicate BCRs below 0.9. The table shows the BCRs for measures, programs, and total. In nearly all cases, the BCR is above 1.0 except for AHI LIHEAP where it is nearly 1.0 and for multi-zone heat pumps where it is lower. Multizone heat pumps produce more savings than one single-zone heat pump but cost proportionally more. The bottom four rows show individual results for retrofit and lost opportunity assumptions. All heat pumps in the AHI program are single zone.

Table 22. Benefit Cost Ratios for Measures and Programs

Measure	HP	Type/ Program	N	BCR AESC 2018 (yr1=2020)	BCR AESC 2021 COC (yr1=2021)
All Heat Pumps	All	All	21,586	1.12	1.21
Heat Pumps HESP-all	All	HESP	20,171	1.11	1.20
Heat Pump Single Zone - Tier 1	Single zone	Tier 1	2,902	1.26	1.36
Heat Pump Single Zone - Tier 2	Single zone	Tier 2	12,134	1.36	1.46
Heat Pump Multi-Zone ALL	Multi-zone	HESP, all	5,135	0.81	0.88
Property Assessed and LIHEAP	All	AHI	1,415	1.25	1.31
MiniSplit HP Property Assessed	All	AHI Property Assessed	1,216	1.29	1.35
MiniSplit HP LIHEAP	All	AHI LIHEAP	199	0.90	0.98
Heat Pump Single Zone - ALL	Single zone	Retrofit	15,036	1.08	1.20
Heat Pump Single Zone - ALL	Single zone	Lost Opportunity	15,036	2.60	2.40
Heat Pump Multi-Zone ALL	Multi-zone	Retrofit	5,135	0.72	0.79
Heat Pump Multi-Zone ALL	Multi-zone	Lost Opportunity	5,135	1.58	1.50

13 ADVANCED METERING INFRASTRUCTURE (AMI) ANALYSIS

The evaluation team obtained 15-minute pre- and post-installation household-level electrical consumption data for 46 homes. Of these homes, 33 had sufficient AMI and metering data for a direct comparison and showed no large heating relationship between electricity use and temperature before heat pump installation[11] and some relationship after installation indicating heat pump use.

These data are highly variable, as expected, and correlating each hourly data point to outside air temperature does not yield a clear pattern. If instead, the data are combined to daily electricity use, and this is regressed on average outdoor temperature, a clear pattern emerges. For homes with electric heat, either resistance or heat pumps and no confounding high uses of electricity, there is a linear relationship between electricity use and temperature. For example, Site 22, as shown in Figure 75 shows no clear pattern before or after heat pump installation, and meter data that agrees showing very infrequent use. This site was not included in the comparison because the AMI data could not be regressed on temperature.

13.1 EXAMPLE SITE WITH CLEAR POST INSTALLATION ELECTRICITY USE TEMPERATURE DEPENDANCY

Figure 71 shows daily electricity use regressed on average outdoor temperature. Available AMI was limited to a few months, but there is no clear pattern or relationship, with electricity use largely flat at 15 – 20 kWh/day albeit with a good deal of variation. Figure 72 shows electricity use after installation of a heat pump. There is a clear relationship between daily electricity use and outdoor air temperature, with usage at a base level above 50°F at 15 – 20 kWh per day. Electricity use rises with decreasing temperature with a linear fit intercept at 101 kWh/day at a daily average temperature of 0°F.

[11] Boiler pumps and furnace fans can cause a small increase in electricity use with declining outdoor temperatures. Here we are referencing a large relationship indicating a previous heat pump or some use of electrical resistance heating.

Figure 71. Pre-Installation of Daily kWh Used regressed on Average Daily Outdoor Air Temperature

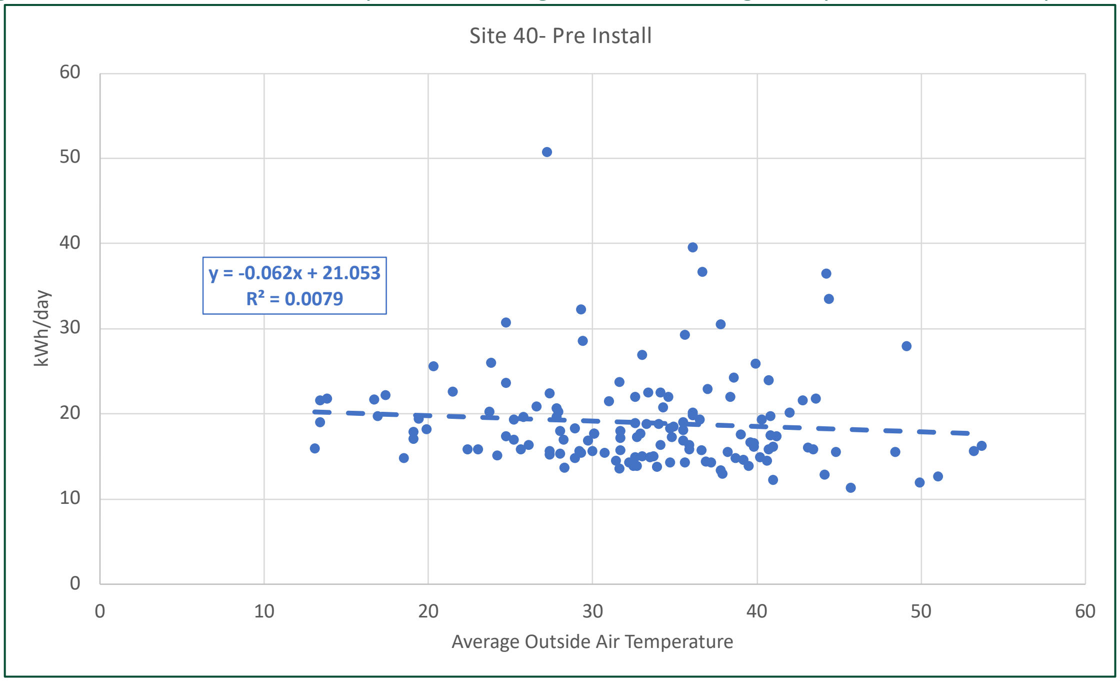


Figure 72. Post Installation of Daily kWh Regressed on Average Daily Air Temperature

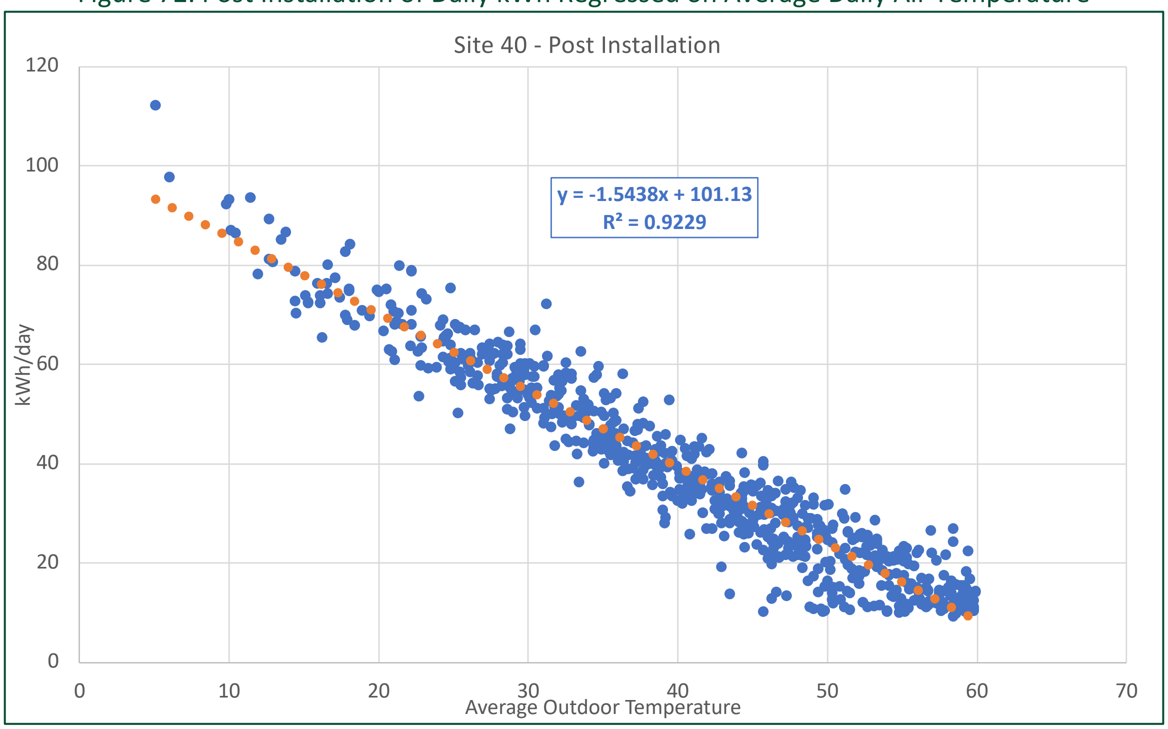


Figure 73 shows daily metered heat pump use graphed with total electricity use. The lines are parallel but not coincident because the meter is not registering the baseload of electricity that is not consumed by the heat pump. The linear fits are about 18 kWh/day apart at cold temperatures and closer to 10 kWh at 50°F, similar to the observed baseline use in Figure 71 . There is variability in the AMI and meter data because on any given day heating setpoints, hot water use, and occupancy vary widely. On average, however the linear fits are clear visually and the R^2 values are about 90% indicating that the linear models fit well.

In Figure 74 we remove the average baseline and see that the meter curves and the AMI curves minus baseline are close. In this case, using AMI data would have estimated heat pump usage fairly closely.

Figure 73. Post Installation Daily AMI and Metered Heat Pump kWh versus Average Daily Temperature

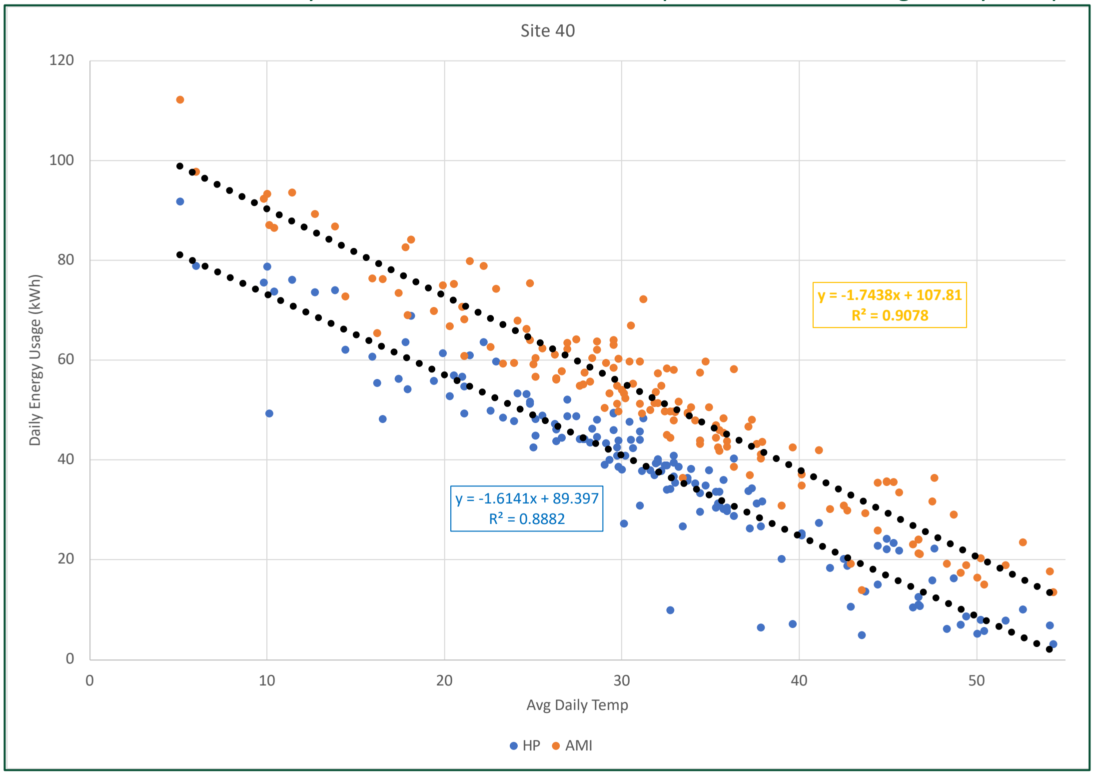
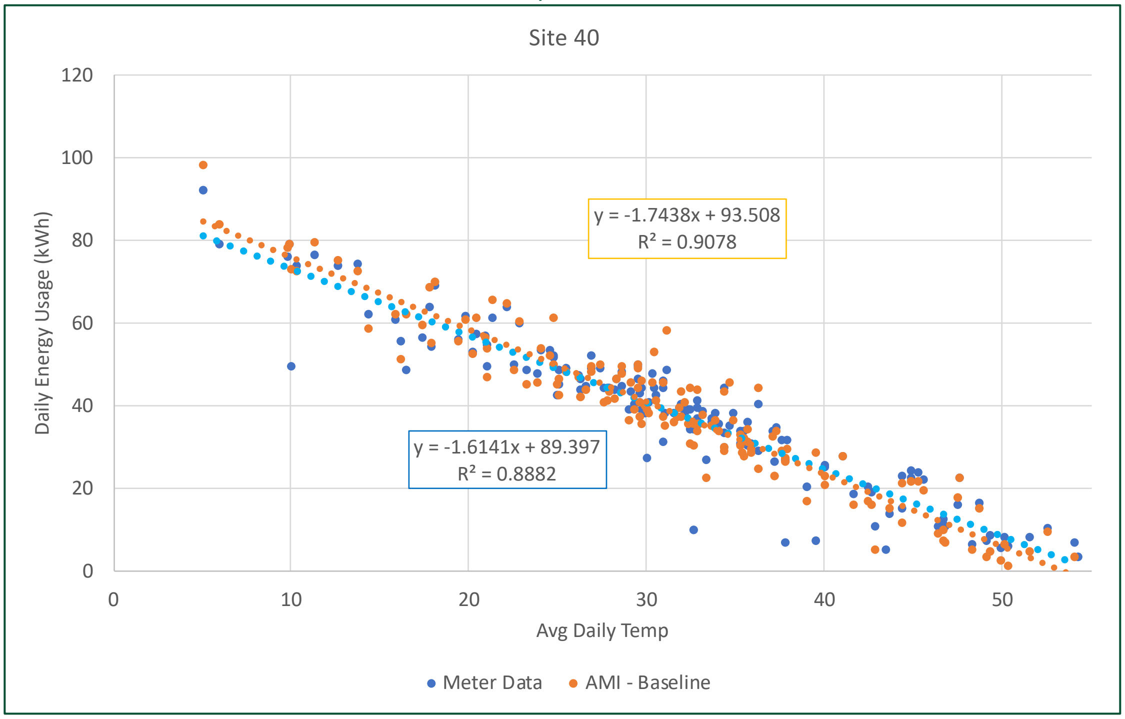


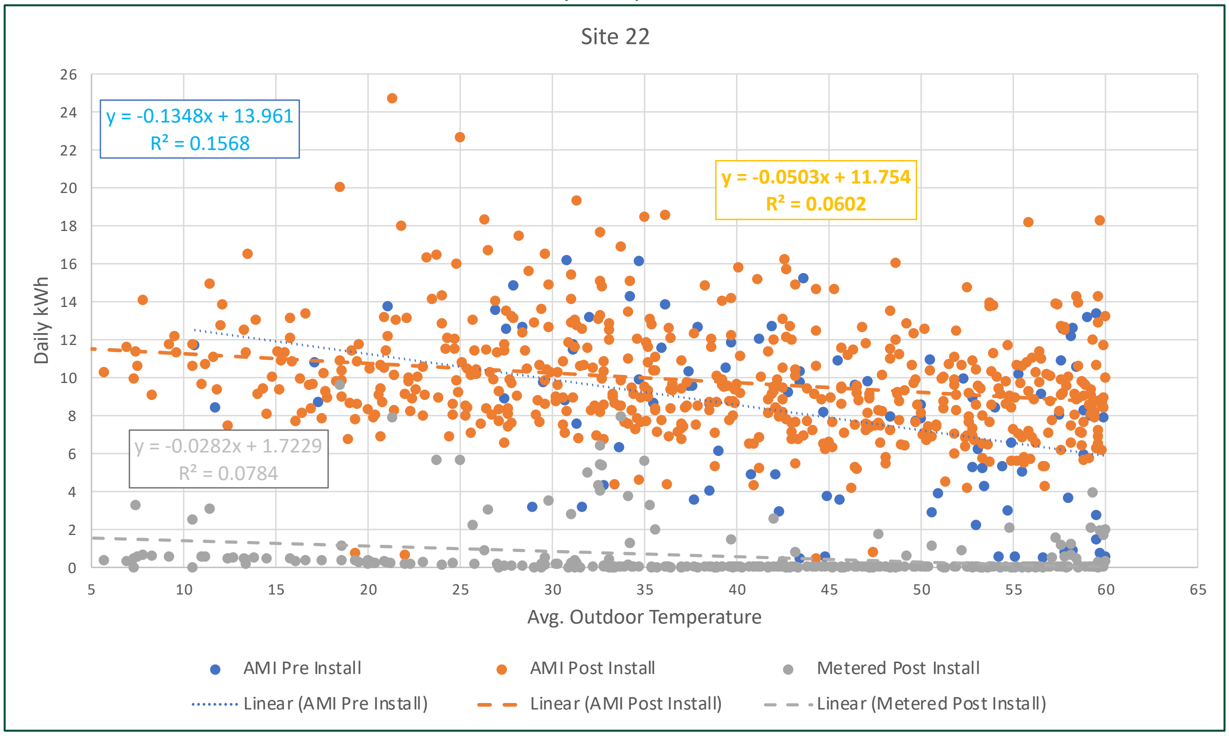
Figure 74. Post Installation Daily AMI minus Baseline and Metered Heat Pump kWh versus Average Daily Temperature



13.2 EXAMPLE SITE WITH NO CLEAR POST INSTALLATION ELECTRICITY USE TEMPERATURE DEPENDANCY

Some sites used their heat pumps very little. Figure 75 shows pre- and post-installation daily electrical usage versus outdoor air temperature and heat pump metering data is also shown. We can see that the data for pre- and post- installation is highly variable and there is no clear relationship with decreasing outdoor temperature. It is clear that there is little relationship between temperature and electricity use pre- or post- installation of the heat pump, indicating that wood or fossil fuel is used for heating in both periods. Based on the AMI data, there is little to no heat pump use. The heat pump metering data agrees with this finding. Other than a few days of usage, there is generally no use of the heat pump at temperatures below about 57°F.

Figure 75. Site 22: Pre- and Post-Installation Daily AMI and Metered Heat Pump kWh versus Average Daily Temperature



13.3 COMPARISON OF AMI-DERIVED MODELED AND METERED TEMPERATURE DEPENDENT ELECTRICITY USE

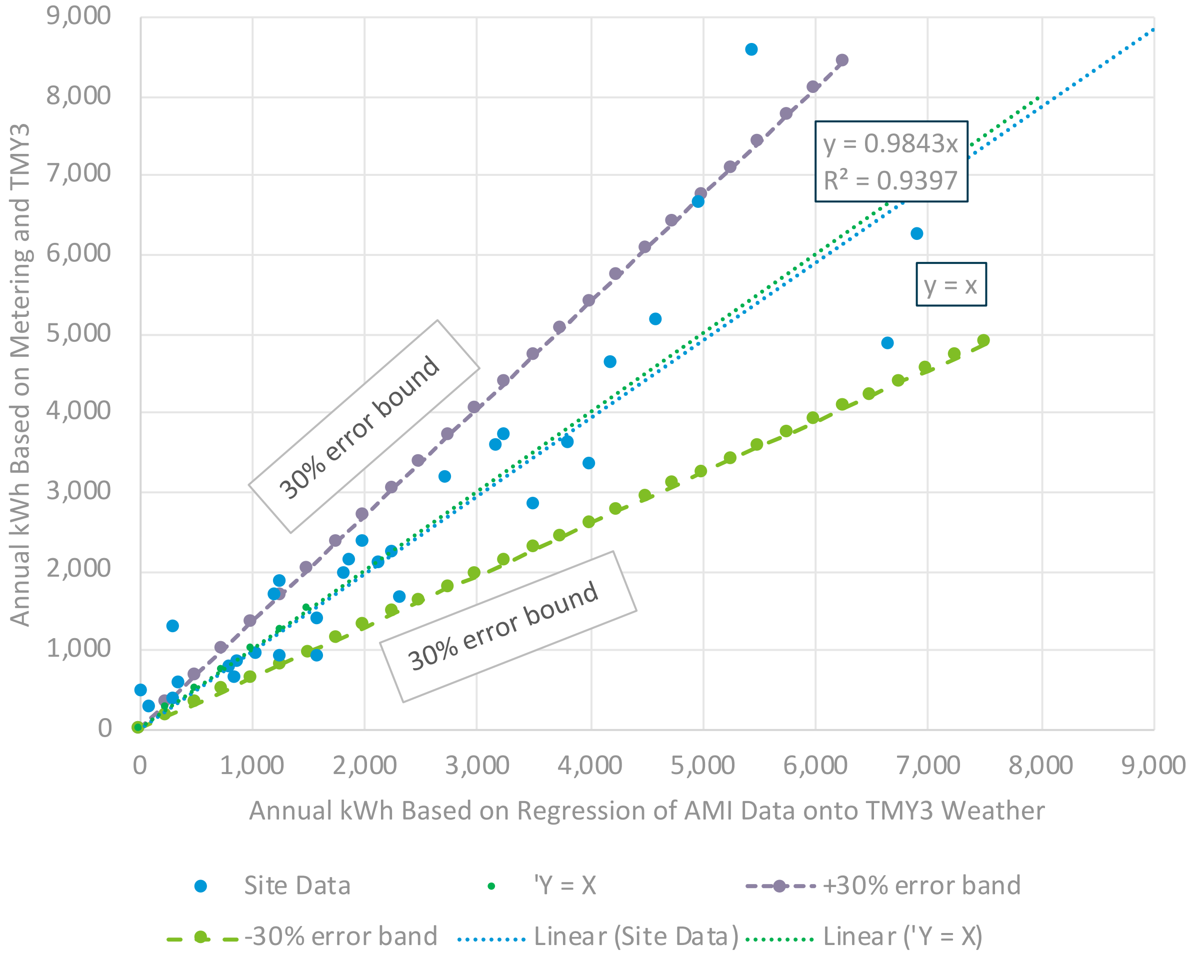
In Figure 76, the evaluation team compared paired samples of 33 metered data and AMI regressions.

One would not expect perfect matches because of these factors:

- Regression models will not exactly predict usage and usage at cold temperatures will increase or decrease the slope of the model disproportionally impacting the AMI model's accuracy.
- In some cases, other winter electricity uses in the home, including heating and non-heating, will increase usage and metered usage will be less than AMI data.

Modeled temperature dependent electricity use based on AMI data and metered use match reasonably well on average. A regression fit shows a slope of 0.98 where an exact fit would have a regression slope of 1.0. The R^2 indicating goodness of fit of the linear model is reasonably high at 0.94. On a site basis however, the data can vary widely. Figure 76 shows that most data fit within a +-30% error bound but some data particular that for low use sites can exceed this bound as does one outlier.

Figure 76. Modeled Pre- and Post-Installation Daily kWh Use Based on AMI versus Metered Heat Pump kWh



This comparison shows that where available, AMI data can be useful to identify heat pump electrical usage in some homes on average, but that it will not provide clear predictions for all homes. Specifically, it works somewhat well for homes that did not have previous electric heat and that make predictable use of their heat pumps for heating. It also shows that the AMI estimates can match metering reasonably well on average but can vary widely for a single home. If AMI data is used by itself, the AMI analysis will identify electrical usage subject to the limitations above. The analysis does not, however, measure heating provided. The usage data will include heating use, defrost use and electricity used in fan-only mode. It will also not measure efficiency (e.g. COP) so converting AMI data to heating provided and savings includes a good deal of uncertainty.

14 SUMMARY

This project metered 124 homes completing a study of residential heat pumps across all 16 counties in Maine, and in climate zones identified in the USDA plant hardiness zone map that experience temperatures below -25°F. The evaluation showed that heat pumps were popular, well-liked by their purchasers, and displaced large amounts of fossil fuel, even if used less than anticipated.

14.1 EVALUATED IMPACT

- Program heat pumps saved about 20% more fuel than reported. This was because the reported savings were based on the difference between cold weather heat pumps and standard efficiency heat pumps and because usage was about half of that predicted in the TRM model. These two factors nearly cancelled out but evaluated savings were slightly higher than reported savings.

- Measured heating provided was about 16.6 MMBtu while assumed heating in the TRM model was 25.1 MMBtu, for the 1st tier 1 unit and 28.1 MMBtu/y for the 1st tier 2 unit. Weighted average was 27.9 MMBtu/y, just over 1.5 times the amount found. Section 10 discussed the factors determining usage and showed that based on on-site user interviews and observed heat zoning, 40% of sites were predicted to have low usage. This was confirmed by metered data. Reasons for low usage included intention for cooling only, favored use of a pre-existing heating system, the heat pump zone overlapping with a single-zone furnace, and winter home vacancy.

- Metered efficiencies in the form of seasonal COP averaged 2.57, which is just above the TRM value of 2.48 and just below the 2017 Home Energy Savings Program Impact Evaluation metered value of 2.7.

- The evaluated savings led to benefit-cost ratios that were about 1.2 and ranged from 0.88 to 1.46 at the measure level (Table 22). The results were primarily due to the prevalence of retrofit installations for which the applicable costs represent the entire cost of high-efficiency heat pumps, and the savings between that heat pump and a fossil fuel heating baseline.

14.2 NET-TO-GROSS RESULTS

- The evaluation team determined a 16% free-ridership rate for the HESP program and 2% for the AHI program.

- The evaluation team determined a spillover rate of 2%, for the HESP program and 0% for the AHI program, resulting in net-to-gross ratios of 86% and 98% respectively.

14.3 OTHER FINDINGS

The study found that hourly building-level electricity data could be useful in calculating the seasonal use of a heat pump if sufficient pre- and post-installation data were available, if there was no electrical heating prior to installation of the heat pump, and if the heat pumps were either used very little or often. AMI analysis was less useful in determining usage for homes that had electrical heat prior to the heat pump installation and used mixtures of heating systems.

14.4 OVERALL IMPACT

The average heat pump used 1,897 kWh per year for heating, had a mean seasonal COP of 2.57, and on average, saved the equivalent of 2,988 kWh versus an electric baseline and 14.4 MMBtu versus an 80% efficient fossil system.

- **Rebated heat pump installations produced large and widespread annual energy savings.** The HESP and AHI rebated heat pump measures resulted in 57,000 therms of natural gas savings, 325,000 MMBtu (2.3 million gallons) of fuel oil savings, and 44,000 MMBtu (489,000 gallons) of propane savings. Heat pumps also displaced 46,000 MMBtu of pellet and cord wood heat.

- **Rebated heat pumps saved about 278 kWh when providing cooling compared with baseline systems.**

- **Participating customers are highly satisfied with their heat pumps and the program overall.** On a five-point scale, with 5 being "extremely satisfied," customer ratings ranged from 4.4 for comfort when heating with a heat pump, to 4.7 for most other questions including satisfaction with contractor, and overall experience with Efficiency Maine.

- **Contractors noted positive effects from their participation in the program.** Participating installers show high satisfaction with the program overall, giving it an average rating of 7.75 out of 10. 80% use tips provided by Efficiency Maine in training customers, 60% indicate that they handle more inquiries due to the program and 50% credit the vendor locator tool in driving inquiries to them.