FINAL REPORT

Commercial & Industrial High-Performance Heat Pump Program Impact Evaluation

Efficiency Maine

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DNV

GLOSSARY OF TERMS

Absolute precision – Precision is a measure of uncertainty that is standard in the industry. Absolute precision is distinguished from relative precision (see below) as it shows uncertainty in absolute terms as a percentage of 100% of the realization rate.

Advanced Metering Infrastructure (AMI) - An integrated system of smart meters, communications networks, and data management systems that enables two-way communication between utilities and customers.[1] Electric AMI meters allowed analysis of 15-minute power data as part of this evaluation.

Base temperature – The outside air temperature at which a facility switches from heating mode to cooling mode. Base temperature is synonymous with "switchpoint." Heating base temperature is the highest outside air temperature at which the facility requires heating.

Coefficient of performance – A unitless efficiency measurement for an HVAC system, defined as the ratio of Btu output (delivered heating or cooling Btu) with Btu input (the power draw of the HVAC system). The higher the COP, the more efficient the system. Heat pump COPs typically exceed 3-4, as compared with fossil-fuel heating systems with COPs below 1. In this report, COP values reflect real-world performance as measured by the DNV team.

Coefficient of variation – A statistical measure of the dispersion of data points relative to the mean within a population. Coefficient of variation is quantified as the ratio of standard deviation to the mean.

Complementary sites – The evaluation initially involved assessment of a sample of 70 ductless mini-split heat pumps rebated by the program (see "core sites" below). To diversify the facility types addressed in the study, the DNV team and Efficiency Maine added another 33 installations for measurement and verification during the heating season. These additional sites are referred to as complementary.

Confidence interval – When paired with a precision estimate, the likelihood of a sample-based estimate falling within a given range of the true value. For example, for electric energy savings, 80/10 confidence/precision implies that the DNV team is 80% confident that the result falls within ±10% of the true value.

Cooling degree days (or cooling degree hours) – A measurement that quantifies a facility's cooling energy requirement. Cooling degree days (CDDs) represent the number of degrees that a daily average temperature is above the facility's base temperature (see definition above). We occasionally use the term "cooling degree hours" (CDHs) in this report, which is equivalent to the number of degrees that an hourly average temperature is above the facility's base temperature—i.e., the product of CDD and 24 hours/day.

Core sites – The HP installations corresponding to the original evaluation sample. Installations added to the core sites are referred to as complementary (see definition above).

Displacement – In the context of HVAC installations, displacement involves a shift in how a building's heating or cooling load is satisfied among different systems including heat pumps.

Energy period factors (EPFs) – Per the Efficiency Maine TRM, EPFs are used to allocate the annual energy savings into one of the four energy periods defined as:

Winter Peak: 7:00 AM to 11:00 PM on non-holiday weekdays during October through May (8 months)

[1] Definition transcribed from https://www.energy.gov/sites/prod/files/2016/12/f34/AMI%20Summary%20Report_09-26-16.pdf

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)

Evaluation timeframe – The period of program activity studied by an evaluation. This evaluation assessed projects rebated by Efficiency Maine between July 1, 2017, and December 31, 2019.

Evaluated impacts – The savings estimate independently quantified by the evaluator after the energy impact evaluation has been completed.

Free-ridership – The percent likelihood that a participating customer would have adopted the energy-efficient option absent program intervention. Free-ridership assessment in this study included two primary components: intention and influence. Intention research examines what the participant would have done in the absence of the program; influence assessment acts as a check on the potential bias of the intention by understanding the influence of different program interventions on a participant's decision-making process.

Heating degree days (or heating degree hours) – A measurement that quantifies a facility's heating energy requirement. Heating degree days (HDDs) represent the number of degrees that a daily average temperature is below the facility's base temperature (see definition above). We occasionally use the term "heating degree hours" (HDHs) in this report, which is equivalent to the number of degrees that an hourly average temperature is below the facility's base temperature—i.e., the product of HDD and 24 hours/day.

Heating Season Performance Factor (HSPF) – A heating efficiency rating for heat pumps that compares heating output (in Btu) with electric input (in Watt-hour).

Effective HSPF ($HSPF_e$) – To compare real-world performance with rated heating efficiency, we occasionally convert COP to $HSPF_e$ in this report. $HSPF_e$ is equivalent to the product of heating COP and a 3.412 Btu/Watt-hour conversion factor.

Heating signature – The observed correlation of heat pump energy use with outside air temperature during the heating season.

High-performance heat pump – The term used by program administrators that encompasses several high-efficiency heat pump measure solutions, including ductless and mini-ducted mini-split systems. All systems sampled for M&V were ductless mini-split systems serving one or more zones at commercial facilities.

kWh per 1,000 Btu/h rated capacity – In order to normalize evaluation results to rated heat pump capacity, we use this atypical unit in Sections 4.2 and 4.3. The kWh value represents the annualized electric energy consumed by the HP during heating or cooling seasons; the denominator reflects the rated heating or cooling capacity (in Btu/h) divided by 1,000. The evaluation did not assess whether the installed systems were over- or under-sized to meet the heating and cooling loads at sampled facilities.

Lost opportunity – 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.

Measurement and verification – The process of planning, measuring, collecting, and analyzing data for the purpose of verifying and reporting energy savings within an individual facility resulting from the implementation of energy conservation measures.[2]

MMBtu at site – A consolidated savings value that combines electric energy savings at the customer site (i.e., excluding generation, transmission, and distribution losses) with fossil fuel energy savings.

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.

PRISM – The PRInceton Scorekeeping Method is a statistical procedure which uses available billing and weather data to produce accurate estimates of energy impacts. The PRISM method is further explained in Appendix C.

Qualified partner – Pre-approved installation contractors that partner with Efficiency Maine Trust to promote energy efficiency options among Maine utility customers.

Relative precision – Precision is a measure of uncertainty that is standard in the industry. For impact evaluations, relative precision expresses uncertainty as a percentage of the realization rate.

Reported savings – Project energy savings claimed by program administrators. Reported savings serve as the denominator in the calculation of the realization rate.

Retrofit – A replacement of preexisting, operating equipment that has not reached the end of its effective useful life. The annual savings (the focus of this evaluation) reflect the efficiency gain from the rebated system as compared with the preexisting *in situ* system.

Realization rate (RR) – The ratio of evaluated savings and reported savings. Calculated as the total evaluated savings divided by the total reported savings, the RR defines what percentage of savings are realized by the program.

Seasonal energy efficiency ratio (SEER) – A cooling efficiency rating for heat pumps that compares heating output (in Btu) with electric input (in Watt-hour). SEER is equivalent to the product of rated cooling COP and 3.412 Btu/Watt-hour.

> **Effective SEER ($SEER_e$)** – To compare real-world performance with rated cooling efficiency, we occasionally convert COP to $SEER_e$ in this report. $SEER_e$ is equivalent to the product of cooling COP and a 3.412 Btu/Watt-hour conversion factor.

Site – A physical location at which an energy efficiency project has been implemented.

Spillover – Additional energy efficiency savings due to program influences beyond those directly associated with program participation. Participant spillover (PSO) refers to the non-incented energy efficiency measures installed by program participants as a result of their participation. Non-participant spillover (NPSO) refers to non-incented program measures implemented by vendors who were directly or indirectly influenced by the program.

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[2] Definition transcribed from https://evo-world.org/en/m-v/what-is-m-v

1 EXECUTIVE SUMMARY

This report presents results of an impact evaluation of high-performance heat pumps (HPs)[3] installed through the Commercial and Industrial (C&I) Prescriptive Program (the program) administered by Efficiency Maine. The program connects contractors (Qualified Partners or QPs) with Maine's commercial customers to install high-efficiency equipment. Efficiency Maine contracted DNV, along with subcontractors Cadmus, Bruce Harley Energy Consulting, EcoMetric Consulting, and Ridgeline Energy Analytics (the DNV team), to conduct an impact evaluation of the program's HP installations between FY2017 and FY2019 (July 1, 2016 – June 30, 2019).

1.1 Objectives

The evaluation's primary objectives included quantifying energy and peak demand impacts based on measurement and verification (M&V) and analysis of advanced metering infrastructure (AMI) data, estimating free-ridership and spillover through customer and vendor surveys, and assessing benefits and costs using evaluation results and Efficiency Maine's cost-benefit analysis tool.

1.2 Methods

To achieve the project objectives, the DNV team conducted:

- Customer surveys of business owners to collect facility information, characterize the incented HPs and usage patterns, and assess their satisfaction with the program and contractor.
- Vendor surveys to collect information about HP sales practices and activity with program-affiliated and non-program installations, equipment costs, customer decision-making, program influence on HP sales, and barriers to selling qualifying HPs.
- Measurement and verification of a sample of 70 HPs incentivized by the program among three prevalent facility types: lodging, multifamily, and office. Field engineers visited each of the 44 unique facilities associated with the 70 sampled HPs and deployed cloud-communicating devices to measure the power of outdoor equipment, amperage to indoor equipment, and amperage of auxiliary heating systems where applicable. For a subset of eight higher-rigor deployments, field engineers monitored the temperature and relative humidity of the supply air stream and spot-measured the airflow at various fan speeds with the objective of developing coefficient of performance (COP) curves as a function of outside air temperature. For all systems sampled for M&V, deployed meters collected data from December 2020 through October 2021.[4] Efficiency Maine and the DNV team agreed to extend the sample by adding another 33 HPs for M&V during the heating season; the additional sample points are referred to as *complementary* in this report.[5]
- Regression analysis of HP power consumption data against two independent variables: outside air temperature and time of week. Using COP curves defined by the eight higher-rigor sites, annualized HP power data defined the heating and cooling loads satisfied by the incented HPs. After developing the most appropriate heating and cooling baselines from site-specific information, the DNV team compared the heating and cooling loads and performance efficiencies between baseline and as-built conditions. Final, site-specific impact results include savings or increases and associated realization rates (RRs) by fuel source: electricity, natural gas, and delivered fuels, as applicable.
- Premise-level analysis of AMI data and fuel delivery data to assess at-the-meter impacts from HP installations. Compared to equipment-level metering among a sample of projects, at-the-meter analysis of a census of heat pump

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3 In this report, high-performance heat pumps or HPs refer to ductless mini-split or mini-duct systems serving one or more zones at commercial facilities.

4 Through web surveys and field questionnaires, the DNV team confirmed that the customers' operation had generally resumed to normal following the quarantine periods of spring 2020.

5 The evaluation sample design focused on the three most prominent building types in the participant population—lodging, multifamily, and office—and bucketed the remaining building types into a category called "other." When the limited variety of building types in the sample prompted Efficiency Maine to inquire about HP usage across a wider range of building types, the team worked with Efficiency Maine to create a complementary M&V plan that included M&V of an additional 33 program-rebated HPs across other facility types such as retail, health/wellness, restaurant, and manufacturing.

participant facility energy use is less costly and eliminates self-selection bias possible in voluntary M&V sub-metering studies. A primary concern with premise-level analysis, however, is the accuracy of the heating and cooling annual energy consumption predictions. The objectives of this analysis phase included not only quantification of program impacts at the meter but also a feasibility assessment of AMI viability in future program evaluations.

- Analysis of benefits and costs using Efficiency Maine's Cost Benefit Analysis Tool (CBAT) and evaluation results.
- Net-to-gross analysis incorporating free-ridership (FR) and spillover components. Free-ridership refers to the portion of energy savings that participants would have achieved in the absence of the program. Spillover, which includes both participant spillover (PSO) and non-participant spillover (NPSO) components, refers to the energy savings from non-rebated energy efficiency upgrades made outside of the program that are influenced by the program. The NTG ratio (NTGR) is calculated through the following formula:

$$NTGR = 1 - FR + PSO + NPSO$$

Detailed methodology can be found in Section 3.

1.3 Results

Table 1-1 presents the program-reported and evaluated MMBtu impacts at site,[6] distinguished among the primary sampling strata (building type), among the 70 systems sampled for M&V.

Table 1-1. Comparison of Reported and Evaluated MMBtu Impacts at Site among M&V Sample

Sector	Subsector	N	n	Reported Savings across All Energy Sources (MMBtu/yr)	Evaluated Savings across All Energy Sources (MMBtu/yr)	RR	RP at 80% Confidence
Commercial	Lodging[1]	245	14	1,135	317	0.28	±34%
	Office	307	16	2,110	2,090	0.99	±34%
	Other	977	17	6,819	7,745	1.14	±39%
Multifamily		768	23	2,738	7,886	2.88	±28%
Total		**2,297**	**70**	**12,801**	**18,038**	**1.41**	**±22%**

N = Total count of HP installations incented by the program between 2017 and 2019
n = Sample of HP installations drawn for M&V evaluation
RR = Realization rate: evaluated savings divided by reported savings
RP = Relative precision
[1] Of the fourteen sampled installations at lodging facilities, the evaluators determined that one of the facilities was a seasonal inn (closed for the winter). The remaining lodging facilities operate year-round with seasonal variation captured by the M&V metering period.

Overall, rebated HP installations realized 41% more MMBtu at site than predicted by the program. The DNV team determined two primary contributors to the 141% MMBtu RR that partially offset one another:

- **Baseline revision** – The evaluator's assessment of system-specific baselines, as explained in Section 3.5.1, resulted in a 177% increase in evaluated savings as compared with reported. Evaluators determined that 56% of sampled HP installations offset fossil fuel heating; on the other hand, the program generally claimed incremental savings as compared with a code-compliant HP baseline.[7]

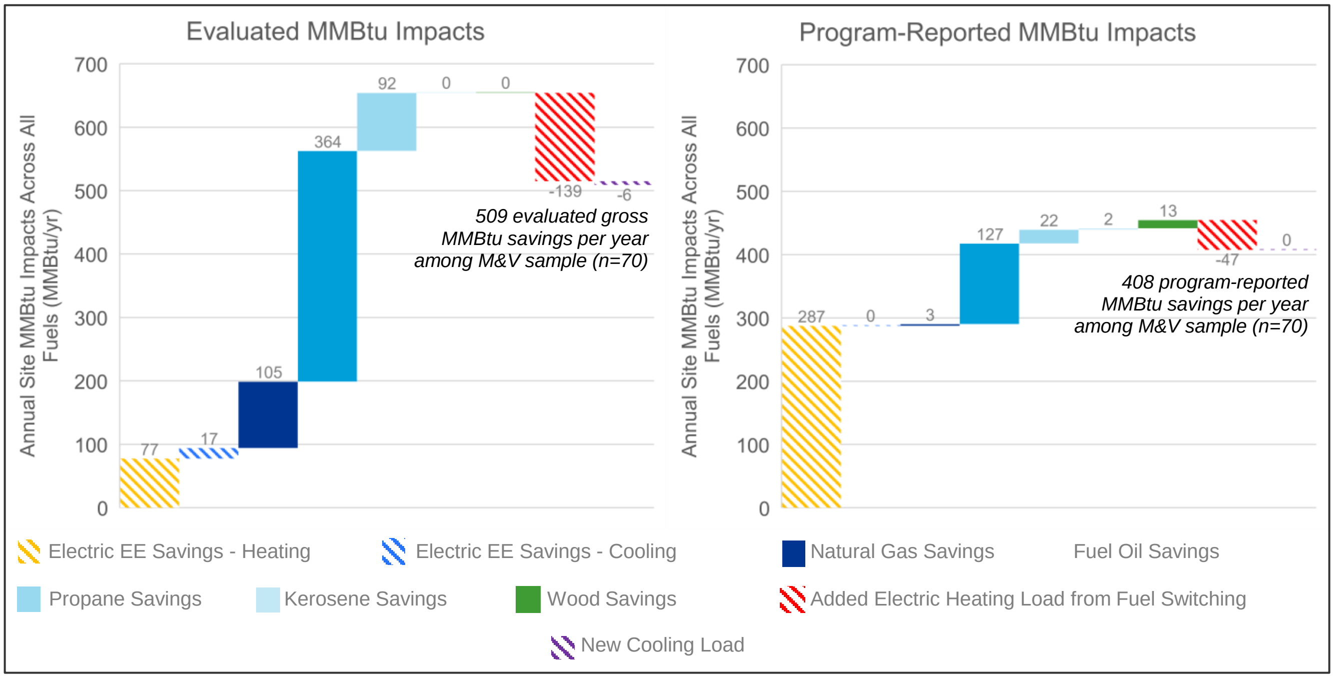
[6] The MMBtu savings presented in this report reflect a blend of electric and fossil fuel impacts as a result of the fuel switch. Evaluated MMBtu savings are measured against the evaluator's determined baselines as summarized in Section 4.2.1. All MMBtu savings in this report reflect *site* MMBtu— i.e., no electric production, transmission, or distribution efficiencies are incorporated.

[7] Program-reported savings among the population of 2017-19 HP installations were distributed across fuel type (in site MMBtu): 82% electricity, 11% oil, 5% natural gas, 2% propane. The Efficiency Maine modeling that accounted for differences is capacity versus outside air temperature resulted in some fossil fuel savings for lost opportunity heat pumps due to greater heating offset by the high-efficiency heat pump compared to a standard-efficiency one.

- **Reduced heating output** – Overall, the DNV team determined that the incented HPs operated less frequently during the heating season than anticipated by the program. Per the Efficiency Maine Technical Reference Manual (TRM), program-reported savings reflected an annual heating output of 25 MMBtu per HP per year; in contrast, we determined that the incented HPs produce 10 MMBtu of heat per year on average. This -146% difference mitigated the significant baseline difference above.

Figure 1-1. compares evaluated (left-hand figure) and program-reported impacts by fuel, combined across the 70 installations sampled for M&V. Electric impacts (converted to MMBtu at site) are designated by the striped bars, while fossil fuel impacts are designated by solid bars. Added electric load from fuel switching is illustrated by the red striped bar. Electric savings due to increased efficiency in heating and cooling seasons are designated by the orange- and blue-striped bars, respectively. Please note that the ratio between total evaluated savings (509 MMBtu per year) and program-reported savings (408 MMBtu per year) slightly differs from the 141% RR in Table 1-1, as the results in Figure 1-1. do not incorporate evaluation sample weights.

Figure 1-1. Evaluated vs. Reported Impacts by Fuel among M&V Sample



The figure illustrates that rebated HP installations offset a broader diversity of fuels than the program's assumption of code-standard heat pump baselines. The right-hand waterfall chart, illustrating the makeup of the program-reported savings claims, shows a predominance of electric heating savings from the program's presumed code-compliant HP baseline.[8] The left-hand waterfall, illustrating the evaluator's findings, shows a higher prominence of displaced fossil fuels and associated added electric load from fuel switching.

The DNV team examined impact results among various segments of interest to ascertain patterns in operation or savings; observations include:

8 Program-reported savings among the population of 2017-19 HP installations varied by fuel type (in site MMBtu): 82% electricity, 11% oil, 5% natural gas, 2% propane. According to Efficiency Maine staff, savings claims changed over the evaluation timeframe. Throughout the full evaluation timeframe, the program assumed all HPs to be Lost Opportunity with a baseline of a standard efficiency heat pump. On July 1, 2019 (FY2020), the TRM HP savings claims were updated to reflect revised modeling that accounted for capacity differences versus outside air temperature of the high efficiency and standard efficiency HPs. That modification of the modeling resulted in some fossil fuel savings for LO HPs due to greater heating offset by the high-efficiency HP compared to standard-efficiency.

- Multi-zone HPs produce more heat and save more MMBtu than single-zone HPs. On average, HPs serving a single zone saved 3.6 MMBtu per year per HP (n=44), whereas HPs serving multiple zones (2.8 zones served on average) saved 13.1 MMBtu per year per HP (n=26). After normalizing the savings results to average capacity, the DNV team determined that multi-zone systems saved approximately twice as much MMBtu as single-zone systems.
- The DNV team found no significant difference in heat output or savings per HP between projects involving a single HP installation (n=34) and projects involving more than one HP installation (n=36).
- HPs that displaced fossil fuel-fired heating systems operated more frequently during the heating season and subsequently saved more MMBtu (11.6 MMBtu savings per year per HP, n=32) than HPs that displaced electric resistance heating systems (4.6 MMBtu savings per year per HP, n=12).
- HPs associated with customers that reported via web survey to continue to frequently use their legacy heating system saved significantly less (2.1 MMBtu savings per year per HP, n=4) than HPs associated with customers that no longer use the legacy heating system (6.7 MMBtu savings per year per HP, n=18) or HPs associated with customers that infrequently use the legacy heating system (8.5 MMBtu savings per year per HP, n=16).
- HP specifications varied widely among the 70 sampled systems. For example, rated heating capacity (at 17°F test condition) ranged from 6,700 Btu/hr for a single-zone unit to 35,400 Btu/hr for a multi-zone system. The DNV team normalized the achieved impacts by rated equipment capacity[9] for comparison purposes with normalized output results from premise-level analysis. The DNV team found that **HPs sampled for M&V consumed 62 kWh per rated 1,000 Btu/h during the heating season** and 9 kWh per rated 1,000 Btu/h during the cooling season annually.

1.3.1 Premise-level results

The DNV team also assessed the impacts from program-rebated HPs by comparing site-specific AMI data before and after installation. The DNV team conducted AMI analysis using three techniques: pre/post AMI analysis using the PRInceton Scorekeeping Method (PRISM), post-only AMI analysis using PRISM, and post-only AMI analysis using machine learning to train the model with M&V data. Additionally, the team approached the pre/post analysis from the fossil fuel perspective by assessing the anticipated decrease in heating fuel consumption as a result of the HP installation. Another objective of the AMI data analysis was to determine if and when an AMI-based approach is viable for evaluation analysis moving forward.

The DNV team explored the viability of pre/post analysis of Efficiency Maine's HP participants by first attempting to collect as much pre/post AMI data as possible within the evaluation population. The team estimated weather-normalized energy consumption for all participant sites having AMI data at least one year prior to and one year after HP installation. Of the 415 sites with AMI data, 242 had sufficient data for pre/post-install analysis (hourly energy use data for at least one year prior to and one year after the heat pump installation). **The overall electric heating energy use attributed to HP installations changed by +44 kWh per rated 1,000 Btu/h** (an increase in electric energy use[10]). The team investigated the pre/post data further and found a slight increase in cooling energy for all 242 sites (+1.3 kWh per rated 1,000 Btu/h). If we assume the new heat pumps have higher cooling efficiency than the in-situ systems, an increase in cooling energy use is not expected unless there is an increase in the cooling load. Such a change could be attributed to a new addition of conditioned space, an increase in occupancy, some other type of increase in internal heat gains, or from a lower cooling temperature setpoint. Due to this and other uncertainties with traditional pre/post analysis, the DNV team determined that PRISM analysis may be unreliable for a significant number of projects over the evaluation timeframe.

[9] HP capacities are typically rated in Btu/h; for the purposes of this analysis, the DNV team divided the rated heating capacity (at the 17°F design condition) by 1,000 Btu/h to quantify the normalized values presented in various results sections of this report.

[10] In the premise-level analysis sections of this report, the plus sign indicates an increase in post-install energy use as compared with pre-install use. A minus sign indicates a decrease.

The DNV team next analyzed only the post-installation AMI data to estimate heating use associated with the heat pump installations, categorized by different scenarios based on AMI data availability, credibility, and heating signature.[11] The normalized heating kWh estimates varied greatly depending on the different screening scenarios. We estimated that program-rebated HPs consume **a range of average annual normalized heating energy between +44 and +63 kWh per rated 1,000 Btu/h.** This range corroborates the normalized heating energy use result of +62 kWh per rated 1,000 Btu/h per year as derived from sites sampled for M&V.

In parallel with the AMI-based analysis, the DNV team, with support from Efficiency Maine, expended significant effort collecting and analyzing fuel delivery data. The DNV team requested heating fuel delivery data from all program participants completing the survey. 106 surveyed participants reported using some type of delivered fossil fuel before and/or after heat pump installation in the area(s) served by the HP(s). Ultimately, the team received data from 30 participants comprising 46 HP installations. Based on analysis of fuel delivery data, the average decrease in annual site-level delivered fuel consumption (30 MMBtu) is approximately equivalent to 270 gallons of oil saved, which is approximately equivalent to +3,509 kWh (**+108 kWh per rated 1,000 Btu/h[12]) of added electric load on average per site**.[13]

The DNV team determined additional conclusions from the AMI analysis:

- **AMI data for HVAC interventions can be categorized into three heating load shapes**: 1) "full displacement" – continuous heating kW increase with decreasing temperature, 2) "partial displacement" – increase with decreasing temperature up to the switchover point, and 3) "low usage" – no apparent heating signature. Classification of sites into distinct categories will minimize uncertainty (e.g., the low-usage site results will not affect the full-displacement site results).
- **Facilities with more than one AMI meter were more likely to exhibit questionable results.** Multifamily buildings demonstrated statistically significantly low heating usage, but the DNV team questions the validity of this finding due to higher uncertainty in selecting the appropriate AMI meter at a given multifamily facility. Billing analysis at multifamily facilities is historically difficult due to the likelihood of multiple utility meters serving common areas and tenant units.
- **Sites showing an increase in cooling usage suggest non-routine changes may have occurred between pre- and post-installation periods**. Approximately half of the AMI analysis pool showed an increase in cooling usage after HP installation, calling into question the validity of pre/post comparison. Non-routine events (e.g., change in occupancy or business hours, space expansion, set-point adjustment) likely occurred at these sites, thereby disqualifying the pre-installation data as representative of baseline. In such cases, analysis of post-installation AMI data only may be most appropriate.
- **Ultimately, the DNV team determined that the M&V results were more stable and credible than the premise-level results.** The uncertainties explained in the bullets above caused the team to define the evaluated gross savings using the M&V results.

1.3.2 Net impact results

Through quantification of net-to-gross ratio (NTGR), the DNV team estimated the share of gross impacts attributable to the program influencing the customer to install high-efficiency HPs. **The DNV team estimates an NTGR of 73%** for HPs rebated over the 2017-19 evaluation timeframe. Following the formula provided in Section 1.2, the NTGR value is comprised of a 35% free-ridership rate, 6% participant spillover rate, and 2% non-participant spillover rate. 194 program participants provided valid responses to free-ridership questions in the participant survey; about a third of respondents indicated they

[11] The term "heating signature" used in this report refers to the correlation of heat pump energy use with outside air temperature. See Section **Error! Reference source not found.** for example of a site with a strong heating signature.

[12] From the 21 HPs' rated heating capacities at the 17°F design condition, the DNV team estimated an average rated heating capacity of 32,500 Btu/h. The electric equivalent is calculated using assumed fossil fuel and HP COPs of 0.8 and 3.2, respectively.

[13] This result represents site-level savings and therefore includes sites that received more than one incented HP.

would have done the identical project even if the program and rebate did not exist. Another third of respondents indicated that the program partially influenced them to adopt higher efficiency and/or accelerate HP installation faster than they otherwise would have. The DNV team estimated an 8% spillover rate, which served to slightly increase the NTGR. Spillover was primarily comprised of participants indicating that their experience with the program led to the adoption of other, non-rebated energy efficiency measures in categories such as lighting and water heating.

1.3.3 Cost-benefit results

The DNV team applied the gross and net savings results from this study to Efficiency Maine's Cost Benefit Analysis Tool (CBAT) to assess the cost-effectiveness of C&I HP measures. Table 1-2 shows the benefit/cost ratio (BCR) for the prescriptive HP measures offered by the program over the evaluation timeframe. The DNV team ran several iterations of the CBAT using the avoided costs in effect during the evaluated period (AESC 2018) and using the avoided costs approved for Triennial Plan V that started on July 1, 2022 (AESC 2021[14]). Values in green indicate BCRs that pass the cost-effectiveness threshold of 1, and values in red indicate BCRs below the cost-effectiveness threshold.

Table 1-2. Benefit-Cost Ratio Results among Various Segments, 2018 and 2021 AESC Screening Methods

HP Type	Sector	Event Type	n	AESC 2018, Evaluated Gross	AESC 2021, Evaluated Gross	AESC 2018, Evaluated Net[1]	AESC 2021, Evaluated Net[1]
All	**All**	**All**	**70**	**0.79**	**1.07**	**0.79**	**1.07**
All	Multifamily	All	23	0.61	0.88	0.61	0.88
All	Commercial	All	47	0.92	1.21	0.92	1.21
Single-Zone	Multifamily	All	14	0.59	0.83	0.59	0.83
Single-Zone	Commercial	All	31	0.88	1.26	0.88	1.26
Single-Zone	All	All	45	0.76	1.08	0.76	1.08
Multi-Zone	Multifamily	All	9	0.71	0.93	0.71	0.93
Multi-Zone	Commercial	All	16	0.94	1.15	0.94	1.15
Multi-Zone	All	All	25	0.83	1.05	0.83	1.05
Single-Zone	All	Retrofit[2]	31	0.61	0.87	0.61	0.87
Single-Zone	All	Lost Opportunity[2]	14	1.70	2.28	1.70	2.28
Multi-Zone	All	Retrofit[2]	19	0.69	0.87	0.69	0.87
Multi-Zone	All	Lost Opportunity[2]	6	1.93	2.43	1.93	2.43

[1] Efficiency Maine follows the National Standard Practice Manual (NSPM) for Cost-Benefit Analysis and counts incentives paid to free riders as a passthrough that has no impact on the calculated benefit-to-cost ratio. As a result, net BCRs are identical to their gross counterparts.
[2] The evaluation sample did not include any projects that were classified by the program as Retrofit. The DNV team reclassified the 70 HP systems sampled for M&V into the appropriate event type based on evaluation baseline.

The table shows that prescriptive HP measures overall were cost-effective when considering the avoided costs in effect at the time of this writing (AESC 2021). HP installations at Multifamily facilities incurred slightly more costs than benefits due to a higher prevalence of retrofit projects which incur full installation costs. For that segment, the DNV team determined that the tenants did not use the HPs enough during the heating season to displace sufficient fossil fuel heating to overcome the full installation costs of the HPs. BCRs using the avoided costs in effect during the evaluated period (AESC 2018) generally fell below 1. As shown in the last four rows of the table, Lost Opportunity installations, for which the costs and benefits reflect a federal standard HP baseline, were significantly more cost effective than Retrofit installations.

[14] AESC 2021 avoided costs incorporate non-embedded costs of carbon.

Section 4.5 contains additional details on cost-benefit analysis assumptions, data sources, and results.

1.3.4 TRM insights

Analysis of equipment-level M&V data revealed relevant operating parameters such as coefficients of performance (COPs) and heating and cooling outputs. This parameter-level analysis is intended to provide real-world HP operating characteristics to inform future iterations of the Efficiency Maine TRM. Table 1-3 compares evaluation results with program-assumed parameters reflected in deemed savings values in the current TRM.

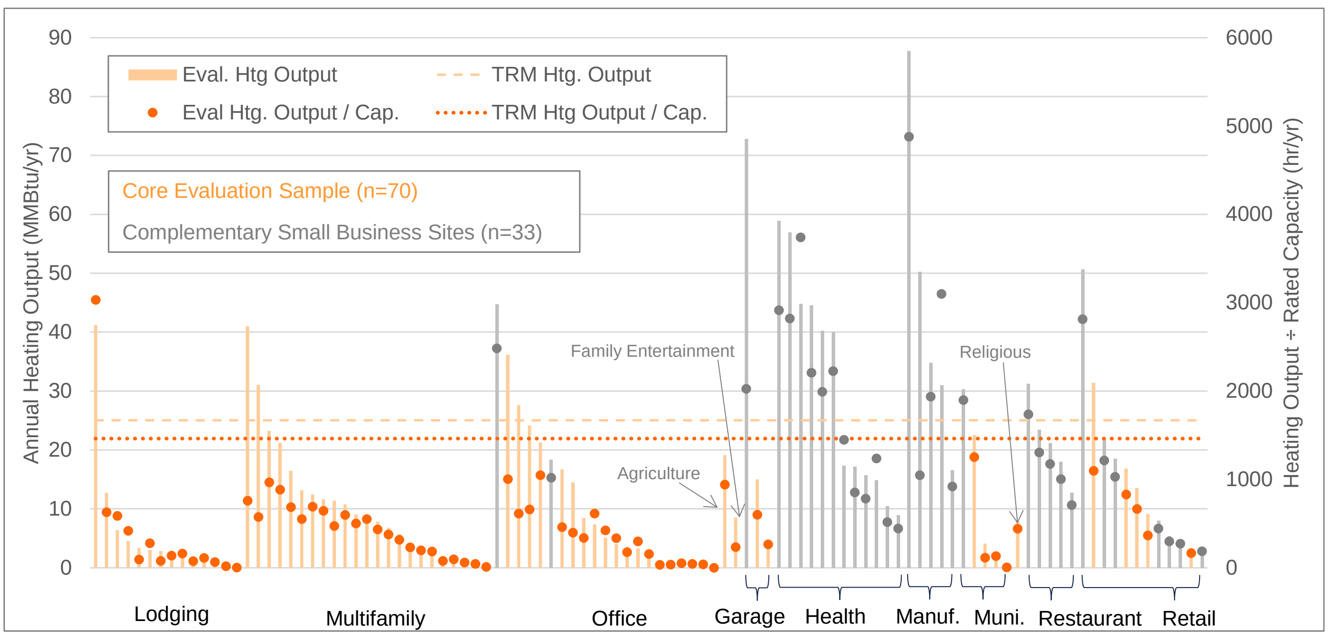
Table 1-3. Comparison of Evaluation Results with Current TRM Parameters

Metric	Heating		Cooling	
	Current TRM	Evaluated	Current TRM	Evaluated
AHRI-Rated Capacity (Btu/hr)	20,644	22,401	17,589	19,877
Coefficient of Performance*	2.47	3.17	4.99	6.73
Annual Output (MMBtu/yr)	25.05	9.80	3.14	2.83
Output ÷ Capacity (hrs/yr)	1,462	426	226	156

* Coefficient of performance is equivalent to *effective* heating season performance factor ($HSPF_e$) or *effective* seasonal energy efficiency ratio ($SEER_e$) divided by 3.412 Btu per Watt-hour for heating and cooling, respectively. $HSPF_e$ and $SEER_e$ incorporate evaluated performance data at a range of outside air temperatures, normalized to the manufacturer's HSPF and SEER ratings at the design condition.

The DNV team further analyzed the heating output result by facility type among not only the 70 HPs sampled for evaluation but also among 33 "complementary" HPs selected for heating output analysis among a broader list of facility types. Figure 1-2 illustrates the site-by-site annual heating output results organized by facility type. The figure includes different y-axes on the left- and right-hand sides. The left-hand y-axis denotes annualized heating output in MMBtu, while the right-hand y-axis represents the ratio of annualized heating output to rated heating capacity to illustrate the effect of equipment size on output.

Figure 1-2. Annual Heating Output per HP Installation by Facility Type



The figure shows that, among the core evaluation sample (orange bars), HPs at Multifamily facilities produced the highest heating output on average, whereas HPs at Lodging facilities produced the lowest heating output.[15] Complementary M&V sites produced higher heating output on average than core evaluation sites, with HPs Manufacturing and Garage/Repair facilities producing the highest heating output, though low sample size is a consideration.

1.4 Conclusions

This study assessed the gross and net impacts of HP installations among C&I customers that participated in the program between 2017 and 2019. The program's design and eligibility criteria, and the HP market, have evolved in the three years since. Therefore, the DNV team has framed the following conclusions wherever possible to be applicable to the program moving forward.

Program Accomplishments

- **Rebated HP installations led to meaningful annual energy savings and carbon emissions reduction.** The C&I Prescriptive Program's HP measures resulted in 37,119 therms of natural gas savings, 85,881 gallons of fuel oil savings, and 35,494 gallons of propane savings. Overall, the realized energy savings offset approximately 1,356 tons of CO_2 from fossil fuel combustion per year. Each rebated HP led to 8 MMBtu of annual energy savings (at site) and 1,301 pounds of annual CO_2 emissions reduction per installation.
- **Participating customers are highly satisfied with their HPs and the program overall.** On a ten-point scale, with 10 being "extremely satisfied," customer ratings across various program features ranged from 8.6 (incentive amount) to 9.2 (satisfaction with HPs).
- **Qualified partners (QPs) noted positive effects from their participation in the program.** 31% and 21% of surveyed QPs noted an increase in customer base and an increase in sales volume, respectively, as a result of their association with the program.
- **Overall, rebated HPs led to cooling savings when compared with baseline systems.** 12 of 70 sampled HP installations introduced new cooling load to a previously uncooled space that would have remained uncooled if not for the incented HP. But when compared with the customer's preferred alternative cooling system, the remaining 58 installations led to cooling savings that offset this electric penalty.

Gross Impact Results through M&V

- **As determined through M&V of 70 sampled HPs, the program-incented HPs realized 41% more MMBtu savings than predicted.** The DNV team approached the study using two methods of defining evaluated gross impacts: measurement and verification and AMI-based premise-level analysis. As discussed in the premise-level analysis conclusions below, the evaluated gross savings are defined by the M&V results due to various uncertainties surrounding the premise-level results.
- **Evaluated savings exceeded program-reported values primarily due to a higher share of displaced fossil fuel heating than predicted by the program.** The DNV team determined that over half of the 70 sampled HP installations displaced fossil fuel heating; on the other hand, the program-reported savings claims reflected only an 18% share of displaced fossil fuels.
- **The DNV team determined lower-than-expected output from rebated HPs during the heating season**. The 70 HPs sampled for M&V operated approximately 60% less frequently during the heating season than assumed within TRM-based deemed savings. The DNV team primarily attributes this difference to the continued use of supplementary heating systems (see below bullet). Survey results indicated that nearly half of participants do not fully use the incented

[15] M&V site visits included interviews with facility representatives on topics such as seasonal fluctuations or lingering effects from the COVID-19 pandemic. Representatives from the 14 Lodging facilities included in the M&V sample stated that their operation had generally resumed to normal, and that the December 2020 – October 2021 metering period was representative of typical operation.

HPs throughout the heating season. To properly account for these differences in savings claims moving forward, the program could consider additional screening of applicants and/or additional contractor-collected data to refine savings claims to more accurately reflect anticipated share of heating load.[16]

- **The status of legacy heating systems greatly affected achieved savings.** Customers that reported to continue to frequently use their legacy heating system realized 69% less MMBtu savings than customers that reported to no longer use the legacy heating system. Should Efficiency Maine consider additional segmentation of deemed savings in the TRM, we recommend differentiating deemed savings by the decommissioning status of the legacy heating system.
- **Achieved savings and heating output varied by customer sector within the core evaluation sample.** The team designed the core evaluation sample (n=70) to focus on three prominent facility types within the participant population: lodging, multifamily, and office. Among the core sample, HPs in multifamily buildings demonstrated highest savings (288% site MMBtu RR) while those in lodging facilities demonstrated the least (28% site MMBtu RR). Due to relatively low sample sizes among facility-specific segments, we recommend additional research before developing facility-level deemed savings estimates in future iterations of the TRM.
- **HPs in the complementary sample generally showed higher heating output than those in the core evaluation sample.** The DNV team and Efficiency Maine agreed to add 33 HPs to the heating season M&V pool to assess HP heating operation among a broader group of facility types. The complementary sample (n=33) showed higher heating output on average, with HPs at manufacturing, garage, and restaurant sites producing the highest annualized outputs. We note that complementary HPs underwent additional screening during application pre-approval to confirm that those facilities are heated throughout the full heating season. Core sites did not undergo such additional screening.
- **M&V data showed several differences with performance assumptions embedded in Efficiency Maine TRM deemed savings values.** As stated above, evaluation results reflected an annual heating output value 60% less than the current TRM assumption. On the other hand, higher-rigor sites showed performance efficiencies 28% and 35% better than current TRM assumptions for heating and cooling, respectively. These parameter-level findings can be used to refine deemed savings assumptions in future TRM iterations, barring major changes in program design elements such as eligibility criteria, minimum efficiency requirements, or baseline treatment.
- **The evaluated savings led to overall benefit-cost ratios above the cost-effectiveness threshold of 1.** The DNV team determined that HP installations were cost-effective when considering AESC 2021 avoided costs. However, HP installations at Multifamily facilities incurred slightly more costs than benefits due to a higher prevalence of retrofit projects. For that segment, the DNV team determined that the tenants did not use the HPs enough during the heating season to displace sufficient fossil fuel heating to overcome the full installation costs of the HPs.

Premise-Level Analysis

- **Analysis of pre- and post-installation AMI data showed a plausible range of normalized annual heating energy use per rebated HP from +44 to +63 kWh per 1,000 Btu/h of rated capacity.** The DNV team approached the AMI analysis from different perspectives and found varying results depending on various factors including the availability of pre-installation AMI data and whether the electric heating energy increased or decreased after HP installation.
- **Exclusion of sites with cooling energy increases led to stronger correlation between AMI models and M&V results.** The DNV team hypothesizes that sites with cooling energy increases apparent in AMI data were more likely to have experienced non-routine events (e.g., change in occupancy or load) that prevents the treatment of pre-installation AMI data as baseline.
- **Premise-level analysis of AMI data revealed several uncertainties.** Some sites showed a likelihood of changes in heating load for which the preexisting AMI data no longer represents the baseline. Additional uncertainties included the

[16] For example, in New York, Clean Heat Programs have evolved to distinguish between full-displacement and partial-displacement HP installations, with varying incentives and savings assumptions for each. The NY Clean Heat program is currently being evaluated with a report expected late 2023.

presence of other electric heating equipment in pre- or post-project scenarios, other AMI meters at the customer facility, or customer survey data that contradicted the AMI data. The DNV team recommends four techniques to ensure that premise-level HP analysis approaches are viable in future evaluations:

- Classify sites into different heating usage categories – Categorizing sites into different heating displacement scenarios (full displacement, partial displacement, low/no use) will minimize uncertainty.
- Exclude sites with cooling energy increase – As mentioned above, such sites were more likely to have undergone non-routine changes that disqualifies the pre-installation data as representative of baseline.
- Use pre-install AMI data if available – Post-only AMI analysis overestimated HP impacts in this study, likely due to the presence of other electric heating sources not attributable to the program.
- Cross-check survey data and AMI meter selection – The DNV team found that customer-reported usage characterizations did not always align with AMI analysis results. Additionally, we determined higher uncertainty with facility types likely to have more than one utility meter (e.g., multifamily).

- **Premise-level review of AMI data may be useful for future program implementation and evaluation.** AMI data provides program administrators and evaluators the ability to categorize sites into different heating displacement scenarios (e.g., full displacement, partial displacement, low/no use). Variation in usage and impacts among these scenarios may empower program administrators to make changes to deemed savings estimates, measure design, eligibility criteria, and incentive tiers. AMI data will also allow program administrators and evaluators to continually assess the effects of such program changes on encouraging customers to minimize the consumption of fossil fuels.

Net Impact Results

- **The DNV team determined a 35% free-ridership rate for the HP measures rebated over the evaluation timeframe.** This value is derived from survey responses of customers that indicated they would have done the exact same project regardless of the program (68 of 194 respondents) and customers that would have partially scaled back or postponed the project if not for the program's influence (64 respondents). Customers indicated that their prior experience with the program, the program incentive, and their experience with the qualified partner were most influential to their decision-making.
- **The DNV team estimates a spillover rate of 8%, resulting in a net-to-gross ratio of 73%.** Spillover is mostly attributable to participant spillover (6% of program-reported site MMBtu savings) with the remainder to non-participant spillover (2%). The most common participant spillover measure categories were lighting, HVAC, and water heating.

2 BACKGROUND AND OBJECTIVES

Efficiency Maine administers the Commercial and Industrial (C&I) Prescriptive Program (“the program”) that connects qualified contractors with Maine’s commercial customers to install high-efficiency equipment. Program offerings include ductless heat pumps (HPs) that satisfy heating and cooling loads at significantly higher efficiency than legacy fossil fuel-fired systems.

Efficiency Maine contracted the DNV team to evaluate the energy and demand impacts of the HP systems rebated by the program between 2017 and 2019. The DNV team designed the impact evaluation to achieve the objectives listed below among the study’s four research areas: surveys, gross impact evaluation, net impact evaluation, and benefit/cost analysis.

2.1 Survey objectives

- Assess the following topics through survey of participating customers:
  - Reported HP use strategy by season
  - Perceived energy savings and energy use
  - Changes in setpoints and other heating/cooling equipment use
  - Perceived change in comfort, if any
  - Reasons to purchase and install HP and program influence on purchase decision, installation, and operation
  - Satisfaction with the equipment, contractor, and the program
  - Self-reported information on what was replaced/supplemented by the HP and characteristics of prior equipment, including how the equipment was operated/used
  - Self-reported information on whether the HP introduces new heating and/or cooling capacity.
- Assess the following topics through survey of qualified partners[17] (QPs):
  - Program influence on installation and sales, and distributor’s stocking practices
  - Average installation cost of program-qualifying equipment
  - Average installation cost of alternative equipment
  - Percent of sales volume of program-qualifying equipment
  - Barriers to program-qualifying HP sales
  - Sales influenced by the program
  - System operation knowledge conveyed to customers

2.2 Gross impact evaluation objectives

- Quantify annual energy consumption during heating and cooling seasons via measurement and verification (M&V) of a sample of systems and advanced metering infrastructure (AMI) data analysis findings.
- Quantify peak summer and winter demand impacts via M&V of a sample of systems and AMI analysis findings.
- Establish annual load profile, peak coincidence, and energy period factors via M&V of a sample of systems and AMI analysis findings.
- Quantify annual heat output produced by rebated HPs via M&V of a sample of systems, AMI analysis findings, the existing part-load library, and intensive metering of selected sites to determine part-load curves for associated HP kWh, a coefficient of performance (COP), and annual heat delivered.
- Establish appropriate baseline using information collected through the customer survey and on-site visits.

[17] Qualified partners are vendors registered to participate in Efficiency Maine commercial programs.

- Quantify annual heat produced by other heating equipment during post-installation phase, as approximated through billing analysis where available, to illustrate the portion of heat delivered by rebated HPs.
- Quantify annual energy impacts (change in consumption compared to baseline) via M&V of a sample of systems and a baseline questionnaire to determine the appropriate baseline. The team will also identify whether a usage is new to the building or if it replaced some existing heating or cooling capacity.
- Develop equipment usage profile by season and time of day based on aggregate activity of the observed HP systems.
- Estimate HP coefficient of performance (COP) as a function of outdoor air temperature based on intensive site measurements, manufacturer's data, and an existing HP data library.
- Estimate HP average heat rate (Btu/h delivered) as a function of outdoor air temperature based on intensive site measurements, manufacturers' data, and an existing HP data library.
- Assess heating and cooling equipment control strategies for HPs and existing systems, including on/off, temperature-based control, integration with existing systems, thermostat type and location, and fan and vanes settings.

2.3 Net impact evaluation objectives

- Estimate free-ridership through customer and vendor surveys.
- Estimate spillover through customer and vendor surveys.
- Quantify program-level net-to-gross ratio based on free-ridership and spillover estimates.

2.4 Benefit/cost 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 the following, using Efficiency Maine's CBAT:
  - Verified measure costs based on costs of installed efficiency measures and appropriate baseline costs
  - Lifetime benefits of verified savings (gross and net)
  - Lifetime costs of fuel use increases (gross and net)
  - Measure-level benefit/cost ratios using prescribed and alternate methods
- Compile program delivery and marketing costs using Efficiency Maine's program records.
- Determine program level benefit/cost ratio using prescribed methods and sensitivity analysis.
- Identify key drivers of differences between program-estimated benefit/cost ratio and those calculated from verified savings and costs and sensitivity analyses. The team bases these on the findings from the objectives above.

3 METHODOLOGY

This section describes the methods the DNV team used to fulfill the study objectives.

3.1 Data sources

The DNV team requested and collected several datasets to support impact evaluation activities. Table 3-1 describes each data source and its provider.

Table 3-1. Summary of Evaluation Data Sources

Data Source	Data Provider	Description
Program tracking data	Efficiency Maine	Program tracking data formed the basis of the evaluation dataset of record from which statistical samples were drawn.
Customer contact data	Efficiency Maine	Program tracking data included customer names, addresses, phone numbers, and email addresses for survey engagement, AMI account matching, and site visit scheduling.
Vendor contact data	Efficiency Maine	The DNV team requested additional vendor contact information to support surveys with participating qualified partners (QPs).
Electric AMI data	Central Maine Power and Versant electric utilities	The DNV team requested pre- and post-project 15-minute AMI data from the electric utilities supplying participating customers.
Delivered fuels data	Fuel suppliers	Some participating customers used propane, fuel oil, or wood as heating sources before or after the project. After receiving customer authorization via survey, the DNV team collected pre- and post-project fuel delivery data to assess the impact of the HP installation.
Weather data	National Oceanic and Atmospheric Administration (NOAA)	The DNV team collected historical weather across Maine's 20 NOAA weather stations to develop weather-normalized regressions in the impact analysis.

3.2 Surveys

The DNV team designed and executed two surveys to fulfill the study objectives, as described in the next subsections.

3.2.1 Customer surveys

In the fall of 2020, we surveyed participating business owners to collect the following information:

- Basic facility information (e.g., facility type)
- Installation information (e.g., existing space or new construction/expansion)
- Operating patterns for the facility overall and for the installed HP systems
- Program influence on decision-making
- Satisfaction with the program, contractor, and the installed equipment
- Preferred alternatives for heating and cooling, in the absence of the program
- Interest in participating in M&V phase of study

The DNV team administered customer surveys using the web-based platform Qualtrics. 232 participating customers, representing 27% of the participant population, ultimately completed the 20-minute survey, as indicated in the Table 3-2 disposition. Based on our team's survey experience with similar non-residential programs, the 27% success rate represents a better-than-typical response and does not cause concern for non-response bias.

Table 3-2. Customer Survey Disposition

Description	Count	Percentage of Population
Unique addresses receiving a HP	887	N/A*
Unique customers receiving a HP	844	100%
Unique customer survey responses	255	30%
Unique customers completing full survey	232	27%

* The evaluation sample considered customer address as the primary identifying variable to distinguish among different sites. Nonetheless, percentages in this table are based on the maximum number of unique customers (844) that could have responded to the survey.

3.2.2 Vendor surveys

In the winter of 2020-21, the DNV team surveyed active qualified partners (QPs) that were associated with heat pump enrollments over the evaluation timeframe. The survey was designed to achieve the objectives identified in Section 2.1 and collected the following information:

- Basic information on HP sales practices and activity with program-affiliated and non-program installations
- Information on costs of standard vs. high-efficiency equipment and the effect of program rebates
- Perception of their influence on customer decision-making
- Program influence on their sales/installations of non-rebated HPs
- Barriers to selling qualifying heat pumps

The DNV team completed telephone surveys with 30 QPs out of a possible 164.[18] To ensure that QPs were properly represented, we designed a sampling approach based on the QPs' number of enrollments and geographic location. Four strata were considered in the QP survey sample design:

- High activity: more than 16 enrollments
- Low-moderate activity: 2-15 enrollments
- Low-moderate activity of interest: 2-15 enrollments, located in northern regions
- Very low activity: 1 enrollment

The DNV team surveyed all high-activity QPs, who accounted for half of the enrollments in the evaluation population. Table 3-3 indicates the population, share of enrollments, target sample, and achieved sample for QP surveys.

[18] Efficiency Maine has approximately 421 active QPs, but the majority were not associated with a C&I heat pump installation between 2017 and 2019.

Table 3-3. Qualified Partner Survey Sample Design

Stratum	Selection Basis	Population	Percent of Enrollments	Target Sample	Achieved Sample
High activity	Census	13	50%	13	9
Low-moderate activity, of interest	Census	4	8%	4	2
Low-moderate activity	Random	82	35%	13	19
Very low activity	Exclude	65	7%	0	0
Total		**164**	**100%**	**30**	**30**

3.3 M&V sample design

Respondents to the customer survey formed the basis of the on-site M&V sample. Table 3-4 illustrates the key characteristics of the evaluation's M&V sample design.

Table 3-4. On-site M&V Sample Design Characteristics

Characteristic	Description
Population	2,297 heat pumps rebated between 2017 and 2019
Primary stratification variable	Building type (Multifamily, Office, Lodging, and Other Commercial)
Target relative precision at confidence interval	±10% on portfolio results at 80% confidence interval ±20% on facility type results at 80% confidence interval
Assumed coefficients of variation	0.7 for multifamily; 0.6 for non-residential
Sampling method, to control bias	Stratified random sampling
Sampling unit for design	Per-system heat pump unit energy impact*

* Program tracking data aggregated savings across all systems installed at a given facility address. The DNV team divided the total reported savings by the system quantity to determine per-system impact in site MMBtu. All MMBtu savings in this report reflect *site* MMBtu— i.e., no electric production, transmission, or distribution efficiencies are incorporated. Electric energy savings (in kWh) were converted to site MMBtu after multiplication by 0.003412 MMBtu per kWh.

To ensure sufficient representation among segments of interest, the DNV team designed a sample of 79 systems from a pool of 232 customer survey respondents, as indicated in Table 3-5. The evaluator's review of the 2017-19 HP measures showed that only Lost Opportunity installations were rebated over that timeframe; therefore, the sample did not stratify between event type (Retrofit versus Lost Opportunity). The DNV team designed the sample with facility type as the primary stratification variable, anticipating differences in HP operation among four facility categories: multifamily, office, lodging, and other. Ultimately, the DNV team collected sufficient data for 70 systems across 44 unique facilities, which constituted the final sample design.[19]

Table 3-5. M&V Sample Design Targets vs. Achieved

Technology	Subcategory	Population of Systems	% of Systems in Population	Target Sample	Target Relative Precision at 80% Confidence	Achieved Sample
Multifamily	Multifamily	768	33%	25	17.7%	23
	Office	307	13%	18		16
Commercial	Lodging	245	11%	17	12.1%	14
	Other	977	43%	19		17
Total		**2,297**	**100%**	**79**	**10.0%**	**70**

[19] After cleaning and reviewing the metered data for all sampled systems, the DNV team ultimately excluded nine systems from the sample due to anomalous or misrepresentative data.

The DNV team initially recruited a total of 8 unique facilities comprising 25 HPs, but these sites ultimately were dropped and replaced due to circumstances at the site. The DNV team believes this to be at least partially attributable to hesitance around the COVID-19 pandemic, as well as a perceived disruption to business activities or building tenants. Nonetheless, the recruitment rates associated with the achieved sample are typical for a non-residential evaluation, and we believe the achieved sample is representative of the population of heat pumps in the program.

3.4 Measurement and verification

The DNV team conducted M&V to fulfill the gross impact evaluation objectives defined in Section 2.2. This section details the methods used to collect and analyze the M&V data that ultimately define this study's gross impact results.

3.4.1 Site visits

Field evaluation staff visited all facilities associated with the systems sampled for M&V. During each site visit, the field engineer interviewed facility staff at the beginning of each site visit. The customer then led the field engineer in a walkthrough of the commercial facility. Field engineers inspected all components of the installed heat pump(s), associated thermostats and controls, and any auxiliary heating/cooling equipment still in use. If present, any pre-existing and/or ancillary HVAC systems were inspected and documented. Field engineers identified and documented the areas and characteristics served by the heat pumps and other HVAC systems, photographing all relevant HVAC equipment, thermostats, nameplates, and other relevant equipment or building characteristics.

At all but two facilities,[20] the team deployed communicating meters from which data could be retrieved remotely. Table 3-6 shows the points monitored on all systems sampled for M&V. Appendix E includes the specification sheets for the various equipment deployed in this study.

Table 3-6. Monitored Points for All Sampled M&V Systems

Equipment	Meter Location	Power	Amps	Temp.
Outdoor unit	At disconnect, including both outdoor and indoor equipment (1 phase)	X		
Outdoor unit	Refrigerant supply (to differentiate heating and cooling)			X
Indoor unit(s)	At outdoor unit, after supply wiring splits		X	
Auxiliary heat (where applicable)	At unit's combustion fan, or in panel if not accessible		X	

The data above was used in conjunction with an existing heat pump performance library, which includes intensive M&V of heat pumps systems over several recent impact evaluations throughout the northeast. Eight of the sampled heat pumps in this study were measured to this intensive standard to add additional entries to this performance library. Table 3-7 shows the additional points monitored at the intensive systems.

Table 3-7. Monitored Points for Eight Intensive M&V Systems

Equipment	Meter Location	Power	Temp/RH	Flow
Indoor unit(s)	Spot flow hood test of indoor unit at different speeds	X	X	X
Indoor unit(s)	Supply air temperature and return air temperature and humidity		X	
Outdoor unit	Spot measurement during test	X	X	

20 System constraints at two facilities required the DNV team to use non-communicating meters.

In addition to these intensive sites, a further 23 systems received the indoor air temperature and humidity monitoring to increase the number of observations used to develop the delivered Btu assumptions for those sites without full intensive measurements.

The DNV team measured equipment in the condition it was discovered on-site—e.g., filters were not cleaned, snow not cleared. Field staff did not identify any instances of safety hazards presented by the on-site conditions that required intervention. After monitoring sampled systems for the winter, summer, and at least one shoulder season, field engineers retrieved the deployed meters in the fall of 2021. Through web surveys and field questionnaires, the DNV team confirmed that the sampled customers' operation had generally resumed to normal following the quarantine periods of spring 2020.

3.4.2 Complementary M&V during heating season

The evaluation sample design focused on the three most prominent building types in the participant population—lodging, multifamily, and office—and bucketed the remaining building types into a category called "other." When the limited variety of building types in the sample prompted Efficiency Maine to inquire about HP usage across a wider range of building types, DNV worked with Efficiency Maine to create a complementary M&V plan to meet the following objectives:

- Understand more granularly which building types lead to greater HP usage and subsequent savings potential for targeted marketing,
- Identify other key characteristics that influence HP output.

To meet these objectives, DNV conducted complementary M&V of 33 single-zone HPs at 17 "other" facility types. The DNV team collected metered data over a 10-month window (December 2020 to October 2021) to capture heating, shoulder, and cooling season operation. DNV leveraged the analytic framework of the C&I evaluation to develop results and combine them with operating profiles from the C&I evaluation to produce a more robust dataset of heating output profiles by facility type. The complementary HPs were not included in the gross impact evaluation results defined by the core evaluation sample in Table 3-5.

This complementary task started midway through the core C&I evaluation's data collection activities. Field work for the complementary task was conducted separately. The metering setup consisted of deploying a 75-amp CT on a single leg of the power supply to each condenser unit to capture whole-unit amperage. The data was used to produce a unit-level operating profile. DNV deployed wireless metering equipment to allow real-time data processing and continuous results development while meters were still in the field.

Participants were recruited for this task by tapping into the prescriptive heat pump measure project stream. As qualified partners applied for prescriptive heat pump incentives, DNV screened applications by facility type and number of heat pump zones (1) and then reached out to potential candidates and QPs to solicit interest in participation. Recruitment targeted specific building types based on criteria established from discussions with Efficiency Maine staff (avoiding office, lodging, and multifamily with an emphasis on restaurants and retail businesses, among others). For projects with customers who agreed to participate, QPs deployed the metering equipment at the time of heat pump installation and confirmed the connection status with a DNV staff member offsite.

The recruitment progress's use of the prescriptive stream limited DNV to the flow of incoming project applications. To reach the meter deployment targets before the end of the heating season, DNV began recruiting customers from the core evaluation population that were not selected in the sample, using the same screening criteria described above. Field staff deployed meters at such post-install sites using similar protocols as described earlier in this section. Overall, the complementary M&V sample was comprised of 11 installations from the Heat Pump Retrofits for Small Businesses program, with the remaining 22 from the C&I Prescriptive Program.

DNV developed usage profiles for 33 single-zone heat pumps located at 17 different facilities to complement the 70 profiles developed for the core C&I evaluation. Breakdowns of the metered unit counts by facility type and unit size can be found in Table 3-8 and Table 3-9, respectively.

Table 3-8. Heat Pump Profile Count by Facility Type

Facility type	PY2017-19 Population[1]	Core C&I Evaluation	Complementary Metering	Total
Multifamily	768	23		23
Office	307	18	2	20
Lodging	245	14		14
Retail	107	5	7	12
Health/Wellness[2]	62		12	12
Manufacturing	50		5	5
Municipal/Government	35	4	1	5
Restaurant	75		5	5
Garage/Repair	34	2	1	3
Other	330	4		4
Grand Total	**2,013**	**70**	**33**	**103**

[1] The population included several other less prominent facility types not sampled for evaluation: warehouse, grocery, education, assembly, fitness centers among others. As a result, the population count in this table differs from the total population of 2,297 installations.

[2] The health/wellness category comprised a variety of business types, including dental, ophthalmology, veterinary, behavioral health, physical therapy, outpatient, and chiropractor facilities.

Health/wellness, retail, restaurants, and manufacturing facility types were among the largest additions to the profile population. The DNV team made a purposeful effort to add more restaurant profiles to the study, but recruitment proved difficult as industry-wide staffing issues resulted in fewer facilities operating during the meter deployment window.

Table 3-9. Installed Unit Heating Capacity by Facility Type

Facility Type	<18 kBtu/hr	18-24 kBtu/hr	24-36 kBtu/hr	>36 kBtu/hr
Multifamily	1	13	7	2
Office	6	9	1	4
Lodging	9	2		3
Retail	2	10		
Health/Wellness	3	9		
Manufacturing	1	3		1
Municipal/Government	4			1
Restaurant		5		
Garage/Repair		1	1	1
Other	1	3		
Grand Total	**27**	**55**	**9**	**12**

All units metered through the complementary effort were single-zone units, while the core sample included some facilities with multi-zone systems.

3.5 Analysis

This section describes the analysis techniques used by the DNV team to quantify the results presented in Section 4.

3.5.1 M&V data analysis

The DNV team used a time-of-week and temperature (ToWT) model to analyze the remotely collected M&V data. The ToWT model serves as an industry-standard protocol for non-residential interval data analysis and was originally developed at Lawrence Berkeley National Laboratories[21] and further refined by CalTRACK working groups.[22] The method considers two independent variables to develop normalized energy usage behavior: a binary occupied/unoccupied flag based on observed energy use patterns and outdoor air temperature. The DNV team believes this to be the most reliable regression analysis methodology to develop normalized usage for assessing energy and demand impacts at non-residential facilities.

The DNV team slightly modified the CalTRACK regression method for use with heat pump M&V data. The next subsections demonstrate the analysis steps taken with each evaluated system.

Collect and Clean Meter Data

The DNV team collected heat pump real power consumption via communicating devices for all systems (except two, which employed non-communicating devices), cleaned the data, and aligned with local weather data and time. The team examined the data for out-of-range values such as a power that exceeds the heat pump specifications.

Regress using ToWT Methods

The DNV team developed two separate regression methods to ensure the best regression approach based on the metered data available. The first and more prominent method represents a three-month rolling average period per ToWT method, with the previous and next calendar month's data weighted 50% and the current calendar month's data weighted 100%. This approach most reliably characterizes systems for which operation or control may change, such as seasonal set-points or manual control. Given the likelihood that customers may control the HPs manually, the team applied this first regression method whenever possible.

The first approach presented issues when the three-month period included data gaps.[23] The DNV team therefore employed a second regression method that uses no monthly weighting scheme but instead uses all available input data for any period. The second regression method can more reliably extrapolate over periods not observed but is less preferable than the first method for the reasons described in the prior paragraph.

Examine Regressions and Choose Best Fit for Normalized Analysis

Analysts graphed both pairs of data regressions over the normalized period as well as over the observed period for visual confirmation of good fit. Figure 3-1, below, demonstrates an example of a visual confirmation plot. The left-hand figure compares the regressions over a period of five months, whereas the right-hand figure compares the regressions over three days. Analysts performed further checks by comparing power to air temperature ratios for observed and regressed data.

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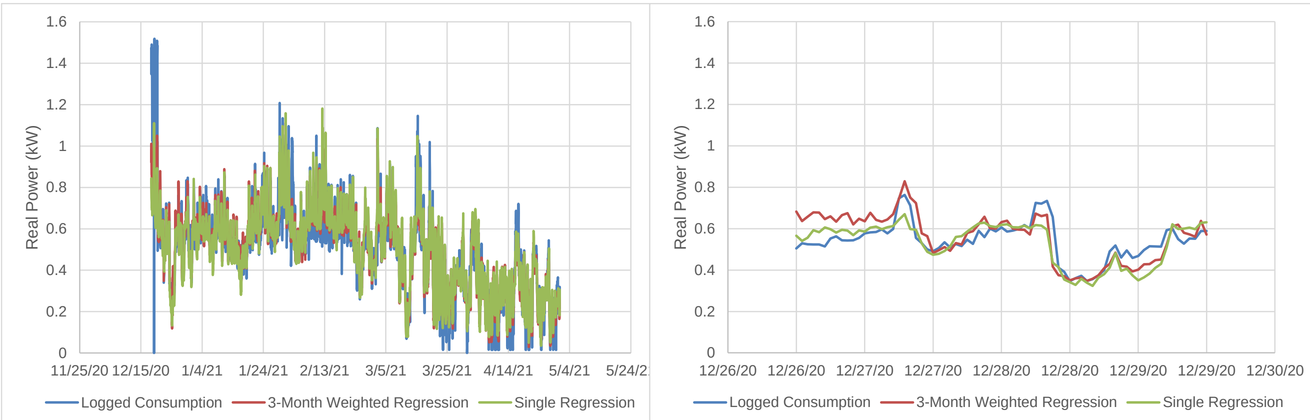
21 Lawrence Berkeley National Laboratories, "Quantifying Changes in Building Electricity Use, with Application to Demand Response," April 2011. https://eta-publications.lbl.gov/sites/default/files/LBNL-4944E.pdf

22 http://docs.caltrack.org/en/latest/methods.html

23 Overall, the DNV team encountered infrequent gaps in data transmission. The data gap issue primarily emerged as a result of the 10-month metering period used in this study—we deployed the meters in December 2020 and retrieved them in October 2021. Therefore, using the three-month model to predict operation in November was not always feasible.

Figure 3-1. Comparison of Regression Methods with Metered Data



The DNV team analyzed the data gaps and for each month of the typical year analysis either the 3-month or single regression was selected to represent the heat pump's behavior – 3-month wherever reasonably possible, and single-regression to fill in gaps where there was insufficient meter data, such as when a meter was deployed partway through the heating season.

Establish Performance versus Outside Air Temperature

A separate, study-wide activity examined the intensive meter data from this evaluation and previous similar evaluations in the Northeast to generate coefficient of performance (COP) curves for HPs during heating and cooling modes. The DNV team developed an aggregate performance curve that incorporated the measured performance of 28 program-rebated HPs among a variety of sizes and manufacturers across Maine and New York to quantify how system efficiency is affected by outdoor air temperature.[24] The aggregate performance curve was then scaled to characterize each sampled HP's performance (and associated baseline HPs, where applicable) using the ratio of the HP's Air-Conditioning Heating and Refrigeration Institute's (AHRI's) rated heating season performance factor (HSPF) to average HSPF of the aggregate curve at the AHRI-specified outside air temperature standards. The DNV team performed a similar but separate analysis for HP cooling performance as well.

Quantify Normalized Heating and Cooling Outputs

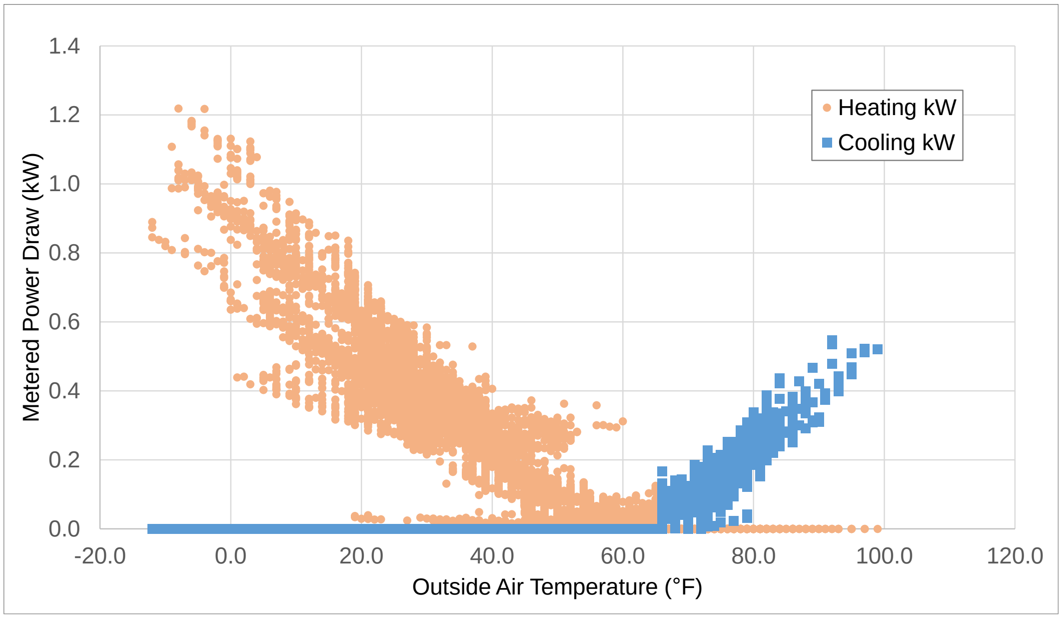
To distinguish between heating and cooling modes, analysts combined site-specific information (e.g., per the data collection form's question "At what outdoor temperature do you typically begin heating the facility?") with the observed shape of hourly kW versus OAT. Analysts considered several factors— the minimum observed hourly kW over a year, the customer's stated typical outside air temperatures for heating and/or cooling activation, and typical switch-points for similar facilities—to select each sampled facility's typical switch-point between heating and cooling modes.[25] Figure 3-2 illustrates an example of metered power draw versus outside air temperature over the full metering period. In this case, the customer stated that the facility typically activates their cooling system at 65°F; the metered data corroborates the customer's estimation and shows the metered power draw increase from 65°F upward.[26]

[24] All 28 metered systems displayed the same curve shape, though there was unexpected variance among some systems. Some variations were likely due to site-specific use patterns, like the interactions with other heating systems in the building, programmed sequence of operations, or manual overrides or abnormal periods of unoccupied time. Due to the variations, the DNV team used one aggregated performance curve, rather than associating each of the M&V heat pumps to one specific reference performance curve. This reduces unexplained variance in the analysis and decreases the impact of propagating site-specific phenomena to other HPs.

[25] The DNV team originally intended to determine switch-point using metered refrigerant line temperature. However, analysis of these metered data showed significant noise and spikes in temperature due to intermittent defrost cycles, limiting the viability of this method.

[26] The Figure 3-2 example corresponds to one of two incented HPs serving 1,200 square feet of conditioned space at a municipal building. The example HP is rated 12,000 Btu/h for heating and 9,000 Btu/h for cooling with a maximum rated power of 2.6 kW.

Figure 3-2. Distinguishing Heating and Cooling Modes among Metered kW Values Versus OAT



Analysts next multiplied the hourly heat pump consumption by the corresponding COP at a given outdoor temperature, as defined by the performance curves described above. The product of heat pump kWh input with COP provides the heating or cooling output of the heat pump—i.e., the conditioning load displaced from the baseline system.

Establish Baseline

The DNV team assessed each metered HP individually to determine the most appropriate baseline. As shown by an example in Table 3-10, baseline decisions incorporated event type (existing space vs. new construction or renovation), information from customer surveys and on-site interviews, and the operability and feasibility of pre-existing HVAC system(s). Each site visit included an in-depth discussion with the customer. In cases when the pre-existing equipment did not constitute the baseline, DNV field engineers investigated the customer's hypothetical decisions on heating and cooling systems if they had not participated in the program. Sections 3.5.3 and 4.4 explain how the DNV team treated such counterfactual gross baselines within net-to-gross analysis to ensure no double-counting of potential free-ridership.

Table 3-10. Baseline System and Efficiency Sources by Event Type

Heat Pump Installed Because…	Heating Baseline System and Efficiency	Cooling Baseline Efficiency
Replacing operable unit	On-site identified system type, fuel, and efficiency	On-site identified system type and efficiency
Replacing end of life unit Addition (newly conditioned space) New construction	Preferred alternative system identified by site contact	Preferred alternative system identified by site contact

Figure 3-3 and Figure 3-4 illustrate the decision-making criteria for establishing system-level heating and cooling baselines, respectively. For selection of code-compliant systems in replace-on-burnout or new construction scenarios, the DNV team relied on federal minimum efficiency requirements in effect at the time of project application. For code-compliant HPs, federal standards corresponded to 8.2 HSPF and 14.0 SEER.

Figure 3-3. Heating Baseline Criteria

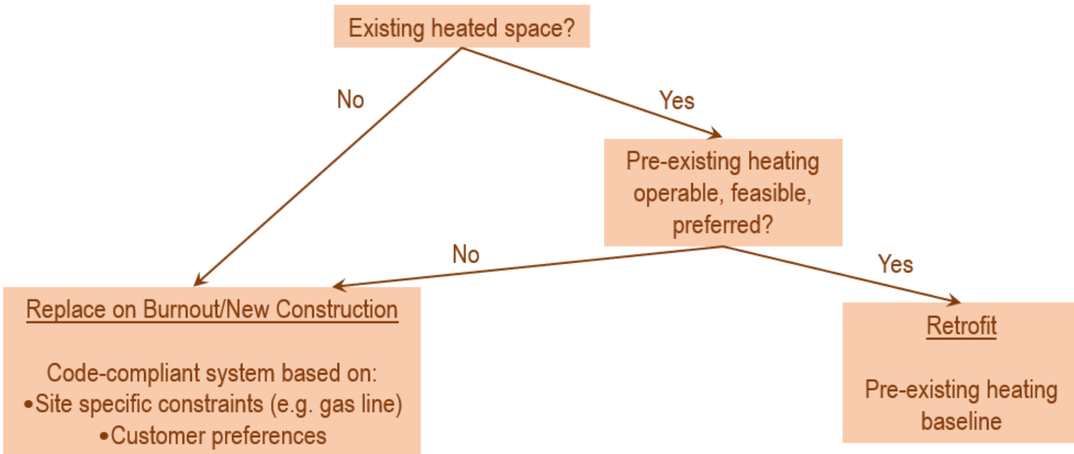
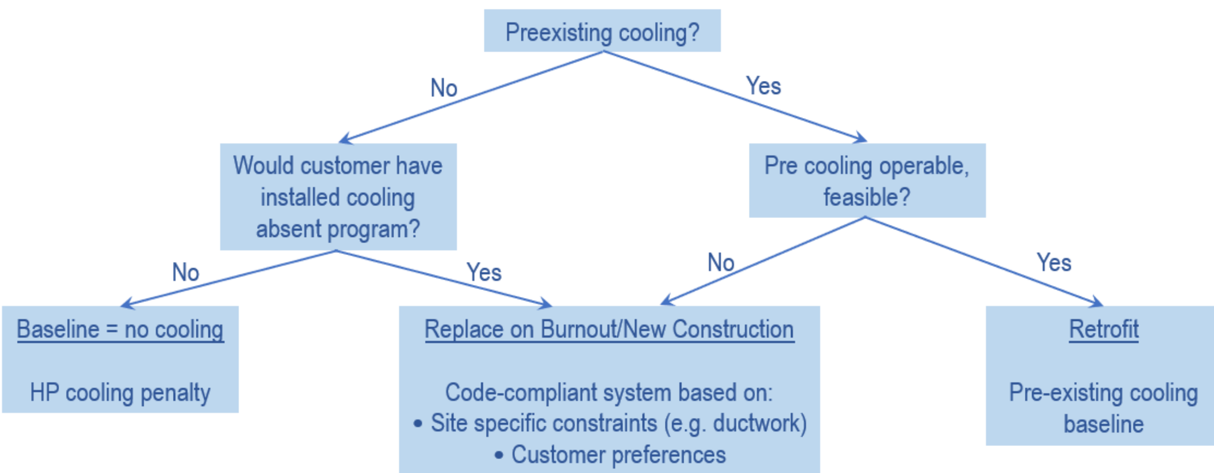


Figure 3-4. Cooling Baseline Criteria



Quantify Impacts

The DNV team quantified annual energy impact for each metered heat pump system by comparing the heating and cooling loads and performance efficiencies between baseline and as-built conditions. In general, to establish baseline energy consumption, the DNV team presumed that the heating and cooling loads satisfied by rebated heat pumps are equal to the heating and cooling loads that would have been met by the baseline systems. To ensure fair comparison, the DNV team normalized the metered performance data to typical weather conditions at the nearest NOAA weather station. Final, site-specific impact results include savings or penalties and associated RRs by fuel source: electricity, natural gas, and delivered fuels, as applicable.

3.5.2 Premise-level consumption analysis

In parallel with M&V activities, the DNV team conducted premise-level analysis of AMI data to quantify at-the-meter impacts of HP installations and assess the feasibility of AMI analysis in future program evaluations. Utility AMI data is increasingly used in impact evaluations to estimate weather-dependent heating and cooling energy consumption of equipment affected by program intervention. Compared to equipment-level metering among a sample of projects, billing analysis of a census of heat pump participant facility energy use is less costly and eliminates self-selection bias possible in voluntary M&V sub-metering studies. A primary concern with billing analysis, however, is the accuracy of the heating and cooling annual energy consumption predictions. Some factors that may impact accuracy of heat pump energy consumption estimates include:

- Unknown amount of connected heating and cooling loads
- Unpredictable (e.g., sporadic) user-driven usage patterns
- Control strategy (e.g., control of heat pumps with other heat sources)
- Low proportion of heat pump power to whole facility load

Unique to this evaluation was the availability of system-level M&V data for the limited sample of systems as described in Section 3.4. Comparison of premise-level AMI data with system-level M&V data allowed the DNV team to refine the AMI disaggregation techniques to more accurately estimate hourly HP electric energy consumption within the whole-facility hourly kWh consumption data. The DNV team used a variety of data sources and techniques to attempt to improve the accuracy of AMI-based HP energy use predictions as described in the next sections.

3.5.2.1 Data sources

The DNV team requested or collected and compiled the following data in Table 3-11 to conduct the AMI analysis.

Table 3-11. AMI Analysis Data Sources

Data Source	Unit Count	Description
Program tracking data	926 unique enrollment IDs	Program participation database including participant contact information and address, heat pump specification data, installation location and date
Participant survey responses	217 survey responses	Variety of participant responses about baseline and existing heating and cooling systems, heat pump operational strategy, facility size
Fuel consumption data	30 fuel delivery accounts	Historic delivered fuel usage data (#2 heating oil, kerosene, propane) from fuel dealers for a sub-set of survey respondents
AMI data	414 electric accounts	Data contained hourly records of energy consumption in businesses within CMP and Versant service territory
Local climatological data (LCD)	20 weather stations	The LCD dataset was accessed from NOAA and contained hourly measurements of temperature, relative humidity, windspeed and other meteorological quantities recorded concurrently with the AMI data. These data were measured at 20 weather stations.[27]
Typical meteorological year (TMY3) data	20 weather stations	TMY3 data was downloaded from the National Renewable Energy Laboratory and represented industry-standard typical weather conditions across the LCD dataset.[28]

[27] Downloaded from: ftp://ftp.NCEI.noaa.gov/pub/data/noaa/

[28] Downloaded from: https://data.nrel.gov/system/files/156/BuildStock_TMY3_FIPS.zip

Data Source	Unit Count	Description
Equipment-level M&V data, additional on-site data	70 systems among 44 unique sites	Sub-metered heat pump system power of 70 heat pumps at 44 unique sites beginning late 2020 through October 2021. Field technicians also recorded on-site observations to verify program tracking data and to validate survey responses.

3.5.2.2 Data acquisition and cleaning

The DNV team conducted several data processing steps to review, validate, and transform the fuel delivery, AMI data, and tracking data into an analysis dataset:

- Imported and cleaned the tracking, AMI, and weather station datasets into Statistical Analysis System (SAS) software.
- Merged tracking and electric AMI datasets using meter ID.
- Mapped each property to the nearest weather station using the property zip code.
- Manually estimated fuel consumption period based on delivery dates.
- For the electric AMI analysis, obtained hourly temperatures to determine variable base[29] heating degree hours (HDHs) and cooling degree hours (CDHs) for each weather dataset associated with each site.
- For the fuel analysis, obtained daily average temperatures to determine variable base heating degree days (HDDs) for each weather dataset associated with each site.
- Merged the HDD/HDHs and CDD/CDHs onto the AMI data, for each hour and adjusted for daylight saving time so all data match local time.
- Obtained hourly variable base TMY3 HDHs and CDHs to weather-normalize the AMI data.

Data anomalies, outliers, missing data points, incomplete records, and other data issues all introduce potential bias into a billing analysis. The DNV team used several rules to flag, review, and possibly remove accounts that failed to meet certain conditions:

- **Ensure sufficient pre- and post-installation AMI data for analysis**. All accounts had to contain a minimum of nine months of pre- and post-installation usage data.
- **Flag failed hourly PRISM models**. The DNV team performed disaggregation models in the pre and post period for various reference base temperatures. If there was no seasonality in the usage in the pre-or post-period periods, the models yielded negative coefficients, and these were flagged for further review.
- **Remove outliers and vacancies**. The DNV team performed account-level reviews of pre- and post-installation period use for all individual participants and removed anomalies (such as periods of vacancies) that could bias the savings results.
- **Select appropriate AMI meter from accounts with multiple meters**. For sites having multiple AMI meters, the DNV team selected the most probable meter, based on heating and cooling-related energy consumption estimates and total connected heating and cooling capacity reported in the tracking database.

The DNV team received some amount of AMI data for half (457 of 926) of the unique facilities comprising the evaluation population. Table 3-12 summarizes the sites with AMI data that passed the initial screening. The sites removed (n=43) were typically screened out due to insufficient data in the post period, too many AMI meters (e.g., 5 or more unique AMI datasets), or due to significant change in baseload energy consumption in the post-installation period (typically an indication of vacancy that does not reflect normal business operation). Sites were only removed if the team identified issues with the post-

[29] Heating base temperature is the temperature at which the building requires heating. Base temperatures were established for each AMI and fuel dataset, by selecting the temperature that produces the best-fit (highest R-squared) regression. Additional information on the PRISM billing data method is provided in Appendix C.

installation AMI data. The DNV team received AMI data for 28 of the 44 metered sites[30] (64%), and each of these accounts passed the aforementioned screening tests.

Table 3-12. Site Counts of AMI Meter Frequency, Pre- and Post-Heat Pump Installation

AMI Data Collected before Heat Pump Installation	Count of Sites	Sites with 1 Post-Install AMI Meter	Sites with 2+ Post-Install AMI Meters
1 pre-install meter	270	246	24
2 pre-install meters	19	0	19
3 pre-install meters	11	0	11
4 pre-install meters	5	0	5
5 pre-install meters	3	0	3
Post-only	105	90	15
Total Number of Sites	413	336	78

When asked about the heating fuel used before the heat pump installation, 125 of the 217 surveyed participants indicated they used some type of delivered fossil fuel. About half (n=60) provided their fuel dealer contact information. Efficiency Maine supported the DNV team's effort to collect and analyze delivered fuel data by working directly with fuel dealers to obtain pre- and post-project delivery data. As indicated in Table 3-13, Efficiency Maine was able to collect 29 viable[31] pre- and post-installation delivered fuel datasets.

Table 3-13. Summary of Survey Respondents Fuel Type, Fuel Dealer Contact Provided, Data Received

Fuel type	Baseline Fuel Type from Survey	Provided Fuel Dealer Contact Info	Viable Data Received
Natural gas	15	0	0
Propane	27	15	4*
#2 fuel oil	70	40	25
Kerosene	6	5	0*
#4, #6, or unknown fuel oil	7	0	0
Total	**125**	**60**	**29**

* Three sites reporting #2 Fuel Oil also provided propane (n=2) or kerosene (n=1) consumption data that the DNV team reviewed.

3.5.2.3 Modeling approach

To estimate electric heating and cooling energy impacts of the program-rebated HPs, the DNV team designed and conducted a statistical billing analysis. The team relied on historical hourly electric AMI data to estimate participant-level consumption and program savings associated with the heat pump installations using the industry-standard PRInceton Score-keeping Method (PRISM). The team incorporated typical meteorological year (TMY3) data to normalize usage and control for weather. Because this is a relatively heterogeneous population, we did not include a nonparticipant comparison group. Therefore, this analysis examines the weather-normalized, pre/post change in electric energy use using post-period weather and does not account for other non-programmatic factors. Additional information on the PRISM method can be found in Appendix C.

The hourly model specification produces weather-normalized annual, monthly, daily, and hourly energy consumption estimates. Using actual weather data, the model also produces hourly estimates during the concurrent sub-metering period, from December 2020 through October 2021.

[30] AMI data were not necessarily unavailable for the remaining sites. The team, with support from Efficiency Maine staff and utilities, was unable to collect AMI data from all metered sites for various reasons. Reasons include failed address matching (i.e. site address or account owner name couldn't be associated with a utility account and subsequently with a specific AMI meter), a recent change in utility account ownership, AMI meters not enabled until after the pre-install period, or AMI metering not enabled.

[31] Delivered fuel viability generally meant data from at least one year before and after heat pump installation and having sufficient granularity for regression analysis. 4 sites provided only annual purchase data but the DNV team confirmed the oil tanks were filled to a consistent level at each delivery.

The team used the heating components of the PRISM model detailed in Appendix C to estimate the change in annual consumption of delivered fuels. The delivery date and fuel volume were known, so the team assumed the amount delivered represented the fuel consumed between the delivery and date of the prior delivery. The total daily HDDs observed between each fuel delivery was paired with the amount of fuel delivered to develop linear regressions of fuel usage before and after heat pump installation.

3.5.2.4 Cohort assessment

In other heat pump program evaluations, full- and partial-displacement heat pump installations exhibited notably different operating and savings characteristics. The DNV team's hypothesis was that segmenting sites into groups based on heating strategy would improve the accuracy of the heating disaggregation models. Therefore, the team categorized sites into groups (i.e., "cohorts") by analyzing data to predict the operating strategy, which could subsequently be validated by survey responses.

The team sought to identify cohorts analytically for each site by first using only data that are readily available: hourly AMI data (before and after heat pump installations), actual and normal (TMY3) weather data from closest local weather station, and Efficiency Maine tracking data. Some of the key tracking data include building type, location, square footage, installation date, nameplate information, and presence of other heating system(s).

The team defined these cohorts: 1) "full displacement," meaning heat pumps are used as the exclusive or primary heat source in a building, room, or space; 2) "partial displacement," meaning heat pumps installed in conditioned space with other operational heating systems; and 3) "low, unpredictable usage", meaning heat pumps used irregularly, rarely, or never for heat. Additional information on cohort determination can be found in Appendix C.

3.5.3 Net-to-gross analysis

Net-to-gross (NTG) assessment takes into consideration both free-ridership (FR) and spillover. Free-ridership refers to the portion of energy savings that participants would have achieved in the absence of the program. Spillover, which includes both participant spillover (PSO) and non-participant spillover (NPSO) components, refers to the energy savings from non-rebated energy efficiency upgrades made outside of the program that are influenced by the program. The NTG ratio (NTGR) is calculated through the following formula:

$$NTGR = 1 - FR + PSO + NPSO$$

The DNV team assessed free-ridership through a participant survey that explored the intention of the participant—i.e., if they would have installed the HP if they had not received the program rebate. The survey also explored the program's influence on the efficiency and timing of the installed measure in the counterfactual scenario—i.e., if they would have installed the same or different equipment or if they would have delayed the installation. The DNV team also administered a survey among the program's qualified partners (QPs) to gather their perspectives on customer influences and estimate the prevalence of HP installations beyond the program.

Free-ridership

The DNV team assessed free-ridership in the participant survey using two equally weighted components: free-ridership intention and free-ridership influence. Free-ridership intention looks at what the participant would have done in the absence of the program[32], whereas free-ridership influence acts as a check on the potential bias of the intention by understanding the

[32] As discussed in Section 3.5.2, gross baseline determination for new construction or normal replacement projects also included information on the customer's preferred alternative heating and cooling systems absent the program. Since the net-to-gross results are in the form of a ratio applied to the gross savings, for projects for which the customer would have installed a HP anyway, the NTGR may further reduce the incremental gross savings between a program-eligible HP and code-compliant HP. For each project overlapping between the M&V sample (n=70) and the NTG respondent pool (n=194), the DNV team compared the gross baseline and NTGR results to ensure no double-counting.

influence of different program interventions on a participant's decision-making process. Details on the key survey questions and logic implementation can be found in Appendix A.

Spillover

This section describes the methodology for participant and non-participant spillover, as well as the roll-up to estimate program spillover. The team identified and estimated program spillover by summing participant spillover after program participation and non-participant spillover through program vendors as shown below.

$$\text{Total Spillover} = \text{Participant Spillover} + \text{Non-Participant Spillover}$$

Participant spillover

Participant spillover refers to the non-incented energy efficiency measures that participants installed as a result of participating in the program. The team surveyed participants to list out these additional measures and quantified the influence of program or contractor experience in participants installing the additional measures. The team estimated measure level savings by first calculating expected annual energy usage by end use based on square footage and building type and applying measure specific savings factors. Details on key questions and participant spillover logic flow can be found in Appendix A.

$$\text{Participant Measure Spillover} = \text{Deemed Measure Savings} \times \text{Influence Value}$$

Non-participant spillover

Non-participant spillover refers to non-incented program measures implemented by vendors who were directly or indirectly influenced by the Heat Pump Program. We leveraged the program vendor surveys to quantify the number of additional heat pump projects each vendor did that qualified for the incentive but did not receive one. We also quantified the influence of the program on the program vendor's recommendations of qualifying heat pumps to determine program attributable non-participant spillover. Details on the key survey questions and methodology for non-participant spillover logic flow can be found in Appendix A.

$$\text{Non-Participant Spillover} = \text{Number of unincented sales} \times \text{Program Influence Value} \times \text{Vendor Influence Value}$$

4 RESULTS

This section presents the results of customer surveys, vendor interviews, M&V data analysis, AMI data analysis, and cost-benefit analysis.

4.1 Survey results

This section summarizes findings from surveys with participating customers and vendors.

4.1.1 Customer surveys

This section provides key takeaways from web-based surveys of 232 participating customers. Appendix B includes additional insights from the customer survey. Responses are not weighted by building type unless otherwise noted, as the distribution of responses by building type resembled the distribution of building types in the overall population.

4.1.1.1 HP usage by season

The vast majority of respondents reported using their heat pumps for both heating and cooling. The survey asked respondents if they used their heat pumps for heating, cooling, or both. Of all those surveyed, 93% of respondents stated that they use their heat pumps for both heating and cooling. A very small portion reported using their heat pumps exclusively for heating (3%) or exclusively for cooling (4%). Analysts reviewed responses by system category (e.g., single- or multi-zone) and found no significant variations from the overall response shares.

A majority of respondents indicated they use their heat pumps on all or most days of the heating season. The survey asked respondents who use their heat pumps for heating how often they use their heat pumps during the heating season. Over half (54%) reported using their heat pumps on all heating season days, and an additional 31% said they used their heat pumps on most cool and all cold days. Table 4-1 shows the breakdown of customer-reported heat pump usage frequency during the heating season.

Table 4-1. Frequency of HP Use during Heating Season

Please indicate when you use your heat pump(s) to heat your space. Single Response, n=200		
Response	Count	Percent
All heating season days	108	54%
Most cool and all cold days	62	31%
Only the coldest days	11	6%
Very rarely	8	4%
Shoulder seasons or cool days only	8	4%
Other	3	2%

Most participants still use their pre-existing heating system. When asked if they still use their pre-existing heating system, three-quarters of respondents said yes; 48 respondents (29%) reported still using their pre-existing heating system frequently, another 66 respondents (40%) reported infrequent use, and 5 respondents (3%) reported still using their pre-existing heating system because their heat pumps were installed in a separate space.

Most respondents reported using their heat pumps on all or most days of the cooling season. The survey asked respondents who use their heat pumps for cooling how often they used their heat pumps during the cooling season. Three-quarters of respondents reported using their heat pumps on all or most cooling season days. Table 4-2 below shows when respondents use their heat pumps for cooling.

Table 4-2. Frequency of HP Use during Cooling Season

When do you use your heat pump(s) in cooling mode? Single Response, n=202		
Response	Count	Percent
All cooling season days	88	44%
Most warm and all hot days	63	31%
Only the hottest days	39	19%
Very rarely	5	3%
Other	5	3%
Never	2	1%

4.1.1.2 Changes in setpoint

65% of respondents indicated that, during the heating season, they keep their affected spaces the same temperature as they did prior to the installation of their heat pumps. About one-fifth of respondents (18%) keep their space warmer (about 8 degrees on average), and 8% keep their spaces cooler (about 6 degrees on average).

About the same number of respondents reported not having changed their setpoints during the cooling season and keeping their affected spaces cooler. 28% of respondents reported that during the cooling season, they keep their space the same temperature as they did prior to the installation of their heat pumps. Almost the same share of respondents (27%) reported that they keep their space cooler (about 9 degrees on average), while only 1% said they keep their space warmer (about 6.5 degrees on average).

4.1.1.3 Motivation and benefits

Most respondents reported that they had saved energy and that their comfort levels had increased since installing their heat pumps. 72% of respondents said that, since installing their heat pumps, they had saved energy (considering all fuels and electricity). Additionally, the vast majority of respondents said that their comfort levels had increased (85%) or stayed the same (12%) since installing their heat pumps.

More efficient heating and cooling was the most cited reason why respondents purchased the program-incentivized heat pumps. This survey question allowed multiple responses. 62% indicated they were motivated to heat and/or cool their spaces more efficiently, while 34% wanted to reduce their heating costs and 24% wanted to add heating or cooling where it wasn't previously. Table 4-3 shows the breakdown of participant motivators.

Table 4-3. Customer Motivations to Install Heat Pumps

What motivated you to purchase and install the heat pump(s)? Multiple Response, n=232		
Motivation	Count	%
To heat or cool more efficiently	142	62%
To reduce heating costs	78	34%
Wanted to add heating/cooling where none was present previously	56	24%
To reduce cooling costs	47	20%
Needed to replace broken or aging equipment	41	18%
To reduce environmental impacts of heating/cooling	41	18%
Needed to supplement heating/cooling from the main system	32	14%
Other	10	4%
To avoid health and safety issues (mold, etc.)	8	3%
Needed equipment that fit in tight spaces	6	3%

4.1.1.4 Experience with program and contractor

Respondents are highly satisfied with their heat pumps and the program overall. The survey asked respondents to rate five aspects of their program experience on a 0-to-10-point scale, with 0 being “not at all satisfied” and 10 being “extremely satisfied.” All but one program component (the incentive amount) received an average rating of at least 9. Table 4-4 shows the respondents’ average ratings for all program components. There were no significant patterns when examining this data by building type.

Table 4-4. Average Satisfaction Rating of Program Features (n=232)

Program Feature	Average Rating
The installed heat pumps	9.2
Program application process	9.0
Heat pump contractor	9.1
Incentive amount	8.6
Overall program experience	9.1

Most respondents reported that the installation contractor explained how to operate the heat pump, and that the “how-to” explanation was very helpful. 94% of respondents reported that they discussed how to operate the heat pumps with installation contractors. The survey asked these respondents to indicate whether the contractor’s explanation was very, somewhat, or not at all helpful. 80% indicated that their contractors’ explanation was very helpful.

Most respondents recalled receiving materials from Efficiency Maine about how to operate their heat pumps, and the majority found the information helpful. The survey asked respondents to indicate whether Efficiency Maine’s mail or email materials on how to operate their heat pumps was very, somewhat, or not at all helpful. Most respondents (70%) recalled receiving Efficiency Maine’s materials, and of those, 87% found it to be at least somewhat helpful. About a third of respondents (31%) do not recall using, asking for, or receiving information from Efficiency Maine on heat pump operation.

4.1.2 Vendor surveys

The DNV team interviewed 30 qualified partners (QPs) that installed HPs during the evaluation timeframe. A summary of key takeaways is provided in this section. Appendix B includes additional results from the vendor survey.

4.1.2.1 Program influence on stocking and sales practices

Seventeen vendors (56%) stated that their **overall sales volume increased** once they learned about the program, while 17% thought it remained the same, and 7% stated that sales decreased. The estimated increase in sales volume before and after participating in the program, on average across all surveyed vendors, was 27%. Analysts examined responses by vendor selection strata and found that the high-volume contractors mostly indicated their sales volume remained the same, so the change is occurring primarily in vendors with lower program participation.

Table 4-5 below summarizes responses about whether the presence of the program had an impact on distributor stocking practices of energy efficient heat pump options. **Slightly less than half stated they had seen an increase in stock variety or volume of efficient heat pumps**, while 38% stated they observed little to no impact on distributor practices as a result of the heat pump program. The remainder were unsure, or cited pandemic-related changes that made it difficult to fairly assess the question. The survey question allowed multiple responses.

Table 4-5. Program Effect on Distributor Stocking Practices (Multiple Response, n=30)

Response Category	Percent
Have seen impact – increased stocks	45%
Have seen impact – decreased stocks	0%
Little to no impact	38%
Unsure of impact	14%
Unsure of impact - pandemic influence	28%

4.1.2.2 Barriers to program-qualifying HP sales

When asked what barriers have prevented their sales of program-qualifying HPs, **contractors identified barriers such as cost, program criteria, program administration, marketing/commercialization, and training/education**. Table 4-6 below groups the responses into common themes mentioned. The survey question allowed multiple responses.

Table 4-6. Barriers to Qualifying HP Sales (Multiple Responses, n=30)

Barrier	Percent
No Barriers	31%
Cost of Qualifying Equipment	21%
Efficiency/Program Criteria	21%
Amount of Paperwork	17%
Administration/Bureaucracy	14%
Lack of Marketing/Commercialization	10%
Lack of Training/Education	7%

4.1.2.3 Effects of program participation

When asked how their business has been impacted by participation in the program, **vendors most frequently noted increases in customer base and sales volume**. Table 4-7 below summarizes these themes.

Table 4-7. Other Program Impacts on Business (Single Response, n=30)

Theme	Count of Responses	Percent
Increased customer base	8	31%
Increased number and ease of sales	5	21%
Increased size/scope of projects	4	21%
Little to no impacts	4	14%
Unclear impacts	5	17%

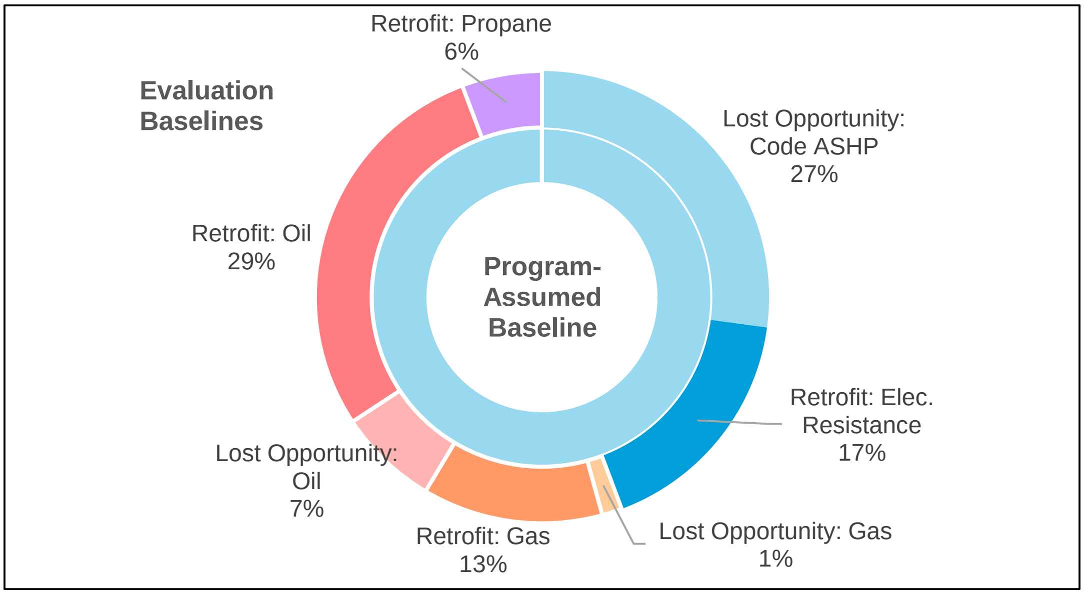
4.2 Gross impact results

This section examines the gross evaluated impacts from equipment-level M&V data. Section 4.2.1 presents the results of the DNV team's baseline assessment, which was the primary driver in gross evaluated impact results. Sections 4.2.2 through 4.2.7 present the gross impact results and key contributors to RRs by various segmentation variables.

4.2.1 Baseline determination

The DNV team processed the site-specific data from web surveys and field inspections to characterize the baseline heating and cooling systems at sampled facilities. The program treated all HPs over the evaluation timeframe as Lost Opportunity installations with incremental savings as compared with code-standard HP baseline.[33] On the other hand, the DNV team determined a variety of displaced fossil fuels which generally served to increase the evaluated site MMBtu savings significantly. Figure 4-1's outer ring illustrates the distribution of the evaluated baseline heating systems and fuels across the 70 HPs sampled for M&V. The figure differentiates between Retrofit installations (pre-existing conditions baseline) and Lost Opportunity installations, which incorporated the customers' preferred heating systems absent the program. The inner ring represents the program's presumed Lost Opportunity treatment (code-standard HP baseline) for all projects.

Figure 4-1. Comparison of Evaluated and Program-Reported Heating System Baseline Distributions



The DNV team determined that fossil fuel systems constituted 56% of heating baselines, with the remainder distributed between code-compliant HPs (27%) or electric resistance (17%).

As with any impact evaluation, baseline is a critical determinant of evaluated impacts. With a fuel-switching measure such as HPs, baseline can be even more impactful, as illustrated by the hypothetical example in Table 4-8 and Figure 4-2. Consider a single-zone HP rated at 12,000 Btu/h of heating capacity that operates at full-load for 1,000 hours per heating season with a coefficient of performance (COP) of 3.17.[34] Annual heating savings vary significantly by baseline as shown in the second column from the right of Table 4-8.

33 Program-reported savings among the population of 2017-19 HP installations varied by fuel type (in site MMBtu): 82% electricity, 11% oil, 5% natural gas, 2% propane. According to Efficiency Maine staff, savings claims changed over the evaluation timeframe. Throughout the full evaluation timeframe, the program assumed all HPs to be Lost Opportunity with a baseline of a standard efficiency heat pump. On July 1, 2019 (FY2020), the TRM HP savings claims were updated to reflect revised modeling that accounted for capacity differences versus outside air temperature of the high efficiency and standard efficiency HPs. That modification of the modeling resulted in some fossil fuel savings for LO HPs due to greater heating offset by the high-efficiency HP compared to standard-efficiency.

34 As discussed in Section 4.6, the DNV team determined an average heating COP of 3.17 across the M&V sample of 70 HPs.

Table 4-8. Variation in Savings and Costs by Event Type and Baseline from Hypothetical HP Installation

Event Type	Baseline[1]	Baseline COP/Efficiency	Baseline Heating Consumption (MMBtu/yr)	HP Heating Consumption (MMBtu/yr)	Annual Savings (MMBtu/yr)	Cost
Lost Opportunity	Code-Compliant HP	2.40	5.0	3.8	1.2	$525[3]
Lost Opportunity	Fossil Fuel	0.82	14.6		10.8	$4,111[3]
Retrofit	Electric Resistance	1.00	12.0		8.2	$5,696[4]
Retrofit	Fossil Fuel	0.70[2]	17.1		13.4	$5,696[4]

[1] For fossil fuel baselines, MMBtu savings (second column from the right) combine the reduction in fossil fuel MMBtu with the associated increase in electricity (converted to MMBtu at site). For cost-effectiveness analysis, the electric increase is incorporated as an added cost.
[2] We assumed a lower fossil fuel system efficiency for retrofit projects to account for aged equipment and degradation.
[3] Referenced from Efficiency Vermont TRM pages 93 and 224.
[4] Average of tracked cost data from sampled M&V installations determined by the DNV team to be retrofit installations.

Figure 4-2 illustrates the variation in savings (y-axis) plotted against the measure cost (x-axis) for the different event/baseline scenarios.

Figure 4-2. Variation in Savings and Costs by Event Type and Baseline from Hypothetical HP Installation

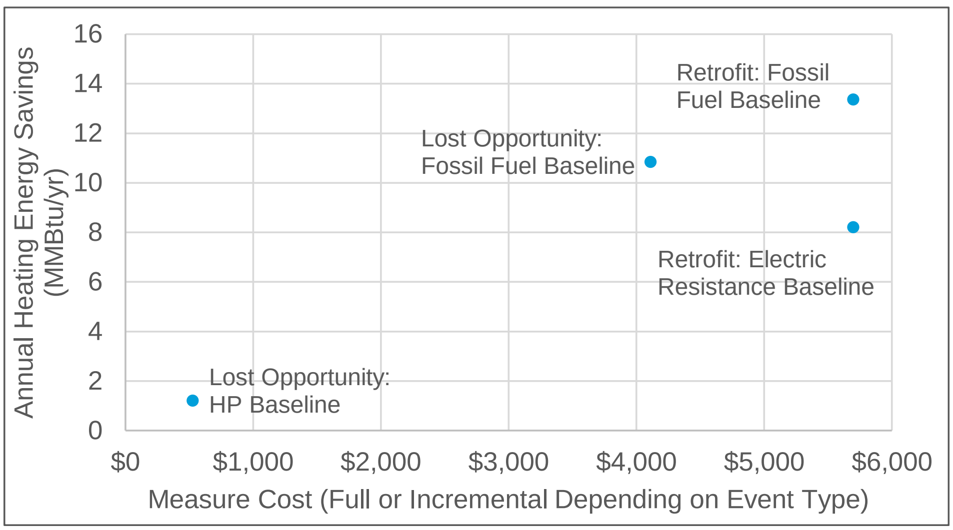
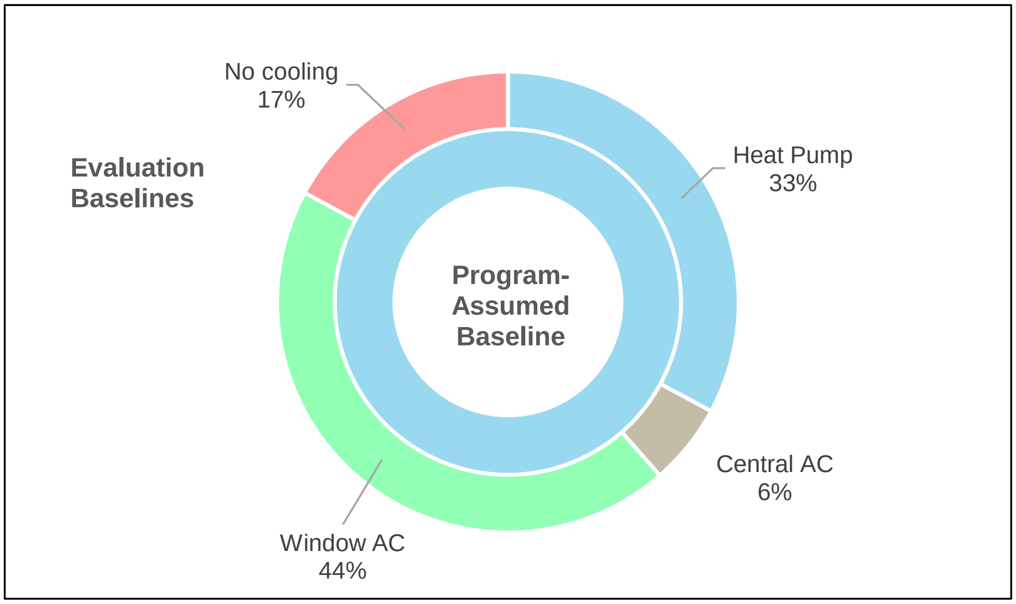


Figure 4-3 illustrates the distribution of cooling baselines. Again, the figure reflects the pre-existing conditions, when applicable, as well as the customers' preferred cooling systems absent the program. Approximately half of the evaluation sample did not have a mechanical cooling system before HP installation; however, about two-thirds of these customers reported that they would have installed a cooling system regardless of program participation. Ultimately, 17% of sampled customers had a no-cooling baseline resulting in electric penalties from the HP installation.

Figure 4-3. Distribution of Cooling System Baselines across Core Evaluation Sample



4.2.2 MMBtu impacts and realization rates

Table 4-9 summarizes the gross evaluated impacts as determined through analysis of 70 rebated HPs sampled for M&V. Table 4-9 compares the program-reported and evaluated MMBtu impacts at site,[35] distinguished among the primary sampling strata (building type).

Table 4-9. Comparison of Reported and Evaluated Site MMBtu Impacts among M&V Sample

Sector	Subsector	N	n	Reported Savings across All Energy Sources (MMBtu/yr)	Evaluated Savings across All Energy Sources (MMBtu/yr)	RR	RP at 80% Confidence
Commercial	Lodging[1]	245	14	1,135	317	0.28	±34%
	Office	307	16	2,110	2,090	0.99	±34%
	Other	977	17	6,819	7,745	1.14	±39%
Multifamily		768	23	2,738	7,886	2.88	±28%
Total		**2,297**	**70**	**12,801**	**18,038**	**1.41**	**±22%**

N = Total count of HP installations incented by the program between 2017 and 2019
n = Sample of HP installations drawn for M&V evaluation
RR = Realization rate—evaluated savings divided by reported savings
RP = Relative precision
[1] Of the fourteen sampled installations at lodging facilities, the evaluators determined that one of the facilities was a seasonal inn (closed for the winter). The remaining lodging facilities operate year-round with seasonal variation captured by the M&V metering period.

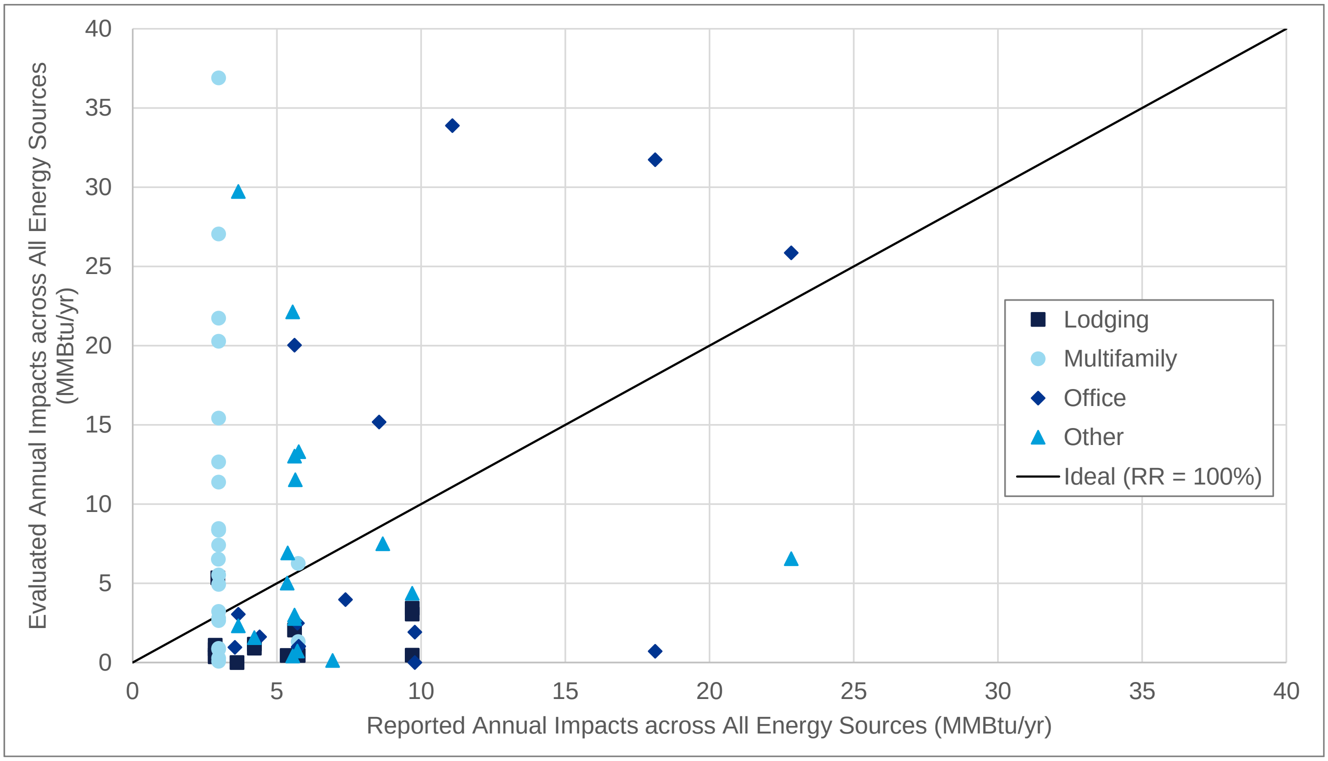
Overall, rebated HP installations realized 41% more MMBtu at site than predicted by the program. Installations at Multifamily buildings achieved the highest evaluated MMBtu impacts at nearly three times the program-reported estimate. Installations

[35] The MMBtu savings presented in this report reflect a blend of electric and fossil fuel impacts as a result of the fuel switch. Evaluated MMBtu savings are measured against the evaluator's determined baselines as summarized in Section 4.2.1. All MMBtu savings in this report reflect *site* MMBtu— i.e., no electric production, transmission, or distribution efficiencies are incorporated.

at facilities classified as Office or Other achieved MMBtu impacts similar to the program-reported estimates, while installations at Lodging facilities achieved 72% less MMBtu impacts than predicted by the program.[36]

Figure 4-4 compares the evaluated MMBtu savings (vertical axis) with reported savings (horizontal axis) differentiated by facility type. The ideal evaluation result— a RR of 100%— is illustrated by the diagonal black line. The figure illustrates that the majority of Multifamily installations achieved higher MMBtu savings than reported, whereas all Lodging installations had lower evaluated savings than reported.

Figure 4-4. Evaluated vs. Reported MMBtu Savings by Facility Type

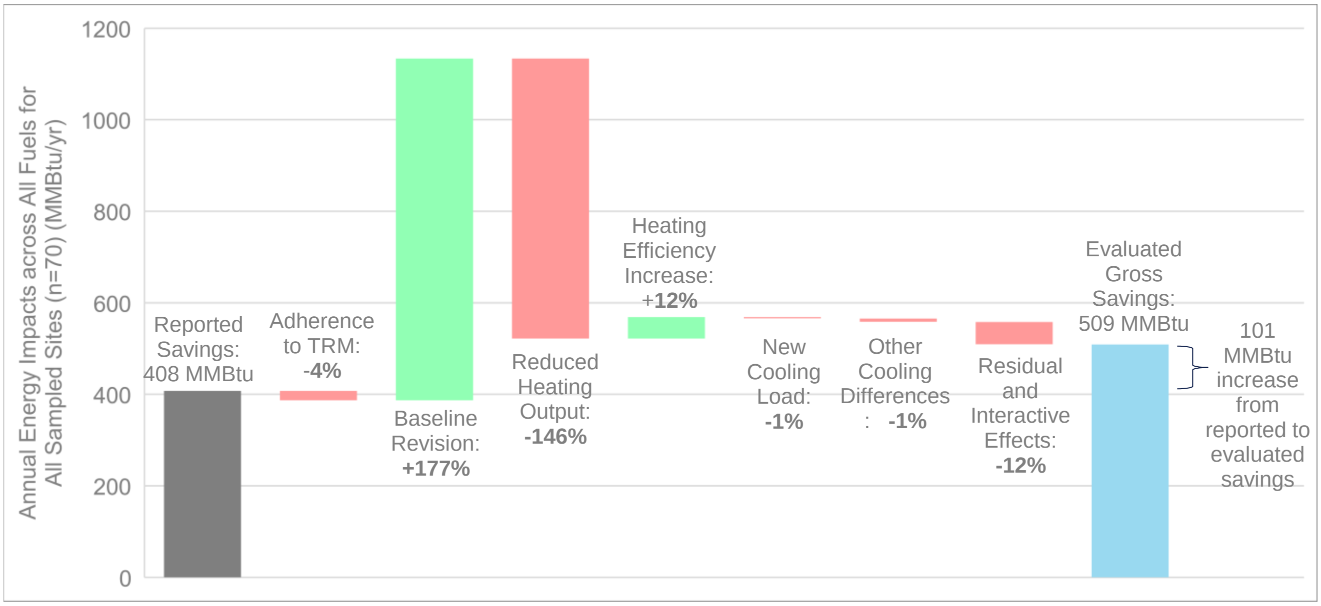


4.2.3 Savings differences

The DNV team determined significant differences between study findings and program assumptions that contributed to the 141% MMBtu RR. Figure 4-5 presents a waterfall chart of MMBtu savings differences by category between evaluated and program-reported impacts.

36 M&V site visits included interviews with facility representatives on topics such as seasonal fluctuations or lingering effects from the COVID-19 pandemic. Representatives from the 14 Lodging facilities included in the M&V sample stated that their operation had generally resumed to normal, and that the December 2020 – October 2021 metering period was representative of typical operation.

Figure 4-5. Waterfall Chart of Evaluated and Reported Savings Differences by Category



The program-reported savings across the 70 installations in the M&V sample (408 MMBtu per year, unweighted) serves as the leftmost starting point. Ultimately, the DNV team determined annual savings of 509 MMBtu (unweighted) across the M&V sample.[37] Savings difference categories from left to right include:

- **Adherence to TRM** – Comparison of program-reported savings claims with evaluator-recreated savings using tracking data and TRM assumptions showed a -4% decrease in evaluated impacts.
- **Baseline revision** – The evaluator's assessment of system-specific baselines, as explained in Section 3.5.1, resulted in a 177% increase in evaluated savings as compared with reported. For 82% of installations in the evaluation frame, the program claimed incremental savings as compared with a code-compliant HP baseline. As discussed in Section 4.2.1, the DNV team determined a fossil fuel heating baseline for 57% of sampled HPs, leading to significantly more MMBtu savings per installation.
- **Reduced heating output** – Overall, the DNV team determined that the rebated HPs operated less frequently during the heating season than anticipated by the program. The DNV team attribute this difference primarily to the continued use of supplementary heating systems. As indicated in Table 4-1, nearly half of surveyed participants stated that they do not fully use the incented HPs throughout the heating season. Section 4.2.7 illustrates that savings and operation vary significantly as a function of the presence and frequency of use of other heating systems.[38] After the significant increase from baseline revision, and using the original reported savings as the denominator, reduced heating output decreased the evaluated savings by 146%.
- **Heating efficiency increase** – Evaluated site MMBtu increased by 12% when measured COP was compared with assumed values embedded in program-reported deemed savings.
- **New cooling** – The DNV team determined a slight decrease in savings due to new cooling load from customers that otherwise would not have installed mechanical cooling systems absent the program.
- **Other cooling differences** – Comparison of other cooling savings contributors, including cooling COP and annual output, showed a similarly slight decrease in evaluated savings.

[37] The figure summarizes *unweighted* evaluated savings; therefore, the ratio of evaluated (509 MMBtu) to reported savings (408 MMBtu) differs from the 141% MMBtu RR in Table 4-9. The DNV team chose to show unweighted results in Figure 4-5, as the sampling weights slightly skewed the effect of certain categories.

[38] Notably, this result differs from the survey response results in Table 4-1 indicating that a majority of customers use their HPs on all heating season days. The DNV team attributes this difference primarily to HPs running at partial load even when a customer believes they are fully operating.

- **Residual and interactive effects** – The last category includes residual differences that cannot be assessed due to insufficient tracking data as well as interactivities that cannot be fully isolated when calculating categorical differences above.

4.2.4 Impacts by fuel

Table 4-10 further compares the evaluated and program-reported impacts among electric and fossil fuel energy sources, which encompasses natural gas as well as delivered fuels (propane, fuel oil, kerosene, and wood).

Table 4-10. Comparison of Reported and Evaluated Impacts Among Electric and Fossil Fuel Energy Sources

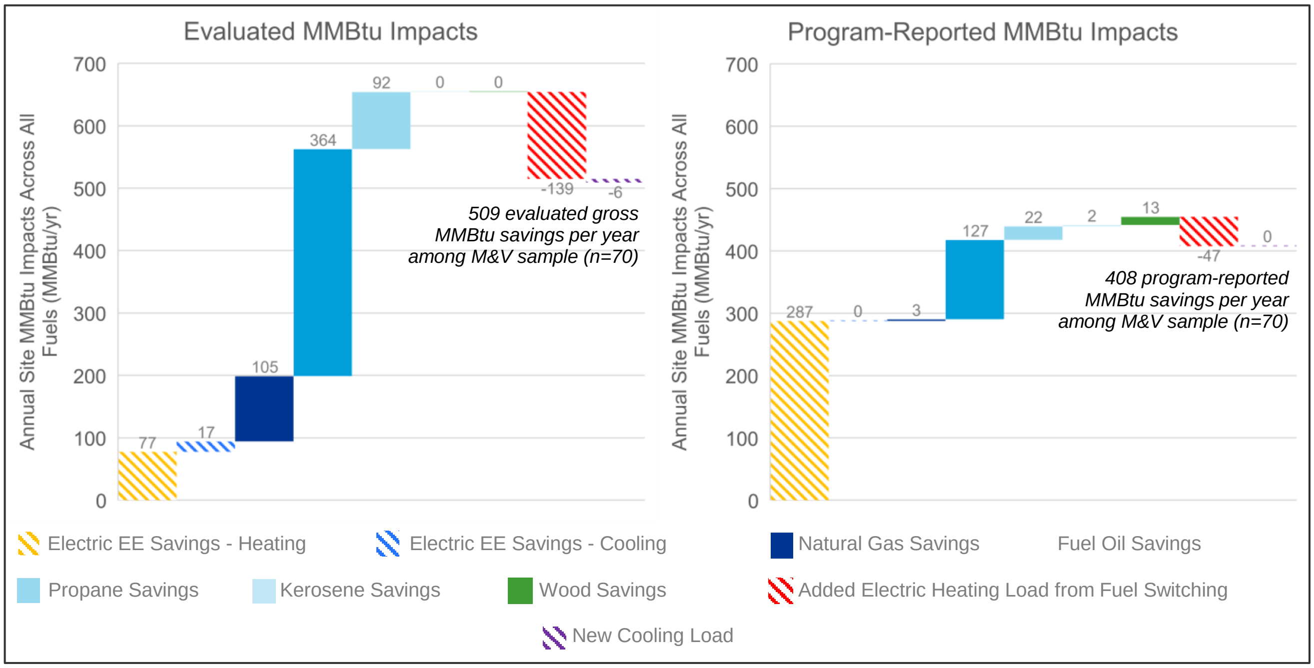
				Electric Impacts (MWh/yr)			Fossil Fuel Impacts (MMBtu/yr)		
Sector	Subsector	N	n	Reported	Evaluated	RR	Reported	Evaluated	RR
Commercial	Lodging[1]	245	14	307	42	0.14	89	N/A*	N/A*
	Office	307	16	357	-257	-0.72	893	1,417	1.59
	Other	977	17	1,294	-389	-0.30	2,404	6,018	2.50
Multifamily		768	23	506	-115	-0.23	1,012	N/A*	N/A*
Total		**2,297**	**70**	**2,463**	**-719**	**-0.29**	**4,398**	**7,435**	**1.69**

* The program did not claim fossil fuel impacts for sampled installations at Lodging and Multifamily facilities, preventing the calculation of sector-specific RRs.
N = Total count of HP installations incented by the program between 2017 and 2019
n = Sample of HP installations drawn for M&V evaluation
RR = Realization rate: evaluated savings divided by reported savings
[1] Of the fourteen sampled installations at lodging facilities, the evaluators determined that one of the facilities was a seasonal inn (closed for the winter). The remaining lodging facilities operate year-round with seasonal variation captured by the M&V metering period.

For installations at Multifamily, Office, and Other buildings, the DNV team determined significantly higher fossil fuel displacement than claimed by the program. As a result, evaluated electric impacts were negative at these three facility types. On the other hand, the DNV team determined more electric-to-electric projects at Lodging facilities, resulting in a positive electric RR.

Figure 4-6 compares evaluated (left-hand figure) and program-reported impacts by fuel combined across the 70 installations sampled for M&V. Electric impacts (converted to MMBtu at site) are designated by the striped bars, while fossil fuel impacts are designated by solid bars. Added electric load from fuel switching is illustrated by the red striped bar, while electric savings due to increased efficiency in heating and cooling seasons are designated by the orange- and blue-striped bars, respectively. Please note that the ratio between total evaluated savings (509 MMBtu per year) and program-reported savings (408 MMBtu per year) slightly differs from the 141% RR in Table 4-9. The figure illustrates unweighted results from the 70 installations sampled for M&V, as statistical weighting of fossil fuel results was not possible for Lodging and Multifamily segments (see first footnote to Table 4-10).

Figure 4-6. Evaluated vs. Reported Impacts by Fuel among M&V Sample



The figure illustrates that rebated HP installations offset a broader diversity of fuels as compared with the program's predominant assumption of code-compliant heat pump baselines. The right-hand waterfall chart, illustrating the makeup of the program-reported savings claims, shows a predominance of electric heating savings from the program's Lost Opportunity treatment and presumed code-compliant HP baseline. The left-hand waterfall, illustrating the evaluator's findings, shows a higher prominence of displaced fossil fuels and associated added electric load.

4.2.5 Peak demand impacts and energy period factors

Table 4-11 and Table 4-12 compare program-reported and evaluated demand savings during winter and summer peak coincident periods, respectively. The DNV team determined an overall increase in electric demand during the winter peak period due to the higher displacement of fossil fuel heating than anticipated by the program, as was determined for all sectors except Lodging. The mix of fossil fuel-to-HP conversions (electric penalty) and electric-to-HP conversions (electric savings) led to poorer relative precisions than achieved for MMBtu impacts.

Table 4-11. Comparison of Program-Reported and Evaluated Winter Peak Demand Savings

Sector	Sub-sector	N	n	Reported Winter Peak Demand Savings (kW)	Evaluated Winter Peak Demand Savings (kW)	RR	RP at 80% Confidence	Evaluated Winter Peak Demand Impact per HP (kW)
Commercial	Lodging	245	14	90	7	0.08	±302%	0.030
	Office	307	16	109	-61	-0.56	±141%	-0.198
	Other	977	17	370	-95	-0.26	±200%	-0.097
Multifamily		768	23	96	-31	-0.32	±194%	-0.040
Total		**2,297**	**70**	**665**	**-179**	**-0.27**	**±118%**	**-0.078**

N = Total count of HP installations incented by the program between 2017 and 2019
n = Sample of HP installations drawn for M&V evaluation
RR = Realization rate: evaluated savings divided by reported savings
RP = Relative precision

Table 4-12 shows that the DNV team determined lower summer peak demand savings than claimed by the program.[39] The 63% summer peak demand RR is primarily due to two reasons:

1) Lower cooling operation than anticipated – we determined 11% lower cooling output than assumed within the program's TRM-based deemed savings (see Table 4-26 and Section 4.6.2 for additional information).

2) New cooling – the M&V sample included 12 HP installations that introduced new cooling that otherwise would not have been installed absent the program.

Table 4-12. Comparison of Program-Reported and Evaluated Summer Peak Demand Savings

Sector	Sub-sector	N	n	Reported Summer Peak Demand Savings (kW)	Evaluated Summer Peak Demand Savings (kW)	RR	RP at 80% Confidence	Evaluated Summer Peak Demand Impact per HP (kW)
Commercial	Lodging	245	14	12.3	12.8	1.04	±142%	0.052
	Office	307	16	25.5	8.4	0.33	±45%	0.027
	Other	977	17	68.6	53.2	0.78	±62%	0.054
Multifamily		768	23	32.3	12.4	0.38	±92%	0.016
Total		**2,297**	**70**	**138.7**	**86.8**	**0.63**	**±229%**	**0.038**

N = Total count of HP installations incented by the program between 2017 and 2019
n = Sample of HP installations drawn for M&V evaluation
RR = Realization rate: evaluated savings divided by reported savings
RP = Relative precision

Table 4-13 presents the energy period factors (EPFs) among the 70 HPs sampled for M&V. An example set of commercial heat pump EPFs from the 2022 Efficiency Maine TRM Appendix B is also included for comparison purposes. Overall, the DNV team determined EPFs similar to those assumed in the TRM. Notably, evaluated summer EPFs were higher than the TRM values.

[39] In Section 4.6, the report explores the annual heating and cooling outputs of each sampled HP. In general, customers claimed to use the rebated HPs for both heating and cooling, and the output data generally reflects that, albeit with lower output values than assumed by the program.

Table 4-13. Energy Period Factors from Evaluation Results and Efficiency Maine TRM

Period	Evaluation Results	Efficiency Maine TRM
Winter on-peak (7:00 AM to 11:00 PM on non-holiday weekdays during October through May)	35.5%	35.9%
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)	40.0%	49.5%
Summer on-peak (7:00 AM to 11:00 PM on non-holiday weekdays during June through September)	13.8%	8.3%
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)	10.7%	6.3%

4.2.6 Normalized impacts and usage

HP specifications varied widely among the 70 sampled systems. For example, rated heating capacity (at 17°F test condition) ranged from 6,700 Btu/hr for a single-zone unit to 35,400 Btu/hr for a multi-zone system. The DNV team therefore normalized the achieved impacts by rated equipment capacity in 1,000 Btu/h for comparison purposes with normalized output values in Section 4.3's premise-level results. Table 4-14 presents normalized impacts and usage per 1,000 Btu/h among the sampled sectors. Impacts refer to the energy savings when comparing program-incented HPs with appropriate baseline conditions. Usage refers to the annual operation of the program-incented HPs.

Table 4-14. Impacts and Annual Usage Values Normalized by Installed Heating Capacity, by Sector

				Impacts			Use	
Sector	Subsector	N	n	All Fuels MMBtu/yr per 1,000 Btu/h	kWh/yr per 1,000 Btu/h	Fossil Fuel MMBtu/yr per 1,000 Btu/h	Heating kWh/yr per 1,000 Btu/h	Cooling kWh/yr per 1,000 Btu/h
Commercial	Lodging	245	14	0.2	21.3	0.1	67.6	5.1
	Office	307	16	0.4	-18.0	0.5	52.4	12.4
	Other	977	17	0.5	-18.5	0.5	54.6	7.6
Multifamily		768	23	0.6	7.9	0.5	59.3	11.6
Total		2,297	70	0.5	-4.6	0.55	61.9	9.2

N = Total count of HP installations incented by the program between 2017 and 2019
n = Sample of HP installations drawn for M&V evaluation

Table 4-14 shows that HPs installed at Lodging facilities led to the lowest MMBtu impacts but featured the highest heating output among the sampled segments. This difference is attributable to baseline—all 14 HPs at Lodging facilities were determined to be Lost Opportunity installations for which the baseline reflects a code-compliant HP with resulting incremental savings.

Table 4-15 presents normalized impacts and usage per 1,000 Btu/h by primary heating fuel as designated by the DNV team's baseline determination. Results are differentiated by the primary evaluation baseline heating fuel, but the sample included isolated cases of secondary fuels—e.g., spaces heated primarily by electric resistance but secondarily by fossil fuel. In such cases, the total impacts include impacts from secondary fuel sources as well.

Table 4-15. Impacts and Annual Usage Values Normalized by Installed Heating Capacity, by Evaluation Baseline Heating Fuel

Primary Baseline Heating Fuel	n	Impacts			Use	
		All Fuels MMBtu/yr per 1,000 Btu/h	kWh/yr per 1,000 Btu/h	Fossil Fuel MMBtu/yr per 1,000 Btu/h	Heating kWh/yr per 1,000 Btu/h	Cooling kWh/yr per 1,000 Btu/h
Electric	32	0.3	74.0	0.0	54.0	6.0
Fossil Fuel	38	0.7	-61.8	0.9	67.7	11.5
Total	70	0.5	-4.6	0.5	61.9	9.2

n = Sample of HP installations drawn for M&V evaluation

The tables show that rebated HPs consumed 62 kWh per 1,000 Btu/h during the heating season and 99 kWh per 1,000 Btu/h during the cooling season annually. HPs in Lodging facilities showed the lowest normalized MMBtu savings indicating that the low MMBtu savings is primarily due to a lower share of displaced fossil fuel than other sectors. HPs displacing fossil fuel heating systems led to more MMBtu savings per 1,000 Btu/h than HPs displacing electric heating sources. HPs displacing fossil fuel showed higher heating and cooling kWh consumption per 1,000 Btu/h. While normalized results show interesting differences between fossil fuel and electric baseline heating sources, we hesitate to draw broader conclusions given relatively low sample sizes of the two segments.

4.2.7 Segmentation analysis

The DNV team examined impact results among various segments of interest to ascertain patterns in operation or savings. This additional analysis is intended to assist program administrators in targeting the most optimal HP rebate candidates moving forward. While the evaluation sample was not designed to achieve statistical significance on any of the below findings, we have included the sample size associated with each analyzed segment to indicate credibility in results. Due to low sample sizes among certain segments, we urge caution when interpreting these results as possible trends.

- Multi-zone HPs produce more heat and save more MMBtu than single-zone HPs. On average, HPs serving a single zone saved 3.6 MMBtu per year per HP (n=5), whereas HPs serving multiple zones saved 13.1 MMBtu per year per HP (n=25). The average multi-zone system served 2.8 zones for an average savings of 4.7 MMBtu per year per zone. After normalizing the savings results to average capacity, the DNV team determined that multi-zone systems saved about twice as much MMBtu as single-zone systems.
- The DNV team found no significant difference in heat output or savings per HP between projects involving a single HP installation (n=34) and projects involving more than one HP installation (n=36).
- HPs that offset pre-existing fossil fuel-fired heating systems operated more frequently during the heating season and subsequently saved more MMBtu (11.6 MMBtu savings per year per HP, n=32) than HPs that offset pre-existing electric resistance heating (4.6 MMBtu savings per year per HP, n=12). While fossil fuel-fired systems have combustion losses that electric resistance systems do not, and this accounts for about 2.3 MMBtu of the difference, the majority of the difference is explained by the greater frequency of use of HPs displacing fossil fuel heating.
- HPs associated with customers that reported via web survey to continue to frequently use their legacy heating system saved significantly less (2.1 MMBtu savings per year per HP, n=4) than HPs associated with customers that no longer use the legacy heating system (6.7 MMBtu savings per year per HP, n=18) or HPs associated with customers that infrequently use the legacy heating system (8.5 MMBtu savings per year per HP, n=16).

4.3 Premise-level results

Using the methods detailed in Section 3.5.2, the DNV team assessed the impacts from program-rebated HPs by comparing AMI data before and after installation. This analysis phase intended to quantify the evaluated impacts using utility meter data among an expanded sample of projects. The DNV team notes that only energy impacts were assessed via AMI analysis given the relatively low differences in power draw observed between pre- and post-installation peak hours.

The DNV team conducted AMI analysis using three techniques: pre/post AMI analysis using the PRInceton Scorekeeping Method (PRISM), post-only AMI analysis using PRISM, and post-only AMI analysis using machine learning to train the model with M&V data. Additionally, the team approached the pre/post analysis from the fossil fuel perspective by assessing the anticipated decrease in heating fuel consumption as a result of the HP installation. Results from each method are presented in Sections 4.3.1 through 4.3.4.

Another objective of the AMI data analysis was to determine if and when an AMI-based approach is viable for evaluation analysis moving forward. Viability assessment included data cleaning, screening, and tests among several independent variables and unknowns, including:

- Do there appear to be non-routine events (e.g., change in load, occupancy, business hours) that prevent the use of pre-install conditions as baseline?
- Are there other electric heating systems not attributable to the program on the meter?
- Is the observed increase in electric heating energy use feasible given the characteristics of rebated HPs?
- Does the site contain more than one AMI meter? If so, how can we confidently select the affected one?
- Do results match from fuel delivery data analysis, AMI analysis, and M&V analysis approaches when available?

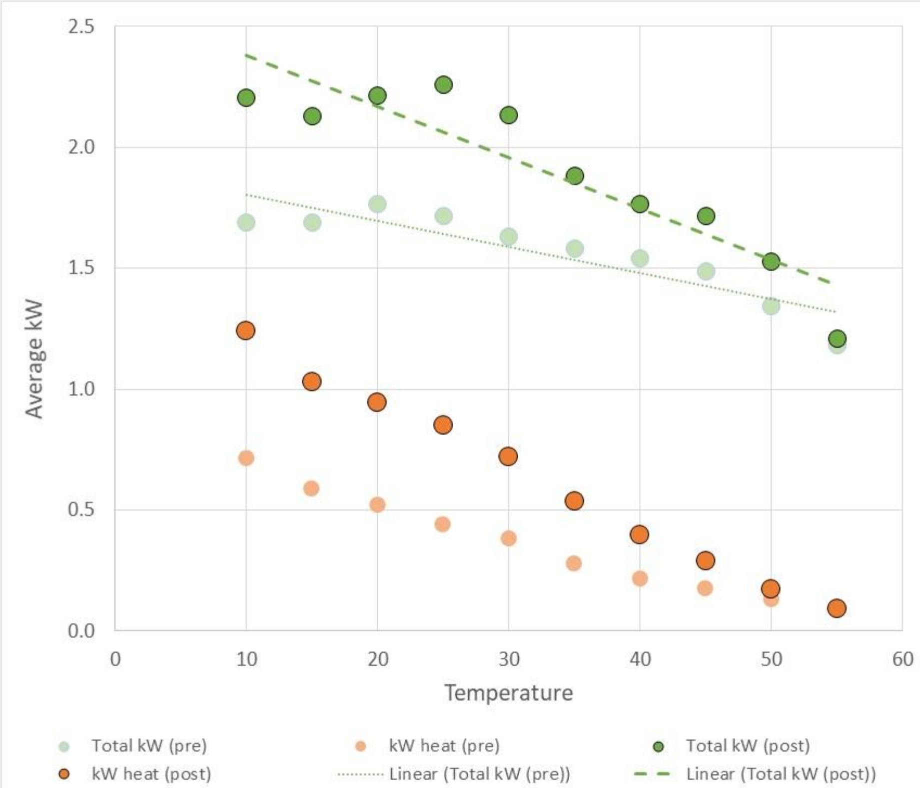
The section concludes with an assessment of the viability of AMI-based evaluation among different sectors and installation types in Section 4.3.5.

4.3.1 PRISM pre/post results

The most straightforward method of assessing gross impacts from an energy efficiency installation involves comparison of weather-normalized usage before and after the intervention. However, several criteria must be met for pre/post analysis to be viable: the pre-project conditions must reflect the evaluation baseline, and there must be no significant "non-routine events" that affect the pre- or post-installation consumption (e.g., other energy efficiency measures, changes in operation, and changes in heating or cooling loads).

The DNV team explored the viability of pre/post analysis of Efficiency Maine's HP participants by first attempting to collect as much pre/post AMI data as possible within the evaluation population. The team estimated weather-normalized energy consumption for all participant sites having AMI data at least one year prior to and one year after HP installation. Of the 415 sites with AMI data, 242 had sufficient data for pre/post-install analysis (hourly energy use data for at least one year prior to and one year after the heat pump installation). The team conducted a standard site-specific AMI billing analysis using the PRISM method described above, disaggregating hourly weather-normalized heating and cooling usage. Figure 4-7 shows the average per-site power draw for the total meter (green plots) and computed heating-only power draw (orange plots) versus temperature for all sites with pre/post AMI data.

Figure 4-7. Average Per-Site Power Draw versus Outside Air Temperature for Sites with Sufficient AMI Data (n=242)



The pre-installation AMI data in Figure 4-7 (light green plot) shows that the average power draw increases as temperature decreases. This temperature dependence indicates the presence and use of electric heating systems[40] prior to the program heat pump installations. This means some portion of the weather-dependent heating energy use may be attributed to other electric systems. This observation from the 242 sites with pre-installation AMI data suggests that heating-related energy use from post-only AMI disaggregation analysis may over-estimate heat pump energy use. The DNV team investigated this suggestion further in the next section.

As expected, the overall heating energy use changed by +44 kWh per 1,000 Btu/h rated capacity (an increase in energy use[41]). The team investigated the pre/post data further and found a slight *increase* in cooling energy for all 242 AMI sites (+1.3 kWh per 1,000 Btu/h rated capacity). If we assume the new heat pumps have higher cooling efficiency than the in-situ systems, an increase in cooling energy use is not expected unless there is an increase in the cooling load. Such a change could be attributed to a new addition of conditioned space, an increase in occupancy, some other type of increase in internal heat gains, or from a lower cooling temperature setpoint. Nearly half the sites (112 of 242) showed an increase in cooling usage. Consequently, there is a high probability that the cooling requirements changed in some way. Such changes may impact heating usage as well, calling into question the validity of pre/post AMI analysis to estimate actual impacts attributed to HP installation.

Table 4-16 shows annual pre- and post-install consumption for sites with increased cooling use (n=112) separately from sites with decreased cooling use (n=130). The table also shows average pre- and post-install heating consumption for sites showing an increase in heating use (n=191) separately from sites showing a decrease in heating use (n=51). The similarity

[40] May include electric heat sources (e.g., heat pumps, electric resistance heat) or auxiliary components of other heating fuel systems (e.g., air handler, circulation pumps, etc).

[41] In this section the plus sign indicates an increase in post-install energy use as compared with pre-install use. A minus sign indicates a decrease.

in post-installation heating between units that have cooling increases and decreases indicates that changes in the cooling load are not significantly affecting the heating load.

Table 4-16. Standard PRISM Analysis: Annual Heating and Cooling Energy Use

		Cooling			Heating		
AMI Data Pre/Post Change	**Sites**	Pre-Install Cooling kWh per 1,000 Btu/h	Post-Install Cooling kWh per 1,000 Btu/h	Cooling Change kWh per 1,000 Btu/h	Pre-Install Heating kWh per 1,000 Btu/h	Post-Install Heating kWh per 1,000 Btu/h	Heating Change kWh per 1,000 Btu/h
Cooling Increase	112	17.3	26.7	+9.4	66.8	108.8	+42.1
Cooling Decrease	130	15.8	10.8	-5.0	60.2	104.8	+44.6
Heating Increase	191	14.6	14.7	+0.0	57.8	120.5	+62.7
Heating Decrease	51	22.9	28.9	+6.0	82.3	56.0	-26.3
All	**242**	**16.3**	**17.7**	**+1.3**	**63.0**	**106.9**	**+43.9**

The increase in heating energy use is expected for sites with new heat pumps that effectively offset non-electric heat sources. A decrease in heating energy use would be expected for any scenario in which the heat pump displaces electric resistance heat or a less efficient heat pump. The team compared survey data (which included prior heating system information) to the AMI heating analysis results, expecting to observe a higher prevalence of decreased heating kWh from surveyed customers reporting to previously use electric resistance heat. Of the 51 sites with heating increase, 12 corresponded with completed participant surveys. Of those, only 2 customers indicated the heat pump offset electric resistance heat. Some anecdotal evidence from site visits offers one plausible explanation for this. The field technicians occasionally noted presence of secondary electric space heaters at various M&V sites, despite the customers self-reporting to use either oil or propane as the primary pre-existing heating source.[42]

Analysis of pre- versus post-installation AMI data may be appropriate for determining savings from a HP installation, but other changes (e.g., occupancy fluctuations, weatherization measures) decrease the accuracy of the result. Furthermore, savings cannot be estimated if the baseline is something other than existing equipment. As a result of the following the factors:

1. The magnitude of observed electric heat use prior to heat pump installation,
2. The limitations of collecting comprehensive information via customer survey about all primary *and secondary* heating systems that could interact with the installed HP, and
3. The similarity in electric heating increase between the cooling increase and cooling decrease scenarios,

the DNV team determined that traditional PRISM pre/post analysis may be unreliable for a significant number of projects over the evaluation timeframe.

4.3.2 PRISM post-only results

The DNV team next analyzed the post-installation AMI data to estimate heating use associated with the heat pump installations. The team imposed the various screening criteria considered in the previous section and estimated the annual heating energy use for each applicable scenario for each site.[43] As shown in Table 4-17, the team categorized the remaining sites (n=358) based on AMI data availability, credibility, and heating signature. The table shows that heating kWh per rated

[42] Field technicians visited sites at least one year after HP installation. Therefore, the number of sites that had used but did not report some type of supplemental electric space heat may be greater than the instances observed by field technicians.

[43] One example screening exercise was comparing AMI heating energy consumption versus the maximum possible heating kWh if all rebated HPs operated at full load for all hours of the heating season. The team removed 57 sites that showed higher AMI heating energy consumption than possible with the rebated HPs. The likely reason for this scenario is the presence of other electric heating systems not rebated by the program over the evaluation timeframe; these uncertainties are likely to have exaggerated the evaluated impacts.

1,000 Btu/h estimates vary greatly depending on the different screening scenarios. Each scenario is further explained in the rightmost column.

Table 4-17. Electric Heating Consumption Estimates by Scenario

Scenario	Site Count	Pre-Install Heating kWh per 1,000 Btu/h	Post-Install Heating kWh per 1,000 Btu/h	Estimated kWh per 1,000 Btu/h from Rebated HPs	Notes
All viable sites, post-install AMI only	358	0 (assumed)	117117	+117	As explored in the rows below, the DNV team believes this value overestimates heating energy use attributed to rebated HPs since a share of sites demonstrated evidence of other non-program electric heat sources.
Pre- and post-install AMI data available	242	63	107	**+44**	This estimate is the simple difference between pre- and post-install heating consumption for all sites with viable pre/post data. This is a **reasonable lower-bound average annual HP consumption estimate,** because the difference alone does not ascribe any reduction in pre-install electric heating energy to the heat pump, and some electric displacement likely occurs.
Pre/post analysis shows decrease in heating use	51	82	56	Unknown	A decrease in energy use is expected for sites installing HPs that displace less efficient electric heating systems. If heat pumps consumed 56 kWh per 1,000 Btu/h and operated with average COP=3, the equivalent electric resistance consumption is approximately 168 kWh per 1,000 Btu/h. The actual observed consumption for this group was 82 kWh per 1,000 Btu/h, meaning the post-only consumption may include some other heating use not accounted for, or that some sites had a change in heat load, or that the pre-project condition included other heat pumps. For this reason, a credible normalized kWh cannot be determined.
Pre/post analysis shows increase in heating use	191	59	121	**+63**	These sites showed an expected increase in heating energy use due to displacement of pre-existing fossil fuel heating. Omitted from this group are sites with decrease in heating use as described in the row above; including those 51 sites lowers the normalized annual heating energy closer to the +44 kWh per 1,000 Btu/h

Scenario	Site Count	Pre-Install Heating kWh per 1,000 Btu/h	Post-Install Heating kWh per 1,000 Btu/h	Estimated kWh per 1,000 Btu/h from Rebated HPs	Notes
					value two rows prior. Therefore, the DNV team concludes that 63 kWh per 1,000 Btu/h represents **a reasonable upper-bound average annual HP consumption estimate.**

Based on the various PRISM pre/post and post-only analyses, the DNV team estimated a range of average annual normalized heating energy use between +44 and +63 kWh per 1,000 Btu/h rated capacity. This range corroborates the normalized annual heating energy use result of +62 kWh per 1,000 Btu/h as derived from M&V sites (Section 4.2.6).

4.3.3 Calibrating with M&V data through machine learning

The team next tried to improve the AMI analysis by calibrating its modeling assumptions with equipment-level M&V data. The DNV team employed machine-learning concepts that involve fitting a random forest regression model to metered heat pump energy use, as determined through the M&V phase of this study, among a variety of relevant independent variables including the coincident hourly AMI data, weather, hour of day, and day of the week. The best model is selected through a process of testing and validation. This study included 22 sites (covering 44 HPs) with AMI data and coincident M&V data.

The team trained the regression models using data associated with 17 sites (the training data set), and then tested model accuracy on 5 sites that were withheld (the testing dataset). The process is repeated using all combinations of training/testing datasets, and the model with the lowest total hourly residual error is selected.[44] Appendix C contains a detailed comparison of results from traditional PRISM and machine-learning methods. In the end, the DNV team determined that the sum of the residual error was not significantly different for these methods, with the standard PRISM model overestimating electric heating energy use by 7% more overall than the machine learning model.

The DNV team next investigated factors that could explain the difference between metered and modeled estimates, focusing on data that can be readily identified and used in subsequent evaluation efforts when HP metered data might not be available. Examples of such information include building type, installed heating capacity per square foot of conditioned space, AMI temperature dependence, and change in cooling use before and after heat pump installation.

4.3.3.1 AMI results by facility type

Table 4-18 lists the HP heating use estimates by facility type and margin of error. Multifamily was the only facility type with average HP heating use that was statistically different from the population. A result has statistical significance if the average +/- margin of error is greater or less than that of the population—i.e., the error bounds of both groups do not overlap.

[44] For this analysis, sub-meter M&V data is considered the most accurate estimate of real-world operation.

Table 4-18. Normalized Annual Heating Use by Building Type from AMI Results

Building Type	Count	HP Heating Use Estimate (kWh per 1,000 Btu/h)	Relative Precision at 90% Confidence Interval	Margin of Error	Coefficient of Variation
All Other Types*	123	72.4	12.4%	8.9	0.83
Other*	85	75.3	16.1%	12.2	0.89
Office	82	73.3	16.2%	11.9	0.88
Retail	28	72.2	26.4%	19.0	0.82
Multi-Family	21	38.3	46.3%	17.8	1.23
Lodging	19	47.7	42.4%	20.3	1.07
Total	**358**	**69.9**	**7.7%**	**5.44**	**0.89**

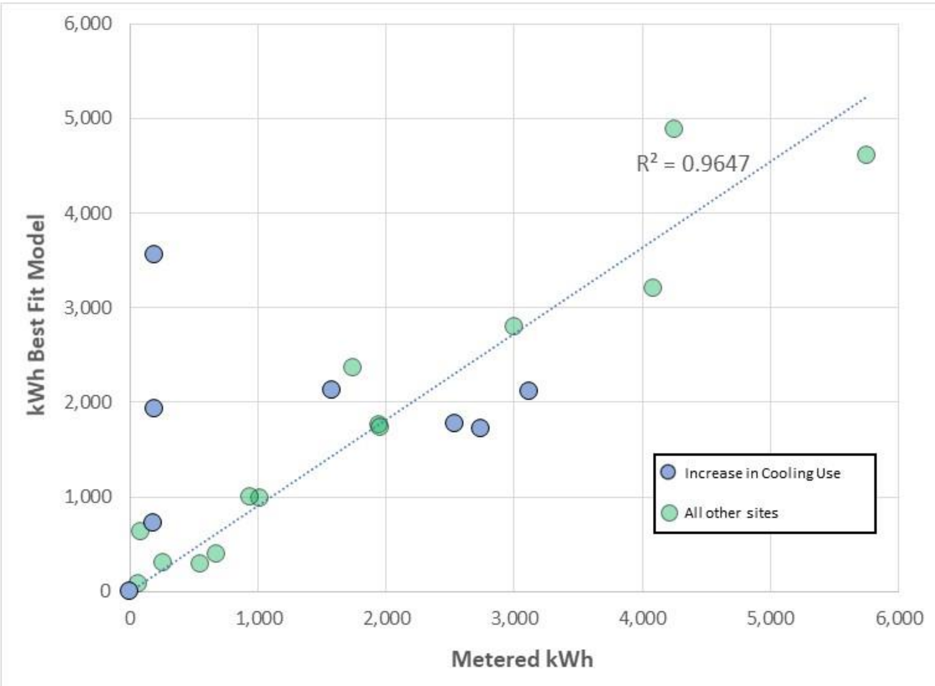
* The group "All Other Types" includes, for example, retail, restaurant, health, manufacturing, and religious. "Other" was reported as Other in the tracking data, meaning these building types could not be categorized into the typical building segment names or the type was unknown.

As discussed in Section 4.2.6, the M&V findings showed normalized heating energy use from HPs in multifamily buildings similar to other commercial building types. Conversely, results from AMI analysis suggest multifamily buildings have the lowest HP heating energy usage of the building types listed in Table 4-18. One plausible explanation for the contradictory result could be attributed to the higher prevalence of multiple AMI meters per multifamily facility. Compared to all other building types, multifamily HP installations were more likely to be associated with more than one AMI meter; therefore, the probability of selecting the wrong AMI meter was higher for this segment.

4.3.3.2 AMI results by change cooling use

The number of comparison points (n=22) is relatively small, but the team was able to identify another potential predictive factor that should be considered: an increase in cooling energy use as a result of HP installation. 8 of 22 sites in the comparison pool showed an increase in cooling use after HP installation, suggesting a non-routine change in facility conditions that may invalidate the use of pre-installation data as representative of baseline. When these 8 sites were removed (identified by blue points in Figure 4-8) the R^2 improves from 0.82 for all data (green and blue points) to 0.96 (green points only), while the AMI-to-M&V ratio (1.05 as illustrated by the blue line) remains unchanged.

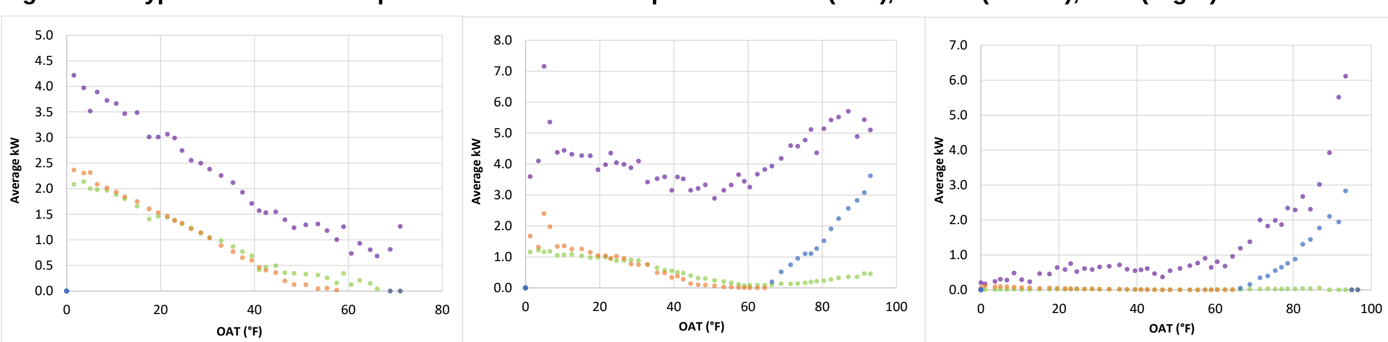
Figure 4-8. Comparison of Annual Heating Energy between Machine Learning AMI (y Axis) and M&V (x Axis)



4.3.3.3 AMI results by temperature dependence

The team also discovered one other noteworthy factor through visual inspection of the metered data and AMI data: temperature dependence of AMI data. The team identified three unique temperature-dependent AMI load shape patterns that correlated with metered to modeled ratios: 1) "full displacement," meaning heat pumps are used as the exclusive or primary heat source in a building, room, or space; 2) "partial displacement," meaning heat pumps installed in conditioned space and used with other heating systems; and 3) "low, unpredictable usage", meaning heat pumps used irregularly, rarely, or never for heat. Figure 4-9 illustrates examples of the three load shape patterns as a function of outside air temperature. Appendix C includes regression coefficients for each load shape that could be leveraged in future evaluations.

Figure 4-9. Typical AMI Load Shapes vs. Outside Air Temperature* - Full (Left), Partial (Middle), Low (Right)



** Purple = AMI raw data. Orange = AMI heating usage estimate. Green = M&V data. Blue = AMI cooling usage estimate.*

Table 4-19 shows the normalized heating energy results correlated with displacement level according to the survey respondent. The full-displacement usage (104 kWh per 1,000 Btu/h rated capacity) was higher than the low- and partial-displacement usage values, but the differences were not statistically significant. The subset of sites with AMI data that also had M&V data and survey responses (n=13) suggests the M&V results for "full" displacement better align with expected usage. The number of sites with survey responses, AMI pre/post data, and M&V data, however, were too few to develop an assertion about the value of survey responses – the differences were not statistically significant.

Table 4-19. Normalized Annual Heating Use by Heating Displacement Magnitude from AMI Results

Displacement Magnitude	Survey Count (With AMI Data)	AMI Heating Energy (kWh per 1,000 Btu/h)	Metered Count (M&V)	M&V Data (kWh per 1,000 Btu/h)
Low	12	51.5	0	N/AA
Partial	35	58.3	6	26.1
Full	24	104.3	7	105.4
Total	**71**	**75.7**	**13**	**68.1**

Future HP rebate recipients will include customers at different facility types, customers that expanded their conditioned space, customers that adjusted their temperature setpoints, or customers that partially offset their fossil fuel-fired heating system. The distinctions illustrated in Figure 4-8 and Figure 4-9 should not be used to exclude certain customers from future evaluation samples—that would bias the results—but could be leveraged to maximize precision and minimize the sample sizes required for defensible results.

4.3.4 Pre/post heating fuel analysis

Another way of approaching the premise-level HP impact analysis is from the perspective of the displaced heating fuel. In parallel with the AMI-based analysis, the DNV team, with support from Efficiency Maine, expended significant effort collecting and analyzing fuel delivery data. However, the team had limited success triangulating results when comparing fossil fuel consumption decreases[45] with heating electricity increases as determined from M&V and AMI analyses. The results of this analysis are included to show the site-by-site variance in fossil fuel impacts that could be attributed to heat pump usage during the heating season. Additionally, this section includes two case studies that illustrate ideal and problematic scenarios when comparing HP impacts from fuel delivery, AMI, and M&V perspectives.

The DNV team requested heating fuel delivery data from all program participants completing the survey. 106 surveyed participants reported using some type of delivered fossil fuel before and/or after heat pump installation; ultimately, the DNV team received data from 30 participants comprising 46 HP installations. Of the 30 participants, the DNV team could not retrieve pre-installation fuel usage data for 5, and 4 showed an increase in fuel use, leaving 21 datasets with sufficient pre/post fuel usage data.

Table 4-20 illustrates the site-by-site results from three analysis methods: pre/post fuel consumption analysis, AMI analysis, and M&V analysis. The table shows annual heating load estimates before and after the HP installation, normalized to TMY3 typical weather conditions. The table also illustrates the difference in heating energy use by estimating an equivalent kWh value from the change in fossil fuel use. The team converted fossil fuel MMBtu to an equivalent annual electric energy use (heating kWh). The heating kWh values, calculated from the observed change in fossil fuel MMBtu, represents the electric energy that a heat pump would use to make up for the observed fossil fuel decrease. To convert MMBtu to kWh, the team assumed a fossil fuel heating system combustion efficiency of 80% and an average rated HSPF of all heat pumps installed at each site (10.2 HSPF)[46]. The rightmost columns of the table include blank fields for which AMI and/or M&V data was not available.

[45] See Section 3.5.2.2 and Appendix C for the approach used to estimate fossil fuel heating use change.

[46] Analysts assumed rated HSPF, not effective HSPF, in this calculation for fair comparison with assumed rated combustion efficiency. This study's M&V activities did not include data collection on effective combustion efficiency of the legacy fossil fuel-fired boilers or furnaces.

Table 4-20. Site-by-Site Comparison of Delivered Fuel Analysis, AMI Analysis, and M&V Analysis Results

Index	Fuel Type	Annual Heat Load Associated with Fossil Fuel before HP Install (MMBtu)	Annual Heat Load Associated with Fossil Fuel after HP Install (MMBtu)	% Change Reduction in Annual Fossil Fuel Heat Load	Annual Heat Pump Heating Electric Energy Use (kWh)		
					MMBtu From Fuel Data Analysis Converted to kWh	From Electric AMI Analysis	From Electric Equipment M&V Analysis
1	#2 Fuel Oil	363	304	16%	3,785	3,086	285
2	#2 Fuel Oil	87	19	78%	5,710	2,709	2,836
3	#2 Fuel Oil	405	393	3%	911	342	428
4	#2 Fuel Oil	60	58	4%	221	81	171
5	#2 Fuel Oil	277	234	15%	3,508	2,458	3,352
6	#2 Fuel Oil	92	73	20%	1,487	4,352	
7	#2 Fuel Oil	71	57	20%	1,204	4,142	
8	#2 Fuel Oil	277	234	15%	1,169	633	
9	Propane	25	6	77%	1,726	5,634	
10	#2 Fuel Oil	88	8	92%	6,576	1,413	
11	#2 Fuel Oil	59	25	58%	3,367	5,130	
12	#2 Fuel Oil	92	69	25%	1,682	539	
13	Propane	3	1	42%	105	6,864	
14	#2 Fuel Oil	381	295	23%	7,408		183
15	#2 Fuel Oil	41	3	91%	3,024		2,658
16	#2 Fuel Oil	927	882	5%	4,187		
17	#2 Fuel Oil	197	155	21%	3,003		
18	#2 Fuel Oil	113	55	52%	4,902		
19	#2 Fuel Oil	123	12	91%	8,186		
20	#2 Fuel Oil	100	0	100%	9,051		
21	#2 Fuel Oil	320	295	8%	2,474		
Average from Fuel Analysis					3,509 (n=21)		
Average for Sites with Fuel + AMI		195	151	23%	2,419 (n=13)	2,876	
Average for Sites with Fuel + M&V					3,510 (n=7)		1,416

The average change in annual fuel heating use (44 MMBtu, a 23% decrease) is approximately equivalent to 397 gallons of oil saved (assuming 138,500 Btus per gallon of oil, 80% efficiency). This 23% decrease is equivalent to 3,509 kWh of added electric load on average per year.

13 sites had sufficient data for pre/post fuel consumption analysis and AMI analysis. Among these 13 sites, the DNV team determined a lower electric heating kWh increase in both analysis approaches. 7 sites overlapped between the M&V sample

and the pre/post fuel consumption analysis pool; M&V data from these 7 sites showed 60% lower electric heating kWh increase than from the pre/post fuel analysis. Given the low sample sizes in overlaps among pre/post fuel analysis, AMI analysis, and M&V analysis approaches, the DNV team is unable to draw broader conclusions on these differences. However, these results suggest pre/post analysis of oil and propane data may not be a reliable method for estimating heat pump heating energy use. Table 4-21 presents the same results normalized by total installed HP heating capacity and illustrates that variation in HP capacity[47] was not a key driver of the differences in Table 4-20.

Table 4-21. Site-by-Site Comparison of Normalized Fuel Analysis, AMI Analysis, and M&V Analysis Results

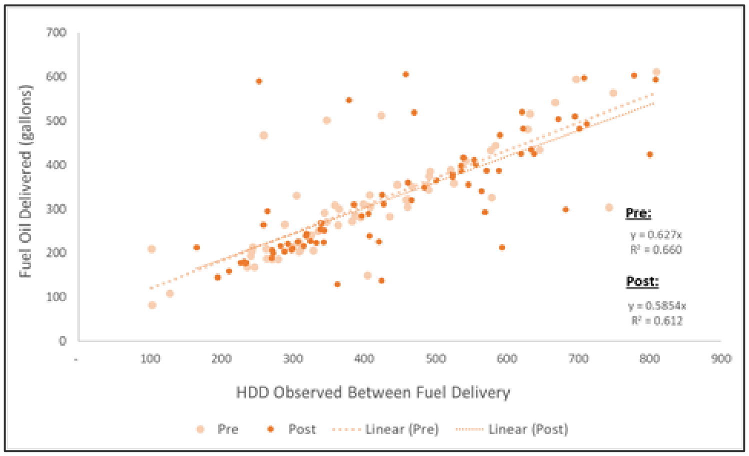
Index	Fuel Type	Annual Heat Load from Fuel Data Analysis (MMBtu)	Total Installed HP Heating Capacity (1,000 Btu/h)	Normalized Annual Program Heat Pump Heating Electric Energy Use (kWh per 1,000 Btu/h)		
				From Fuel Data Analysis	From Electric AMI Analysis	From Electric Equipment M&V Analysis
1	#2 Fuel Oil	59	10.9	347	283	26
2	#2 Fuel Oil	68	36.4	157	74	78
3	#2 Fuel Oil	12	18	51	19	24
4	#2 Fuel Oil	2	48.8	5	2	4
5	#2 Fuel Oil	43	36.6	96	67	92
6	#2 Fuel Oil	19	49.6	30	88	
7	#2 Fuel Oil	14	12	100	345	
8	#2 Fuel Oil	43	36	32	18	
9	Propane	19	22	78	256	
10	#2 Fuel Oil	80	108	61	13	
11	#2 Fuel Oil	34	44	77	117	
12	#2 Fuel Oil	23	18	93	30	
13	Propane	2	48	2	143	
14	#2 Fuel Oil	86	54.9	135		3
15	#2 Fuel Oil	38	36	84		74
16	#2 Fuel Oil	45	18.9	222		
17	#2 Fuel Oil	42	12	250		
18	#2 Fuel Oil	58	31.6	155		
19	#2 Fuel Oil	111	64	128		
20	#2 Fuel Oil	100	147	62		
21	#2 Fuel Oil	25	25	99		
Average from Fuel Analysis				108 (n=21)		
Average for Sites with Fuel + AMI		44		87 (n=13)	112	
Average for Sites with Fuel + M&V				125 (n=7)		43

47 The evaluation did not assess whether the installed systems were over- or under-sized to meet the heating and cooling loads at sampled facilities. As a result, the normalized results in Table 4-21 could be skewed by installations with oversized HPs.

The next sections provide case studies of two sites that had AMI, fuel delivery, and M&V data.

4.3.4.1 Case study: poor correlation

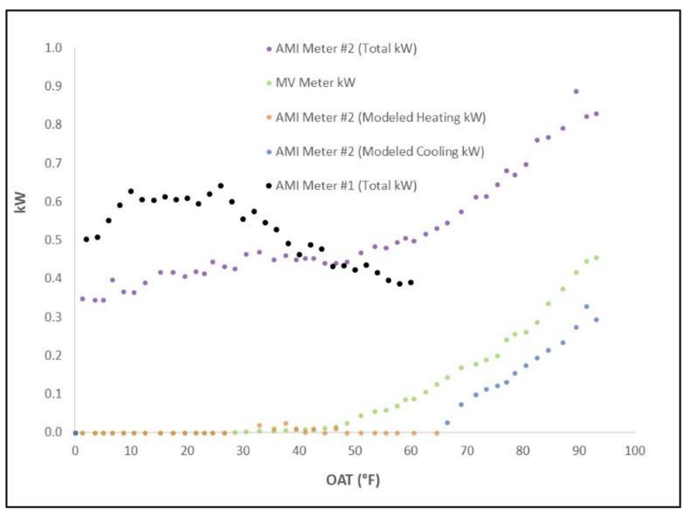
As an example of the complexities with AMI and fuel delivery data analysis, this site showed frequent oil deliveries spanning multiple years, with a strong temperature-dependent consumption signature (see figure below). Comparing weather-normalized pre- and post-install consumption values showed annual oil savings of 118 gallons (16 MMBtu) per year.



Site and HP Information:

- **Installation date**: *10/15/2018*
- **Facility**: *Multifamily, 8,256 square feet total, 800 square feet of HP conditioned area*
- **HP**: *one single-zone unit*
- **Heating ratings**: *13.4 HSPF, 14,500 Btu/h*
- **Cooling ratings**: *25.3 SEER, 18,000 Btu/h*
- **Additional heating**: *oil boiler with separate (non-integrated) thermostat, boiler and HP used simultaneously 75% of the time*
- **Baselines**: *oil boiler, window A/C*

The site had two AMI meters, one with a very clear heat signature (1,514 kWh/yr heating) and the other with much lower apparent electric heat use (228 kWh/yr heating). The team initially analyzed the AMI meter with higher heating energy use. However, M&V data were available for this site, and there were instances that the M&V hourly usage exceeded the coincident total AMI usage– a clear indication the initial AMI meter selection was incorrect. The team next analyzed the alternate AMI meter. The figure below shows average total AMI meter data for both meters. The correlation labeled “AMI Meter #1” (black plot) shows a stronger heating energy signature whereas the other AMI meter (purple plot, “AMI Meter #2”) has very little or no apparent increase in energy use as temperature decreases. The heating use estimated from this meter (orange plot) is low but aligns closely with the M&V data (green). Another observation about heat pump operation at this site is the cooling use at relatively cold temperatures. Comparing green (M&V) and blue (AMI disaggregation analysis), the AMI analysis did not estimate cooling consumption until the outdoor temperature exceeded about 65 degrees. This case study illustrates the hazards with premise-level analysis: low usage leading to high volatility in results, multiple AMI meters, and mismatch between fuel decrease and expected electricity increase.



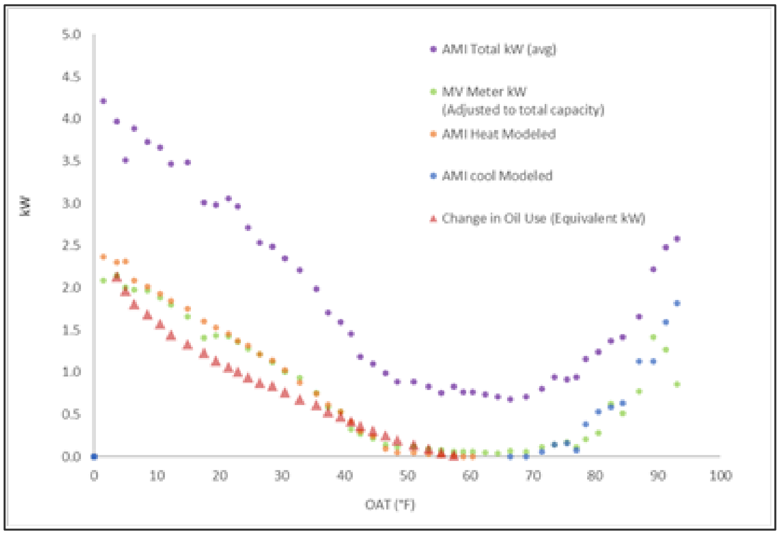
4.3.4.2 Case study: strong correlation

This "ideal" example of premise-level analysis showed alignment in annual electric heating energy use among AMI, fuel delivery, and M&V data analysis approaches. The DNV team was initially confident that the site might show meaningful results, as its survey responses confirmed no change in conditioned space, confirmed complete removal of the pre-existing oil-fired boiler, and confirmed that the new HPs are the only heating equipment serving the space. Barring unknown non-routine events, these characteristics should theoretically show strong heating signatures and alignment between electric and fossil fuel data. The three sets of results aligned within 20%:

- Annual electric heating energy use from AMI analysis: 67 kWh per 1,000 Btu/h
- Equivalent normalized kWh estimate from fuel delivery analysis: 96 kWh per 1,000 Btu/h
- Annual electric heating energy use from M&V analysis: 92 kWh per 1,000 Btu/h

This alignment is illustrated in the right-hand figure. This example shows that AMI or fuel-based analysis can be viable, but a number of caveats must be met.

<u>Site and HP Information:</u>
- ***Installation date**: 12/5/2019*
- ***Facility**: Office, 1,950 square feet*
- ***HP**: one two-zone unit*
- ***Heating ratings**: 11.2 HSPF, 22,400 Btu/h*
- ***Cooling ratings**: 21.7 SEER, 34,400 Btu/h*
- ***Additional heating**: none*
- ***Baselines**: oil furnace, window A/C*



4.3.5 Viability of premise-level analysis

The PRISM, machine-learning, and delivered fuel analysis results illustrated the following conclusions on whether premise-level analysis is a viable approach for heat pump program evaluation.

- **Collecting and cleaning pre-install AMI data is worthwhile**. The DNV team found significant differences in electric heating energy attributable to rebated HPs between pre/post AMI analysis and post-only AMI analysis approaches. Pre/post analysis is likely to underestimate HP consumption, while post-only analysis likely overestimates consumption due to the presence of other electric heat sources not attributable to the program. Review of pre-install AMI data will allow future analysts to categorize sites into appropriate segments to minimize uncertainty.
- **AMI data for HVAC interventions can be categorized into three heating load shapes**: 1) "full displacement" – continuous increase with decreasing temperature, 2) "partial displacement" – increase with decreasing temperature up to the switchover point, and 3) "low usage" – no apparent heating signature. Again, classification of sites into distinct categories will minimize uncertainty (e.g., the low-usage site results will not affect the full-displacement site results). The standard PRISM disaggregation model, coupled with hourly coefficients determined in this study (see Appendix C), should be used for future evaluations.
- **Facilities with more than one AMI meter were more likely to exhibit questionable results.** Multifamily buildings demonstrated statistically significantly low heating usage, but the DNV team questions the validity of this finding. Billing analysis at multifamily facilities is historically unreliable due to the likelihood of multiple utility meters serving common areas and tenant units. That proved true in this study, as multifamily buildings had the highest share (50%) of AMI data

determined to be "not viable." Further contradicting the AMI result is the M&V data, which showed multifamily as having the highest heating output among the three sampled facility types.

- **Sites showing an increase in cooling usage suggest non-routine changes may have occurred between pre- and post-installation periods.** Approximately half of the AMI analysis pool showed an increase in cooling usage after HP installation, calling into question the validity of pre/post comparison. Non-routine events (e.g., change in occupancy or business hours, space expansion) likely occurred at some sites, thereby disqualifying the pre-installation data as representative of baseline. In such cases, analysis of post-installation AMI data only may be most appropriate. Another explanation for increased cooling use, described in Section 4.1.1.2, is reported change in comfort. About one in four (27%) respondents said they typically keep the space cooler in the summer with the heat pump.
- **Participant survey data did not always align with AMI observations**. When comparing AMI heating energy estimates with participants' self-reported usage patterns, the DNV team found only modest differences among the different usage categories. For example, systems reported as used only rarely or partially had only 6% lower heating consumption than those reported to be used as the primary source of heat. Several anecdotal findings from site visits (e.g., observed use of electric space heaters at one site, addition of a separate heat pump) sometimes explained why survey responses are not always reliable. As described in Section 4.3.3, clustering similar sites into various cohorts—by facility type, by displacement magnitude—may limit the impact of this uncertainty on the larger evaluation pool.

4.4 Net impact results

This section presents the net-to-gross (NTG) evaluation results for HP measures rebated by the program. The NTG ratio (NTGR) is defined as:

$$NTGR = 1 - Freeridership + Spillover$$

The DNV team estimates a measure-level NTGR of 73%, as indicated in Table 4-22.

Table 4-22. Measure-Level Net-to-Gross Ratio

Program/Measure	Free-Ridership	Spillover	NTGR
C&I Prescriptive – Ductless Heat Pump	35%	8%	73%

Sections 4.4.1 and 4.4.2 further explore the free-ridership and spillover results, respectively.

4.4.1 Free-ridership results

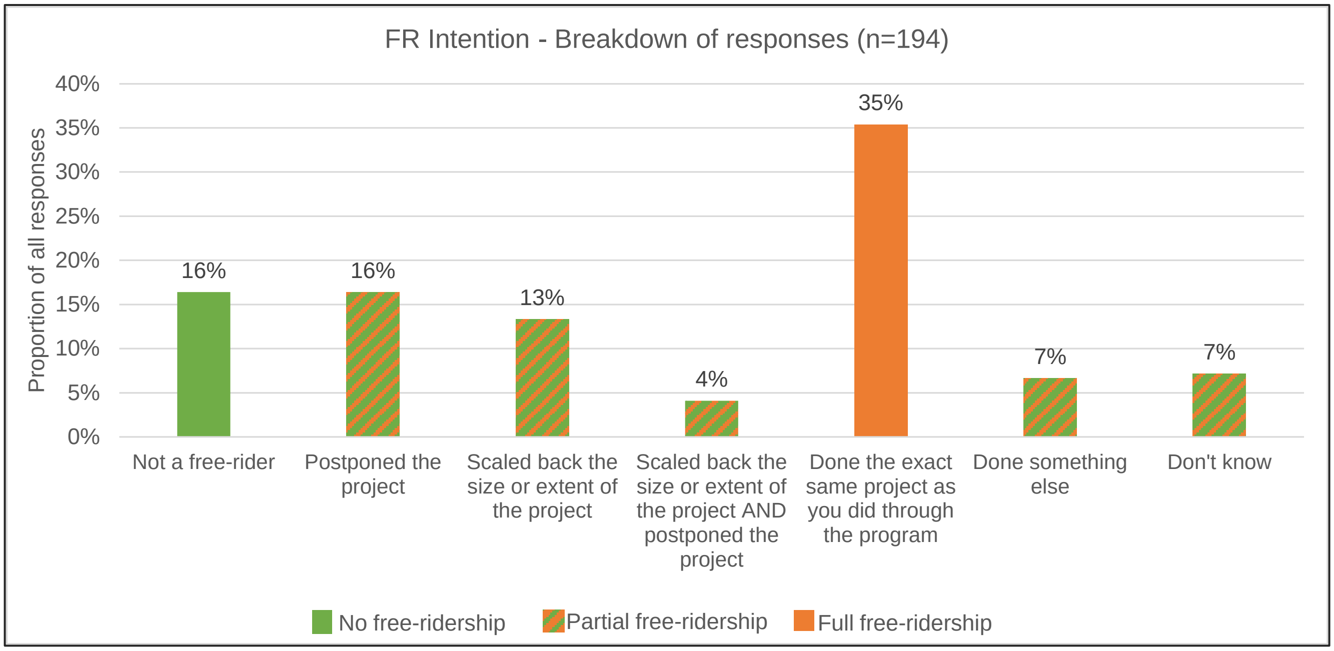
The free-ridership survey questions focused on the most likely scenario that participants would have pursued if they had not received the heat pump rebate,[48] exploring likely impacts on project size and timing. The free-ridership calculation methodology is detailed in Appendix A. The DNV team also asked about any other funding sources received and the influence of the program on deciding to install a heat pump through the program.

The DNV team determined a 35% free-ridership rate for the HP measures rebated over the evaluation timeframe. A total of 194 participants provided valid responses to the free-ridership questions in the participant survey and were included in the analysis. As explained further in Appendix A, the free-ridership rate is comprised of two components: intention and influence. DNV analysts determined intention and influence scores of 48% and 22%, respectively, on a percentage scale with 100% denoting a full freerider. 35% of respondents indicated that they intended to complete the identical project, even if

[48] As discussed in Section 3.5.2, gross baseline determination for new construction or normal replacement projects also included information on the customer's preferred alternative heating and cooling systems absent the program. For each project overlapping between the M&V sample (n=70) and the NTG respondent pool (n=194), the DNV team compared the gross baseline and NTGR results to ensure no double-counting. Since the net-to-gross results are in the form of a ratio applied to the gross savings, for projects for which the customer would have installed a HP anyway, the NTGR further reduces the incremental gross savings depending on the factors discussed in the next paragraph.

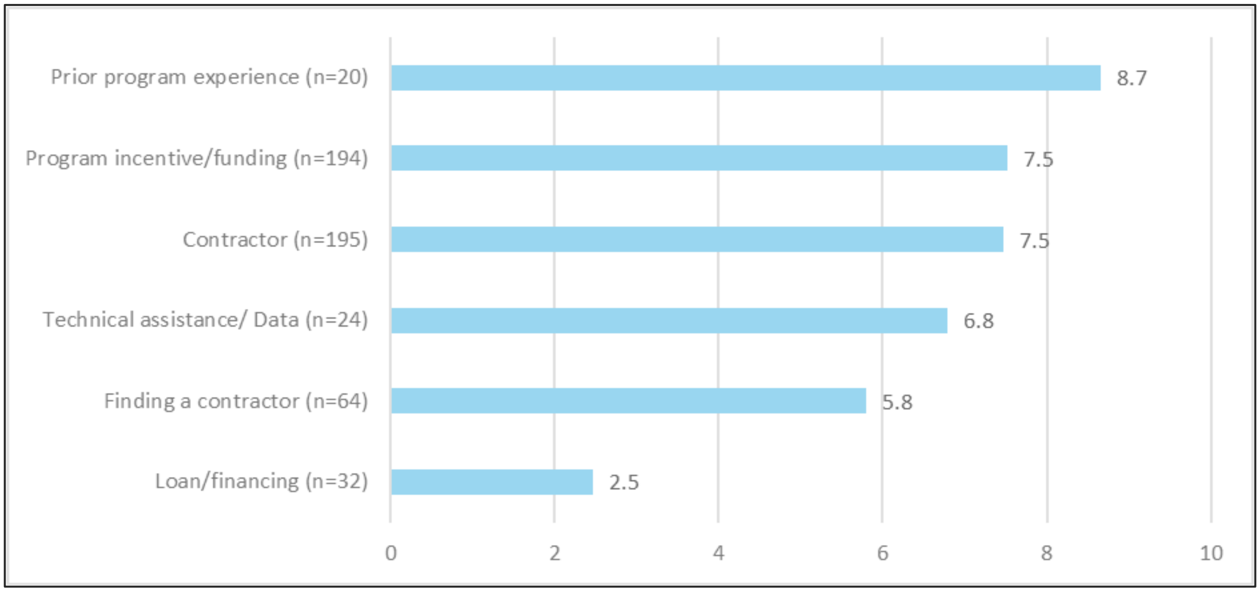
the program and rebate did not exist; such respondents were determined to be full free riders (see Figure 4-10). Another 33% of respondents revealed partial free-ridership where, without the program, they would have scaled back or postponed their project. Among respondents who would have postponed their project, a majority (55%) would have postponed more than one year, indicating the program's influence in accelerating energy savings. Note that there were 13 respondents who indicated they would have done something else in the absence in the program; the DNV team reclassified these responses into other response categories based on their open-ended responses.

Figure 4-10. Free-Ridership Intention Distribution (n=194)



The most influential program factors were prior experience with the program, the program incentive, and contractor. On a scale of 0 being "not at all influential" to 10 being "extremely influential", participants who had participated in the program in prior years indicated a high level of influence (8.7 out of 10) to proceed with a HP project due to past participation. As shown in Figure 4-11, other factors provided lower levels of influence but were generally more influential than not.

Figure 4-11. Average Influence of Individual Program Factors on Customer Decision to Proceed with HP Project (10 = Extremely Influential)



4.4.2 Spillover results

To assess spillover for the heat pump program, we estimated both participant spillover (PSO) and non-participant spillover (NPSO). The sum of these two spillover values is the estimate of overall program spillover. The Spillover calculation methodology is detailed in Appendix A.

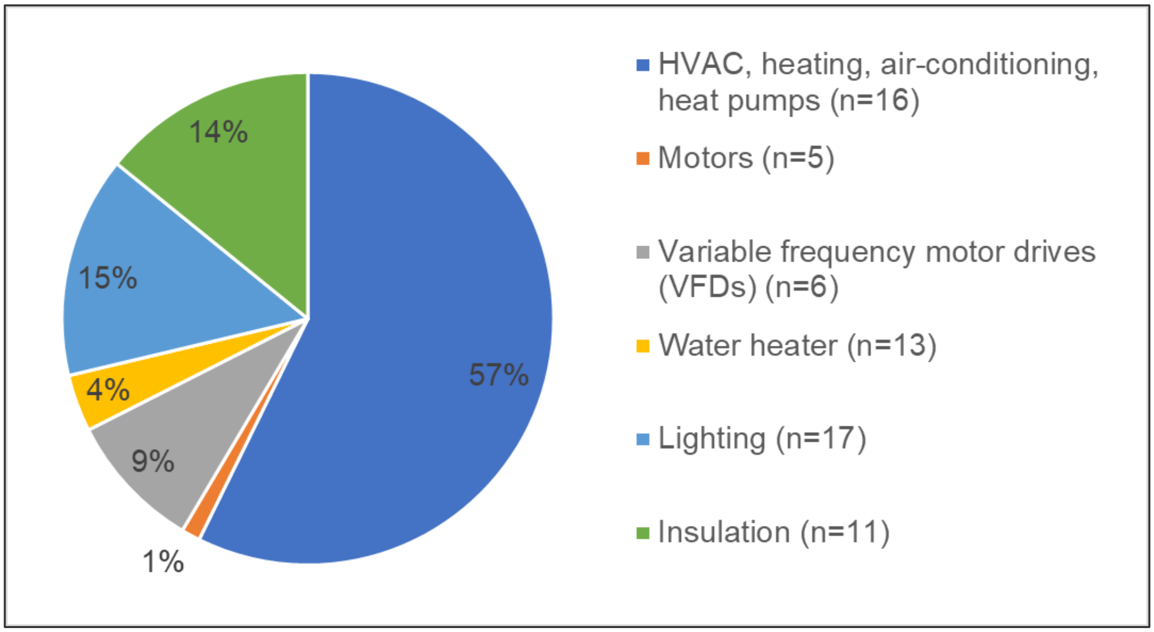
4.4.2.1 Participant spillover

Based on the survey findings and measure-level analysis, the DNV team estimates the PSO to be 6% of program-reported site MMBtu savings. A total of 196 participants completed the PSO survey questions. About a third of participants surveyed (60 of 196) indicated they installed additional energy efficiency measures after participating in the program for which they did not receive an incentive. The most commonly reported spillover measure categories were lighting,[49] HVAC, and water heating. Note that 12 customers indicated installing Solar/PV as a measure after participating in the program.[50] Figure 4-12 shows the portion of total spillover savings attributable to each measure. The HVAC measure group was the primary driver of PSO site MMBtu savings, accounting for 57% of total PSO.

[49] The DNV team understands that lighting projects in Maine generally receive an incentive. The survey confirmed with the customer that they did not receive an incentive for any measures considered in PSO analysis. We did not attempt to verify this further.

[50] Solar PV projects were excluded from PSO analysis.

Figure 4-12. Distribution of Participant Spillover Site MMBtu Savings by Category



4.4.2.2 Non-participant spillover

The DNV team determined NPSO savings of 2% of program-reported site MMBtu savings, resulting in a total spillover rate of 8%. A total of 30 vendors completed the NPSO survey questions. About a quarter of vendors (7 of 30 vendors) reported to install at least one additional project that would have qualified for an incentive but did not receive one.[51] The team also interviewed vendors on two aspects of influence considered in the NPSO calculation: 1) the program's influence on the vendor's recommendations to install qualifying heat pumps, and 2) the vendor's influence on the customer to install qualifying heat pumps. Our analysis shows that vendors find themselves influential to a customer's decision-making (8.6 out of 10) and that the program is somewhat influential to a vendor's recommendation for qualifying HPs (6.7 out of 10).

4.5 Cost/benefit analysis

The DNV team applied the gross and net savings results from this study to Efficiency Maine's Cost Benefit Analysis Tool (CBAT) to assess the cost-effectiveness of C&I HP measures. Table 4-23 shows the benefit/cost ratio (BCR) for the prescriptive HP measures offered by the program over the evaluation timeframe. The DNV team ran several iterations of the CBAT using the avoided cost values in effect during the evaluated period (AESC 2018, updated to reflect 2021 dollars) and using the avoided cost values approved for Triennial Plan V that started July 1, 2022 (AESC 2021[52]). BCRs are distinguished by sector (commercial, multifamily), HP configuration (single-zone, multi-zone), and installation type (retrofit, lost opportunity) to capture differences in cost and benefits among different scenarios. Values in green indicate BCRs that pass the cost-effectiveness threshold of 1, and values in red indicate BCRs below the cost-effectiveness threshold. Section 4.5.1 summarizes the underlying assumptions considered in the cost-benefit analysis.

[51] 4 of the 7 indicated only one additional project without an incentive, whereas the remaining 3 estimated an additional 5 to 11 projects.

[52] AESC 2021 avoided costs incorporate non-embedded costs of carbon.

Table 4-23. Benefit-Cost Ratio Results among Various Segments, 2018 and 2021 AESC Screening Methods

HP Type	Sector	Event Type	n	AESC 2018, Evaluated Gross	AESC 2021, Evaluated Gross	AESC 2018, Evaluated Net[1]	AESC 2021, Evaluated Net[1]
All	**All**	**All**	**70**	**0.79**	**1.07**	**0.79**	**1.07**
All	Multifamily	All	23	0.61	0.88	0.61	0.88
All	Commercial	All	47	0.92	1.21	0.92	1.21
Single-Zone	Multifamily	All	14	0.59	0.83	0.59	0.83
Single-Zone	Commercial	All	31	0.88	1.26	0.88	1.26
Single-Zone	All	All	45	0.76	1.08	0.76	1.08
Multi-Zone	Multifamily	All	9	0.71	0.93	0.71	0.93
Multi-Zone	Commercial	All	16	0.94	1.15	0.94	1.15
Multi-Zone	All	All	25	0.83	1.05	0.83	1.05
Single-Zone	All	Retrofit[2]	31	0.61	0.87	0.61	0.87
Single-Zone	All	Lost Opportunity[2]	14	1.70	2.28	1.70	2.28
Multi-Zone	All	Retrofit[2]	19	0.69	0.87	0.69	0.87
Multi-Zone	All	Lost Opportunity[2]	6	1.93	2.43	1.93	2.43

[1] Efficiency Maine follows the National Standard Practice Manual (NSPM) for Cost-Benefit Analysis and counts incentives paid to free riders as a passthrough that has no impact on the calculated benefit-to-cost ratio. As a result, net BCRs are identical to their gross counterparts.

[2] The evaluation sample did not include any projects that were classified by the program as Retrofit. The DNV team reclassified the 70 HP systems sampled for M&V into the appropriate event type based on evaluation baseline.

The table shows that prescriptive HP measures overall were cost-effective when considering the avoided costs in effect at the time of this writing (AESC 2021). HP installations at Multifamily facilities incurred slightly more costs than benefits due to a higher prevalence of retrofit projects which incur full installation costs. For that segment, the DNV team determined that the tenants did not use the HPs enough during the heating season to displace sufficient fossil fuel heating to overcome the full installation costs of the HPs. BCRs using the avoided costs in effect during the evaluated period (AESC 2018) generally fell below 1. As shown in the last four rows of the table, Lost Opportunity installations, for which the costs and benefits reflect a federal standard HP baseline, were significantly more cost effective than Retrofit installations.

Table 4-24 presents a sensitivity analysis of BCR results by adjusting various inputs—evaluated gross savings and costs—using the AESC 2021 test.

Table 4-24. Benefit-Cost Ratio Results with Varying Gross Savings and Costs

AESC 2021 at Various RRs and Costs	All HPs n=70	Multifamily n=21	Commercial n=49
Upper bound of 80% CI of verified gross savings, medium costs	**1.75**	1.83	2.13
Lower bound of 80% CI of verified gross savings, medium costs	**0.60**	0.38	0.64
Upper bound of 80% CI of verified gross savings, low costs	**2.08**	2.19	2.52
Lower bound of 80% CI of verified gross savings, high costs	**0.50**	0.33	0.54

Table 4-24 shows that upper-bound gross savings led to BCRs beyond 1, even in the Multifamily sector with a prevalence of Retrofit installations. Lower-bound gross savings led to BCRs well below 1, even in the Commercial sector with a prevalence of Lost Opportunity installations. Adjusting the costs increased and decreased the BCRs accordingly.

4.5.1 Cost-benefit analysis assumptions

The DNV team applied the following assumptions in the cost-benefit analysis:

- Incremental and full measure costs are summarized in Table 4-25 and were derived from the following sources:
  - Averages of site-specific equipment and labor costs as recorded in program tracking database for sampled HPs,
  - Efficiency Vermont Technical Reference Manual,[53]
  - Cost assumptions currently reflected in CBAT.

Table 4-25. Full, Baseline, and Incremental Cost Assumptions and Sources

Installation Category	Full Cost	Baseline Cost	Incremental Cost	Source
Single-zone, Retrofit	$3,139	N/A	N/A	Average of tracked costs among M&V sample data – single-zone installations
Single-zone, Lost Opportunity	$2,763	$2,238	$525	EVT TRM 2018 based on average equipment ratings from evaluation sample
Multi-zone, Retrofit	$5,704	N/A	N/A	Average of tracked costs among M&V sample data – multi-zone installations
Multi-zone, Lost Opportunity	$3,660	$3,223	$436	EVT TRM 2018 based on average equipment ratings from evaluation sample

- Program incentives for multi-zone HPs vary by number of zones served. To estimate the average incentive across all multi-zone installations, the DNV team calculated a weighted average incentive value based on the number of zones served by the multi-zone HPs in the evaluation sample.
- The DNV team consolidated the various baseline scenarios into two event types: Lost Opportunity and Retrofit. In isolated cases, a customer added a HP to a previously unconditioned or undeveloped space and stated that they otherwise would have modified their existing fossil fuel system to accommodate the new space. Since the savings for such installations is measured against an existing fossil fuel baseline—and since the HP cost is closer to full cost than incremental in such cases—the DNV team treated these installations as Retrofits in the cost-benefit analysis.
- In accordance with the NPSM, Efficiency Maine counts incentives paid to free-riders as a passthrough that has no impact on the calculated benefit-to-cost ratio.
- The DNV team did not include program administration costs in the BCR analysis, as the program rebates several other energy efficiency measures beyond HPs.

4.6 TRM insights

This section presents the results of the DNV team's analysis of equipment-level M&V data to reveal relevant operating parameters such as COPs[54] and heating and cooling outputs, both annualized and normalized to installed capacities. This analysis is intended to provide real-world HP operating characteristics to inform future iterations of the Efficiency Maine TRM.

Table 4-26 compares evaluation results with program-assumed parameters reflected in deemed savings values in the current Efficiency Maine TRM. Parameters are further investigated in the subsections following.

53 https://puc.vermont.gov/sites/psbnew/files/doc_library/Vermont%20TRM%20Savings%20Verification%202018%20Version_FINAL.pdf

54 This and other sections characterize performance by coefficient of performance (COP), which is a unitless measurement of energy output versus energy input. To compare evaluation results with equipment specifications, we also use effective heating season performance factor ($HSPF_e$) for heating or effective seasonal energy efficiency ratio ($SEER_e$) for cooling. Effective HSPF and SEER are equivalent to COP times 3.412 Btu per Watt-hour.

Table 4-26. Comparing Evaluation Results with Current TRM Parameters

Metric	Heating		Cooling	
	Current TRM	Evaluated	Current TRM	Evaluated
AHRI-Rated Capacity (Btu/hr)	20,644	22,401	17,589	19,877
Annual Average COP	2.47	3.17	4.99	6.73
Annual Output (MMBtu/yr)	25.05	9.80	3.14	2.83
Output ÷ Capacity (hrs/yr)	1,462	426	226	156

4.6.1 Heating output

As detailed in Section 3.5.1, the DNV team processed metered electric data and correlated it with outside air temperature-dependent performance curves to determine the annual heating output per sampled HP system. Figure 4-13 and Table 4-27 illustrate the annual heating output results by facility type, including both the orange-shaded core evaluation sample (n=70) and the grey-shaded complementary heating season M&V (n=33). The figure compares annual heating output (vertical bars) and the ratio of heating output to installed heating capacity (circular points) with values reflected in the current TRM's deemed savings (horizontal dashed lines). Table 4-27 summarizes the results by facility type.

Figure 4-13. Annual Heating Output per HP Installation by Facility Type

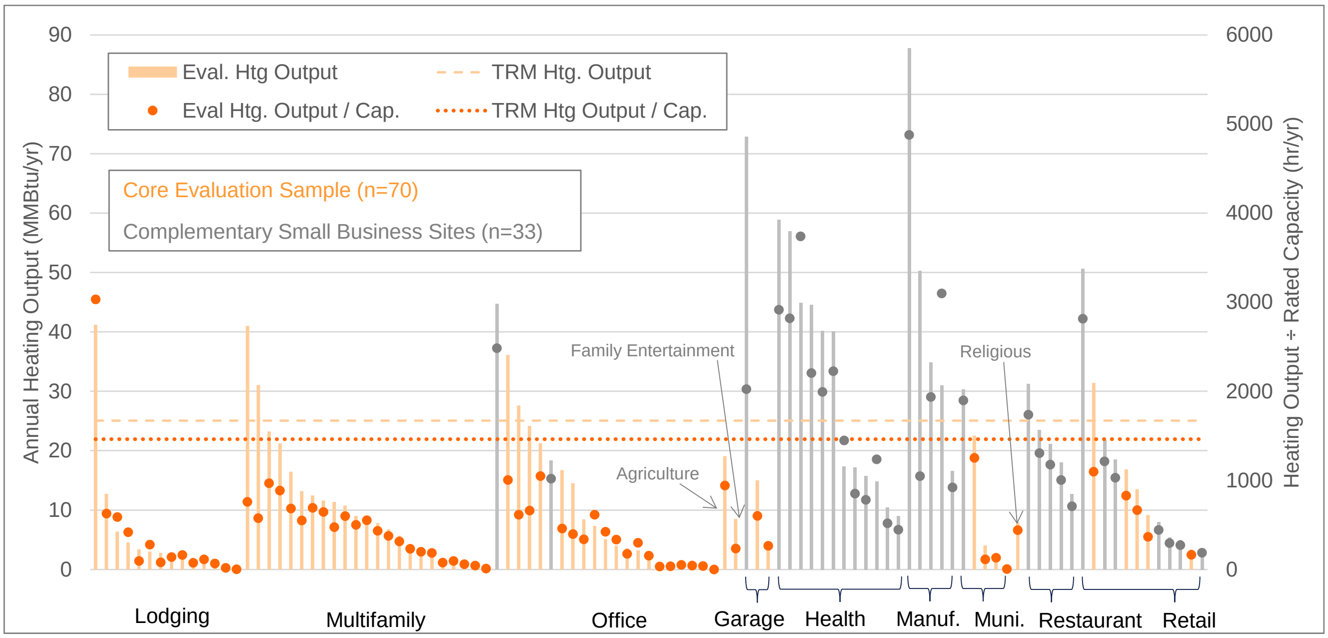


Table 4-27. Annual Heating Output per HP Installation by Facility Type

Facility Type	Count	Average Annual Heat Delivered (MMBtu/yr)	Annual Heat Delivered ÷ Rated Capacity (hr/yr)
Agriculture	1	19.1	941
Family Entertainment Center	1	8.5	234
Garage/Repair	3	30.7	963
Health/Wellness	12	30.8	1,764
Lodging	14	5.9	406
Manufacturing	5	44.1	2,375
Multi-family	23	10.7	431
Municipal/Government	5	11.8	679
Office	21	11.6	487
Religious	1	7.9	441
Restaurant	5	21.3	1,185
Retail	12	15.6	781

Among the core evaluation sample (orange bars), HPs at Multifamily facilities produced the highest heating output on average, whereas HPs at Lodging facilities produced the lowest average heating output.[55] Complementary M&V sites (grey bars) produced higher heating output on average than core evaluation sites, with Manufacturing and Garage/Repair facilities producing the highest heating output, though low sample size is a consideration. It is worth noting that small business sites selected for complementary M&V underwent additional screening during application pre-approval to confirm that those facilities are heated throughout the full heating season. Core sites did not undergo such additional screening, perhaps contributing to the difference in heating output observed between the two segments.

Overall, 82 of the 103 evaluated HPs had an annual heating output lower than the value assumed in the Efficiency Maine TRM. Conversely, 21 of the evaluated HPs had an annual heating output higher than the value assumed in the TRM, and 15 of the evaluated HPs had an annual heating output/rated capacity ratio higher than that assumed in the TRM. All facility types with more than one HP evaluated had at least one HP that exceeded the TRM assumptions on heating output and heating output/rated capacity ratio.

Figure 4-13 illustrates some notable outliers; the DNV team has provided additional context on one outlier HP to illustrate potential reasons for its relatively high output. The leftmost Lodging site differs markedly from other Lodging sites in the evaluation sample. This customer expanded their guest rooms to include a former storage space previously heated with an oil-fired boiler. The customer installed a single-zone HP with a rated heating capacity of 8,100 Btu/h. Since the HP was installed in a newly renovated space, the DNV team designated the installation as Lost Opportunity with a code-compliant HP baseline. The customer self-reported that the HP was the lone source of heating in the space, and that they use the HP continuously throughout the heating season. The HP is manually controlled and rarely adjusted.

[55] M&V site visits included interviews with facility representatives on topics such as seasonal fluctuations or lingering effects from the COVID-19 pandemic. Representatives from the 14 Lodging facilities included in the M&V sample stated that their operation had generally resumed to normal, and that the December 2020 – October 2021 metering period was representative of typical operation.

The DNV team also examined heating output by rated capacity to assess if higher-capacity HPs provide more heat. As Table 4-28 shows, higher-capacity units generally produced more heat than lower-capacity systems, though low sample size is a consideration for two strata in the complementary sites.

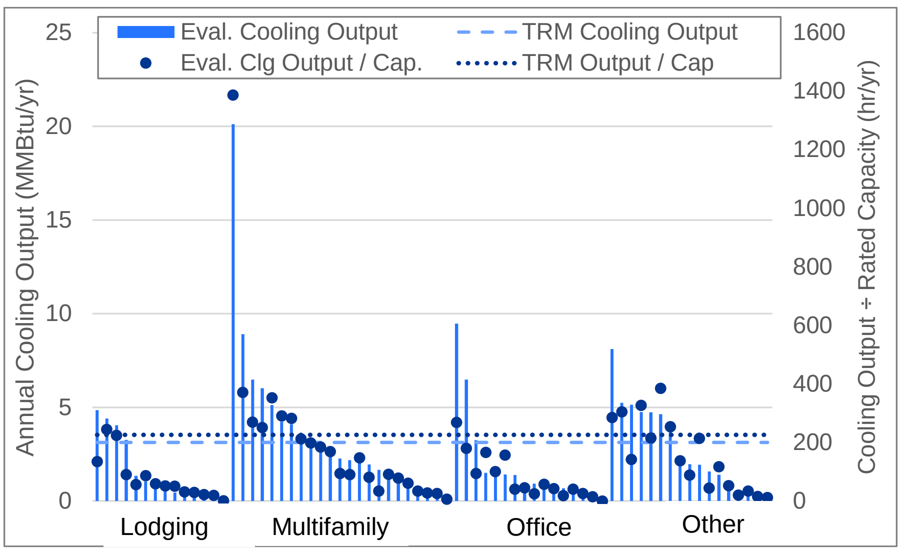
Table 4-28. Comparison of Heating Output by HP Size Category among Core and Complementary Samples

	Core			Complementary		
HP Heating Capacity	Count	Average Annual Heat Delivered (MMBtu/yr)	Annual Heat Delivered ÷ Rated Capacity (hr/yr)	Count	Average Annual Heat Delivered (MMBtu/yr)	Annual Heat Delivered ÷ Rated Capacity (hr/yr)
< 18 kBtu/h	16	5.9	473	5	27.7	2,231
18 - 24 kBtu/h	29	7.22	381	26	27.55	1,471
24 - 36 kBtu/h	12	12.7	509	0	N/A	N/A
≥ 36 kBtu/h	13	16.33	410	2	61.5	1,465

4.6.2 Cooling output

The DNV team similarly analyzed annual cooling output by facility type, as illustrated by Figure 4-14. This analysis was limited to the core evaluation sample only, as the complementary M&V period did not extend into the cooling season. As a reminder, cooling season savings constituted less than 1% of the evaluated annual MMBtu savings.

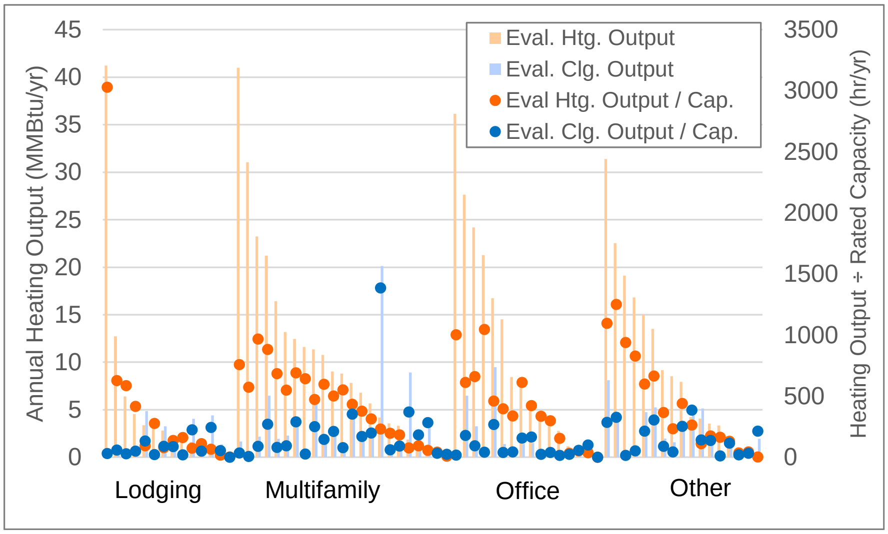
Figure 4-14. Annual Cooling Output per HP Installation by Facility Type



Similar to the heating output results, HPs at Multifamily facilities produced the highest cooling output, while HPs at Lodging facilities produced the lowest. The outlier in Figure 4-14 corresponds to a single-zone HP rated at 14,500 Btu/h cooling capacity installed in a multifamily space without any pre-existing cooling.

The DNV team investigated if high-heating HPs corresponded with high-cooling HPs; however, the two sets of results do not appear to correlate as illustrated by Figure 4-15.

Figure 4-15. Annual Heating and Cooling Outputs per HP Installation by Facility Type



4.6.3 Performance

As detailed in Section 3.5.1, the DNV team quantified coefficients of performance during heating and cooling seasons by comparing measured energy output of the supply air stream with measured electric input. Figure 4-16 illustrates an example heating COP curve for a single-zone system with a rated HSPF of 14.

Figure 4-16. Example Heating Coefficient of Performance Curve

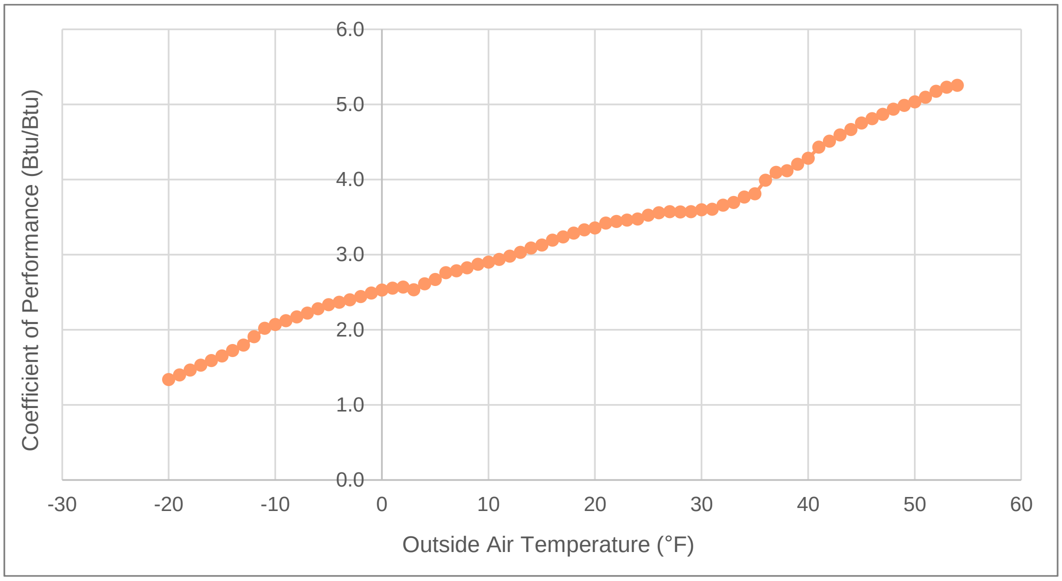


Table 4-29 compares the effective $HSPF_e$ and $SEER_e$ with manufacturer-rated values as well as the program-assumed values reflected in the current TRM. All HSPF and SEER values represent averages weighted by rated heating and cooling capacities, respectively.

Table 4-29. Effective, Manufacturer-Rated, and Program-Assumed HSPFs and SEERs across Evaluation Sample

Performance Metric	Effective (Measured)*	Manufacturer-Rated	Program-Assumed Effective Values within TRM†
HSPF (Heating)	10.82	12.09	8.42
SEER (Cooling)	22.97	21.43	17.03

* While HSPF and SEER typically refer to efficiency *ratings*, for comparison purposes, the DNV team has converted COPs to $HSPF_e$ and $SEER_e$ in this column.

† These values reflect the program's assumed effective weighted HSPF and SEER at which the rebated HP will displace existing heating and cooling systems. These values are embedded within the program's deemed savings values for heating and cooling impacts.

The effective $HSPF_e$ is 11% lower than the manufacturer-rated value primarily due to more frequent operation at colder temperatures than the manufacturer's test conditions.

4.6.4 Load profiles

The evaluation objectives included assessment of peak-period operation and generation of hourly load profiles among various periods of interest. Section 4.2.5 includes peak demand impact results and energy period factors (EPFs); the EPFs are repeated in Table 4-30 for convenience.

Table 4-30. Energy Period Factors from Evaluation Results and Efficiency Maine TRM

Period	Evaluation Results	Efficiency Maine TRM
Winter on-peak (7:00 AM to 11:00 PM on non-holiday weekdays during October through May)	35.5%	35.9%
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)	40.0%	49.5%
Summer on-peak (7:00 AM to 11:00 PM on non-holiday weekdays during June through September)	13.8%	8.3%
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)	10.7%	6.3%

Figure 4-17 through Figure 4-22 illustrate notable hourly load profiles over the periods specified in the figure titles. Appendix D includes additional load profiles. The DNV team has delivered an interactive spreadsheet repository of load profiles should Efficiency Maine prefer to conduct additional analysis.

Figure 4-17. Average HP Load Profiles by Month of Year (n=70)

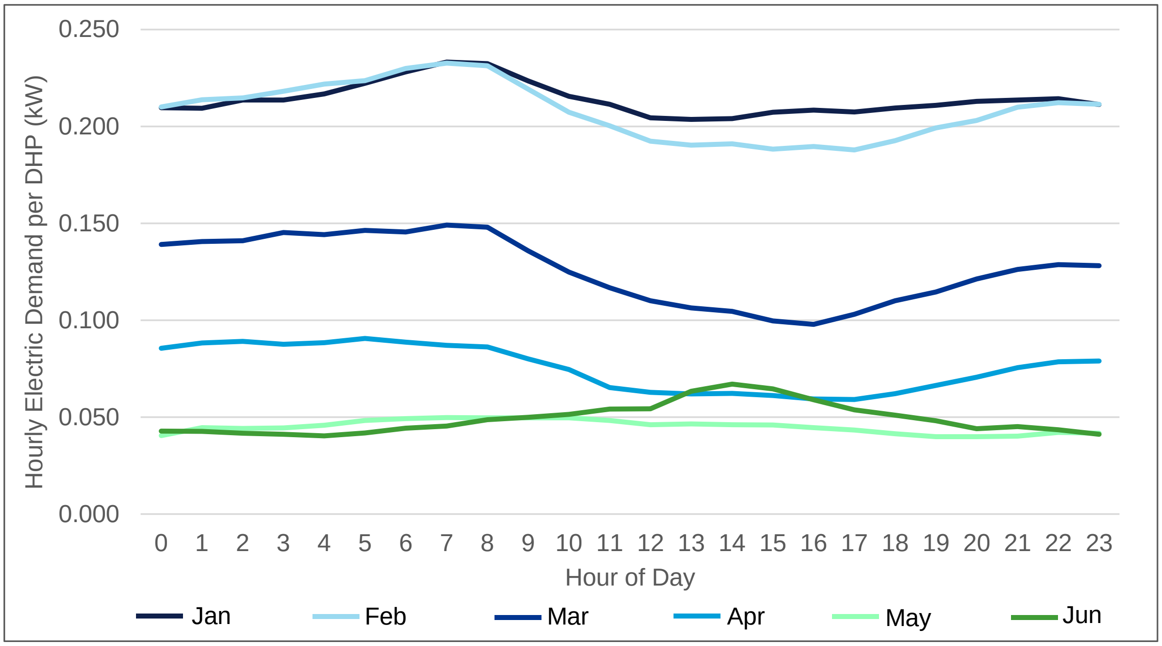


Figure 4-17 illustrates that HPs operating in the winter months of January and February demonstrate about 40%-60% higher power draw than during the spring months of March and April. HP power draw during summer months is significantly lower than during winter months.

Surprisingly, the hour-by-hour profiles do not appear to fluctuate much with hour of day. Operation is highest in winter mornings when businesses presumably open; during nights when temperatures are coldest, the demand for heat may be lower, especially if the customer is utilizing built-in controls to set back temperature. Also "flattening" the load profile shape is the fact that each day of a given month is averaged together—among all 70 evaluated HPs— to determine power draw at a given temperature. Figure 4-18 illustrates the average power draw across the 70 evaluated HPs on two example days in January correlated with outside air temperature on the right-hand y-axis. These and other January days were averaged together to create the January curve in Figure 4-17.

Figure 4-18. Average HP Power Draw on Two Example Days in January

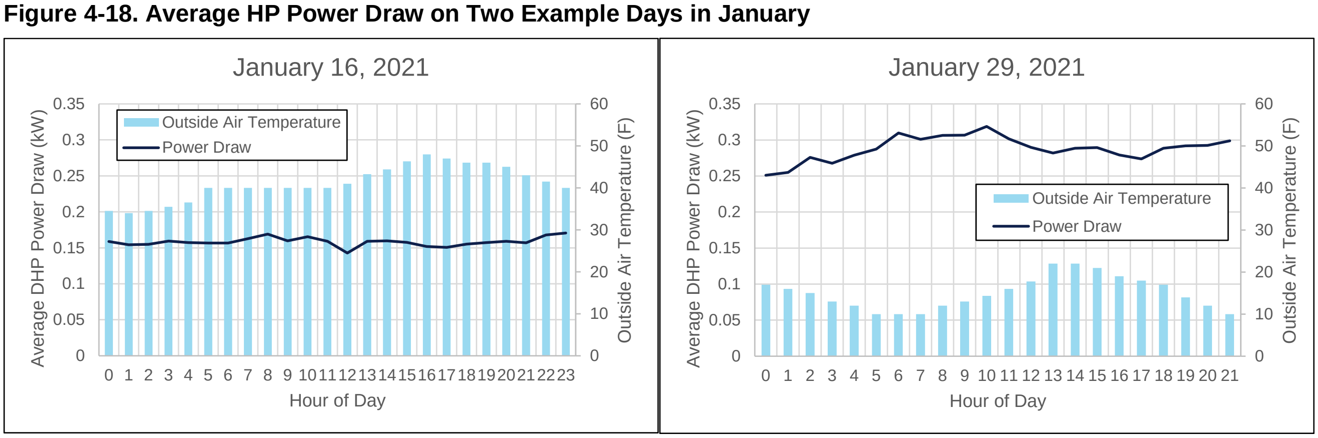


Figure 4-17 reflects all 70 systems sampled for M&V, including those demonstrating low heating season use. Figure 4-19 illustrates monthly load profiles excluding 17 systems (25% of sample) that demonstrated the lowest heating season use.

Figure 4-19. Average HP Load Profiles by Month of Year Excluding Lowest-Use Systems (n=53)

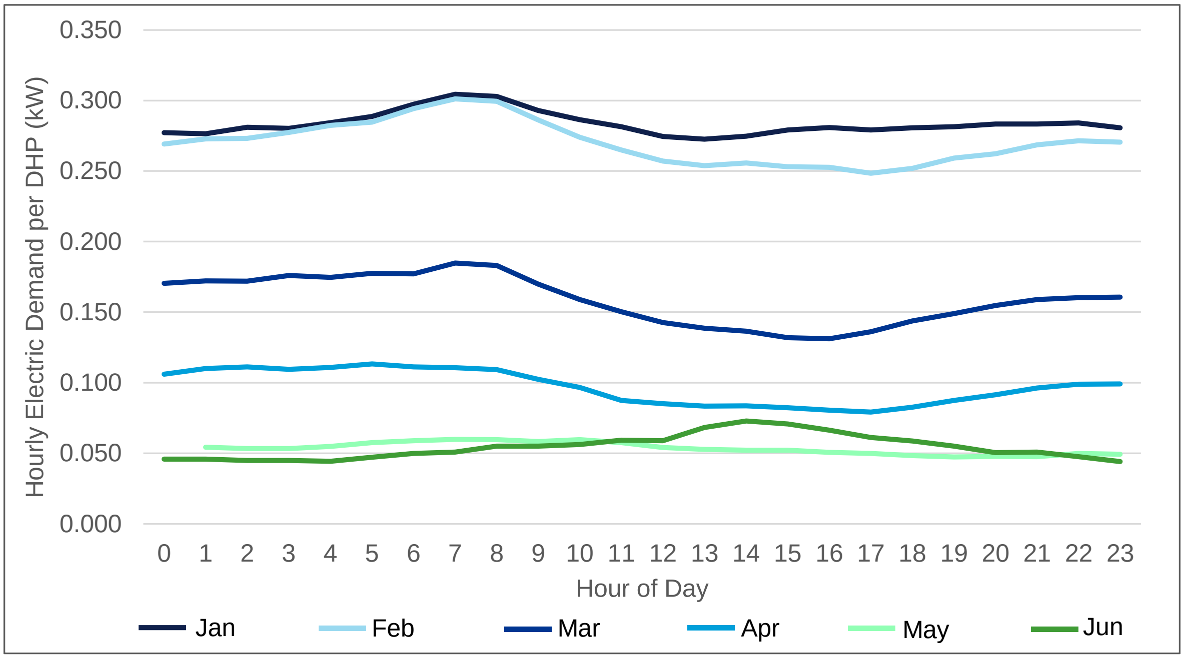
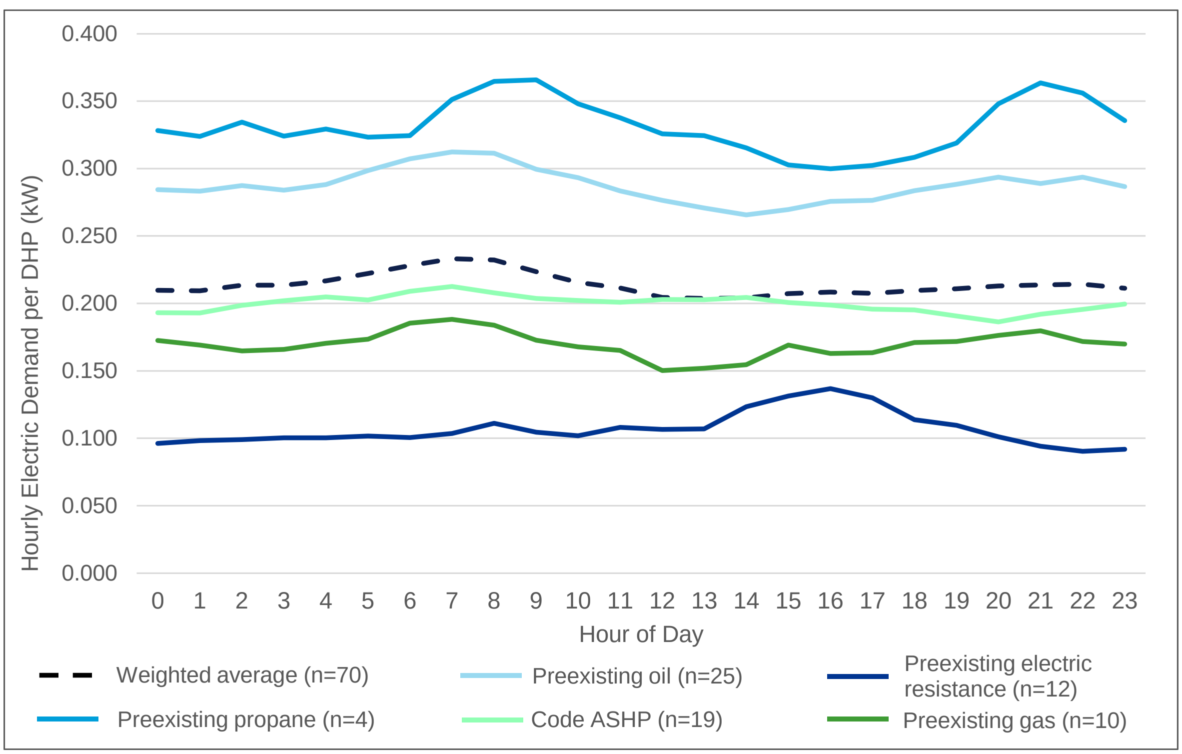


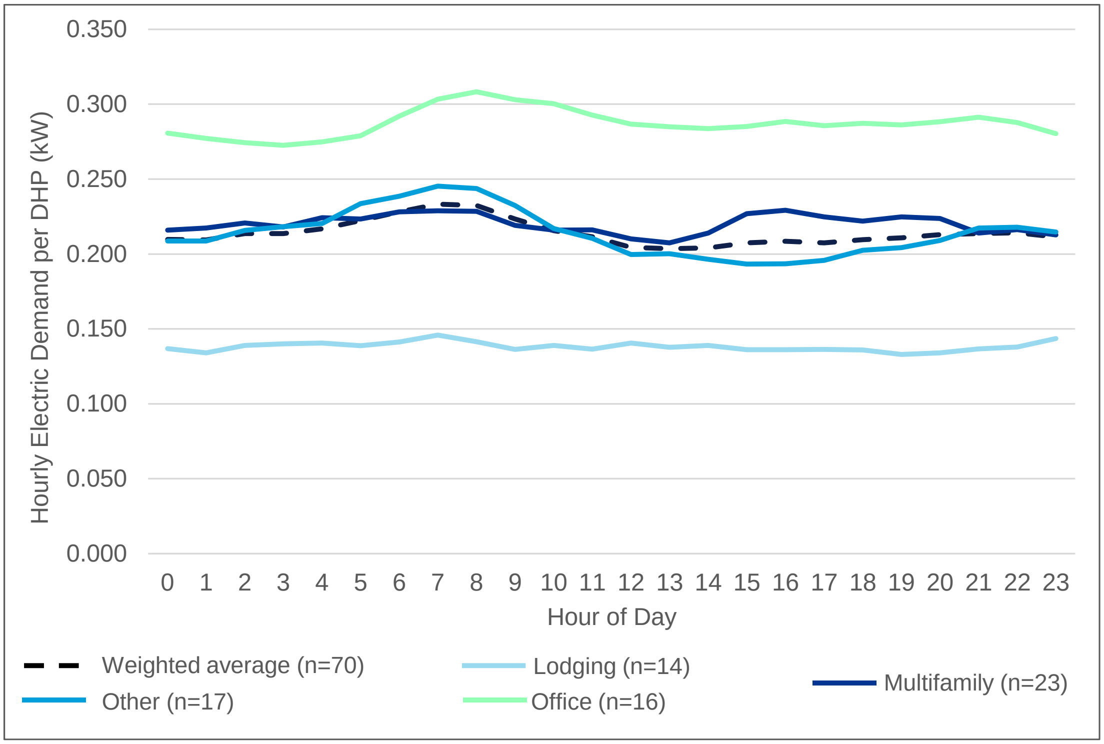
Figure 4-20 illustrates the hourly load profiles of HPs in January by pre-existing heating type. HPs replacing propane and oil systems drew more power than those replacing gas or resistance heat.

Figure 4-20. HP Winter Load Profiles by Primary Pre-existing Heating Type (n=70)



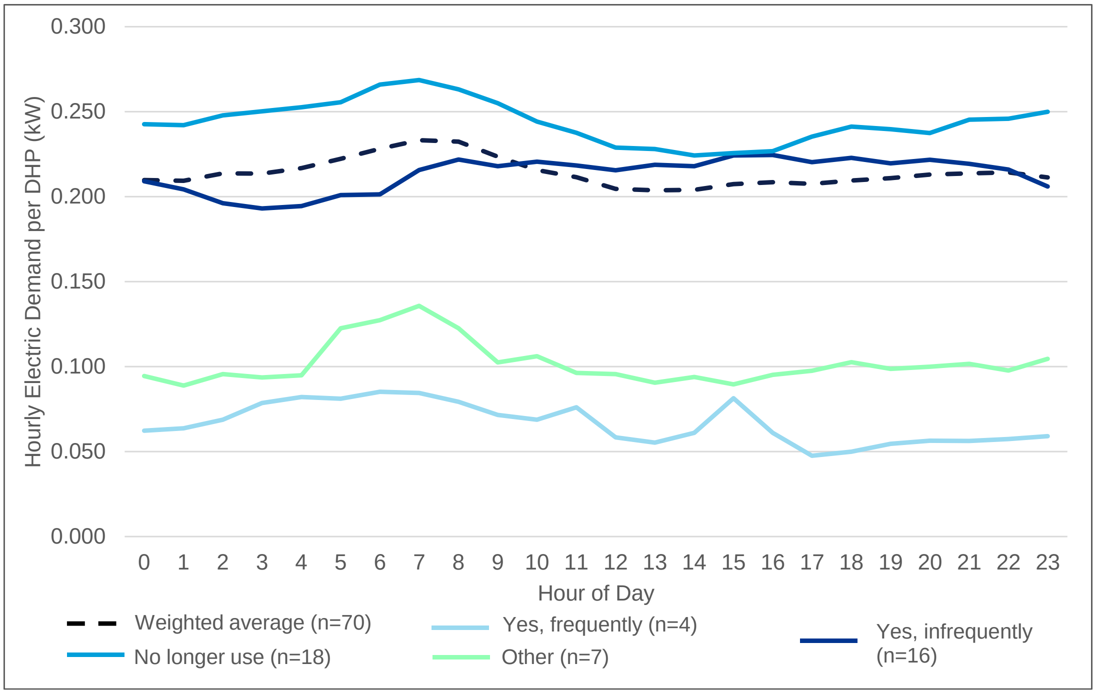
As shown in Figure 4-21, HPs in Offices drew the most power, on average, during the month of January. HPs at Lodging facilities drew the least, which aligns with our findings in Section 4.2.

Figure 4-21. HP January Load Profiles by Facility Type (n=70)



The participant survey included a question on the retention and usage of pre-existing heating systems. Response options included "no, we no longer use the pre-existing heating system," "yes, and we still use the pre-existing heating system frequently," and "yes, but we only use the pre-existing heating system infrequently." As illustrated in Figure 4-22, HPs at facilities that removed their legacy heating system showed the highest average power draw, whereas HPs at facilities that frequently use their legacy systems showed the least.

Figure 4-22. HP January Load Profiles by Usage of Legacy Heating System (n=70)



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5 CONCLUSIONS

This study assessed the gross and net impacts of HP installations among C&I customers that participated in the program between 2017 and 2019. The program's design and eligibility criteria, and the HP market, have evolved in the three years since. Therefore, the DNV team has framed the following conclusions wherever possible to be applicable to the program moving forward.

5.1 Program accomplishments

- **Rebated HP installations led to meaningful annual energy savings and carbon emissions reduction.** The C&I Prescriptive Program's HP measures resulted in 37,119 therms of natural gas savings, 85,881 gallons of fuel oil savings, and 35,494 gallons of propane savings. Overall, the realized energy savings offset approximately 1,356 tons of CO_2 from fossil fuel combustion per year. Each rebated HP led to 8 MMBtu of annual energy savings (at site) and 1,301 pounds of annual CO_2 emissions reduction per installation.
- **Participating customers are highly satisfied with their HPs and the program overall.** On a ten-point scale, with 10 being "extremely satisfied," customer ratings across various program features ranged from 8.6 (incentive amount) to 9.2 (satisfaction with HPs).
- **Qualified partners (QPs) noted positive effects from their participation in the program.** 31% and 21% of surveyed QPs noted an increase in customer base and an increase in sales volume, respectively, as a result of their association with the program.
- **Overall, rebated HPs led to cooling savings when compared with baseline systems.** 12 of 70 sampled HP installations introduced new cooling load to a previously uncooled space that would have remained uncooled if not for the incented HP. But when compared with the customer's preferred alternative cooling system, the remaining 58 installations led to cooling savings that offset this electric penalty.

5.2 Gross impact results through M&V

- **As determined through M&V of 70 sampled HPs, the program-incented HPs realized 41% more MMBtu savings than predicted.** The DNV team approached the study using two methods of defining evaluated gross impacts: measurement and verification and AMI-based premise-level analysis. As discussed in the premise-level analysis conclusions below, the evaluated gross savings are defined by the M&V results due to various uncertainties surrounding the premise-level results.
- **Evaluated savings exceeded program-reported values primarily due to a higher share of displaced fossil fuel heating than predicted by the program.** The DNV team determined that over half of the 70 sampled HP installations displaced fossil fuel heating; on the other hand, the program-reported savings claims reflected only an 18% share of displaced fossil fuels.
- **The DNV team determined lower-than-expected output from rebated HPs during the heating season.** The 70 HPs sampled for M&V operated approximately 60% less frequently during the heating season than assumed within TRM-based deemed savings. The DNV team primarily attributes this difference to the continued use of supplementary heating systems (see below bullet). Survey results indicated that nearly half of participants do not fully use the incented HPs throughout the heating season. To properly account for these differences in savings claims moving forward, the program could consider additional screening of applicants and/or additional contractor-collected data to refine savings claims to better reflect anticipated share of heating load.[56]
- **The status of legacy heating systems greatly affected achieved savings.** Customers that reported to continue to frequently use their legacy heating system realized 69% less MMBtu savings than customers that reported to no longer

[56] For example, in New York, Clean Heat Programs have evolved to distinguish between full-displacement and partial-displacement HP installations, with varying incentives and savings values for each. The NY Clean Heat program is currently being evaluated with a report expected late 2023.

use the legacy heating system. Should Efficiency Maine consider additional segmentation of deemed savings in the TRM, we recommend differentiating deemed savings by the decommissioning status of the legacy heating system.

- **Achieved savings and heating output varied by customer sector within the core evaluation sample.** The team designed the core evaluation sample (n=70) to focus on three prominent facility types within the participant population: lodging, multifamily, and office. Among the core sample, HPs in multifamily buildings demonstrated highest savings (288% site MMBtu RR) while those in lodging facilities demonstrated the least (28% site MMBtu RR). Due to relatively low sample sizes among facility-specific segments, we recommend additional research before developing facility-level deemed savings estimates in future iterations of the TRM.
- **HPs in the complementary sample generally showed higher heating output than those in the core evaluation sample.** The DNV team and Efficiency Maine agreed to add 33 HPs to the heating season M&V pool to assess HP heating operation among a broader group of facility types. The complementary sample (n=33) showed higher heating output on average, with HPs at manufacturing, garage, and restaurant sites producing the highest annualized outputs. We note that complementary HPs underwent additional screening during application pre-approval to confirm that those facilities are heated throughout the full heating season. Core sites did not undergo such additional screening.
- **M&V data showed several differences with performance assumptions embedded in Efficiency Maine TRM deemed savings values.** As stated above, evaluation results reflected an annual heating output value 60% less than the current TRM assumption. On the other hand, higher-rigor sites showed performance efficiencies 28% and 35% better than current TRM assumptions for heating and cooling, respectively. These parameter-level findings can be used to refine deemed savings assumptions in future TRM iterations, barring major changes in program design elements such as eligibility criteria, minimum efficiency requirements, or baseline treatment.
- **The evaluated savings led to overall benefit-cost ratios above the cost-effectiveness threshold of 1.** The DNV team determined that HP installations were cost-effective when considering AESC 2021 avoided costs. However, HP installations at Multifamily facilities incurred slightly more costs than benefits due to a higher prevalence of retrofit projects. For that segment, the DNV team determined that the tenants did not use the HPs enough during the heating season to displace sufficient fossil fuel heating to overcome the full installation costs of the HPs.

5.3 Premise-level analysis

- **Analysis of pre- and post-installation AMI data showed a plausible range of normalized annual heating energy use per rebated HP from +44 to +63 kWh per 1,000 Btu/h of rated capacity.** The DNV team. approached the AMI analysis from different perspectives and found varying results depending on various factors including the availability of pre-installation AMI data and whether the electric heating energy increased or decreased after HP installation.
- **Exclusion of sites with cooling energy increases led to stronger correlation between AMI models and M&V results.** The DNV team hypothesizes that sites with cooling energy increases apparent in AMI data were more likely to have experienced non-routine events (e.g., change in occupancy or load) that prevents the treatment of pre-installation AMI data as baseline.
- **Premise-level analysis of AMI data revealed several uncertainties.** Some sites showed a likelihood of changes in heating load for which the preexisting AMI data no longer represents the baseline. Additional uncertainties included the presence of other electric heating equipment in pre- or post-project scenarios, other AMI meters at the customer facility, or customer survey data that contradicted the AMI data. The DNV team recommends four techniques to ensure that premise-level HP analysis approaches are viable in future evaluations:
    - Classify sites into different heating usage categories – Categorizing sites into different heating displacement scenarios (full displacement, partial displacement, low/no use) will minimize uncertainty. In Appendix C, the DNV team has provided hourly coefficients for possible use in future evaluations.

- Exclude sites with cooling energy increase – As mentioned above, such sites were more likely to have undergone non-routine changes that disqualifies the pre-installation data as representative of baseline.
- Use pre-install AMI data if available – Post-only AMI analysis overestimated HP impacts in this study, likely due to the presence of other electric heating sources not attributable to the program.
- Cross-check survey data and AMI meter selection – The DNV team found that customer-reported usage characterizations often did not align with AMI analysis results. Additionally, we determined higher uncertainty with facility types likely to have more than one utility meter (e.g., multifamily).

- **Premise-level review of AMI data may be useful for future program implementation and evaluation.** AMI data provides program administrators and evaluators the ability to categorize sites into different heating displacement scenarios (e.g., full displacement, partial displacement, low/no use). Variation in usage and impacts among these scenarios may empower program administrators to make changes to deemed savings estimates, measure design, eligibility criteria, and incentive tiers. AMI data will also allow program administrators and evaluators to continually assess the effects of such program changes on encouraging customers to minimize the consumption of fossil fuels.

5.4 Net impact results

- **The DNV team determined a 35% free-ridership rate for the HP measures rebated over the evaluation timeframe.** This value is derived from survey responses of customers that indicated they would have done the exact same project regardless of the program (68 of 194 respondents) and customers that would have partially scaled back or postponed the project if not for the program's influence (64 respondents). Customers indicated that their prior experience with the program, the program incentive, and their experience with the qualified partner were most influential to their decision-making.
- **The DNV team estimates a spillover rate of 8%, resulting in a net-to-gross ratio of 73%.** Spillover is mostly attributable to participant spillover (6% of program-reported site MMBtu savings) with the remainder to non-participant spillover (2%). The most common participant spillover measure categories were lighting, HVAC, and water heating.

APPENDIX A. Net-to-Gross Methodology

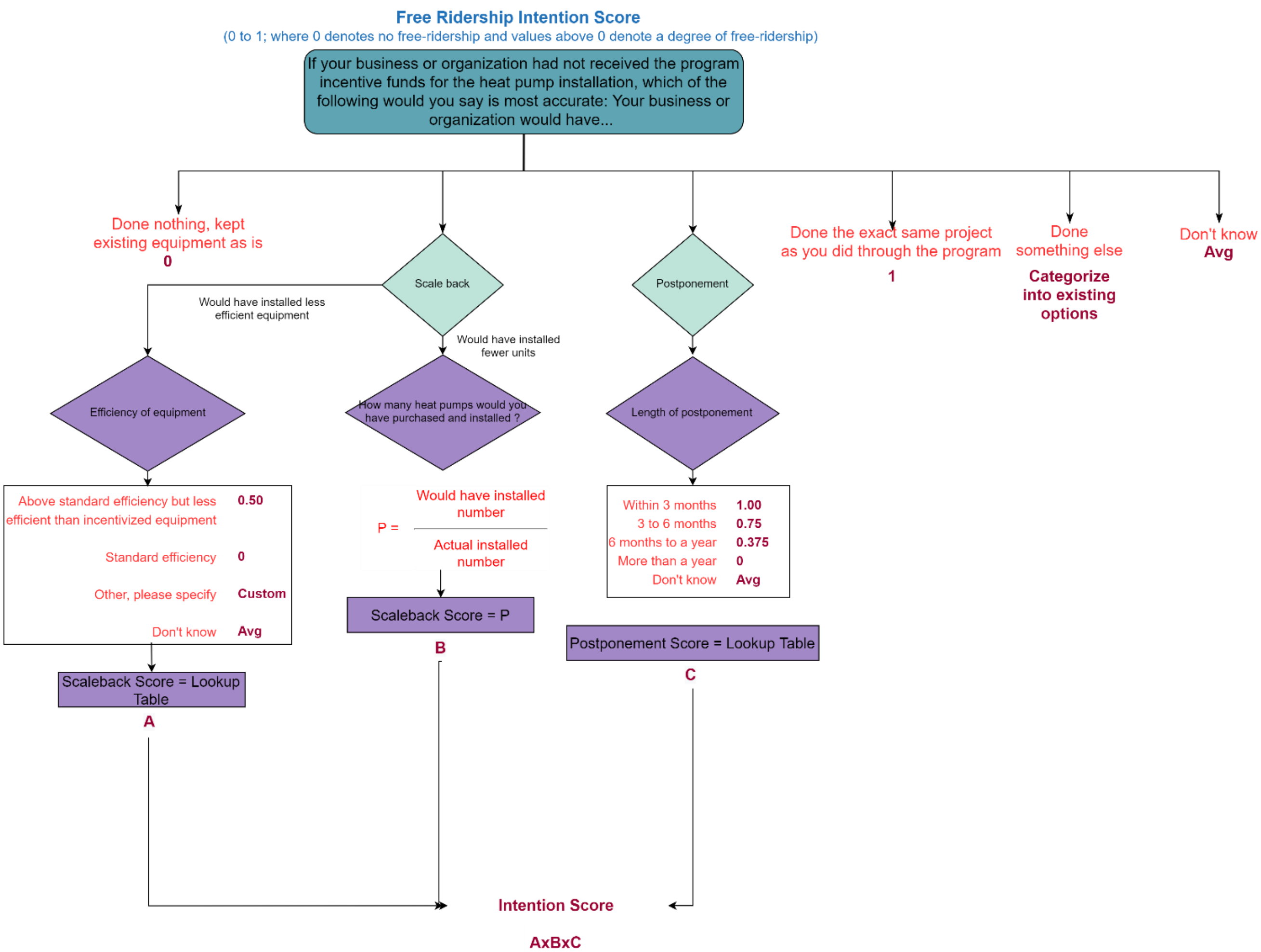
The DNV team estimated the program-level net-to-gross (NTG) ratios for Efficiency Maine's Commercial & Industrial Program's HP measure using data collected from program participants and vendor surveys. The NTG ratio (NTGR) incorporates both free-ridership and spillover components through the following formula:

$$NTGR = 1 - Freeridership + Spillover$$

Free-Ridership

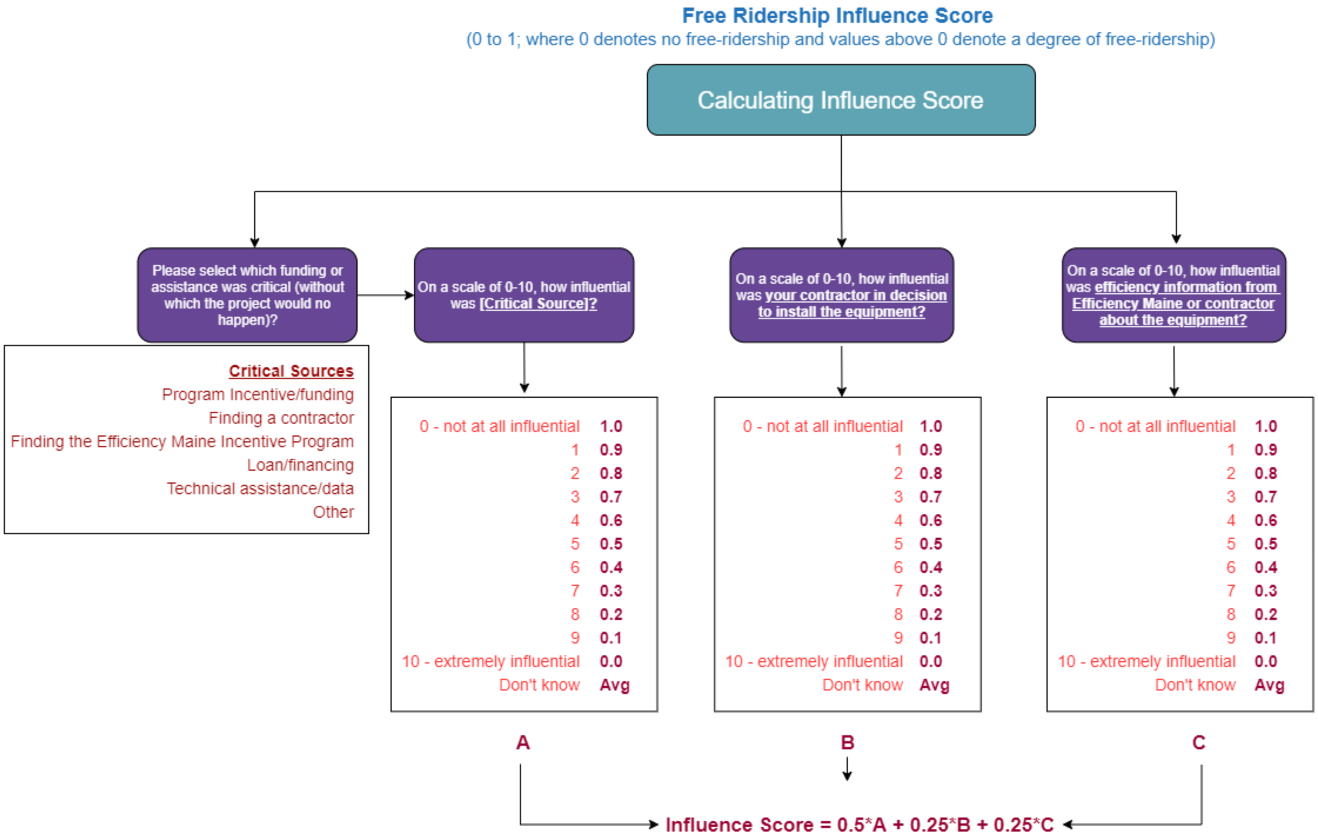
The DNV team assessed free-ridership in the participant survey using two equally weighted components, with the second component acting as a check on the potential bias of the first component. The first component explores the intention of the participant. The DNV team asked the participant to identify if they would have installed the heat pump if they had not received the rebate from the program. The response choices for each item were: yes, no, or don't know. Participants who indicated they still would have installed a measure without the program rebate were asked additional questions: 1) whether the installation would have happened at the same time or not, and if not, when would the installation happen; and 2) whether the measure quantity of HPs would change. See Figure A-1 for an illustration of the free-ridership intention calculation.

Figure A-1. Free Ridership Intention Score Calculation Logic Model



The second component explored the influence of three potential program effects the participant may have encountered: the rebate received, the contractor who installed the equipment, and the information from the program administrator or contractor about the equipment. For each of these potential influences, the team asked participants to use a scale from 0 to 10, where 0 means "not at all influential" and 10 means "extremely influential," to indicate how much influence that effect had on their decision to purchase and install. The DNV team analyzed the survey results using the logic model depicted in Figure A-2.

Figure A-2. Free-Ridership Influence Score Calculation Logic Model



Both intention and influence components yield scores ranging from 0 to 1, based on the degree to which the response indicated free-ridership. For example, a response in the first component that indicated the customer would not have purchased and installed the measure without the program rebate would yield a score of 0, indicating this component did not identify free-ridership. The second component was scored based on the average rated influence of contractor, the rebate, and program-related information. For example, if the customer indicated that the rebate and contractor had moderate influence, this component would have an intermediate score (e.g., 0.25), indicating partial free-ridership.

Each of the components has a 50% weight. When the two component scores are added, the analysis generates a total score ranging from 0 to 1. A 0 indicates no free-ridership, a 1 indicates complete free-ridership, and a score in between those numbers indicates partial free-ridership.

The team used the participant-level free-ridership scores to calculate a savings-weighted average free-ridership score for the program's HP measure as a whole.

Spillover

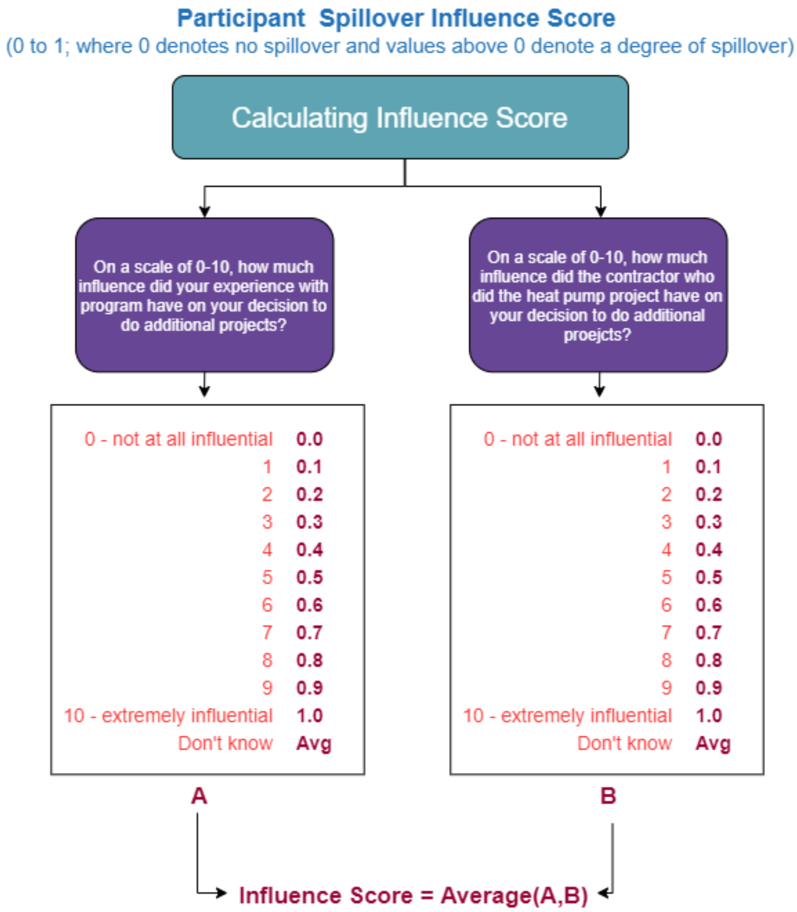
This section describes the methodology for quantifying participant and non-participant spillover, the two components of program-level spillover as shown in the formula below.

$$Spillover = Participant\ SO + Nonparticipant\ SO$$

Participant Spillover

To determine spillover after program participation, the DNV team asked participant survey respondents to indicate any additional energy saving measures or actions they implemented since their participation in the program. To qualify as spillover, the additional projects must not have received incentives from Efficiency Maine. For each measure identified by the participant in the survey, the team asked participants to use a scale from 0 to 10, where 0 means "not at all influential" and 10 means "extremely influential," to indicate how much influence their experience with the program had on their decision to purchase and install additional measure(s). The DNV team analyzed the survey results using the logic model depicted in Figure A-3.

Figure A-3. Participant Spillover Influence Score Calculation Logic Model



The team averaged the influence ratings across the items a participant purchased and installed to weight the participant spillover for each spillover measure that each participant reported to generate an influence value between 0 and 1. A 0 indicates that the program had no influence on the participant's decision to install the measure(s), and a 1 indicates that the program extremely influenced their decision to install the measure(s). Participant measure spillover is calculated in the following way, with the deemed measure savings values based on our team's estimate of typical savings for the implemented measure:

$$Participant\ Measure\ SO = Deemed\ Measure\ Savings\ \times Influence\ Value$$

If a deemed savings value was not available or appropriate, the survey attempted to collect data to estimate spillover project size from the participant, typically by estimating size relative to that of the funded measure. Spillover measures also saved both electricity and fossil fuels. Analysts converted kWh savings to site-equivalent MMBtu to express spillover as a percentage value.

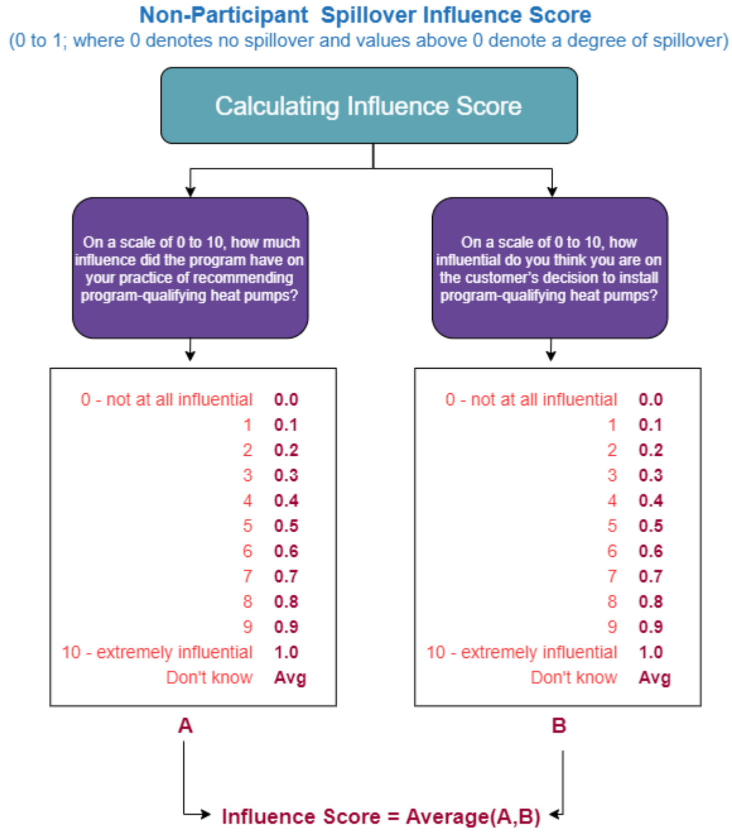
Non-Participant Spillover

Non-participant spillover refers to non-incented program measures implemented by qualified partners (QPs) who were directly or indirectly influenced by the program. The DNV team leveraged the vendor surveys to identify and quantify non-participant spillover and program influence. The survey asked QPs the following key non-participant spillover questions:

1. From 2017 through 2019, about what proportion of HP installations at rebate-eligible customers actually applied for a HP rebate through the program?
2. About what proportion of your rebate-eligible customers specifically requested the equipment type or model (for example, specific HP model) on their own without your recommendation?
3. On a scale of 0 to 10, where 0 means no influence and 10 means great influence, how much influence did the C&I HP program have on your practice of recommending program qualifying equipment?
4. On a scale of 0 to 10, where 0 means no influence and 10 means great influence, how much influence did you have on customers' decisions to install program-qualifying equipment?

The DNV team used vendor survey responses to estimate non-participant spillover over the evaluation timeframe. The calculation first used the QPs' estimate of the percentage of customers who applied for rebates (Question #1, above) and the program tracking data to estimate the number of unrebated projects completed by QPs in the population. The DNV team then calculated the number of unrebated projects that were recommended by contractors using Question #2 response above. Finally, we incorporated the two influence ratings – the influence of the program on Trade Ally recommendations (Question #3) and the contractor influence on customer decision-making (Question #4), to estimate the final number of unrebated projects influenced by the program. Figure A-4 shows a flow diagram detailing how the non-participant spillover influence score was calculated from the two influence ratings.

Figure A-4. Non-Participant Spillover Influence Score Calculation Logic Model



Finally, the DNV team weighted the result to reflect the number of projects completed across the full population of QPs active in the program over the 2017-19 timeframe.

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APPENDIX B. Survey Results

This appendix presents the findings of the participant and vendor surveys, analyzed by key topic area. Further analysis of respondents was conducted where there are notable relationships within the data.

A total of 232 participants responded to the customer survey, including nearly all impact M&V participants. Responses were analyzed for all users who completed at least 75% of the survey (208 of the respondents did complete 100% of the survey, a further 24 completed some amount more than 75%).

As discussed above in the sampling section, no weighting of responses is required since the distribution of responses by building strata is close to the distribution of building strata in the overall population.

Customer's reported HP use strategy by season

The vast majority of respondents use their heat pumps for both heating and cooling. The survey asked respondents if they used their heat pumps for heating, cooling, or both. Of all those surveyed, 93% of respondents stated that they use their heat pumps for both heating and cooling. A very small portion reported using their heat pumps exclusively for heating (3%) or exclusively for cooling (4%). Note that we asked respondents to report usage for each system type they had (i.e., single-, two-, three-, or four-zone), and no significant variations from the overall proportions were found.

Heating Season

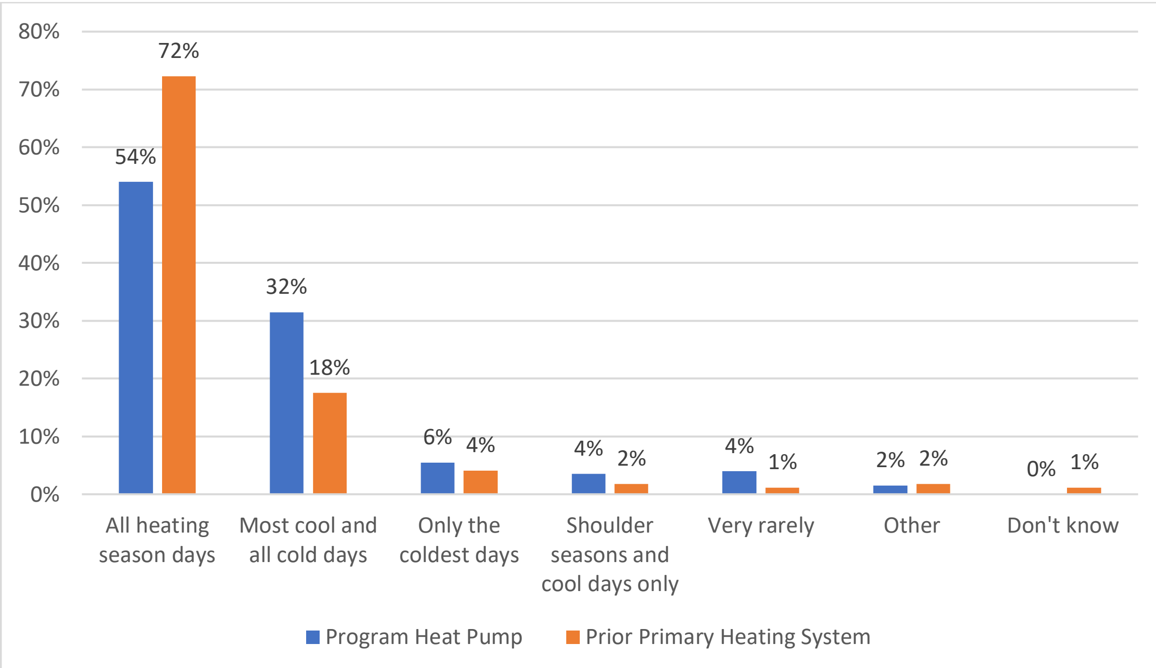
A majority of respondents indicated they use their heat pumps on all or most days of the heating season. The survey asked respondents who use their heat pumps for heating how often they use their heat pumps during the heating season. Over half (54%) reported using their heat pumps on all heating season days, and an additional 31% said they used their heat pumps on most cool and all cold days. Table B-1 below shows the breakdown of heat pump usage frequency during the heating season.

Table B-1. Frequency of use of the program heat pump during the heating season

Please indicate when you use your heat pump(s) to heat your space. Single Response, n=200		
Response	Count	Percent
All heating season days	108	54%
Most cool and all cold days	62	31%
Only the coldest days	11	6%
Very rarely	8	4%
Shoulder seasons or cool days only	8	4%
Other	3	2%

The survey also asked respondents the same question (frequency of use) about their primary heating system *before* the install of their heat pumps. While a larger portion of participants used their pre-existing heating system on all heating days (72%) than the proportion who use their heat pumps on all heating days (54%), more participants said they use their heat pumps on most cool and all cold days (32%) than those who used their pre-existing heating system on most cool and all cold days (18%). Overall, there does not seem to be a meaningful variation in how participants are using their new heat pumps for heating and how they used to use their pre-existing heating systems. Figure B-1 below shows when participants use their heat pumps versus when they used to use their pre-existing heating systems.

Figure B-1. Pre-existing Heating System Prior to HP Install vs. HP – Frequency of Use (n=200, Single Response)



Many participants report still using their pre-existing heating system. However, whether a participant still uses their pre-existing heating system does not impact the frequency with which the participant reports using their heat pump for heating. When asked whether they still use their pre-existing heating system, almost three-quarters of participants said yes; 48 participants (29%) reported still using their pre-existing heating system frequently, another 66 participants (40%) reported infrequent use, and 5 participants (3%) reported still using their pre-existing heating system because their heat pumps were installed in a separate space. However, cross-tabulations of these results reflect no significant correlation between continued use of a pre-existing heating system and the frequency with which a participant reports using their heat pumps for heating. Additionally, it is notable that a larger proportion of participants who listed the need for supplementary heating as a key motivator for their purchase of the program-incentivized heat pumps reported still using their pre-existing heating equipment than those whose heat pump purchases were not motivated by the need for supplementary heat[57]. In other words, those who indicated they wanted supplementary heating from the project were using their pre-existing heating system more often than those who did not.

During impact evaluation activities, a preliminary review identified seven heat pump systems at three facilities with no consumption during the heating season at all. Of those three facilities, two completed the survey and both indicated the units were used for heating (one seasonally, one not often).

Cooling Season

A majority of respondents indicated they use their heat pumps on all or most days of the cooling season. The survey asked respondents who use their heat pumps for cooling how often they used their heat pumps during the cooling season. Three-quarters of respondents reported using their heat pumps on all or most cooling season days. Table B-2 below shows when participants use their heat pumps for cooling.

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[57] Chi-square significant at p=0.018.

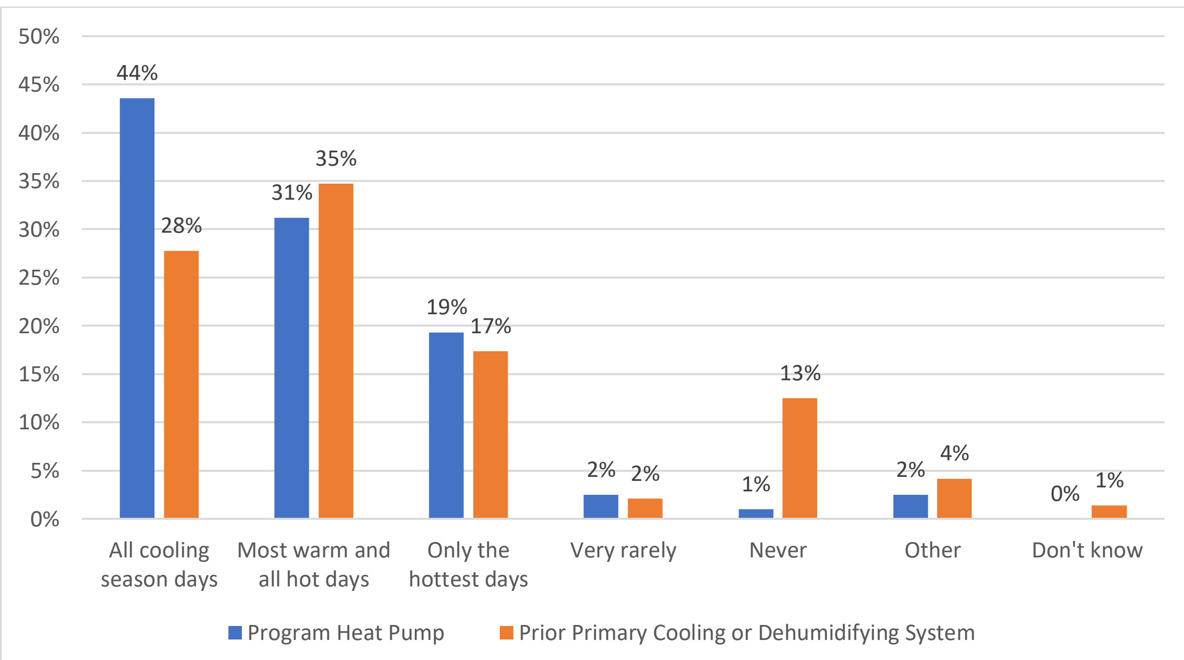
Table B-2. Frequency of use of the program heat pump during the cooling season*

When do you use your heat pump(s) in cooling mode? Single Response, n=202		
Response	Count	Percent
All cooling season days	88	44%
Most warm and all hot days	63	31%
Only the hottest days	39	19%
Very rarely	5	3%
Other	5	3%
Never	2	1%

* Note: this question excludes any respondent who indicated they did not have any cooling equipment prior to installing the HP, or only had a dehumidifier.

Participants are cooling their spaces more frequently with their heat pumps than they did with their pre-existing cooling systems. 13% of respondents reported never cooling their spaces with their pre-existing cooling system; that proportion dropped to 1% following heat pump installation. Similarly, the percentage of respondents who now cool "all cooling season days" increased from 28% to 44%. These findings are shown in Figure B-2 below.

Figure B-2. Pre-existing Cooling System Prior to HP Install vs. HP – Frequency of Use (n=202, Single Response)



Only a small portion of those who use their heat pumps for cooling regularly use their heat pumps' dry mode function. When asked when they used their heat pumps in dry mode to improve dehumidification, just 23% reported using this setting on most or all cooling season days. Most respondents (66%) indicated they use this setting "never", "very rarely", or "only on the hottest days." A handful (7%) used the open response field to report that they use dry mode on muggy or high-humidity days, or only "as needed."

Customer's changes in setpoints and other heating/cooling equipment use

Most participants indicated that during the heating season, they keep their spaces the same temperature as they did prior to the installation of their heat pumps. During the heating season, the majority of respondents (65%) keep their spaces the same temperature as they did before their heat pumps were installed. About one-fifth of participants (18%) keep their space warmer (about 8 degrees on average), and 8% keep their spaces cooler (about 6 degrees on average).

About the same number of participants reported not having changed their setpoints during the cooling season and keeping their spaces cooler. Of note, nearly half of participants (46%) reported that during the cooling season, they keep their space the same temperature as they did prior to the installation of their heat pumps. Almost the same proportion of participants (44%) reported that they keep their space cooler (about 9 degrees on average), while only 2% said they keep their space warmer (about 6.5 degrees on average).

Customer's perceived energy savings and comfort level

A majority of participants reported that they had saved energy and that their comfort levels had increased since installing their heat pumps. Almost three-quarters (72%) of participants said that, since installing their heat pumps, they had saved energy (considering all fuels and electricity). Additionally, the vast majority of respondents said that their comfort levels had increased (85%) or stayed the same (12%) since installing their heat pumps.

When taken in combination with the setpoint discussion above, it appears that respondent comfort likely considers more than just the setpoint temperature of the rooms, which mostly remained unchanged. A number of factors could contribute to increased comfort, such as shorter times to bring a room up to setpoint temperature, improved air circulation and filtration, HVAC system noise reductions, or simply knowing the heat is more energy efficient. These topics were not covered by the survey.

Customer's reasons to purchase and install HP and program influence on purchase decision, installation, and operation

Heating or cooling more efficiently was the most cited reason why participants purchased the program-incentivized heat pumps. We asked respondents to indicate what their motivations were for purchasing and installing their heat pumps. Over half of participants (62%) indicated they were motivated to heat and/or cool their spaces more efficiently, while a third (34%) wanted to reduce their heating costs and a quarter (24%) wanted to add heating or cooling where it wasn't previously. Table B-3 shows the breakdown of participant motivators.

Table B-3. Motivation for installing the program-incentivized heat pump

What motivated you to purchase and install the heat pump(s)? Multiple Response, n=232		
Motivation	Count	%
To heat or cool more efficiently	142	62%
To reduce heating costs	78	34%
Wanted to add heating/cooling where none was present previously	56	24%
To reduce cooling costs	47	20%
Needed to replace broken or aging equipment	41	18%
To reduce environmental impacts of heating/cooling	41	18%
Needed to supplement heating/cooling from the main system	32	14%
Other[1]	10	4%
To avoid health and safety issues (mold, etc.)	8	3%
Needed equipment that fit in tight spaces	6	3%

[1] Notable other responses included: shifting control and/or payment of heating and cooling to tenants, more precise control of temperature and humidity.

These responses were all assessed based on building strata to determine if there were differences in motivation based on the building type.

Customer's satisfaction with the equipment, contractor, and the program

Participants are highly satisfied with their heat pumps and the program overall. The survey asked participants to rate various aspects of their program experience on a 0- to 10-point scale, with 0 being "not at all satisfied" and 10 being "extremely satisfied." All but one program component (the incentive amount) received an average rating of at least 9.0. Table B-4 shows participant average ratings for all program components. The DNV team found no significant patterns when examining this data by building type.

Table B-4. Average satisfaction rating of program components (n=232)

Program Component	Average Rating
Installed heat pumps	9.2
Program application process	9.0
Heat pump contractor	9.1
Incentive amount	8.6
Overall program experience	9.1

Customer's self-report on what was replaced/supplemented by the HP and characteristics of prior equipment.

The survey asked respondents several survey questions about the HVAC systems being replaced or supplemented by the heat pumps and how they used that equipment prior to the installation of their heat pumps.

Most participants' pre-existing heating systems were a furnace or boiler. The most common heating fuel was #2 oil, followed by propane, electricity, then natural gas. Table B-5 shows the equipment type of the primary heat equipment that used to heat the space now served by the program heat pump.

Table B-5. Pre-existing heating system and fuel type

What type of fuel did your previous primary heating equipment use? Single Response	Before the new heat pump system was installed, what was the primary equipment you used to heat your space? Single Response		
Fuel Type	Equipment Type	Count	%
#2 Oil (n=75)	Furnace or boiler	75	47%
Propane (n=27)	Furnace or boiler	19	12%
	Room wall heater	8	5%
Electric (n=26)	Room plug-in/space heaters	9	6%
	Central ASHP or GSHP	4	3%
	Room HP or Window Unit	2	1%
	Baseboard resistance	10	6%
	Other	1	1%
Natural Gas (n=16)	Furnace or boiler	16	10%
Wood (n=7)	Pellet/chip/biomass	6	4%
	Cord	1	1%
Kerosene (n=6)	Furnace or boiler	3	2%
	Room wall heater	3	2%
#4 or #6 Oil (n=2)	Furnace or boiler	2	1%

Most participants' pre-existing cooling system was a room air conditioner. Of note, a quarter of respondents reported not having any cooling or dehumidification equipment in their space before installing their heat pumps. Table B-6 below shows the primary cooling equipment previously used to cool the space now occupied by the program heat pump.

Table B-6. Pre-existing cooling system type

Before the new heat pump system was installed, what was the primary equipment you used to cool your space? Single Response (n=199)		
Response	Count	%
Room air conditioners	75	32%
(None) We had no cooling or dehumidification equipment before we installed the heat pump system	59	25%
(None) Fans	30	13%
A central air conditioner	13	6%
An air handler with a chiller plant	5	2%
A ductless heat pump	5	2%
We did not use cooling equipment, but did use a separate dehumidifier	5	2%
A rooftop unitary cooling system (RTU)	3	1%
Don't know	2	1%
Other	1	0%
A ground-source heat pump	1	0%

A greater proportion of participants still have their pre-existing heating system in use compared to the proportion that still use their pre-existing cooling system. When asked if their prior primary heating system is still in use, almost three-quarters of respondents (72%) said yes. Conversely, only 20% of participants reported that they still use their pre-existing cooling systems. Of these participants, nine (35%) used fans as their primary cooling equipment (the rest mostly had window units or central air conditioning). Table B-7 shows the breakdown in frequency of use of the prior heating and cooling systems following the installation of the program heat pump.

Table B-7. Pre-existing heating system use after heat pump installation

Is the primary heating/cooling system that you used before installing your new heat pump(s) still being used to provide any heating/cooling in your space? Single Response	Heating (n=171)		Cooling (n=140)	
Response	Count	%	Count	%
Yes, but only infrequently	66	40%	21	16%
Yes, and we still use it frequently	48	29%	6	4%
No	48	29%	105	78%
Yes, because HPs were installed separately from spaces conditioned by pre-existing HVAC equipment	5	3%	N/A	N/A
Don't know	-	-	3	2%

Customer's self-report on whether the HP introduces new heating and/or cooling capacity.

To ascertain whether the heat pump introduced new heating and/or cooling capacity at their facility, the survey asked participants if the floor area of their conditioned space in the building increased, decreased, or stayed the same with the installation of the heat pump.

Most respondents reported that the heated and/or cooled area stayed the same, and about 10% of participants said that their heated and/or cooled area is now larger than it was previously. There are numerous equipment configurations that can satisfy each of these scenarios. Table B-8 details changes in heated floor area.

Table B-8. Change in heated floor area with heat pump installation

Is the amount of heated/cooled floor area in your building the same, larger, or smaller than before you installed the new heat pump(s)? Single Response		
Response	% of responses about heated floor area (n=171)	% of responses about cooled floor area (n=139)
Floor area is the same as it was before	87%	86%
Floor area is now larger than it was before	11%	10%
Other	2%	1%
Floor area is now smaller than it was before	1%	1%
Don't know	0%	1%

System operation knowledge conveyed to customers

Most participants reported that they discussed how to operate their heat pumps with the contractor who installed them, and that the contractor's "how-to" explanation was very helpful. A clear majority of participants (94%) reported having discussed how to operate their heat pumps with their contractors. We asked these participants to indicate whether the contractor's explanation was very, somewhat, or not at all helpful. Over three quarters (80%) indicated that their contractors' explanation was very helpful.

Most participants who recalled getting an explanation from Efficiency Maine about how to operate their heat pumps found the information very helpful. The survey asked participants to indicate whether Efficiency Maine's mail or email explanation on how to operate their heat pumps was very, somewhat, or not at all helpful. Most participants (70%) recalled receiving Efficiency Maine's explanation, and of those, 87% found it to be at least somewhat helpful. About a third of participants (31%) do not recall using, asking for, or receiving information from Efficiency Maine on heat pump operation. See Table B-9 for the breakdown of participant feedback on Efficiency Maine's heat pump operation information.

Table B-9. Participant feedback on Efficiency Maine's HP operation information

How helpful was Efficiency Maine's explanation (email and mail) on how to operate your heat pump(s)? Single Response (n=229)		
Response	Count	%
Very helpful	85	37%
Somewhat helpful	54	24%
Not at all helpful	20	9%
Don't know	53	23%
Did not ask for, use, or receive help from EMT	17	7%

Only 13 participants said that they found it challenging to operate their heat pumps or reported having other issues. Of those, 10 said that the heat pump controls are complex, and 4 reported that the heat pumps don't provide adequate heating and cooling.

Vendor Survey

30 vendors were surveyed on several topics related to the program's influence on their sales, distributor practices, education of customers, and more. This section details the findings of the survey.

The DNV team completed telephone surveys with 30 QPs out of a possible 164.[58] To ensure that QPs were properly represented, we designed a sampling approach based on the QPs' number of enrollments and geographic location. Four strata were considered in the QP survey sample design:

- High activity: more than 16 enrollments
- Low-moderate activity: 2-15 enrollments

[58] Efficiency Maine has approximately 421 active QPs, but the majority were not associated with a C&I heat pump installation between 2017 and 2019.

- Low-moderate activity of interest: 2-15 enrollments, located in northern regions
- Very low activity: 1 enrollment

The DNV team surveyed all high-activity QPs, who accounted for half of the enrollments in the evaluation population.

Program influence on installation contractor's installation and sales, and distributor's stocking practices

Seventeen respondents (56%) stated that their overall sales volume increased after learning about the program, while 17% thought it remained the same, and 7% stated that sales decreased. The estimated change in sales volume before and after was averaged across all respondents and showed a net sales volume increase of 27%.

Responses were examined by vendor selection strata and found that the high-volume contractors mostly indicated their sales volume remained the same, so the change is occurring primarily in vendors with smaller program participation.

Table B-10 below summarizes responses about whether the presence of the program had an impact on distributor stocking practices of energy efficient heat pump options. Slightly less than half stated they had seen an increase in stock variety or volume of efficient heat pumps, while 38% stated they observed little to no impact on distributor practices after the presence of the heat pump program. The remainder were unsure, or cited pandemic-related changes that made it difficult to fairly assess the question. Please note that the question allowed multiple responses.

Table B-10. Program effect on distributor stocking practices (N=30, Multiple Responses Allowed)

Response Theme	Percent
Have seen impact – increased stocks	45%
Have seen impact – decreased stocks	0%
Little to no impact	38%
Unsure of impact	14%
Unsure of impact - pandemic influence	28%

Contractor's average installation costs

All vendors were asked to provide an average price for qualifying and non-qualifying equipment for several zone configurations for a commercial facility. The Table B-11 below summarizes the findings. Values in the table have been restricted to just those respondents willing to answer for both qualifying and non-qualifying units.[59]

Table B-11. Average Sales price of Heat Pump Equipment

Zone Configuration	Average Cost: Program Qualifying	Average Cost: Non-qualifying	Cost Difference	Responses (n)
Single Zone	$4,140	$3,948	$192	13
Two Zone	$6,159	$5,945	$214	15
Three Zone	$8,052	$7,802	$250	15
Four Zone	$10,175	$9,906	$269	14

[59] The DNV Team reviewed these responses for inclusion in the cost-benefit analysis in Section 4.5. The QPs' responses on incremental costs generally aligned with our cost research; however, due to relatively low sample sizes from the vendor survey, we ultimately relied on secondary cost sources in the cost-benefit analysis.

Contractor’s percent of sales volume of program-qualifying equipment

The average percentage of heat pump sales volume made up of eligible equipment reported by the vendors is 71%. Half of all respondents reported a minimum percentage of 85% or more of eligible equipment sales volume. Out of the high-volume program participant strata vendors, half stated that at least 95% of their sales were of program-qualifying heat pumps.

Contractor’s barriers to program-qualifying HP sales

When asked what barriers they have experienced, contractors identified recurring themes such as cost, program criteria, program administration, marketing/commercialization, and training/education. Table B-12 below groups the responses into common themes mentioned. Since some respondents mention more than one barrier, the percentages exceed 100%.

Table B-12. Barriers to Qualifying Heat Pump Sales (N=30, Multiple Responses Allowed)

Barrier	Percent
No Barriers	31%
Cost of Qualifying Equipment	21%
Efficiency/Program Criteria	21%
Amount of Paperwork	17%
Administration/Bureaucracy	14%
Lack of Marketing/Commercialization	10%
Lack of Training/Education	7%

The most common response was that the vendor experienced no specific barriers. The most common barriers that were mentioned were the higher costs of the qualifying equipment (six respondents mentioned), and the amount of paperwork associated with the application and getting the rebate (five respondents mentioned). Some representative quotes for the top three themes are given below:

- On cost: *“[The] equipment is over-priced. Tech is getting better, but the prices don’t seem to be coming down like other technologies… [like Solar PV]”*
- On efficiency/program criteria: *“Most of the time [we] run into issues with it just not being a good fit for an application, [we] try to make it so they can put in equipment that qualifies but [it’s] not always the right application. Size wise for heat pumps needed for bigger spaces they don’t qualify for rebate because of the HSPF rating but is what’s needed to space, or multizone units that can’t handle Btus needed for the space”*
- On paperwork: *“The registration process is unwieldy, time limits for the whole process are unrealistic and unwieldly. [EMT’s] support is difficult, their requirements to fulfill are unrealistic and have never seen any report of the benefit of all the requirements they make us go through. We have to supply information that is difficult to find and is not clear what form they have.”*

Contractor’s sales influenced by the program

When vendors were probed on what impacts to their business they have experienced as a result of the program, a few themes emerged. Table B-13 below summarizes these themes among the 30 unique responses.

Table B-13. Other program impacts on business (N=30, Multiple Responses Allowed)

Theme	Tally of responses	Percent
Increased customer base	8	31%
Increased number and ease of sales	5	21%
Increased size/scope of projects	4	21%
Little to no impacts	4	14%
Unclear impacts	5	17%

System operation knowledge conveyed to customers

Vendors were asked how they educated customers on how to use their heat pump. There were several recurring themes, including use of the EMT-provided guide, general operations and care instructions, remote or thermostat instructions, controls/timers/setbacks instructions, any special tips/tricks, and leaving callback information for follow-up. Table B-14 below summarizes responses along these themes. Note that since most contractors mention more than one, the total percent exceeds 100%.

Table B-14. Vendor Education to Customers on HP Operation (N=30, Multiple Responses Allowed)

Response Theme	Percent
General Operations and Care	62%
Additional Tips/Tricks	55%
Remote or Thermostat instructions	52%
EMT Guide/Paperwork	41%
Leave callback information	21%
Controls/Timers/Setback instructions	14%
No Training Provided	0%

No responses stated that they provided no training at all. The majority of vendors reported going over general maintenance and care, tips and tricks, and remote/thermostat instructions. Many also stated they use EMT's HP Guide provided paperwork as educational material to leave with the customer.

APPENDIX C. Premise-Level Methods and Results

This appendix presents additional details on premise-level analysis techniques and results from analysis of AMI data and fuel delivery data.

Hourly PRISM Models

The following specification is estimated for the heating and cooling PRISM model for various heating and cooling bases in both the pre- and post-period for each hour and each customer. This used the following specification:[60]

$$kW_{it} = \alpha_i + \beta_1 HDH_{it} + \beta_2 CDH_{it} + \varepsilon_{it}$$

Where for each customer '*i*' and hour '*t*':

kW_{it}	=	Hourly kW consumption in the pre- or post-program period
α_i	=	The participant intercept, representing the hourly kW baseload
β_1	=	The model space heating slope (used in the heating only, heating+cooling model)—the average change in hourly kW resulting from an increase of one hourly heating degree hour (HDH)
HDH_{it}	=	The base 45–65 hourly HDHs for the specific location (used in the heating only, heating+cooling model)
β_2	=	The model space cooling slope (used in the cooling only, heating+cooling model)—the average change in hourly kW resulting from an increase of one hourly cooling degree hour (CDH)
CDH_{it}	=	The base 65–85 hourly CDHs for the specific location (used in the cooling only, heating+cooling model)
ε_{it}	=	The error term

Using the above model, the team computed weather-normalized annual kWh consumption as:

$$NAC_i = \alpha_i * 8760 + \beta_1 LRHDD_{it} + \beta_2 LRCDD_{it}$$

Where, for each customer '*i*' and annual time period '*t*':

NAC_i	=	Normalized annual kWh consumption
$\alpha_i * 8760$	=	Annual baseload kWh usage (non-weather sensitive)
$LRHDD_{it}$	=	Annual, long-term heating degree days of a TMY3 in the 1991–2005 series from NOAA, based on home location
$\beta_1 LRHDD_{it}$	=	Weather-normalized, annual weather-sensitive (heating) usage (i.e., HEATNAC)
$LRCDD_{it}$	=	Annual, long-term cooling degree days of a TMY3 in the 1991–2005 series from NOAA, based on home location
$\beta_2 LRCDD_{it}$	=	Weather-normalized, annual weather-sensitive (cooling) usage (i.e., COOLNAC)

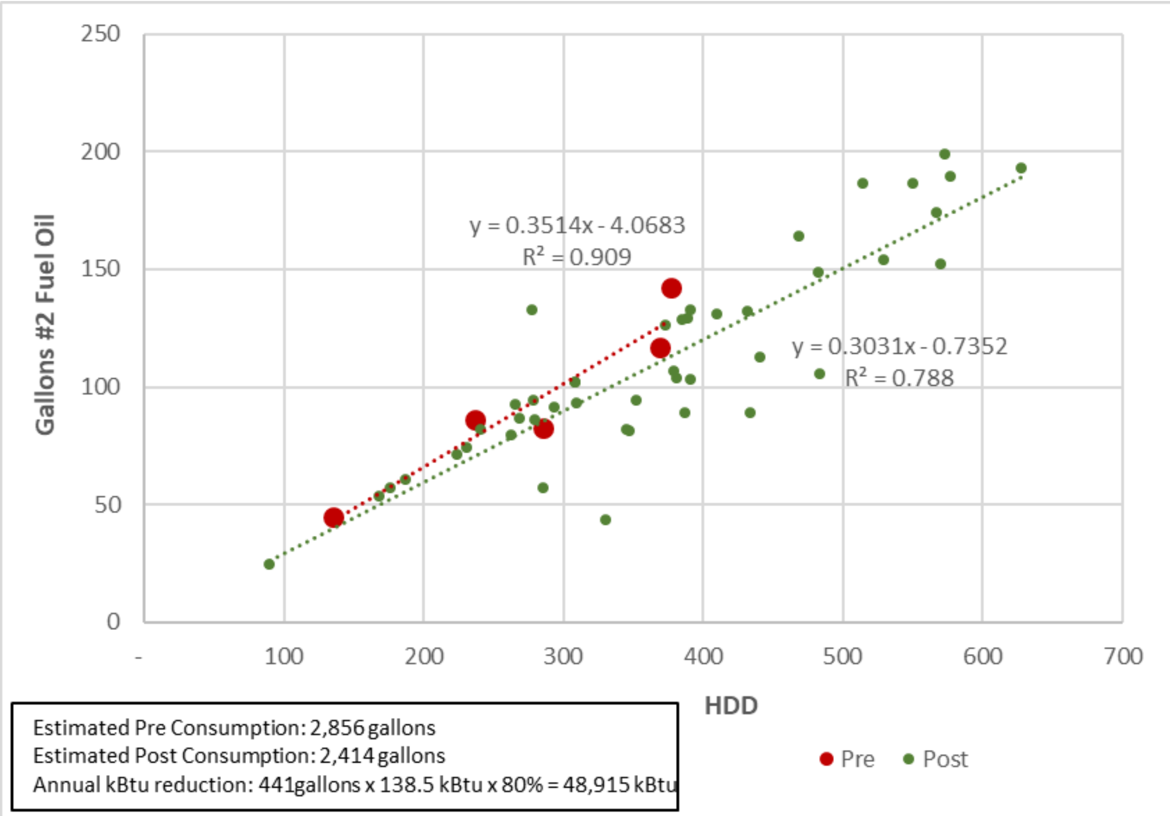
The hourly model specification produces weather normalized annual, monthly, daily, and hourly energy consumption estimates. Using actual weather data, the model also produces hourly estimates during the concurrent sub-metering period, from December 2020 through October 2021.

The team used the heating components of the PRISM model described above to estimate the change in annual consumption of delivered fuels. The delivery date and fuel volume were known, so the team assumed the amount delivered represented the fuel consumed between the delivery and date of the prior delivery. The DNV team plotted the total daily HDDs observed between each fuel delivery versus amount of fuel delivered to develop linear regressions of fuel usage

[60] There are 24 hourly models estimated for weekdays and 24 hourly models estimated for weekends for the year – since we have 8760 observations in a year the variation in the hourly models is the daily variation in the specific hour – so each hourly model has 365 observations included in the regression. Other more detailed specifications were attempted as well such as separate models for each hour and each day of the week, and for each hour and weekdays/weekends.

before and after heat pump installation. Figure C-1 shows an example of relatively granular data from one site that received fuel oil deliveries twice per month during the winter. In this example, data were only available beginning 4 months prior to heat pump installation which increases uncertainty of the fuel usage prediction[61].

Figure C-1. Example of Fuel Purchase Data Before and After Heat Pump Installation



To estimate the change in heat delivered by the fossil fuel[62] heating system, the team used best-fit linear regressions to calculate weather-normalized pre and post annual fuel usage and assumed the heating system operated with 80% efficiency. The regressions in Figure C-1 were used to estimate a reduction of 440 gallons of fuel oil which equates heating load reduction of approximately 49 MMBtu. If the reduction in fuel oil is attributed to the heat pump installation, one would expect an increase in electric energy consumption of about 4,450 kWh for heat pump(s) with efficiency of 11 HSPF.

Analysis of Potential Changes in Conditioning Loads

Figures C-2 and C-3 show the distribution of sites according to the change in annual cooling and heating consumption, respectively (in bins of 42 kWh per 1,000 Btu/h). Site counts to the left of the hashed line correspond to an increase in energy use.

[61] Most sites had sufficient data before or after heat pump installation, but many had some type of challenge or concern with the accuracy of the prediction. For example: low data granularity (fuel purchased 2-3 times/year), data for multiple tanks (one or more may not be associated with the heat pump), or high volume relative to heat pump installed capacity.

[62] Assumed heat content per gallon: Heating oil: 138,500 Btus, Kerosene: 131,890 Btus, Propane: 91,500 Btus.

Figure C-2. Distribution of Cooling Energy Change after HP Installation (Average Increase of 1.3 kWh per 1,000 Btu/h)

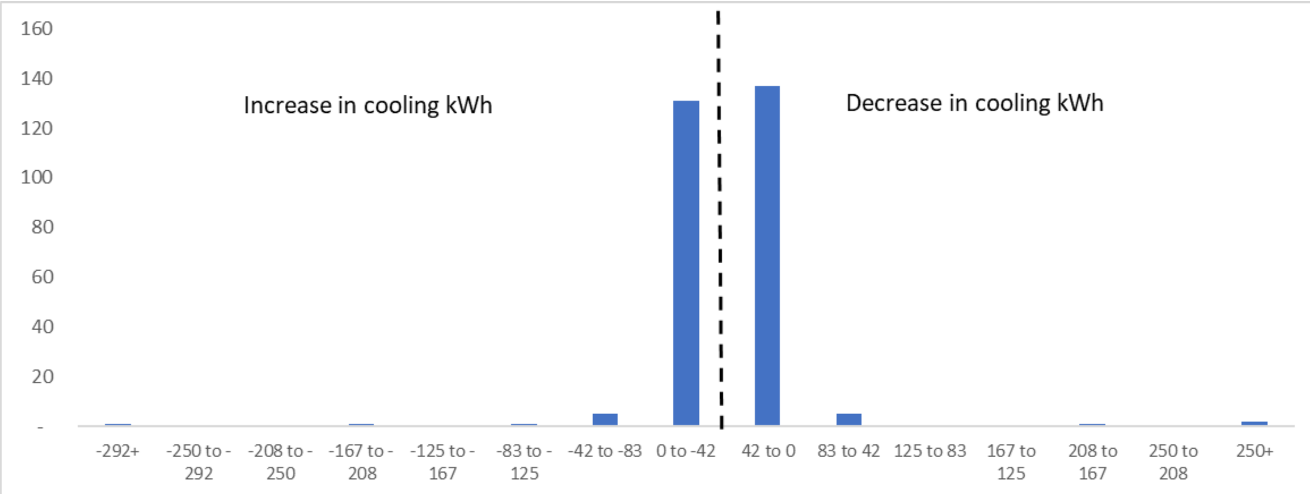
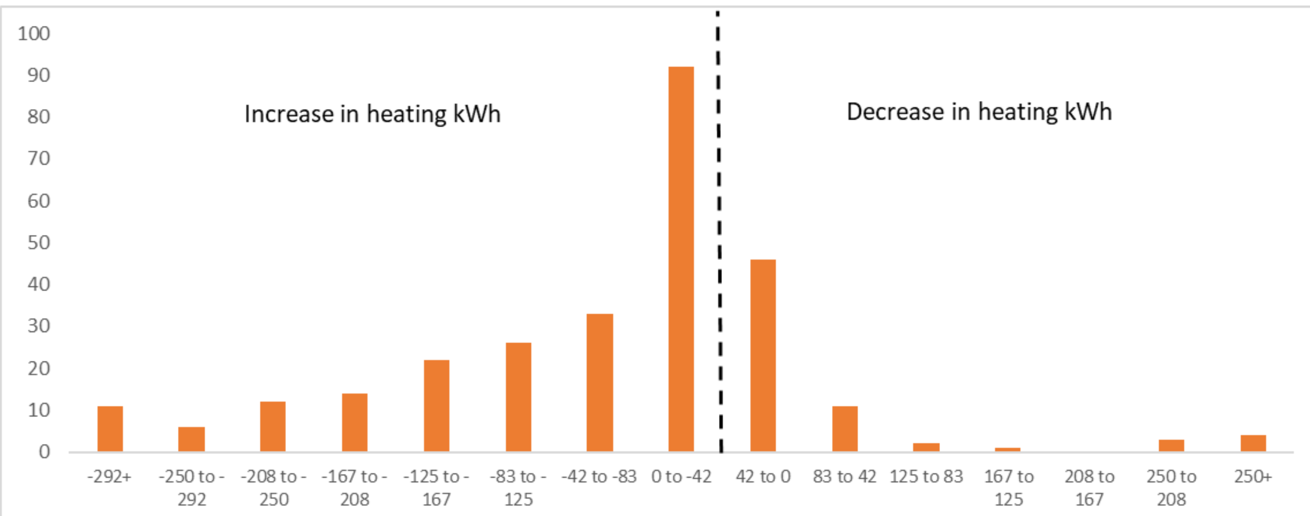
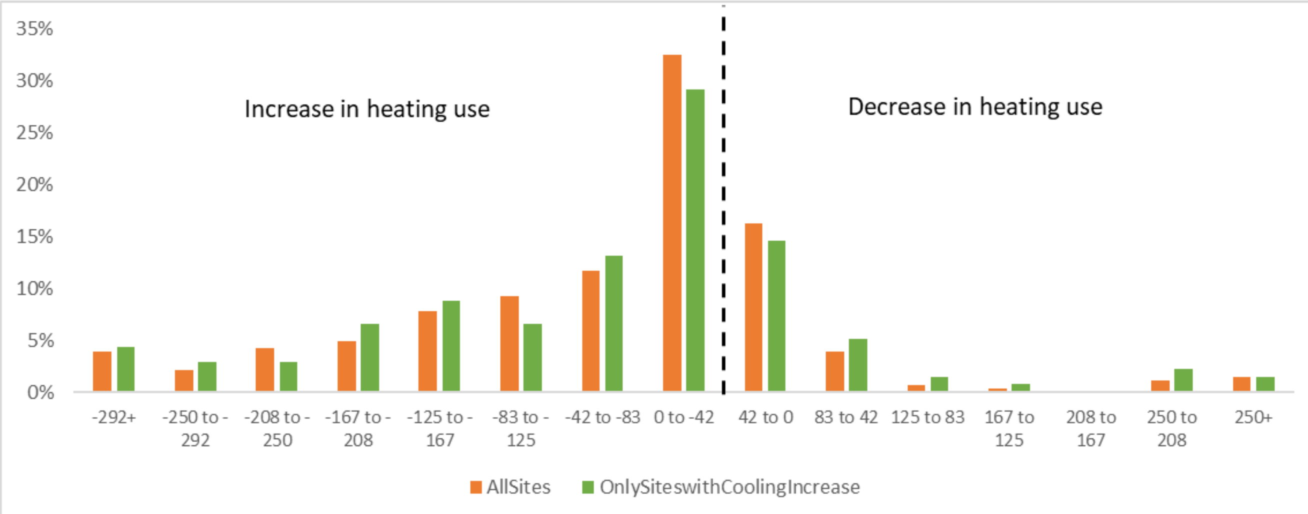


Figure C-3. Distribution of Heating Energy Change after HP Installation (Average Increase of 47 kWh per 1,000 Btu/h)



The orange bars in Figure C-4 represent the same data from Figure C-3 and the green bars represent the sub-set of sites that had an increase in cooling energy use.

Figure C-4. Comparing Heating Energy Change for Subset of Sites with Cooling Increase



One might expect sites showing an increase in cooling load to also show an increase in heating load (e.g., space expansion); such sites were omitted from this pre/post analysis, as the pre-project data could not be normalized to reflect post-project typical conditions. Figure C-4 shows that when isolating sites with an increase in cooling, the heating use distribution does not change significantly. Table C-1 summarizes these data, showing similar average heating energy change, regardless of the change in cooling.

Table C-1. Pre/Post Heating Energy Change for Cooling Energy Increase versus Cooling Energy Decrease

AMI Pre/Post Change in Cooling	Logical Hypothesis	Sites	Cooling Change kWh per 1,000 Btu/h	Heating Change kWh per 1,000 Btu/h
Cooling Energy Increase	An increase in cooling is not expected. This may indicate a change in building cooling load or operation. Pre/Post data should not be used to estimate savings.	112	+9.4	+48.8
Cooling Energy Decrease	Cooling energy use decreases (as expected) validating use of pre/post data to estimate impacts attributed to heat pump installation.	130	-5.0	+47.3

Comparing AMI Analysis Methods: PRISM vs. Machine Learning

As discussed in Section 4.3, the DNV team attempted multiple methods of AMI analysis to minimize uncertainty in results. The two primary candidate methods were PRISM and machine-learning analysis; Figure C-5 compares results from each, showing the hourly residual error for the standard PRISM model and for the machine-learning model. If a model over-estimates energy use, the residual error is negative.

Figure C-5. Comparing Residual Error between PRISM Model and Machine Learning Model

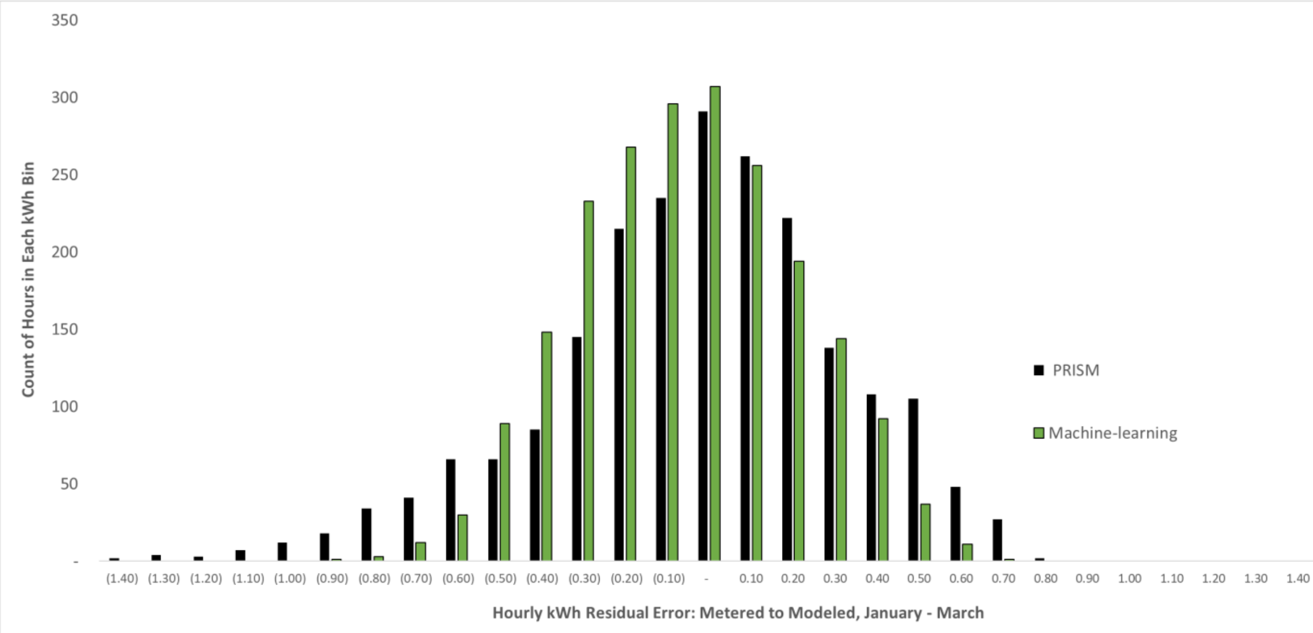


Figure C-5 shows that the PRISM model overestimates electric heating energy use—i.e., shows negative residual error based on difference between model and M&V data— more frequently than the machine-learning model. However, the sum of the residual error was not significantly different for these methods, with the standard PRISM model overestimating electric heating energy use by 7% more overall than the machine learning model.

Figure C-6 compares the two models as a function of outdoor temperature, with the machine learning model (blue) more closely matching the M&V data (green) than the standard PRISM model (grey). The models appear to diverge most notably when temperatures range from 40 to 60 degrees. The PRISM model underestimates usage at this temperature range, primarily for two reasons:

- Only one type of consumption (heating or cooling) at a specific temperature is estimated: either heating or cooling, but not both. As temperatures become milder, dual instances of heating or cooling at a given outdoor temperature become more plausible.
- The standard PRISM model cannot detect heat pump standby energy consumption, which is generally constant save for auxiliary components used only during winter (e.g., crank case heater, drip pan heater). At milder temperatures, standby energy consumption accounts for a higher percentage of total HP energy consumption.

Figure C-6. Comparing Modeled Results with M&V Results versus Outside Air Temperature

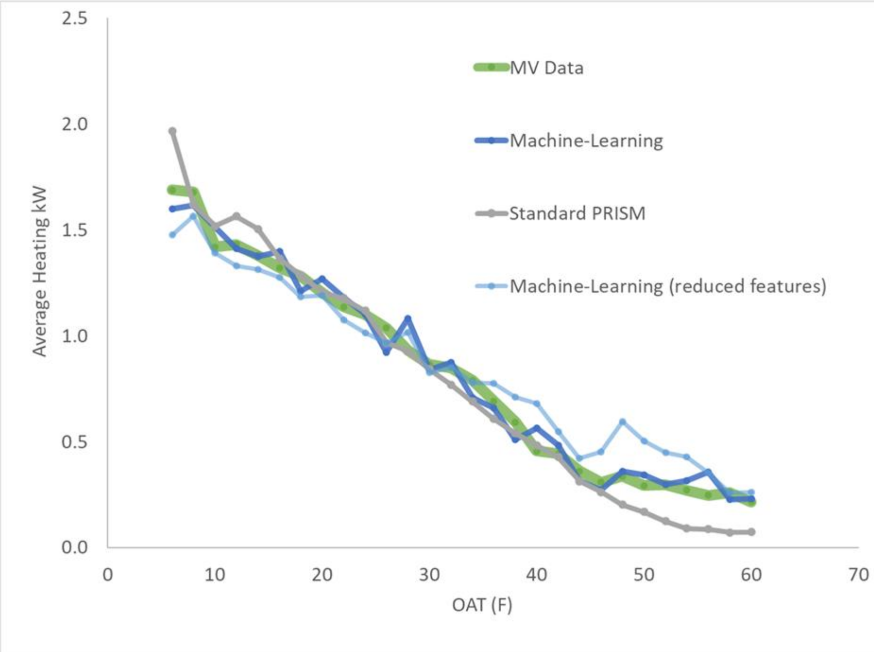


Table C-2 compares the machine-learning AMI results with M&V results for 22 sites that overlapped between the two evaluation techniques. While the average results were similar between the two methods, the site-specific ratios in results ranged from 0.05 to 1.94.

Table C-2. Site-by-Site Machine Learning AMI Results versus M&V Results

Index	M&V Metered Heating kWh (Adjusted for Total Installed Capacity)	AMI Modeled	AMI kWh ÷ M&V kWh	Increase in Cooling Energy?
A	187	724	0.26	Yes
B	65	71	0.91	No
C	684	387	1.77	No
D	1,583	2,130	0.74	Yes
E	555	285	1.94	No
F	2,740	1,711	1.60	Yes
G	1,958	1,731	1.13	No
H	5,756	4,610	1.25	No
I	3,007	2,793	1.08	No
J	3,120	2,109	1.48	Yes
K	192	3,551	0.05	Yes
L	941	992	0.95	No
M	0.23	0.18	1.25	Yes
N	4,088	3,195	1.28	No
O	1,019	978	1.04	No
P	4,250	4,883	0.87	No
Q	1,742	2,362	0.74	No
R	91	627	0.15	No
S	2,543	1,772	1.44	Yes
T	1,945	1,756	1.11	No
U	261	304	0.86	No
V	198	1,926	0.10	Yes
Total (n=22)	**1,678**	**1,768**	**1.05**	

Load Shape Classifications

For future studies that involve AMI data from customers receiving an HVAC upgrade, the DNV team recommends classifying sites into subgroups based on the temperature dependence of pre/post AMI data. Figures C-7 through C-9 show examples of three load shape classifications: full displacement, partial displacement, and low/no apparent heating use. First, the team has provided some additional background information on cohort classification.

In other heat pump program evaluations, full- and partial-displacement heat pump installations had notably different operating and savings characteristics. The DNV team's hypothesis was that by segmenting sites into groups based on heating strategy, they would be able to improve the accuracy of the heating disaggregation models. Therefore, they categorized sites into groups (i.e., "cohorts") by analyzing data to predict the operating strategy, which could subsequently be validated by survey responses.

The team sought to identify cohorts analytically for each site by first using only data that are readily available: hourly AMI data (before and after heat pump installations), actual and normal (TMY3) weather data from closest local weather station, and program tracking data. Some of the key tracking data include building type, location, square footage, installation date, nameplate information, and presence of other heating system(s).

The team defined these cohorts: 1) "full displacement," meaning heat pumps are used as the exclusive or primary heat source in a building, room, or space; 2) "partial displacement," meaning heat pumps installed in conditioned space with other heating systems; and 3) "low/no apparent heating usage," meaning heat pumps used irregularly, rarely, or never for heat. Figures C-7, C-8, and C-9 illustrate examples of each cohort.

Figure C-7. Full Displacement Load Shape Example

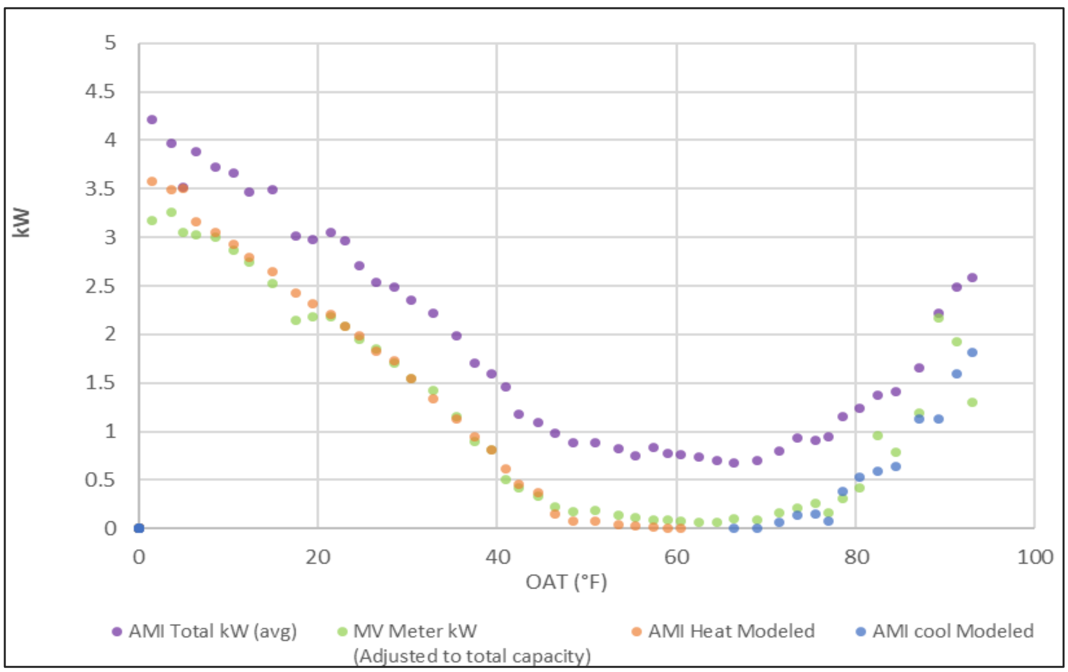


Figure C-8. Partial Displacement Load Shape Example

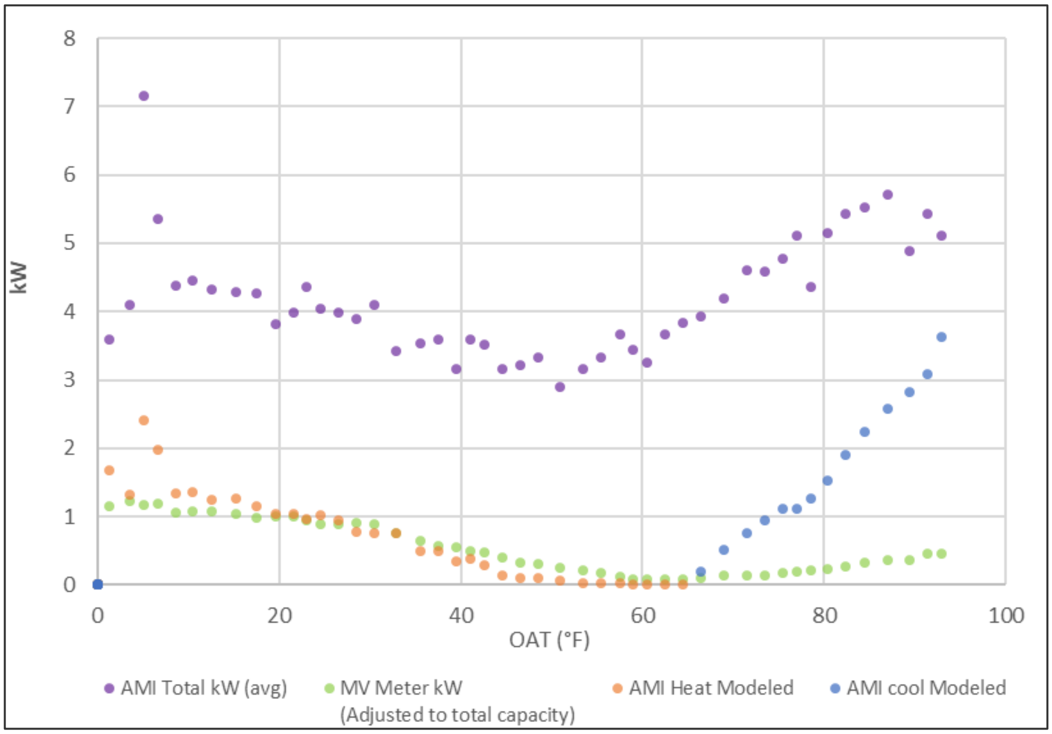
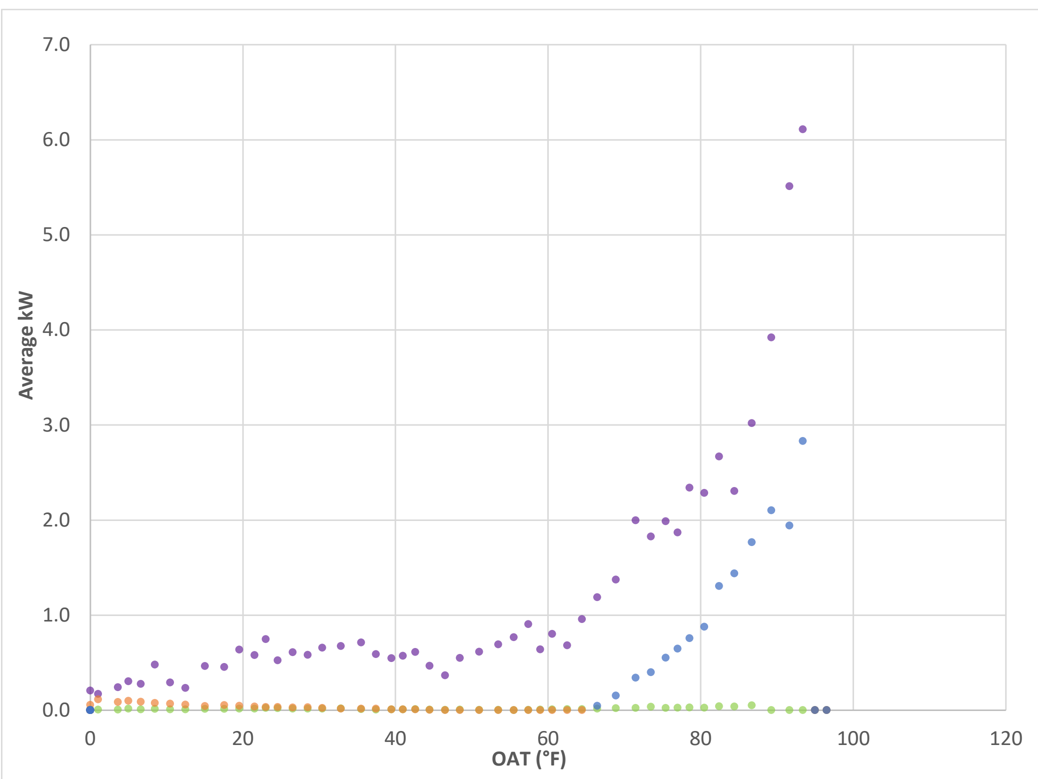


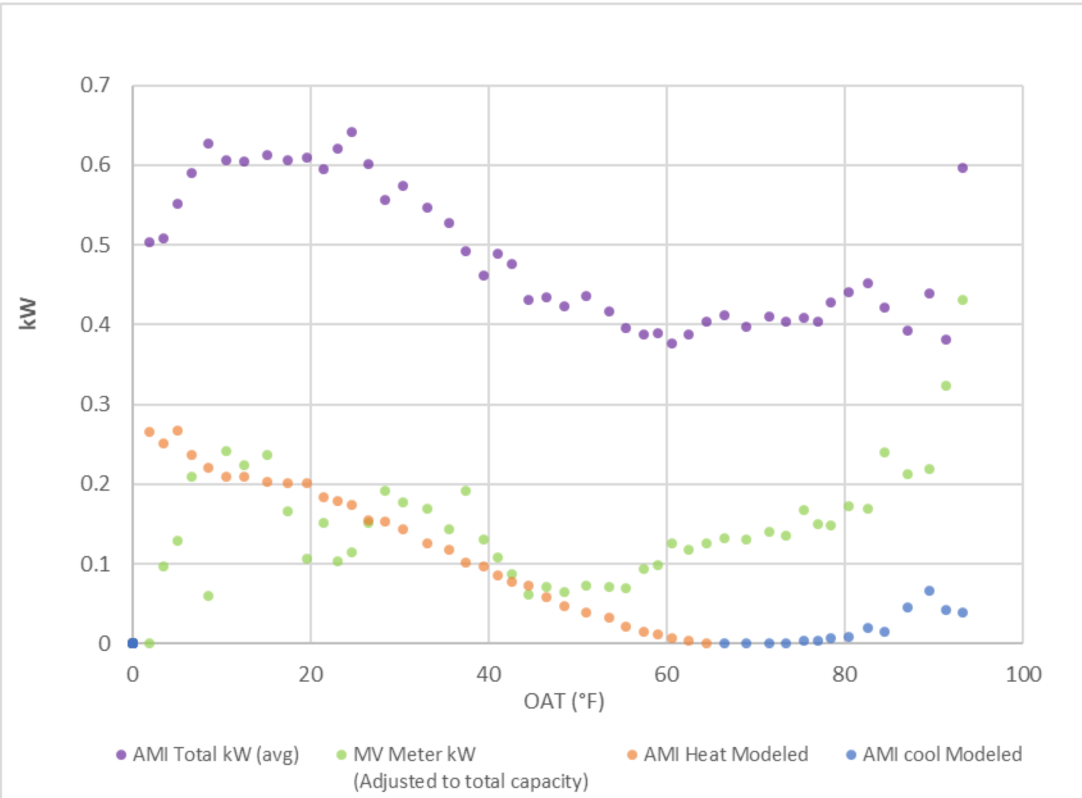
Figure C-9. Low/No Apparent Heating Use Load Shape Example



The PRISM method generally overestimates weather-dependent usage for partial displacement scenarios – specifically when the HP usage is curtailed during the coldest temperatures, as illustrated in Figure C-8 where the green M&V points do not continue to increase as outside air temperature decreases. A machine-learning model (or any type of model that is calibrated using M&V data) is developed using all available data. Consequently, the load shape characteristics from one type of HP operational strategy impact the model and may increase error for HPs using a different operational strategy.

Consider another example, Figure C-10, which was classified within the "partial displacement" cohort.

Figure C-10. Partial Displacement Load Shape Example



The AMI data (purple plot) shows a reduction in energy use as temperature decreases. The green plot (actual HP meter data) also shows decreased and more sporadic usage when the temperate falls below about 25° F. This is consistent with the survey response: *"we try to turn off the heat pumps when it's really cold out"*. Figure C-10 illustrates that AMI-estimated heating use (orange) does not follow the M&V data's load shape (green). The AMI-estimated heat pump use continues to increase as temperature decreases even though cold-temperature curtailment is apparent from the M&V data. Unique disaggregation models developed exclusively from homogenous sites and applied to the same type of sites would undoubtedly improve modelled predictions[63].

It is worth noting in this example that any improvement in modelled annual heating use is relatively low, simply because there are relatively few hours at the coldest temperatures. However, if winter peak demand impacts are of interest, heating load shape characterization should be emphasized.

[63] This hypothesis could not be validated in this study. Further segmenting the limited sub-set of sites with AMI and M&V data (n=22) results in a sample too small to develop a disaggregation model.

Classification of sites into the three distinct cohorts illustrated in Figures C-7, C-8, and C-9 will minimize uncertainty—i.e., the low-usage site results will not affect the full-displacement site results. The standard PRISM disaggregation model, coupled with hourly coefficients determined in this study (see Table C-3) could be used for future evaluations. These coefficients represent the time-dependent HP usage independent of outside air temperature. As hourly coefficients further deviate from 1.0, factors other than outside air temperature have an increasing impact on HP energy consumption. Some examples of factors other than outside air temperature that may explain the hourly variance in HP usage include the following:

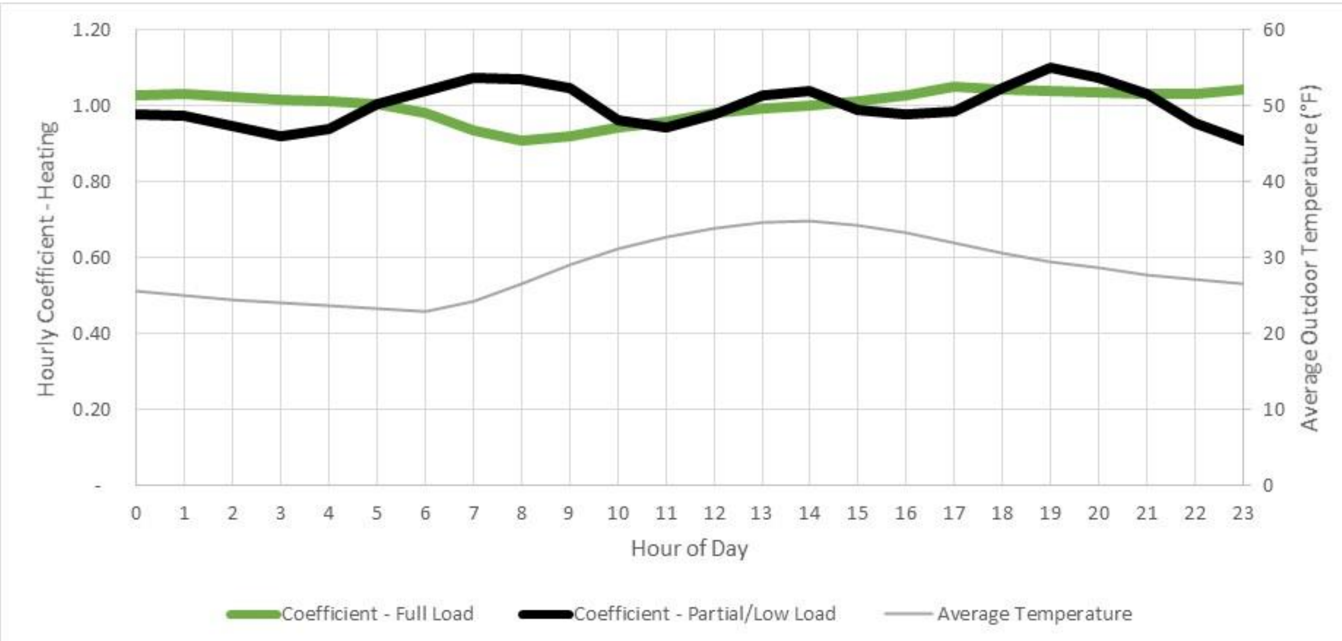
- Temperature setpoint changes – occupant changes the thermostat, thermostat has programmed schedule, or occupant shuts off the heat pump.
- Internal heat gains – other heating systems or sources of heat reduce the heating load on the heat pump.
- Solar heat gains – sun shining, especially through windows, adds heat to the space at certain times.
- Thermal mass (thermal transient) of the building – as outdoor temperature changes, the indoor temperature lags, due to thermal mass of the building.

Table C-3. Hourly Coefficients Independent of Temperature

Hour	Coefficient: Full Displacement	Coefficient: Partial Displacement and Low Usage
0	1.03	0.98
1	1.03	0.97
2	1.02	0.95
3	1.02	0.92
4	1.01	0.94
5	1.00	1.00
6	0.98	1.04
7	0.93	1.07
8	0.91	1.07
9	0.92	1.05
10	0.94	0.96
11	0.96	0.94
12	0.98	0.98
13	0.99	1.03
14	1.00	1.04
15	1.01	0.99
16	1.03	0.98
17	1.05	0.99
18	1.04	1.05
19	1.04	1.10
20	1.04	1.07
21	1.03	1.03
22	1.03	0.95
23	1.04	0.91
Average	**1.00**	**1.00**
Average Deviation	**3.3%**	**4.3%**

The average absolute deviation from 1.0 was 3.3% for full displacement heat pumps and 4.3% for partial and low use heat pumps, meaning full displacement HP usage is slightly less dependent on factors other than outdoor temperature. The coefficients in Table C-3 are presented in Figure C-11.

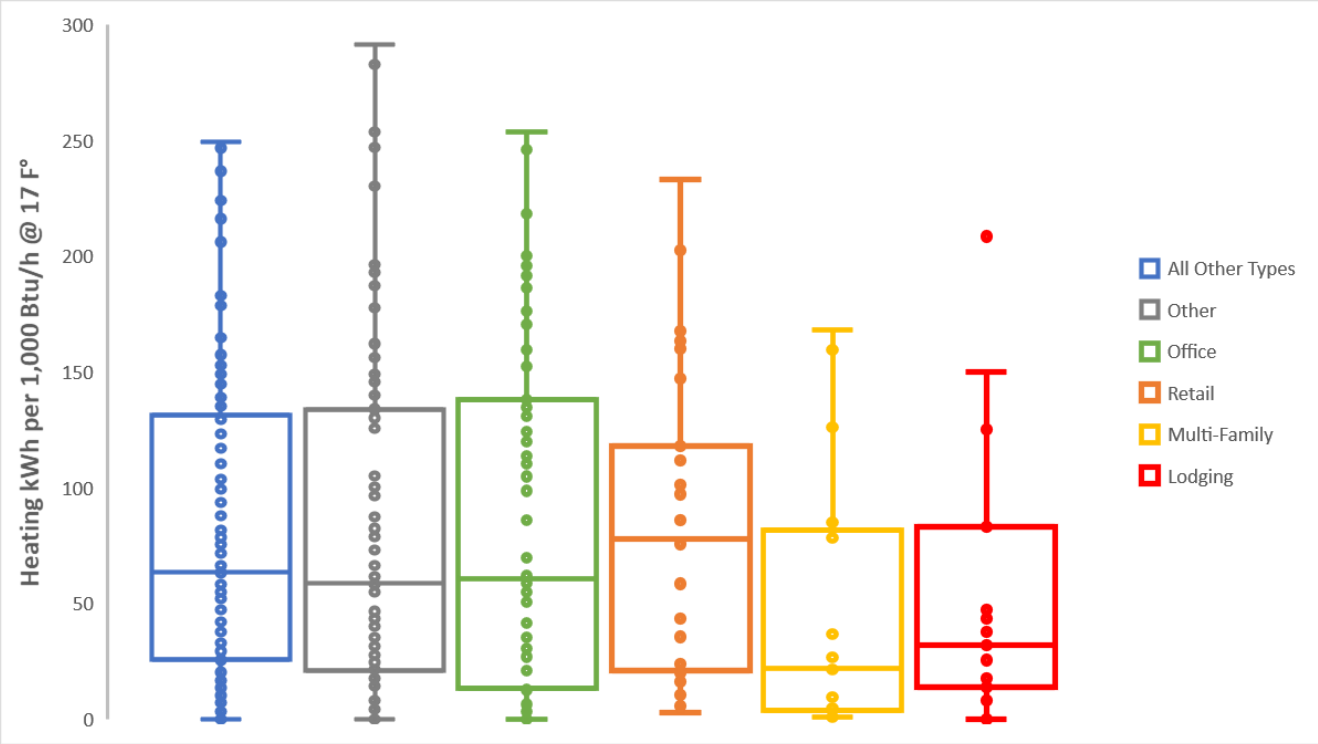
Figure C-11. Visualization of Hourly Coefficients



Results by Building Type

Figure C-12 illustrates the AMI analysis results by building type.

Figure C-12. AMI Segmentation Analysis – Results by Building Type



APPENDIX D. Additional Load Profiles

This appendix contains additional hourly kW usage profiles from analysis of 70 HPs sampled for measurement and verification. Profiles are organized by various segmentation variables: facility type, pre-existing heating fuel, single vs. multi-zone configuration, and legacy heating system use.

Facility Type

Figure D-1. HP January Load Profiles by Facility Type

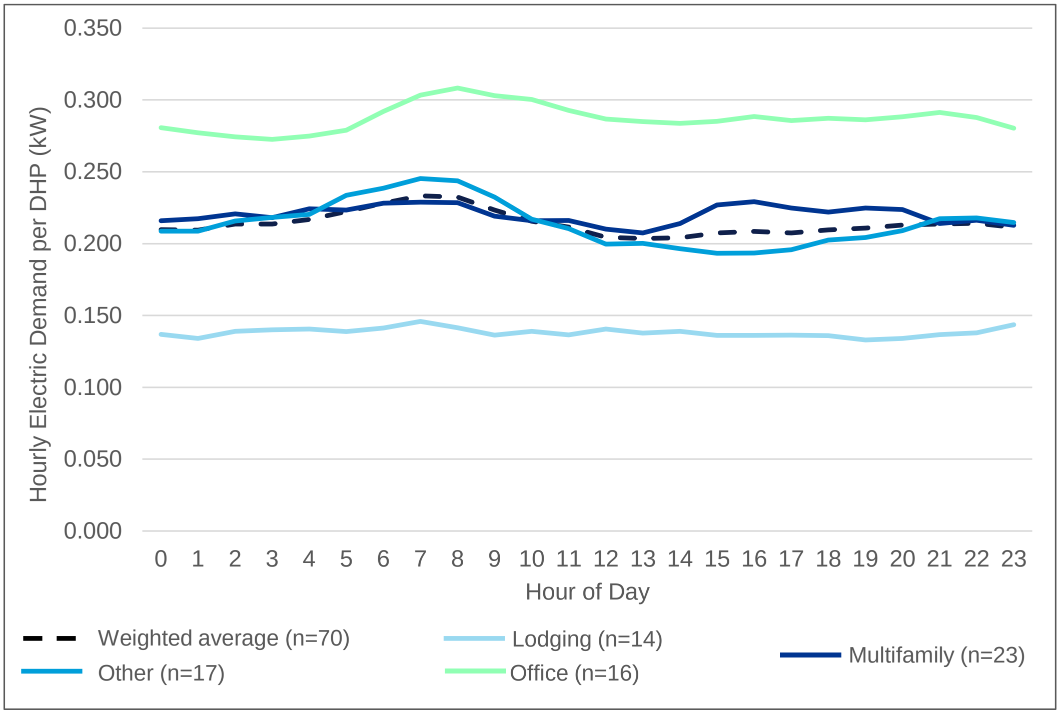


Figure D-2. HP April Load Profiles by Facility Type

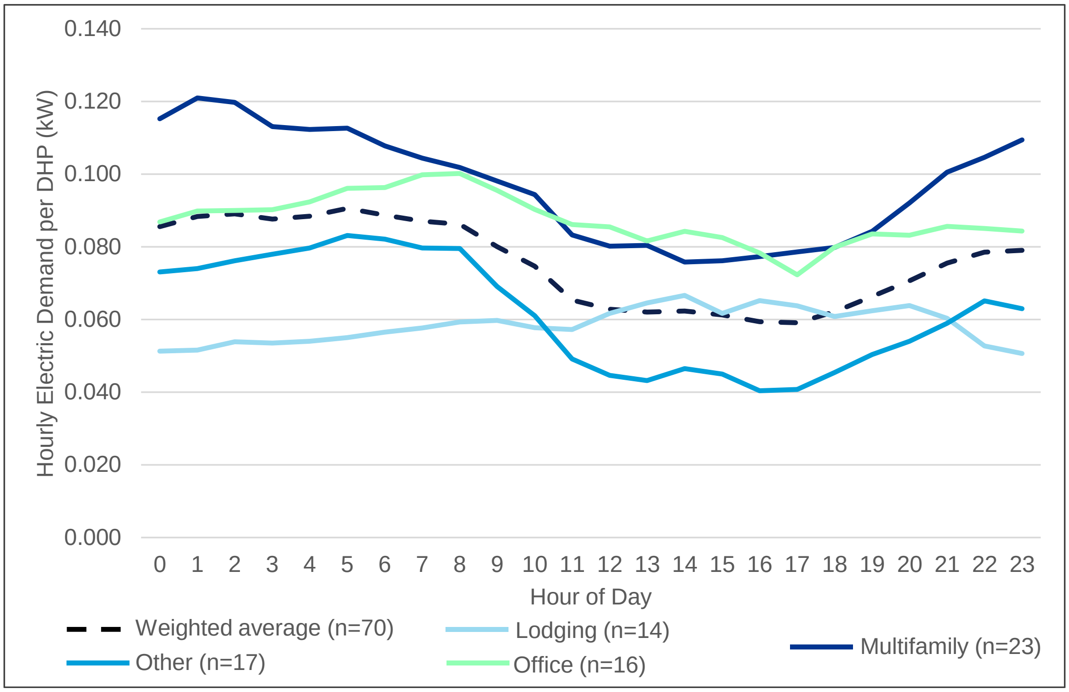
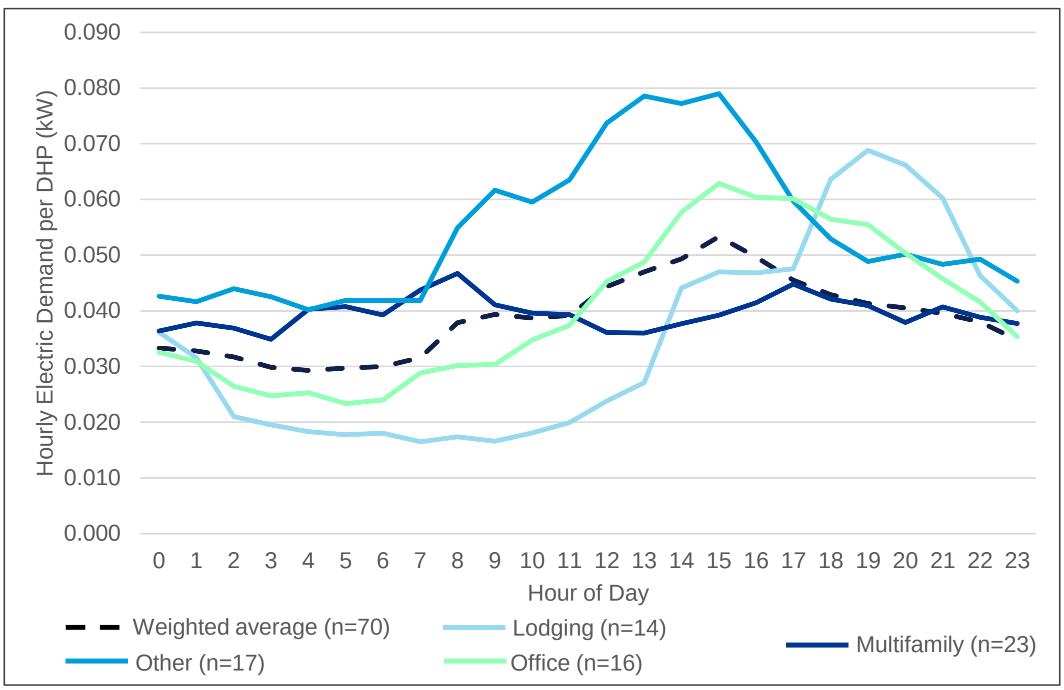


Figure D-3. HP July Load Profiles by Facility Type



Pre-existing Heating Fuel

Figure D-4. HP January Load Profiles by Primary Pre-existing Heating Fuel

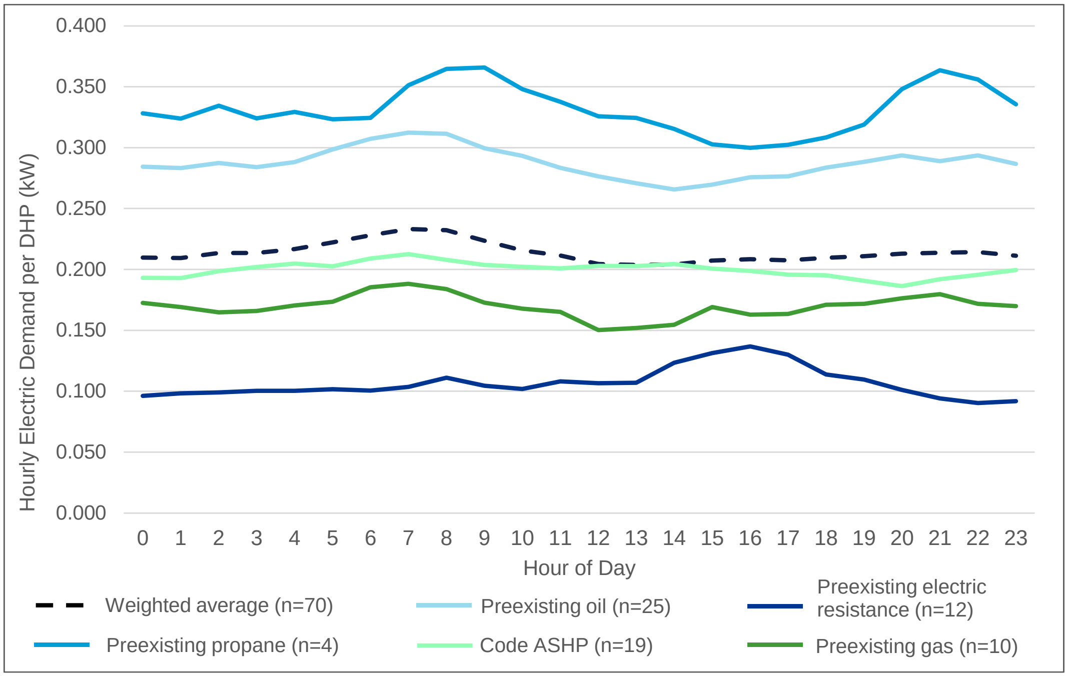


Figure D-5. HP April Load Profiles by Primary Pre-existing Heating Fuel

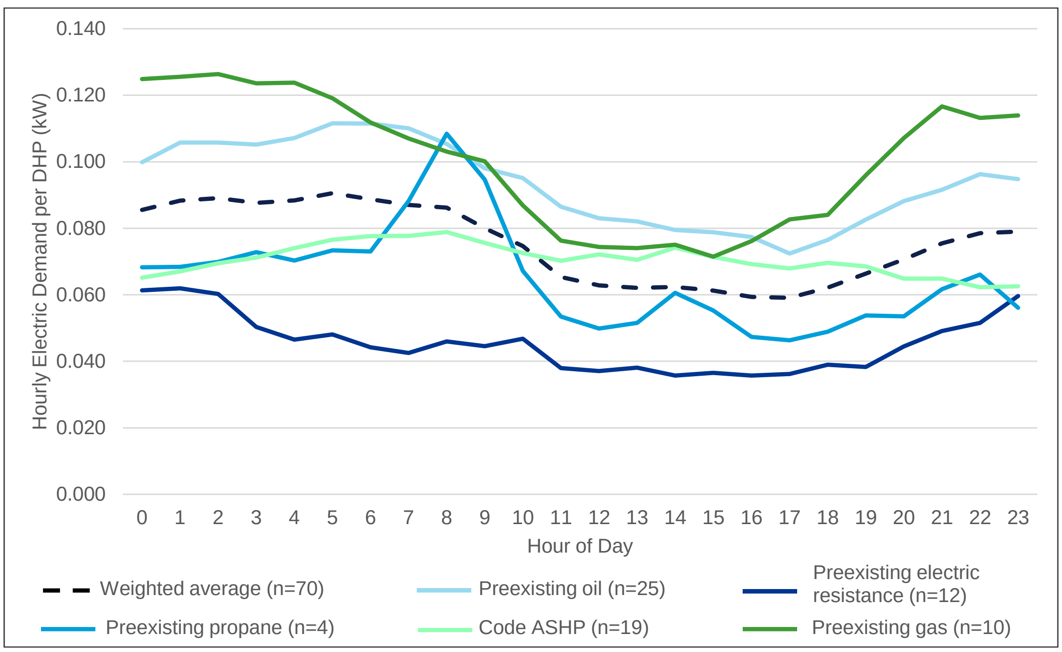
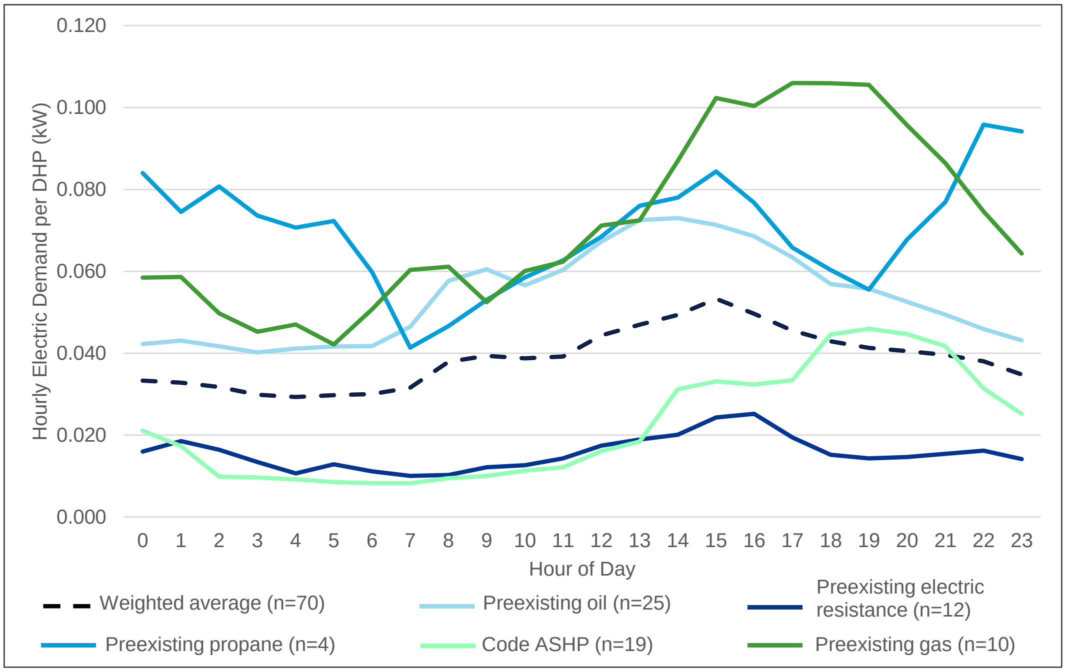


Figure D-6. HP July Profiles by Primary Pre-existing Heating Fuel



Single vs. Multi-Zone Configuration

Figure D-7. HP January Load Profiles by Zone Configuration

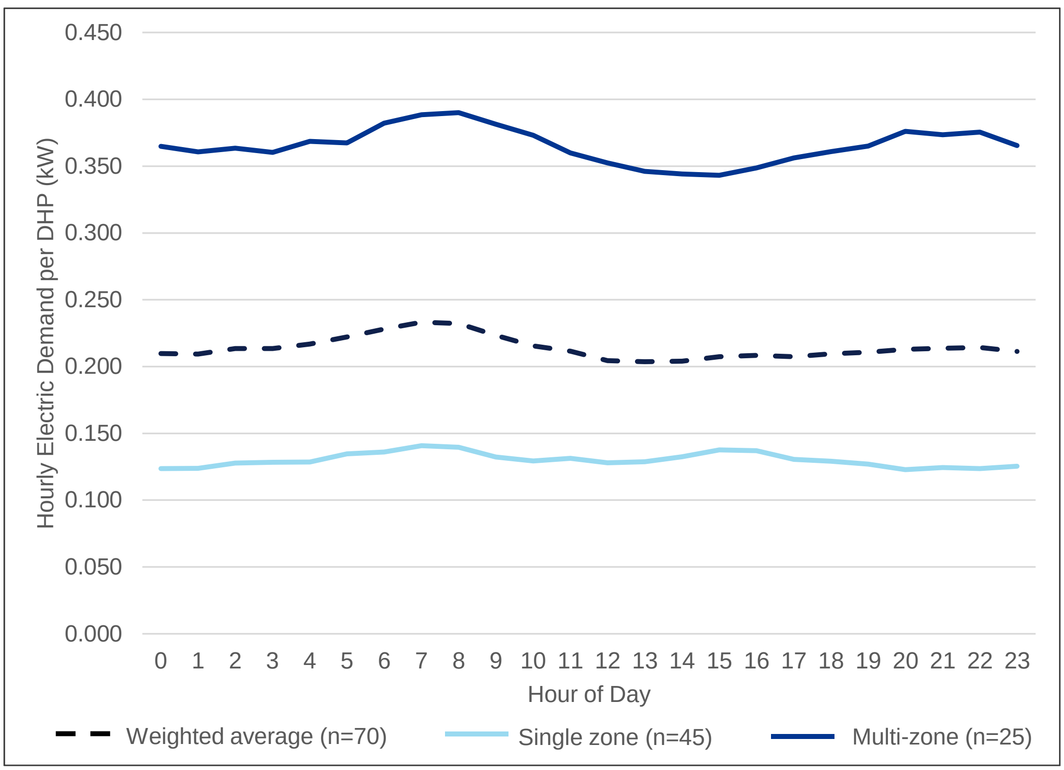


Figure D-8. HP April Load Profiles by Zone Configuration

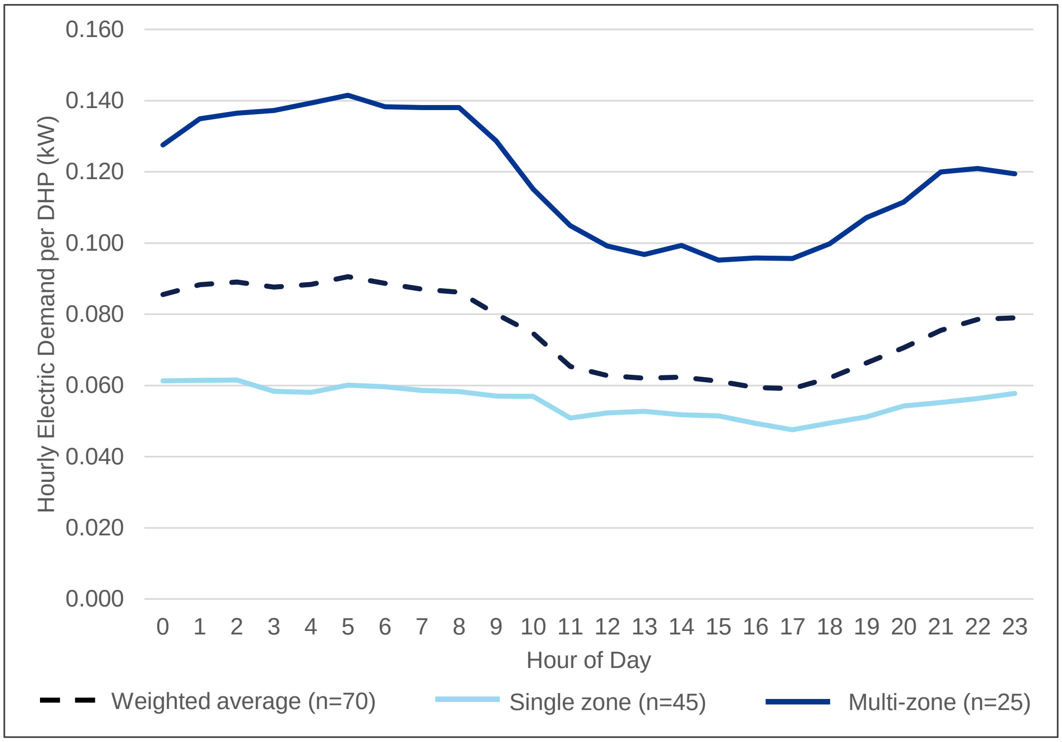
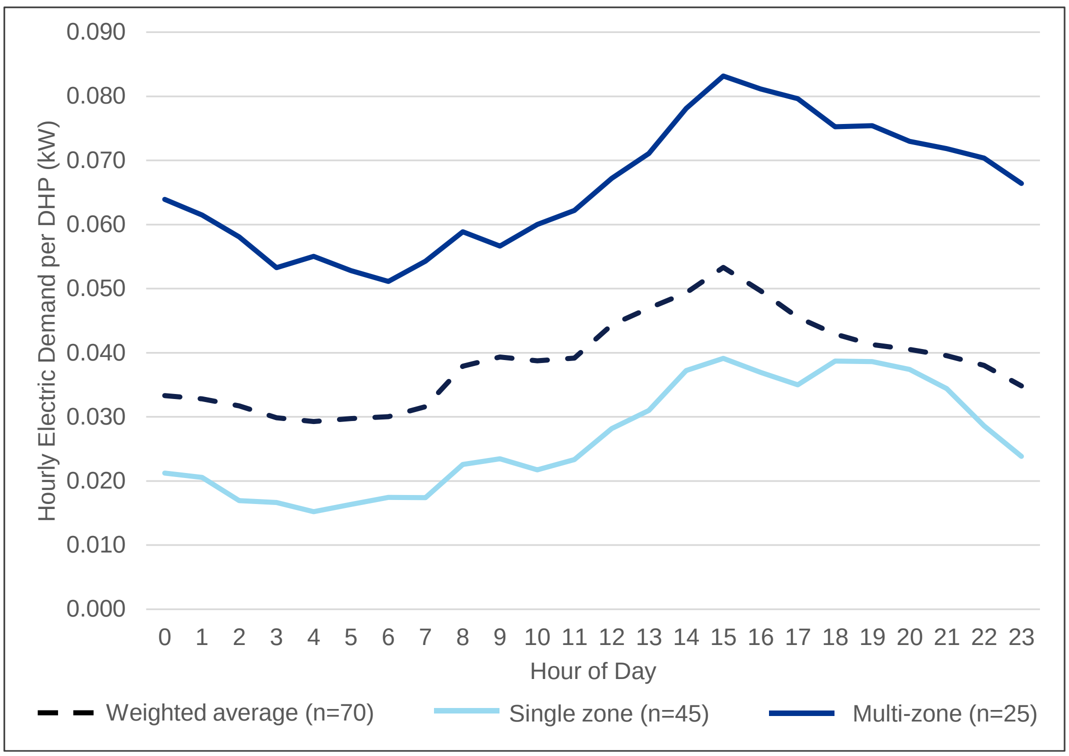


Figure D-9. HP July Load Profiles by Zone Configuration



Legacy Heating System Use

Figure D-10. HP January Load Profiles by Legacy Heating System Use

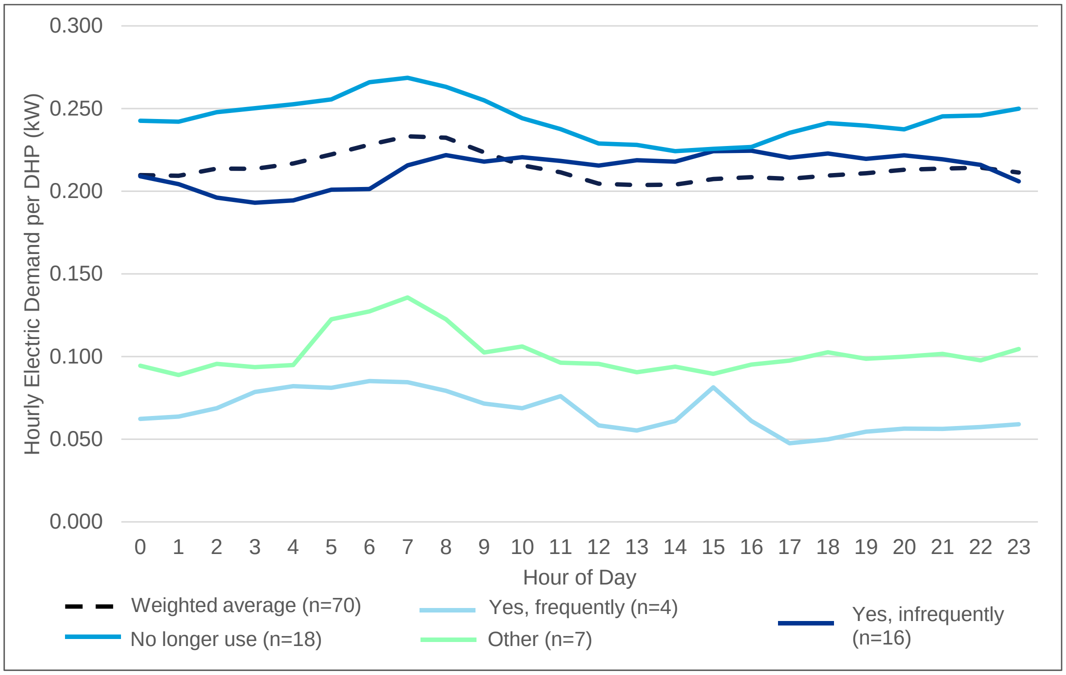


Figure D-11. HP April Load Profiles by Legacy Heating System Use

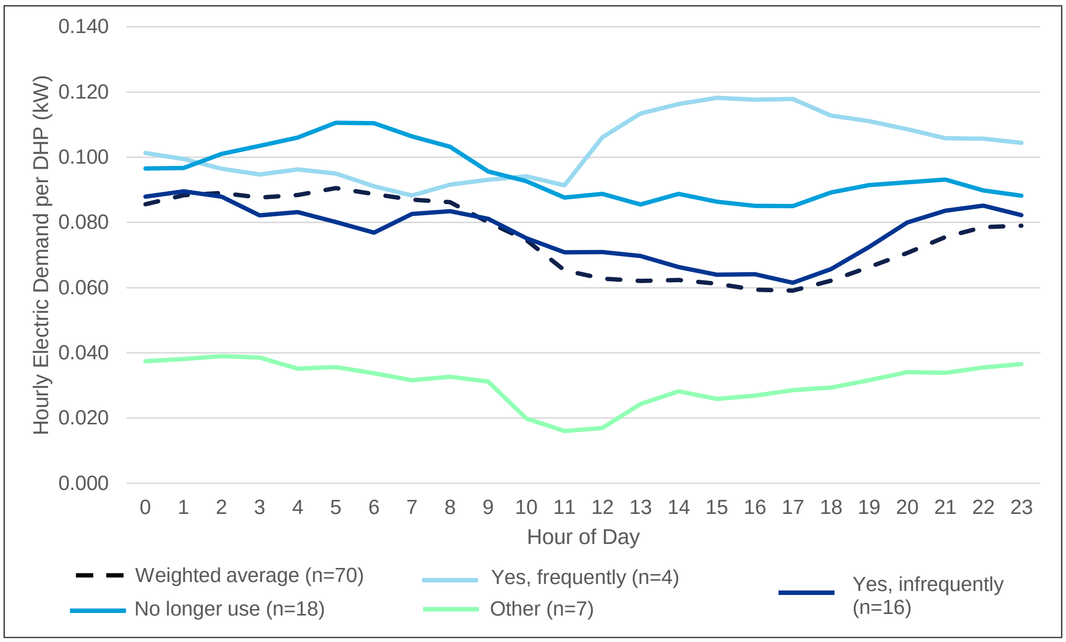
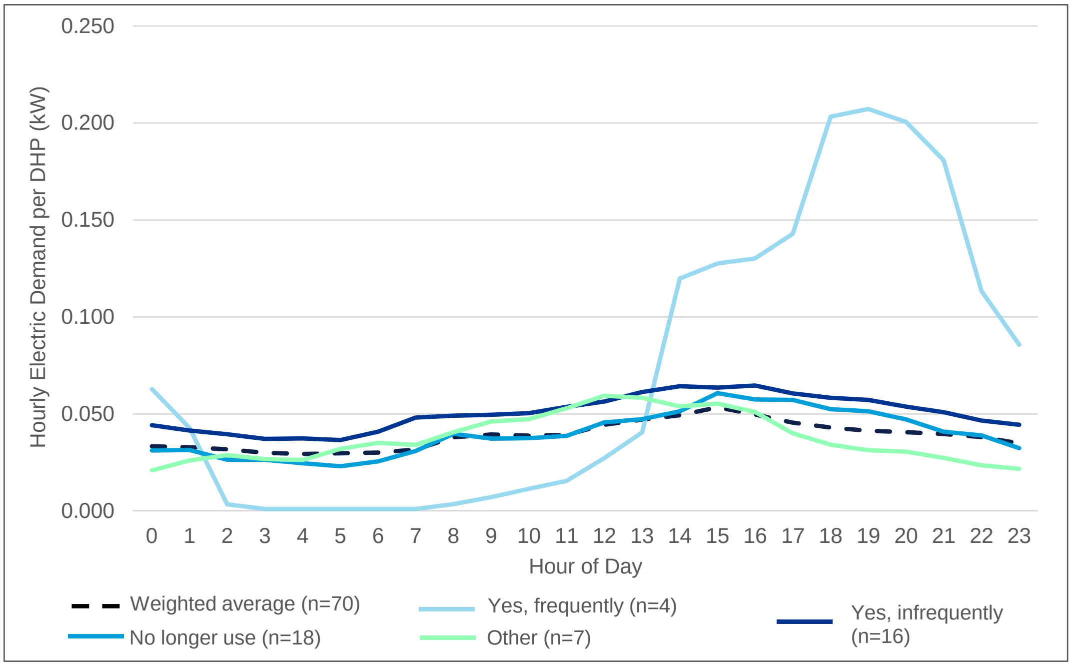


Figure D-12. HP July Load Profiles by Legacy Heating System Use



APPENDIX E. Meter Specifications

This appendix includes specification sheets for the meters deployed during this study's M&V activities.

MAGNELAB

Split-Core AC Current 4 to 20 mA Transducer
MCT-0016-XXX, 4 to 20mA DC Output

16mm Opening With Ratings Up to 100 Amp

Description:

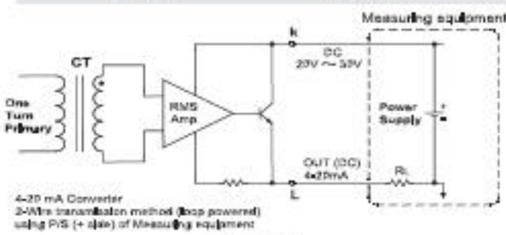
Magnelab's MCT-0016-XXX split-core current transducer "senses" AC current up to 100 Amps passing through the center conductor. Split-core transducers are ideal for installation on existing electrical wiring by snapping around the conductor. The MCT-0016-XXX has a self-locking mechanism.

Features:

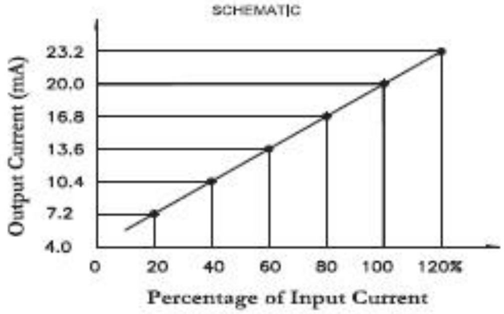
- Rated input up to 100 Amp
- Output of standard 4 to 20 mA DC
- Accuracy ± 2% FS, Ripple within 2% of output voltage
- Maximum load resistance 600 Ohms at Power Supply 24 V
- 24 Vdc Loop Power 20 - 30 Vdc (25 mA max.)
- Max allowable current 120% continuous, 150 % 1 min
- Frequency range 50/60 Hz
- 2 X M3-Screw terminals
- Installation Category CAT III
- UL recognized IEC 61010-1, CE, and RoHS compliant
- Operating temperature -20° to 50°C

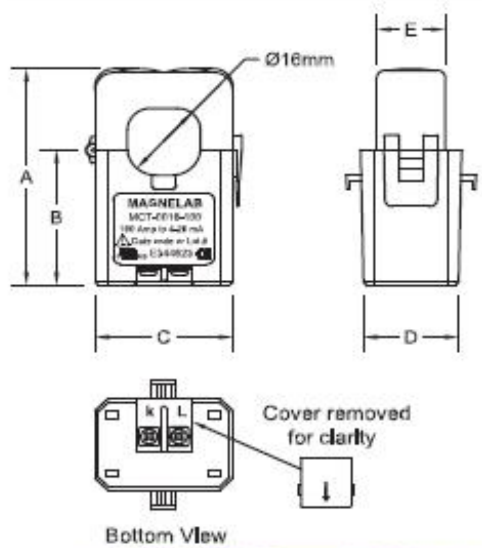
PART NUMBER AND RATING	
MCT-0016-005	5 Amp
MCT-0016-010	10 Amp
MCT-0016-020	20 Amp
MCT-0016-050	50 Amp
MCT-0016-100	100 Amp

DIMENSION	INCH	MM
A	2.22	56.00
B	1.44	36.60
C	1.19	30.00
D	1.24	31.00
E	0.76	19.00



SCHEMATIC





cULus CE RoHS2 ISO 9001:2008

B Magnelab.com

ONSET

HOBO® T-WNB-3D-240 Sensor

WattNode 208/240 VAC 3-phase Delta/Wye kWh Transducer Sensor

The WattNode provides accurate measurement at low cost to meet your needs for sub-metering, net-metering, energy management, and performance contracting applications. This WattNode Delta-connection kWh Transducer works with Magnelab AC Current Transformers and a Pulse Input Adapter to provide True RMS kilowatt hours of energy used, even for loads with non-sinusoidal waveforms. Because these sensors tie directly into the line, they should be used only by qualified personnel. This model supports a 3-phase Delta-connection of 208/240 VAC.

Key Advantages:

- Measures 1, 2, or 3 phases in 2, 3, or 4 wire configurations.
- Use with wide choice of CTs (sold separately),ratings from 5 to 1500 amps.
- Accurate measurement of 1-,2-, or 3-phase configurations.
- Easy to install and wire.
- Pulse output - Compatible with pulse input logger models.
- Small size - Can be installed in existing service panels or junction boxes.
- Diagnostic LEDs – Confirms proper installation for all phases.
- Bidirectional metering – Net metering for PV (photovoltaic) solar and wind power generation with only one meter.
- Metering of variable frequency drives.
- Line powered - No external supply required.
- Detachable terminal blocks - Easy to install and remove.
- UL, cUL Listed - Designed and tested for safety and use throughout North America.
- CE Mark – Can be installed throughout the EU.

HOBO T-WNB-3D-240 Sensor Specifications

Operating: voltage range: ±20% of nominal
Frequency: 60 Hz
CT input: 0-0.5 VAC operating, 3 VAC maximum
Connectors: UL, CSA recognized, detachable screw terminals (14 AWG), 600V
Operating temp range: -30 to 60°C (-22 to 140°F)
Operating humidity range: 0 to 90% RH, non-condensing
Dimensions: 8.5 cm x 14.3 cm x 3.8 cm (3.3 in. x 5.6 in. x 1.5 in.)
Weight: 295 g (10.4 oz.)
Number of data channels: 2

To download the manual from Continental Control Systems LLC click here.

Click here to view a typical installation

Delta or Wye configuration ranges: 208, 480 Volts AC
1 Phase 2 Wire 208V (No neutral)
1 Phase 2 Wire 240V (No neutral)
1 Phase 3 Wire 120V/240V
3 Phase 3 Wire 208V (No neutral)
3 Phase 4 Wire 120V/208V
Accuracy: ±0.45% of reading + 0.05% FS through 25th harmonic
(dependent on CT used and line variation accuracy could be 1.5% to 4% of reading)

Contact Us

Sales (8am to 5pm ET, Monday through Friday)
- Email sales@onsetcomp.com
- Call 1-508-759-9500
- In U.S. toll free 1-800-564-4377
- Fax 1-508-759-9100

Technical Support (8am to 6pm ET, Monday through Friday)
- Contact Product Support www.onsetcomp.com/support/contact
- Call 1-508-759-9500
- In U.S. toll free 1-877-564-4377

Onset Computer Corporation
470 MacArthur Boulevard
Bourne, MA 02532

WattNode® Pulse

Installation and Operation Manual

- WNB-3Y-208-P
- WNB-3Y-400-P
- WNB-3Y-480-P
- WNB-3Y-600-P
- WNB-3D-240-P
- WNB-3D-400-P
- WNB-3D-480-P

Continental Control Systems LLC
http://www.ccontrolsys.com

Rev V17b

(M5)

Specifications

Models

Model	Nominal Vac Line-to-Neutral	Nominal Vac Line-to-Line	Phases	Wires
WNB-3Y-208-P	120	208–240	3	4
WNB-3Y-400-P	230	400	3	4
WNB-3Y-480-P	277	480	3	4
WNB-3Y-600-P	347	600	3	4
WNB-3D-240-P	120*	208–240	3	3–4
WNB-3D-400-P	230*	400	3	3–4
WNB-3D-480-P	277*	480	3	3–4

**Note: the delta models have an optional neutral connection that may be used for measuring wye circuits. In the absence of neutral, voltages are measured with respect to ground. Delta WattNode models use the phase A and phase B connections for power.*

Table 10: WattNode Models

Model Options

Any of these models are available with the following options:

- **Bidirectional Outputs** - *(this is the standard model)* This model has two pulse output channels. **P1** generates pulses in proportion to the total real positive energy, while **P2** generates pulses in proportion to the total real negative energy. The individual phase energies are all added together every 200 ms. If the result is positive, it is accumulated for the **P1** output; if negative, it is accumulated for the **P2** output. If one phase has negative power (-100 W), while the other two phases have positive power (+100 W each), the negative phase will subtract from the positive phases, resulting in a net of 100 W, causing pulses on **P1**, but no pulses on **P2**. There will only be pulses on **P2** if the sum of all three phases is negative.
- ***Option P3*: Per-Phase Outputs** - Models with this option have three pulse output channels: **P1**, **P2**, and **P3**. Each generates pulses in proportion to the real positive energy measured on one phase (phases A, B, and C respectively).
- ***Option DPO*: Dual Positive Outputs** - This option is like the standard model with bidirectional outputs, but with the addition of the **P3** output channel. The **P3** channel indicates positive real energy, just like the **P1** channel. This is useful when the meter needs to be connected to two different devices, such as a display and a data logger. See Manual Supplement MS-11: Option DPO (Dual Positive Outputs) for details.
- ***Option PV*: Photovoltaic** - The photovoltaic option measures residential PV systems. It allows one WattNode meter to measure the bidirectional total house energy, and the PV (or wind) generated energy. See Manual Supplement MS-10: Option PV (Photovoltaic) for details.
- ***Option Hz*: Custom Pulse Output Frequency** - WattNode meters are available with custom full-scale pulse output frequencies ranging from 0.01 Hz to 600 Hz (150 Hz maximum for ***Options P3, DPO,*** and ***PV***). For custom frequencies, specify ***Option Hz=nnn***, where ***nnn*** is the desired full-scale frequency. To specify different frequencies for **P1**, **P2**, and **P3**, use ***Option Hz=rrr/sss/ttt***, where **P1** frequency = ***rrr***, **P2** frequency = ***sss***, **P3** frequency = ***ttt***.
- ***Option SSR*: Solid State Relay Output** - Replaces the standard optoisolator outputs with solid state relays capable of switching 500 mA at up to 40 Vac or ±60 Vdc. See **Option SSR Outputs** below for details.
- ***Option TVS=24*** - Install 24 V bidirectional TVS protection diodes across P1, P2, and P3 outputs. Used with ***Option SSR*** when driving 12 Vdc electromechanical counters to protect the solid-state relays from the inductive kickback of the counter.

- ***Option PW: Pulse Width*** - This specifies the pulse **ON** (closed or conducting) period in milliseconds. For example, ***Opt PW=100*** configures 100 millisecond pulse **ON** periods. See Manual Supplement MS-17: Option PW (Pulse Width) for details.
- ***Option Kh: Watt-hour Constant*** - This specifies the watt-hour constant, or the number of watt-hours that must accumulate for each pulse generated by the meter. Each pulse includes an **ON** (conducting) and **OFF** period. The number of watt-hours may be small, even less than one, or large. For example, ***Opt Kh=1000*** specifies one pulse per 1000 watt-hours (one pulse per kilowatt-hour). See http://www.ccontrolsys.com/w/Option_Kh.
- ***Option CT: Current Transformer Rated Amps*** - This specifies the rated amps of the attached current transformers. This is only used in conjunction with ***Option Kh***. It may be specified as ***Opt CT=xxx*** or ***Opt CT=xxx/yyy/zzz*** if there are CTs with different rated amps on different phases. See http://www.ccontrolsys.com/w/WattNode_Pulse_-_Option_CT_-_CT_Rated_Amps.

Accuracy

The following accuracy specifications do not include errors caused by the current transformer accuracy or phase angle errors. "Rated current" is the current that generates a CT output voltage of 0.33333 Vac.

Condition 1 - Normal Operation

Line voltage: -20% to +15% of nominal
Power factor: 1.0
Frequency: 48 - 62 Hz
Ambient Temperature: 25°C
CT Current: 5% - 100% of rated current
Accuracy: ±0.5% of reading

Condition 2 - Low CT Current

All conditions the same as Condition 1 except:
CT Current: 1% - 5% of rated current
Accuracy: ±1.0% of reading

Condition 3 – Very Low CT Current

All conditions the same as Condition 1 except:
CT Current: 0.2% - 1% of rated current
Accuracy: ±3.0% of reading

Condition 4 - High CT Current

All conditions the same as Condition 1 except:
CT Current: 100% - 120% of rated current
Accuracy: ±1.0% of reading

Condition 5 - Low Power Factor

All conditions the same as Condition 1 except:
Power factor: 0.5 (±60 degree phase shift between current and voltage)
Additional Error: ±0.5% of reading

Condition 6 - Temperature Variation

All conditions the same as Condition 1 except:
Ambient Temperature: -30°C to +55°C
Additional Error: ±0.75% of reading

*Note: **Option PV** WattNode models may not meet these accuracy specifications for the **P3** output channel when measuring a two-phase inverter or multiple inverters.*

Measurement

Creep Limit: 0.067% (1/1500th) of full-scale. Whenever the apparent power (a combination of the real and reactive power values) for a phase drops below the creep limit, the output power (real) for the phase will be forced to zero. Also, if the line voltage for a phase drops below 20% of nominal Vac, the output power for the phase will be set to zero. These limits prevent spurious pulses due to measurement noise.

Update Rate: ~200 milliseconds. Internally, the consumed energy is measured at this rate and used to update the pulse output rate.

Start-Up Time: approximately 500 milliseconds. The meter starts measuring power and generating pulses 500 milliseconds after AC voltage is applied

Current Transformer Phase Angle Correction: 1.0 degree leading. Current transformers (CTs) typically have a leading phase angle error ranging from 0.2 degrees to 2.5 degrees. The WattNode meter is normally programmed to correct for a 1.0 degree phase lead to provide good accuracy with typical CTs.

Over-Voltage Limit: 125% of nominal Vac. If the line voltage for one or more phases exceeds this limit, the status LEDs for these phases will flash alternating red-green as a warning. Extended over-voltage operation can damage the meter and void the warranty. See **Line Voltage Too High (p. 21)**.

Over-Current Limit: 120% of rated current. Exceeding 120% of rated current will not harm the WattNode meter but the current and power will not be measured accurately.

Pulse Outputs

Factory Programmable Full-Scale Pulse Frequencies:

- **Standard (All Models):** 4.00 Hz
- **Custom (Bidirectional Output Models):** 0.01 Hz to 600 Hz
- **Custom (Option P3, Option PV, Option DPO):** 0.01 Hz to 150 Hz

Absolute Maximum Pulse Output Frequencies:

- **Standard Models (Bidirectional Outputs):** 900 Hz
- **Option P3, Option PV, Option DPO:** 200 Hz

Output Waveform: square-wave, ~50% duty cycle

- **Option PW:** programmable pulse **ON** (closed or conducting period, 1 to 65535 milliseconds

Optoisolator Outputs:

- **Isolation:** 5000 Vac RMS
- **Breakdown Voltage (collector–emitter):** 60 V (exceeding this may destroy the outputs)
- **Maximum Reverse Voltage (emitter-collector):** 5 Vdc (exceeding may destroy the outputs)
- **Maximum Leakage (OFF) Current (collector–emitter):** 100 nA
- **Recommended Load Current (collector–emitter):** 1 µA (microamp) to 5 mA (milliamp)
- **Maximum Load (collector–emitter) Current:** ~8 mA
- **Approximate ON Resistance (as measured by a DMM):** 100 Ω to 2000 Ω
- **Approximate OFF Resistance (as measured by a DMM):** > 50 MΩ

Saturation Voltage vs. Load Current: this is the typical voltage (at room temperature) measured between the **COM** terminal and **P1**, **P2**, or **P3** when the optoisolator is on (conducting). Ideally, this voltage would be zero, but instead, it varies with the load current.

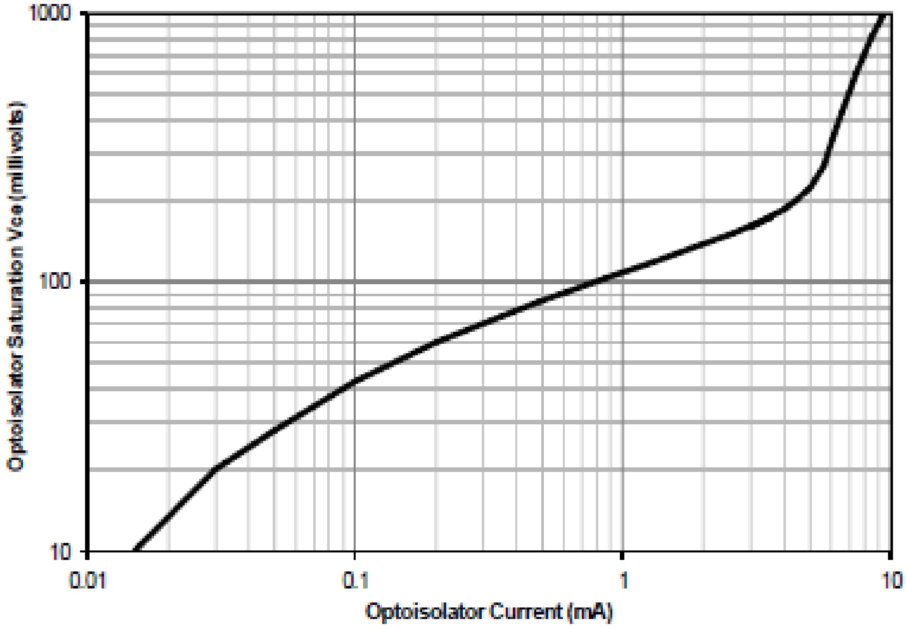


Figure 13: Optoisolator Saturation Voltage vs. Load Current

Output Rise Time (microseconds): approximately ***Rpullup / 100***, where ***Rpullup*** is the pull-up resistor value (in ohms) and the pull-up voltage is 5 Vdc. Rise time is defined as the time for the output voltage to rise from 20% to 80% of the pull-up voltage.

Output Fall Time: approximately 2-3 microseconds with a 5 Vdc pull-up voltage.

Option SSR Outputs:

Isolation: 5000 Vac RMS

Breakdown Voltage: ±60 Vdc or 40 Vac; can switch positive, negative or AC voltages

Maximum Leakage (Off) Current: 1000 nA (1 µA)

On Resistance: 1.0 to 2.5 Ω

Maximum Load Current: 500 mA

Output Turn On Time (milliseconds): 1.8 ms typical, 5.0 ms maximum

Output Turn Off Time (milliseconds): 0.5 ms typical, 2.0 ms maximum

Maximum Recommended Pulse Frequency: 30 Hz

Electrical

Power Consumption: The following table shows typical power consumption and power factor values with all three phases powered at nominal line voltages. The power supply draws most of the total power consumed, while the measurement circuitry draws 1-10% of the total (6-96 milliwatts per phase, depending on the model). Due to the design of the power supply, WattNode meters draw slightly more power at 50 Hz.

NTC Thermistors, Standard Lug Sensors, 150 °C

ADDITIONAL RESOURCES

3D Models   Design Tools   SPICE Models

- NTC curve computation: www.vishay.com/thermistors/ntc-curve-list/

QUICK REFERENCE DATA		
PARAMETER	**VALUE**	**UNIT**
Resistance value at 25 °C [(1)]	10K	Ω
Tolerance on R_{25}-value [(1)]	± 1 to ± 2	%
$B_{25/85}$-value [(1)]	3435, 3984	K
Tolerance on $B_{25/85}$-value	± 0.5 to ± 1	%
Operating temperature range at zero dissipation	-40 to +150	°C
Min. dielectric withstanding voltage between terminals and lug	2700	V_{AC}
Min. insulation resistance between terminals and lug at 500 V_{DC}	100	MΩ
Weight	2.0 to 3.2	g

Note

(1) Other R_{25}-values, $B_{25/85}$-values, and tolerances are available upon request

FEATURES

- **150 °C long term stability** (5000 h dry heat)
- Easy mounting using ring tongue terminal
- Rugged construction
- Cable with ETFE insulation according to NEMA HP-3, type Z, rated 600 V_{RMS}, cable test voltage **3.4 kV**
- AEC-Q200 qualified (grade 1)
- UL recognized, file E148885 (UL category XGPU2)
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

APPLICATIONS

- Suitable for surface sensing applications, especially when a good electrical insulation and a good thermal contact with the chassis is required for:
  - Automotive equipment
  - EV and battery management
  - Power electronics, heat sink
  - Consumer appliances

DESCRIPTION

A NTC thermistor chip is soldered to AWG#26 multi-stranded silver plated copper leads with ETFE insulation and insulated with epoxy coating. The insulated sensor is attached to a tin plated copper ring lug via a middle buffer layer. The lead wires are twisted.

MOUNTING

- By means of M3 (stud #3, #4) or M3,5 (stud #5, #6) screw. Leads to be soldered or crimped
- The device is suitable for screwing e.g. on metal surface
- The leads are suitable for soldering e.g. on PCB
- Consult Vishay for other cable length, cable section, screw sizes, insulation, connector crimping or other features

ELECTRICAL DATA AND ORDERING INFORMATION

R_{25} (Ω)	R_{25}-TOL. (± %)	$B_{25/85}$ (K)	$B_{25/85}$-TOL. (± %)	L_1 (mm)	DESCRIPTION	SAP MATERIAL AND ORDERING NUMBER	
						RoHS COMPLIANT WITH EXEMPTION [(1)]	**RoHS COMPLIANT**
10 000	1	3984	0.5	150 ± 10	NTC Lug01T 10K 1 % 3984 K 150 °C ETFE AWG26 150 mm	NTCALUG01T103F	NTCALUG01T103FA
10 000	1	3435	1.0	150 ± 10	NTC Lug01T 10K 1 % 3435 K 150 °C ETFE AWG26 150 mm	NTCALUG01T103FL	NTCALUG01T103FLA
10 000	2	3984	0.5	40 ± 5	NTC Lug01T 10K 2 % 3984 K 150 °C ETFE AWG26 40 mm	NTCALUG01T103G400	NTCALUG01T103G400A
10 000	2	3984	0.5	150 ± 10	NTC Lug01T 10K 2 % 3984 K 150 °C ETFE AWG26 150 mm	**NTCALUG01T103G**	**NTCALUG01T103GA**
10 000	2	3984	0.5	200 ± 10	NTC Lug01T 10K 2 % 3984 K 150 °C ETFE AWG26 200 mm	NTCALUG01T103G201	NTCALUG01T103G201A
10 000	2	3984	0.5	500 ± 10	NTC Lug01T 10K 2 % 3984 K 150 °C ETFE AWG26 500 mm	NTCALUG01T103G501	NTCALUG01T103G501A

Note

(1) RoHS exemption 7(c)-I: electrical and electronic components containing lead in a glass or ceramic other than dielectric ceramic in capacitors, e.g. piezo-electronic devices, or in a glass or ceramic matrix compound