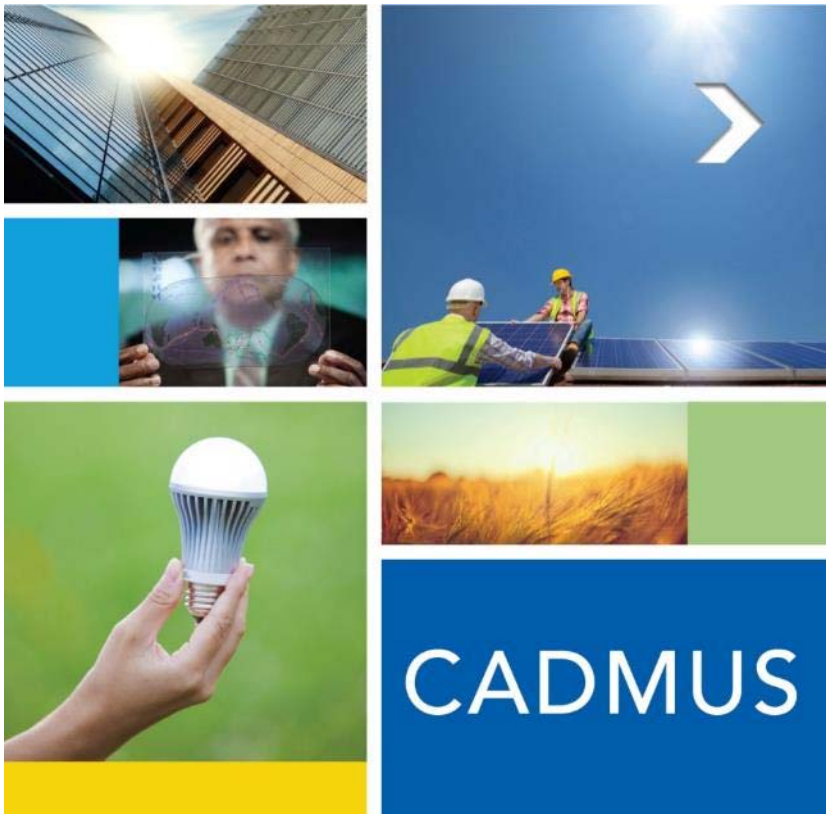

Evaluation of Cold Climate Heat Pumps in Vermont

November 3, 2017

Vermont Public Service Department
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Montpelier, VT 05620-2601

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Glossary of Terms and Acronyms

AMI	Advanced Metering Infrastructure (smart meter)
COP	Coefficient of performance
ccHP	Cold climate ductless mini-split heat pump
EER	Energy efficiency ratio
EFLH	Equivalent full-load hours
HSPF	Heating seasonal performance factor
HVAC	Heating, ventilation, and air conditioning
SEER	Seasonal energy efficiency ratio
TMY	Typical meteorological year

Executive Summary

The popularity of cold climate ductless mini-split heat pumps (ccHPs) continues to increase, partly due to promotion of this technology by energy efficiency programs in the Northeast and across the nation. A comprehensive understanding of ccHP impacts in the state of Vermont will help utility and program planners make informed program decisions.

The Vermont Public Service Department (PSD) solicited Cadmus to evaluate ccHP systems operating in Vermont. Pursuant to Public Service Board Order, Sec. 21a. 30 V.S.A. § 8001(b), the PSD outlined three high-level objectives for the evaluation:

- To assess ccHP use in Vermont by investigating energy consumption, performance, and operational characteristics
- To estimate the average gross electric energy and demand impacts and the fossil fuel offsets attributable to a ccHP installation
- To better understand the extent to which the state should promote cold climate heat pump efficiency measures to various markets

To meet the objectives, Cadmus conducted site visits, analyzed advanced metering infrastructure (AMI) data, and surveyed Vermont homeowners receiving a rebate for the purchase and installation of a program-qualifying ccHP. During site visits, Cadmus metered ccHPs and other heating systems, recorded heating fuel consumption, analyzed utility interval meter data, and collected qualitative data to understand homeowner perspectives. By examining heating and cooling energy use as well as information collected through homeowner surveys and site visits, Cadmus sought to assess homeowners' motivations to install ccHPs, use and satisfaction with ccHP equipment, alternative or baseline equipment options, and fuel-switching and load-building occurrences.

Beginning in November 2015, the study covered *in situ* ccHP usage through the 2017 heating season by metering a total of 77 ccHPs at 65 unique service accounts. In July 2017, Cadmus conducted an online survey of homeowners who had installed a ccHP in 2016 and had used it for at least one heating and cooling season. In total, Cadmus surveyed 135 homeowners (with 94 homeowners completing the online survey and 41 completing an in-person survey).

Figure 1 shows heating and cooling equivalent full-load hours (EFLH) for each ccHP metered—a parameter comparable to the Vermont Technical Reference Manual (Vermont TRM). As shown, heating use was significantly higher than cooling use.

Figure 1. Summary of Normalized Cold Climate Heat Pump Use

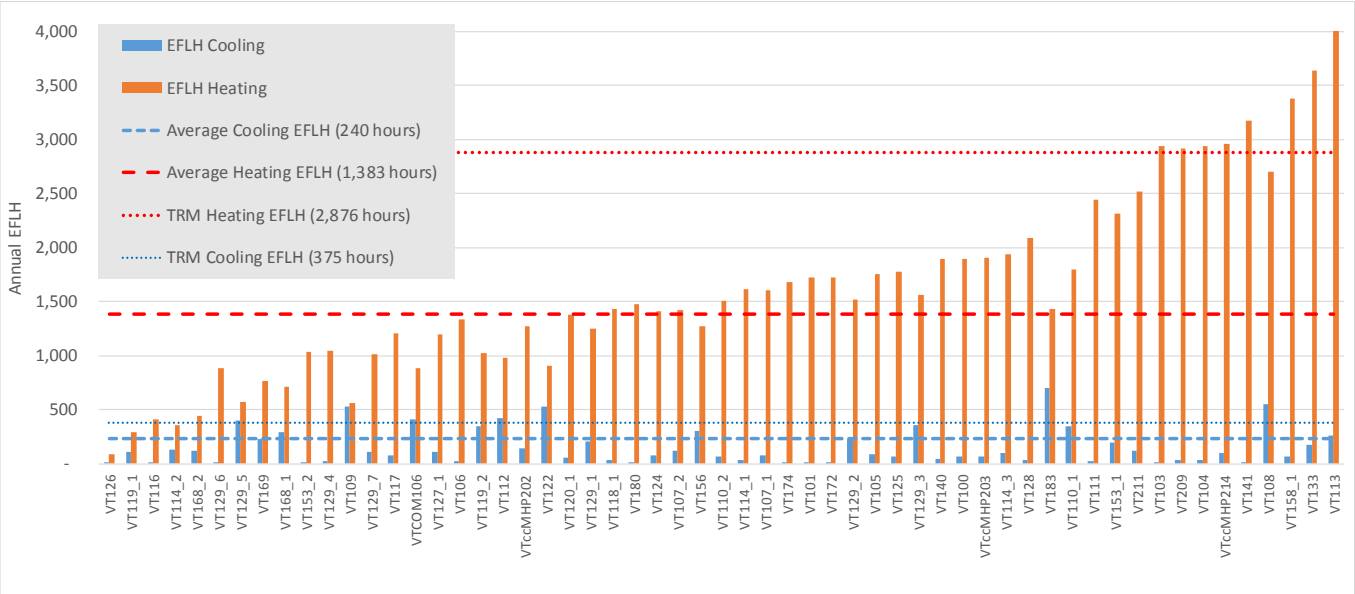

Table 1 provides findings from the metering study and compares these findings to parameter assumptions in the Vermont TRM. Heating and cooling average EFLH were lower than the TRM EFLH estimates. Cadmus found that ccHPs rarely constituted an exclusive heating system. Other systems often provided heat, either because a space opened to an adjacent space heated by another system or because of the way that homeowners chose to operate their alternate heating systems and ccHPs. Significant temperature setbacks during extended periods of vacancy also decreased ccHP use in some homes during the heating and cooling season. Consequently, fossil fuel heat offset and average ccHP use was lower than expected. Although heating use was quite variable (see Figure 1), the selected sample of homes was sufficient, achieving 12.1% relative precision of ccHP heat use at the 90% confidence interval. Variability of cooling use was relatively high; the sample achieved 23.5% relative precision at the 90% confidence interval.

Table 1. Overview of Cold Climate Heat Pump Use and TRM Assumptions

Season	Metered Energy Use (kWh)	Capacity Output (MMBtu)	Metered EFLH	VT TRM EFLH	Realization Ratio	Relative Precision at 90% Confidence Interval*
Heating	2,085	21.4	1,383	2,876	48%	12.1%
Cooling	146	3.5	240	375	64%	23.5%

*Based on variance in EFLH.

On average, a ccHP consumed 2,085 kWh and supplied 21.4 MMBtu of heating capacity during the heating season. The resulting average heating seasonal efficiency of 10.7 kBtu/kWh[1] is approximately 90% of the average nameplate rated efficiency (11.9 heating seasonal performance factor, or HSPF). To calculate heating savings, Cadmus assumed the capacity provided by the ccHP would directly offset an equivalent amount of heating capacity otherwise provided by the alternate heating system.

Table 2 lists the existing fuel types and the average proportion of fuels used across all homes in the metering study. The impact of a single ccHP installation generated all savings shown in Table 2. A ccHP installation produced negative electric energy (kWh) savings because the majority (93%) of heat was provided by oil, propane, or wood-burning systems prior to a ccHP installation.

Table 2. Retrofit Savings per Cold Climate Heat Pump Installed

Percent of MMBtu Provided by Existing Heating System	Heating System Efficiency Assumptions	Fuel Heat Content Assumptions	Savings	Units
7%	COP of electric resistance heat = 1	3.412 kBtu per kWh	-1,664	kWh (Includes Electric Resistance Offset)
25%	85%	91.2 kBtu/gal	69.1	Gallons of Propane
46%	78%	138.8 kBtu/gal	91.0	Gallons of #2 Fuel Oil
22%	60%	15.3 MMBtu/cord	0.66	Cords Wood

Cadmus assessed the likelihood that electric load increased during summer due to participation in a ccHP program. Interview responses provided counterfactual information which Cadmus used to categorize each ccHP installation into one of the three hypothetical baselines categories listed in Table 3. A ccHP replacing a window AC generates positive savings. A ccHP installed in a location that did not previously have cooling by a homeowner who would not have installed any cooling system generates

[1] This value, comparable to nameplate HSPF, is the ratio of total heating capacity delivered in a typical heating season to total energy consumption.

negative savings. All other scenarios presume a baseline (14.5 SEER) cooling system would have been installed in a ccHP program's absence. Table 3 shows the savings for each baseline category and the proportions of each category.

Table 3. Cooling Savings Summary

Savings Type	Baseline Category			Proportion from Homeowner Interviews			Weighted Average
	Window Air Conditioner	No Previous Cooling	14.5 SEER Heat Pump	Window Air Conditioner	Load Building	14.5 SEER Heat Pump	
Energy (kWh)	286	-146	93	15%	20%	65%	74
Peak Demand (kW)*	0.284	-0.190	0.158				0.11

* Average value for warmest 1% of cooling hours during summer season. For additional peak periods see Figure 13.

The weighted average savings in Table 3 represents Cadmus' best estimate of program impacts during the cooling season. The value includes a hypothetical baseline (14.5 SEER) so is not comparable to savings determined from the analysis of pre/post billing data. However, savings from a ccHP replacing a window AC may be estimated from billing data so Cadmus analyzed AMI data for homeowners completing an online survey, and compared the results to the metered sample. Table 4 shows the savings from AMI analysis. Cooling energy decreased by a small amount (12 kWh), evidence that ccHPs are not increasing electric load during the cooling season.

Table 4. Change in Cooling Energy Use for AMI Sample

Previous System	Δ kWh (Normalized to Metered ccHP Size)
No Cooling	-95
Fan only	-40
Window or portable AC	202
Average	**12**

Fifteen percent of the metered ccHPs replaced a window AC. Survey results from the AMI sample found more homeowners (27%) replaced a window air conditioner with a ccHP. However, the savings (202 kWh) determined from AMI analysis were lower, so the overall contribution of savings for window AC retrofits in both samples was similar. Because Cadmus was unable to meter the window ACs replaced by ccHPs, the pre- and post-install savings value in Table 5 (202 kWh) may be more realistic (For additional information, see Appendix E. AMI Smart Meter Data Analysis).

Table 5. Advanced Metering Infrastructure Analysis Results Compared to Metered Results

Cooling System Baseline	*Pre - Post Cooling Load Δ (AMI Analysis)	Relative Weight (AMI)	Relative Weight (Meter Data Analysis)
Window or portable air conditioner	202 kWh	27% x 202 kWh = 54 kWh	15% x 286 kWh = 43 kWh

*Value weighted by reported cooling capacity and adjusted to match the metered sample.

Pre-post AMI analysis does not include hypothetical counterfactual assumptions; it simply shows the change in cooling energy consumption due to a ccHP installation. Although ccHP installations can increase cooling energy consumption in some scenarios, Cadmus found net positive savings for two independent samples analyzed in different ways, an indication that ccHP programs do not increase summer cooling load.

Introduction

The popularity of heat pumps is increasing due in part to the promotion of this technology by energy efficiency programs in the Northeast and across the nation. A comprehensive understanding of the impact of ccHPs operating in the state of Vermont will help utility and program planners to make informed program decisions.

The Vermont PSD is responsible for evaluating Community Energy & Efficiency Development (CEED) Fund programs. Through 2015, fewer than 100 customers participated in the CEED program. Cadmus evaluated the impact of this program using analysis of utility interval data and tracking data. We submitted a memo of findings in May 2015. Because of the requirement to conduct an evaluation of the CEED heat pump program, the PSD decided to increase the scope of the evaluation to cover ccHPs in general. Given the relatively small size and availability of data from previous CEED program evaluation efforts, Cadmus worked with the PSD to expand the study.

Efficiency Vermont maintains a list of cold climate heat pumps that qualify for the program's promotional incentive.[2] A standard set of criteria to differentiate cold climate from standard mini-split heat pumps does not exist. Certified laboratories conduct standardized tests (defined by the Air Conditioning, Heating and Refrigeration Institute in AHRI 210/240 test criteria) to determine heat pump performance and efficiency at outdoor temperatures from +17°F to +47°F. Although some manufacturers publish heat pump performance data at much colder temperatures (e.g., as low as -20°F), the performance is based on either the manufacturer's own tests or engineering calculations. The actual performance of heat pumps at the extremely cold temperatures typical in Vermont (i.e., colder than -10°F) is relatively uncertain. In addition, without primary data, it is unknown how Vermont homeowners choose to operate their ccHPs and other heating systems in extremely cold conditions.

Both the PSD and Cadmus agreed that intended operation and performance of ccHPs at extremely cold temperatures (relative to performance at milder temperatures)[3] was highly uncertain. Performance during the coldest times of the year is undoubtedly a critical time for homeowners who use their ccHP as the primary heat source. For these reasons, the PSD considered the findings from ccHP research

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[2] Online: https://www.efficiencyvermont.com/Media/Default/docs/rebates/qpls/efficiency-vermont-cold-climate-heat-pumps-qualifying-products.pdf

[3] Cadmus conducted metering studies of mini-split heat pumps in Massachusetts, Illinois, New York City, and in the Northwest, but none of the studies observed use and performance at temperatures as low as temperatures typically observed in Vermont.

during the coldest times to be critically important; the findings may determine the direction of ccHP incentive programs in the state.

Research Objectives

Cadmus conducted research related to each of the objectives outlined by the PSD to develop a comprehensive characterization of ccHPs as well as a series of recommendations relating to the future deployment of the technology. Cadmus collected data of ccHPs operating in Vermont to examine these elements:

- How homeowners use their equipment to heat and cool spaces in their home
- Total heating and cooling output and equipment efficiency
- Power and energy consumption of the equipment at 2-minute intervals from November 2015 through April 2017
- Heating season electric and fossil fuel impacts and interactions with existing heating systems
- Cooling season electric impacts
- Correlation of ccHP performance with measurable parameters such as installation location, building shell characteristics, and planned usage strategy

In addition to long-term meter data, Cadmus collected qualitative data to understand homeowner perspectives. By examining both heating and cooling energy use and information collected from homeowner surveys and site visits, Cadmus sought to examine the motivation to install a ccHP, the use and satisfaction with ccHP equipment, alternative or baseline equipment options, and occurrences of fuel-switching and load building.

Approach

To evaluate the ccHP measure, Cadmus conducted an *in situ* evaluation of ccHPs installed in Vermont. The study covers *in situ* ccHP performance during the 2015/2016 heating season, the 2016 cooling season, and the 2016/2017 heating season.

Cadmus recruited a random sample of ccHPs for the evaluation. In November 2015, we visited 42 homes and two small businesses to install meters on 57 ccHPs and to install meters on the other heating systems (e.g., oil boilers, wood stoves). In February 2015, we recruited five more homes with newly installed multi-head ccHPs. Cadmus completed its recruitment with an additional 17 homeowners prior

to the 2016/2017 heating season, resulting in a final total of 77 metered ccHPs at 65 unique service accounts.[4]

We installed a meter on one ccHP at each home to record heating and cooling capacity and energy consumption at two-minute intervals. We installed power meters on the additional ccHPs at all homes with more than one ccHP. (See Appendix C. Metering Equipment for additional information.) Cadmus interviewed homeowners at each home to obtain their perspectives, to glean information about planned operation of their heating and cooling systems, and to discuss tracking and recording of heat fuel quantity.

We returned to all homes in May 2016 to download meter data, relaunch data loggers, work with homeowners to quantify heating fuel consumption, and conduct airflow measurements of the ccHP indoor units. We visited homes again in late October 2016 to download data and to relaunch loggers, and we continued the collection of meter data through the 2016/2017 heating season. Cadmus removed meters in April 2017 and collected additional heating fuel consumption data at that time. Appendix A. Technical Information~~Appendix A. Technical Information~~ describes Cadmus' meter data analysis methods.

In July 2017, Cadmus conducted an online survey of homeowners who installed a ccHP in 2016 and had used it for at least one heating and cooling season. In total, Cadmus surveyed 135 homeowners (with 94 homeowners completing the online survey and 41 completing an in-person survey). For a summary of survey data, see Appendix B. Survey Responses.[5]

ccHP Technology and Metering Study Overview

Cold climate heat pump technology and the market for cold climate systems continues to evolve. The majority (n=57) of ccHPs that Cadmus metered were installed in late 2014 or early 2015. The additional (n=17) ccHPs that Cadmus metered during the 2016/2017 heating season were installed in early 2016. Although some ccHP models in the metering study are replaced by newer models, Cadmus' review of program tracking data from 2014 through 2017 found the metered sample reasonably represents the population of program ccHPs in Vermont. (See Table 15 for a list of all ccHPs metered).

[4] Three sites were removed from the study due to meter failures.

[5] Survey questions and response options are provided in Appendix B.

As the ccHP market changes, homeowner usage strategies may change. To look for trends that may limit the applicability of the results of this study, Cadmus compared the motivations of homeowners in the metering study to homeowners who installed a ccHP in 2016.

Cold Climate Heat Pump Efficiency and Performance

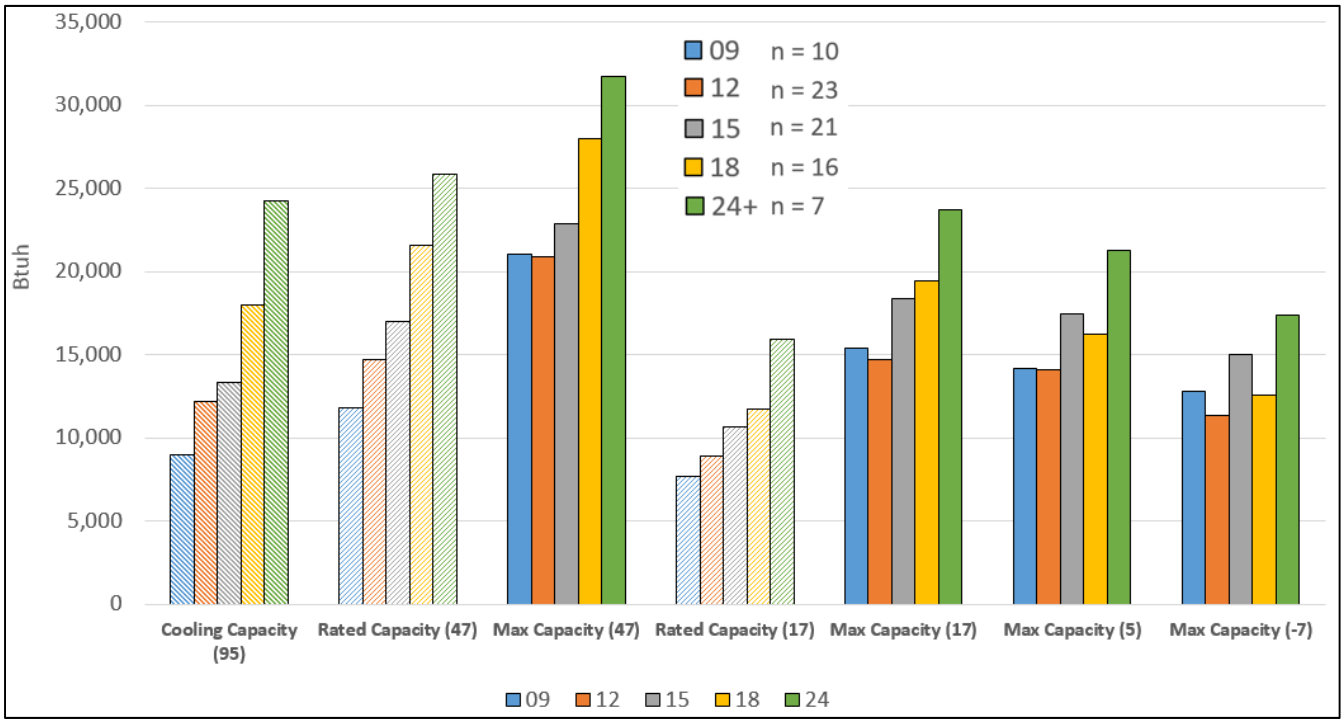
Common technical reference manual savings algorithms use AHRI rated values to estimate savings. These include heating seasonal performance factor (HSPF), seasonal energy efficiency ratio (SEER), energy efficiency ratio (EER), and rated heating/cooling capacity. The Vermont TRM[6] will use a more rigorous savings calculation method that incorporates ccHP performance characteristics, so Cadmus conducted its analysis to produce results that align with the TRM heating and cooling savings methodology.

Figure 2 summarizes the average capacity of the metered ccHPs, grouped by outdoor unit model number. Model numbers[7] provide an approximate estimate of capacity. With increasing system size, rated capacity (see light-hashed bars in Figure 2) increases as expected.

[6] Under review. See analysis workbook "Tier III Single Zone CCHPSavingsAnalysis Update.xlsx."

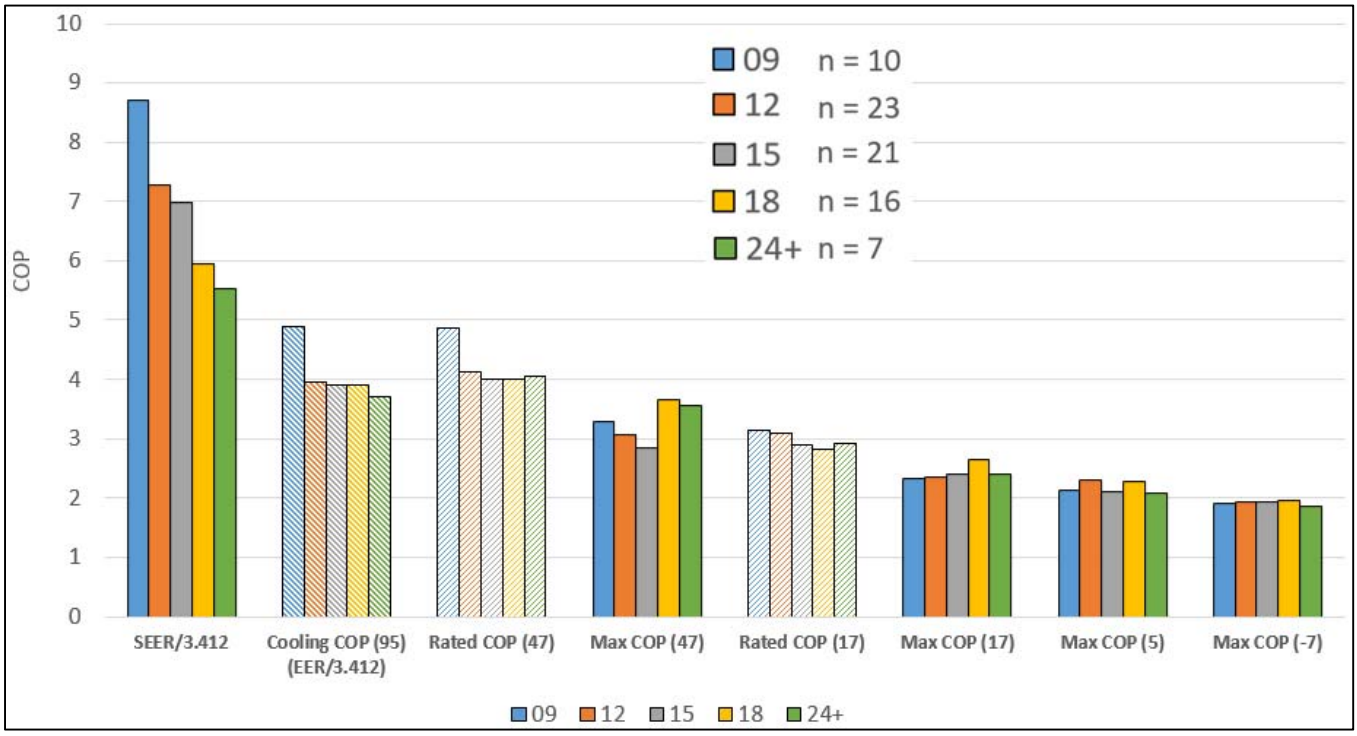
[7] The model number of most ccHPs has an embedded number that approximately estimates system cooling capacity (e.g., MUZ-FH09NA has cooling capacity of 9,000 BTUh).

Figure 2. Summary of Average Capacity of Metered Cold Climate Heat Pumps



Compared to the rated capacity versus ccHP size, the correlation of maximum capacity with size has a less consistent trend because manufacturers can use different compressor speeds to achieve either a desired coefficient of performance (COP) or desired capacity. Figure 3 shows the average COP of the metered ccHPs. By comparing the figures, we can see that the 09 and 12 ccHPs have similar maximum capacity and similar COP at each maximum capacity. Some of the 09 and 12 units are physically identical; the only difference is the speed at which the compressor operates to achieve its AHRI rated efficiency and capacity values. Note that the Max COP values in Figure 3 represent the efficiency when the ccHP operates at maximum capacity—these are not the highest COP values.

Figure 3. Summary of Average Coefficient of Performance of Metered Cold Climate Heat Pumps



For ccHPs in the metering study, Cadmus found that performance data varies significantly when comparing similar units made by different manufacturers.[8] Figure 4 (Daikin) and Figure 5 (Mitsubishi) show the range of capacity, power, and COP for ccHPs with the same rated capacity (21,600 Btu at 47°F). If, for example, the heating load of a room is 20,000 Btu at 5°F, the Mitsubishi unit can meet the load requirements, but the Daikin can provide only 12,000 Btu.[9] However the Mitsubishi unit may use twice as much power.

[8] Online: http://www.neep.org/sites/default/files/ColdClimateAir-SourceHeatPumpSpecificationListing-Updated%207.27.17.xlsx

[9] The chart on the left of each figure shows an estimate of heat load of the space, based on a 10% over-size factor for the maximum capacity at 5°F.

Figure 4. Example of Manufacturer's Information for Daikin Cold Climate Heat Pump

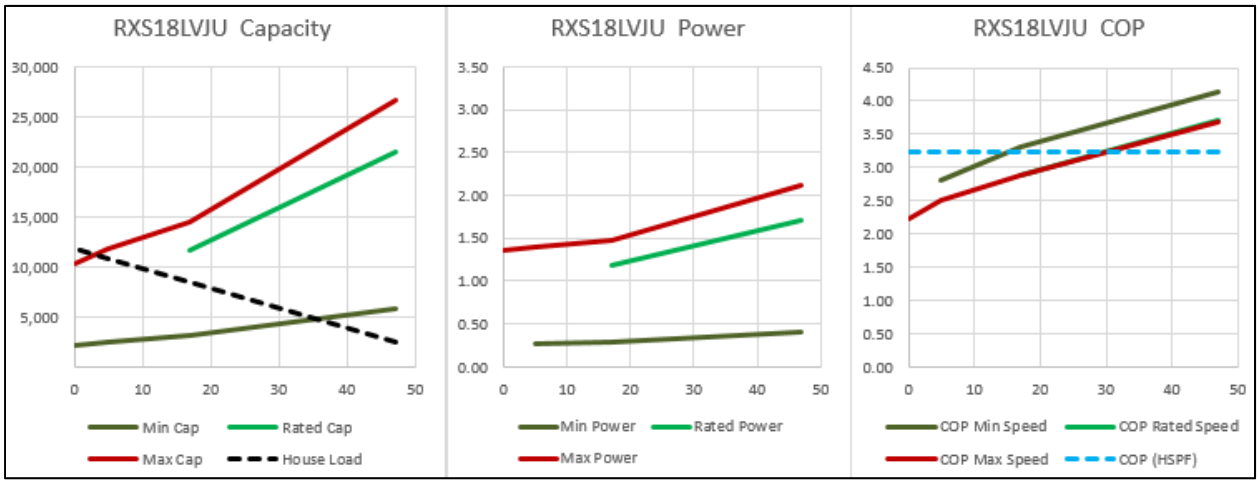
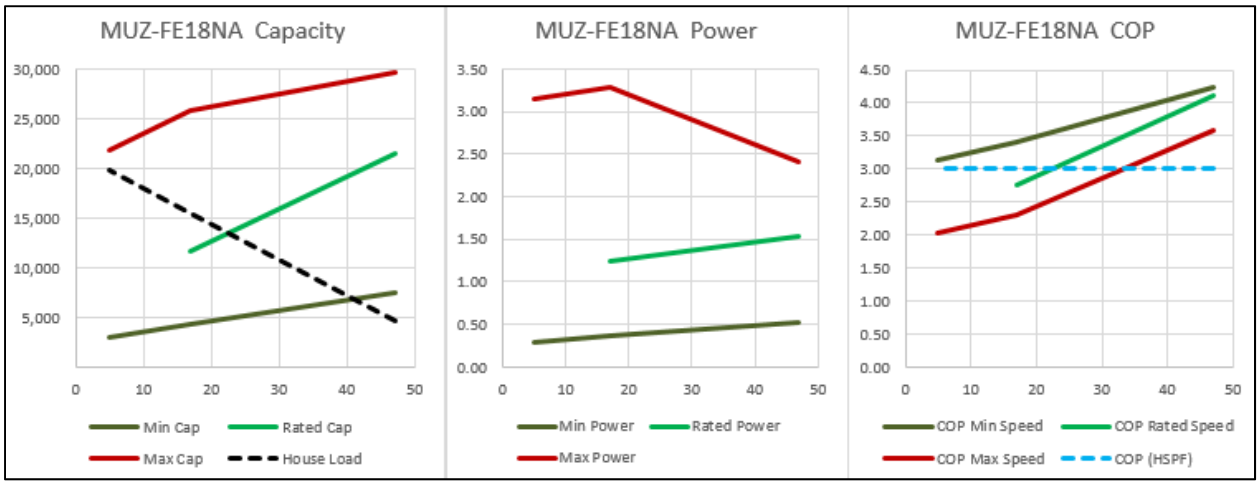


Figure 5. Example of Manufacturer's Information for Mitsubishi Cold Climate Heat Pump



A thorough review of model-specific performance data is important, especially while new models enter the market in Vermont. Table 15, in Appendix A. Technical Information~~Appendix A. Technical Information~~, lists all ccHPs metered in this study.

Homes in the Study

For this metering study, Cadmus randomly selected Vermont homeowners who installed one or more ccHPs between November 2014 and August 2015. Only Daikin, Fujitsu, and Mitsubishi units were

sampled (n= 17, 31, and 29 respectively). These are the predominate ccHP brands installed through the program, although Carrier, Haier, and Panasonic also have qualifying systems.

Figure 6 shows the locations of the homeowners in the study and the weather stations (marked in green circles) used to estimate average annual ccHP energy use and savings.

Figure 6. Distribution of Sites Metered in Vermont

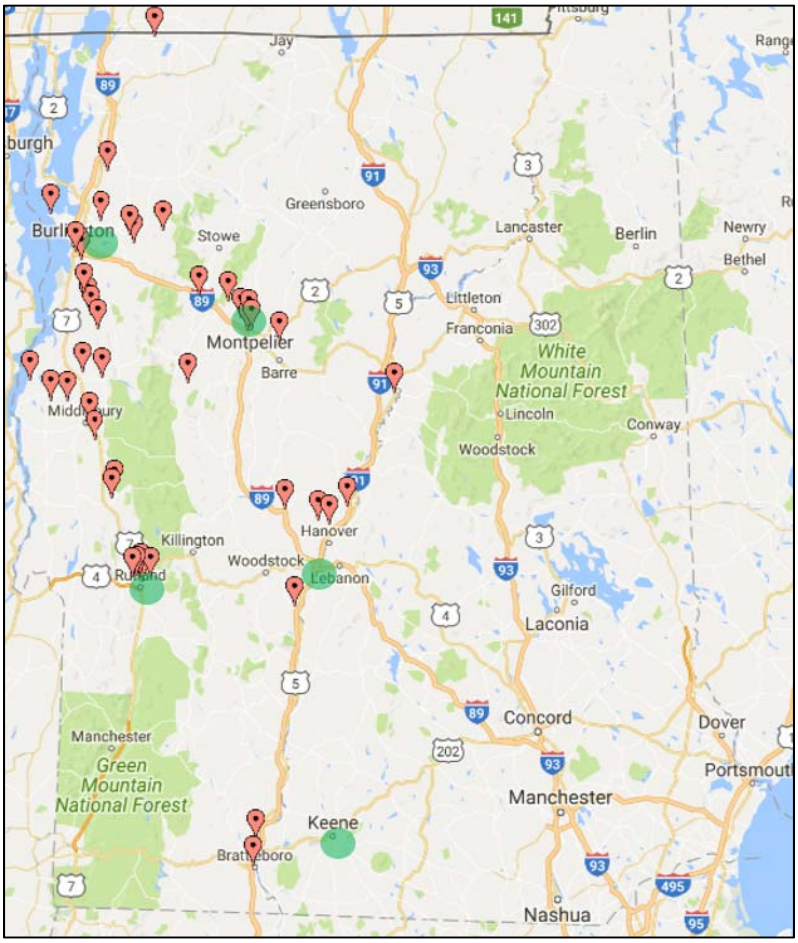
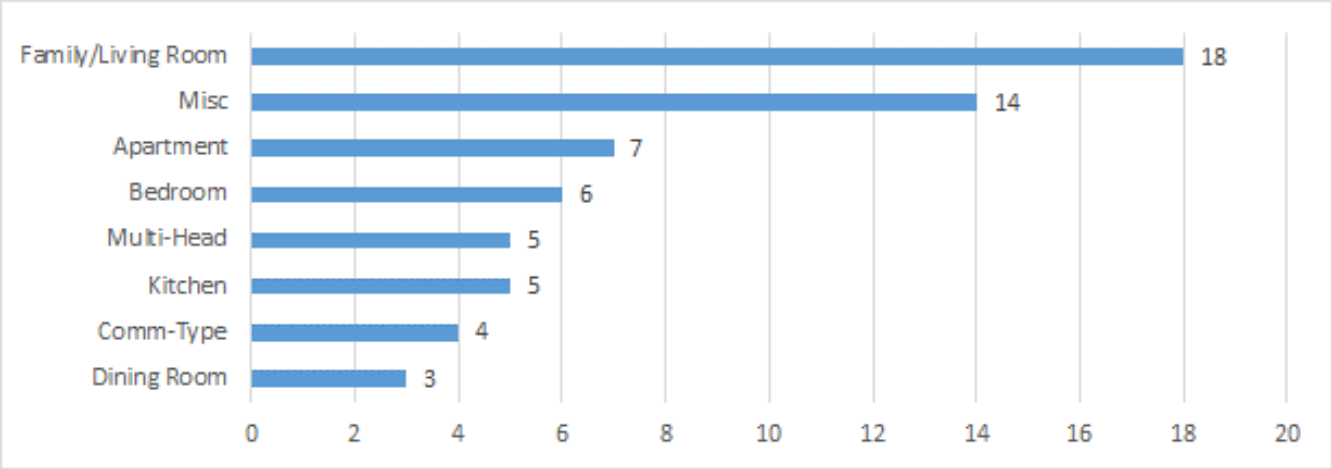


Figure 7 lists the number of ccHP indoor units by room type. This overview does not include data from the 17 metered housing units that Cadmus included during the 2016/2017 winter because that group was exclusively apartments. The Misc category represents various locations such as these:

- In-law apartment
- Finished basement

- Finished attic
- Sunroom (seasonal)
- Workshop
- Office

Figure 7. Overview of Cold Climate Heat Pump Locations in Homes (N=62)



Although model-specific differences exist when comparing similar ccHP systems (refer to Figure 4 and Figure 5), and although user behavior drives differences in ccHP consumption and savings, the results of the metering study are aggregated; these are intended for program planning purposes. If future ccHP systems or homeowner characteristics differ from units metered in this study, the PSD should review the applicability of the results of this study.

Findings

Cadmus collected detailed energy and performance data for ccHPs from November 2015 through April 2017. The 2016 winter was one of the mildest on record. In most populated areas of the state, temperatures dropped below -10°F only once for about one night. Anticipating a more normal winter with longer periods of extremely cold temperatures, the PSD chose to extend the metering study through the 2017 winter. However, the 2017 winter also was relatively mild. Consequently, Cadmus was unable to assess the performance during extended (e.g., weeklong) periods of sub-zero temperatures. But by continuing the metering study, Cadmus determined ccHP use during the fall and assessed the stability of ccHP use during two heating seasons.

Summary of ccHP Energy Use and Demand

Figure 8 shows heating and cooling EFLH for each ccHP metered. To calculate EFLH, Cadmus divided the total annual heating and cooling energy by system power at the AHRI rated conditions (5°F for heating and 95°F for cooling). This simple metric normalizes variance in energy consumption due to differences in system capacity and efficiency. As evident in Figure 8, heating use is significantly higher than cooling use.

Figure 8. Summary of Normalized Cold Climate Heat Pump Use

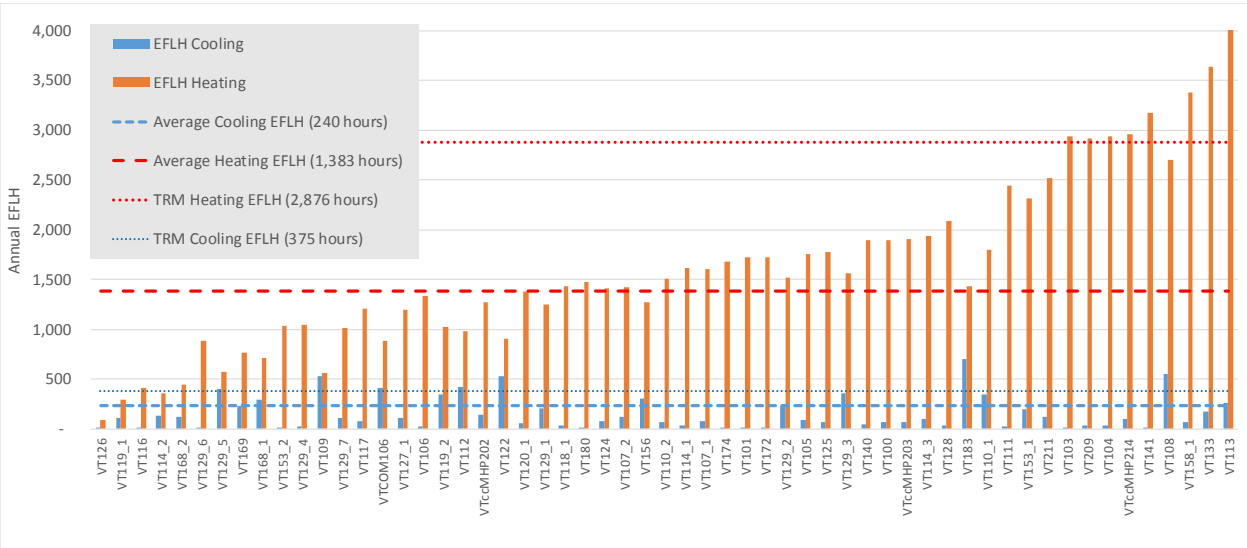
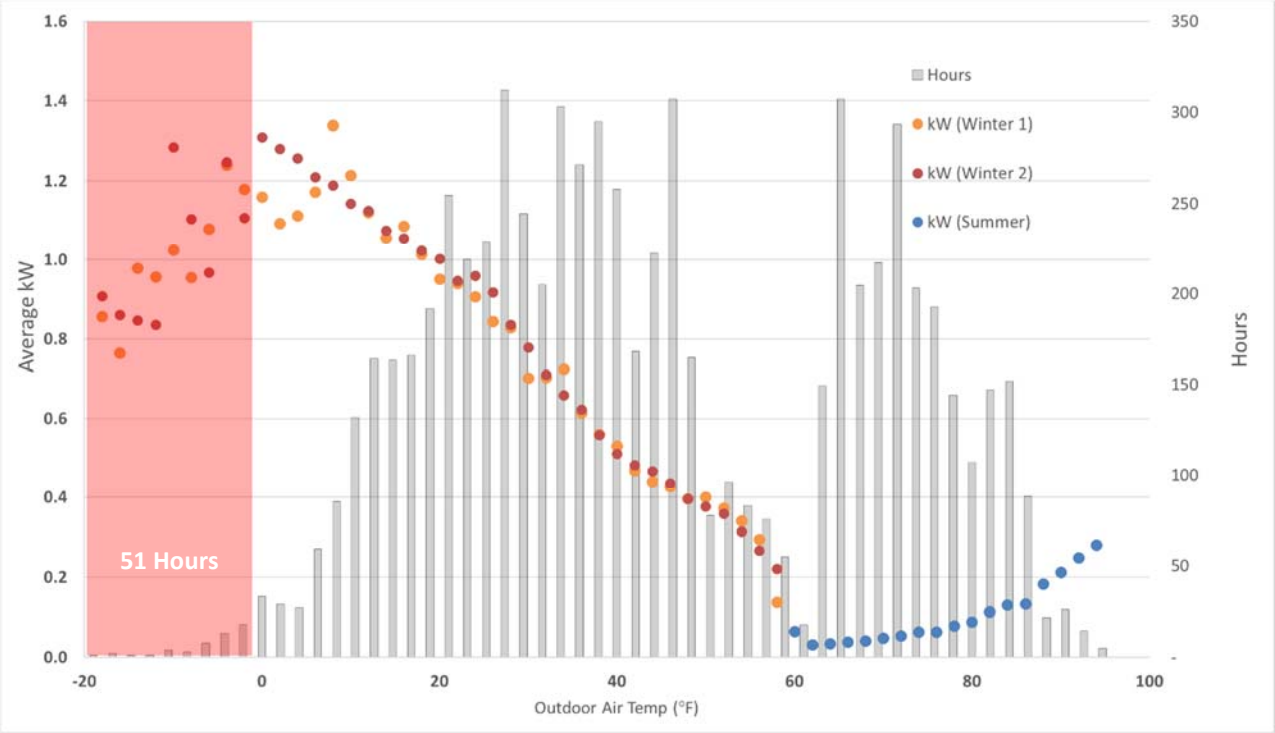


Figure 9 shows the seasonal average demand of all ccHPs for each season. Although the average demand varies between the first and second winter, after normalizing to the same weather data, the difference in energy consumption was slight (2017 winter meter data produced a heating consumption

of 2% greater than data from the 2016 winter). The figure also shows the average hours observed for each two-degree temperature bin and the average power for all ccHPs metered. The hours represented in the figure (7,230 hours) are less than the total annual hours (8,760 hours) because we weather-normalized each ccHP. For example, if a ccHP never operates when the outdoor temperature is 70°F, the normal hours at 70°F are not used in the weather normalization calculation for that ccHP. This effectively reduces the average bin hours shown in Figure 9. For additional information about the weather normalization method that Cadmus used, see Weather Normalization Methodology in Appendix B.

Figure 9. Seasonal Cold Climate Heat Pump Demand and Hours



The red-shaded region in Figure 9 highlights the hours observed below 0°F. The variance (and uncertainty) of the average ccHP demand is high because the number of observations at the extreme temperatures is low and because some homeowners chose to turn their ccHP off at the coldest temperatures. Although both winters were relatively mild and Cadmus hoped to determine an accurate and reliable demand profile during sub-zero temperatures, the uncertainty of ccHP consumption at the coldest temperatures has little impact on annualized heating consumption and savings estimates. The

box and whisker plots in Figure 10 and Figure 11 show the range in heating and cooling demand of all ccHPs at each 2-degree temperature bin for all hours of the year.

Figure 10. Box and Whisker Plot of Average Heating Demand (kW)

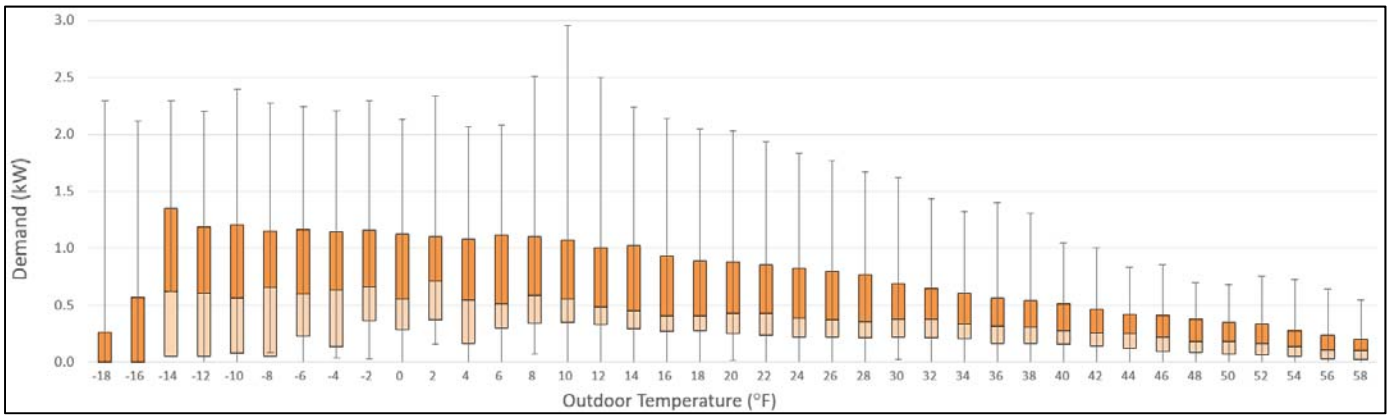
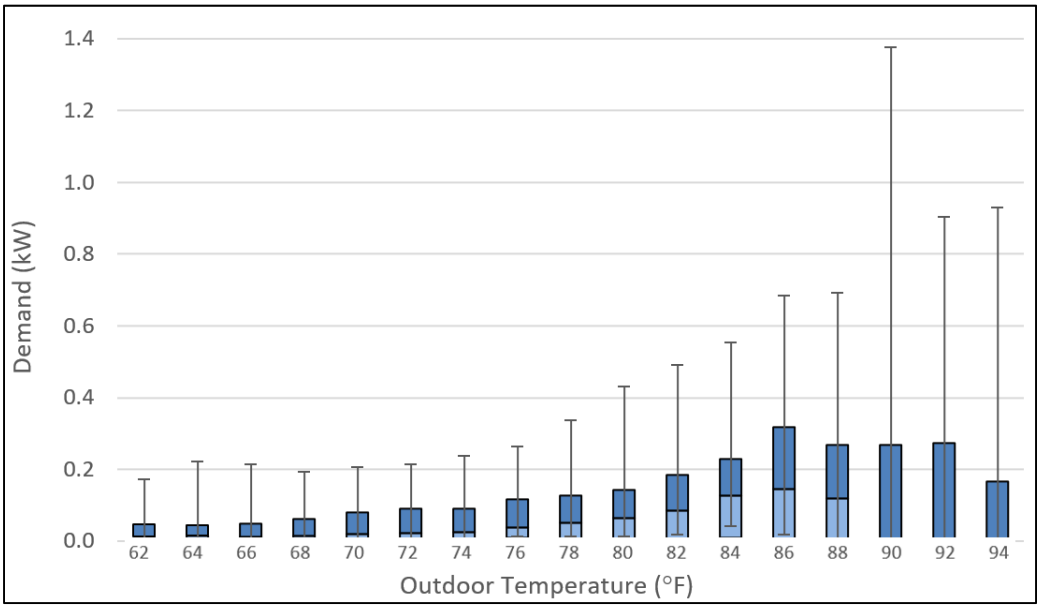


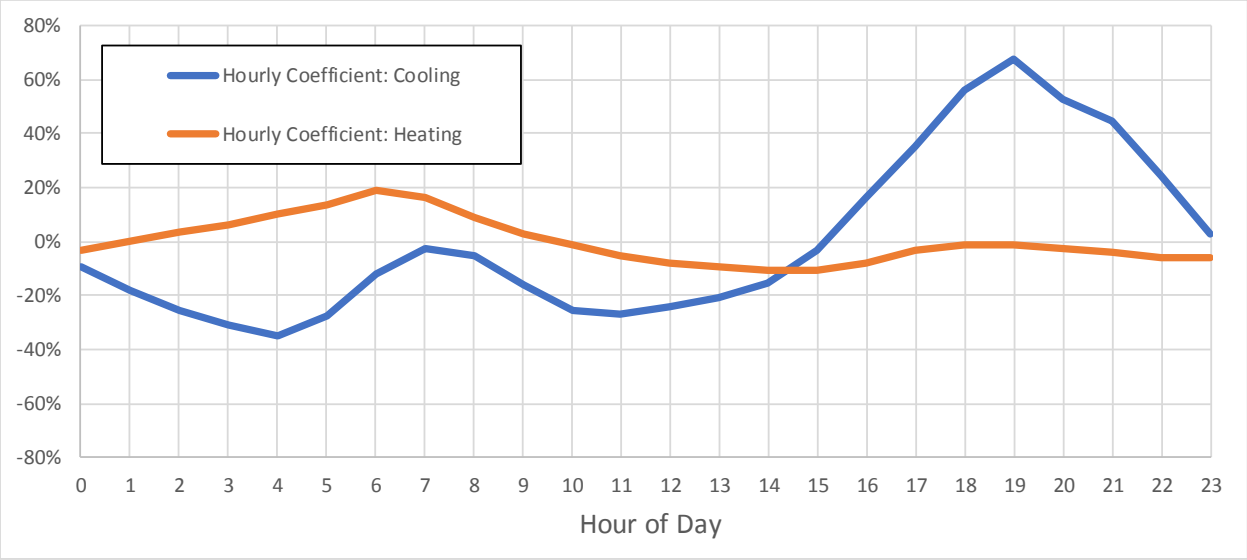
Figure 11. Box and Whisker Plot of Average Cooling Demand (kW)



Cadmus analyzed ccHP demand for each hour of day during the heating and cooling seasons and normalized the demand for differences in temperature. Figure 12 shows the variance in ccHP demand for each hour of the day for the heating and cooling seasons. The highest heating use occurs during the hour of 6 a.m. while the highest cooling use occurs during the hour of 7 p.m. The heating and cooling

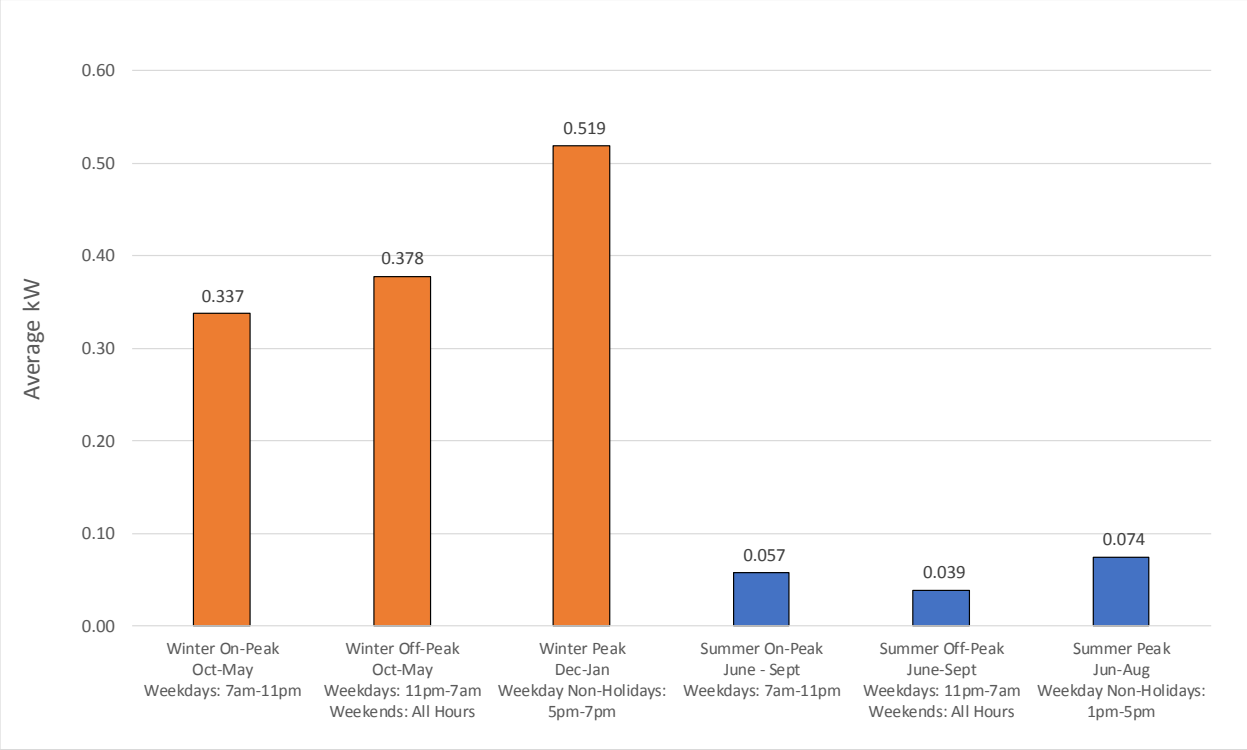
curves in Figure 9 show the ccHPs temperature dependence while the curves in Figure 12 show the ccHPs time of day dependence.

Figure 12. Hourly Variance in ccHP Demand



The team calculated average demand for different on- and off-peak demand periods, as defined in Figure 13. The winter off-peak demand is slightly greater than winter on-peak demand. The summer on-peak demand is nearly 60% greater than summer off-peak demand.

Figure 13. Summer and Winter On-Peak and Off-Peak Demand



The average kW values in Figure 13 represent all metered ccHPs (i.e., the values include instances of ccHPs with 0 kWh).

The following sub-sections compare the metering results to the analogous assumptions in the Vermont TRM and describe assumptions used and the findings from primary data collection.

Heating Season Findings

Table 6 presents the average capacity and COP from manufacturers' published performance data for all ccHPs metered.

Table 6. Published Average Capacity and Coefficient of Performance for Metered Cold Climate Heat Pumps

	Average Capacity (Btu/h @ 47°F)	Average Rated Nameplate Capacity (Btu/h @ 17° F)	Average Maximum Capacity (Btu/h @ 5° F)	Average Maximum Capacity (Btu/h @ -7°F)*
Rated Capacity	17,388	10,427	N/A	N/A
Rated COP	4.16	2.97		
Maximum Capacity	23,897	17,575	16,116	13,175
Maximum Capacity COP	3.20	2.43	2.20	1.97

*Available for 67 of 77 ccHPs for outdoor temperatures of 0°F or colder: -7°F on average.

The Vermont TRM calculates ccHP heating savings based on heating capacity estimates that vary with ccHP size. The TRM fossil fuel offset is 44.5 MMBtu for the ccHPs metered. As shown in Table 7, the estimated average increase in electric consumption due to installation of the ccHPs in the study is 5,003 kWh.

Table 7. TRM Estimates for Metered Cold Climate Heat Pumps in the Study

Quantity Metered	Nominal Cooling Capacity (Btu/h)	MMBtu (Q above 5°F)	Total MMBtu Savings	Δ kWh Increase
0	6,000	26.0	29.9	3,355
10	9,000	32.0	36.8	4,137
23	12,000	36.0	41.4	4,655
21	15,000	39.5	45.4	5,105
16	18,000	43.1	49.5	5,562
7	24,000	44.9	51.6	5,802
Weighted Average from Metering Study	14,392	38.7	44.5	5,003

Table 8 provides findings from the metering study and compares findings to parameter assumptions in the TRM. During the winter, ccHPs consumed energy when not providing heat because they use power (average of approximately 38 Watts) in “standby mode” and use energy to defrost the outdoor unit when operating in “defrost mode”. On average, a ccHP consumed 2,085 kWh during the heating season and consumed 1,880 kWh when providing heat. Standby mode energy consumption averaged 76 kWh and average defrost mode energy consumption was 129 kWh.

Cold climate heat pumps supplied an average of 21.4 MMBtu of heating capacity. The table shows the achieved precision of ccHP heat use at the 90% confidence interval (12.1%).

Table 8. Overview of Cold Climate Heat Pump Energy Consumption and Heating Capacity Provided

Savings Type	Total Metered kWh	Metered kWh: Heating Mode	Metered MMBtu	VT TRM MMBtu	MMBtu Realization Ratio	Relative Precision at 90% Confidence Interval*
Heating	2,085	1,880	21.4	44.5	48%	12.1%

*Based on variance in EFLH.

The average AHRI nameplate efficiency of the ccHPs was 11.9 HSPF. Through this metering study, we found an average HSPF for the ccHPs of 10.7 kBtu/kWh,[10] approximately 88% of the nameplate value. The TRM fossil fuel heating consumption estimate (in MMBtu) assumes that a ccHP is sized to deliver all the heat to the space for all outdoor temperatures above 5°F. Cadmus found that the ccHP was rarely the exclusive heating system and that other systems often provide heat when the outdoor temperature was warmer than 5°F for several reasons, primarily because:

- the space was open to an adjacent space that was heated by another system
- the homeowner sometimes chose to operate their alternate heating system in conjunction with the ccHP.

During site visits, Cadmus collected information from homeowners to determine the heating system and fuel type that the ccHP replaced. (For additional information, see Fossil Fuel Heating Data Collection in Appendix B). We also installed meters on each heating system in the home and collected fuel usage data. Table 9 shows savings estimates (per installed ccHP) for the fuel types observed in the metering study, and it shows the assumptions that Cadmus used to estimate those savings.

[10] Comparable to nameplate HSPF this is the ratio of total heating capacity delivered in heating season to total energy consumption. Consistent with nameplate HSPF, the ratio does not include standby mode energy.

Table 9. Retrofit-Type Measure: Savings per Installed Cold Climate Heat Pump

Percent of MMBtu Provided by Existing Heating System	Heating System Efficiency Assumptions	Fuel Heat Content Assumptions	Savings	Units
7%	COP of electric resistance heat = 1	3.412 kBtu per kWh	-1,664	kWh (Includes Electric Resistance Offset)
25%	85%	91.2 kBtu/gal	69.1	Gallons of Propane
46%	78%	138.8 kBtu/gal	91.0	Gallons of #2 Fuel Oil
22%	60%	15.3 MMBtu/cord	0.66	Cords Wood

The savings estimates for each fuel type in Table 9 are additive, representing the total impact of one ccHP during the heating season. For example, if a ccHP offsets heat previously delivered by propane heat, the ccHP installation would save 276 gallons of propane (four times the value in Table 9). To proportion savings to each fuel type, we determined the average total heating capacity of the homes in the study (92 MMBtu) and allocated MMBtu delivered by fuel type by reviewing data from fuel bills, fuel consumption data from homeowner records and invoices, and meter data from runtime loggers. Appendix B: Fossil Fuel Heating Data Collection includes additional information about the heating fuel data analysis.

The savings listed in Table 9, appropriate for a ccHP retrofit installation, assume that the installation occurred because a ccHP rebate was available. To estimate savings for a ccHP retrofit, we assumed that the capacity provided by the ccHP directly offsets an equivalent amount of heating capacity that would otherwise have been provided by the alternate heating system. Nearly half (48%) of the homeowners in the metering study acknowledged that they might use the ccHP to keep the space warmer than they did previously (see Appendix B. Survey Responses). Cadmus was unable to adjust savings due to the potential impact of increased energy from improved comfort. The PSD may want to continue to research the impact of ccHP programs to assess when the program is responsible for ccHP installation (a retrofit-type measure) or whether a heat pump installation would have occurred naturally (resulting in incremental savings due to efficiency improvement and high heating capacity at cold temperatures).

Cadmus estimated savings for a non-retrofit scenario (i.e., when a ccHP program influences the installation of a higher-efficiency and higher cold-temperature capacity heat pump). We reviewed manufacturers' specification data to determine baseline heat pump performance (e.g., 8.2 HSPF) versus temperature, and to develop heating performance curves (i.e. COP vs. temperature). Although the manufacturer-rated HSPF may be different from the actual heating season average efficiency, Cadmus assumed that the *difference* in energy consumption between a baseline and program-qualifying ccHP

correlated to the ratio of AHRI rated HSPF values. In other words, if a 10 HSPF system had an *in situ* operating efficiency of 7 HSPF, we did not calculate savings relative to a fixed minimum efficiency (8.2 HSPF) baseline heat pump. Rather, we assumed that the baseline heat pump also would have operated less efficiently while providing equivalent capacity, and would maintain the following relationship as a function of temperature (T):

$$\frac{HSPF_{EE}}{HSPF_{BASE}} = \frac{\frac{\cancel{total\ capacity\ provided}}{efficient\ kWh\ consumption}}{\frac{\cancel{total\ capacity\ provided}}{baseline\ kWh\ consumption}} = \frac{baseline\ kWh\ consumption(T)}{efficient\ kWh\ consumption(T)}$$

To estimate savings from energy consumption, we used only the energy consumed when the ccHP was providing heat, and we assumed that a baseline heat pump would not operate below 5°F. We acknowledge the possibility that a baseline heat pump could use more energy (e.g., through less efficient defrost control sequencing), but we do not have *in situ* performance data of baseline heat pumps to estimate savings. Thus, the final electric (kWh) savings estimates in Table 10 may be conservative.

Table 10. Cold Climate Heat Pump Savings Based on Minimum Efficiency Heat Pump

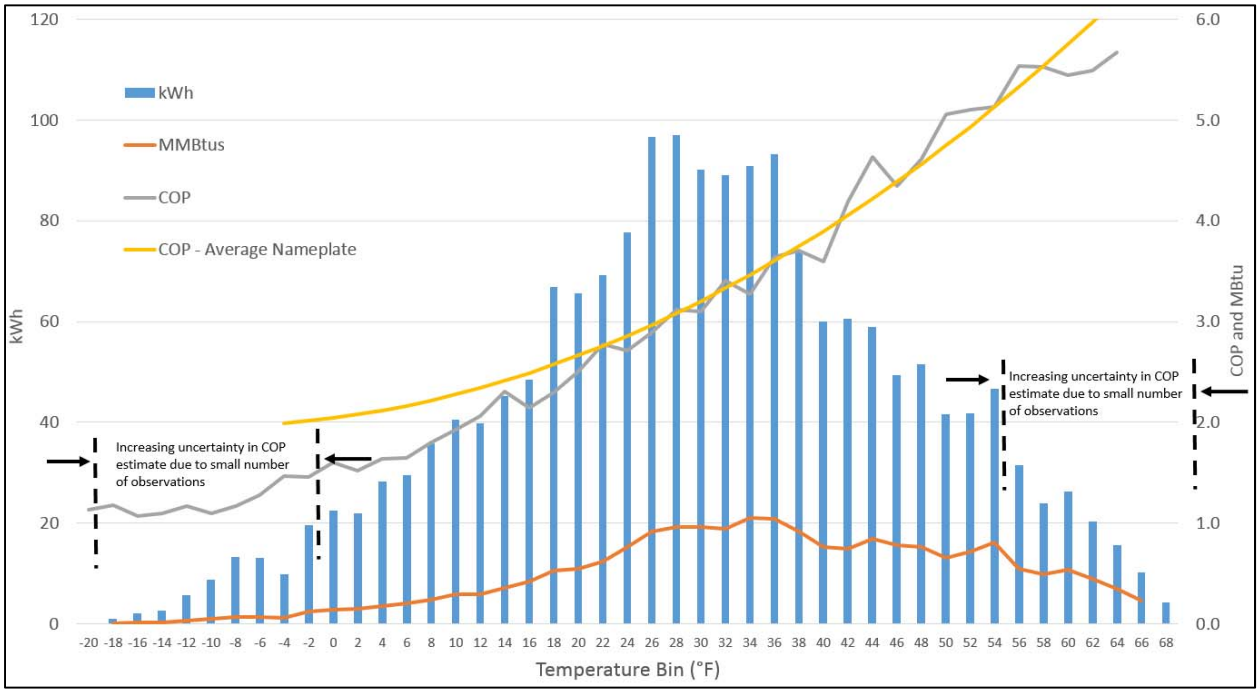
Savings	Units
845	kWh Saved above 5°F
774	Total kWh Saved (Includes electric resistance heat offset below 5°F for 7%) (Includes less ccHP consumption below 5°F)
3.1	Gallons of Propane
4.0	Gallons of #2 Fuel Oil
0.03	Cords of Wood

Compared to fuel savings in Table 9, the propane, oil, and wood impacts listed in Table 10 are significantly less because we assume that for all temperature above 5°F, the baseline and cold climate (program-qualifying) heat pump offset an equivalent amount of fuel. Note the savings in Table 9 (retrofit-type install) should not be added to the savings in Table 10 (higher efficiency-type install).

Figure 14 shows the average energy consumption (kWh) in 2-degree temperature bins for all ccHPs metered. This figure also shows the average heating capacity delivered and the resulting COP. Finally,

this figure shows the expected average nameplate COP from manufacturers' performance data.[11] As evident in this figure, the observed COP is less than the nameplate COP at the coldest temperatures. The energy consumption in each temperature bin is an indication of the number of observations at each temperature, which affects the reliability of the COP estimate. (See also Figure 10).

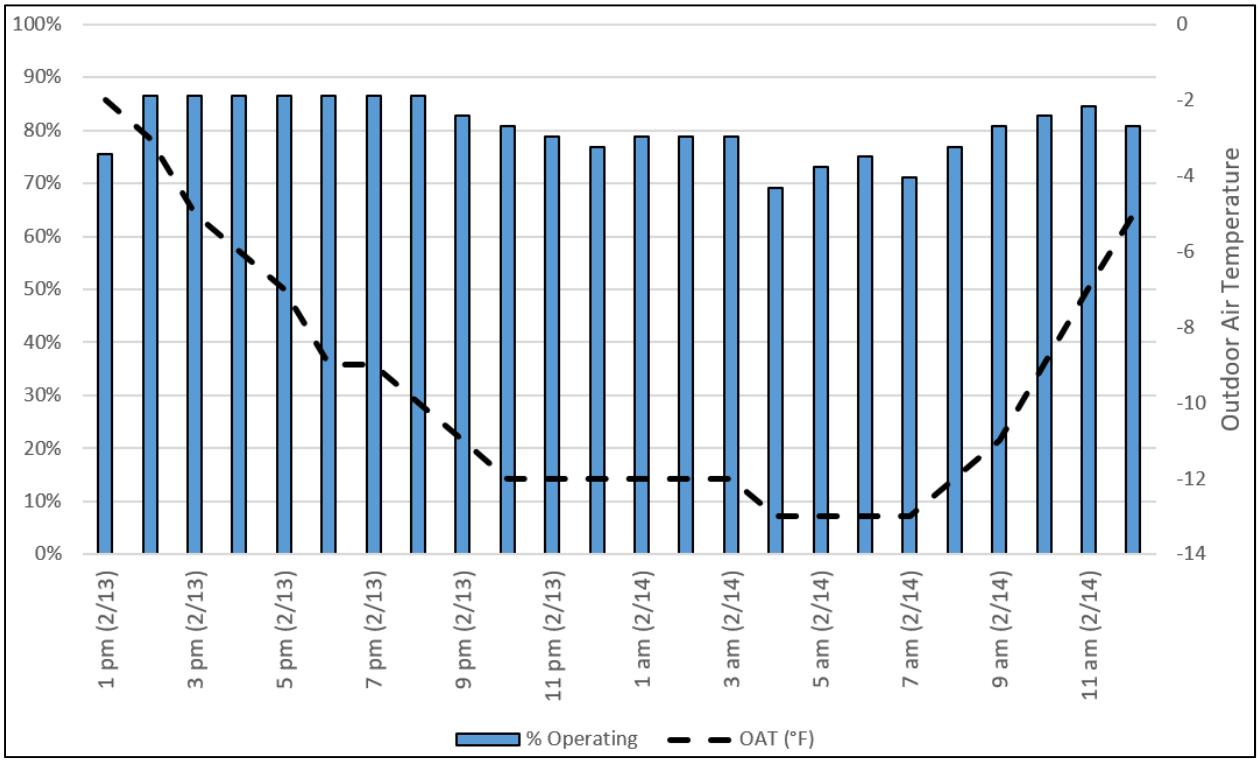
Figure 14. Normalized Energy Consumption and Heating Capacity Delivered



Although the 2015/2016 and 2016/2017 winters were relatively mild, Cadmus found that most homeowners chose to operate their ccHPs during the coldest time of the year. Figure 15 shows the percentage of ccHPs that operated for at least 10 minutes during each hour of the coldest 24-hour period of the metering period, which started at 1 p.m. on February 13, 2016. The temperature curve in this chart is the weighted average temperature across weather stations. (For an explanation of temperature data summary analysis, see Figure 28 and the section titled Weather Normalization Methodology).

[11] Cadmus compiled the published COP values versus temperature for all ccHPs to develop an average COP versus temperature curve.

Figure 15. Percent of Cold Climate Heat Pumps Operating on Coldest 24-Hour Period: February 13-14, 2016:



Cooling Season Findings

The Vermont TRM uses an algorithm that requires ccHP nameplate cooling capacity, efficiency, and an EFLH value to estimate energy savings. EFLH is not directly measured because it is the ratio of total energy consumed in a season to the rated (peak) full-load power.[12] The actual ccHP capacity and power varies significantly with compressor speed and outdoor temperature. Consequently, the actual runtime hours would be significantly more than EFLH because ccHPs do not need to run at full load for most of the season. Cadmus calculated cooling savings using ccHP capacity, efficiency, and EFLH parameters to compare metered results to TRM estimates. We estimated the seasonal cooling energy consumption for each ccHP using the following equation, which follows the logic of the TRM savings algorithm:

[12] Another definition of EFLH is the ratio of the total capacity provided in a season to the nameplate rated capacity.

$$kWh_{\ cooling\ season} = \frac{nameplate\ capacity\ [kbtuh] \times EFLH_{cooling}}{SEER}$$

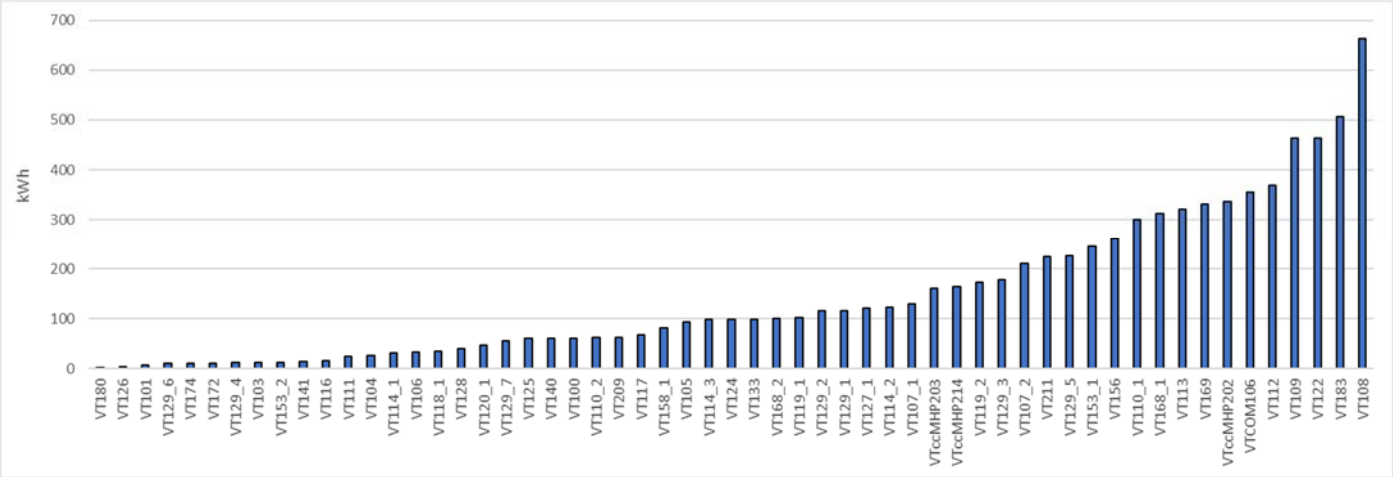
Table 11 shows a summary of the Vermont TRM and metering results for EFLH, system efficiency, and energy consumption. The TRM EFLH and consumption estimates were calculated using the study values, including an average efficiency of 23.7 SEER and average cooling capacity of 14,392 Btu/h per unit.

Table 11. Overview of Cold Climate Heat Pump Cooling Energy Consumption

Source	Cooling Capacity (Btu/h)	SEER	kWh Consumption	EFLH	Realization Ratio	Relative Precision
Vermont TRM	14,392	23.7	182	375	64%	N/A
Metering			146	240		23.5%

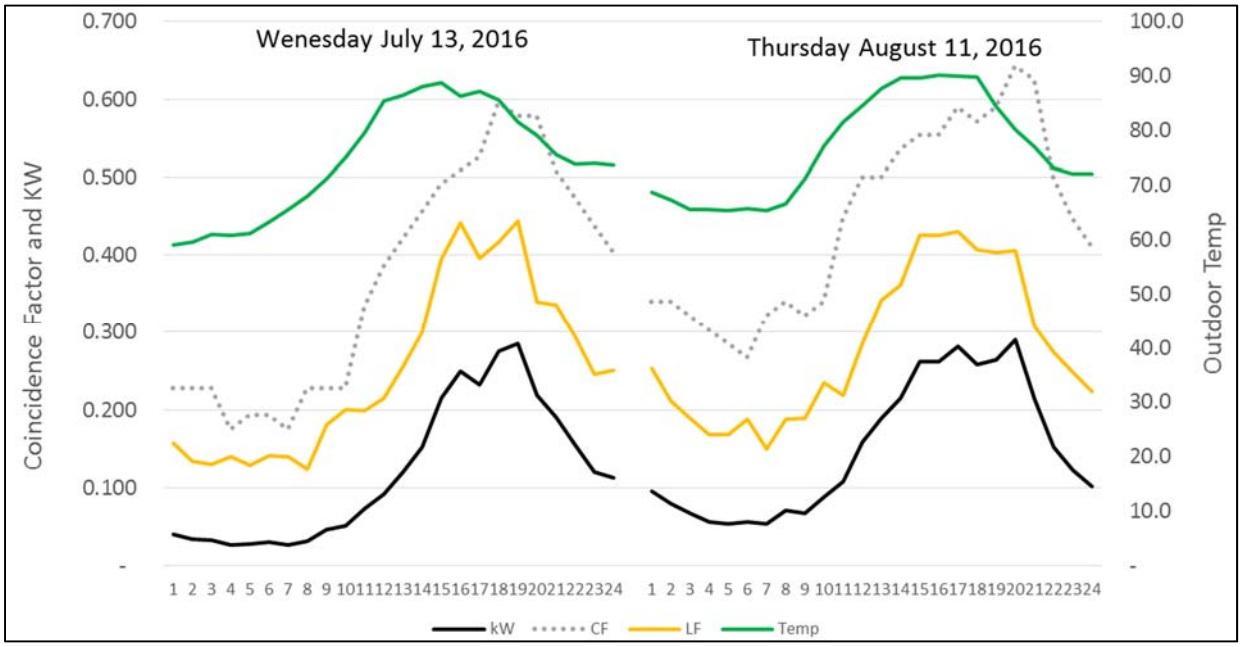
Cadmus weather-normalized all results to determine the energy consumption and savings expected in an average year. Figure 16 shows the annual cooling energy consumption for each ccHP metered.

Figure 16. Cooling Energy Consumption (kWh): Summer 2016



Cadmus aggregated all meter data for all hours of the summer to determine the peak connected load of the population of ccHPs metered. Figure 17 shows the peak demand for the top two days during the summer.

Figure 17. Peak Demand: Top Two Days



These plots show that the average connected demand of all ccHPs reaches approximately 300 Watts. The coincidence factor (CF) shows that nearly 60% of the ccHPs were operating, and that the average load factor (LF) for operating ccHPs was just above 40% of the rated load (based on rated kW at 95°F).

These data indicate that the peak cooling load is significantly less than the peak heating load, which exceeds 1.2 kW when the outdoor temperature drops below 0°F (see Figure 9). A low load factor means the ccHPs are operating at low speed and relatively high efficiency.

Based on Cadmus' review of active single-head wall-mounted mini-split heat pump systems listed in the AHRI database, our discussions with contractors about the cheapest ccHP options on the market, and our review of distributor data, a baseline estimate of 14.5 SEER and 9 EER is a reasonable estimate of efficiency for a baseline ductless heat pump.

We also calculated savings for a window air conditioner, assuming average operating efficiency for the cooling season of 8 EER and coincident peak operating efficiency of 7 EER. Table 12 shows the energy and peak demand savings for each baseline scenario. The table also shows the energy and demand impacts if the program is responsible for load building. This situation occurs if a homeowner would not otherwise have installed a cooling system. (For information related to load-building potential, see Appendix B. Survey Responses.)

Cadmus used survey responses to assess the likelihood that electric load increased during the summer due to participation in the ccHP program. Cadmus assumed load building occurred if respondents met any of these criteria:

- Did not have a cooling system previously
- Said they would not have installed a cooling system if they could not have installed a ductless heat pump
- Said their decision to purchase a ccHP was "very influenced" either by their contractor or by the program directly
- Said they keep the space cooler now than before
- Installed the ccHP primarily for heating

Table 12. Cooling Savings Summary

	Window Air Conditioner	14.5 SEER Heat Pump	No Previous Cooling	Window Air Conditioner Baseline	Ductless Heat Pump Baseline	Load Building	Weighted Average
kWh Saved	286	93	-146	15%	65%	20%	74
Peak kW Saved	0.284	0.158	-0.190				0.11

Assessment of baseline technology for a system that is used for both heating and cooling is a challenge. The weighted average savings values in Table 12 represent Cadmus' best estimate of program impacts.

Additional Findings and Insights

We reviewed and categorized the collected data in various ways to determine whether we could use any type of information that is easy to collect (relative to on-site long-term meter data). For each installation categorization, we compared ccHP performance relative to nameplate HSPF and compared ccHP use (EFLH). The categories we tested include:

- Installation location (e.g. room type)
- ccHP size
- Number of ccHPs installed in the home
- The homeowners' planned usage strategy (e.g. use exclusive heat source, use a secondary heat source)
- Solar panels installed at home

- Alternate fuel type (e.g. homes with propane versus home with oil, etc)
- Shell characteristics of the home (good versus poor insulation and air sealing)

Cadmus compared both the EFLH and the performance of ccHPs within each category. For many of the data categories we tested, the variance in results was too high to develop conclusive parameter adjustments (i.e. the difference was not statistically significant, exceeding 10% precision at the 90% confidence interval).

Cadmus did not find statistically valid EFLH differences within any category. EFLH can vary from zero (never used) to ~3,000+ hours (used continuously at full load). Because many factors influence EFLH and because the range of possible hours is so wide, to isolate the influence of just one factor would have required a larger sample. Although not statistically valid, the sections below describe some of the findings, which the PSD should consider if planning additional research activities.

Cadmus developed a realization ratio of metered performance (in kBtu/kWh) to nameplate HSPF. Typically, compressor speed and outdoor conditions (see Figure 4 and Figure 5) impact a ccHPs efficiency. Unlike EFLH, the range in the realization ratio of performance is narrow. A ccHP would not perform with efficiency of 0 kBTU/kWh; a homeowner would not tolerate a system that does not provide heat. Cadmus did find statistically significant differences in performance between ccHPs in homes with good versus poor shell characteristics, in homes with solar versus homes without solar, and in homes that use wood heat versus homes that do not. The following sections include these findings and other informative but inconclusive insights. Given the multitude of possible correlations of ccHP use and performance with site-specific information, we present only the apparent and straightforward correlations in this report.

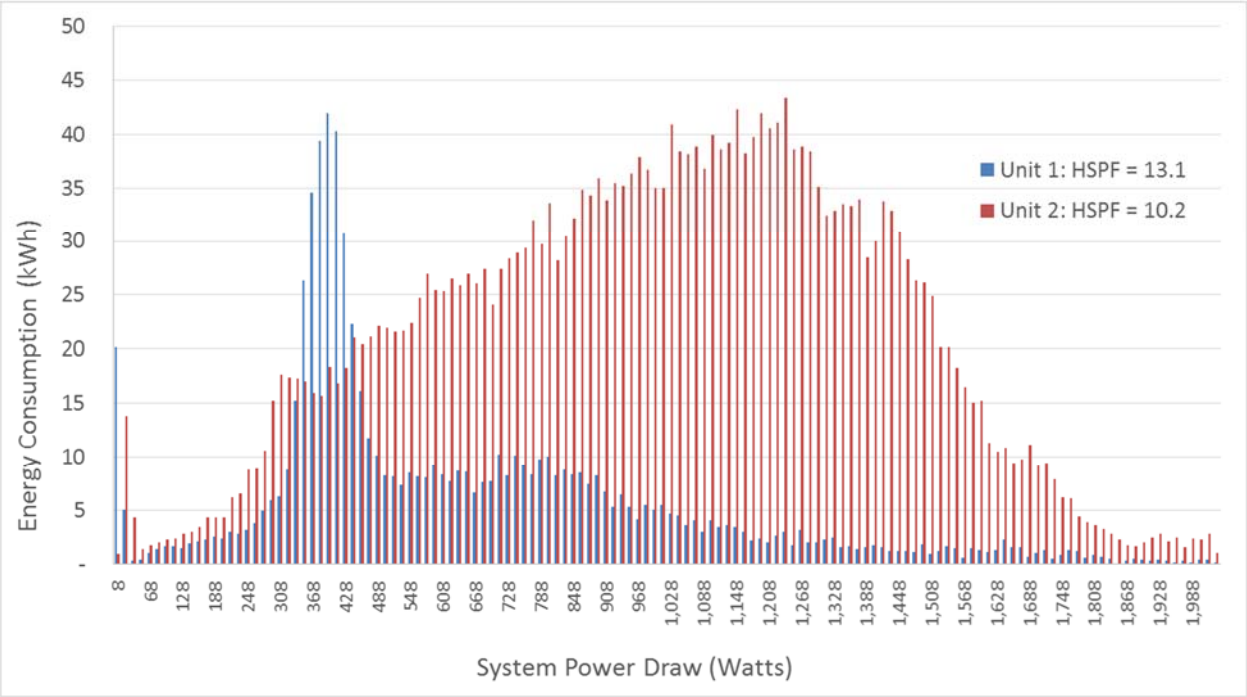
Performance and Sizing of ccHPs

The nameplate rated HSPF and SEER for a heat pump is calculated by following the AHRI 210/240 protocol, which requires laboratory measurements of instantaneous steady-state performance at several outdoor temperatures and fixed compressor speeds. HSPF and SEER are then calculated from bin temperature analysis of a specified region (usually U.S. region IV, VT is region VI). Heat pumps installed in residential homes operate at outdoor conditions that are often quite different from the AHRI test conditions. For example, ccHPs operate with variable speeds and capacity (which affects efficiency), which are unquestionably different from the AHRI test speeds. Consequently, the average seasonal heating efficiency (*in situ* HSPF) and SEER may vary from the nameplate rating. Cadmus found ccHPs operated at 88% of the average nameplate HSPF. *In situ* HSPF varied from 57% to 119% of nameplate HSPF. Performance may vary for different reasons, so we reviewed the granular meter data in different

ways to determine whether quantifiable factors affected performance. The examples below describe the approach.

Figure 18 shows the total energy consumption metered during the 2015/2016 winter at increments of 15 watts for two identical ccHPs installed in different single-family homes in the Burlington area. This figure, which compares two identical systems operating in different homes, helps to explain why a ccHP would operate less efficiently than expected.

Figure 18. Comparison of Operation of Identical Cold Climate Heat Pumps (MUZ-FH12NA) During Heating Season



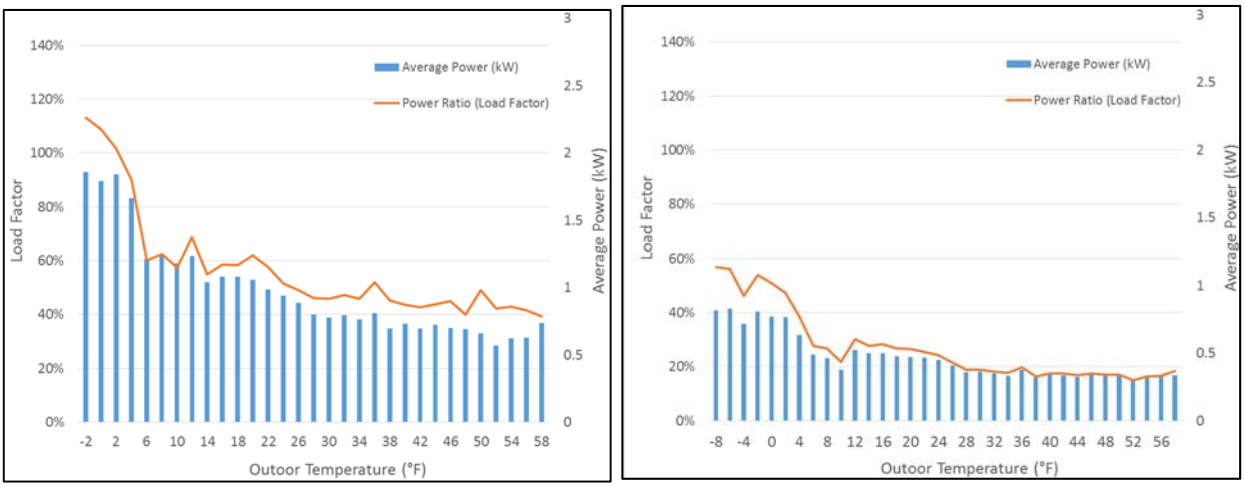
At a given outdoor temperature, efficiency increases as ccHP power decreases. The bars in Figure 18 clearly indicate that a higher proportion of energy consumption for Unit 1 (blue bars) occurred at lower power than Unit 2 (red bars). Cadmus reviewed all data collected[13] and found that Unit 1 operated at lower load because the capacity requirements of the space were lower for Unit 1 than for Unit 2. This

[13] This chart alone does not conclusively explain why performance varied between the two identical ccHPs. Other factors may include indoor and outdoor conditions, homeowner decision to turn system on/off, quality of installation, defrost cycles, or filter restrictions.

type of visualization is helpful because it can give an indication of how a ccHP operates throughout a season: higher energy consumption at higher power effectively decreases operating efficiency. Compared to Unit 2, Unit 1 may be oversized for the space that it serves.

To further investigate how a system is sized for the space, we determined the maximum power as a function of temperature for each ccHP from manufacturers' published power values.[14] We compared expected maximum power to actual average power.

Figure 19. Load Factor Versus Outdoor Temperature



If a ductless heat pump is properly sized, one would expect a load factor of nearly 100% during the coldest hours of the year. There were several ccHPs that were clearly unable to meet the heating demand as outdoor temperature dropped. The left chart in Figure 19 shows the ccHP operated at higher power than its maximum power value[15] when the outdoor temperature fell below 2°F. In other words, the system operated continuously at maximum capacity and was unable to meet the heating demand at the design temperature. Conversely, the chart on the right shows an average load factor of just under 60% when the outdoor temperature is -8°F.

The evidence (in the left chart in Figure 19) suggests that the ccHP was undersized for the space if the equipment was intended to provide full load at -2°F. Consequently, the *in situ* HSPF of this system was

[14] http://www.neep.org/sites/default/files/ColdClimateAir-SourceHeatPumpSpecificationListing-Updated1.1.17.xlsx

[15] Values below 17°F are not certified by AHRI

lower (76% of nameplate) than its rated HSPF. There are many confounding factors that make it difficult to assess how well a system is sized for the space it serves, including these:

- System shutdowns (whether consistent or sporadic) by homeowner
- Homeowner decisions regarding heat operation in a ccHPs coincident zone
- Heat entering a ccHPs zone from an adjacent space (such as from sporadic use of a basement wood stove)
- Solar gains
- Opening and closing doors to adjacent zones

Although properly sizing a ccHP may help to ensure ideal operating efficiency,[16] there are many factors that affect how a system should be sized. For example, Figure 20 shows the load factor and average power of a ccHP that was intentionally shut off when the outdoor temperature dropped below 0°F. This particular homeowner planned to turn off the ccHPs in the belief that it was not cost-effective to run the them at sub-zero temperatures. Though this system could be undersized for peak conditions, it is not undersized for its planned operation.

[16] In the case of single-head variable speed ccHPs, an oversized system could operate more efficiently than a smaller system in the same space.

Figure 20. Intentional Shutdown Below 0°F

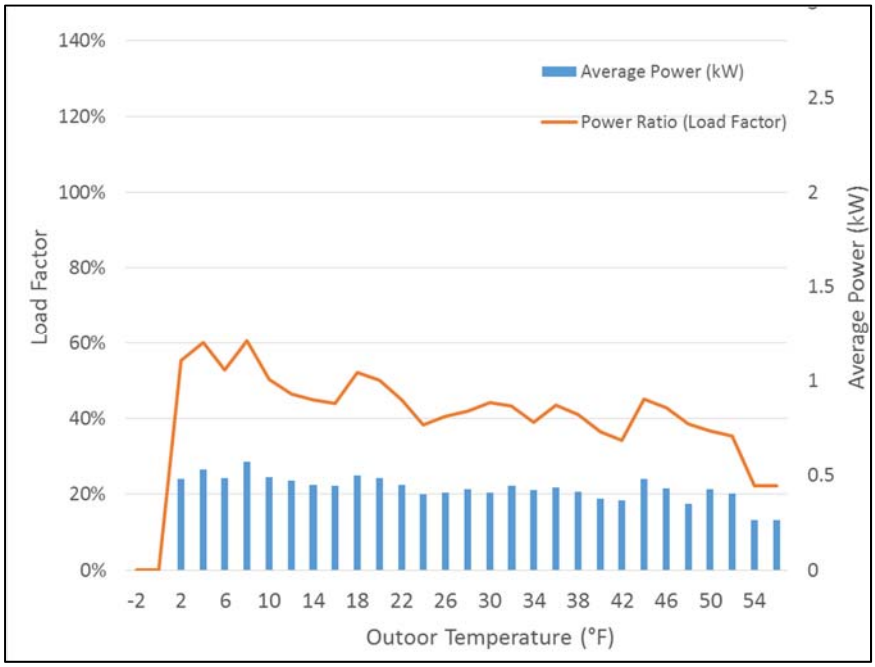
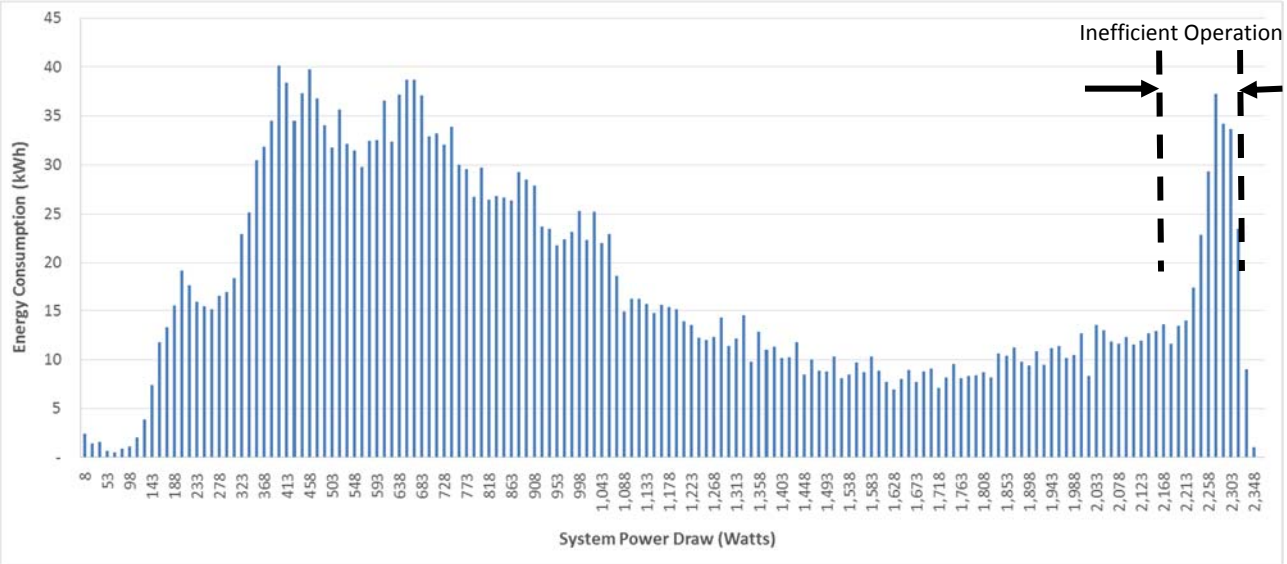


Figure 21 shows an example of a ccHP installed in a spare room in a home. The indoor temperature in this room frequently dropped to 55°F because the homeowner set the thermostat to that temperature when the room was not in use. The homeowner changed the temperature setpoint from 55°F to 73°F numerous times during the winter. Consequently, the system operated at its highest speed (maximum power) numerous times, which effectively reduced the average seasonal operating efficiency. Though this system was sized to meet the heating demand of room,[17] the large temperature changes resulted in periods of inefficient operation.

[17] Based on assessment of load factor at coldest conditions. Assessment of proper sizing cannot be definitively confirmed; additional meter data (expected 2016/2017 winter) are required.

Figure 21. Energy Consumption Versus Power: Occasional Max Speed Operation

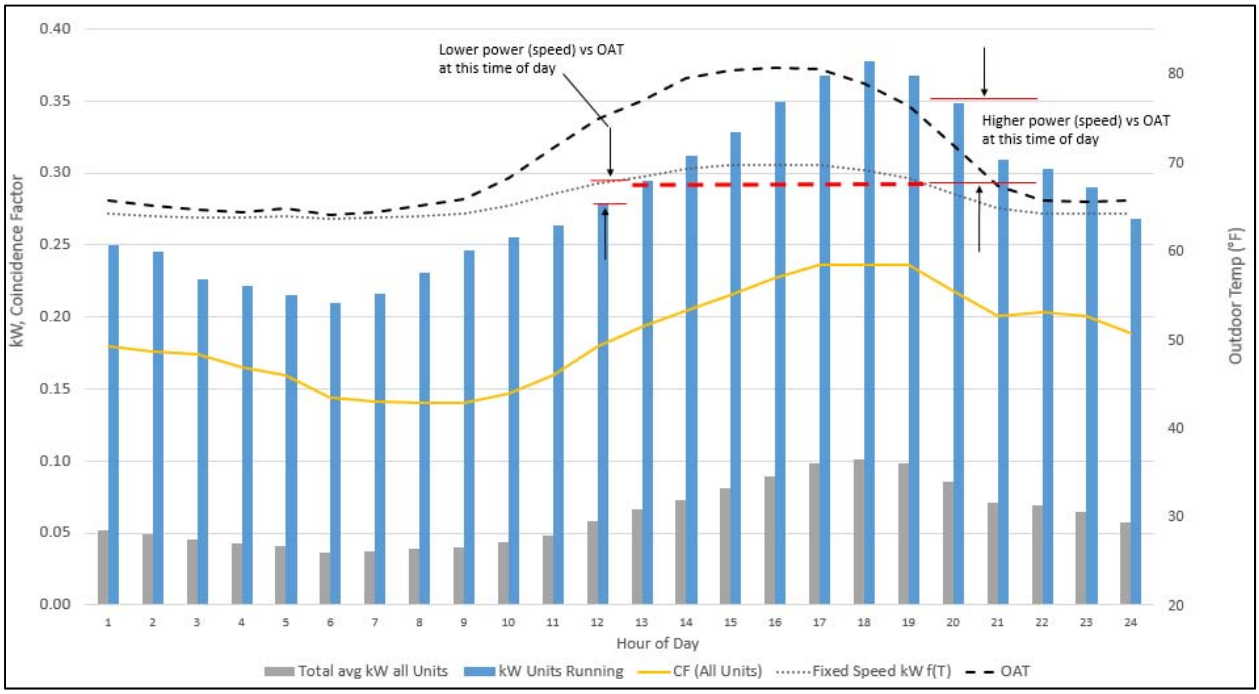


At a minimum, Cadmus reviewed every meter dataset showing energy consumption variance with power (e.g., Figure 18 and Figure 21) and with outdoor temperature (e.g., Figure 19 and Figure 20).

Some ccHPs operated more efficiently than others, and visual inspection of the power data clearly showed some ccHPs were operating at higher load (and were, therefore, less efficient) either because of the high heat demand of the space (left chart in Figure 19) or because of high load operation due to large indoor temperature changes (Figure 21).

The ccHPs in Vermont were primarily installed to offset alternate heat sources. As evident in Figure 9, heating use was significantly higher than cooling use making ccHPs "over-sized" for the cooling load. For this reason, ccHPs tend to operate at low load (higher efficiency) in cooling mode. Nevertheless, Cadmus inspected cooling load to assess the performance. Figure 22 shows a summary of all ccHPs metered from June 1 through August 31. The grey dotted line shows the expected load if the compressor is operating at fixed speed and, therefore, when only the outdoor temperature affects power. Comparing actual kW at 1 p.m. to 8 p.m., the kW at 8 p.m. is higher, meaning the ccHPs tend to operate less efficiently later in the day. This is expected because the cooling load in homes lags outdoor temperature and because people tend to use cooling systems more in the evening, when occupancy increases.

Figure 22. Cooling Season Aggregate Cold Climate Heat Pump Load



Cadmus found very few instances of ccHPs operating inefficiently (at maximum capacity) during the cooling season. We did not develop recommendations related to ccHP cooling operation.

Findings: Cold Climate Heat Pump Performance

Table 13 lists the correlations that had statistically significant results for nameplate rated HSPF and the metered *in situ* HSPF[18]. The table includes results from 30 ccHPs. We removed ccHPs from the analysis if any of these conditions existed:

- We did not meter capacity (only used ccHP with advanced metering setup)
- There was insufficient energy use or ccHP operation to establish a reliable performance estimate
- We were unable to characterize the shell characteristics of the home

[18] The "% Difference" result is statistically significant if the relative precision is less than 10% at the 90% level of confidence.

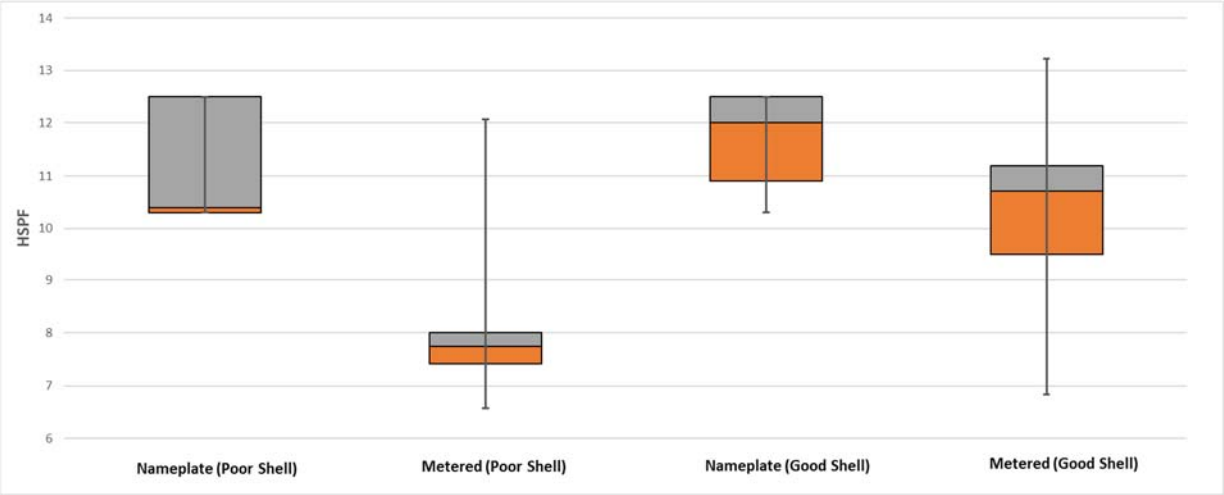
Table 13. Correlating Performance to Various Parameters

	Average Nameplate HSPF	Average Metered kBtu/kWh	% Difference	Average Nameplate HSPF	Average Metered kBtu/kWh	% Difference
Parameter	**Parameter = true**			**Parameter = false**		
Does not have solar Installed?	11.58	8.99	**78%**	11.55	10.06	**87%**
Has Wood Fire Heat Source?	11.45	9.13	**80%**	11.73	10.40	**89%**
Building Shell/Insulation assessed as "poor"	11.20	8.09	**72%**	11.74	10.41	**89%**

Of the three groups in Table 13, the only parameter group with a statistically valid *difference* was the building shell assessment group. At the 90% confidence interval, the lower-bound % difference for well-insulated homes (83%) is greater than the upper bound % difference for poorly-insulated homes (79%).

The box and whisker plots in Figure 23 show the range in seasonal performance for homes with good and poor shell characterizations.

Figure 23. Box and Whisker Plots of Metered and Nameplate Seasonal Performance



Of the 30 ccHPs represented in Table 13 and in Figure 23 we identified 10 ccHPs that operated in homes with "poor" shell characteristics. When conducting site visits, we used the following criteria to categorize homes as either "poor" or "good" regarding shell and/or insulation characteristics:

- Homeowner's assessment of home's draftiness, and any other relevant information provided
- Stated or observed R-values
- Age of home
- In-field observations of doors, windows, and other likely sources of air infiltration

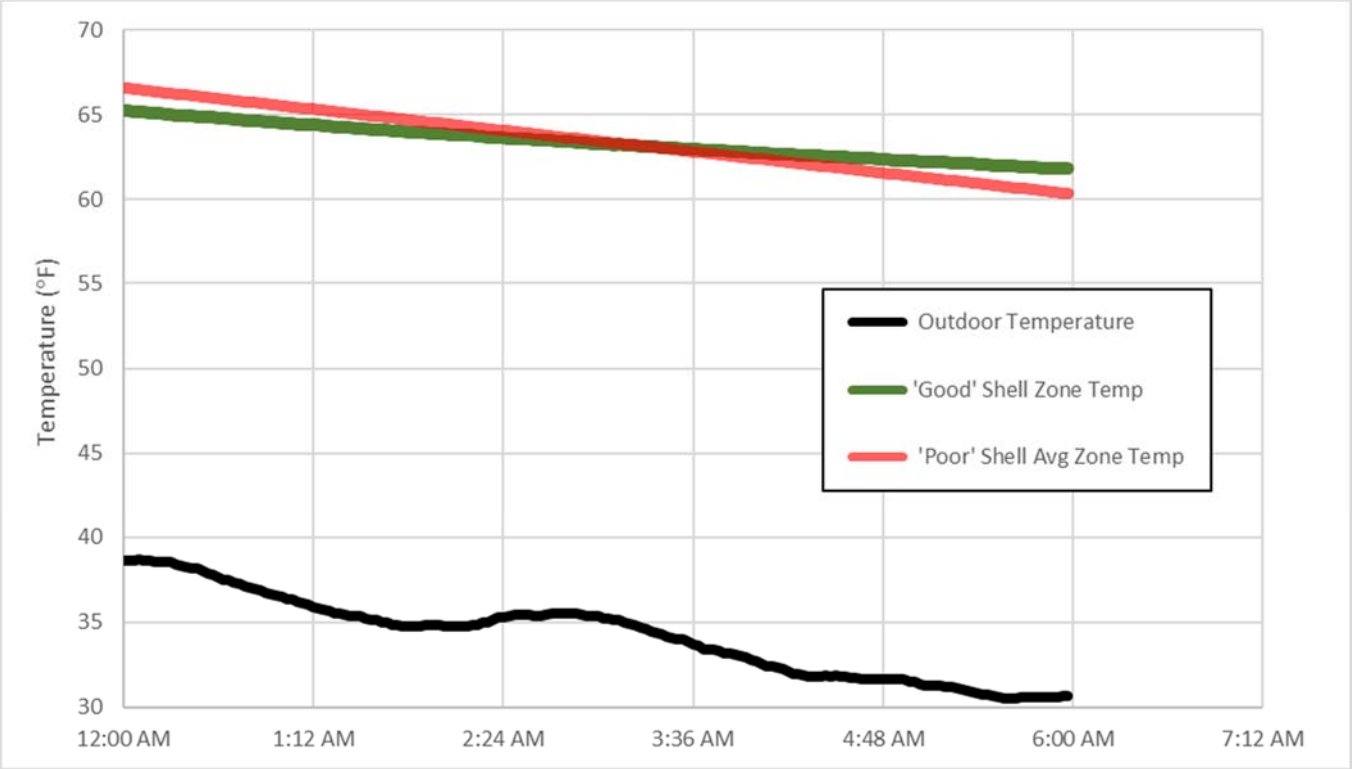
We also used an analytical approach to validate the good/poor shell characterization of each home. Initially Cadmus planned to develop an MMBtu per square foot value to compare homes. The results of this activity proved inconclusive for two main reasons:

1. The indoor temperature set point drives MMbtu use, and indoor temperatures varied significantly throughout the heating season.
2. Cadmus' estimate of MMbtu delivered by wood-burning stoves has relatively high uncertainty

Instead, Cadmus selected several nights with little or no heat use of any type by confirming the ccHP and alternate heating systems did not operate. For each home, we reviewed the indoor temperature sensors (e.g. return air temperature sensor) in the space with the ccHP and plotted the temperature change in

each home. Figure 24 shows the average temperature decline for each group. We confirmed that the slope (rate of temperature decline over time) of each of the 10 homes with "poor" building shells was greater than the slope of the other homes.

Figure 24. Shell Assessment with Review of Thermal Cooling



Although the "good" versus "poor" assessment of a home's shell characteristics is subjective, the in-field data collected and analytical approach support the assertion that the 10 homes assessed as "poor" have greater heat loss than the homes assessed as "good". If future evaluation activities validate that a home's shell characteristics are better than an average home in Vermont, such a validation can support an HSPF adjustment, as follows:

- HSPF adjustment for home with 'good' shell characteristics: 92%
- HSPF adjustment for home with 'poor' shell characteristics: 88%
- HSPF adjustment for home with unknown shell characteristics: 90% (value found in this study)

It is worth noting that homes with poor shell characteristics were much less likely to have solar panels installed (30%) when compared to the rest of the homes in the sample (63%). Also, wood was used as a

source of heat much more frequently in homes with poor shell characteristics (56%) than in the other homes (6.3%). Some homeowners with solar generation indicated that they wanted to use as much electric heating energy as possible because they over-produce energy. These homeowners could be more likely to run the heat pump continuously, so their homes would have less varied temperature changes caused by factors such as sporadic use of other heating systems.

Here are some of the reasons that ccHPs may operate less-efficiently in a building with poor shell characteristics:

- Higher probability of temperature fluctuations, causing high-speed operation
- Higher probability of undersized system due to increased probability that the space will have heating needs that cannot be met by any available single-head ccHP on the market (heat pumps have a heating capacity limit; the largest indoor units are unable to deliver more than ~15,000 Btu at sub-zero temperatures)
- Lower instance of solar energy generation and, therefore, greater probability of sporadic operation/temperature changes (see paragraph above)
- Lower probability of energy efficiency mentality (in other words, homeowners concerned with efficiency are more likely to maintain a home with good insulation characteristics and to operate their heating system efficiently)

Informative but Inconclusive Findings

Through unplanned, in-depth interviews while on site, Cadmus field staff found that at least half of the homeowners participating in the study were very knowledgeable about heating systems and were interested in the operation of their ccHPs. More than half had a plan to operate the system in a way that they believed would maximize heating efficiency or reduce their heating bills. However, we were unable to correlate higher ccHP performance for the group of knowledgeable and interested homeowners.

Figure 25 and Figure 26 show categorization by room type. These charts show EFLH (determined from metered energy consumption and nameplate heating and cooling capacity), actual kWh, metered EFLH, and the TRM EFLH estimates. The number of ccHPs in each room type is too small to develop results with statistical significance. However, this summary may indicate that ccHPs installed in bedrooms may use less energy and, therefore, generate less savings than ccHPs installed in other locations of a home.

Figure 25. Summary of Heating Use by Space Type

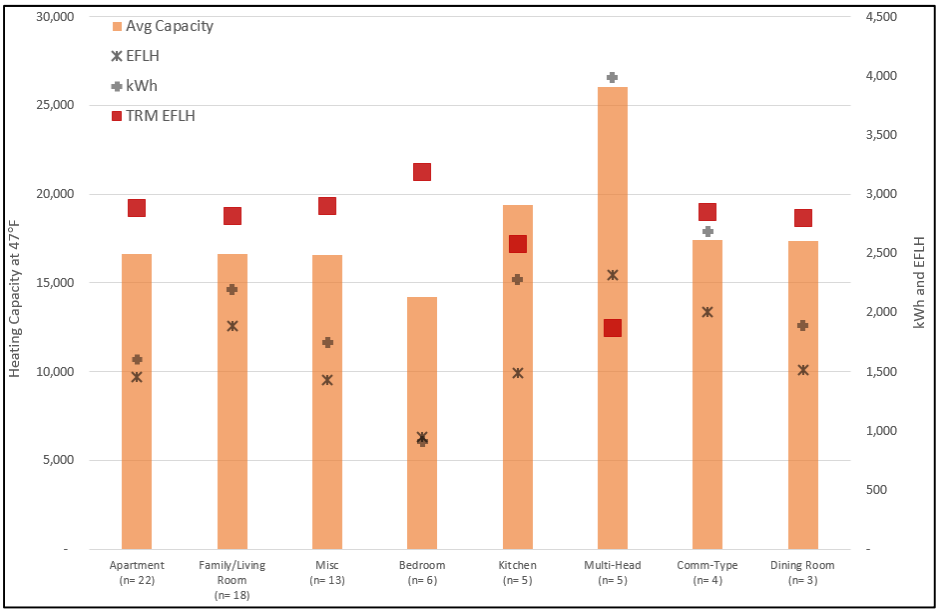
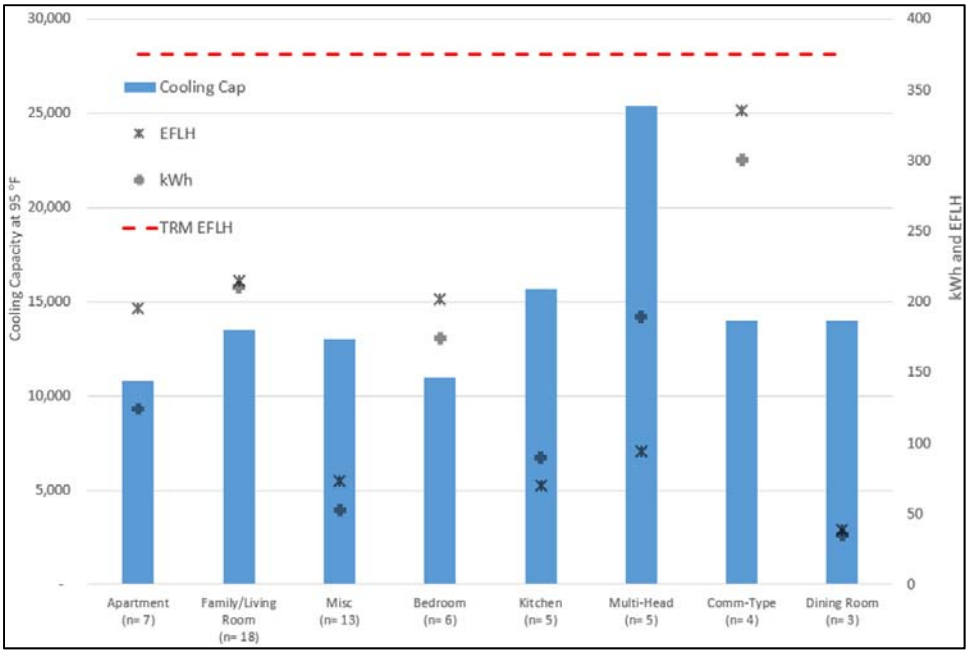


Figure 26. Summary of Cooling Use by Space Type



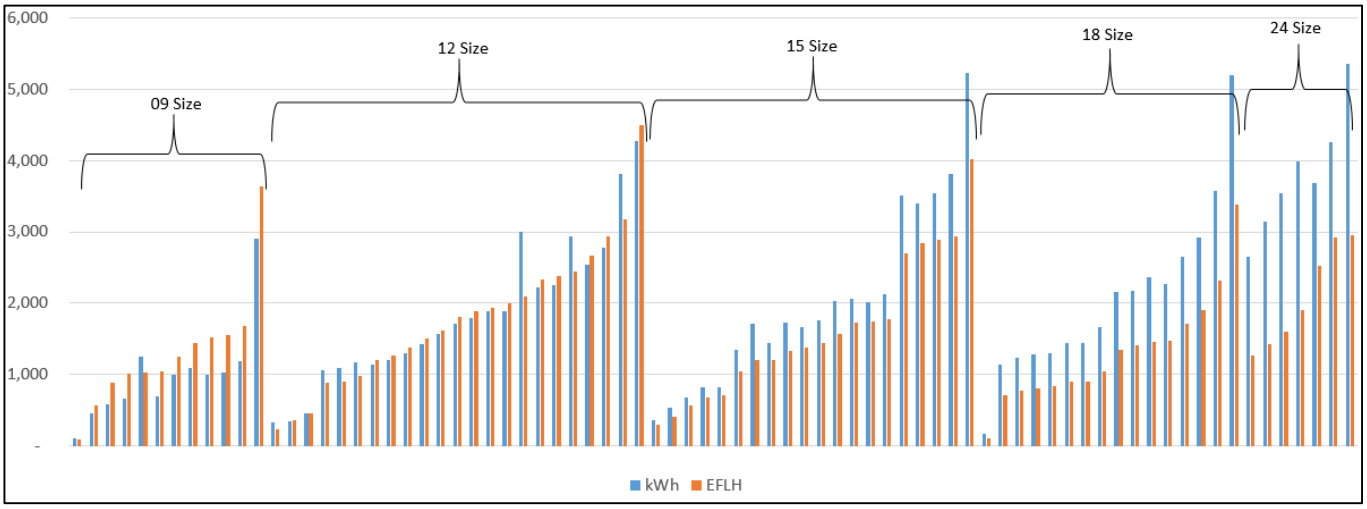
Another example that we looked at was the use of ccHPs in single-family homes with only one ccHP. We compared the ccHP energy use in those homes to average energy use of the ccHPs in homes with more than one system. Table 14 shows no significant difference between the two groups. This summary does not include the five multi-head ccHPs.

Table 14. Cold Climate Heat Pump Usage in Homes Installing One System Versus Homes with Multiple Systems

Installation Type	Count	Cooling (Btu)	Heating (Btu)	Cooling (kWh/ton)	Heating (kWh/ton)	Total (kWh/ton)
Home with only one ccHP	25	14,040	18,703	110	1,104	1,215
Home with more than one ccHP	26	12,962	17,005	112	1,161	1,273

Figure 27 compares ccHP heating use for each size category. Although some difference in EFLH and consumption may exist, Cadmus did not find statistically valid differences between the groups.

Figure 27. Annual Heating EFLH and kWh by Cold Climate Heat Pump Size



Appendix A. Technical Information

Table 15 lists the ccHPs metered in this study, by outdoor unit model number.

Table 15. Cold Climate Heat Pumps Metered

Quantity Metered	Manufacturer	Outdoor Model	Type	HSPF	SEER	EER	Rated (47) Cap	Rated COP (47)	Rated (17) Cap	Rated COP (17)	Max Cap (5)	COP (5)
2	Daikin	RXS24LVJU	Single-zone	10.6	20	12.5	25400	3.37	13781	2.63	14028	2.26
3	Daikin	RXS12LVJU	Single-zone	12.5	23	12.8	14400	4.35	7816	3.4	8051	2.81
9	Daikin	RXS18LVJU	Single-zone	11	20.3	12.7	21600	3.935	11725	2.89	11924	2.49
1	Daikin	RXL09QMVJU	Single-zone	12.5	20	12.5	10942	4.21	7121	3.14	10918	1.97
2	Daikin	3MXS24NMVJU	Multi-zone	12.5	17.9	12.7	24000	4.82	16230	3.69	18930	2.26
2	Fujitsu	AOU15RLS3H	Single-zone	13.3	25.3	13.9	18000	4.59	11200	3.06	20500	2.07
10	Fujitsu	AOU15RLS2H	Single-zone	12	25	13.8	16000	3.91	10200	2.72	16500	2.34
5	Fujitsu	AOU12RLS2	Single-zone	12	25	13.8	16000	3.91	10200	2.72	16500	2.34
1	Fujitsu	AOU15RLS2	Single-zone	12	25	13.8	16000	3.91	10200	2.72	16500	2.34
1	Fujitsu	AOU15RLFFH	Single-zone	11	20.3	12.5	18000	3.68	11600	2.62	18500	1.77
2	Fujitsu	AOU12RLFFH	Single-zone	11	20.3	12.5	18000	3.68	11600	2.62	18500	1.77
3	Fujitsu	AOU9RLS2	Single-zone	12.5	27.2	16.1	12000	4.4	9400	2.54	15000	2.18
5	Fujitsu	AOU9RLS3	Single-zone	14.2	33	18	12000	5.33	7000	3.46	15000	2.09
1	Fujitsu	AOU12RLS3H	Single-zone	13.8	29.3	15.2	16000	4.64	9600	3.18	16500	2.15
1	Fujitsu	AOU24RLXFZH	Multi-zone	10.3	20	13.3	25000	4.04	15400	2.6	25500	2.09
7	Mitsubishi	MUZ-FE18NA	Single-zone	10.3	20.2	14.2	21600	4.11	11700	2.76	21830	2.03
7	Mitsubishi	MUZ-FH15NA	Single-zone	12	22	12.5	18000	4.06	11000	3.16	18000	1.79
4	Mitsubishi	MUZ-FE12NA	Single-zone	11.5	24.55	13.35	13600	4.2	8150	3.15	13600	2.335
8	Mitsubishi	MUZ-FH12NA	Single-zone	12.5	26.1	13.8	13600	4.2	8000	3.26	13600	2.21

1	Mitsubishi	MUZ-FH09NA	Single-zone	13.5	30.5	16.1	10900	4.5	6700	3.27	10900	2.32
2	Mitsubishi	MXZ-3C30NAHZ	Multi-zone	11	18	12.5	28600	4	18000	2.65	28600	1.75

Cadmus analyzed on-site survey and metering data. We reviewed and categorized the analysis results in various ways, but given the multitude of possible correlations of ccHP use with site-specific information, we presented only a few obvious or straightforward correlations in this draft report. Cadmus will continue to investigate data and welcomes feedback from reviewers.

Meter Data Analysis

Through previous heat pump metering studies, Cadmus has developed analytical procedures and tools to inspect data quality and perform analysis calculations. All data analyses undergo senior-level quality control review to ensure the accuracy of calculations and confirm the consistency of findings with general expectations.

Analysis of Cold Climate Heat Pump Performance

Cadmus used two standard metrics to compare heat pumps in the heating season: the coefficient of performance (COP) and the heating seasonal performance factor (HSPF). COP, defined at a given time for a given temperature, results from the following equation:

$$COP = \frac{heat\ provided\ by\ DHP\left(\frac{Btu}{h}\right)}{equivalent\ electric\ power\ input\ \left(\frac{Btu}{h}\right)} = \frac{heat\ provided\ by\ DHP\ \left(\frac{Btu}{h}\right)}{3.412\ \frac{\frac{Btu}{h}}{W} * \ electrical\ power\ input\ (W)}$$

HSPF, defined for an entire heating season, results from the following equation:

$$HSPF\ \left(\frac{Btu}{Watt\ hour}\right) = \frac{total\ heating\ provided\ (Btu)}{electical\ energy\ consumed\ (Watt\ hours)}$$

Cadmus used two standard metrics to compare heat pumps in the cooling season: COP and seasonal energy efficiency ratio (SEER). Cooling COP, also defined at a given time for a given temperature, results from the following equation:

$$COP = \frac{cooling\ provided\ by\ DHP\left(\frac{Btu}{h}\right)}{equivalent\ electric\ power\ input\ \left(\frac{Btu}{h}\right)} = \frac{cooling\ provided\ by\ DHP\ \left(\frac{Btu}{h}\right)}{3.412\ \frac{\frac{Btu}{h}}{W} * \ electrical\ power\ input\ (W)}$$

SEER, defined for an entire heating season, results from the following equation:

$$SEER\left(\frac{Btu}{Watt\ hour}\right) = \frac{total\ cooling\ provided\ (Btu)}{electical\ energy\ consumed\ (Watt\ hours)}$$

Note About Nameplate Rated HSPF and SEER

The nameplate rated HSPF and SEER for a heat pump is calculated by following the AHRI 210/240 protocol, which requires laboratory measurements of instantaneous steady-state COP at several outdoor temperatures and fixed heat pump speeds. HSPF and SEER are then calculated from bin temperature analysis of a specified region (usually U.S. region IV). Heat pumps installed in residential homes operate at outdoor conditions that may be different from the AHRI test conditions. Mini-split heat pumps operate with variable speed and capacity (which affects efficiency), which are unquestionably different from the AHRI test speeds. Consequently, the *in situ* HSPF and SEER may vary from the nameplate rating. Cadmus discussed the AHRI testing protocols and nameplate rated efficiency values with several heat pump manufacturers, who all confirmed that the only way to determine the actual efficiency and performance of a heat pump is through detailed, extended metering studies.

Cadmus installed meters to record components of the ccHP performance across a range of conditions to show how systems actually operate. To determine the heating capacity supplied by the ccHP, we used the following equation:

$$Capacity\left[\frac{Btu}{hr}\right] = CFM\ *4.5*(h_{SUPPLY} - h_{RETURN})$$

Where:

CFM	=	Volumetric airflow rate estimated from metered amperage of indoor fan (cubic feet per minute)
4.5	=	Constant value based on specific density of air (0.075 lb/ft^3), converted from minutes to hours
h_{SUPPLY}	=	Supply air enthalpy (Btu/lb)
h_{RETURN}	=	Return air enthalpy (Btu/lb)

Cadmus directly measured the electrical energy consumed (denominator in HSPF and SEER equations) using a WattNode (listed in Table 17).

Weather Normalization Methodology

We used the following equation, an hours per bin temperature approach, to calculate annual, weather-normalized kWh consumption for a ccHP for each heating season from 2008 through 2017:

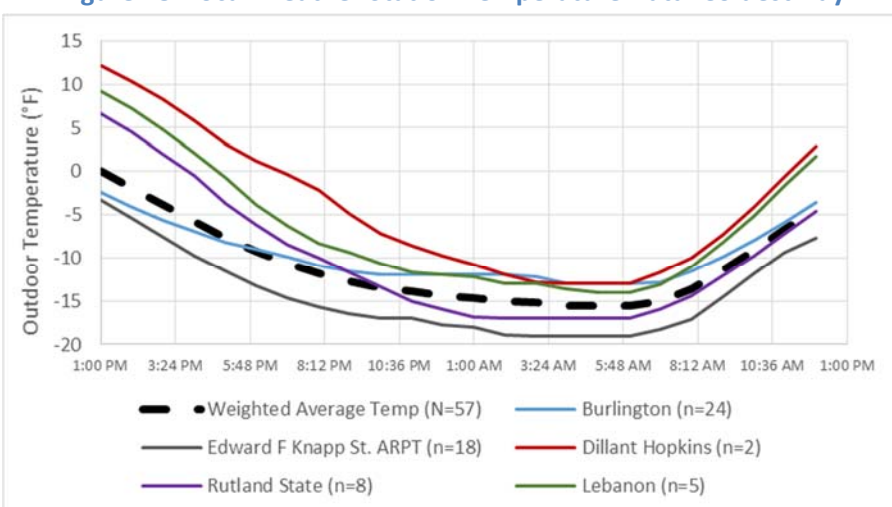
$$kWh_{HEAT} = \sum_{i=T_L}^{T_H} (kWh_{METERED}) * \frac{Hours_{2008-2017}}{Hours_{ACTUAL}}$$

To calculate annual, weather-normalized kWh consumption for a ccHP for each cooling season from 2008 through 2016:

$$kWh_{Cool} = \sum_{i=T_L}^{T_H} (kWh_{METERED}) * \frac{Hours_{2008-2016}}{Hours_{ACTUAL}}$$

Cadmus determined the closest local weather station for each site. Although we metered outdoor temperature at each home, we required local weather station data to normalize energy consumption to historic actual hourly data from the same weather station. The metered sample spanned the state of Vermont, and we used five different TMY weather stations across the state. Figure 28 shows a snapshot of temperatures for the five different weather stations, with the quantity of ccHPs metered at each weather station. Generally, we developed site-specific normalized seasonal values (as in Figure 27). The example in Figure 14, however, uses a weighted average of the temperatures from the five weather stations. We used this method to display aggregate data of ccHP energy and power versus temperature for the charts and figures in this report.

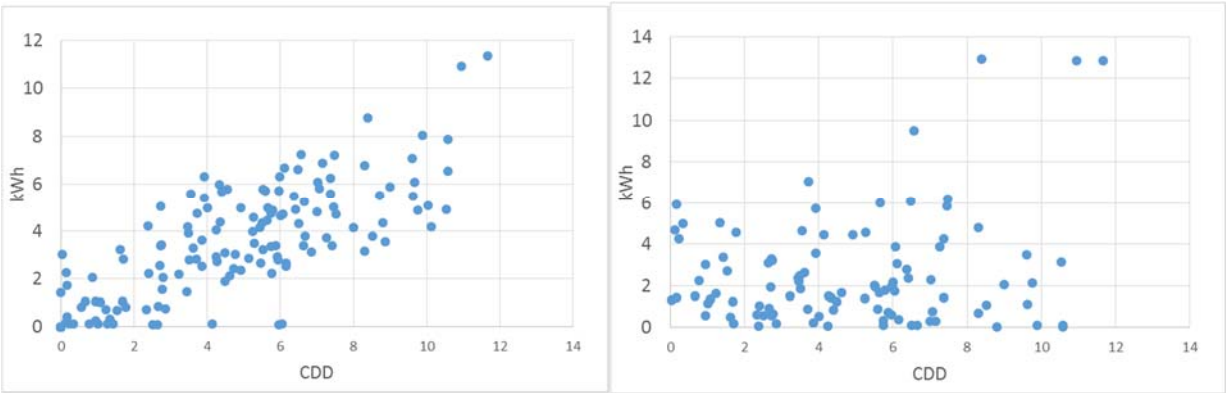
Figure 28. Local Weather Station Temperature Data: Coldest Day



The 2016 summer was approximately 19% warmer than a typical summer. Our final average normalization factor was 10%, not 19%, because ccHPs at many sites did not show a strong relationship

between ccHP energy consumption and temperature. Figure 29 shows the daily energy consumption vs daily cooling degree days for two different ccHPs. The energy consumption in the plot on the left exhibits a clear temperature-dependent correlation. The plot on the right does not appear to have strong temperature dependence.

Figure 29. Comparing Daily Energy Use Versus Daily Cooling Degree Days



For ccHPs that showed strong energy signatures, we followed the bin temperature method described above to normalize the energy consumed. For ccHPs that did not show temperature dependence (e.g., the plot on the right in Figure 29), we did not adjust the metered consumption.

Cadmus did not use single 8,760-hour TMY3 data to normalize consumption. Instead, we modeled energy consumption for each ccHP for each year. Figure 30 shows the average annual energy consumption for each ccHP. Average annual consumption (146 kWh) is about 10% higher than the TMY estimate.

Figure 30. Annual Average Cooling Consumption

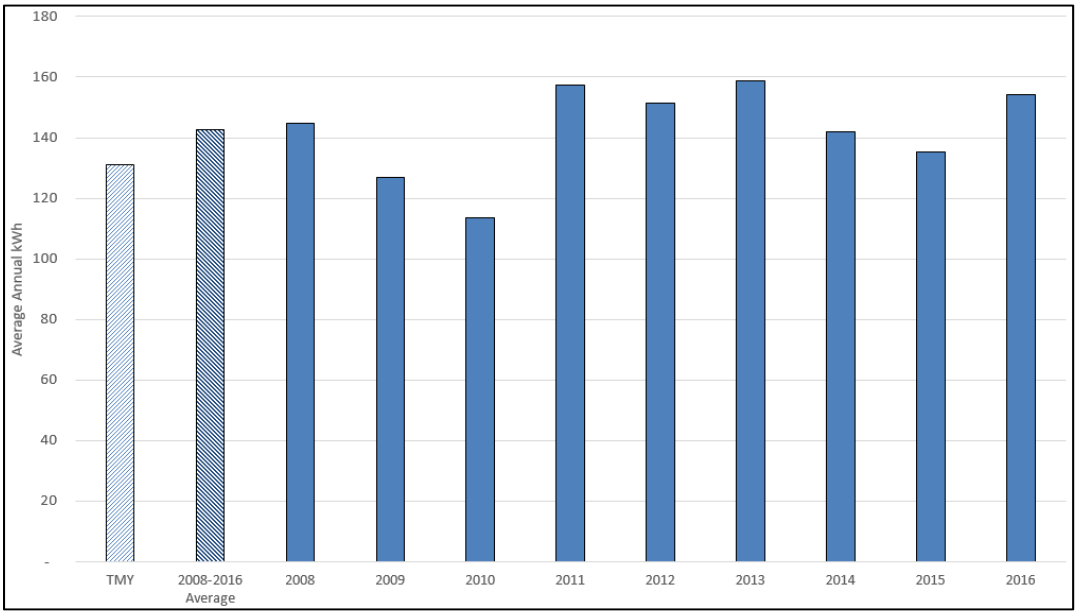


Figure 31 compares annualized results for each ccHP using meter data from the 2016 winter and 2017 winter (each ccHP is modeled/annualized twice). Although variance in the data occurs, on average, the meter data from the two winters produces very similar results.

Figure 31. Comparing Annualized Energy Consumption of Cold Climate Heat Pumps: Two Models

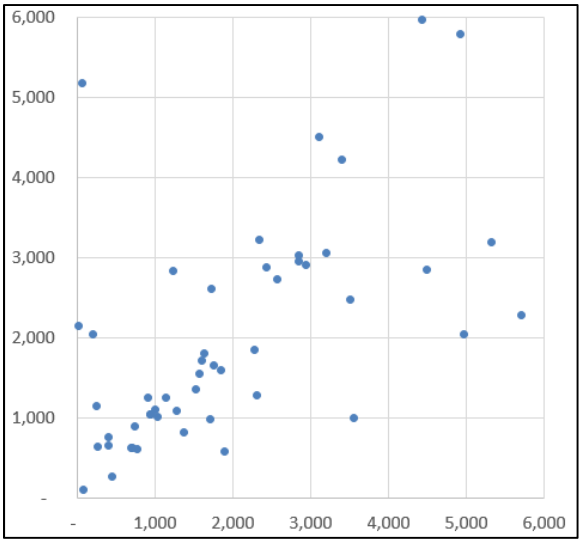
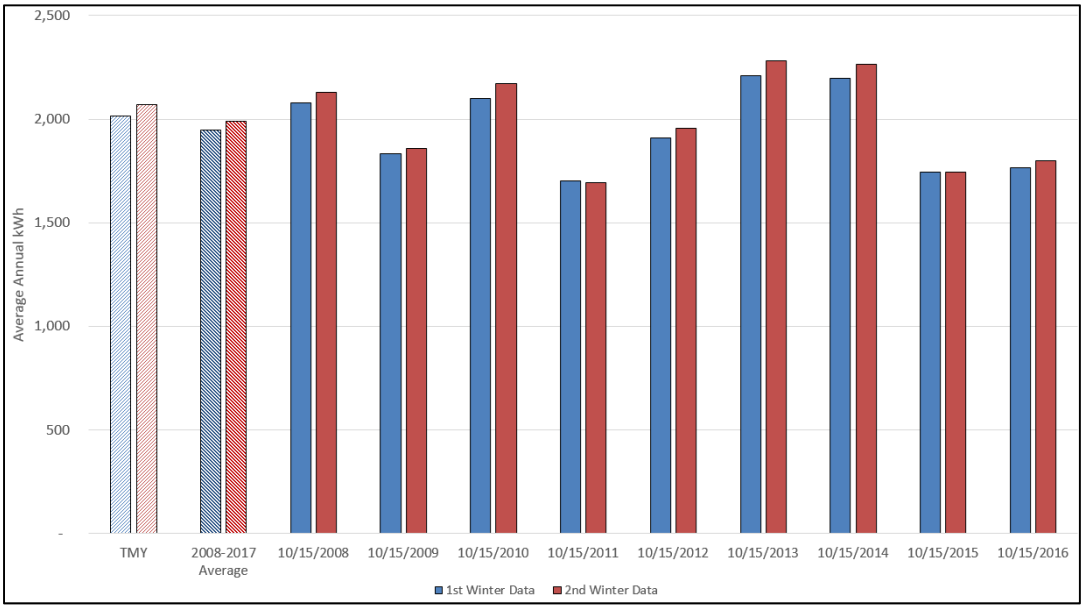


Figure 32 shows the average annual energy consumption for each ccHP for each heating season since 2008. We modeled heating consumption for each site and each winter separately. Figure 32 shows the first winter and second winter data sets produce very similar results. Overall, the average annual consumption (2,085 kWh) is about 4% less than the TMY estimate.

Figure 32. Annual Average Heating Consumption

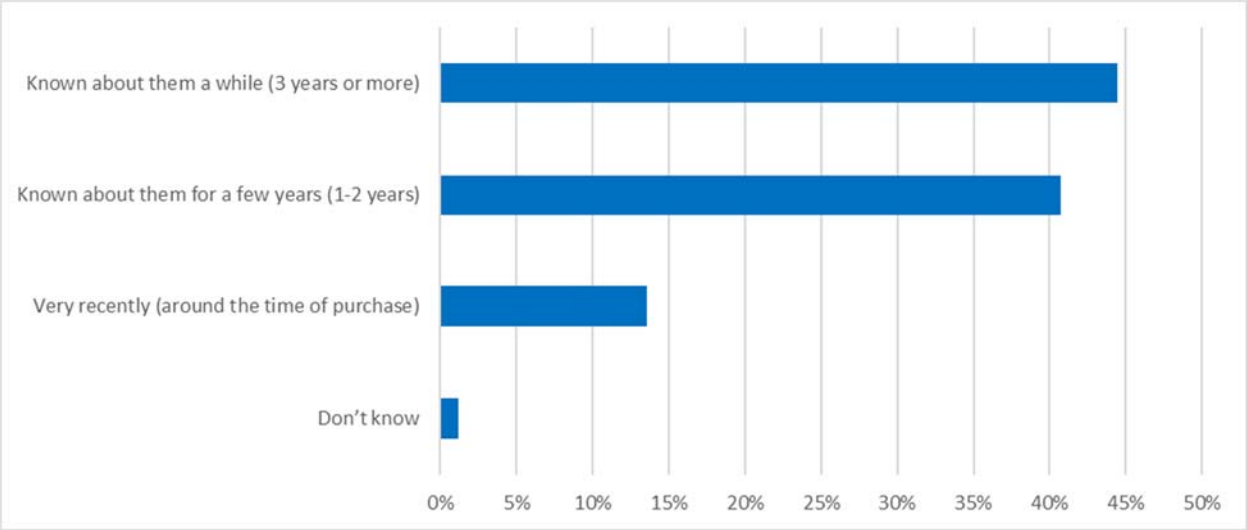


Appendix B. Survey Responses

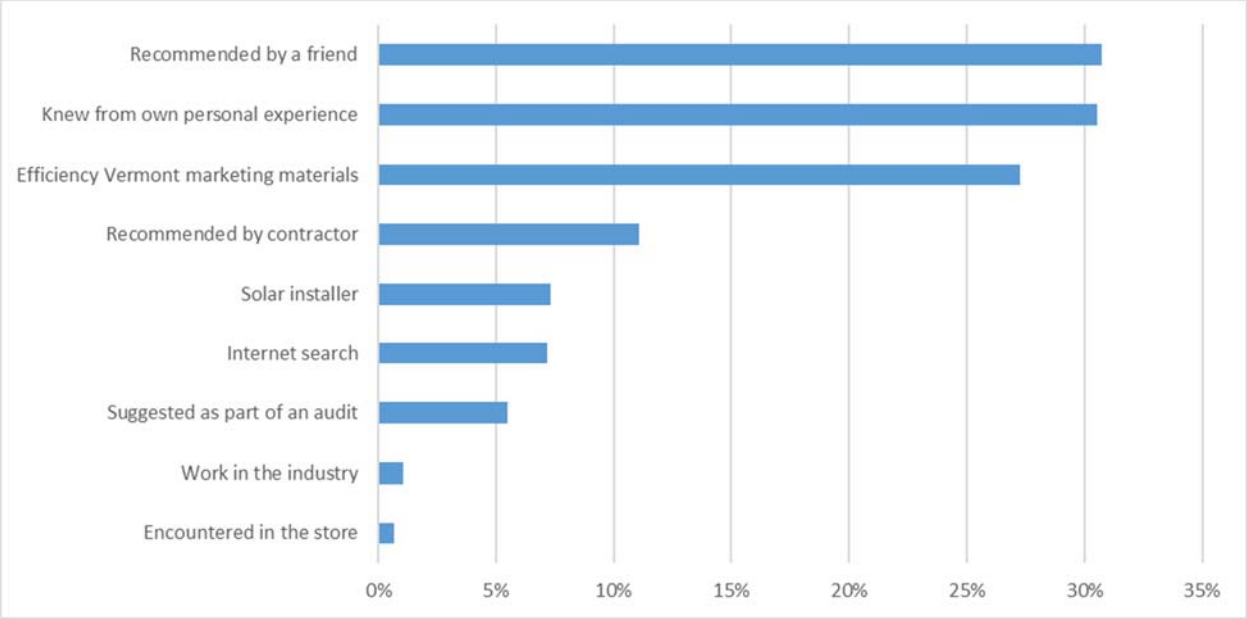
In July 2017, Cadmus conducted an online survey of homeowners who installed a ccHP in 2016 and had used it for at least one heating and cooling season. In total, Cadmus surveyed 135 homeowners (with 94 homeowners completing the online survey and 41 completing the in-person survey).

Motivation to Purchase

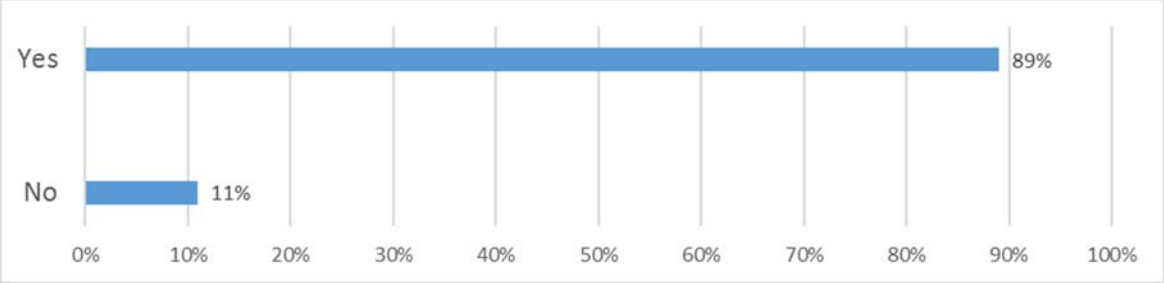
Although mini-split heat pump systems have been around awhile, many people are unfamiliar with them. When did you first learn about mini-split heat pumps?



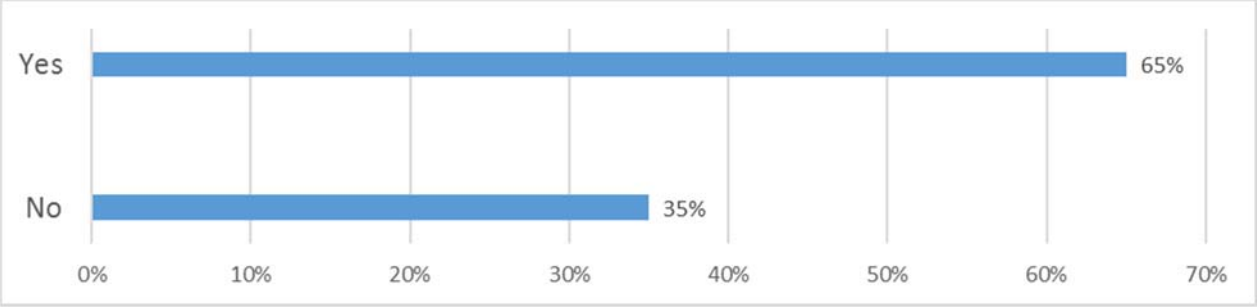
How did you learn about mini-split heat pumps?



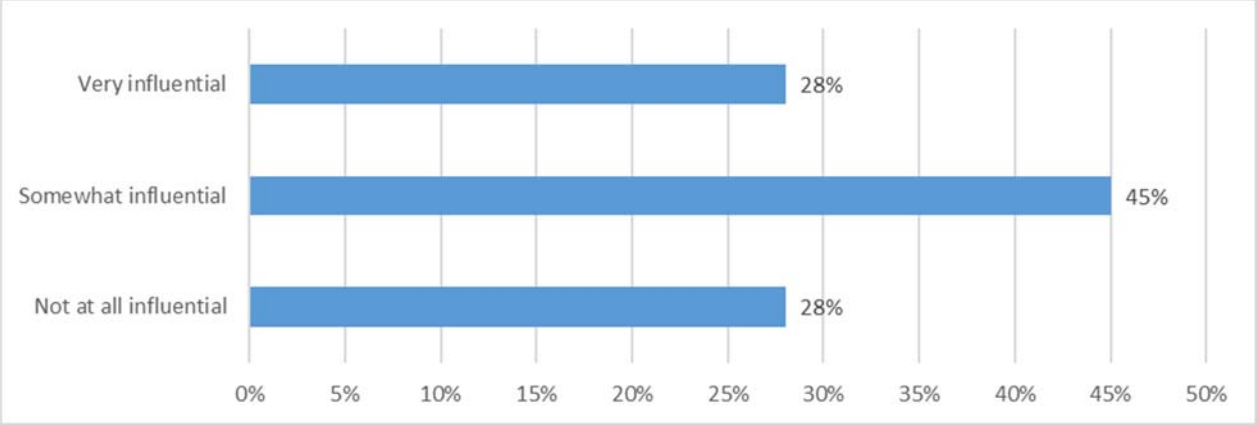
Are you aware that Efficiency Vermont provided a discount (like an instant rebate) for the purchase of your heat pump(s)?



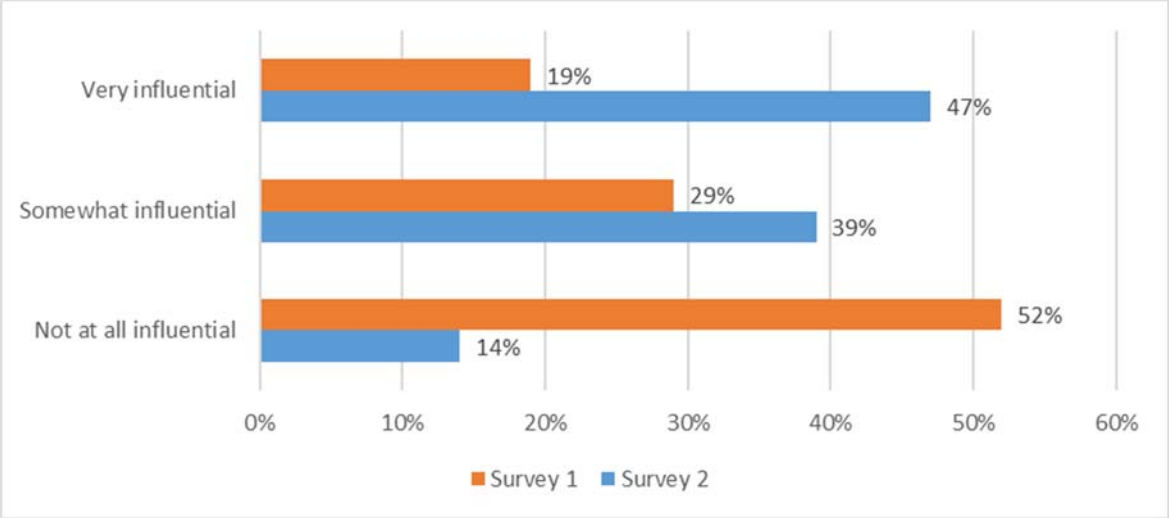
Did you have specific plans to install a mini-split heat pump before learning about any discounts offered in Vermont?



How influential was the rebate in your decision to install a mini-split heat pump?

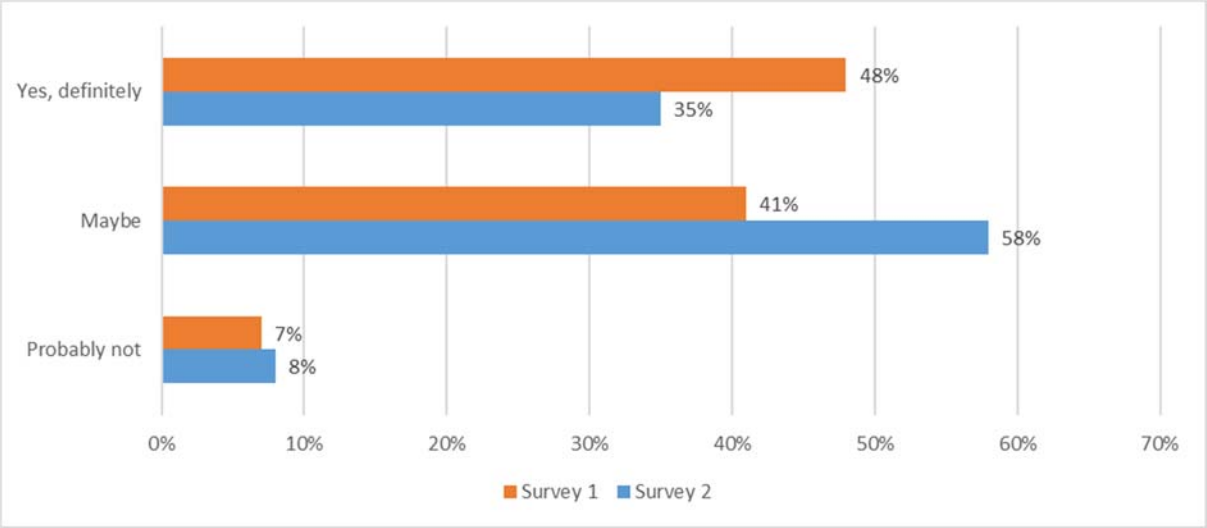


How influential was your HVAC contractor in your decision to install a mini-split heat pump?

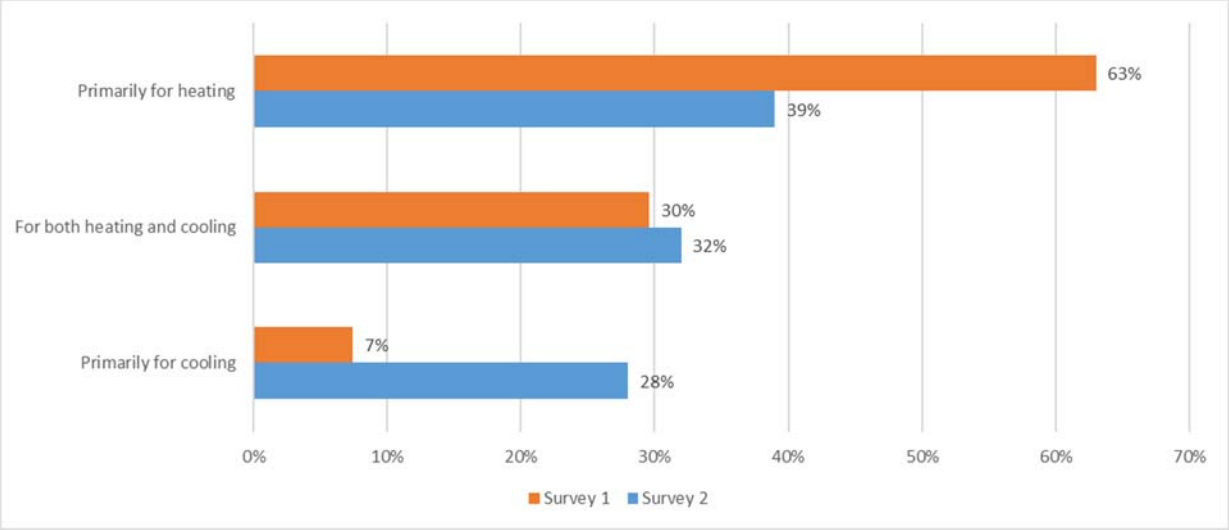


We chose to show survey results separately because there was such a large change between the first and second survey in response to this question. More than half of the first survey homeowners claimed that their HVAC contractor was not at all influential in their decision to install a ccHP, although only 14% of the respondents of the survey made the same claim.

If your contractor was not influential and/or a discount was not available, do you think you would have installed the exact same cold climate heat pump?

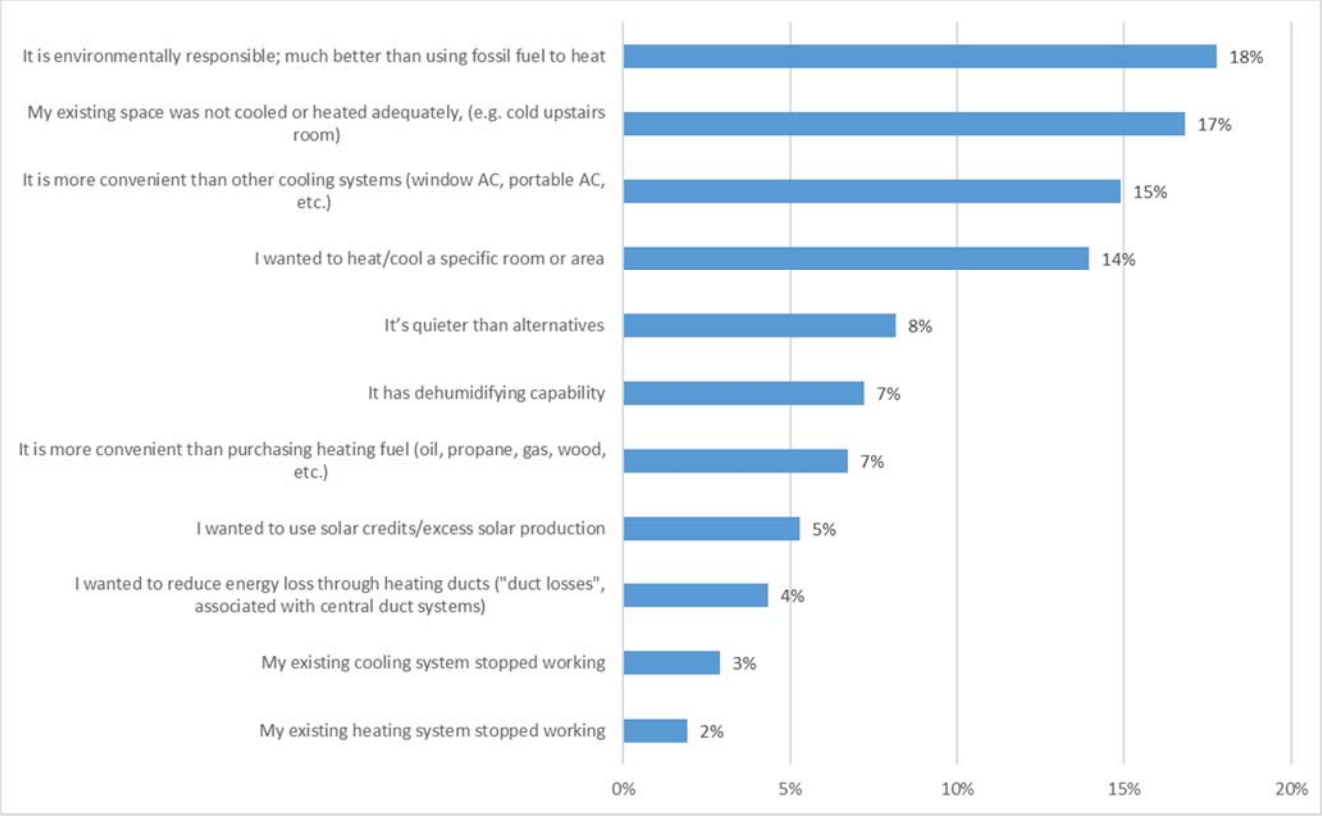


Did you purchase the mini-split primarily for heating, primarily for cooling, or for both heating and cooling?



Note: The first and second surveys asked this question differently, so responses were combined for direct comparison. From the online survey (Survey 2), 2% of respondents said they purchased the ccHP exclusively for cooling use, and 7% of respondents said they purchased solely for heating.

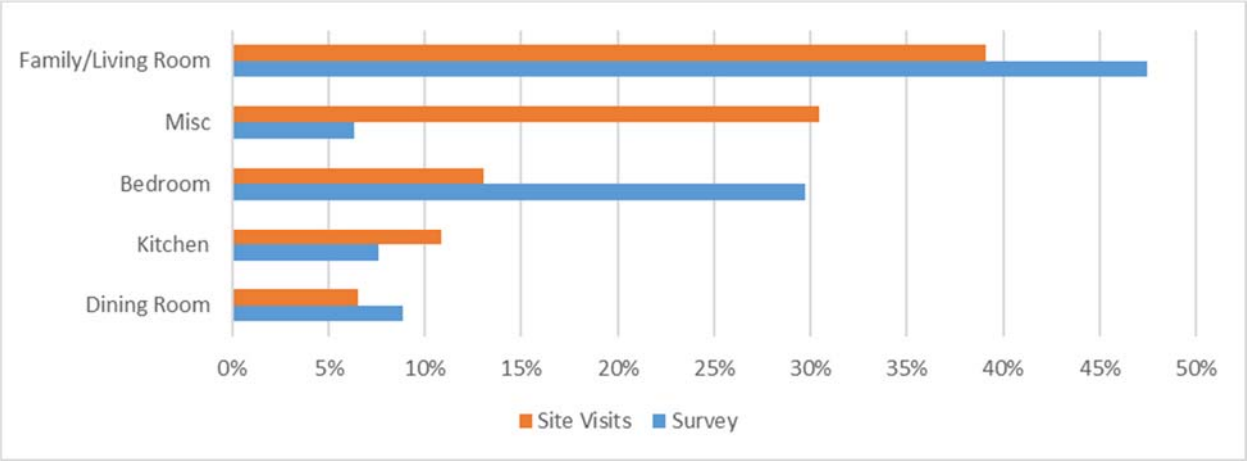
Which of the following best describes your motivation for purchasing your mini-split heat pump(s)?



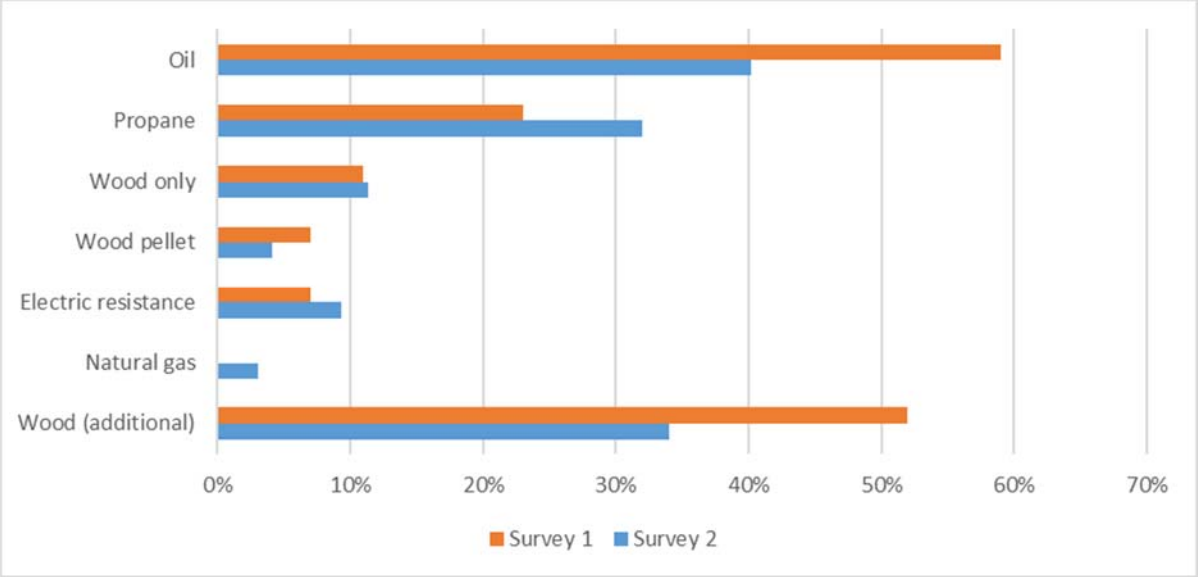
Note: This question allowed multiple responses, so each response (Most Important or Very Important) is weighted based on the number of responses offered. Nineteen of the 94 respondents who completed the survey offered other reasons for purchasing a ccHP, 11 of whom said the most important reason was that it made sense to use electric heat because of excess solar production. If Cadmus had included this option as a response category, more respondents may have chosen this reason.

Heating-Specific Information

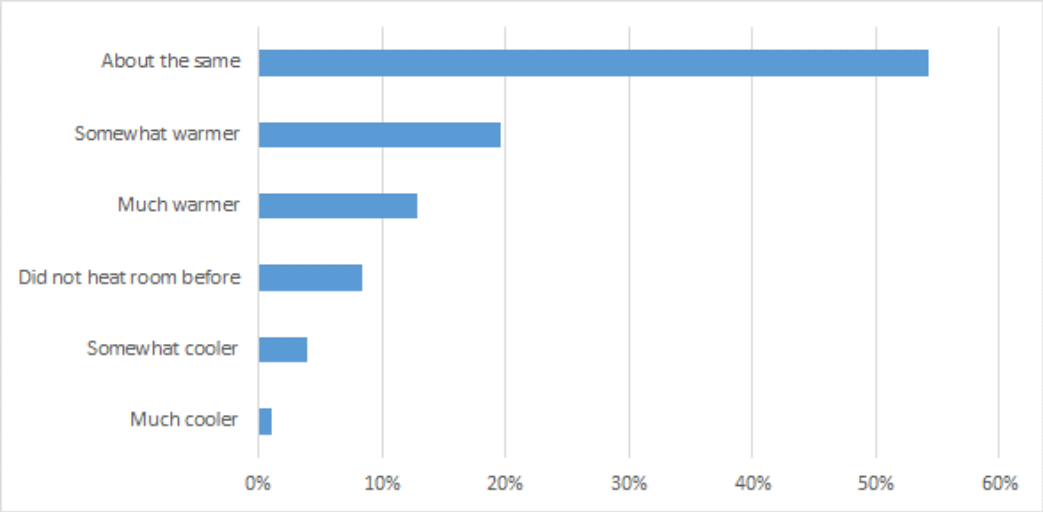
Where is each indoor ccHP located?



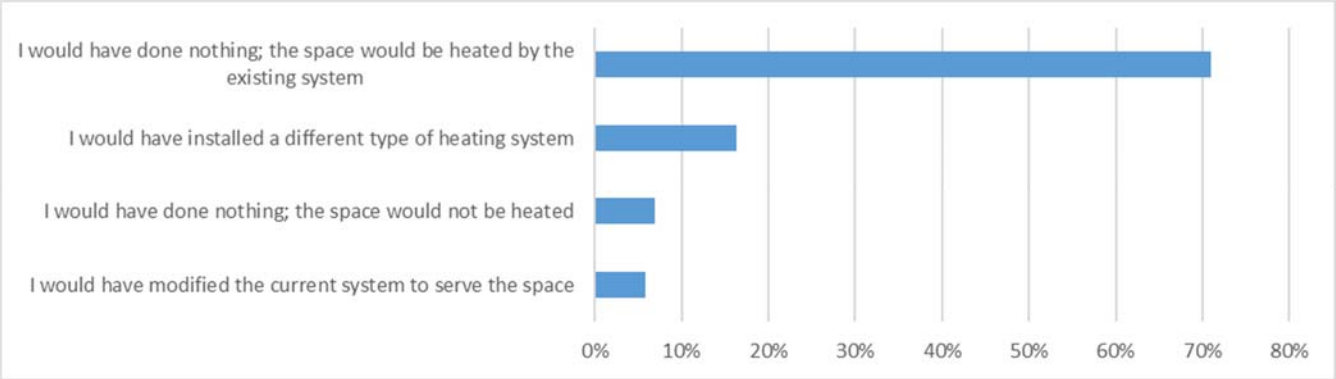
Heating fuel type of each alternate heating system:



Thinking back to the way you heated the room before you installed the mini-split, would you say you control the temperature differently now?



If ductless mini-split heat pump technology was not an option for you, what would you have done to heat these rooms?

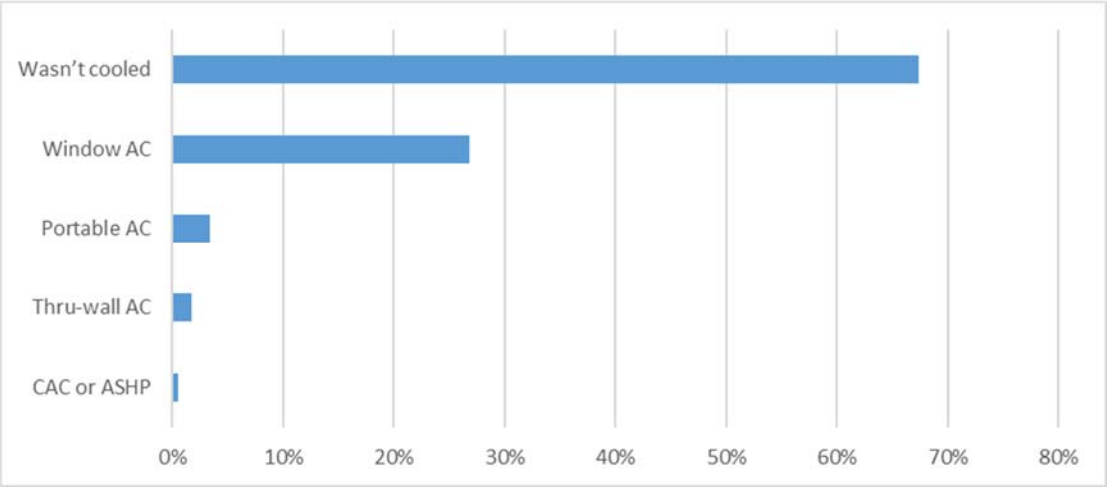


Some 91% of respondents made no physical change to the existing heating system after installing the ccHP. The systems replaced or removed include these:

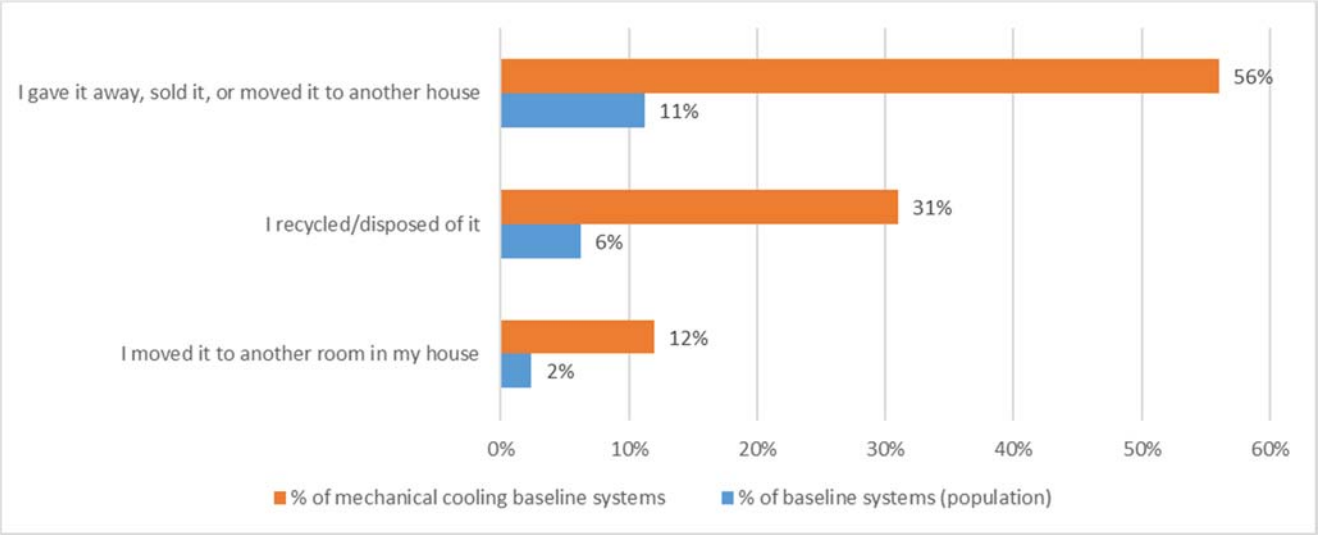
- Wood stove (4%)
- Electric baseboard heating (3%)
- Forced air furnace (2%)

Cooling-Specific Information

For each room having a mini-split heat pump, how did you cool the room before you installed the mini-split?

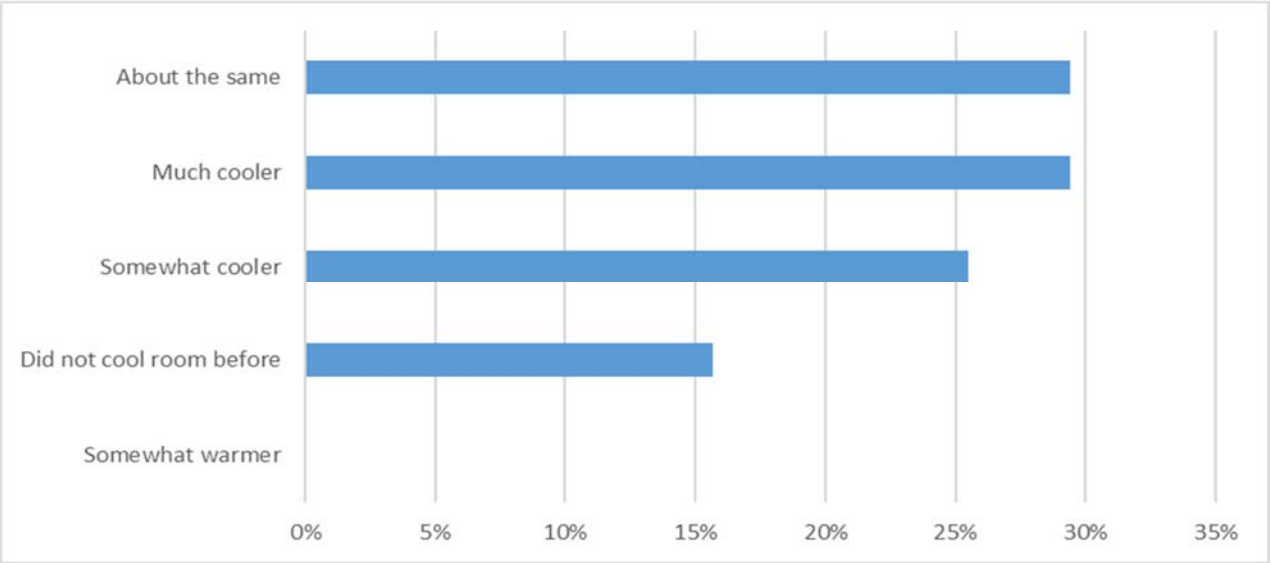


What did you do with the previous cooling system that the ccHP replaced (based on respondents who had window, portable, or thru-wall air conditioners)?

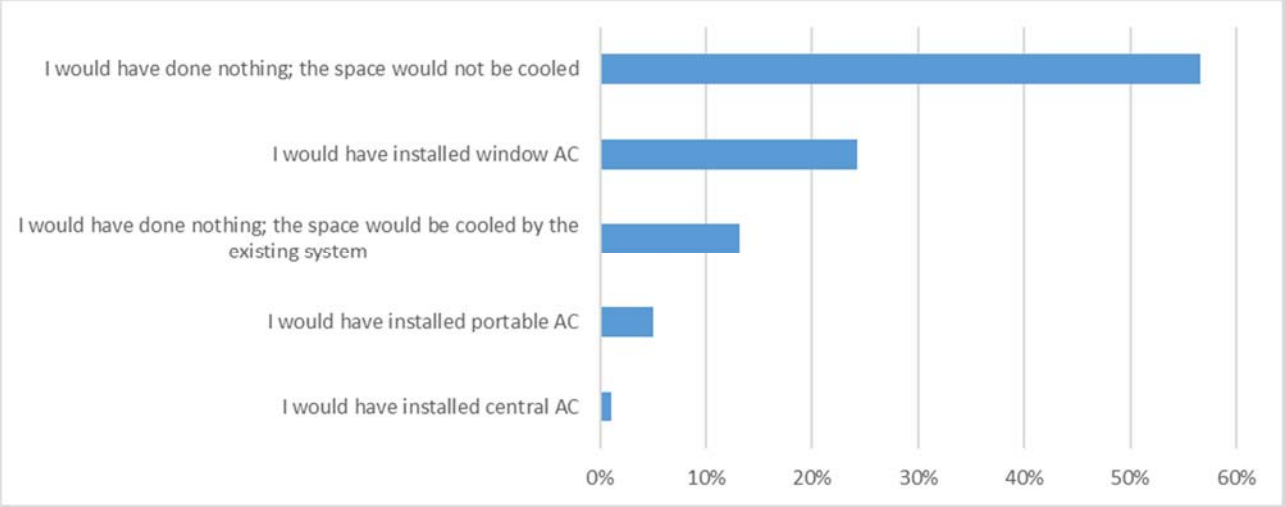


The blue bars in the chart above show the proportion of the population of ccHPs replacing a mechanical cooling system. Per homeowner responses, 6% of the previous systems are no longer on the electric grid; 13% of the previous systems may still be operating, but in a different space.

Thinking back to the way you cooled the room before you installed the mini-split, would you say you control the temperature differently now?



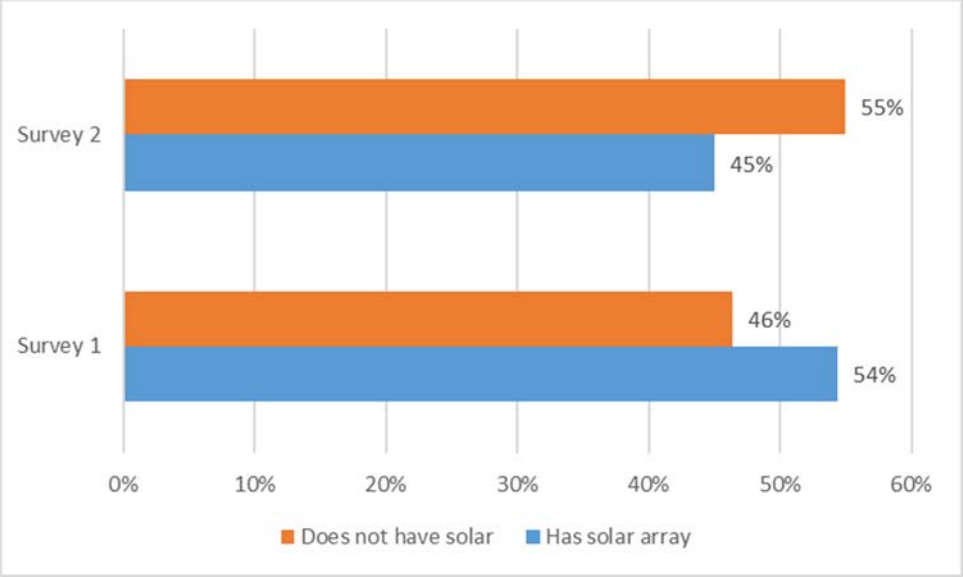
If ductless mini-split heat pump technology was not an option for you, what would you have done to cool these rooms?



According to the chart above, more than 50% of homeowners would not have installed a ductless mini-split heat pump. Approximately 24% of the population of homeowners in this group also said they now keep the room much cooler than they did before. Some 13% of the population said their HVAC contractor or the incentive were very influential in their decision to install the ccHP. This information indicates that 13% of ccHP homeowners may cause load growth (negative kWh impact) during the cooling season.

Additional Information Collected

Do you have solar panels?



Fossil Fuel Heating Data Collection

Cadmus worked with homeowners to collect yearly fuel consumption data. Some homeowners provided invoices from their distributor (see Figure 33 and Figure 34).

Figure 33. Fuel Summary Example Spreadsheet – From Distributor

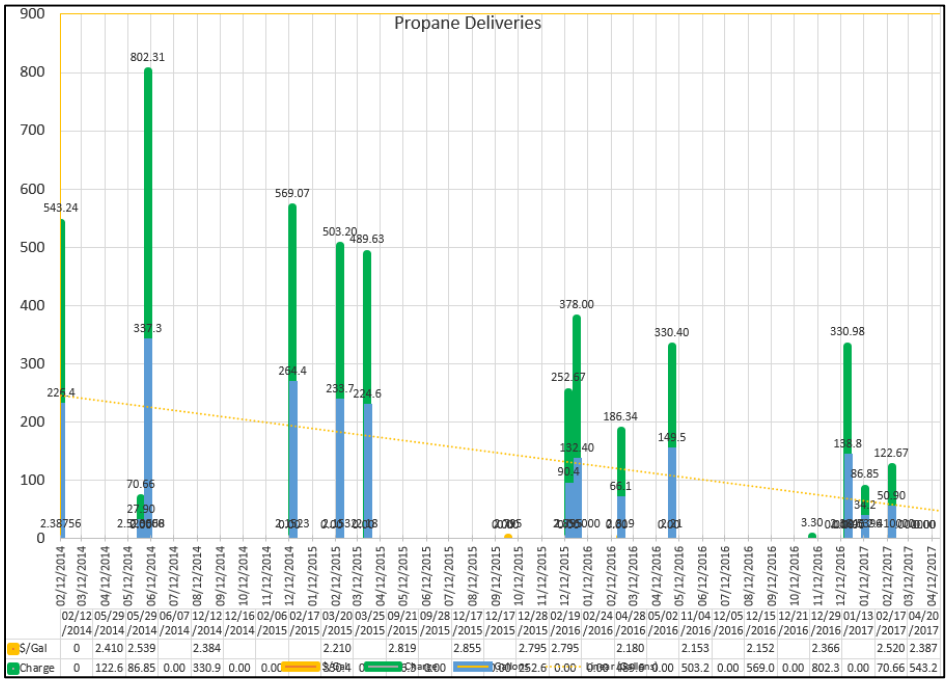
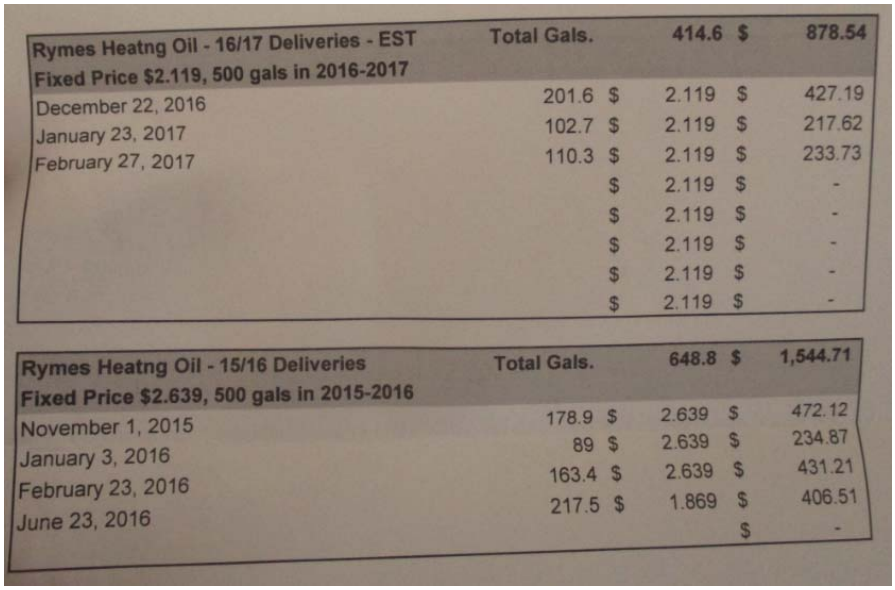


Figure 34. Fuel Summary Example – From Distributor



Rymes Heatng Oil - 16/17 Deliveries - EST	**Total Gals.**	**414.6**	**$**	**878.54**
Fixed Price $2.119, 500 gals in 2016-2017				
December 22, 2016	201.6 $	2.119	$	427.19
January 23, 2017	102.7 $	2.119	$	217.62
February 27, 2017	110.3 $	2.119	$	233.73
	$	2.119	$	-
	$	2.119	$	-
	$	2.119	$	-
	$	2.119	$	-
	$	2.119	$	-
Rymes Heatng Oil - 15/16 Deliveries	**Total Gals.**	**648.8**	**$**	**1,544.71**
Fixed Price $2.639, 500 gals in 2015-2016				
November 1, 2015	178.9 $	2.639	$	472.12
January 3, 2016	89 $	2.639	$	234.87
February 23, 2016	163.4 $	2.639	$	431.21
June 23, 2016	217.5 $	1.869	$	406.51
			$	-

Some homeowners diligently recorded fuel consumption by month (see Figure 35) or by year (Figure 36).

Figure 35. Fuel Summary Example – Recorded by Homeowner

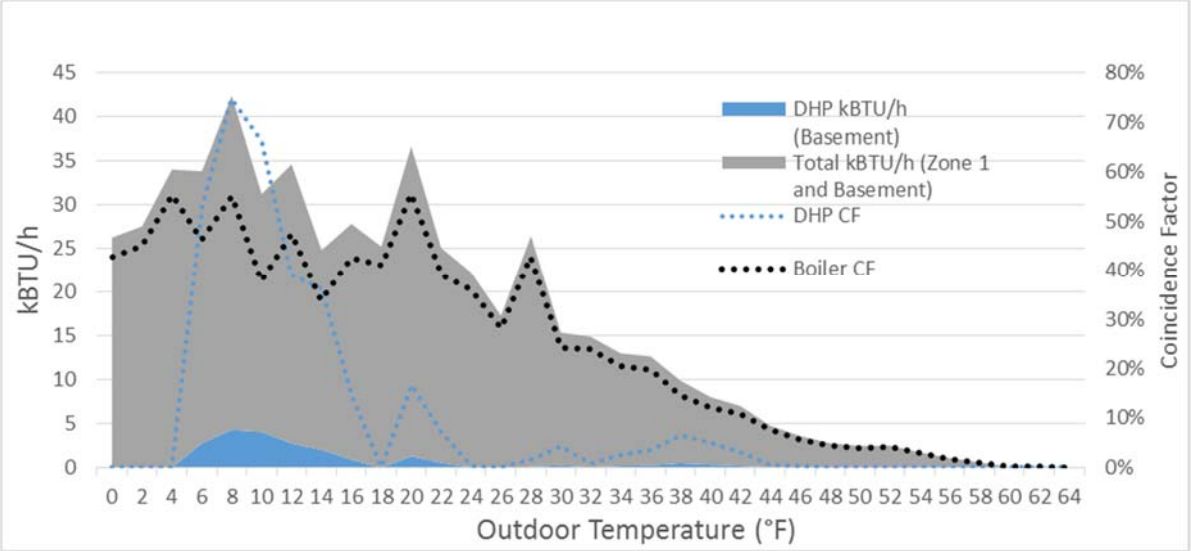
		Aug-Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul		Total
12-13	Av Temp					22	19	29						
	Gal	55	54	104	114	216	140	127	125	76				1011
13-14	Av Temp					23	14	19	39	53	62	68		
	Gal		60	89	165	168	275	130	106	66				1059
14-15	Av Temp	59	53	37	30	20	9	21	39	56	62	67		
	Gal	52		87	251	150	172	268	115			59		1154
								Began HP						
15-16	Av Temp	66	50	44										
	Gal			115	108	216	108	95		91				733
16-17	Av Temp													
	Gal	59	66	99	117	143	100	207						791

Figure 36. Fuel Summary Example – Recorded by Homeowner

	April-March	Oil Gals	Oil $$$	Propane Gals	Propane $$$	Electricity KWH	Elect $$$	Total $$$
	12/13	1,076	$ 4,002	531	$ 1,443		$ 1,000	$ 6,445
	13/14	1,060	$ 3,896	608	$ 1,800	4,581	$ 1,000	$ 6,696
Heat pumps Jan 2015	14/15	1,376	$ 4,939	420	$ 1,152	6,060	$ 1,313	$ 7,404
	15/16	834	$ 1,613	387	$ 809	6,286	$ 1,124	$ 3,546
HP Hot water March 2016	16/17	548	$ 1,343	303	$ 794	8,679	$ 1,539	$ 3,676
		4,894	$ 15,793	2249	$ 5,998	25,606	$ 5,976	$ 27,767

For some homes, Cadmus was able to take the total annual fuel consumption and use actual runtime data to estimate the capacity provided by both the ccHP and the alternate heating system. Figure 37 shows an example. Cadmus calculated the MMBtu savings for the boiler system based on the heat provided by the ccHP. If the ccHP did actually offset heat that would have otherwise been supplied by the boiler, the equivalent fuel savings was 55 gallons of oil.

Figure 37. Metering Cold Climate Heat Pump and Alternate Heating System



Ultimately, Cadmus did not determine the fuel impacts for each individual ccHP. Instead we assumed that the heat provided by the ccHP offset an equivalent amount of heat that otherwise would have been offset by the heating system on an aggregate level. We made this assumption, and aggregated all fuel consumption data, for the following reasons:

- There were few instances that we could isolate the heating capacity provided by the other heating system to the space with the ccHP. Most spaces were open to adjacent spaces, and many had a third heat source (e.g., wood stove).
- To produce reliable fuel delivery estimates at an individual home, a large sample of fuel delivery data is required.
- Other factors may have impacted homeowner fuel use. More than half of the homeowners made some type of building shell improvement during the data collection period.

We used fuel consumption estimates and determined the fuel proportion values in Table 16.

Table 16. Summary of Fuel Offset by Cold Climate Heat Pump

Type	Btu Proportion: Metering Study	TRM Assumption
Electric Resistance	7%	0%
Propane	25%	15%
Oil	46%	51%
Wood	22%	12%
Natural Gas	0%	21%

Note: When homeowners claimed they used the ccHP to offset electric resistance heat, we assumed full conversion (i.e., electric resistance baseboard heat would not be used) because all homes with electric baseboard heat also had a wood stove or other heat source that could provide heat to the home, and because homeowners stated their intention to avoid using all electric baseboard heat.

The results in Table 16, based only on the homes in the metering study, should not supersede the assumption in the TRM. These results apply to the homes in the study. The number of homes was relatively small; consequently, the proportions in Table 16 are not statistically valid at the 90% confidence interval.

Appendix C. Metering Equipment

Cadmus field technicians installed data loggers that monitored the ccHP systems and other heating equipment for the duration of the 2015/2016 heating season. In May 2016, Cadmus technicians visited each homeowner site to download data from data loggers.

On-Site Metering and Logger Installations

The primary purpose of metering is to determine how ccHPs operate and perform in the state of Vermont. Surveys and manufacturers' data provide a general boundary for savings and savings opportunities, but metering provides actual energy consumption and usage-evaluated savings, as well as insights into user tendencies.

For this study, Cadmus designed two options for on-site metering:

1. The **advanced** metering option is a comprehensive approach to estimate system power, load, and performance throughout the heating season. Described in below, the metering setup includes data loggers on the outdoor unit, indoor unit, indoor spaces, and other heating systems. We measured the airflow and amperage of each indoor unit's fan speed to establish the correlation of fan amperage to fan speed. Then we metered amperage and used the correlated fan speed (and other data) to estimate the amount of heat delivered.
2. The **power-only** metering option is an abbreviated approach that does not include metering at the indoor unit. The meters recorded energy consumption, but not heating or cooling capacity. To estimate the heating or cooling capacity (performance), Cadmus used data results from the advanced metering option of similar ccHPs. This option is especially useful when time on the site is limited, when metering a second or third ccHP installed in a home, and/or when indoor unit access is restricted (either by homeowner choice or by barriers that affect installation of the indoor unit sensors).

Data from both the **advanced** and **power-only** metering options contributed to all the research. Table 17 shows a summary of data collected and the loggers associated with each metering option.

Table 17. On-Site Data Collection Points

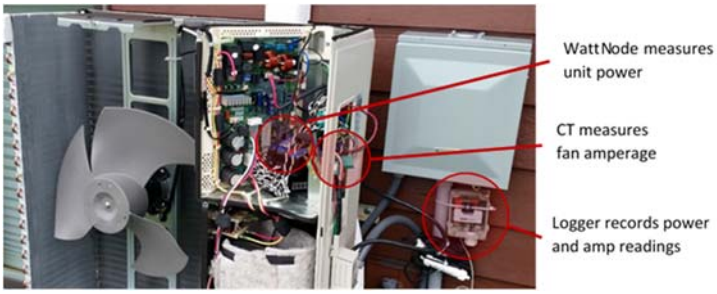
System	Parameter	Measurement Equipment	Interval	Advanced	Power-Only
ccHP Outdoor Unit	Energy consumption	WattNode, 20A current transducers + pulse adaptor	2-minute	✓	✓
Outdoor Weather	Temperature and relative humidity at outdoor unit	Temperature/relative humidity sensor with solar shield	2-minute	✓	✓
ccHP Indoor Unit (each)*	Fan amperage	1A current transducers	2-minute	✓	
	Supply air temperature and relative humidity	Onset UX100-023	2-minute	✓	
	Return air temperature and relative humidity	Onset UX100	2-minute	✓	
	Spot airflow measurements	Flow hood: Alnor Balometer EBT731	Spot measurement	✓	
	Indoor space temperature (at thermostat)	Onset U12	2-minute	✓	✓
Other Heating Equipment	Gas valve runtime	Onset motor logger	Instantaneous	✓	✓
	Boiler pump or zone valve runtime	Hawkeye CT with logger	Instantaneous	✓	✓
	Wood Stove	Onset temperature logger		✓	✓

* Outdoor units are either single-or multi-head systems; Cadmus metered all the indoor heads under the "advanced" metering option.

Outdoor Unit and Weather (Advanced and Power-Only Methods)

To log total ccHP system power, we metered the energy consumption of the whole ccHP system as well as the temperature and humidity near the outdoor unit (see Figure 38).

Figure 38. Example of Metering Equipment on Outdoor Unit



Indoor Unit and Space Conditions (Advanced Method Only)

For the advanced metering method, technicians measured airflow and installed temperature data loggers to monitor system capacity throughout the study period. Combined with the total system power data, these indoor measurements provide an estimate of the actual efficiency of the ccHP system.[19] To log capacity, Cadmus conducted these activities:

- Performed spot airflow measurements of the indoor unit at each fan speed
- Metered indoor unit fan amperage to correlate amps to airflow
- Metered the supply air temperature and humidity of the indoor unit
- Metered the return air temperature and humidity of the indoor unit

Figure 39 shows an example of metering equipment on the indoor unit.

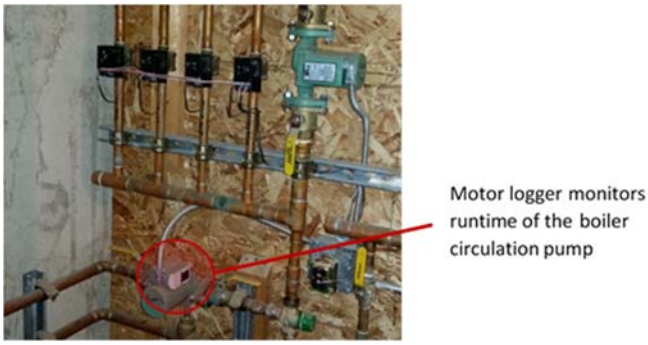
Figure 39. Example of Metering Equipment on Indoor Unit

[19] Efficiency is the ratio of heating capacity provided to total system energy consumption.

Other Heating Equipment

To understand how the ccHPs interact with alternate heating system(s), Cadmus installed meters that record the runtime with an on/off event logger (see Figure 40) and installed temperature loggers near a heating system (e.g., wood stove). Typically, a runtime logger records the amount of time the gas valve is open. If the heating system has a common single-stage burner with known heating capacity, the runtime provides a precise estimate of heating fuel consumption.

Figure 40. Example of Metering Equipment on Boiler



Appendix D. Other Heat Pump Research Studies

Organizations across the country are examining the use of ductless heat pumps (DHPs) to improve energy efficiency and reduce customer costs for heating and cooling. The following list of research studies is not comprehensive. In addition to the EEPS Cycle I metering study, these are examples of research that is complete or ongoing.

Ductless Mini-Split Heat Pump Assessment (Con Edison, 2015-present)
Cadmus is conducting an ongoing DHP study with Con Edison. The objectives of the study are to conduct impact and process evaluations using billing analysis, and phone and on-site interviews, and metering. From one year of metering 60 ductless heat pumps, we will develop heating and cooling load shapes, determine an in-field COP to compare with manufacturers' specifications, assess installation and equipment sizing quality, and estimate the impact of DHPs on electric use and displaced fuels. Cadmus will use the interviews to understand how residents use this technology in their homes, gauge perceived benefits of homeowners, and determine appropriate types of homes to implement DHPs.

Mini-Split Heat Pump Metering Study (Massachusetts Electric Program Administrators, 2014-present)
Cadmus completed a DHP study in the State of Massachusetts at 135 homes. All our research objectives, methods, and protocols were thoroughly scrutinized by numerous industry experts. During the site visits, we conducted in-depth homeowner interviews, with a focus on program participation and collecting information to determine the most appropriate baseline system separately for heating and for cooling. Cadmus installed sensors and energy meters on heat pumps that record energy consumption at one-minute intervals. In addition to heat pump metering equipment, we installed meters on all heating and cooling systems such as boilers, furnaces, and CAC systems.

All-Electric Home Metering Study (Ameren Illinois, 2014-2015)
From June 2014 through May 2015, Cadmus metered the total energy consumption and calculated savings for 40 multi-head DHPs installed in all-electric multifamily homes. We incorporated the results of the study into the 2015 Statewide Illinois Technical Reference Manual.

Residential Heating, Water Heating, and Cooling Equipment Evaluation: Net-to-Gross, Market Effects, and Equipment Replacement Timing (The Electric and Gas Program Administrators of Massachusetts, 2012)

Cadmus focused this study on estimating net-to-gross (NTG) values for multiple high-efficiency heating equipment measures, including DHPs. Key findings include:

- DHP spillover averaged 7%, while freeridership averaged 45%, giving an NTG percentage of 62%
- The DHP NTG value was lower than all other measures, likely due to the lack of incentives
- Early replacement rates for DHPs are essentially zero

The report is available online: http://www.rieermc.ri.gov/documents/2013%20Evaluation%20Studies/CADMUS_2013_HEHE_Cool%20Smart_NTG_Evaluation_Report.pdf

Ductless Heat Pump Meta Study (NEEP, 2014)

For this study, Energy Futures Group and Energy & Resource Solutions aggregated the results of 40 studies and multiple industry interviews to examine the performance and market potential of DHPs in the Pacific Northwest, Mid-Atlantic, and New England. They analyzed multiple DHP performance measures, including energy savings and hourly demand load shape. Key findings and recommendations included:

- Heating energy savings varied significantly by location and use, ranging from 1,200 kWh to 4,500 kWh per year per ton
- Cooling energy savings were reported as "modest," which is expected based on the regions of study
- Because DHPs do not typically operate at their rated output power, predictions of peak impact should not be extrapolated from these values
- DHP use is expected to grow along with the demand for heating alternatives

The report is available online: http://www.neep.org/file/2123/download?token=UTQseZkX

Ductless Mini Pilot Study (Massachusetts Program Administrators, 2008)

For this study, KEMA Inc. evaluated the energy and demand impacts of a pilot program that implemented DHPs at 95 sites in Connecticut and 50 sites in Massachusetts. The majority of units were Mitsubishi Mr. Slim. The study included power metering at 22 Connecticut sites and 18 Massachusetts

sites. KEMA estimated energy savings and demand reduction using data recorded for electric heat and billing data. Key findings include:

- Energy savings were highest for customers replacing electric heat sources
- Demand reduction was highest for customers without supplemental heat

The report is available online: http://www.energizect.com/sites/default/files/Final%20DSHP%20Evaluation%20Report%20ver3%20%282%29.doc

Ductless Mini-Split Heat Pump Comfort Evaluation (U.S. Department of Energy and National Renewable Energy Laboratory, 2013)
For this study, NREL investigated the spatial distribution of temperature and relative humidity in two households in Austin where DHPs were installed and how these distributions effected comfort.

The report is available online: http://www.nrel.gov/docs/fy13osti/56710.pdf

Ductless Heat Pump Impact and Process Evaluation: Lab-Testing Report (Northwest Energy Efficiency Alliance [NEEA], 2011)
For this study, Ecotope, Inc., supported by Research Into Action, Inc., Stellar Processes, and Herrick Labs, analyzed the performance of DHPs in a lab and in the field. The lab testing was focused on the units' efficiencies and performance at low temperatures (down to -5°F) and revealed that the measured potential for energy savings are consistent with manufacturers' claimed values and that the units work well in the cold. The team compared COP data from the lab and field and show consistent trends, and found that current values for HSPF and SEER are inaccurate. They recommended that DHPs are promising options for energy savings when installed as a heating system retrofit or in new buildings.

The report is available online: https://neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation-lab-testing-report.pdf?sfvrsn=18

Ductless Heat Pump Impact and Process Evaluation: Billing Analysis Report (NEEA, 2013)
For this study, Ecotope, Inc., supported by Research Into Action, Inc., and Stellar Processes, analyzed billing data collected from 3,621 homes in the Pacific Northwest as part of a 2008 DHP pilot program to project net energy savings across the region. They determined that take-back from supplemental fuels has a significant effect on savings, reducing them by about one-third of the values found through metering. This effect is most pronounced in the coldest regions involved in the study where wood and propane were commonly found to supply additional heat.

The report is available online: https://neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation--billing-analysis-report.pdf?sfvrsn=6

Ductless Heat Pump Impact and Process Evaluation: Field Metering Report (NEEA, 2012)
The study describes the findings from metering 95 homes in the Northwest that installed DHPs as part of a pilot program offered in 2008 and 2009. The objectives of the study were to describe total energy output by the equipment during heating and cooling periods, as well as determine the reduction in space heating and the equivalent energy savings. In an attempt to reduce the effects of take-back from supplemental heat, Ecotope, Inc., supported by Research Into Action, Inc., and Stellar Processes, selected sites for metering that had a strong, pre-installation electric heat signatures. They found that the occupants tended to set their thermostats slightly higher post installation, resulting in about a 10% reduction of net savings. Findings support that the DHP displacement model is successful in reducing energy usage in buildings heated with zonal electric resistance systems and achieves these savings with minimal capital investment.

The report is available online: http://neea.org/docs/reports/ductless-heat-pump-impact-process-evaluation-field-metering-report.pdf?sfvrsn=16

EM&V Forum: Primary Research –Ductless Heat Pumps (Northeast Energy Efficiency Partnerships, 2014)
For this study, Energy & Resource Solutions presents findings from primary research on the energy efficiency of DHPs in a residential, heating-dominant setting. They metered nine sites in New Hampshire from February to September of 2013. The primary goals of the study were to determine COP as a function of climate conditions, assess DHP performance at low temperatures, understand if customers' heating needs were met, and determine average load shape. The results revealed that DHPs significantly reduce energy usage and when compared with electric resistance heating systems saved an average of $832 per heating season. The equipment was also found to perform at temperatures as low as -18°F, although at a reduced output. The study cautions against using SEER and HSPF ratings when predicting savings because DHP performance varies drastically with climate conditions. Additionally, summer load shape was coincident with target peak periods.

The report is available online: http://www.neep.org/file/986/download?token=rdVhg7el

Integrated Ductless Heat Pump Analysis: Developing an Emerging Technology into a Regional Efficiency Resource (American Council for an Energy-Efficient Economy, 2012)
The study team estimates that in the Northwest there are 500,000 homes eligible for DHPs, representing the potential for 200 MW in savings. Following a 2009 DHP pilot project, this study includes lab analysis

of two DHP units, metering of 95 homes, 300 customer surveys, and billing analysis of all 3,899 participants. The sites selected for the project were single-family, site-built homes heated with zonal electric resistance systems where DHPs would serve as a displacement heat source. The primary goals of the study were to evaluate DHPs as an alternative to electric resistance heat in the Northwest and to estimate costs and savings associated with their use. Key findings included efficiencies being consistent with claimed values by manufacturers, strong DHP performance at low temperatures, and in field COPs being comparable with lab results.

The report is available online: http://aceee.org/files/proceedings/2012/data/papers/0193-000064.pdf

Long-Term Monitoring of Mini-Split DHP in the Northeast (National Renewable Energy Laboratory, 2014)

For a period of three years, the U.S. Department of Energy, Building Science Cooperation monitored eight houses in Massachusetts where DHPs had been installed. The study was focused on DHP performance, heat distribution, and the effect of leaving doors open or closed. DHPs were revealed to be a viable option as a single heat source because maximum power draw was never reached during the study period. The study reports that oversizing units is beneficial because maximum efficiency is achieved when DHPs are running well below their rated capacity. Homeowner behavior was also cited as an important factor in performance, and that best results are delivered when units operate at a constant setpoint rather than being turned on or off repeatedly.

The report is available online:
http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/monitoring-mini-split-ductless-heatpumps.pdf

Ductless Heat Pump Engineering Analysis: Single Family and Manufactured Homes with Electric Forced-Air Furnaces (Bonneville Power Administration, 2012)

For this study, Ecotope, Inc. analyzed DHPs in a displacement model with forced-air furnaces in single-family and manufactured homes. Homeowner behavior played an important role in the findings, and the use of DHPs as the primary heat source was found to be the most effective strategy. Key factors in reducing energy consumption were the increased efficiency of the heat pumps over the furnaces, reduction of duct losses, and focusing heating on central areas. The study estimated that energy usage is reduced by about 5,500 kWh per year and identified a home heating control strategy as the primary determinant of savings; because of this finding, the study suggests using space heaters in conjunction with DHPs and relocating furnace thermostats to non-central areas.

The report is available online: http://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/DHP_FAF_Dec_12.pdf

Ductless Heat Pump Retrofits in Multifamily and Small Commercial Buildings (Bonneville Power Administration, 2012)

Ecotope, Inc. evaluated energy savings based on metering of 12 multifamily units and six small commercial buildings and billing analysis of 188 multifamily units. Reliable estimates of energy usage reduction were only possible at commercial sites with regular occupancy and thermostat setting; in these cases, DHPs were responsible for supplying up to 90% of heating, with average savings of about 4,000 kWh annually. Multifamily sites had savings ranging from 736 kWh per year to 912 kWh per year (these values were significantly below previous estimates). The three primary factors identified as determinants of low savings were increased heat output, supplemental electric resistance heating, and the smaller volume spaces being heated. The study concluded that with an estimated measure cost of $3,000, a DHP was not an economical option for the multifamily units considered.

The report is available online: http://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/DHPx_Multifamily_Small_Commercial_Report_02-08-13.pdf

Appendix E. AMI Smart Meter Data Analysis

Cadmus installed metering devices at a collection of homes, and additionally proposed an alternative method to estimating savings using pre- and post-installation data collected using advanced metering infrastructure (AMI). These types of empirical methods are commonly used across the energy industry to quantify efficiency program energy savings, and they often resemble the approach known as the Princeton Scorekeeping Method. In addition to AMI data, this analysis primarily relies on local weather data and the date of installation data of the measure.

Scope

This appendix details an empirical analysis of AMI data from 48 residential sites that received rebates for cold climate ductless heat pumps. We describe the data sources, modeling techniques, quality control, and final calculation of savings applied to each project. The AMI sample size was small so these results do not supersede results from the metering study. This activity was exploratory, meant to either support findings from the metering study or to indicate possible bias in metered results.

Data Sources

Program Tracking Data

The tracking data contained information on relevant attributes of 48 installations, including installation dates, zip codes, and account numbers. We used these data to determine the pre- and post-measure installation period, geolocate site specific weather stations, and merge weather and AMI data.

Survey Data

Cadmus conducted an online survey and used the information to determine whether the reported baseline equipment correlated with energy savings determined through analysis of AMI data.

Advanced Metering Infrastructure Data

The PSD provided Cadmus with records of electric consumption of the participants completing the survey. This data was provided in 15-minute intervals for periods between winter 2013 and summer 2017.

Weather Data

The temperature dependence of HVAC equipment requires that annual savings values are scaled to an agreed upon “normal” year so as not to skew results when making projections from the evaluation year into the future. This normalization process relies on two sets of weather data: one measured concurrently with the customer AMI data, and a second serving as the “normal” year’s weather. This

first dataset is available from the National Oceanic and Atmospheric Administration (NOAA) for numerous weather stations and is referred to as local climatological data (LCD). Using the zip codes provided in the tracking data, we mapped each site to its nearest weather station before downloading hourly observations. The second dataset is the widely used Typical Meteorological Year 3 (TMY3) that is available from the National Renewable Energy Laboratory (NREL) and provides measurements at hourly intervals for the site-mapped weather stations.

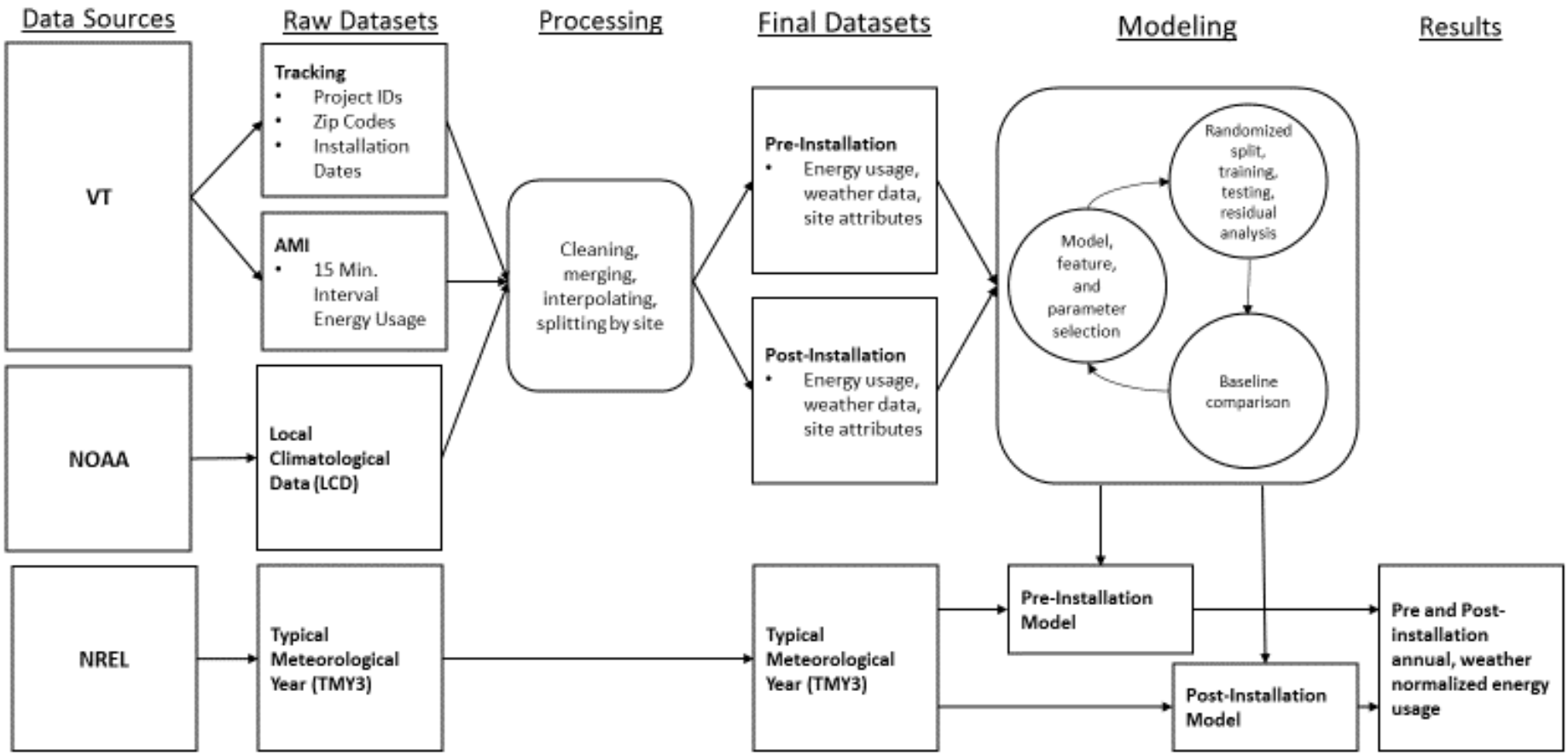
Modeling

Methodology

Figure 41 displays the flow of data from its sources to reported values. After Cadmus received AMI data and sourced weather data from NOAA and NREL, we cleaned and merged these datasets on a per-site basis, and split them into final pre- and post-installation sets. Next, we used an iterative modeling approach to test various model types, inputs, and parameters.

Provided the 15-minute sampling frequency of AMI data and the need for site specific models, the inputs we tested included transformations of hourly weather data, such as heating degree days and cooling degree days (HDDs and CDDs, respectively), and temporal features such as the hour of the day or day of the week. The types of models we tested involved both historically common techniques (such as simple and multiple linear regression) as well as machine-learning algorithms (including regression trees and random forests). We conducted a validation at each iteration of this process to quantify the error introduced by a model and compared results across all tests to finalize an approach.

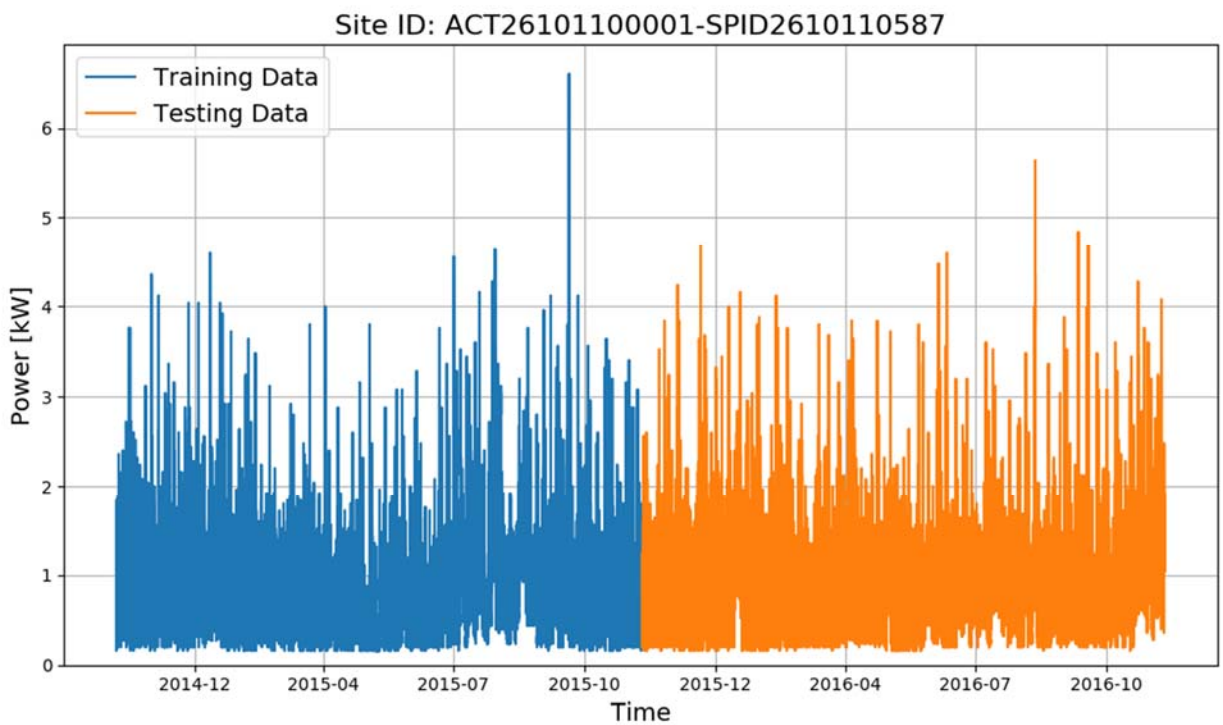
Figure 41. Process Flow Diagram



Validation

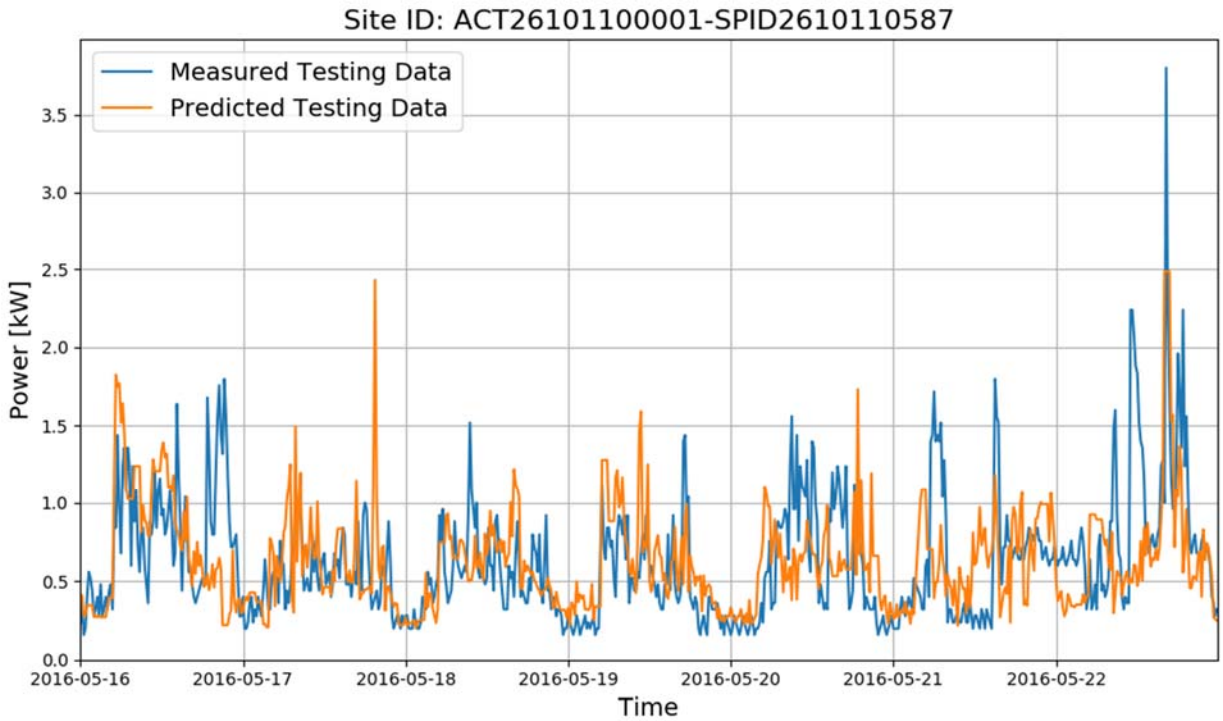
To understand a model's accuracy and draw comparisons with other models, we split datasets, using one portion for model fitting and the other portion as ground-truth for testing model predictions. Figure 42 demonstrates an example of this process. In this figure, we've selected a dataset from the pre-installation period for a single site and plotted the raw energy usage data. The first half of this (training data) is used for model validation and allows us to tune our approach using a selection of model types, inputs, and parameters.

Figure 42. Training and Testing Data



After a final model has been selected, we use it to predict the testing data and score the result using various error metrics. Figure 43 shows a sample of resluts from this process.

Figure 43. Testing Model Prediction



Model Limitations and Quality Control

One advantage of calculating energy savings using pre- and post-installation AMI data is that results can be generated in batches, and scaling the number of sites in the analysis requires only marginal increases in effort because the process remains constant. However, there are limitations to treating all projects equally, and these limitations are best addressed by manually inspecting raw data inputs and developing engineering and experience-based heuristics. Energy efficiency measures are not installed in isolation, and quantifying their benefits relies on the assumption that changes in the operational patterns of a building produce small changes relative to those derived from a project. Provided this issue, our expectation is that the methodology will produce actionable results in most cases, and that those on the boundary can be dealt with on an individual basis or will dampen out in aggregate.

To address these limitations, we established quality control processes that primarily targeted sites with too little pre-installation data or post-installation data. Decisions about “too little” data can be subjective; we focused on data that was measured during periods of only heating and only cooling, and we further checked that a full range of temperatures were observed. Figure 44 shows a site with a complete year of data for the pre- and post-installation periods.

Figure 44. Full Year Pre- and Post-Installation

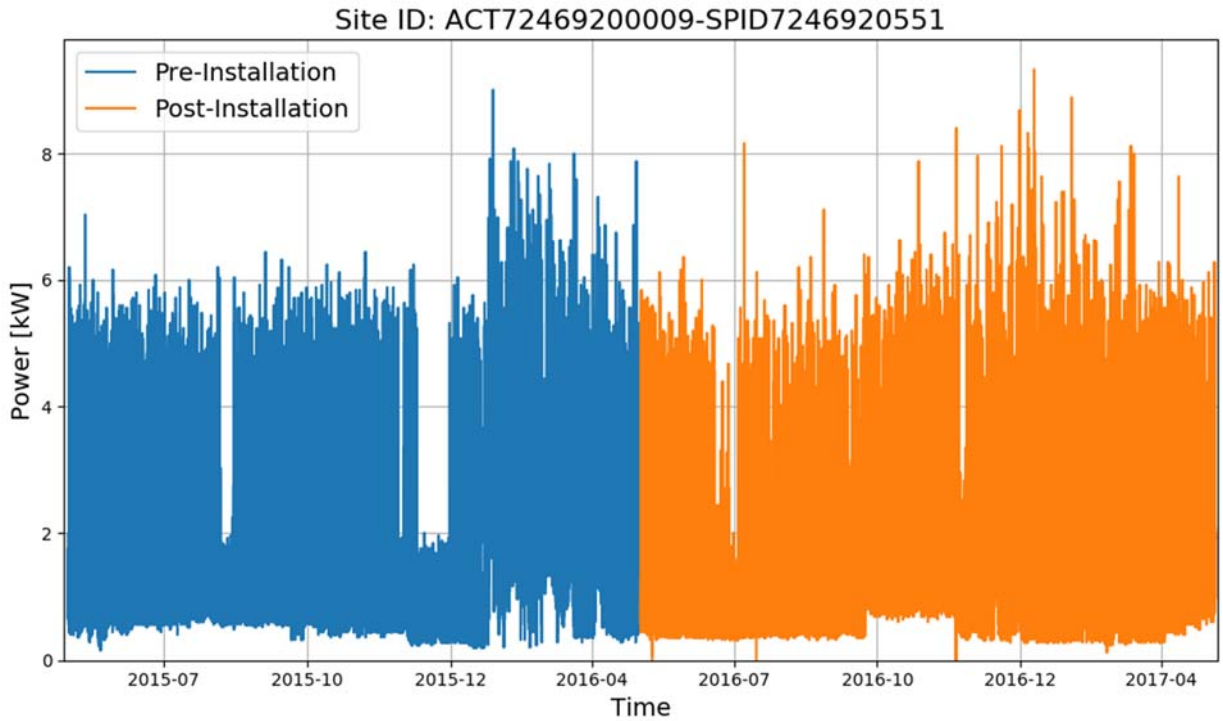


Figure 45 shows this same site as having a full range of temperaures seen during both periods.

Figure 45. Good Coverage of High and Low Temperatures

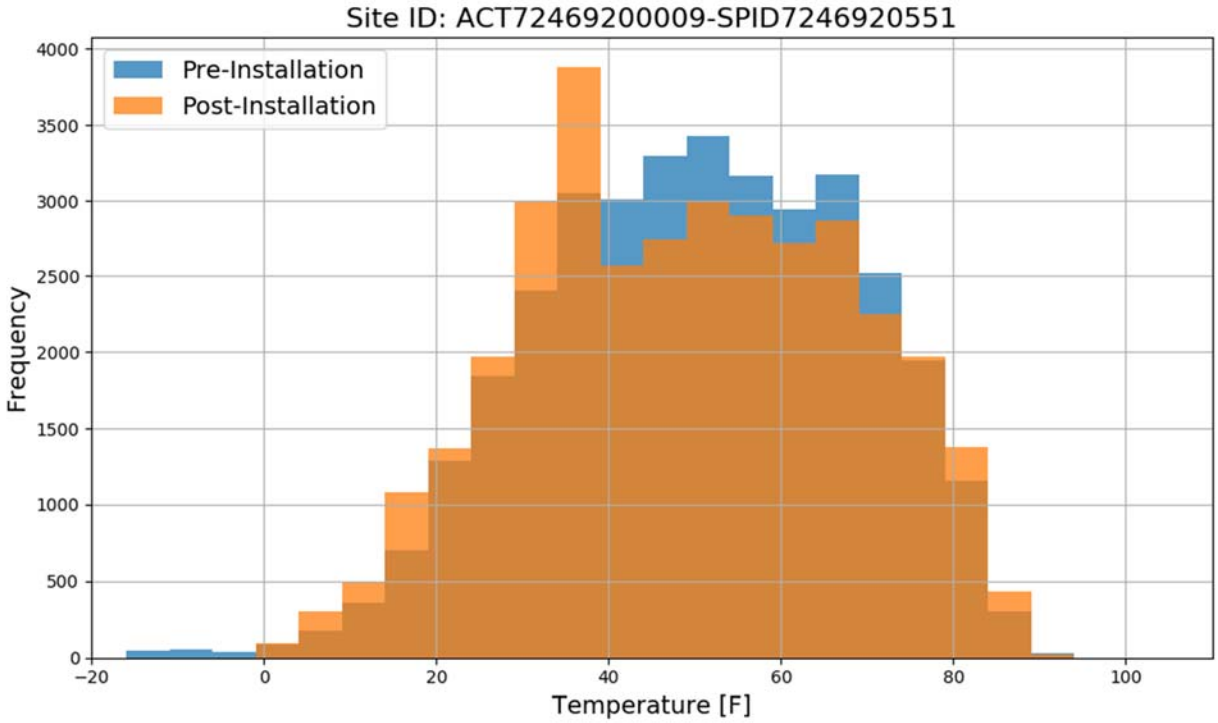


Figure 46 and Figure 47 show these same plots for a site that was excluded from the analysis.

Figure 46. Less Than a Year Pre- and Post-Installation

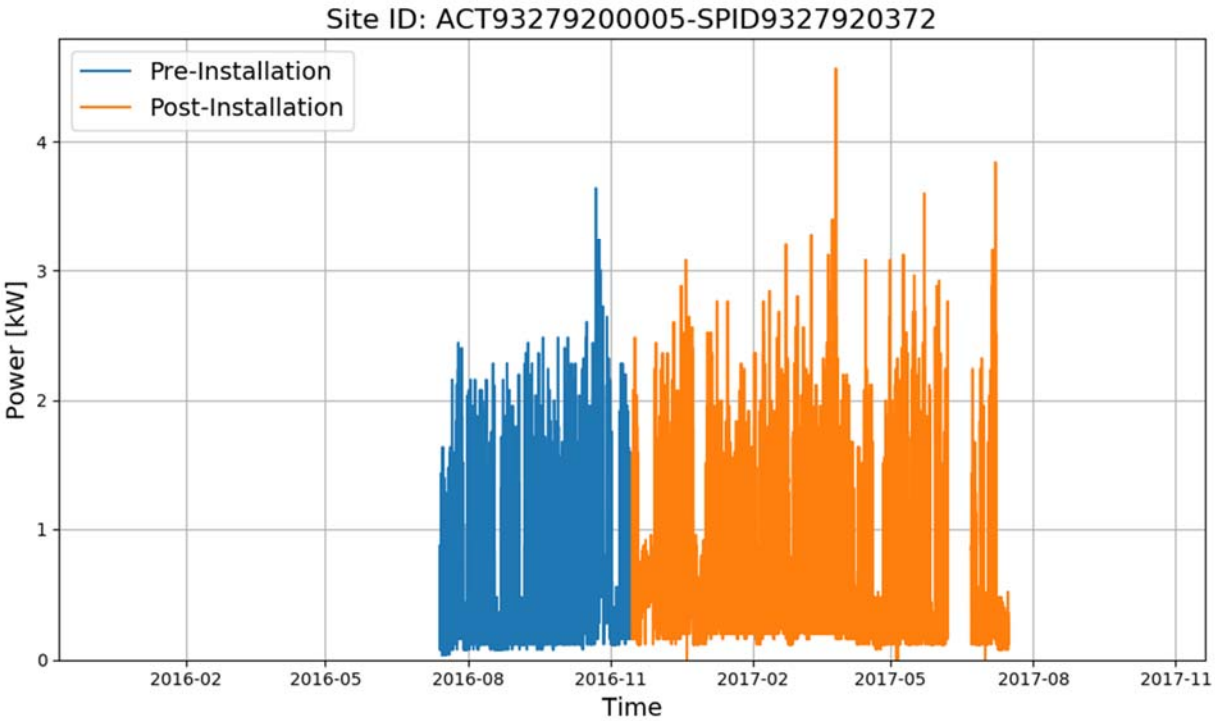
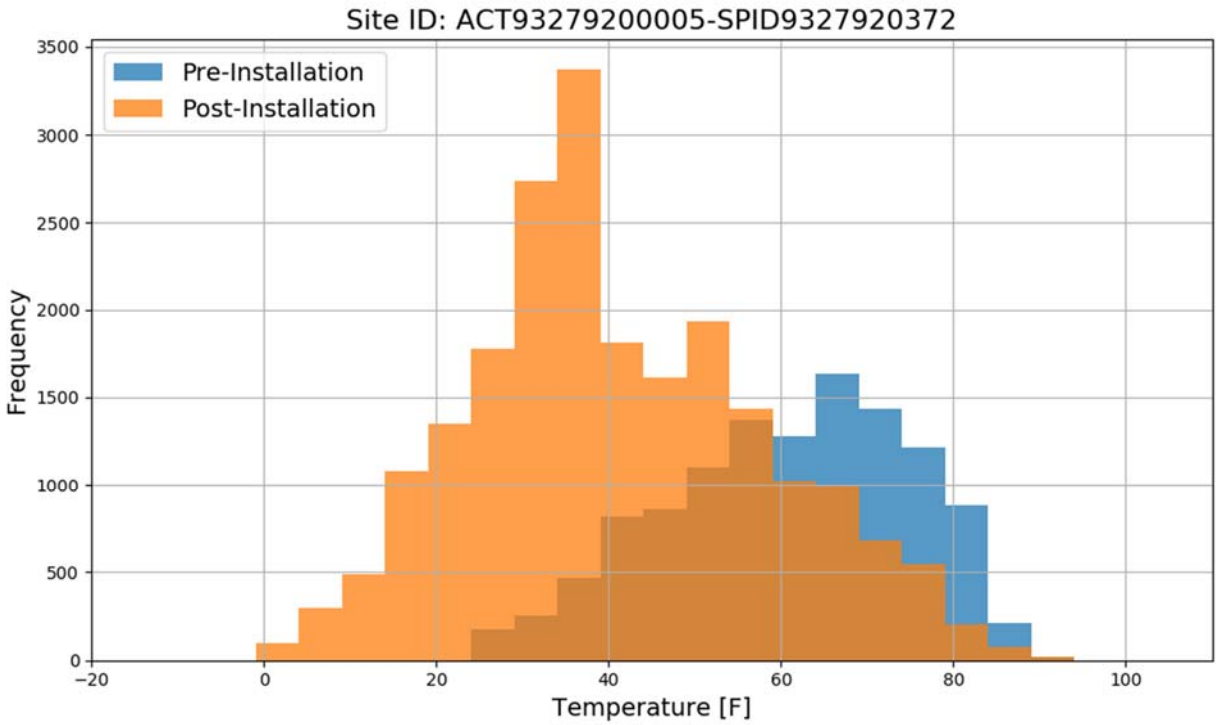


Figure 47. Poor Coverage of High and Low Temperatures During Pre-Installation Period



Sites with without pre- or post-installation were not included in the analysis. Additionally, we removed sites that were not representative of heating or cooling seasons or did not have a complete range of temperatures. Table 18 summarizes the results of the quality control process.

Table 18. Site Quality Control Removal Counts

Classification	Count
Total Sites	48
No Pre- or Post-Installation Data	13
Did Not Pass Quality Control	8
Remaining Sites for Analysis	**27**

Results

After finalizing the model type and inputs, and after cleaning and removing sites as part of the quality control process, Cadmus calculated weather-normalized annual energy savings by training models to the

pre- and post-installation datasets. We inputted a full year of TMY3 weather data into each of these models, summed interval energy usage predictions, and calculated the difference between these sums.

Figure 48. Annual Weather Normalized Energy Savings [kWh]

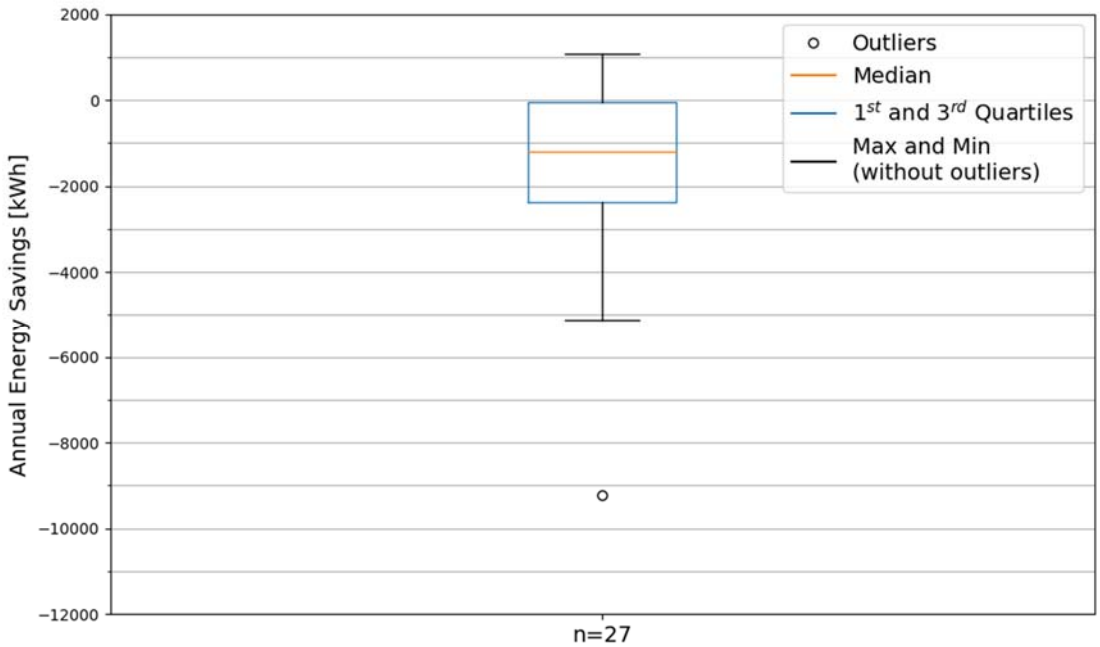


Figure 49. Annual Weather Normalized Energy Savings [kWh]

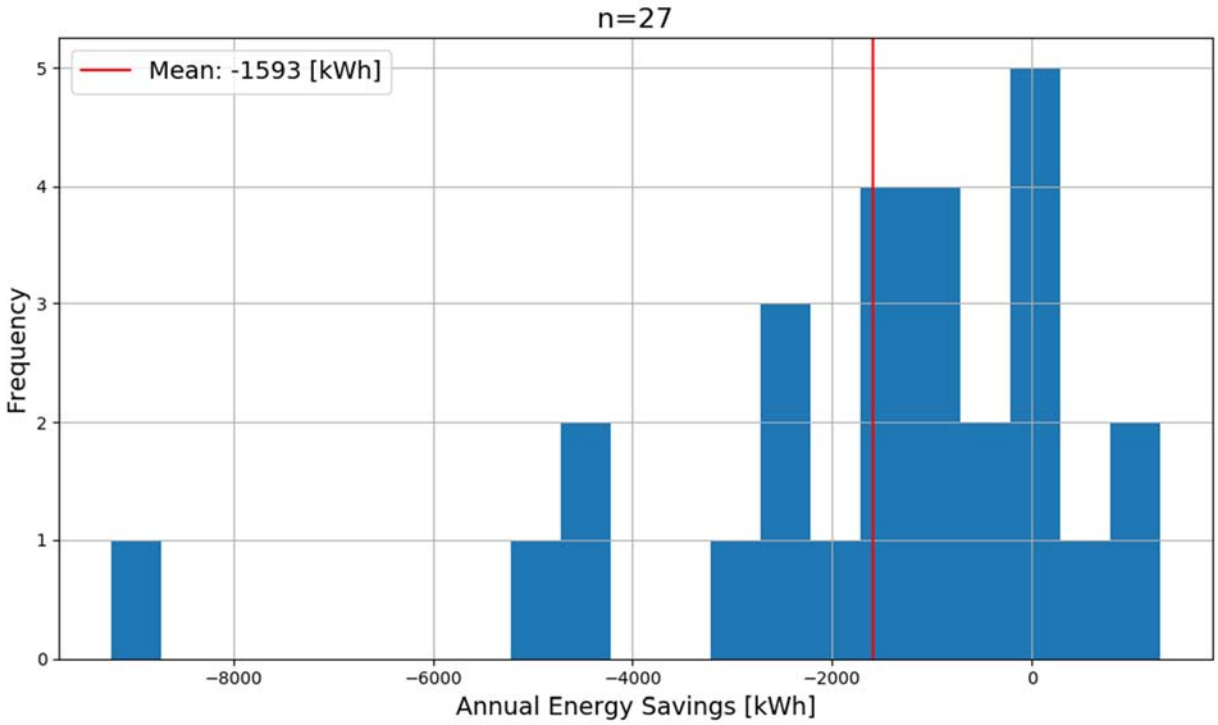


Figure 50. Annual Weather Normalized Heating Energy Savings [kWh]

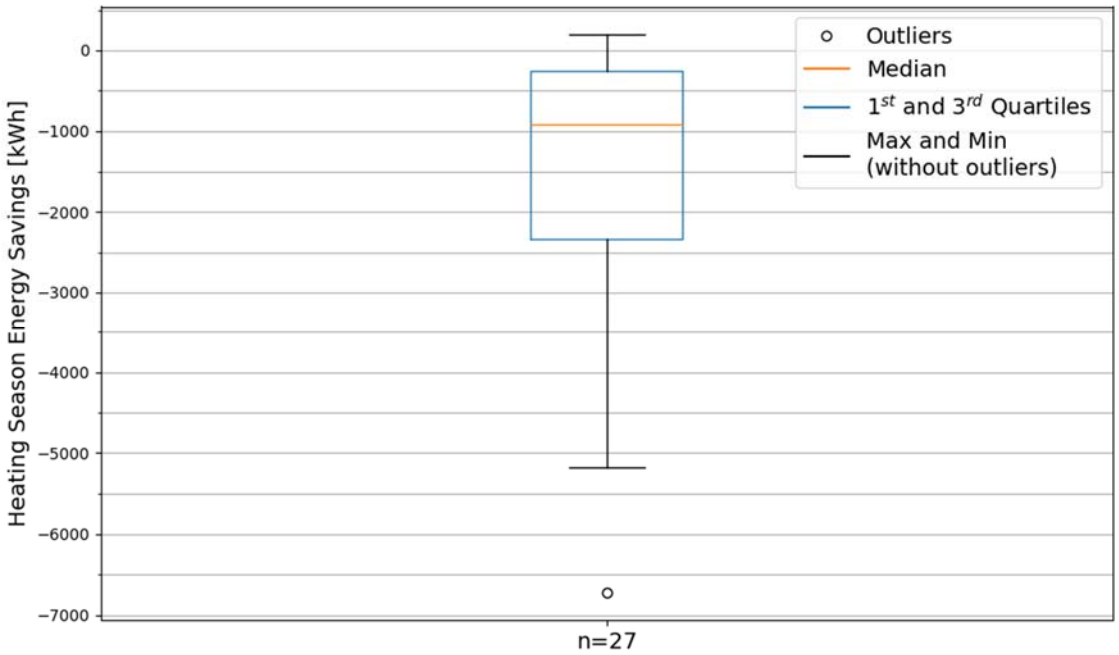


Figure 51. Annual Weather Normalized Heating Energy Savings [kWh]

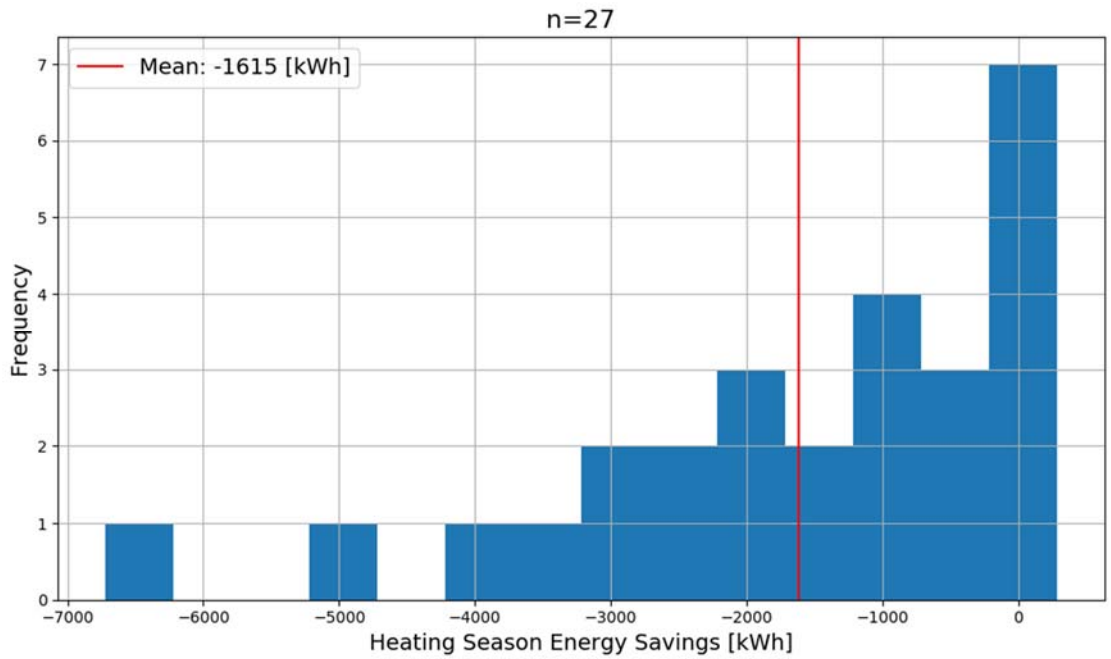


Figure 52. Annual Weather Normalized Cooling Energy Savings [kWh]

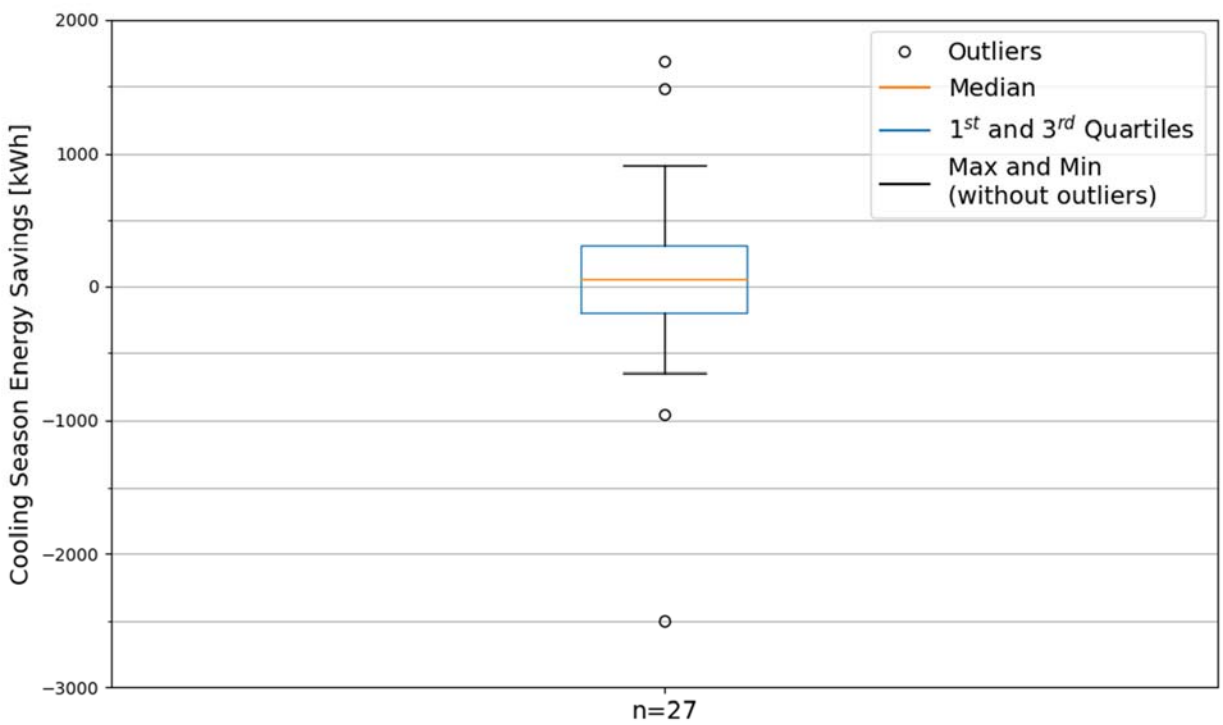
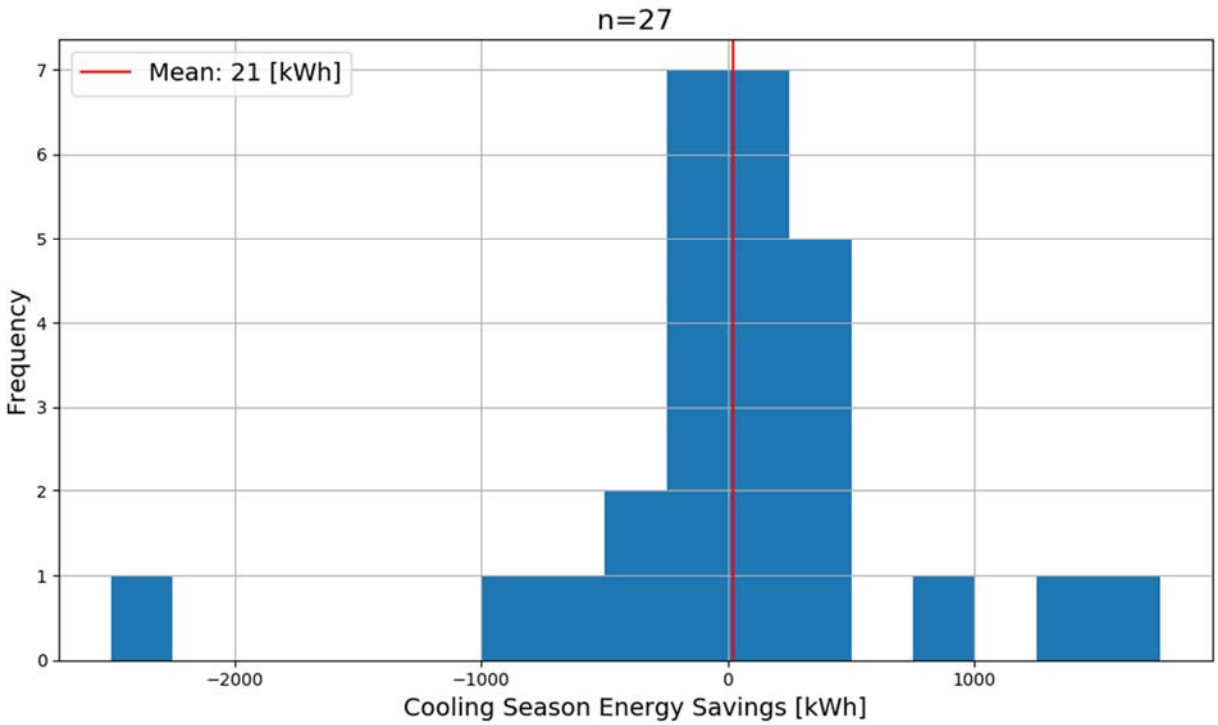


Figure 53. Annual Weather Normalized Cooling Energy Savings [kWh]



Although ccHP installations can increase cooling energy consumption in some scenarios, Figure 53 shows positive energy savings for a home (21 kWh), evidence that ccHPs are not increasing electric load during the cooling season. Table 19 shows cooling energy savings (12 kWh), the savings normalized by a ratio of efficiency and capacity of the ccHPs in each home with AMI data to the average ccHP in the metering study.

Table 19. Annual Weather Normalized Energy Savings

Previous System	Number of Accounts	Δ kWh (Normalized to metered cooling capacity)
No Cooling	10	-95
Fan only	9	-40
Window or portable AC	8	202
Total	**27**	**12**

Survey results from the AMI sample found 27% of homeowners replaced a window air conditioner with a ccHP. Pre-post AMI analysis does not include hypothetical counterfactual assumptions; it simply shows the change in cooling energy consumption due to a ccHP installation.