BONNEVILLE POWER ADMINISTRATION

Residential Ductless Mini-Split Heat Pump Retrofit Monitoring Study: Year-Three Supplemental Report

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A Report of BPA Energy Efficiency's Emerging Technologies Initiative

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The following report was funded by the Bonneville Power Administration (BPA) as an assessment of the state of technology development and the potential for emerging technologies to increase the efficiency of electricity use. BPA is undertaking a multi-year effort to identify, assess and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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Authors

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Acknowledgements

Core Ecotope contributors to this work include David Baylon (President/Principal), Kevin Geraghty (Analyst/Statistician), Bob Davis (Director of Measurement and Verification, and Poppy Storm (Project Manager). Ecotope would like to acknowledge the following BPA Project Team members: Kacie Bedney, Jack Callahan, Mark Johnson, Sarah Moore, and Adam Hadley (formerly at BPA).

Abstract

The Bonneville Power Administration (BPA) launched the Residential Ductless Mini-Split Heat Pump Retrofit Monitoring Study at the end of 2007. The study was a small-scale DHP pilot study and has continued through the spring of 2012. This supplemental report addresses the analysis and findings from the final and third monitoring period (2010–2011). For more in-depth discussion of the study methodology and year-one and year-two findings, please see http://www.bpa.gov/energy/n/emerging_technology/DHP.cfm.[1]

The overall study has provided the region with a small-scale experiment to understand the DHP technology and to provide insights into the analysis and pitfalls that were subsequently used to evaluate the larger regional program implemented by the Northwest Energy Efficiency Alliance (NEEA). These insights included the importance of occupant interviews and detailed home characterization in developing a firm picture of the performance determinants. While the BPA study sample was generally too small to be definitive, it pointed to the size of the savings potential the technology offers. The contributions of this preliminary work improved both the quality and the efficiency of the regional data collection for the evaluation of NEEA's DHP Pilot Project Impact and Process Evaluation (2009–present).

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[1] http://www.bpa.gov/energy/n/emerging_technology/pdf/BPA-Report_DHP-Retrofit-Monitoring-June2009.pdf
http://www.bpa.gov/energy/n/emerging_technology/pdf/BPA-Report_DHP-Retrofit-Monitor-Y2-Sept2010.pdf

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Executive Summary

The Bonneville Power Administration (BPA) launched the Residential Ductless Mini-Split Heat Pump Retrofit Monitoring Study at the end of 2007. The study was a small-scale DHP pilot study and has continued through the spring of 2012. This supplemental report addresses the analysis and findings from the final and third monitoring period (2010–2011). For more in-depth discussion of the study methodology and year-one and year-two findings, please see http://www.bpa.gov/energy/n/emerging_technology/DHP.cfm.[2]

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The BPA study originally included 14 sites in three utility service territories. After the first year, three of these sites dropped out of the study and four additional sites in Monmouth, OR asked not to participate in the metering program that was a part of this pilot (although these sites continued to allow access to billing records). One of these sites was vacated near the end of 2010 and was vacant for the third study year. This site was removed for the third year evaluation. The third study year included three homes providing only billing data and seven homes in Monmouth, OR that continued to provide metered data on DHP and electric resistance space-heating energy use as well as overall energy use and DHW.

The remaining Monmouth sites offer an opportunity to review the persistence of space-heating savings and DHP performance over a period of about 3.5 years. Each site entered the pilot over the course of about six months ending in February 2008 and all the sites were decommissioned in September 2011. As a result, different metering periods were used for each site. The metering periods generally coincide within a month and share a common heating season. In all cases, however, each year is summarized using annualized weather normalized data. All weather normalization in this report is based on annual- and long-term average weather data for Salem, OR. The long-term average was derived from 16 years of weather data at this weather site.

This supplemental report is limited to two primary research questions:

1. Do the savings observed in the previous studies persist through the third year?
2. Do the cooling loads which are experienced in this climate (central Willamette Valley) have a significant impact on energy savings from heating efficiency?

These research questions were designed to improve the understanding of DHPs and build on the previous study years of this group. Like the previous reports, this analysis used a "variable-base degree-day" (VBDD) method (often referred to as PRISM) to analyze electricity bills and weather-normalize savings estimates. The analysis of the metered DHP data also used this weather normalization method to make these performance assessments consistent with the billing analysis results. All data streams were normalized using long-term weather data from Salem, OR. This report summarizes the ten remaining sites in Monmouth using utility billing information collected for the three and a half year study as well as approximately two years of bills collected from the period before the

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[2] http://www.bpa.gov/energy/n/emerging_technology/pdf/BPA-Report_DHP-Retrofit-Monitoring-June2009.pdf
http://www.bpa.gov/energy/n/emerging_technology/pdf/BPA-Report_DHP-Retrofit-Monitor-Y2-Sept2010.pdf

installation of the DHPs. Table E-1 shows the savings evaluated over the three-year study period. This summary shows that in spite of substantial changes in occupancy the savings remain strong throughout the study group. In one site in the billing-only group, substantial unexplained changes in occupancy resulted in an increase in the energy consumption in the third year.

Table E-1: DHP Savings, Monmouth Sites

Analysis Period	Savings		
	10 Total Sites	7 Metered Sites	3 Sites, Billing only
	kWh/yr	kWh/yr	kWh/yr
Year 1	4617	5073	3550
Year 2	5298	6151	3306
Year 3	3978	5109	1336

Analysis of this billing data formed the basis for describing the persistence of savings for this group of houses. The seven homes that continued with meters were used to assess the ongoing performance of the DHPs. Table E-2 shows the ongoing effectiveness of the DHPs. This table shows the remarkable consistency in the output of the DHP even as other changes in occupancy erode the apparent savings from the billing analysis. This suggests that the benefits of the DHP technology are maintained by the occupants even with occupancy changes.

Table E-2: DHP Consumption, Metered

Analysis Period	Heat	SD*	Fraction All Heat
	kWh/yr	kWh/yr	
Year 1	3075	1193	33.7%
Year 2	2688	1379	34.7%
Year 3	2912	1190	37.4%

* Standard Deviation

The results of the current analysis also confirm the results of the previous study years which used a more approximate estimation procedure. Cooling is a very minor energy use in these DHP installations. The overall cooling use for the DHP installations was metered in six of the seven metered sites. The total cooling energy use averaged approximately 100 kWh per year. This usage does not necessarily reduce the energy savings from heating since the use of window AC units probably offset this usage. In this study the cooling usage was part of the original data collected on site, so the amount of savings associated with the cooling requirements could not be calculated. Given the pattern of small, zone AC in this climate, it seems likely that the cooling usage represents an additional unquantified energy savings.

1. Project Background

The Northwest region has embarked on a long-term effort to study the impacts of small split-system heat pumps that are designed to provide zone-level heating and cooling in homes. These systems are largely manufactured in East Asia and use inverter-based compressor and air handler designs. In this region about 500,000 homes have electric zonal heating systems. These systems are not easily retrofit with natural gas since there is no preexisting duct system. While this group of customers has been addressed by extensive weatherization efforts, no technology short of very expensive fuel conversions involving retrofit duct work have been available. In order to control costs, such customers often accept lower thermostat settings and/or supplemental fuels (wood, pellets, or propane) as an alternative to electric resistance heating.

The DHP technology offers a significant alternative for energy conservation in this market. As a result, the Regional Technical Forum (RTF) adopted provisional savings estimates that assumed the zonal nature of this technology would offset sufficient electric resistance space heating that has proved cost-effective as a utility investment. This action carried with it the provision that the BPA and/or NEEA would design a pilot project that would establish the basis for the use of DHPs as a portion of the portfolio of conservation measures employed by the region's electric utilities. There were several assertions in this decision that needed verification before a full scale program could be developed:

- As a zonal heating system, DHPs do not require duct work and are therefore easily retrofit into existing zonal systems. Given the manufacturer's specifications, they offer a rated heating performance that could approach a COP of 4.0 on a seasonal basis. This performance should result in significant heating savings in homes heated with electric resistance units.
- The cost of the DHP equipment would not be prohibitive, but even when a single zone costs in excess of $3000. This suggested that the application should be limited to only one or two zones in a house; preferably the central living spaces.
- Preliminary savings estimates based on the fraction of the preexisting heating energy could be offset by the high efficiency DHP system. Initially, estimates of 30 to 40% were proposed using approximations made by the RTF.
- In some climates the DHPs had the added feature of providing zone cooling. As cooling equipment the DHP was likely to be two to three times as efficient and the window AC units used commonly in zone-heated homes. There was no estimate of the savings or extra energy use that might result from deploying this type of equipment.

BPA responded to the RTF provisional approval by embarking on a two-part pilot study. The first part was a preliminary assessment of the performance efficiency claims of the DHP manufactures. While the ratings were published in accordance with AHRI testing procedures, these procedures were not designed to assess the variable speed compressors and multi-speed air handlers that were characteristic of the DHP equipment. Furthermore, the part load efficiency was largely unknown and the performance at temperatures outside the AHRI testing requirements were not in the literature. As a result, a single unit was tested in a controlled field setting in Goldendale WA to establish the veracity of the equipment (Davis, et al., 2008). The second part of the pilot was to develop a series of installations in cooperation with willing utilities. This effort focused on three utilities which were thought to provide a range of climate conditions. Fourteen installations were done:

- Two in Grant County PUD in Moses Lake WA
- One in Tacoma Power in Tacoma, WA
- Eleven in the City of Monmouth OR near Salem, OR

These installations were monitored using various protocols over the course of approximately one year ending in March of 2009. The results of this monitoring and performance review were reported in the initial Ecotope report, in the summer of 2009 (Geraghty, et al, 2009).

At the end of the first monitoring period, several homes dropped out of the study. Metering equipment was decommissioned from the dropped sites and seven homes consented to remain in the study as metered homes. These seven homes were all in the Monmouth group. The four remaining Monmouth homes consented to allow their bills to be used in the subsequent years of the study. BPA decided to focus on the Monmouth homes for an additional period to address questions of both longer-term heat pump performance and persistence of savings identified in the initial report. These eleven Monmouth homes were studied for another year leading to a second-year report on these DHP installations (Ecotope, 2010). This report focused on savings from the DHP installation and developed a more rigorous approach to evaluating savings from the metered homes. In addition, a simple billing analysis (variable base degree-days, VBDD) was developed for all eleven homes and compared to the findings from the subset of metered homes.

In the third and final year, Ecotope continued to monitor the remaining homes in the metered cohort (seven Monmouth homes) and focused on two final research questions:

1. What is the apparent persistence of savings estimates over the three and a half years of metering at these homes? This research focused on the long-term billing analysis results from each of the eleven sites. This approach was thought to give a test of a long-term billing analysis that might be used in the evaluation of a larger utility program.
2. What is the impact of summer cooling that could be expected from this technology? To answer this question an additional temperature sensor was installed that allowed the metering to distinguish when the DHP was in cooling mode.

This study was meant to provide engineering insight that would be useful in developing both the performance estimates of DHP systems and the analysis techniques that would be used to evaluate a much larger sample. For this study, however, the small sample size makes it impractical for the results of this study to be generalized to a larger population.

In the analysis presented in this report the metered data was not used to directly estimate the savings from the DHP installation. The complexities of the non-metered space heating identified in the second-year report suggested that the savings were better calculated using the changes in actual utility bills over the period from the beginning of the study. Only six of the metered homes still had usable meters and one of these has had an equipment failure that prevented a direct measure of space heating or DHP usage. Nevertheless, the cooling behavior could be addressed in this home in spite of the reduction in available data across the entire study group.

The remaining Monmouth sites offer an opportunity to review the persistence of space-heating savings and DHP performance over a period of about three and a half years. Each site entered the pilot over the course of about six months ending in February 2008 and all the sites were decommissioned in September 2011. As a result, different metering periods were used for each site. The metering periods generally coincide within a month and share a common heating season. In all cases, however, each year is summarized using annualized weather normalized data. All weather normalization in this report is based on annual- and long-term average weather data for Salem, OR. The long-term average was derived from 16 years of weather data at this weather site.

Table 1 shows the disposition of all the sites that participated in this pilot over the three and a half years of the study.

Table 1: Disposition of Sites by Year in the Residential Ductless Mini-Split Heat Pump Retrofit Monitoring Study

	Report Year		
Site	1	2	3
Monmouth 1	M	B	B
Monmouth 2	M	M	M
Monmouth 3	M	B	B
Monmouth 4	M	M	M
Monmouth 5	M	B	B[4]
Monmouth 6	M	M	M
Monmouth 7	M	B	B
Monmouth 8	M	M	M[3]
Monmouth 9	M	B	B
Monmouth 10	M	M	M
Monmouth 11	M	M	M
Tacoma	M	N[2]	N
Moses Lake 1	M[1]	N[2]	N
Moses Lake 2	M[1]	N[2]	N

<u>Key</u>

B – Billing Records Only

M – Quad Meters, Billing Data

N – Did Not Participate

1 Did not include direct meter of total consumption.

2 Did not participate after first year.

3 Heating system channel failed at the beginning of the third year.

4 Site vacant in most of third year. Not included in Analysis.

2. Methods

2.1. Data Sources

The evaluation of the homes in this study used two separate data sources:

1. **Billing records collected from the utility**. These records have been developed over the course of the research and now include up to 42 months of consumption data after the installation of the DHPs. In addition, the bills from the period before the installation have been treated as the base consumption in both of the previous reports. In the current report they continue to serve that function.
2. **Information gathered from the three or more years of metering on the participating homes**. These data served to provide adjustments for the billing analysis and provided the detailed consumption which allowed an assessment of the cooling energy use. The same metering equipment was used over the entire time period and metered total consumption at the main service, consumption on the space-heating circuits that fed the 220 volt electric zone heaters, the energy consumption of the DHP, and the energy consumption of the domestic hot water (DHW) tank. These four channels were supplemented by three temperature sensors: the main living space, the outdoor temperature near the DHP location and the vapor line temperature installed at the DHP. The vapor line temperature sensor was only included for the third year of metering.

2.2. Analysis Methodology

For this supplemental report, the analysis focused mainly on space heating. The primary methodology for evaluating space-heating consumption from utility bills was completed using the variable base degree-day (VBDD) method. This approach has been a part of impact evaluations for twenty-five years and its application in this study has been discussed thoroughly in the year-one and year-two reports (Geraghty et al, 2009), (Ecotope 2010).

In this report the VBDD methodology has been continued largely unchanged. In general, the goal of VBDD is to determine the portion of the bill which varied as a result of changes in temperature. In a heating dominated climate such as Monmouth, the energy use that varies with temperature is derived from the VBDD analysis (sometimes called PRISM). This derivation is then modified to correct for non-space heating loads that also vary seasonally, especially domestic hot water (DHW). Since the Monmouth homes all had at least a year of metering on their DHW consumption, the source for this correction was the metering.

Since the estimation of space heating from any given year is based on a regression fit to the bills collected during the heating season, the heating estimate can be easily adjusted from one year to another to account for changes in temperature. This approach allowed the analysis to be put on the same footing so that variations in weather over the entire study period would not bias the comparison between the years and among homes. A VBDD analysis was applied to homes to develop the base heating consumption and to establish heating consumption in the subsequent years.

A base case heating estimate drawn from the bills collected prior to the DHP installation. This analysis used all the bills that were available. In some cases the bills extended over a three-year period; in other cases only slightly more than a year was used. In all cases, the entire record was used to estimate the space-heating regression. This step allowed the space-heating energy consumption to be normalized to either long-term weather or to the weather that was present in the metering period.

The second VBDD analysis was conducted on each of three "years" of billing data collected after the DHP installation. Because of the variation in post-installation bills, the number of bill cycles in each home varied somewhat, but each period included a heating season that was largely the same for each home. This resulted in three separate heating estimates that tracked the consumption over the three and a half years of the study.

The third application of VBDD was to normalize the metering results. This process was parallel to the analysis of the billing records except that the metered data was aggregated to a daily level and this was normalized over each heating season separately. Appendix A discusses this process in more detail.

The final use of VBDD is to reverse the regression fit and normalize the cooling energy derived from the metered cooling response of the DHP. This process is developed more thoroughly in Section 3 of this report.

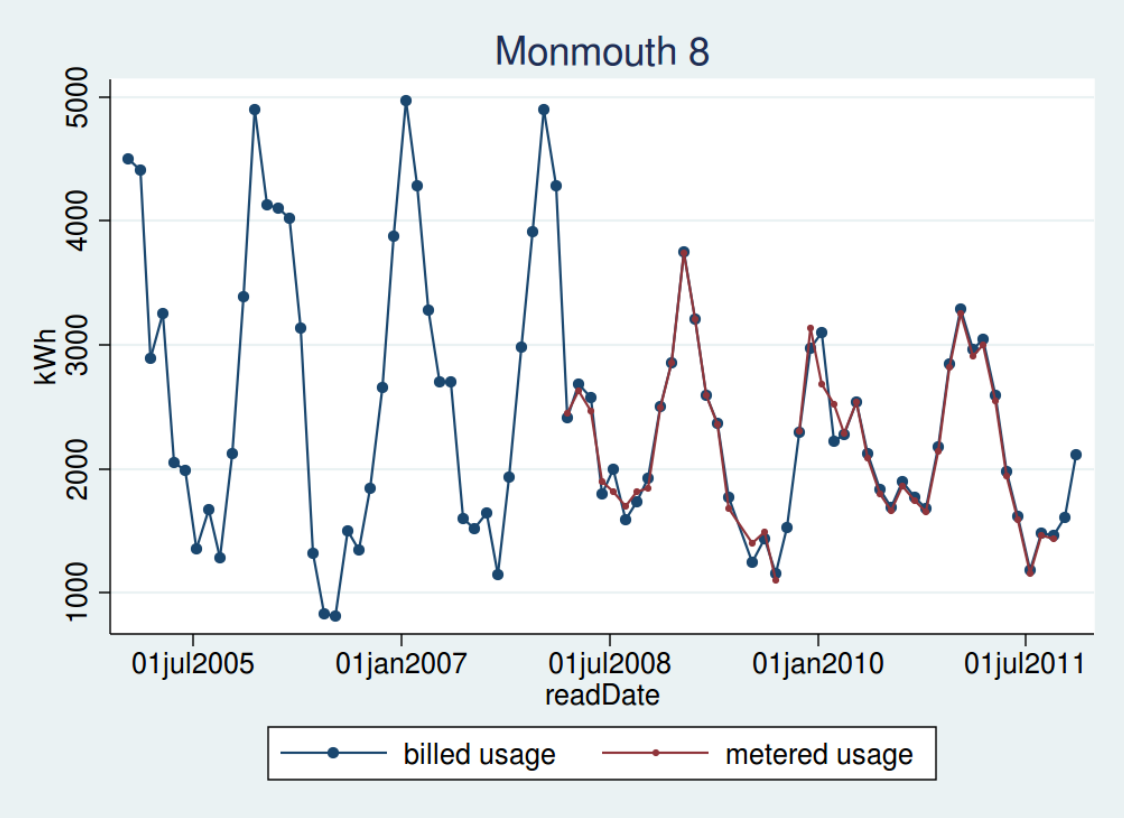
The VBDD analysis uses the standard techniques used to seasonally normalize utility bills. This means that the output for any particular DHP is expressed in terms of the normalized annual consumption (NAC) (Fels, 1986). In developing the base case the NAC is developed from about three years of consumption records. The inclusion of this many bills improves the quality of the heating estimate. The individual years summarized into the NAC are comparable with other similarly developed NACs from the post-installation period.

3. Findings

3.1. Persistence in Space Heating Savings

As discussed in Section 1, different metering periods were used for each site. The metering periods generally coincide within a month and share a common heating season. In the seven homes that continued with year-three metering, the total house meter was compared to the billing data to establish the compatibility of these two data streams. In general, metered whole-house service loads, aggregated to the same intervals as billing data, closely agree. To illustrate this, Figure 1 jointly graphs a representative site's time series of billing data and metered service data aggregated to the same intervals. Occasional offsetting differences between billed data and aggregated metered data are likely attributed to estimated bill errors followed by subsequent billing corrections based on actual meter reads.

Figure 1: Billed Data vs. Metered Whole-House Data



3.2. Billing Analysis

The initial review of savings persistence was conducted on all of the Monmouth sites. This analysis closely parallels a typical utility savings evaluation using normalized changes in consumption to characterize the site savings and performance.

Figure 2 depicts weather-normalized space heating consumption for all eleven Monmouth sites, calculated from monthly billing data using standard VBDD techniques (see Geraghty, 2009, and Fels, 1986 for a detailed description). Three post-installation "years" are shown. The pre-installation period in an average space-heating estimate derived from about three years of pre-installation consumption developed from the utility billing record (see Appendix A for the explanation of the analysis applied to these slightly different time periods). Across the eleven sites a "year" on average, covers about 14 calendar months. About three and a half years of pre-installation records were generally available and these bills formed the basis of the normalized pre-installation heating loads.

Visually it is evident that post-installation space heating consumption continues to show no tendency to increase in eight of the eleven sites. By contrast two sites, Monmouth 1 and Monmouth 4, show marked increases in the last year to pre-installation levels or above. Monmouth 5 has no bar for the final year because it was vacant through most of that period, and ultimately re-occupied by different people. Had it been graphed notwithstanding, the bar would have had close to zero height.

Figure 2: Space Heating during Pre-Install and Three Post-Install Years (Based on Monthly Billing Data)

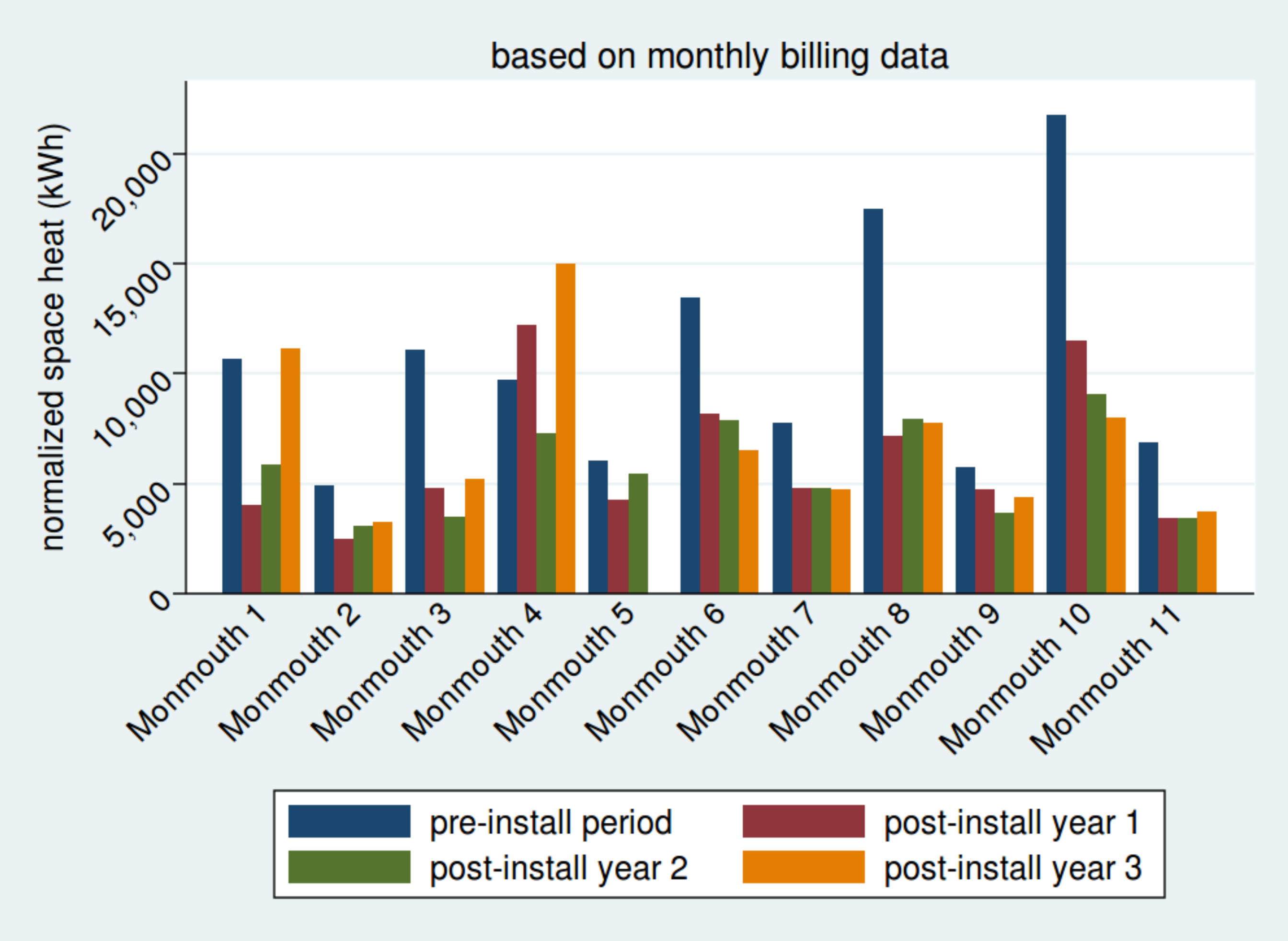


Table 2 summarizes averages across sites for the data graphed in Figure 2. Monmouth 5, the site unoccupied in the third year, is excluded from all averages so that they all use the same sites. The standard deviations are large in this group but the savings are large enough that they still achieve statistical significance. The size of the savings within each year cannot be statistically distinguished one year to the next. Based on the size of these standard errors none of the estimated differences in calculated means between post-installation values attain anything close to statistical significance. This finding should not be surprising; not only are these differences in means numerically relatively small, but the means are calculated with only ten data points. In this group the savings estimates differ greatly from the billing analysis. This variation is attributed to changes in occupant use patterns over the three study years. These savings differ from the other reports in this study because:

- Savings are normalized to long-term weather data.
- Only 10 out of the original 14 homes are included in the third year.
- The saving calculation approach used only billing information and the variation in that data is large compared to the metered space heating.

Table 2: Space-Heating Saving (kWh/yr)

Analysis Period	Heat	SD	Savings
	kWh/yr	kWh/yr	kWh/yr
Base Years	10958	5347	N/A
Year 1	6341	3349	4617
Year 2	5660	2242	5298
Year 3	6980	3690	3978

3.3. Analysis of Metered Data

In this report, the metered DHP performance has been used to confirm the results of the billing analysis. This approach allows the impacts of DHP assessed in the bills to be analyzed in parallel and using similar tools over comparable time periods. It is important to remember that metering does not extend back to the period before the installation of the DHP. Thus, even in this analysis with much more detailed data, the base case heating loads needed to calculate savings are the same as those used in the billing analysis.

VBDD regression was used to estimate weather-normalized energy consumption, and to separate an energy-use data stream into weather-sensitive and weather-insensitive portions. This method is employed here not only on billing data, but also on hourly metered data. On the metered data side, VBDD weather-normalizing analysis was carried out on two data streams:

- **The total electric service metered by the metering package**. Like the DHP data, the results of these metered data were consolidated into daily consumption and normalized using the same procedure as the DHP data. For this analysis the channel metering the DHW load was subtracted from the metered total. This step removed a large load with some seasonal variation, unrelated to the space heating of the home.
- **Metered DHP loads consolidated into daily consumption records and regressed against daily average outdoor temperature (collected on site)**. This consumption record was then weather normalized using the temperature data and normalized with the same long-term weather file used in the billing analysis.

3.3.1. Metered Total Heat

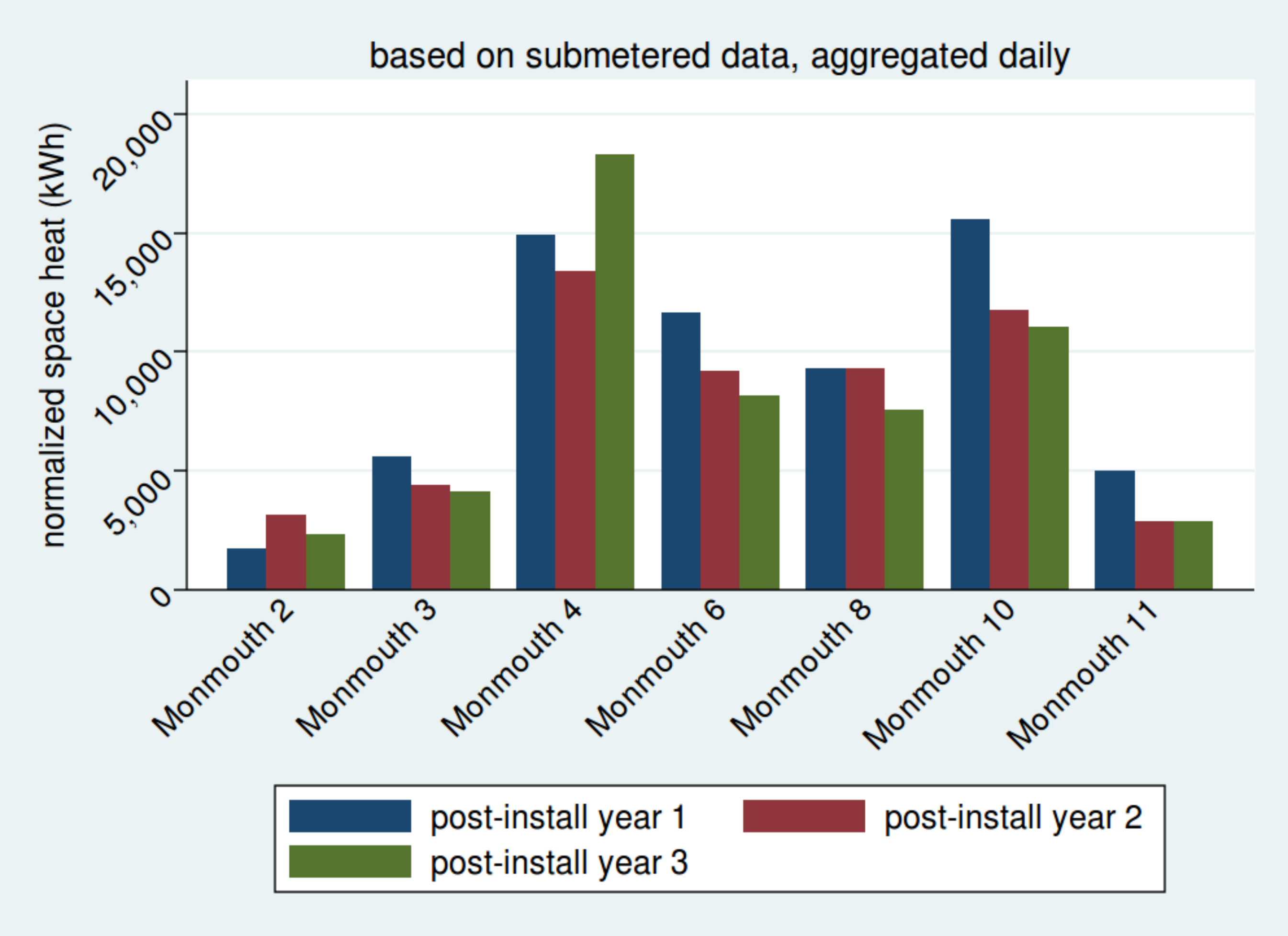
Past analysis (Ecotope 2010) revealed the magnitude of “hidden” space heating, largely in the form of 110V heater (portable electric heaters). The measurement of electric resistance space heating in this metering package focused solely on 220V circuits wired directly from the electric service panel. This metering had the effect of missing these portable heaters. As shown in the second-year report, this heating load average was as much as 24% of the total measured space heating from the DHP and the 220V heating circuits. To quantify this, a seasonal residual was calculated. While this calculation corrected the apparent bias in the space-heating estimates, it did not correct of coincidental loads that appeared to be seasonal (e.g., hot tubs and spas) but were not part of the space heating at all. In this study, very little secondary information was collected on the house and occupants. The analysis could not distinguish actual heating from these other incidental loads. As a result there is a downward bias in savings estimates as some of the apparent space heating in the post-installation period is actually some other use.

To avoid this problem the service loads were analyzed to predict the space heating. The results are directly comparable to the billing analysis done on the base years. Any non-space heating seasonal load that appeared previously would cancel out those loads as they appeared in the post-installation period. Only if there was a change in the consumption pattern or occupancy would this assumption result in a further bias in the savings estimate.

Figure 3 depicts weather-normalized space-heating consumption estimated from metered data, for the seven sites which continued to be metered through year three. The data used for the analysis is metered whole-house “service” consumption; the weather-sensitive portion captured in the graph includes all space-heating consumption, whether separately metered (DHP as well as 220V resistance heat) or seasonal plug loads (110V portable heat). In at least one case it appears that the occupant actually changed their heating system to portable heaters after the installation of the DHP. In all cases, however, this analysis captures all the space heating used. Because only metered data are used for the estimates, only the post-installation years can be calculated. For these seven sites, the general patterns seen in the billing-data-based space-heating estimates are confirmed; stable or declining normalized consumption at six sites, and an increase at one site.

In the exit interview conducted when the metering system was removed, the occupants of Monmouth 4 mentioned that they occasionally hosted a foreign exchange student. The timing of the hosting was irregular but the third year of metering was such a year. The result of this was to heat one or two rooms in a portion of the house that was not heated during normal occupancy. This occupancy change results in the apparent increase in space heating as well as an increase in the use of plug-in space heaters.

Figure 3: Space Heating for Final Seven Monmouth Sites during Three Post-Install Years



The heating requirements predicted from the total metered space heating should be comparable to the heating estimates from the billing analysis. In this case there are noticeable differences. These are almost completely due to the fact that the metered sample includes only seven of the 11 sites included in the billing analysis. Table 3 presents the results of a VBDD analysis of the metered total usage, in this case aggregated to daily consumption.

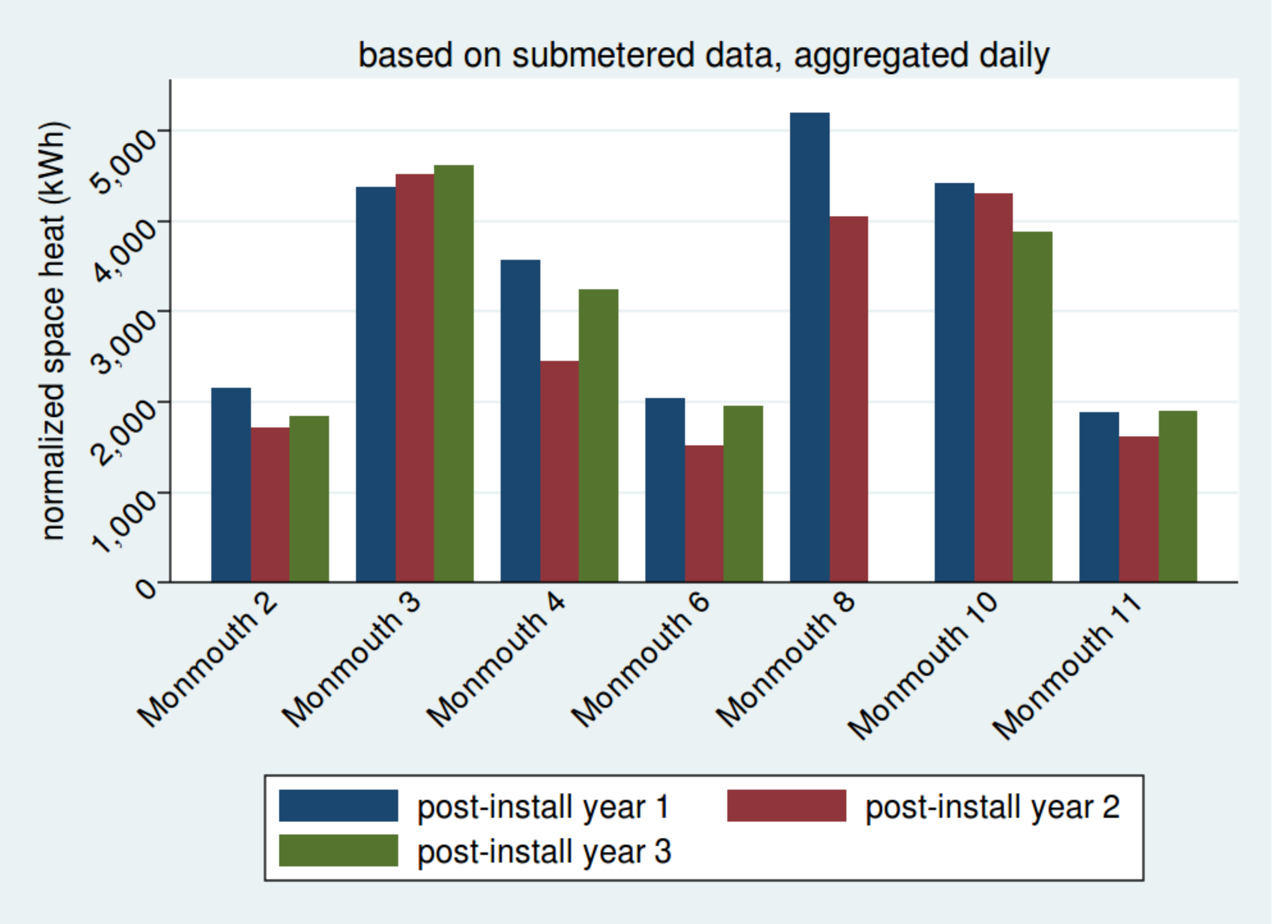
Table 3: Space Heating Derived from Metered Total Consumption (7 sites)

Analysis Period	Heat	SD
	kWh/yr	kWh/yr
Year 1	9122	5247
Year 2	7743	4252
Year 3	7785	5601

3.3.2. Metered DHP Usage

To establish the stability of the DHP use in year-three, a separate analysis of the DHP was conducted using the same weather normalizing VBDD as the previous two reviews. Figure 4 graphs weather-normalized DHP space-heating consumption for post-installation years, for the seven sites which continued to participate in metering. The exception here is Monmouth 8, which did participate in the final year. This site experienced metering equipment failure on the channel recording DHP consumption, and is not included in this analysis.

Figure 4: DHP Heat during Three Post-Install Years



In aggregate, the six remaining sites experienced no significant change in DHP normalized heating energy consumption across all three analysis years. It is apparent that the DHP is used consistently to offset electric resistance heat even if other occupancy requires more aggressive heating in portions of the house that are not immediately affected by the DHP.

Monmouth 4's increase in space-heating energy use reflected a significant increase in space heating brought on by an increase in the number of occupants over this period.

In the four Monmouth sites that dropped out of the metering component of the study, the meters were removed without an exit interview. This oversight was corrected in the remaining group when the meters were removed after two more years of data collection. One of the four sites that did not continue with the metering (Monmouth 1) had a very similar consumption to Monmouth 4. An abrupt doubling of estimated normalized space-heating consumption at this site simply cannot be attributed to minor changes (e.g., thermostat setpoints). We strongly suspect a similar explanation based on occupancy changes would apply in this case. Although significant increases in total space-heating energy use were detected in both Monmouth 4 and Monmouth 1, where we continued to measure space-heating energy consumption the DHPs remained stable, and thus savings attributable to DHP installation persisted.

Table 4 summarizes averages across sites for the data graphed in Figure 4. Only six sites are used in the DHP usage average (Monmouth 8 had no metered DHP data in the final year due to equipment failure).

Table 4: DHP Consumption, Metered (6 sites)

Analysis Period	Heat	SD	Fraction All Heat
	kWh/yr	kWh/yr	
Year 1	3075	1193	33.7%
Year 2	2688	1379	34.7%
Year 3	2912	1190	37.4%

An important observation from Table 4 is that the DHP usage remains constant in spite of changes in occupancy and overall space-heating requirements. Furthermore, the contribution to space heating across the entire metered remains remarkably stable. This suggests that the benefits of the DHP are held relatively constant by the occupants and that the offset to resistance heat in the central zone remains relatively constant.

3.4. DHP Cooling

During the last year of metering, vapor line temperature (VLT) sensors were installed at six of the seven remaining metered Monmouth sites. These sensors recorded VLT at five-minute intervals for an average of 250 days, including in every case the entire “cooling” season and all or most of what could be considered the shoulder season. The principal goal of this data acquisition task was to gain more insight into the extent of cooling use of these Monmouth DHP units. During previous years of the Monmouth study, relying solely on hourly indoor and external temperature to attribute DHP energy use to cooling, we concluded that cooling usage was minor but very difficult to quantify. Five-minute VLT permits logging a much more precise separation of energy use into heating, cooling and fan energy, and thus can confirm or qualify previous conclusions.

Once the separation of DHP energy consumption into cooling, heating, and fan energy is made, DHP cooling energy can be summed to get cooling energy for a given year. To estimate weather-normalized cooling such energy can also be aggregated at daily intervals and used in VBDD regressions, with cooling-degree days rather than heating-degree days playing the role of the determining variable. However, we did not implement this approach because such regressions typically perform poorly with billing data in Northwest climates (the monthly aggregation interval is too coarse). In the western Oregon climates, in any given month, heating and cooling energy are often comingled. These factors lead to a much “noisier” and weaker association between outdoor temperature in the form of cooling degree-days (CDD) and observed DHP cooling usage. Generally, this precludes a reliable VBDD estimate of cooling from utility bills. No separate cooling base case could be computed and so no savings or consumption increase could be calculated.

For the metered homes, however, we separated cooling energy from heating energy using VLT values. Using a daily aggregation allowed a more detailed assessment of the cooling behavior of the participants. Metered VBDD regressions on cooling-degree days perform much better than billing data regressions. Figure 5 below displays the results of a representative VBDD regression in cooling degree-days for one of our six VLT sites. A positive relationship is apparent, but it is not very clean; points falling along the x-axis represent days with positive cooling-degree days at the chosen balance point (82ºF).

Figure 5: A Representative CDD Regression

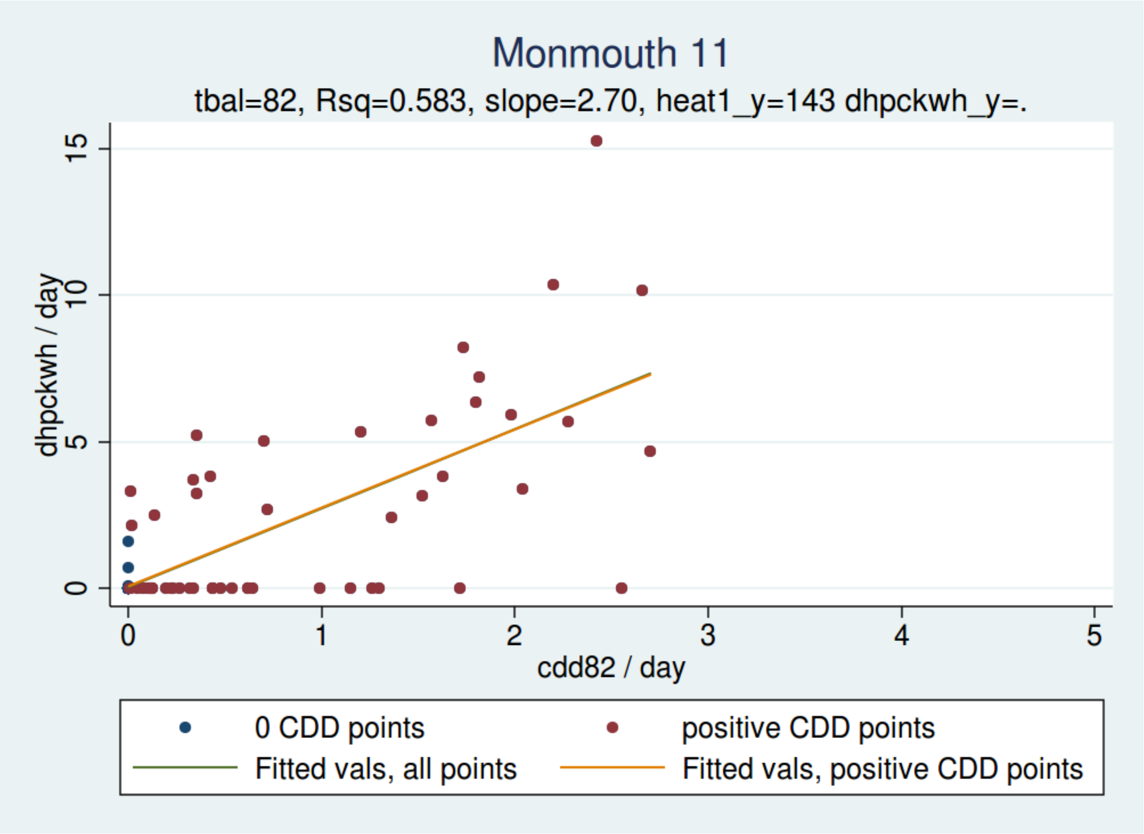


Table 5 displays DHP cooling estimates derived by adding up DHP cooling consumption over the cooling season (column 2) and normalized DHP cooling estimates derived from regressions (column 3). The normalized estimates are slightly larger than the raw cooling season sums for the following reasons:

- The summer (cooling season) of VLT measurement in question was relatively cool.
- The VLT data window did in fact miss some fraction of shoulder season cooling.

Note that Monmouth 8 does not have an estimate of normalized DHP cooling. Due to a partial failure in the VLT temperature sensor at that site, the total DHP cooling load for the VLT period was too small to estimate a VBDD regression.

Table 5: DHP Cooling Estimates

Site	Year 3 DHP Cooling kWh Sum	Normalized DHP Cooling kWh/Yr	Days Of VLT Data
Monmouth 2	177	192	284
Monmouth 3	106	115	297
Monmouth 6	110	125	284
Monmouth 8	-	-	132
Monmouth 10	57	69	297
Monmouth 11	132	152	194
Average	98	130	248

As seen in Table 5, both of the methods deliver very low estimates of cooling energy use in this climate. For each of the two estimates, the DHP cooling is a minor curiosity. These estimates can be compared with the DHP cooling estimates derived from imputed cooling load as a result of outside temperature from the year-two report of approximately 150 kWh/year/site.

It should be pointed out that in some of these homes a window AC unit may have been used in years before the DHP installation. Since our base consumption estimates depend on a billing analysis there is no way to confirm the degree to which these sites employed small zone coolers. No interview was conducted to ascertain if the occupants used cooling of this sort. We can point out, however, that the cooling efficiency of the DHP is more than twice a typical new window AC unit. Thus, if such cooling was used the observed cooling in this study would almost certainly represent an additional energy savings not accounted for in the normalized heating calculations reported above.

3.5. Summary of Findings

Our point estimate for average weather-normalized space-heating savings for our 10 Monmouth sites, based on the pre-installation billing data and third-year billing data, is 3978 kWh/year. The sites that remained in the metering program after the first year performed somewhat better. In the third year, the savings estimate for that group was 5109 kWh/yr. This savings estimate can be attributed to the large differences between the consumption patterns of this group compared to the group that had the meters removed after the first year. Table 6 shows the comparison between the entire remaining sample (one site was actually vacant in the third year and was removed from this summary). This summary shows the importance of a single site within a small sample. One of the billing-only sites (Monmouth 1) had a significant increase in consumption and this single site reduced the apparent savings from the entire group by about 14%. The remaining sites were largely stable over the three and a half years of metering.

Table 6: DHP Savings, Monmouth Sites

Analysis Period	Savings		
	10 Total Sites	7 Metered Sites	3 Sites, Billing only
	kWh/yr	kWh/yr	kWh/yr
Year 1	4617	5073	3550
Year 2	5298	6151	3306
Year 3	3978	5109	1336

This is a conventional, weather-normalized estimate, derived from VBDD regressions on post- and pre-installation billing data. The use of billing analysis to derive the DHP savings estimates differs from the procedure used in the year-two analysis. In that analysis metered space heating was used and adjusted to account for residual (un-metered) heating usage. Using billing analysis provides an alternative to correcting the biases observed in year two. In this report we have reported results based on this approach. Using billing analysis allowed estimates for all occupied homes from the original Monmouth sample.

4. Conclusions

The Residential Ductless Mini-Split Heat Pump Retrofit Monitoring Study was launched at the end of 2007 and was continued until the fall of 2011. The study has provided the region with a small-scale experiment to understand the DHP technology and to provide insights into the analysis and pitfalls that were subsequently used to evaluate the larger regional effort. These insights included the importance of occupant interviews and detailed home characterization in developing a firm picture of the performance determinants. While this sample was generally too small to be definitive it pointed to the size of the savings potential the technology offered.

In another part of the study, detailed measurements were made of a single piece of equipment. These measurements later became the basis for more formal lab testing and for refining the metering design used in the regional NEEA DHP evaluation. The results of this preliminary work improved both the quality and the efficiency of the data collection that followed. In this sense, the small number of DHP sites that were analyzed in the Monmouth area provided significant returns that far outweighed the size of the final analysis.

4.1. Persistence

The persistence of DHP savings was evaluated for all but one of the original Monmouth sites. This site was vacant during most of the last year of the study and virtually no space heating was consumed during this period. We elected to remove this site since it would clearly bias the analysis. In two other sites there were significant occupancy changes that resulted in increases in both overall electric consumption and space-heating consumption. These sites reduced the overall savings but they were included in this analysis. The combination of these sites reduced the savings estimate but the DHP monitoring in at least one site suggested that the use and impact remained constant in spite of the changes in occupancy patterns.

The persistence analysis showed a similar total savings each year of the study. But by far the most important factor was the consistency of the DHP itself. Over this entire period the general pattern is that this equipment continues to provide a similar level of performance and space-heating savings independent of the other changes in occupancy over time. This finding suggests that the technology is very robust and continues to produce savings even with occupancy changes.

4.2. Cooling Loads

The cooling impact measured by the metered VLT sensors establishes the fact that some cooling can be expected even in relatively mild climates such as Monmouth. The size of this cooling load, however, is very small and probably will not affect any billing analysis of heating savings. Moreover, given a cooling baseline of window AC units, the pre-installation cooling use would probably more than offset the cooling energy use of the DHP. As a result of this finding no savings offset is recommended for this technology at least when it is installed in mild cooling climates such as the Willamette Valley in Oregon.

5. References

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Appendix A: Methodological Notes

The length of post-installation metered data available for this follow-up study varied from site to site, from a little over three years (with three complete heating seasons) to almost four years (with almost four heating seasons). Some sites had data gaps induced by intervals between metering equipment failure and replacement, or by delayed retrieval of data (leading to storage buffer overflows). Given this heterogeneity in data availability, we defined three post-installation analysis periods ("years") individually at each site so as to have an equal quantity of analysis data in each of the three years at each site. Similarly post-installation analysis of billing data used period break points which put an equal number of billing records (or a maximum difference of one record) in each of three post-analysis years. For a given site the post-analysis years were thus defined separately for billing data and for metered data. They were not constrained to cover the same exact intervals, although there was of course substantial overlap. Although the word "year" is used, the post-installation periods are not years (but generally somewhat longer than a year) and not even defined as equal-length periods, but rather equal-available-data periods. Given that the focus of analysis is on the longitudinal behavior of each data type stream, rather than comparison across data types, maintaining a strict common definition of data periods across data types is not convenient.

Note that both billing data consumption and whole house service metered consumption contain a few elements (notably domestic hot water, but also lighting) which are not space heating but can "look like" space heating in that they have some apparent positive association with degree-days. This spurious correlation is generally more marked in monthly-aggregated data (such as bills) than in metered data aggregated daily. If the analysis focus is on changes to space-heating energy consumption, rather than absolute levels, this problem can generally be ignored, since a change in space-heating systems generally does not perturb these other uses.

A trigonometric procedure to correct pre-installation space-heating estimates was used in year one and a residual analysis based on metered residual electric load was used in year two. In this analysis, the billing analysis assumes that the seasonal loads of all sorts cancel. Thus, while the absolute heating estimates may be biased by such use, the same bias on both the pre and the post installation bills will cancel and result in an un-biased estimate of space-heating savings.