BONNEVILLE POWER ADMINISTRATION

Residential Ductless Mini-Split Heat Pump Retrofit Monitoring: 2008-2010 Analysis

September 27, 2010

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Executive Summary

Beginning in 2007, BPA sponsored a small pilot project aimed at demonstrating the feasibility of using ductless heat pump (DHP) technology as a retrofit for residential zonal electric space heating. The installations were designed to provide supplemental heating to offset the heating energy requirements from electric resistance zonal heating systems. The DHP was installed to displace space-conditioning requirements with a high-efficiency heat pump in the central zone of each of these homes. The installation was not intended to provide a full replacement heating system.

Fourteen initial pilot installations of these systems were carried out in Monmouth OR, Moses Lake, WA and Tacoma, WA in 2007 and early 2008. These sites received a “quad-metering” monitoring package to record the performance of the DHP installation as well as the installed space heating, domestic hot water (DHW) and total electric use. Seven of these homes (all in Monmouth, OR) continued to allow the metering and were continuously monitored from early 2008 through March of 2010. In addition, utility bills were collected for a period that included at least three years of billing data prior to the DHP installation. These bills were used to establish the base heating consumption and estimate the savings from the DHP installation.

This report summarizes a subset of this group from a second year of metering in seven (all in Monmouth) of the 14 homes, and a second year of billing analysis only on the remaining four Monmouth homes. The primary goals of this study were to:

- Provide a detailed verification of Regional Technical Forum (RTF) energy-savings assumptions.
- Refine the DHP billing analysis methodology for implementing a larger review of DHP retrofits in zonal electric-resistance-heated homes.
- Assess the short-term persistence of savings in these homes with DHP installations.

The analysis used a “variable-base degree-day” (VBDD) methodology (often referred to as PRISM) to evaluate the electric bills and develop baseline energy requirements and the space heating usage prior to the installation of the DHP system. The quad-metering system provided a direct measure of the heating usage during the one-year study period. Results were weather-adjusted to provide a valid estimate of energy savings. For some homes, the second-year savings were estimated from the bills provided from that period without any direct metering of those homes. In these cases the previous metering was used to inform the analysis, especially in establishing the seasonality of the DHW loads. All savings estimates are expressed in terms of the two years of DHP operation (through March 2010) compared to the space heating estimated from the three to five years of electric bills collected prior to the DHP installation.

Our point estimate for average per-site savings in space-conditioning consumption, adjusted for the current study monitoring period, was 4,204 kWh/year. This savings compares with the estimate of 4,442 kWh/year from the previous monitoring period. Variations in usage from DHW and space heaters not metered were identified in the billing analysis and led to separate adjustments in the heating energy savings estimates. The results of this analysis led to the following recommendations and observations:

- Cooling load assessment remains a problem in this data set. For the third monitoring year, a vapor line temperature was specified to get a conclusive space cooling estimate. Cooling loads could represent a significant reduction in the net electric savings from the DHP installations. In the next year’s analysis direct metering of cooling will allow this effect to be better quantified.
- Supplemental space heat provided by 120V plug-in heaters can be significant, and the analysis method must take them into account when evaluating the post-installation space heat load.

- The seasonality of DHW loads (the potential base-load bias) is overestimated by the standard approach used in billing analysis. The use of the quad-meter format allows this bias to be corrected for each individual home.
- Weather normalization procedures are quite useful in understanding the space-heating load but also helpful in understanding the biases introduced by other appliances. The submetered analysis provides the opportunity to evaluate these effects and biases in detail.
- Billing analysis is improved substantially when bills are available over a three-year period. This extended billing period allows more stable estimates of base loads and heating loads.

1. Introduction

The Pacific 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. These systems are largely manufactured in East Asia and use inverter-based compressor and air handler designs. They are (in this effort) designed to deliver conditioned air to a specific zone(s) without ducts. Fourteen initial pilot installations of these systems were carried out in Monmouth OR, Moses Lake, WA and Tacoma, WA in early 2008.

Residential Ductless Mini-split Heat Pump Retrofit Monitoring (Geraghty, et al. 2009) presented a first analysis of energy savings achieved by retrofitting ductless heat pumps (DHP) into these fourteen zonal electric resistance-heated houses. The study suggested an average savings of about 4400 kWh/year relative to pre-installation conditions. This study is a follow-up to that research, with more available data and with some methodological refinements.

Of the 14 pilot installations, the 11 located in Monmouth remain in the analysis data set. Seven of these 11 have ongoing submeters collecting detailed information on energy use in the heating system, as well as the domestic hot water (DHW) and the overall electric energy use of the home.

The objectives of this second-year analysis were designed to confirm the earlier findings and to provide further methodological refinement for use in future evaluation of this technology and application:

- The original study was based on about a year of post-installation submetered data (four electric use channels, electric resistance space heat, DHP use, DHW energy use, and total electric use). In this analysis the goal was to gather an additional year of submetered data and all of the electric use channels to develop a more robust energy savings estimate of the DHP measure.
- Evaluate the second-year savings to ascertain any longer-term tendency towards performance degradation or changes in space-conditioning energy use.
- Review pre-to-post analysis based only on billing data and assesses the findings and conclusions. Post-installation billing data was unavailable in the previous study. Using a greatly expanded set of billing data (three years pre-installation and two years post-installation), the savings were evaluated using conventional billing analysis, and compare this analysis with submetered data from each site.
- Assess the consistency between submetered consumption data and contemporaneous billing data.

This analysis is divided into two annual periods. The first, represented by the previous report (Geraghty, et al, 2009), extended from February 2008 to March 2009. The second period begins in March 2009 and extends through March 2010. In both the submetering summaries and the billing analysis the analysis is divided into these two periods.

2. Changes in Post-Installation Consumption

2.1. Variable-Base Degree-Day Analysis

Seven of the original 11 DHP installations at sites in Monmouth, OR consented to continuing submetering of household consumption. For these seven sites a median of 28 months of submetered data was recorded, encompassing all or most of three heating seasons. This represents a little more than twice the data timespan available for the previous analysis. To test for changes in the seven extended sites over this roughly 28-month period, we cut each household data stream at its temporal midpoint, and compared consumption of the two approximately 14-month halves, with appropriate weather normalizing. Because the seven households had submetering installed, and data downloaded, at slightly different times, the series from different sites were not of precisely the same length, and the temporal midpoint of each data set did not generally fall on exactly the same day. As in the original study, the hourly energy consumption channels captured were ductless heat pump usage (DHP), 220V electric resistance (ER), domestic hot water (DHW), and total service.

In the original 2009 study we performed minimal adjustment or transformation on the post-installation submetered consumption series. To compare post-installation submetered consumption with pre-installation billing data, we time-shifted only the pre-installation billing data to put it on the same weather footing as the post-installation submetered data. Using standard variable-base degree-day (VBDD) regression techniques[1], we applied pre-installation VBDD degree-day response coefficients and balance point, estimated from billing data, to the weather actually encountered in the post-installation submetering period. The analysis was thus framed in terms of the submetering period's weather, rather than in terms of typical or average weather. This was referred to as weather-*adjustment* rather than the more common weather-normalizing. In the current analysis, to put the two post-installation subperiods on an equal weather footing, our approach has been to weather-normalize results from each of the two periods, calculating the consumption that would be expected given long-term average annual heating degree-days calculated from Salem, OR weather station data. The Salem weather station is about 11 miles distant from Monmouth, and at a similar elevation.

To weather-normalize, we applied essentially the same VBDD methodology to the submetered data that is conventionally used on billing data. The use of a shorter aggregation interval offers the advantage of far more independent observations with which to estimate degree-day response coefficients. In practice we settled on daily aggregation. VBDD regressions directly on hourly submetered data were reviewed but the hourly relationship between degree-hours and heating energy use is muddied by such issues as thermostat setbacks, solar gains during daylight hours only, thermal mass effects, and occupant behavior. Most of this intraday variability cancels out with daily data aggregation.

Temperature data collected onsite were used to calculate the daily heating degree-days (HDD) used in these VBDD regressions. We applied this VBDD analysis to all submetered data channels known, or suspected, to contain space-heating energy loads. This included not only the DHP and ER channels, but also "residual" energy use. Residual energy use over a given period is the difference between total service energy use and the sum of all the submetered energy uses (DHP, ER, and DHW). We had no

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[1] See Appendix A of the previous report (Geraghty, Baylon, Davis, 2009) for a discussion of the VBDD method.

prior reason to believe that this residual consumption contained any space-heating end uses or had any significant functional relationship with heating-degree days. But it became clear in the course of VBDD analysis that in fact in at least some cases this residual consumption had a strong relationship with heating degree-days (HDD). It was difficult to come up with reasonable explanations for this relationship that did not involve space heat[2].

2.2. Comparison Within Submetering Periods

Table 1 displays a comparison of submetered energy use components related to space heat in the two adjacent post-installation periods. These space heat energy estimates are composed of DHP submetered total, electric resistance submetered total kWh, and the derived space heat estimate from the seasonality of the residual kWh (the difference between the space heat channels, the DHW channel and the total use channel in the submetered record). Results for each of the seven sites which agreed to continue submetering are shown. All figures are kWh/year, normalized to long-term Salem, OR weather averages using the VBDD method. The average change (delta) for these channels is shown in bold type on the "Mean" row near the bottom of the table. It should be apparent that although some individual sites have noticeable swings in one or more of these components, the average change in each is indistinguishable from zero (as indicated by the t-statistic).

Table 1: Comparison of Space Heat Energy Components in Different Post-Installation Subperiods, 2008-2010

Monmouth Site #	DHP period 1	DHP period 2	DHP delta	ER period 1	ER period 2	ER delta	Residual period 1	Residual period 2	Residual delta
2	1935.09	2079.60	144.51	0.45	4.76	4.31	41.18	1399.74	1358.56
3	3225.14	4020.10	794.96	0.00	0.00	0.00	429.92	69.66	-360.26
4	3155.28	2343.78	-811.50	4222.58	6366.19	2143.62	3968.29	3380.38	-587.91
6	1742.74	1537.87	-204.86	4763.58	4031.63	-731.95	0.00	326.96	326.955
8	4897.75	4731.58	-166.17	4179.16	2615.53	-1563.63	760.68	694.05	-66.63
10	3885.12	4183.72	298.60	2147.07	901.76	-1245.31	3015.94	3158.90	142.96
11	1906.97	1866.60	-40.37	0.00	121.62	121.62	476.55	65.58	-410.97
Mean	2964.01	2966.18	**2.17**	2187.55	2005.93	**-181.62**	1241.79	1299.32	**57.53**
std dev	1180.40	1299.51	495.26	2202.26	2459.17	1218.64	1583.30	1422.73	658.10
t-stat			0.01			-0.39			0.23

Labeling Notes:
Period 1 = February 2008 to March 2009
Period 2 = March 2009 to March 2010
DHP: submetered DHP energy consumption, weather-normalized kWh/yr
ER: submetered electric resistance heat energy consumption, weather-normalized kWh/yr
Residual: degree-day sensitive portion of residual submetered load (metered whole house – DHW - ER- DHP), weather-normalized kWh/yr
mean: average of 7 individual Monmouth sites
std dev: sample standard deviation of 7 individual Monmouth sites
t-stat: standard t-test with 6 degrees of freedom for the hypothesis that the mean is 0

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[2] 110V plug-in resistance heaters would end up in the residual category.

Table 1's estimated values for normalized DHP, ER, and residual consumption are combined in two ways as alternate total space heat estimates in Table 2. The three components show effectively no average change between post-installation subperiods. Because there is so little tendency for post-installation space-heat consumption to change systematically over time, we analyzed all 11 Monmouth sites jointly without distinction between the seven with extended post-installation submetering of data, and the four with only data from the first submetering period.

Table 2: Comparison of Aggregate Space-Heat Energy Consumption in Different Post-Installation Sub periods, 2008-2010 (Using Submetered Data)

Monmouth site #	space heat period 1	space heat period 2	space heat delta	augmented space heat period 1	augmented space heat period 2	augmented space heat delta
2	1935.54	2084.37	148.83	1976.72	3484.11	1507.38
3	3225.14	4020.10	794.96	3655.06	4089.75	434.69
4	7377.86	8709.98	1332.12	11346.14	12090.36	744.21
6	6506.32	5569.50	-936.81	6506.32	5896.46	-609.86
8	9076.92	7347.12	-1729.80	9837.60	8041.17	-1796.43
10	6032.19	5085.48	-946.70	9048.12	8244.39	-803.74
11	1906.97	1988.22	81.25	2383.52	2053.80	-329.72
mean	5151.56	4972.11	**-179.45**	6393.35	6271.43	**-121.92**
std dev	2815.34	2520.95	1078.26	3797.74	3448.24	1100.36
t-stat			-0.44			-0.29

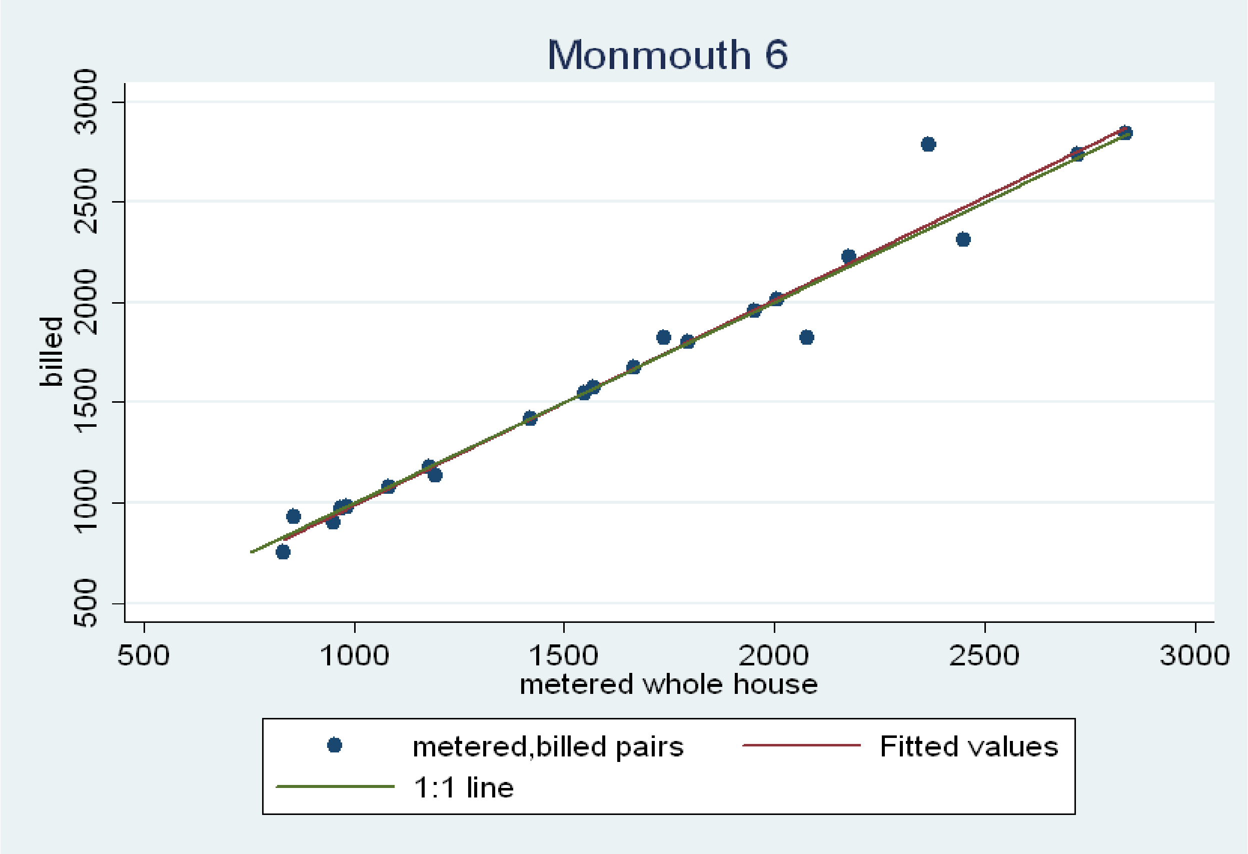
Labeling Notes:
Period 1 = February 2008 to March 2009
Period 2 = March 2009 to March 2010
space heat: sum of DHP and ER energy consumption, weather-normalized kWh/year
augmented space heat: sum of DHP, ER, and HDD-sensitive portion of residual load(if it is >0), weather-normalized kWh/yr
mean: average of 7 individual Monmouth sites
std dev: sample standard deviation of 7 individual Monmouth sites
t-stat: standard t-test with 6 degrees of freedom for the hypothesis that the mean is 0

3. Comparison of Billing Data and Submetered Data in the Post-Installation Period

3.1. Aggregated Monthly Comparisons

This data set offers an ideal opportunity to compare analysis results from billing data with those from submetered data, since both forms of data are available contemporaneously for the entire post-installation period (2008–2010).

Figure 1: Billing Data (kWh) vs. Aggregated Metered Data (kWh) for a Representative Site



A first step is to ensure that the two data sources are mutually consistent over the post-installation period. If metered whole-house kWh consumption data are aggregated to match the intervals between billing data read dates, then they ought to agree with kWh consumption figures from billing data. Figure 1 provides a graph of a representative example of this comparison for one of our seven extended submetering sites. The green line is a 1:1 line through the origin on which all points should lie if the agreement between billed and metered consumption is perfect. It is apparent that in fact there is some point scatter around this line, but that the fit is reasonably close.

There are several reasons for minor discrepancies:

- Even if meter read dates are accurately recorded and are true reads rather than estimates, we still don't know the hour that the read occurred. For convenience we have assumed that all the hourly data on a date of a meter read belong to the concluding read period, although this assumption is only an approximation.
- In many cases estimated, rather than actual, meter reads can account for occasional larger discrepancies seen at a few of our sites.

The brown line in Figure 1 is a fitted least-squares regression line. It coincides reasonably well with the theoretical 1:1 line through the origin, suggesting no important discrepancy between the two data sources. Table 3 displays the results of regressing billed kWh on whole-house metered kWh (the brown line in Figure 1) for all of our 11 Monmouth sites. There is a very slight tendency for the slope to be greater than one, and for the intercept term to be correspondingly negative rather than zero, but it does not rise to the level of statistical significance. One might conjecture that small differences in the algorithm for computing true power used by different metering equipment could account for this tendency.

Table 3: Coefficient Values for Regression of Billed kWh on Whole-House Metered kWh, 2008-2010

Monmouth site #	slope of billed regressed on metered	t-test for slope!=1	constant	t-test for constant!=0
1	0.931	-0.36	5.87	0.02
2	1.056	0.69	-106.06	-0.76
3	1.018	0.47	-19.95	-0.51
4	1.009	0.29	-14.13	-0.20
5	1.008	0.14	-4.60	-0.07
6	1.026	0.63	-40.02	-0.54
7	0.996	-0.11	-0.67	-0.01
8	1.009	0.19	-21.20	-0.19
9	1.016	0.39	-3.97	-0.05
10	1.007	0.17	-17.77	-0.21
11	1.027	0.30	-58.93	-0.36
mean	1.009		-25.59	

3.2. Space Heating Comparisons

The next step was to compare space heat estimates derived from billing data with those derived from submetered data. Using the procedure outlined in Section 2, the various heat energy components are combined together to form total weather-normalized heat energy estimates. In contrast to the separate sub period estimates of Table 2 performed on seven sites, these estimates were performed for all 11 Monmouth sites, and using for each site the entire period of available submetered data. Our policy regarding apparent space heat energy in "residual" was to include it in the overall sum if the HDD response coefficient was positive and significant. We regard this as a conservative rule, since some non-space-heat, non-DHW elements of household consumption (e.g., lighting) are capable of producing at least slight positive seasonal HDD response coefficients. Table 4 displays resulting space heat estimates for our 11 Monmouth sites. A few more details of the regression procedures applied to submetered data and of estimated regression parameters can be found in Appendix A.

Table 4: Post-Installation Space Heat Estimates from Submetered Data, 2008-2010 (in kWh/yr)

Monmouth site #	DHP	ER	residual	total space heat
1*	2361	3196	0	5557
2	1915	0	673	2588
3	3507	0	320	3828
4	2656	5129	3569	11355
5*	1407	2180	0	3586
6	1603	4240	43	5886
7*	2028	1712	175	3915
8	4671	3316	735	8722
9*	2355	736	1251	4342
10	3922	1484	2906	8313
11	1792	62	682	2536
mean	2565	2005	941	5511

*****only one year of post-installation data available
Labeling Notes:
DHP: ductless heat pump kWh/yr, weather-normalized
ER: Electric resistance kWh/yr, weather-normalized
residual: HDD-sensitive portion of residual load, if >0, weather-normalized
total space heat: (DHP + ER +residual) kWh/yr, weather-normalized
mean: average of values from 11 individual Monmouth sites

Table 5 presents weather-normalized space heat estimates for the same post-installation period using billing data. Standard VBDD space heat estimates are shown with the two alternative corrections for seasonal space heat use. Columns (3) and (4) display alternate adjustments to this estimate to account for the bias imparted by DHW energy use. DHW energy use has no direct functional relationship to heating-degree days, but seasonal correlation between input ground-water temperature changes and heating-degree days give rise to a positive, but spurious, statistical relationship between DHW energy use and heating-degree days. Column (3) contains the results of a trigonometric correction procedure developed for the billing data only, with no knowledge of the actual DHW use in the home[3]. Column (4) is an alternate "hybrid" correction suggested by our submetered regressions, and making use of submetered DHW data. We regress submetered DHW data, aggregated by month, onto HDD to the base which the billing data VBDD procedure chose as the "best fit"; we then subtract the resulting HDD slope coefficient from the VBDD billing data slope coefficient to correct it for hot water effects. This hybrid correction is on average about 400kW smaller than the more trigonometric correction used in the previous analysis. Column (5) applies the hybrid correction to the original VBDD heating estimate in column (2) to arrive at the final corrected heating estimate.

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[3] Geraghty et al. 2009, Appendix A, p. 18

Table 5: Post-Installation Space Heat Estimates from Billing Data, 2008-2010 (in kWh/yr)

Monmouth site #	(2) VBDD billing heat est.	(3) trig adjustment	(4) DHW reg adjustment	(5) adjusted VBDD heat
1*	5124	-1409	-555	4568
2	2454	-1009	-332	2122
3	3926	-499	-121	3805
4	10777	-1086	-476	10302
5*	5412	-786	-815	4597
6	8188	-983	-1243	6945
7*	3714	-976	-465	3248
8	9208	-1590	-942	8267
9*	3944	-1093	-573	3371
10	10176	-1238	-1375	8801
11	3292	-1366	-895	2397
mean	6020	-1094	-708	5311

Labeling notes:
* based on only one available year of post-installation data
VBDD = variable-based degree-day
(2): standard unadjusted VBDD space heat estimate
(3): adjustment for seasonal HDD signature of DHW energy use, a trigonometric function of the VBDD regression constant term (baseload estimate)
(4): hybrid regression adjustment for seasonal HDD signature of DHW energy use, using submetered DHW data

Table 6 brings together the total space heat estimates from Table 4 (submetered data) and of Table 5 (billing data). The difference column ("delta") shows some variation in individual cases; overall it is a small difference and not statistically significant. The trigonometric correction procedure, by contrast, would over-correct by roughly 600kWh/yr. Without any DHW correction at all the billing data-derived space heat estimates would err in the other direction, roughly 500kWh too high relative to our submetered data estimates.

Table 6: Billing Data and Submetered Data Space Heat Energy Consumption Estimates Compared, 2008-2010 (in Weather-Normalized kWh/yr)

Monmouth site #	Submetered data (from Table 4)	VBDD billing data (from Table 5)	Delta
1*	5557	4568	988
2	2588	2122	466
3	3828	3805	22
4	11355	10302	1053
5*	3586	4597	-1011
6	5886	6945	-1059
7*	3915	3248	666
8	8722	8267	456
9*	4342	3371	971
10	8313	8801	-488
11	2536	2397	138
mean	**5511**	**5311**	**200**
std dev	2834	2802	765
t-test			0.87
* based on only one available year of post-installation submetered data			

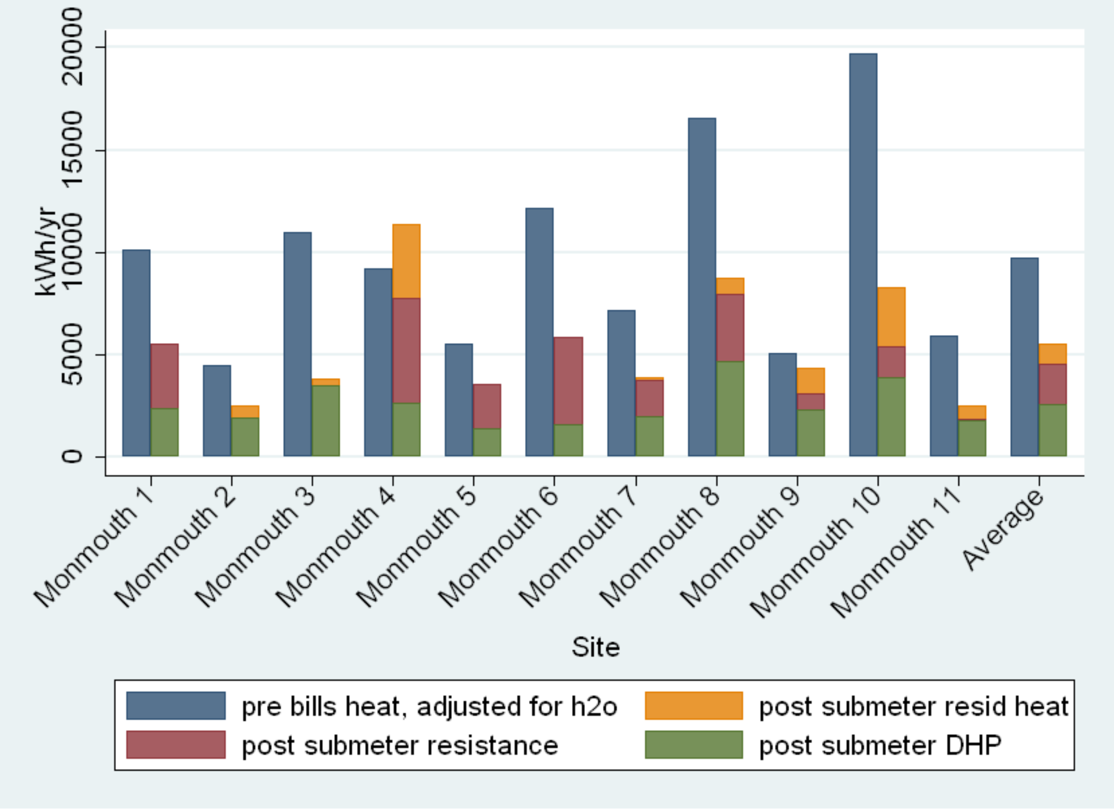
4. Calculating Savings

Having explored correction procedures which bring submetered data estimation results into close agreement with billing-data estimation results, we are now in a position to compare pre-installation space heat estimates (derived from billing data) with post-installation space heat estimates (derived from submetered data). Table 7 compares estimates of pre-installation space heat consumption with estimates of post-installation consumption. All figures have been weather-normalized. The submetered heating estimate was shown in Table 6 while the adjusted pre-period heating estimate was developed from the procedure detailed in Section 3. In Table 7, the Delta column is our best point estimate of change in weather-normalized space heat energy consumption for each of the 11 Monmouth sites. The average is about 4200 kWh/year of space heat savings. Figure 2 following the table depicts this information graphically, with the submeter-derived "post" estimates broken up into their constituent parts.

Table 7: Comparison of Post-Installation and Pre-Installation Space Heat Energy Consumption (in Weather-Normalized kWh/yr)

Monmouth site #	Post submetered data	Adjusted Pre VBDD billing data	Delta
1*	5557	10097	-4540
2	2588	4512	-1924
3	3828	10989	-7162
4	11355	9207	2147
5*	3586	5525	-1939
6	5886	12130	-6244
7*	3915	7148	-3233
8	8722	16556	-7834
9*	4342	5062	-720
10	8313	19672	-11360
11	2536	5935	-3399
mean	**5508**	**9712**	**-4201**
std dev	2837	4909	3766
* Based on only one available year of post-installation submetered data			

Figure 2: Space Heat Energy Consumption Deltas for 11 Monmouth Sites



5. Space Heat Energy Savings Estimates Based on Billing Data Alone

Billing data is inexpensive and easy to acquire relative to submetered data, so it is of interest to see how savings estimates based on billing data alone perform relative to those obtained making use of post-installation submetered data. Uncorrected VBDD regressions applied to billing or other whole-house metered data typically overestimate household space heat energy, because some energy use components which are not space heat are nonetheless correlated with HDD. Simple trigonometric corrections to VBDD space heat estimates, calculable from billing data alone, help alleviate this overestimation problem.

Relative to submetered data, consumption recorded from billing data also has other sources of inaccuracy such as occasional estimated bills. But it is quite possible; nonetheless, that billing-data based methods offer acceptable estimates of changes in space heat energy consumption. Table 8 displays site-by-site and average results for a pure billing data VBDD analysis using an average of three years' pre-installation billing data, and two years four months' post-installation billing data. It is quite striking that the average estimated space heat delta, with or without a trigonometric adjustment, is essentially identical to the point estimate obtained earlier using post-installation submetered data in Table 7. Comparing the last two columns of Table 8, it is also clear that in an average sense the trigonometric adjustment affects estimated change in space heat very little. This suggests that VBDD billing-data-derived space heat energy estimates can provide acceptable estimates of changes in space heat energy use without adjustment, even though they require adjustment as estimates of levels of space heat energy use.

Table 8: VBDD Regression Space Heat Energy, Billing Data Only (in Weather-Normalized kWh/yr)

Monmouth site #	Raw Consumption kWh	Unadjusted Space heat	Adjusted space heat (Trigonometric)
1	-3610.411	-5459.894	-5681.513
2	-761.4069	-2389.231	-2487.735
3	-4226.271	-7211.492	-7399.971
4	3171.217	1158.157	907.7676
5	-2675.832	-589.2681	-549.7329
6	-3917.753	-5184.708	-5264.879
7	-1317.784	-4032.38	-4024.149
8	-5417.422	-8174.584	-8467.294
9	-1213.905	-1773.135	-1641.962
10	-13234.37	-10699.69	-10538.34
11	-1749.422	-3537.575	-3625.011
mean	**-3177.58**	**-4353.98**	**-4433.89**
std dev	4046.51	3475.50	3472.78
t-test	-2.60	-4.15	-4.23

Labeling Notes:
mean: average of 11 individual Monmouth sites
std dev: sample standard deviation of 11 individual Monmouth sites
t-test: standard t-test with 10 degrees of freedom for the hypothesis that the mean is 0

6. A Possible Increase in Non-Space-Heat Consumption

The first data column of Table 8 shows the difference in consumption from the annualized bills without any weather or other adjustment. It is noteworthy that this difference is only a little over 3000 kWh/yr, whereas the difference in weather normalized space heat kWh, (Table 7, Table 8) are in the neighborhood of 4200 kWh. In Table 7, there is a small increase in the average annual heating degree-days from the “pre” to the “post” periods (about 4%). This might account for one-third of the 1200 kWh difference.

We suspect some fraction of this is increased cooling load. We suspect also that some fraction of this may be due to a tendency for HDD response coefficients for DHP systems to be biased low by the ability of DHP systems to switch seamlessly from heating to cooling and back in the course of a single day. To assess the magnitude of this issue, a monitoring system needs to distinguish submetered DHP heating from DHP cooling energy use. More recent metering includes a sensor to distinguish heating from cooling usage.

A third possibility is simply random fluctuation in consumption: seven to 11 sites are not a sufficient sample to be confident in any indirect inference on either these fluctuations or increase in cooling energy use.

7. Summary and Discussion

Our best point estimate for average weather-normalized space heat savings for our 11 Monmouth sites, based on the combined use of post-installation submetered data and pre-installation billing data, is 4,204 kWh/year. A conventional simple weather-normalized estimate, derived from VBDD regressions on post- and pre-installation billing data, yields a very similar point estimate of 4,354 kWh/year. The preceding study (Geraghty et al., 2009) delivered a point estimate for average weather-adjusted savings of 4,442 kWh/year. There are many differences between the two studies not only in the data sets employed, but in the methodology used:

- The current estimates are based on 11 Monmouth sites. The estimate from the preceding study was based on ten Monmouth sites, one site from Tacoma, WA, and two from Moses Lake, WA.
- The current estimates are based on three years of pre-installation billing data, 28 months of post-installation billing data, and either 28 months (seven sites) or 14 months (four sites) of post-installation submetered data. The preceding study’s estimates used one year of pre-installation billing data and 14 months of post-installation submetered data.
- The current estimates are weather-normalized, expressed in terms of expected savings given long-term weather averages in Salem, OR. The preceding study’s estimates were weather-adjusted, expressed in terms of savings given the observed year of post-installation weather.
- The preceding study used a trigonometric procedure to correct pre-installation space heat estimates based on billing data, which we have abandoned in favor of a hybrid procedure based on submetered DHW data on heating degree-days.
- We have included estimates of positive degree-day sensitive consumption in residual load in our post-installation space heat estimates. The preceding study took account only of submetered DHP and ER usage. This is a substantial methodological change, as it has decreased our current savings estimates by an average of about 1,000 kWh/year.

With these caveats in mind, based on results from seven sites with extended submetering, the average weather-normalized space heat consumption is consistent with the results seen in the previous analysis. Further research should target additional data that would resolve the cooling impact and ensure that proper accounting is taken of added cooling loads (if any) in the assessment of the overall savings from this technology. Given an addition of this data it is apparent that the methods used here will provide a very robust estimate of energy savings from the application of DHP technologies in homes with zonal electric heating.

8. References

Geraghty, Kevin, D. Baylon, R. Davis. 2009. *Residential Ductless Mini-Split Heat Pump Retrofit Monitoring*. Prepared for Bonneville Power Administration.

Appendix A: VBDD Regression Procedures Used on Submetered Data for Space Heat Calculations

This appendix details the VBDD regression procedures used on submetered data to calculate space heat energy use estimates.

For use in the regressions, hourly observations have been aggregated by day. Results of five degree-day regressions are displayed in Table 9 for each site. For each group of five regressions, the coefficients for the first four regressions sum to the coefficients for the last one (which has total house consumption as the dependent variable). If we conduct a set of linear regressions using different dependent variables, but with the same set of explanatory variables, the calculated coefficients are additive: if we add all the dependent variables together, and perform the regression of the aggregate dependent variable on the same set of explanatory variables, the resulting coefficients are exactly the sum of the calculated coefficients for the individual dependent variables. In the context of VBDD energy consumption regressions, this means that we can think of coefficients from these submetered data regressions as a decomposition of the coefficients for the aggregate house consumption, which is in effect the same as billing data consumption.

Note that to make the subcomponents of household electric consumption add up to the whole, we must include residual load as one of the subcomponents. Looked at in this way, VBDD regressions on submetered data give us a chance to see what components of household consumption actually contribute to the measured aggregate degree-day response which we observe in billing data. Using this approach the resulting regression should yield positive coefficients on both electric resistance (ER) and DHP submetered consumption (regressing these two channels against heating degree-days).

The DHW submeter is also predicted to have a positive relationship with heating degree-days. Unlike space heat energy use, DHW energy use has no direct functional relationship to heating-degree days; instead it is best related to input ground-water temperature and number of occupants. But seasonal correlation between input ground-water temperature changes and heating-degree days give rise to a positive, but spurious, statistical relationship between DHW energy use and heating-degree days. The regression on HDD results in an estimate of the effect that DHW energy use has on aggregate HDD response coefficients. This in turn gives us a more individually tailored method to correct billing data VBDD space heat estimates for DHW effects, than traditional methods which are based on an aggregate correction that does not refer to the actual DHW use patterns in each home.

The final, “residual” energy use component has in some cases strong positive relationships with HDD which we believe can only be explained as space heat; but in other cases slight or even negative relationships which do not suggest space heat energy use.

Although the VBDD methodology generally permits the degree-day base (balance point) to be estimated endogenously for each regression, we have constrained the balance point for a given site’s regressions to be the same. We chose that degree-day base as the empirical best fit for a combined space heat DHP + ER regression on degree days. There are two reasons for this analytical choice:

1. The additive coefficient property (discussed above) does not hold unless the same predictive variables are used in each regression (and degree days to different bases are different variables);
2. Only with the space heat submetered streams is there any reason to believe there is a real functional relationship between degree-days and consumption; everything else is only correlation.

As expected, DHP and ER slope coefficients are always positive and highly significant, except in cases where no resistance heat was used. DHW, as expected, also has positive and significant slope coefficients; as a component of the total house response coefficient, the DHW slope accounts for between 4% and 18 % of the total. Response coefficients on residual load are, by comparison, something of a surprise. In approximately half the cases, the coefficients are large in magnitude and statistically significant, in some cases two to five times as large in magnitude as the DHW effect. In one case the coefficient is significant and negative.

It is difficult to come up with reasonable explanations for the large coefficients in the residual load regressions that do not involve space heat[4]. We know that submetered ER is all 220V, so any plug-in 120V resistance heaters are subsumed under residual consumption. Possible setup mistakes or compromises in the presence of complex wiring situations and subpanels could have the same effect. We take the position that unless conclusively demonstrated otherwise, any positive HDD response coefficient associated with residual consumption is due to space heat not captured in the ER and DHP submetered streams. This is a conservative assumption; doubtless in some instances where the coefficients are relatively small, we are in fact capturing nothing more than seasonal lighting effects or coincidental noise.

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[4] An outdoor hot tub or heated stock tank might be one such explanation.

Table 9: VBDD Regressions for Post-Install Submetered Data Streams (daily data aggregation)

Monmouth site #	Use	DD base	constant	tconst	slope	tslope	R-squared
1	DHP	56	-0.34	-0.89	1.07	30.81	0.7346
1	DHW	56	11.54	34.49	0.2	6.7	0.1158
1	ER	56	-2.91	-4.61	1.83	31.78	0.7464
1	Residual	56	36.4	37.54	-0.71	-8	0.1571
1	Total	56	44.69	33.05	2.4	19.42	0.5238
2	DHP	51	1.52	10.35	1.01	54.47	0.836
2	DHW	51	13.08	64.51	0.16	6.24	0.0628
2	ER	51	-0.69	-5.93	0.16	10.86	0.1686
2	Residual	51	30.73	53.47	0.5	6.86	0.0749
2	Total	51	44.63	65.72	1.83	21.29	0.4378
3	DHP	56	0.32	1.21	1.46	66.62	0.8333
3	DHW	56	5.45	34.05	0.07	4.92	0.0266
3	ER	56	0		0		
3	Residual	56	9.48	49.16	0.14	8.52	0.0755
3	Total	56	15.25	38.13	1.66	49.55	0.7344
4	DHP	60	-0.72	-2.06	0.89	33.84	0.5903
4	DHW	60	9.29	28.39	0.16	6.63	0.0523
4	ER	60	-2.15	-2.52	1.81	28.2	0.5
4	Residual	60	18.58	23.69	1.09	18.53	0.3016
4	Total	60	25	17.7	3.96	37.29	0.6363
5	DHP	66	0.37	1.34	0.26	16.75	0.4216
5	DHW	66	10.93	22.65	0.1	3.74	0.035
5	ER	66	-1.96	-2.86	0.59	15.45	0.3826
5	Residual	66	15.5	26.06	-0.06	-1.89	0.0091
5	Total	66	24.84	19.51	0.88	12.53	0.2895
6	DHP	56	-0.02	-0.11	0.69	45	0.7366
6	DHW	56	8.61	37.3	0.3	13.62	0.2041
6	ER	56	-1.86	-4.21	2.12	50.98	0.7821
6	Residual	56	23.17	68.94	0.02	0.59	0.0005
6	Total	56	29.9	50.47	3.12	56.22	0.8136
7	DHP	55	1.12	3.8	0.77	27.36	0.6777
7	DHW	55	12.32	36.82	0.22	6.8	0.115
7	ER	55	-3.11	-6.11	1.35	27.69	0.6829
7	Residual	55	24	61.6	0.08	2.23	0.0137
7	Total	55	34.32	44.97	2.42	33.12	0.755
8	DHP	57	4.31	14.67	1.22	44.23	0.7234
8	DHW	57	19.25	37.94	0.17	3.65	0.0175
8	ER	57	-1.54	-2.59	1.52	27.45	0.5017

8	Residual	57	26.73	47.14	0.29	5.43	0.038
8	Total	57	48.75	51.51	3.2	36.1	0.6353
9	DHP	57	0.44	1.49	0.86	33.58	0.757
9	DHW	57	10.27	23.66	0.3	7.95	0.1486
9	ER	57	-0.73	-2.57	0.39	15.95	0.4126
9	Residual	57	30.74	44.12	0.49	8.1	0.1533
9	Total	57	40.72	38.17	2.05	22.03	0.5728
10	DHP	60	1.78	7.35	1	55.34	0.7955
10	DHW	60	13.33	36.37	0.33	11.07	0.1772
10	ER	60	-2.91	-8.62	0.78	30.86	0.5475
10	Residual	60	21.88	29.46	0.89	14.88	0.2802
10	Total	60	35.69	36.26	2.88	39.14	0.6606
11	DHP	53	1	5.64	0.83	40.42	0.724
11	DHW	53	19.65	44.6	0.29	5.34	0.0624
11	ER	53	-1.02	-3.74	0.25	8.04	0.094
11	Residual	53	29.2	39.89	0.4	4.49	0.0449
11	Total	53	49.84	52.53	1.57	14.24	0.2456

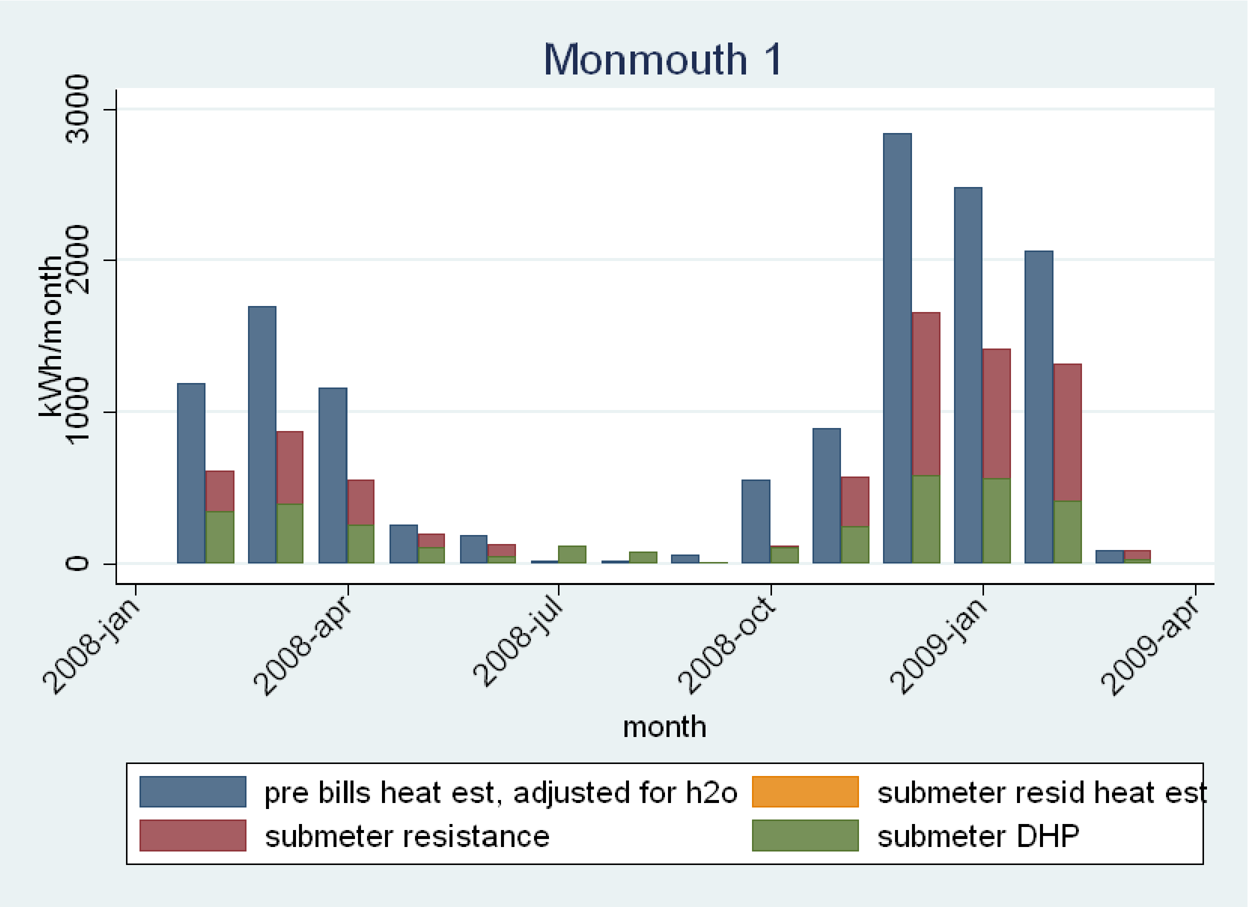
Labeling Notes:
Use: regression dependent variable (metered channel)
DD base: degree-day base used in regression (°F)
const: regression constant term
tconst: t-test value for hypothesis that regression constant is zero
slope: regression slope coefficient for regression of “yvar” on degree-days to DD base
tslope: t-test value for hypothesis that slope is 0

Appendix B: Individual Site Graphs

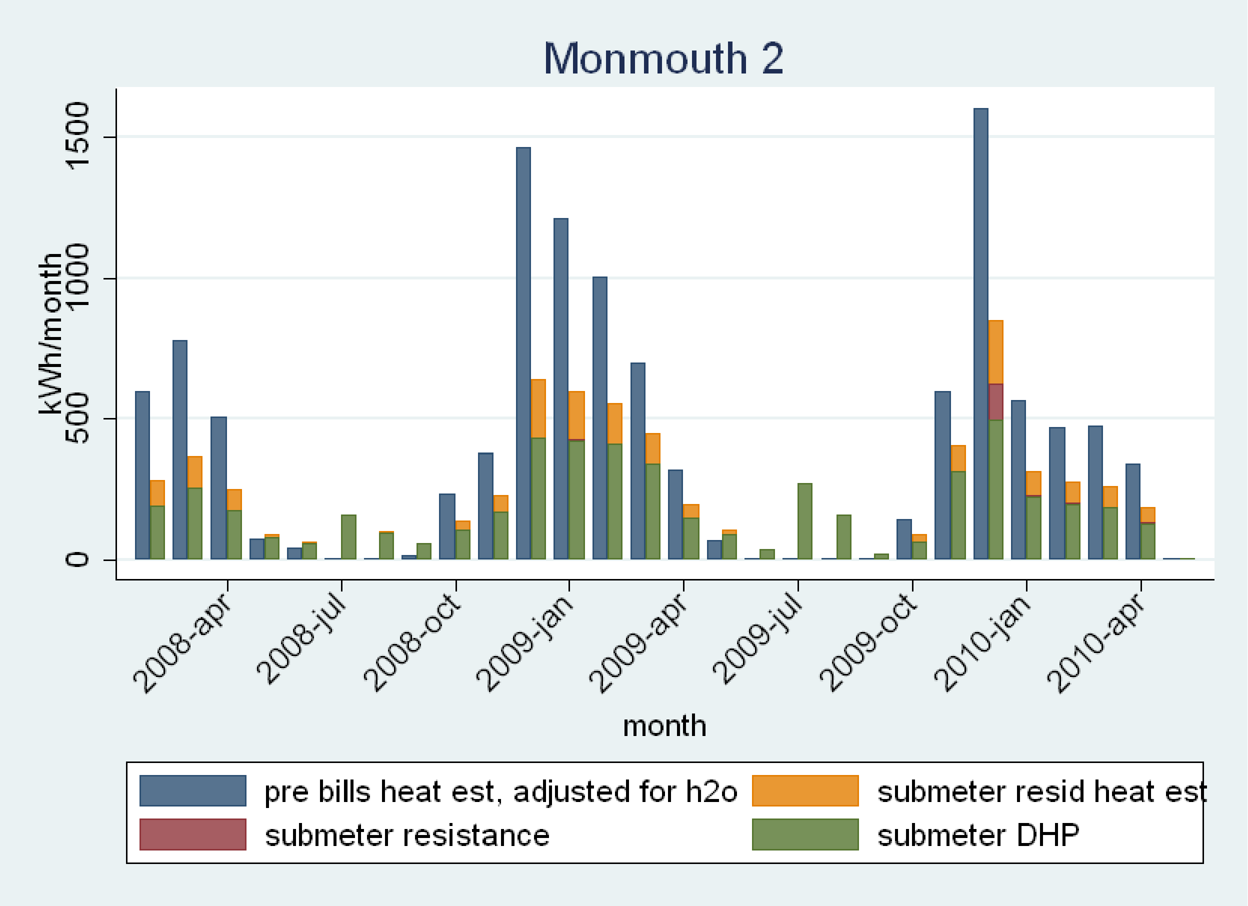
The following individual site graphs depict monthly space heat energy consumption during each site's post-installation submetering period, juxtaposed with estimated pre-installation space heat energy consumption, weather-adjusted to reflect post-installation weather. The monthly DHP and resistance figures used are actual submetered consumption for that month. The monthly "residual" consumption used is the HDD-sensitive proportion of actual residual consumption for that month, as determined by VBDD regression response coefficients. For four sites, a little over one year's data is available; for the remaining seven, a little over two years' data.

Different patterns can be noted at different sites. Summer cooling load seems minor at most sites, but Monmouth 2 shows clear evidence of DHP summer cooling use. Monmouth 11 shows that as well, but also simultaneous summer resistance heat, as if someone forgot to turn off resistance heat and the DHP fought against it all summer. Monmouth 4, and to a lesser extent Monmouth 9 and 10, show the potential importance of "residual" space heat.

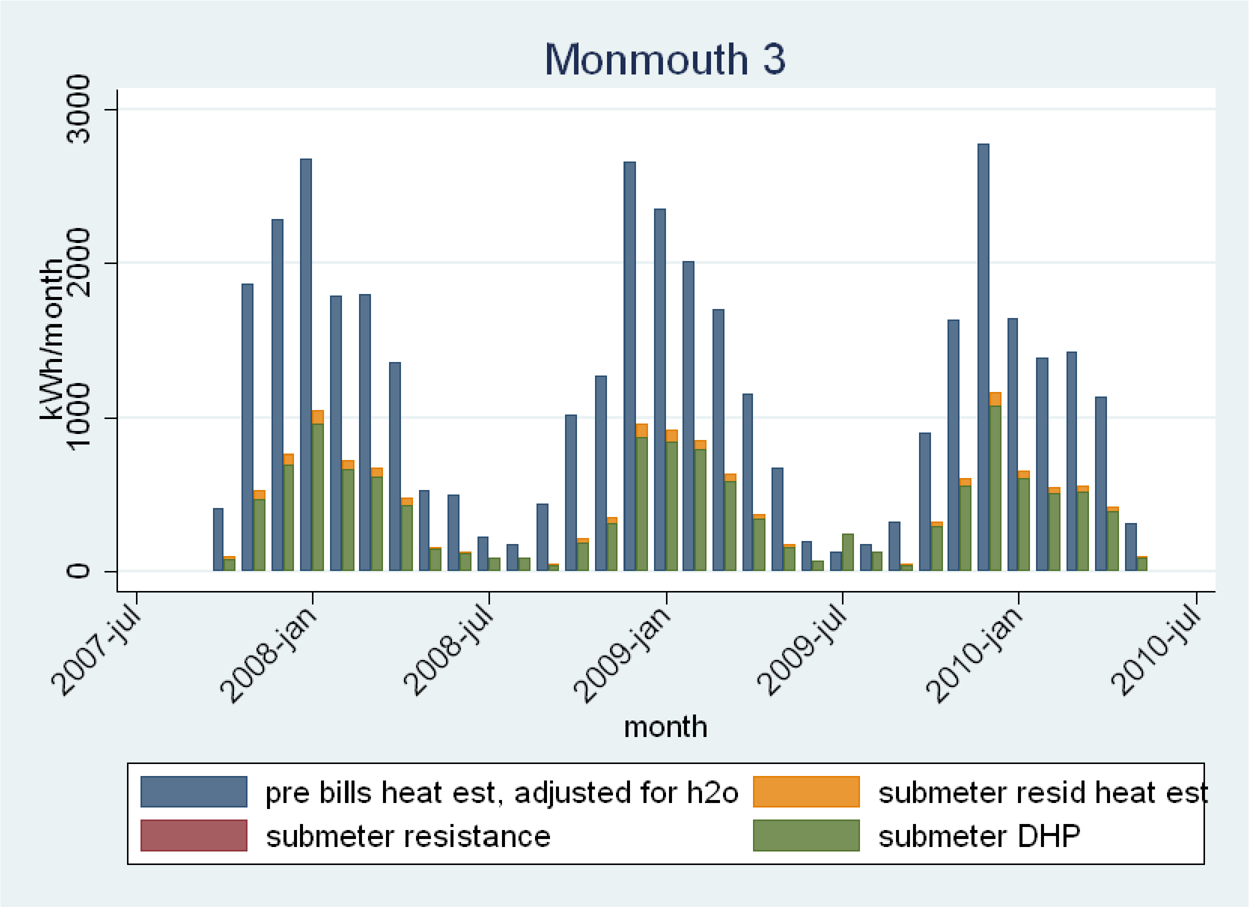
Monthly Space Heat Energy Consumption, Monmouth Site 1



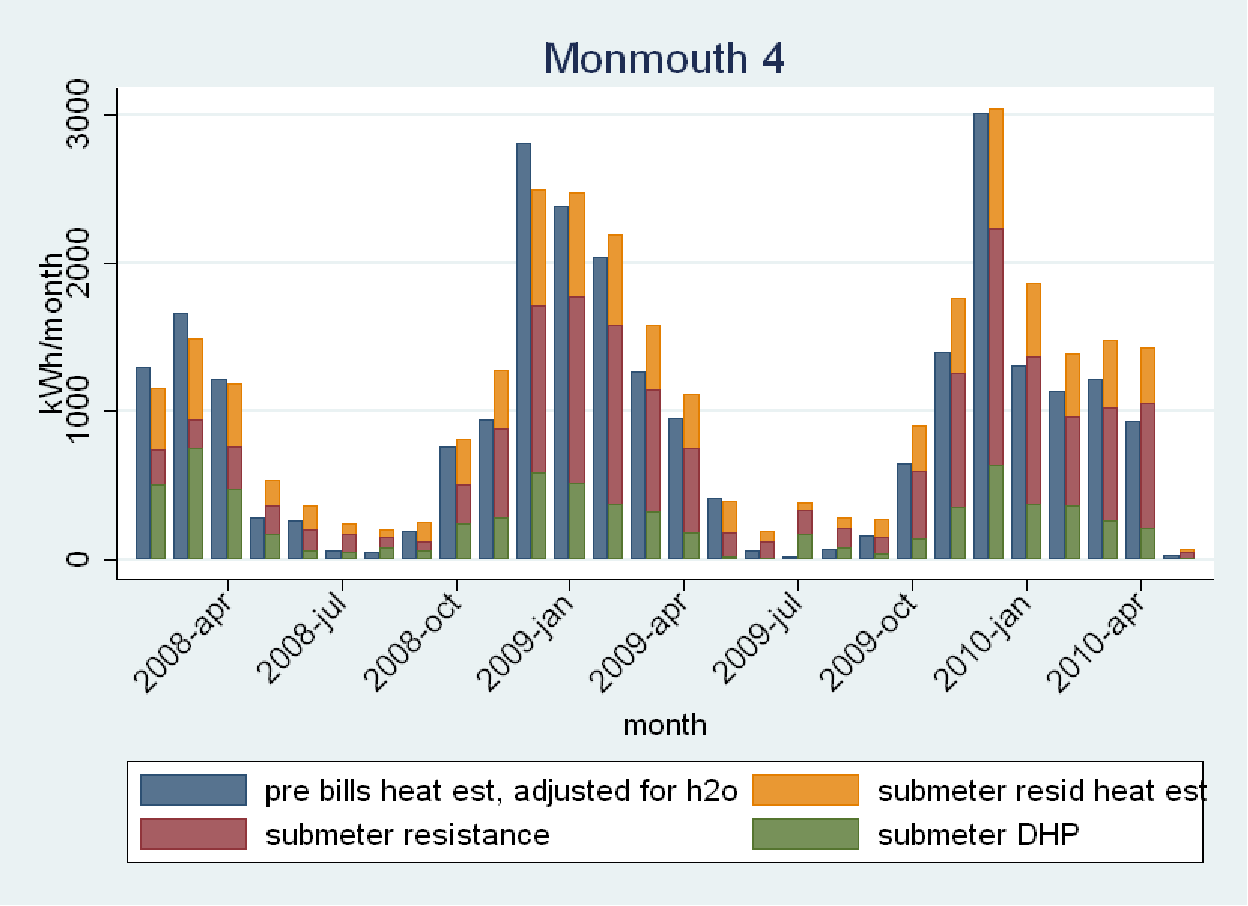
Monthly Space Heat Energy Consumption, Monmouth Site 2



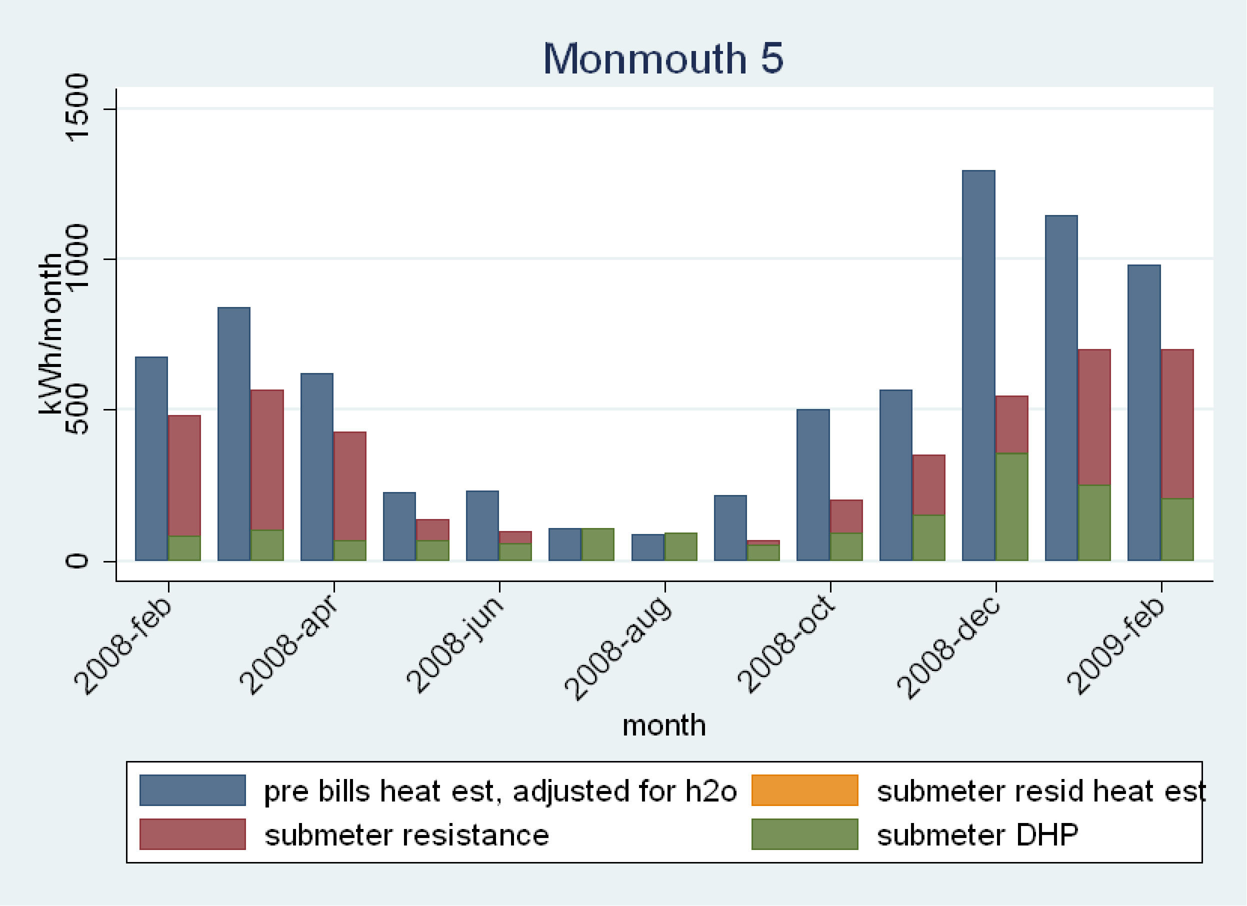
Monthly Space Heat Energy Consumption, Monmouth Site 3



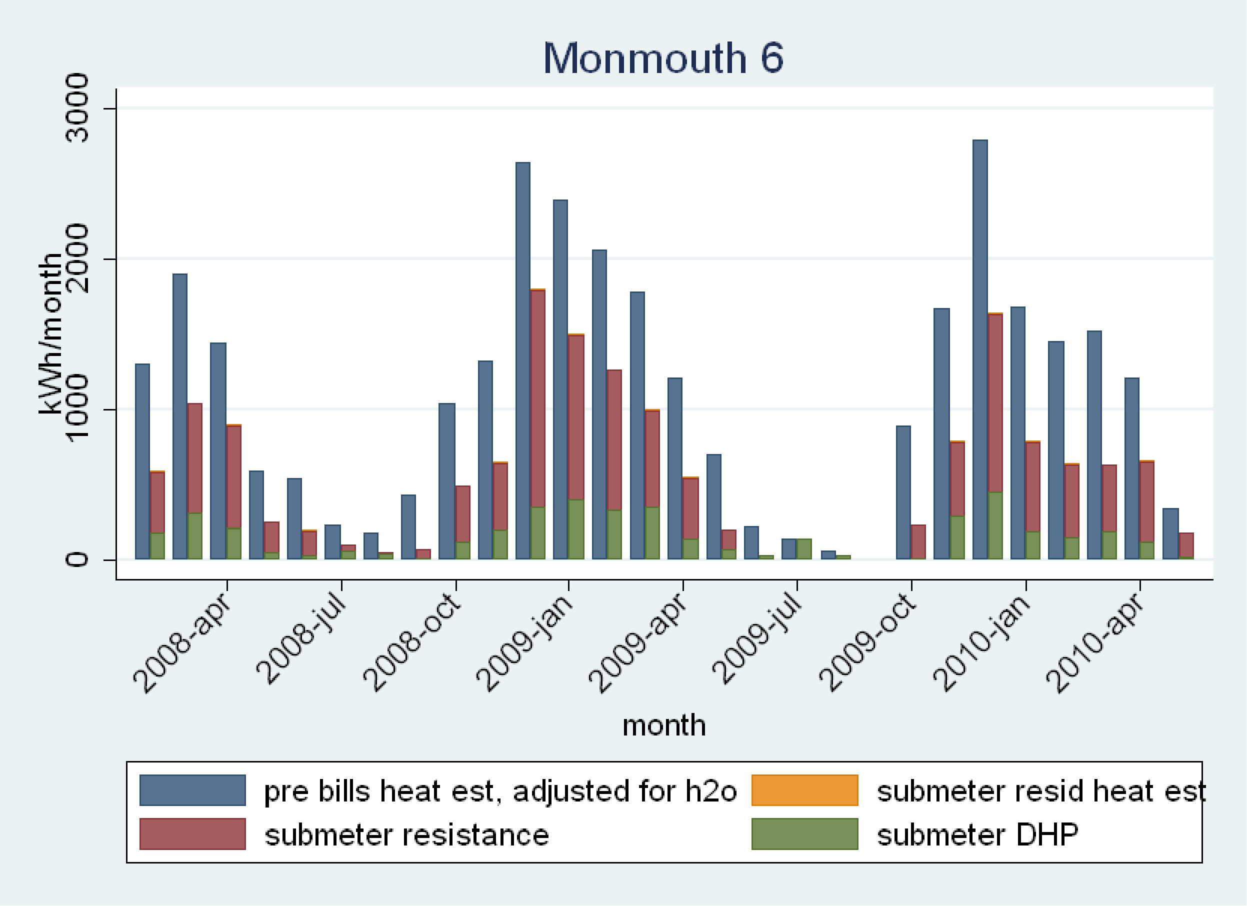
Monthly Space Heat Energy Consumption, Monmouth Site 4



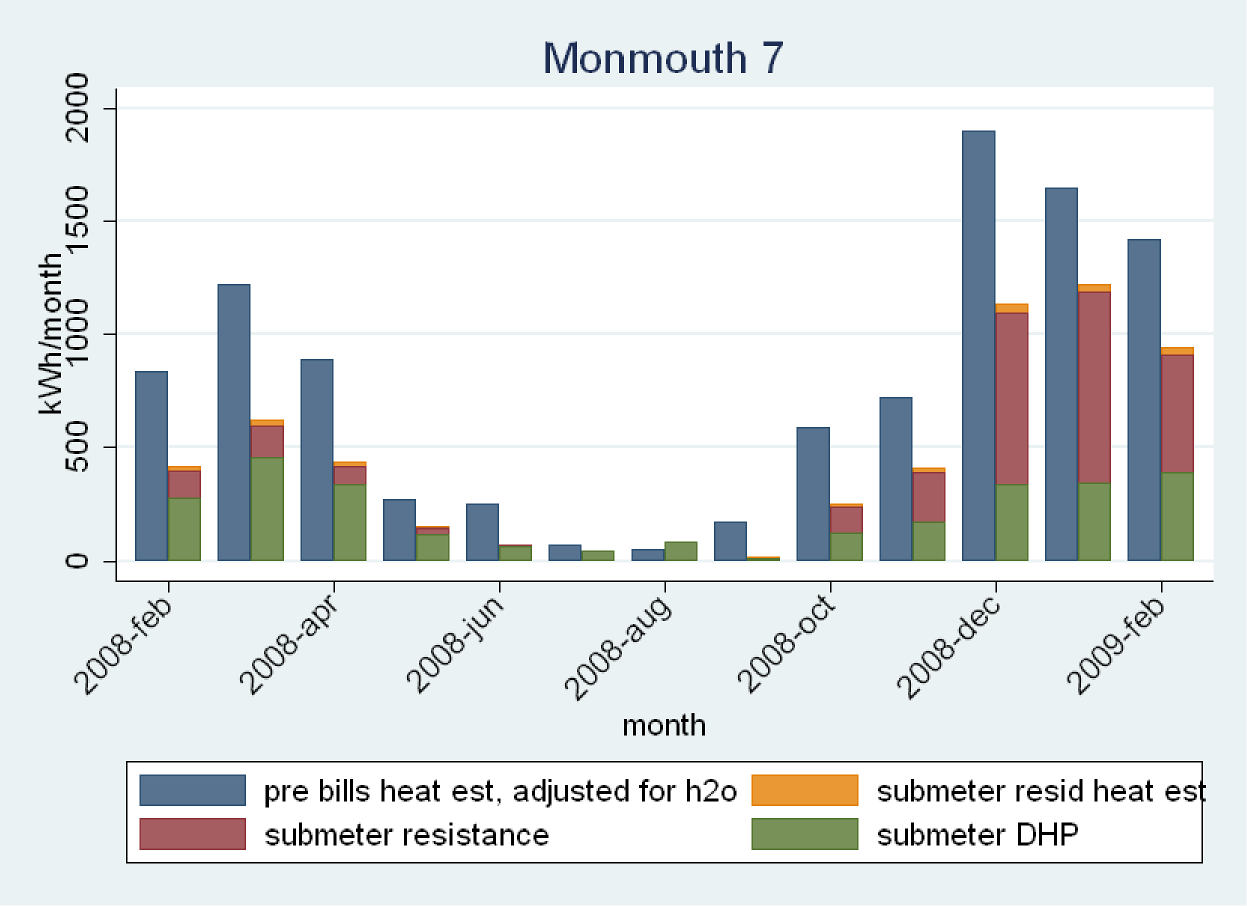
Monthly Space Heat Energy Consumption, Monmouth Site 5



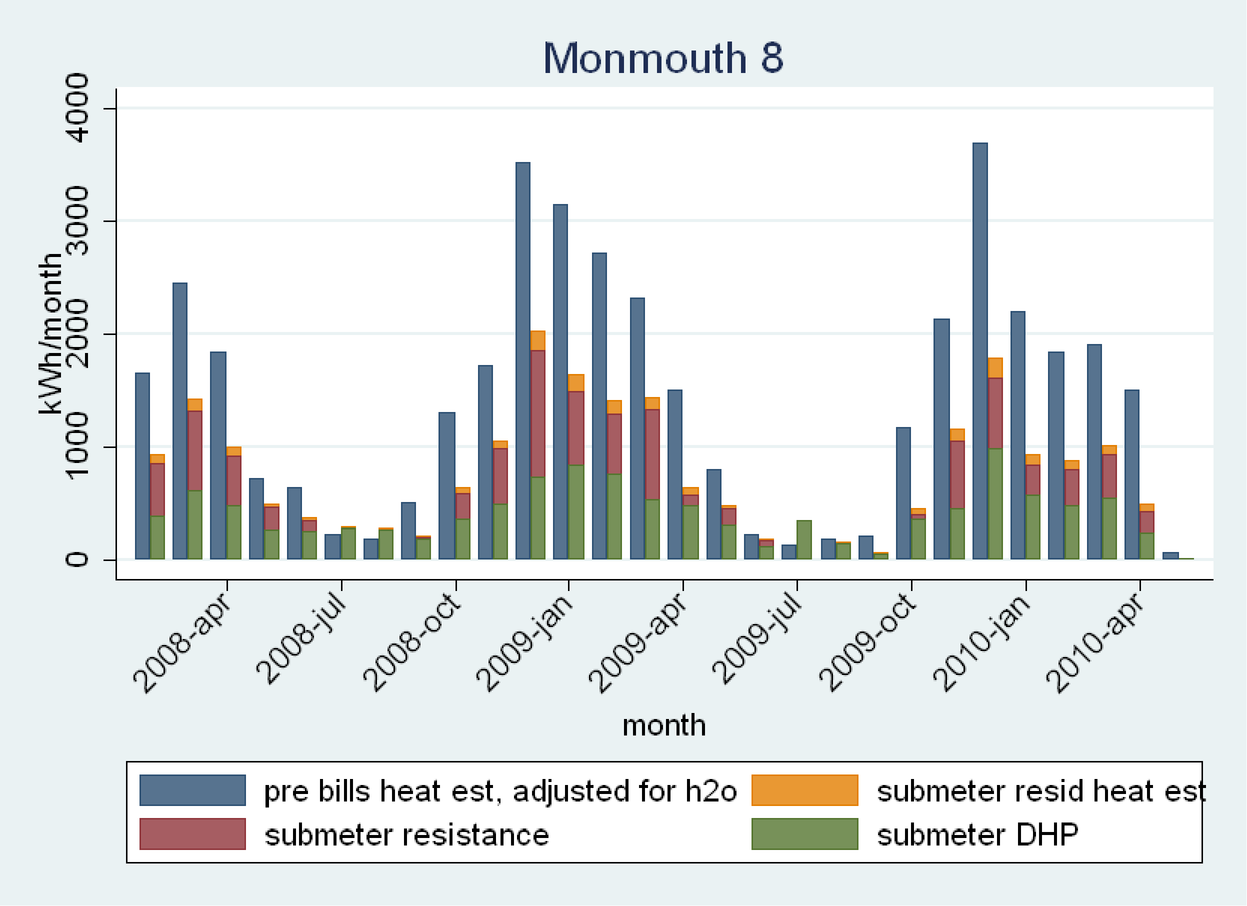
Monthly Space Heat Energy Consumption, Monmouth Site 6



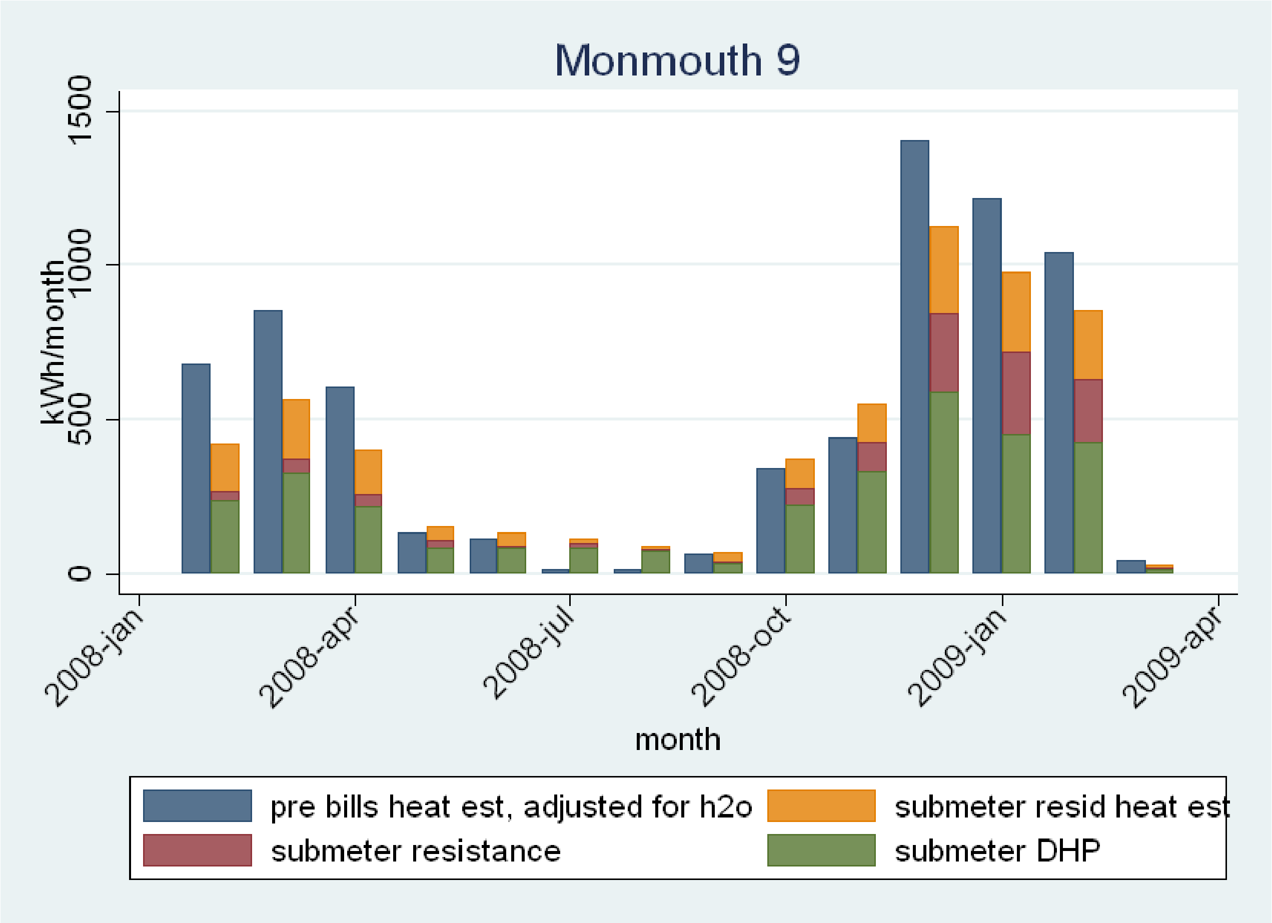
Monthly Space Heat Energy Consumption, Monmouth Site 7



Monthly Space Heat Energy Consumption, Monmouth Site 8



Monthly Space Heat Energy Consumption, Monmouth Site 9



Monthly Space Heat Energy Consumption, Monmouth Site 10