B O N N E V I L L E   P O W E R   A D M I N I S T R A T I O N

Ductless Heat Pump Retrofits in Multifamily and Small Commercial Buildings

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A Report of BPA Energy Efficiency's Emerging Technologies Initiative

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An Emerging Technologies for Energy Efficiency Report

The study described in the following report was funded by the Bonneville Power Administration (BPA) to provide 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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Abstract

This study evaluates the electricity savings that can be gained by installing ductless heat pumps (DHPs) in multifamily and small commercial applications. A total of 12 multifamily units were submetered in two localities; 188 units were included in the accompanying utility billing analysis. Ten small commercial sites were evaluated.

The estimated heating savings for multifamily installations is 824 kWh/year. This is based on an average of the heating savings at the two complexes. The Cooling Zone 2 site showed some cooling savings, but we expect that cooling savings in hotter climates will be balanced out by takeback in milder climates that are adding cooling capability.

With savings of only 824 kWh/year and an assumed measured cost of $3000 for a single indoor head system, the economics of the installation are far from favorable. Assuming a 16 year measure life and a real discount rate of 4%, the levelized cost of the DHP savings is $0.28/kWh, almost three times the Northwest Power and Conservation Council (NWPCC) threshold of $0.101/kWh.

Small commercial sites with consistent occupancy, and which do not have high internal gains or process loads, show significant opportunities for savings. Six of the ten sites metered are consistent with office and retail use patterns. Those six sites saved, on average, 4,185 kWh/yr. The remaining four sites represent commercial building types requiring further research.

Glossary of Acronyms and Abbreviations

AC	air conditioning
BPA	Bonneville Power Administration
Btu	British thermal unit
Btu/ft^2	British thermal units per square foot
COP	coefficient of performance
DHP	ductless heat pump
DHW	domestic hot water
EPRI	Electric Power Research Institute
ER	electric resistance
EWEB	Eugene Water and Electric Board
ft^2	square feet
HDD	heating degree days
HVAC	heating, ventilation, and air conditioning
kWh	kilowatt hours
kWh/DD	kilowatt hours per degree-day
kWh/yr	kilowatt hours per year
NEEA	Northwest Energy Efficiency Alliance
NWPCC	Northwest Power and Conservation Council
NWS	National Weather Service
PRISM	Princeton Scorekeeping Method
PSE	Puget Sound Energy
PTAC	packaged terminal air conditioning
PUD	Public Utility District
RTF	Regional Technical Forum
UA	The sum of the thermal transfer coefficient (U) times the area (A) of the components of the building. Can also include convective losses from infiltration.
VBDD	variable base degree day

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Executive Summary

Ductless mini-split heat pumps (DHPs) have been gaining in popularity in the Northwest. Although previous research has identified significant energy savings from displacing zonal electric resistance in single-family homes (Baylon et al., 2012), savings estimates for other DHP applications have not been researched in the Northwest. This report covers multifamily and small commercial applications of the technology. It is part of a larger Bonneville Power Administration (BPA) study designed to evaluate DHP energy savings in single-family homes with forced air furnaces, manufactured homes, multifamily buildings, and small commercial buildings.

Multifamily

There is a potential for savings in the multifamily sector, but building and occupancy characteristics are different enough from single-family residences that savings cannot be extrapolated from identified single-family savings. The multifamily DHP metering project was designed to address these issues. It included a review of billing data, careful prequalification of sites, comprehensive metering and analysis of the metering results and utility bills.

Site selection was challenging. A total of 782 apartment units were identified for possible inclusion in the study; however, only two complexes qualified, providing a total of 188 units. Ecotope installed submeters in a total of 12 units at these two sites. One complex, in Richland, WA, had built-in packaged terminal air conditioning (PTAC) units and a significant cooling load; the other complex, in Eugene, OR, did not.

The metering protocol was designed to gain a clear picture of DHP and space heat energy use that could be separated out from other energy uses in the home, and that would distinguish between heating and cooling modes. The protocol was based on the protocols developed in other DHP studies and metered domestic hot water (DHW) use in addition to the DHP and space heat.

The billing analysis conducted for this report used a Variable Base Degree Day (VBDD)[1] method to derive base case estimation and savings estimates for the 188 units at the two evaluated multifamily complexes. The method was adapted to better handle the weakness and inconstancy of space-conditioning signals in individual unit bills. Post-installation submetered data from twelve units was used to provide insight into the determinants of savings, and to corroborate billing analysis results.

Calculating heating savings from billing analysis varied from an average of 736 kWh/yr at the Richland complex to an average of 912 kWh/yr at the Eugene complex. The corresponding cooling figures were a savings of 386 kWh/yr (Richland) and an increase of 143 kWh/yr (Eugene). We calculated an overall savings number of 824 kWh by averaging the heating savings from the two complexes; we decided to leave out the cooling numbers, because small increases in cooling energy use in the mild cooling climates will approximately balance out decreases in cooling energy use in the areas with a more significant cooling climate.

With savings of only 824 kWh/year and an assumed measured cost of $3000 for a single indoor head system, the economics of the installation are far from favorable. Assuming a 16 year measure life and a real discount rate of 4%, the levelized cost of the DHP savings is $0.28/kWh, almost three times the NWPCC's threshold of $0.101/kWh.

The heating savings figures are below prior conjectured levels. "Takeback" in the form of significant increases in output heat was observed in the twelve metered units; the average increase in post-installation output heat over pre-installation levels ranged from 39% at Eugene metered units to 78% at the Richland metered units. With no takeback, the observed savings at the twelve metered units would have increased by roughly two thirds. These takeback levels exceed those encountered in previous studies of single-family installations (Baylon et al., 2012).

In the twelve submetered units, conversion to DHP space heating was far from complete; over the metering period resistance heat was estimated to account for 57% of input heating energy at the Richland units and 25% of

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[1] A brief explanation of this method is in Appendix B. For a detailed explanation refer to Geraghty et al., 2009.

input heating energy at the Eugene units. Across these units, degree of conversion to DHP heat was strongly associated with greater savings.

Estimated average space-heating energy budgets prior to DHP installation were relatively modest: 2980 kWh/yr in Richland, and 2181 kWh/yr in Eugene. These figures place upper bounds on potential savings even in the absence of takeback or incomplete elimination of resistance heat. Relevant to this point was an analysis across all 188 units which implied that higher levels of energy consumption prior to DHP installation were strongly associated with higher savings.

Although the modest levels of realized savings encountered at these two multifamily complexes appear discouraging, attention to prior unit consumption levels, elimination of all or almost all resistance heat, and a search for multifamily building types or unit sizes less associated with takeback may still provide the basis for a cost-effective multifamily measure.

Small Commercial

This project has demonstrated the potential for energy savings using DHPs in the small office and small retail commercial building category. The ingredients for savings are regular occupancy (essentially at least 9:00am-5:00pm, 5 days per week), internal gains consistent with typical office or retail practices (restaurants, for example, have too many process loads), and a wintertime heating load. Six of the buildings studied were stand-alone structures; nevertheless, their heat loss rates were small. This factor implies that adjoined commercial spaces, such as strip malls, which, due to their shared walls, can have lower heat loss rates than stand-alone buildings, may also reap the energy savings.

A final ingredient in realizing energy savings is configuring and operating the DHP so that it displaces the vast majority of existing electric resistance heating. In half the sites studied, the DHP provided more than 90% of the heat. That is in contrast to residential DHP retrofits where the DHP provides 45-80% of the space heating (Baylon et al., 2012). Houses tend to have peripheral rooms that a centrally located DHP cannot heat. On the other hand, all the rooms for the small commercial buildings in this study could typically be covered by a single DHP. That leads to less resistance heating and less energy use overall.

Within the study, six of ten submetered sites are similar to one another. They are office or retail types of spaces that are regularly occupied and that do not have large internal gains. In this case, we define “large” gains to be those associated with restaurants or convenience stores. Cooking equipment or refrigeration cases will almost always be in the buildings with the large gains. In contrast, offices and retail spaces, even those with lots of electronics for sale, fall into the low and medium internal gain category. Next, the six businesses are located in stand-alone buildings. These sites show a real potential for DHP retrofit energy savings. Most often, the occupants turn off their existing resistance heating system and get nearly all the heat from the DHP. Five of the six sites show large savings, although one shows mixed results. Taken on average, the six sites show 4,185 kWh/yr of energy savings per site. Assigning a measure cost in the commercial sector is difficult but with a rough estimate of $4000 and assuming a 16 year measure life and a real discount rate of 4%, the levelized cost of the DHP savings is $0.074/kWh, well under the Northwest Power and Conservation Council (NWPCC) ceiling of $0.101/kWh.

Two of the remaining four sites are restaurants with such large internal gains that we are unable to estimate the heating and cooling energy uses in the pre-DHP period. Consequently, it is not possible to directly measure DHP energy savings. In both cases, our submeters show the DHP runs to provide heating and cooling. Since the DHP is much more efficient than either existing system, it is likely using less energy. To find a definitive answer, submetering of the restaurant both before and after the DHP installation is required. This unambiguous measurement of space conditioning energy use would provide a clear picture of what is going on in the restaurants. Using billing data only for the pre-DHP period does not provide such data. For the last two out of the ten sites, varied occupancies and complex building layouts precluded our ability to make a savings estimate. One site is a house run by a transitional housing authority and is more a residential setting than a commercial one. The final site monitored the DHP installation serving the gathering hall of a church. Ultimately, all the buildings and heating systems on the site proved too complex to analyze. As in the restaurant case, submetering both before and after DHP installation would be required to determine the potential savings.

To generalize the project, a next step is to create models of the small office/retail building types, calibrate them to the field data of the six sites in this study, and make predictions of energy use and savings across the Northwest heating and cooling zones. Although the project covered only six buildings, the fact that it included sites in both mild (coastal Washington) and cold (Libby, Montana) climates provides more grounding for the collected data. Such a generalized model of heating and cooling use could become the basis of an energy reduction measure or program. Of the last four project sites, even with detailed pre- and post-metering, it may also turn out that those building types are simply not good candidates for prescriptive DHP installation. A custom, engineered approach to energy management for those types might be the best way to save energy.

1 Introduction

The Northwest 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. The impact of ductless heat pumps (DHPs) on single-family zonal homes is fairly well understood (Baylon and Geraghty, 2012; Baylon et al., 2012). This report is the last in a series of memos and reports documenting the results of a Bonneville Power Administration (BPA) study designed to evaluate DHP energy savings in single-family homes with forced air furnaces, manufactured homes, multifamily buildings, and small commercial buildings. This report covers the multifamily and small commercial portions of the study. It describes site selection and the challenges of recruiting, the metering methodology, and analysis of the available metered and billing data. Finally, it suggests interim electric energy savings results for the regions studied.

1.1 Project Background

From 2007 through 2011, at the request of the Regional Technical Forum (RTF)[2], BPA developed an initial pilot study (the Monmouth study) to provide basic information on the energy savings potential of DHP technologies. This pilot study used modern metering technology to ascertain the performance of these systems in end-users' homes. The target customer group for that study included 14 existing single-family homes with zonal electric heat. The goals of the study were to provide early verification of the RTF's energy savings assumptions, to gain experience to inform a larger review of DHP retrofits in zonal electrically heated homes, and to review data collection procedures and refine the instrumentation protocol. The study concluded that the initial savings estimate associated with this technology in single-family zonal electric homes is about 4,000 to 4,500 kilowatt hours (kWh) per year (Geraghty et al., 2009; Geraghty et al., 2010; Baylon and Geraghty, 2012).

In October 2008, BPA and the Northwest Energy Efficiency Alliance (NEEA) initiated a separate DHP pilot program targeting 2,500 single-family, site-built homes with zonal electric heating systems. The purpose of this study was to capture data that would assist the RTF in determining deemed savings for DHPs in specific housing and heating system applications. NEEA's DHP pilot captured billing history data from up to 2,500 individual homes with DHPs, metered 92 of these sites, and added data loggers and 30 coefficient of performance (COP) meters to an additional 35 sites. This study drew from a broad base of sites across the Pacific Northwest and found average savings of approximately 3,049 to 3,850 kWh per year (depending on measurement technique) across three heating climate zones (Baylon et al., 2012).

This report first covers the multifamily portion of this study, then the small commercial portion.

2 Multifamily DHP Energy Savings

Based on single-family results, the potential for savings in multifamily units was thought to be significant. However, building and occupancy conditions are often sufficiently different from single-family dwellings that it was also conjectured that savings and cost-effectiveness could not be extrapolated. Average unit size is typically smaller, heat loss rates are lower, and occupancy turnover is much higher. The goal for this portion of the study was to determine energy savings that the DHP measure could provide in the retrofit multifamily sector.

The multifamily DHP metering project was designed to provide an initial estimate of savings from the installation of a single unit with one indoor head. The study included a review of utility billing data for a complex in Richland, Washington (Jadwin Village) and a complex in Eugene, Oregon (Oakwood Manor). Jadwin Village has a total of 116 units in 21 buildings, and Oakwood Manor has a total of 72 units in 13 buildings. In addition, a total of 12 units, four in Richland and eight in Eugene, were metered to provide detailed interval data on the functioning operation of the DHP as well as the use of the existing electric resistance heating system. These units were selected as an engineering sample of one to two units per building with various combinations of thermal shell characteristics, solar gains, etc. This project started in September 2010; metering installations started in March

[2] The Regional Technical Forum is run by the Northwest Power & Conservation Council and is responsible for evaluating and approving new energy efficiency measures in the Northwest.

2011 and were completed by September 2011. Meters were removed from the field in September 2012. In the complexes studied, every unit received a DHP.

2.1 Methods

2.1.1 Site Selection

Ecotope began the search for appropriate multifamily sites by looking through NEEA's database of approved installations from the NW Ductless Heat Pump Project. The database was first reviewed in October 2010 to develop an initial list of potential sites. Ecotope evaluated multifamily units in the 400- to 600-square-foot (ft^2) range and up. The filtering resulted in an initial list of 500 potential multifamily units in nine buildings. Most of these sites were eliminated from participation for a variety of reasons (see Table 1).

Table 1. Rejected Complexes

Utility	Complex Description	Number of Units	Outcome
City of Monmouth	Two story building	8	Heating signature too small.
Eugene Water and Electric Board (EWEB)	Not-for-profit housing for people with mental illness	32	Not all billing histories available.
Puget Sound Energy (PSE)	King County Housing Authority project, two-story garden-style complex.	40	Building underwent significant envelope upgrades, which would make it difficult to attribute DHP savings.
Clark County Public Utility District (PUD)	Single-story duplex and fourplexes	150	Project deemed too difficult to proceed. The project will remove the electric baseboards and install multi-head DHPs in the units, which is outside of the scope of the research project.
Wells Rural Electric	8-plex	8	Building damaged in an earthquake and will undergo extensive renovations, including envelope upgrades. Also was a motel and then vacant for four years.
Tacoma PUD	Two-story garden-style complex	20	Building underwent significant envelope upgrades, which would make it difficult to attribute DHP savings.
Seattle City Light	Section 8 housing	54	Building underwent significant envelope upgrades, which would make it difficult to attribute DHP savings.
Snohomish PUD	Affordable Housing	72	Building underwent significant envelope upgrades, which would make it difficult to attribute DHP savings.

As it became clear that the vast majority of projects would not qualify for the study, Ecotope expanded the search for sites by querying our contacts at utilities and housing authorities. By June 2011, there were a total of 782 multifamily units identified, though only two buildings proved to be a good candidates for the study: Jadwin Village (Richland, WA) and Oakwood Manor (Eugene, OR). This winnowing process was difficult and challenging, which delayed the completion of installations.

In early October 2010, the Jadwin Village complex was identified as a good candidate for the study. The complex used electric resistance heat and window air conditioning (AC) units for cooling. The property is a complex of 21 duplex and fourplex buildings with units ranging in size from 600 ft^2 to 1,100 ft^2. More than four candidates at Jadwin were considered for the study; selection was based on a desirable combination of unit size, apparent heating signature, and solar exposure diversity. The latter factor (along with the average summertime temperatures in the TriCities) contributes to the need for cooling as well as heating. Submetering equipment was installed in the four units in March 2011.

Oakwood Manor was identified in early June 2011. The bills were obtained and screened, and in mid-July the project was deemed to be a good candidate. Six multifamily units were selected in mid-summer 2011. Submetering equipment was installed in the six units in August, 2011. Two more units at Oakwood were added to the study on September 1, 2011, bringing the total to 12 multifamily units (versus the original project submetering target of 10 units).

2.1.2 Metering Design

The goal of the electricity submetering was to gain a clear picture of DHP energy use that could be separated from other energy uses in the home, and that would distinguish between heating and cooling modes. Ecotope also metered space heat and domestic hot water (DHW) to model the interaction between the DHP and supplementary heat and eliminate the seasonal effect of DHW use from the analysis. This approach also provided some additional information on multifamily DHW use to complement the regional DHW data set.

The metering design was based on the DHP metering design used in NEEA's regional study and measured service, DHP, space heat, and DHW energy use, as well as indoor, outdoor, and DHP vapor line temperature (to distinguish between heating and cooling operation) (Davis and Geraghty, 2010). At Jadwin Village, we metered whole-complex energy usage, which was believed to help in savings estimation; we were unable to do the same at Oakwood due to the way the complex was wired.

Data were gathered by Onset U30 loggers on site and transferred via 3G connection to Onset and then Ecotope servers. Error-checking as used for NEEA and other BPA DHP studies was extended to the multifamily sites.

2.1.3 Site Characteristics

2.1.3.1 Jadwin Village, Richland

2.1.3.1.1 Overview

Jadwin Village is located in a mixed-use neighborhood of southern Richland and is composed of 116 units: 28 one-bedroom, 56 two-bedroom, and 32 three-bedroom units clustered in four- and eight-plexes. The buildings are all single-story buildings on slab. Most of the buildings are built on a primarily North-South axis; the grounds are bordered with deciduous trees and are adjacent to two major freeways and within a half mile of the Columbia River. Jadwin was built in 1975, and was originally heated with ER baseboard heat and cooled with through-wall packaged terminal air conditioning (PTAC) units. In 2009, the City of Richland was instrumental in converting the apartments to heating and cooling with DHPs. Jadwin is in heating zone 1 and cooling zone 2.

Four apartments were selected for the study based on their heating signatures and solar orientation relative to the other units in the unit's building complex. All selected units are on the ground floor.

Table 2 presents descriptions of the Jadwin units, including the building UA.[3]

[3] The sum of the thermal transfer coefficient (U) times the area (A) of the components of the building. Also includes convective losses from infiltration.

Table 2. Description of Jadwin Units

Building C Site	**Occupancy**	**ft^2**	**Solar Exposure**	**Building UA = 956 (8 units)**
				UA
18264	1 adult from March-Sept and 2 adults since October 2011	479	West & North	130
18247	1 adult	479	East & North	130

Building S Site	**Occupancy**	**ft^2**	**Solar Exposure**	**Building UA = 1317 (8 units)**
				UA
18235	1 adult	759	West & South	175
18232	2 adults and 1 child	759	West & North	175

The same DHP was used for all the units:

- Outdoor: Mitsubishi MUZ FE12NA
- Indoor: Mitsubishi MSZ FE12NA

In addition to the electricity consumption of the individual units, the total energy use of each of the eight-plexes was submetered.

2.1.3.1.2 Challenges

Jadwin Village changed ownership over the course of the study without any notice to Ecotope from either the original management company or the current one. This made it impossible to do a follow-up survey with tenants about usage patterns, setpoints, and satisfaction with the DHP.

2.1.3.2 Oakwood Manor, Eugene

2.1.3.2.1 Overview

Oakwood Manor is located in a densely-packed residential area on Oak Patch Road in west Eugene. Built within a grove of large oak trees, the 72-unit complex, built in 1966, has one-, two-, and three-bedroom units available to low income families or individuals. All metered units are ground-floor units on slab. Oakwood is located in heating zone 1 and cooling zone 1.

Table 3 provides a description of the Oakwood units.

Table 3. Description of Oakwood Units

Site	Occupancy	ft^2	UA
99471	1 adult	576	158
99469	1 adult	732	215
99461	1 adult, 1 child	900	240
99460	2 adults	900	238
99465	2 adults, 2 children	900	238
99464	3 adults, 1 child	900	238
99447	1 adult	600	150
99446	1 adult	600	150

2.1.3.2.2 Installation

Eight sites were installed over a period of two weeks in August and September 2011. No cooling equipment existed in any of the units prior to DHP installation.

The same DHP was used for all units: the Mitsubishi FE09NA.

2.1.3.2.3 Challenges

Overall building/complex metering was not possible at this site due to logistical challenges. It would have been necessary to shut off power at all units for several hours during installation of metering equipment.

2.1.4 Analytic Methods

2.1.4.1 Billing Data Analysis Methodology

2.1.4.1.1 VBDD Heating Analysis

Estimates of heating or cooling energy use based on billing data for the two apartment complexes rely on a variable-base degree day (VBDD) methodology. The basic methodology, a variant of Princeton Scorekeeping Method (PRISM) analysis (Fels, 1986), is described in Geraghty et al. (2009) and briefly in Appendix A.

This basic VBDD methodology was adapted for the multifamily analysis by aggregating bills across units before VBDD estimation. In comparison to single-family housing, individual multifamily units typically have heating energy use that is smaller in relation to non-space-conditioning energy uses in each unit, because units usually adjoin conditioned space on one or more surfaces. It is possible for an occupant of an interior unit with a relatively high tolerance for low temperatures to get most of their heating from neighboring apartments whose occupants heat more aggressively. Multifamily units are also typically characterized by more rapid occupancy turnover and fewer occupants per unit than detached houses. The combination of these factors leads typically to significantly weaker and more variable heating signals in multifamily unit billing data than in single-family housing billing data. In fact, it is often impossible to reliably determine balance points[4] and degree-day response coefficients[5] from unit billing data, leading to “noisy” and unreliable heating estimates.

A relatively straightforward fix for this problem is to aggregate energy-use bills across units in a building or complex before attempting to estimate heating signatures. Variability in non-space-conditioning energy

[4] The balance point is the outdoor temperature at which the occupant turns on the heat.

[5] The response coefficient is the slope of the line where heating usage is the dependent variable and outdoor temperature is the independent variable.

consumption is not highly correlated across units, but variability in units' space heat energy use, which responds to the same outside weather conditions*, is* highly correlated. The effect of this correlation is to diminish the relative importance of variability in non-space-conditioning energy use, and to increase the relative contribution of space heat energy use to overall variability. This leads to relatively clear space heating signals and relatively well-behaved VBDD regressions.

This transformative effect on bills is easy to see in a comparison of plots of individual bills with aggregated bills. 1Figure 1 displays side-by side graphs of billing data for a randomly selected unit at Jadwin Village, and of aggregated billing data for all 116 Jadwin units.

Figure 2 displays a corresponding pair of graphs for the Oakwood complex. In the individual unit graph in each pair, apparent occupancy changes (closely grouped pairs of changes in unit account number) are noted. In both figures, the aggregated bills display a regular pattern of seasonal peaks and valleys, whereas the unit bills have a much less obvious seasonal pattern, with highs and lows that are often not explainable as seasonal effects. The Jadwin unit displayed inFigure 1 in fact appears to show a four-year trend of increasing usage that continues beyond the installation of the DHP.

Figure 1. Comparison of Single-Unit and Aggregated Billing Data for Jadwin Village

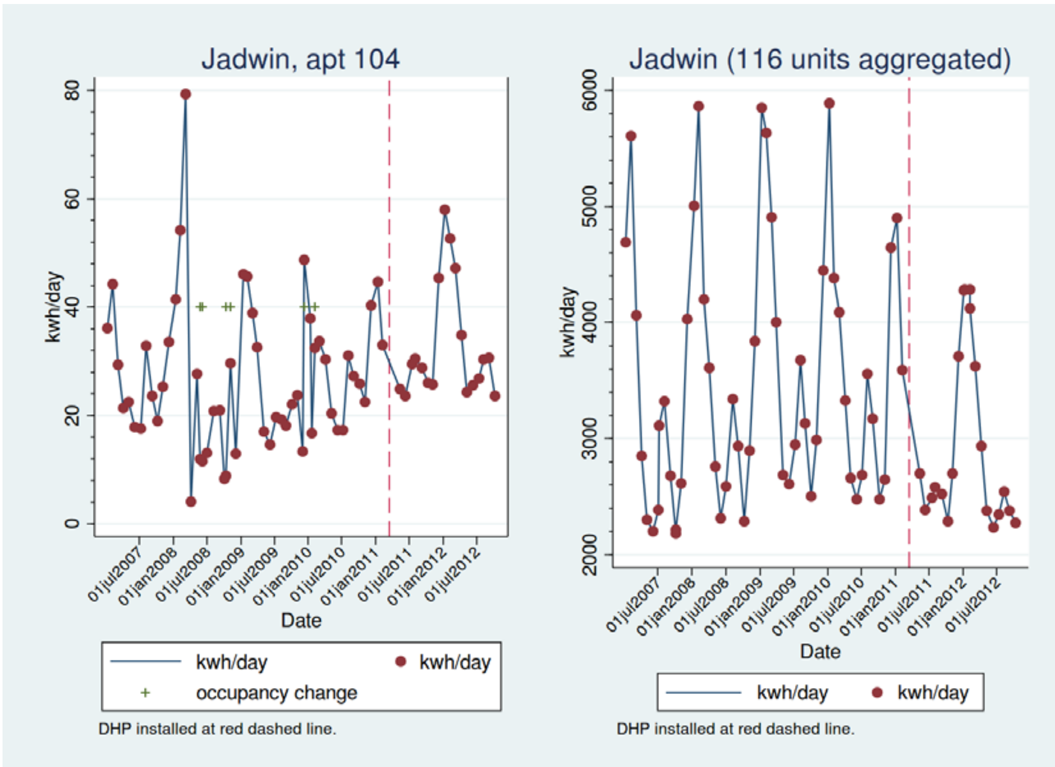
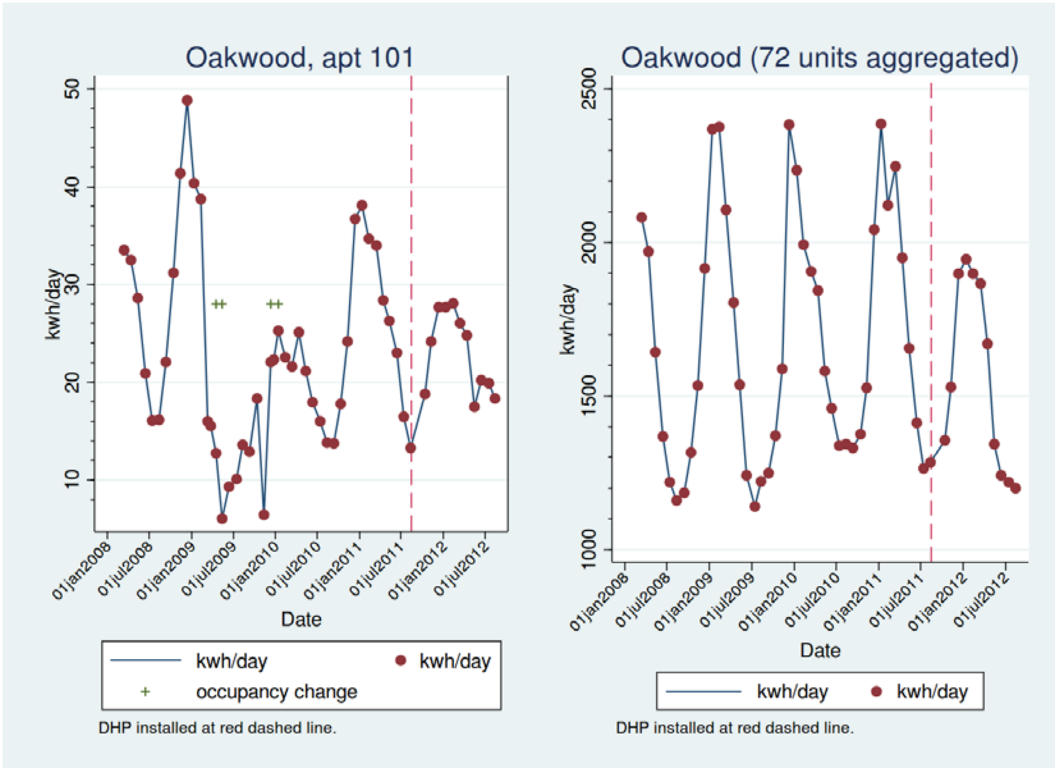


Figure 2. Comparison of Single-Unit and Aggregated Billing Data for Oakwood Manor



2.1.4.1.2 VBDD Cooling Analysis

By using cooling degree-days rather than heating degree days, VBDD methodology can be adapted to estimate seasonal cooling loads as well as seasonal heating loads. In our experience, however, the method of VBDD regressions based on cooling degree-days works poorly or not at all on residential billing data from most of the Northwest. Cooling energy use is so small and so intermittent over most of the region that the weak cooling signal cannot be picked out in monthly energy bills. The Richland-Kennewick-Pasco area is an exception, however: a genuine summer-cooling climate leads to cooling energy use that is large enough and consistent enough to provide plausible VBDD results. **Figure** 1 and Figure 2 show that aggregated Jadwin bills display a subsidiary summer peak corresponding to cooling-season usage, both before and after DHP installation, which is not apparent at Oakwood. Cooling-degree-day regressions can work at Jadwin because of this visible summer peaking, but not at Oakwood. Even at Jadwin, the cooling signal is significantly smaller and weaker and thus harder to estimate accurately than the corresponding heating signal. Because of this relative weakness, cross-unit aggregation of bills is even more advisable for multifamily VBDD cooling regressions than for heating regressions.

2.1.4.2 COP and DHP Output Heat Calculations

Calculating COPs of DHPs in actual use is not only of intrinsic interest but is also a critical component in any calculation of the DHP's relative contribution to total heating and cooling. In Baylon et al. (2012), sensors were deployed that permitted the calculation of actual in-use field heating COPs at five-minute intervals for a number of different DHP models. On the basis of these field data, realized heating COP performance curves were generated for the monitored models as a function of outside temperature. These performance curves were found to be consistent with laboratory test results in a separate study (Ecotope, 2011). The two DHP models deployed at Oakwood and Jadwin were minor variants of one of these analyzed models.

Although the metering equipment deployed at Jadwin and Oakwood did not permit direct calculation of COPs, five-minute monitoring of DHP energy use, outside temperature, and vapor line temperature permitted us to apply the appropriate performance curves to calculate output heat (that is, the heat that is actually delivered into the house). At each five-minute recording interval, vapor line temperature was compared with outside air temperature to determine whether the DHP was operating in heating mode, in cooling mode, or in pure fan mode. Any recorded heating mode input energy (that is, the energy used to run the compressor and the indoor and outdoor fans) was multiplied by the COP appropriate to the recorded outside air temperature to obtain output heat. Heating-energy weighted COPs were then derived by simply taking the ratio of the total annualized heating mode output heat to the total annualized heating mode input heat. In contrast to the heating energy situation, no cooling COP temperature-performance curve was available for the Jadwin and Oakwood models, because the monitored units in Baylon et al. (2012) were not in genuine cooling climates and generated little usable data on cooling performance. For cooling mode output heat calculations, we assumed a cooling COP of 4 for installed DHP units.

2.2 Findings

2.2.1 Billing-Data-Based Change Estimates Using VBDD Regressions

Table 4 displays per-unit estimates of space heat energy consumption both before and after installation of DHPs at the two multifamily complexes. These estimates were derived from billing data aggregated across units. Estimates are weather-normalized (expressed in terms of long-term average weather at the site) rather than weather-adjusted (expressed in terms of weather observed in the post-installation period).[6] Table 4 also displays estimated changes in per-unit space heat input energy consumption from pre-installation to post-installation periods. These estimated changes are not equal to the estimated post-installation space heat less the estimated pre-installation space heat because they also include changes in estimated non-weather-dependent baseload (the constant term from the VBDD regressions). This conservative practice helps to minimize the effect of errors in splitting the two components of consumption. There is no reason to believe that baseload varies systematically between the pre- and post-installation periods.

Table 4: Estimated Per-Unit Heating Savings Using Bills Aggregated Across Units (kWh/yr Input Energy)

Site	# units	Avg. unit size	Pre-install heat (nrm)	Post-install heat (nrm)	kWh change (nrm)
Jadwin	116	865	2980	2244	-736
Oakwood	72	750	2181	1269	-912

# units	number of units used in estimate
Avg. unit size	average unit size (ft^2)
Pre-install heat (nrm)	weather-normalized pre-installation heat, VBDD billing data estimate
Post-install heat (nrm)	weather-normalized post-installation heat, VBDD billing data estimate
kWh change (nrm)	weather-normalized pre-to-post heat change, VBDD billing data estimate

Estimated average per-unit pre-installation space heat energy is 2980 kWh/yr at Jadwin and 2181 kWh/yr at Oakwood. These relatively modest prior consumption figures effectively place an upper limit on conservation potential. Our best estimate of average per-unit changes in heating consumption is a savings of 736 kWh/yr at Jadwin and 912 kWh/yr at Oakwood. These are surprisingly small numbers, even considering the moderate pre-

[6] See Appendix C. Weather-Adjusted Energy Use and Savings Estimates for a discussion of the advantages of weather-adjusting rather than weather-normalizing and tables with weather-adjusted results. In practice, the difference between weather-adjusted and weather-normalized change results is small and well within plausible estimation error bounds.

installation space heating observed. The later analysis of post-installation metered data delves into the possible sources of this relatively low realized savings: realized COP, degree of continued use of electric resistance heat, or possible increases in aggregate output heat after DHP installation.

Table 5 displays per-unit estimates of pre- and post-installation space cooling energy consumption at Jadwin derived from billing data aggregated across units before VBDD estimation. Table 5 also displays the estimated change in per-unit space-cooling consumption from pre-installation to post-installation periods, using the same approach as with the heating estimates. The point estimate for per-unit input cooling savings at Jadwin is 386 kWh/yr. No VBDD cooling results are presented for Oakwood because this methodology does not give reliable results in such a mild cooling climate.

Table 5. Estimated Per-Unit Cooling Savings Aggregated Across Units (kWh/yr Input Energy)

Site	# units	Pre-install cooling (nrm)	Post-install cooling (nrm)	kWh change (nrm)
Jadwin	116	690	157	-386

# units	number of units (apartments) used in estimate
Pre-install cooling (nrm)	weather-normalized pre-DHP-installation cooling, VBDD billing data estimate
Post-install cooling (nrm)	weather-normalized post-DHP-installation cooling, VBDD billing data estimate
kWh change (nrm)	weather-normalized pre-to post cooling change, VBDD billing data estimate

2.2.2 Metered Data Results

Electricity usage at eight units at Oakwood and four units at Jadwin was submetered at five-minute intervals during the post-installation period, for an average of 398 days and 523 days, respectively.

2.2.2.1 Heating Energy COPs and Disaggregation

Table 6 displays estimated energy-weighted heating COPs for the metered sites, calculated using the approach described above in the Analytic Methods section. Average COPs are above 3 at both Jadwin and Oakwood; the slightly higher energy-weighted COP from the Oakwood sites is presumably due to milder winter temperatures.

Table 6 also displays average annualized per-unit metered heat in various categories in the post-installation metering period. Input energy for the DHP in heating mode, output heat energy of the DHP in heating mode, metered 220V (baseboard/wall heater) electric resistance heat, and residual heat are all shown. Residual heat is unmetered 110V plug-in electric resistance heat as estimated from apparent heating signatures in metered residual load.[7] At Jadwin, residual heat is actually roughly as large as metered electric resistance heat. This result can be attributed to a single monitored unit that rarely used the DHP for heat. Counting residual heat, the resistance loads on average account for 57% of total input heating energy at the four metered Jadwin units, and 25% of total input heating energy at the eight metered Oakwood units. Substantial variability exists in this resistance energy fraction across units; four units used no resistance heat, while at the other extreme one unit used 98% resistance heat. Analyzed in terms of delivered output energy (using DHPH out rather than DHPH), electric resistance heat accounted for 29% of delivered heat at Jadwin and 9% at Oakwood.

Table 6. Post-Installation COPs and Per-Unit Heat Disaggregations for Metered Sites (kWh/yr)

Site	# units	COP (heat)	DHPH	ER	Resid. heat	DHPH out	Resist. fraction	Resist. fraction

[7] Residual load in turn is defined as total metered unit energy use, minus the sum of all individually metered loads. See Baylon and Geraghty (2012) for a discussion of the measurement problems posed by unmetered 110V plug-in electric resistance heat, and approaches to estimating it.

							(input)	(output)
Jadwin	4	3.3	1302	900	820	4234	57%	29%
Oakwood	8	3.4	1363	448	0	4616	25%	9%

# units	number of units used in estimate
COP (heat)	energy-weighted COP for DHP in heating mode
DHPH	per-unit DHP heating mode input energy
ER	per-unit 220V electric resistance heat
Resid. heat	per-unit 110V electric resistance heat inferred from the heating signature in the residual load
DHPH out	per-unit DHP heating mode output energy
Resist. fraction (input)	per-unit electric resistance heat (both 110V and 220V) as a percentage of total input heat
Resist. fraction (output)	per-unit electric resistance heat (both 110V and 220V) as a percentage of total output heat

2.2.2.2 Changes in Input and Output Heating

Table 7 compares pre- and post-installation per-unit output heat. The comparison reveals a substantial increase in delivered heat – a 78% (2,603 kWh/yr) increase at the four Jadwin metered units, and a 39% (1,416 kWh/yr) increase at the eight metered Oakwood units. Expressed in terms of input energy, assuming the DHP accounts for all of the increased heat generation, this extra output heat corresponds to an 800 kWh/yr per-unit input energy "takeback" at Jadwin, and a 418 kWh/yr per-unit "takeback" at Oakwood. Takebacks of this magnitude are larger than those observed in previous studies of DHP performance in the single-family sectors (Baylon et al., 2012). The implication of these calculated takebacks is that the occupants are heating the units to a higher average temperature than before DHP installation.

To facilitate comparison with the whole-complex billing data-based changes reported in Table 4,

Table 7 also reports changes in input energy computed solely from billing data for the metered units using VBDD. A comparison of these two tables confirms that input energy change estimates based on submetered data are reasonably close to change estimates based on billing data alone.

Table 7. Per-Unit Changes in Heating Demand for Metered Sites (kWh/yr)

Site	**# units**	**Pre-install heat (adj)**	**Post-install output heat**	**Heat ratio**	**Output heat change**	**Take-back**	**Input heat change**	**VBDD kWh change**
Jadwin	4	3352	5955	1.78	2603	800	-329	-498
Oakwood	8	3648	5064	1.39	1416	418	-1837	-1692

# units	number of units used in estimate
Pre-install heat (adj)	weather-adjusted pre-installation heat, estimated using VBDD on billing data from only metered units (not all units as in Table 4)
Post-install output heat	metered post-installation output heat (DHPH_out + ER +Resid. heat from Table 6)
Heat ratio	ratio of Post-install output heat to Pre-install heat (adj)
Output heat change	Post-install output heat minus Pre-install heat (adj)
Takeback	input energy required to generate Output heat change
Input heat change	metered input heat (DHPH+ER+resid.heat from Table 6) minus pre-install heat (adj)
VBDD kWh change (adj)	weather-adjusted pre- to-post-installation heat change, pure VBDD billing data estimate for submetered units only

2.2.2.3 Changes in Input and Output Cooling

Table 8 compares total annualized per-unit pre- and post-installation input cooling energy for metered sites. (Input energy is the electricity used to run the compressor and fans during the cooling season.) No VBDD estimation was performed for Oakwood metered sites, but Oakwood is assigned a pre-installation value of "0" because space-cooling equipment was not present in Oakwood units prior to DHP installation. In terms of input energy, the result is an estimated per-unit cooling energy decrease of 150 kWh/yr for Jadwin. For Oakwood, where all cooling energy is new, the corresponding figure is a per-unit increase of 143 kWh/year. In contrast to the heating energy situation, no cooling COP temperature-performance curve is available for these models. Nor is a cooling COP available for the pre-installation Jadwin PTAC units. However, assigning an aggregate cooling COP of 2.5 to the PTAC units, and of 4 to the installed DHPs,[8] implies an average pre-to-post increase in per-unit output cooling energy at Jadwin of 213 kWh, or 16%, and at Oakwood of 571 kWh. (The percentage output cooling energy increase at Oakwood is undefined, because there was previously no cooling on site). These numbers imply per-unit input energy "takebacks" of 53 and 143 kWh/yr at Jadwin and Oakwood, respectively (remembering that Oakwood had no prior cooling, so the "takeback" is just the input cooling energy detected in the new DHPs).

Table 8. Per-Unit Changes in Cooling Demand for Metered Sites (kWh/yr)

Site	# units	Pre-install cool	DHPC	Input cooling change	Output cooling change	Cooling ratio	Takeback
Jadwin	4	543	393	-150	213	1.16	53
Oakwood	8	0	143	143	571		143

# units	number of units used in estimate
Pre-install cool	weather-adjusted pre-DHP-installation input cooling energy, estimated using VBDD on billing data
DHPC	DHP cooling mode input energy
Input cool change	DHPC minus pre-install cooling
Output cool change	post-installation DHP output cooling energy minus weather-adjusted pre-installation PTAC output cooling energy (assumed DHP cooling COP of 4, PTAC cooling COP of 2.5)
Cooling ratio	ratio of post-installation output cooling energy to pre-installation output cooling energy
Takeback	input energy required to generate output cool change

2.2.3 Cross-Sectional Regression Analysis of Differences Between Units

There are ample indications of differences in energy-saving and energy-consuming behavior between units. In the 12 metered units, the heaviest-consuming unit used 7.5 times the heating energy in the metered period as the least-consuming unit. Some units completely abandoned electric resistance heat and used only the DHP; one of the 12 used 98% electric resistance heat. In terms of measured change in input heat, pre-to-post changes among the 12 metered units ranged from an estimated decrease of 3,137 kWh/yr to an estimated *increase* of 2,784 kWh/yr.

[8] The lab test report of DHP performance (Ecotope, 2011) evaluated a similar model to the Mitsubishi used at Jadwin and found an average COP very close to 4.

We used cross-sectional regressions to explore some of the determinants of the marked differences in realized savings between units. We settled on two separate regression specifications, one “all units” using only information known for all 188 units at both sites (largely billing data), and the other “submetered units only” using additional information known only for the 12 submetered units. The final specification for the “all-units” regression includes only one independent variable: pre-installation yearly kWh consumption from bills. The estimated coefficient of -0.34 on this variable is highly significant, and implies that within the 188 units examined, a one-kWh/yr greater prior yearly consumption is associated with an increased savings of 0.34 kWh/yr. This apparent positive association between prior consumption and expected savings is not a great surprise: every single-family housing DHP field study to date has shown this same association (Baylon and Geraghty, 2012; Baylon et al., 2012; Geraghty et al., 2010; Geraghty et al., 2009). Other potential explanatory variables were occupancy changes per year (as indicated by account number changes), unit size, and site affiliation (Jadwin or Oakwood). These variables had no explanatory power and were dropped.

The “submetered units only” regression specification added a second explanatory variable to pre-installation yearly kWh: the fraction of post-installation input heat attributable to electric resistance heating. Over the 12 metered sites, this fraction ranges from zero to (very nearly) one. Despite being estimated using a data set of only 12 metered units, both explanatory variables had significant coefficients. The coefficient on pre-installation yearly kWh of -0.29 is quite similar to that obtained in the “all units” regression, and implies that within the 12 metered units examined, a one-kWh/yr greater prior yearly consumption is associated with an increased savings of 0.29 kWh/yr. The coefficient on the electric resistance heating fraction variable of 3,976 was highly significant, and implies a strong inverse relation between the electric resistance heating fraction and savings. The implied decrease in expected savings with every percent increase in electric resistance fraction is almost 40 kWh/yr. Basic engineering reasoning would indicate that, all else being equal, a greater percent shift from electric resistance to DHP heat implies greater savings. Occupant-reported heating set point, occupancy changes, unit size, and site affiliation were also tried and rejected as explanatory variables. A more detailed analysis and discussion of these regression results is presented in Appendix B.

2.3 Conclusions and Recommendations

Based on an analysis of bills for all units at both complexes, realized heating savings are estimated to be 736 kWh/yr at Jadwin and 912 kWh/yr at Oakwood. Realized cooling savings at Jadwin are estimated to be 386 kWh/yr; at Oakwood, cooling savings could not be computed from bills, but the eight submetered sites displayed a small increase in use of 143 kWh/yr, reflecting the installation of compressor-based cooling systems in spaces that formerly lacked them. The two complexes displayed slightly different heating season savings due to a variety of factors; the simple average of the estimated heating savings for both is 824 kWh/year. Both complexes are in NWPCC Heating Zone 1.

Jadwin, in cooling zone 3, also showed some savings of cooling energy (about 400 kWh/year) but most cooling zone 1 and 2 sites, like Oakwood, will have little or no prior mechanical cooling. Further, one would have to assume that DHP installations in these cooling zones would generally result in a small new cooling load (especially in HZ1), which would balance out any cooling savings in cooling zone 3.

With savings of only 824 kWh/year and an assumed measured cost of $3000 for a single indoor head system, the economics of the installation are far from favorable. Assuming a 16 year measure life and a real discount rate of 4%, the levelized cost of the DHP savings is $0.28/kWh, almost three times the NWPCC’s threshold of $0.101/kWh.

The estimated heating savings are significantly below anticipated savings based on engineering calculations. Analysis of the 12 submetered sites suggests that an important determinant of the discrepancy is “takeback” in the form of increased output heat, which was estimated to have increased on average 78% (2,603 kWh) at the four Jadwin metered units and 39% (1,416 kWh) at the eight Oakwood metered units relative to pre-installation levels. It is perilous to extrapolate these precise numbers from metered units to the entire complexes, but the relatively modest complex-level heating savings do suggest significant complex-level takeback. Apparent takeback in single-family settings is often partly a result of fuel switching (e.g. reducing wood heat use), but in a multifamily context higher average internal temperatures leading to increased heating system duty cycles is the only plausible explanation for this takeback.

The second factor accounting for a discrepancy between engineering assumptions and realized results at the submetered units was incomplete conversion from electric resistance heat. Electric resistance heat was calculated to comprise 57% and 25% of post-installation input heat at the Jadwin and Oakwood submetered units, respectively. In a multiple regression context, decreased fraction of input heat in resistance was very strongly correlated with increased realized savings: every one percent decrease in electric resistance heat as a fraction of total input heat implied nearly 40 kWh/yr of additional savings. The precise number should be taken with a good deal of caution, but there is no doubt that the electric resistance/DHP input energy mix has a powerful influence on savings.

A third factor contributing to modest realized savings was the modest prior per-unit space heating apparent at these two complexes: a space heat budget of 2200 to 3000 kWh/yr does not provide huge scope for savings from DHP conversion, even ignoring takeback and persistence of resistance heat. (This is one way to interpret the positive association between prior consumption and realized savings revealed by the cross-sectional regressions.) We believe that all three factors that depress heating savings below engineering potential deserve further investigation. Although occupant takeback of heating savings is not directly under program control, it could easily be that different classes of multifamily buildings are more or less prone to occupant takeback. The two complexes studied are in somewhat different climates (with about 20% more heating degree days at Jadwin in addition to an actual cooling climate) but share certain characteristics, notably being low-rise complexes without common HVAC systems or shared space. The greater degree of takeback observed here compared to single-family settings is something of a mystery, especially since the occupants of both complexes are, on average, not in higher income brackets. One would think they would be motivated to use less electricity so as to pay less each month, but instead it appears they are willing to erode what could be substantial savings by paying about the same or a little less (on average). In some cases (where post-DHP electric resistance use increases greatly), they are willing to pay even more. Occupancy changes complicate explanations but overall, since the cost of output heat is reduced roughly two-thirds by the DHP, the net effect seems to be a preference for increased comfort over energy savings.

The degree of post-installation conversion from electric resistance heat seems easier to control in program design than occupant takeback, because it is fairly easy to envision a program of conversion that completely removed 220V electric resistance heat from units. The only drawback with this approach is that there could be cases where indoor comfort would suffer (during very cold weather or if there was a mechanical failure with the DHP).

The third factor associated with low savings, prior per-unit kWh consumption, is readily discernible in unit bills; conceivably a lower eligibility threshold for per-unit kWh consumption could be set as a condition of measure participation. A study of ten relatively new mid-rise apartment buildings in Seattle (Heller et al, 2009) found mean per-unit space heating energy budgets of roughly 2,759 kWh/yr, comparable to Oakwood and Jadwin. Great variability in space heat budgets existed within this set, ranging from 960 kWh/yr per unit to over 5,000 kWh/yr, suggesting that there may exist a substantial population of multifamily buildings with per-unit space-conditioning energy budgets large enough to provide much more significant savings potential, not apparent in the present study of only two low-rise apartment complexes.

Conclusions on the cooling side should be treated with caution inasmuch as pre- and post-installation cooling energy use at Jadwin is close to the margin of what can be discerned using monthly billing data, and at Oakwood post-installation cooling could not be estimated at all from bills. These results are broadly consistent with our view that in most Northwest climates, adding incidental cooling capacity where none existed before leads to very modest energy use penalties. Cooling benefits, in the Northwest's few genuine cooling climates where less efficient cooling is supplanted, are not insignificant, but seem unlikely to tip the balance in favor of program implementation unless the causes of relatively low heating savings are addressed. \

3 Commercial DHP Energy Savings

"Small commercial" buildings are defined in this project as offices or small retail establishments that use relatively simple heating and cooling systems (such as zonal electric heat, packaged terminal air-conditioners, constant volume rooftop units, etc.). BPA assumes that the DHP will offset only some of the existing heating and cooling energy, although in some cases it is possible that the DHP could supplant the existing system. Several sites in this study did just that. At most sites, DHP usage follows the "displacement, not replacement" model found in single-family residential zonal incentive programs.

3.1 Methods

3.1.1 Site Selection

The project began in early September 2010. In anticipation of the project, 15 small commercial sites were targeted for metering, though only a relative handful of sites were known to BPA and utility contacts. No incentives had been offered to this sector, and many small businesses were unwilling to change heating and cooling systems given their thin operating margins and the relatively unknown technology. Further, due to the zonal nature of many commercial buildings, heating, ventilation, and air conditioning (HVAC) contractors often install multiple indoor heads at commercial sites. Assessing systems with more than two indoor heads was beyond the scope of this project. BPA, Ecotope, and Fluid Market Strategies (Fluid) worked out a recruiting approach in September 2010 that would incentivize small commercial clients and HVAC contractors to install the DHP system. In late October 2010, a recruiting memorandum was distributed to utility contacts who then queried local installers to identify prospects. The recruiting memo outlined requirements for inclusion in the metering study such as size, business type, hours of operation, existence of process loads, and HVAC system type. Eligible businesses that were willing to take part in the study then agreed to a review of their utility bills. Sites with a DHP already installed would receive $200 for participating in the study. Potential sites without a DHP were offered a $1,000 incentive to reduce the first-cost price to the business owner if they went through both DHP installation and metering.

Several utilities expressed interest in the study early on, but either failed to find eligible sites, or sites that were identified were dropped for several reasons. In addition, Fluid reached out to manufacturers' representatives for Mitsubishi, Daikin, Fujitsu, and LG. Only Mitsubishi responded to Fluid's inquiries. Manufacturers' reps typically work with engineers on larger commercial projects, which employ a different model of equipment outside the scope of this study. BPA, Ecotope, and Fluid also reached out to local contractors for leads, though only one (in Flathead Electric's territory) was able to provide eligible sites.

A total of 32 sites were reviewed for inclusion in the study. Of these, only ten were ultimately recruited. Some of the major reasons sites were rejected include:

- Electric bills not received
- Internal heat gains so high that little heating load exists
- Not on a separate utility meter
- Building not occupied prior to study

Ecotope reviewed billing records using a combination of VBDD regression[9] and median low bill techniques; the goal was to find primarily heating-dominated sites, although at least two of the sites that ended up being metered appeared to have cooling-dominated bills. Both of these were small restaurants. The first site was installed in late February 2011. All ten were installed by the end of June. Unfortunately, the second site installed, a cafe, was decommissioned on July 5, 2011, due to difficulty in disaggregating end uses (it turned out several branch circuits contained additional loads which were not identified at the initial submeter installation). A replacement

[9] A brief explanation of this method is in Appendix B. For a detailed explanation refer to Geraghty et al., 2009.

was identified – another restaurant – and submetering equipment was installed on August 3, 2011, keeping a total of ten sites in the study.

Table 9 presents the final list of submetered sites. The sites in the table reflect the broad geographic spread across the region from the Rocky Mountains in Montana to the Washington coast. Further, the submetered sites span a range of activities from offices to restaurants to retail and high-occupancy gathering spaces such as a day care and congregation hall. An earlier report modeling energy use and savings of DHPs in small commercial buildings by Ecotope (Larson and Heater, 2011) showed that the amount of savings depends heavily on the type of activity performed in the building. That activity, in turn, influences occupancy schedule, process loads, and number of occupants. The submetered sites in this study can eventually be compared to those predictions on a case-by-case basis.

Table 9. Small Commercial Submetered Sites

Site ID	City	State	Occupancy Type	Building Type	Floor Area (ft^2)	UA (w/o infiltration) (Btu/ft^2-F)[10]	UA Total (Btu/ft^2-F)
20409	Eltopia	WA	Office	Masonry wall	1120	295	358
20459	Cosmopolis	WA	Day Care / School	Wood-framed building	625	238	292
99925	Bay Center	WA	Office	Wood-framed house	1739	699	772
99940	Monmouth	OR	Office	Wood-framed building	2701	512	706
99926	Libby	MT	Residence (Transitional Housing)	Wood-framed house	668	218	270
20686	Libby	MT	Office & Shop	Insulated masonry wall on slab	224	112	141
99928	Libby	MT	Retail / Computer Repair	Wood-framed building	1360	158	243
99932	McMinnville	OR	Restaurant / Retail	Brick store-front. Part of existing city block building	864	667	714
21726	Battle Ground	WA	Gathering Hall / Church	Wood-framed building	2990	278	520
99520	Sequim	WA	Restaurant	Wood-framed building	1260	512	648

3.1.2 Metering Approach

Metering presented some unusual challenges given the wide variety of buildings in this sector. The same basic setup was used as was used for BPA's Monmouth sites and NEEA's single-family zonal study (Baylon and Geraghty, 2012; Baylon et al., 2012). Two sites required multiple data loggers due to the layout of the electrical panels; several sites in Montana required manual data downloads because cellular service was not available; and site 21726 had a total of five panels that served three buildings, so it was clear that extracting a savings estimate would be difficult.

[10] The sum of the thermal transfer coefficient (U) times the area (A) of the components of the building. Also includes convective losses from infiltration.

3.1.3 Analytic Approach

The commercial building sector is diverse in behavior and building configuration. The diversity precludes a “one-size-fits-all approach” to the analysis. Restricting the sector to include only “small” buildings does rein in the diversity somewhat, yet our study of ten sites still shows a wide variety of use and occupancy. Therefore, it is not useful to generalize about DHP installations in the commercial sector as a whole but instead to examine categories within the sector. Analyzing commercial building behavior is as much a classification problem as anything else. With that in mind, our sites span about five to six categories, which include:

- Offices (4)
- Retail (2)
- Restaurant (2)
- Residence / Transitional Housing (1)
- Gathering Hall (1)
- Day Care / School (1)

Over the course of data collection and analysis it became clear that we had only two occupancy groups: those with regular occupancy and low to medium internal gain levels; and those with irregular occupancy and/or sizable process loads. The first group includes the offices, retail, and day care. The second includes the restaurants, residence house, and gathering hall.

A major goal of classifying the buildings is to enable us to extend the results to other buildings in the Northwest that exhibit similar characteristics. We found the metering and analytic approaches work for small commercial spaces with office and retail occupancy. There are many buildings in the region fitting this description. Of note, the day care is heavily occupied by children when in use, making it potentially representative of schools, albeit for very small buildings. Ultimately, however, it behaves like a heavily occupied office space and fits into the first grouping. The second grouping shows that more work is needed to group and measure behavior in more disparate occupancy types like restaurants and gathering halls.

As an analytical aside, the transitional housing site in Libby (#99926) appears out of place in this report because the occupancy is more like that of a typical residence, but it serves to illustrate the diversity of what is captured under the commercial umbrella. The house, which exhibits single-family occupancy patterns, is administered by a local agency that pays the bills.

In a further distinction from residential buildings, commercial buildings tend to have larger cooling loads. The cooling is a direct result of larger process and internal gains typical of commercial activities. Larson and Heater (2011) emphasized cooling as a potentially significant source of savings for DHP retrofits. Cooling use in this study is apparent from occupant surveys and bills. It is important for some sites but not for all. The restaurants have the highest process loads and thus have the most cooling. Offices can have some cooling in the warmer months. The particular challenge in the case of the current field study is establishing a cooling energy use baseline. In the heating-dominated Northwest climate, it can be difficult to identify cooling energy use from utility bills alone.

3.1.4 Measuring and Determining Changes in Energy Use

Throughout the project, we employed two methods to measure building energy use: billing data and direct submetering. The two big advantages of billing data are that such data exist for every site and provide a long historical record. We use the billing history to set the baseline energy use in the pre-DHP installation period. The two biggest drawbacks of billing data are that they are recorded infrequently, only at monthly intervals, and include all electric loads aggregated into a single amount. In contrast, directly submetering end uses at a site overcomes those disadvantages. For this study, the submetering occurred after the DHP was installed, which precluded disaggregating the baseline usage. Therefore, in the pre-DHP period, we have one method of measuring usage: the bills. In the post-installation case, we have both bills and submeters.

The mixture of pre-installation bills, post-installation bills, and post-installation submeters results in having multiple methods for estimating the change in energy due to installing a DHP. In this project, we investigated all approaches. Ultimately, we switched between approaches when determining a final estimate of the energy change because of the diversity in building types. Some approaches are obviously more appropriate in one case than another. Those are discussed on an individual basis for each site.

On the pre-DHP energy use side, we have the site monthly electricity bills. We employed VBDD techniques to extract the heating energy from the total bill. This method produces an estimate of heating energy used by the baseline heating system. We also examined the bills for evidence of a cooling signature to estimate the associated energy usage. Although the field teams observed window air conditioners installed in many cases, the VBDD method found no distinct cooling signature in any case. Essentially, the cooling usage is too weak to distinguish from the base load variation and the dual heating and cooling use during the shoulder season billing periods. Consequently, for pre-DHP energy use, we have the measured total bill and an estimate of heating energy use.

For the post-DHP energy use, we conducted the same analysis on the bills. Again, there is a total kWh use by month and an estimated heating energy use but no strong signal regarding cooling energy. Additionally, the data loggers on site provide direct measurements of total kWh use and total DHP energy use. Further, the submeters allow the distinction between DHP heating, cooling, and fan-only energy use. Thus, the submeters provide accurate measures of total energy, heating, and cooling energy in the post-DHP period.

Various methods could be used to compare the pre- and post-DHP electricity usage, including: total bills to total bills, total bills to total submetered usage, bill-based heating estimate to bill-based heating estimate, and bill-based heating estimates to submetered heating use. The weather during the pre- and post-DHP periods can be warmer or colder, and the analysis needs to account for this variable. The best analytical practices are to manipulate and adjust the data as little as possible. This is achieved by adjusting the pre-DHP electricity use to the weather in the post-installation period. It is better to adjust the pre-installation data because the existing heating system efficiency is linear with outdoor temperature and heat pump efficiencies are not. Nevertheless, it is also often useful to assess energy use in terms of long-term normalized weather. Normalizing energy use for both the pre- and post- cases increases the noise in the estimation but can allow for comparison to other datasets. The normalized results are presented in the main body of the report and the adjusted weather results are included in Appendix C. Weather-Adjusted Energy Use and Savings Estimates Finally, as a reality check, in every case, we also simply compare total bills pre- and post-installation. The weather typically varies no more than 10% in heating degree days from year to year so that “raw” comparison can prove useful.

3.2 Findings

Despite the sheer diversity in the results of the field work, which itself is important, the analysis shows a similarity among six of the sites in the study. These office and retail spaces show coherent behavior. The other four sites proved either too difficult to submeter and analyze or too diverse in behavior to aggregate into one or more categories. Table 10 shows the results of the six similar sites which have regular occupancy and thermostat settings. The table gives an average result for all six sites but it is important to keep in mind this is not a random sample study and the average only holds for these six specific sites. Subsequent sections discuss the individual cases at each of the ten sites. Appendix D. Small Commercial Site Billing Data History Graphs provides billing data graphs for each site and should be referenced for further information.

Table 10 highlights the challenge of generalizing results from a small sample size. Two of the three top saving sites in the study are west of the Cascade Mountains where the heating season is mild. One expects the colder sites to have more savings simply because of the increased heating demand. But the top saver is in Bay Center, WA not in Libby, MT. In such a small sample, the determinants of savings appear to be system settings, occupant behavior, or installation location, just as much as the heating zone.

Table 10. Energy Savings at Six Small Commercial Sites (Weather Normalized)

Site ID	City	Floor Area (ft^2)	Heat Savings (kWh/yr)	Cool Savings (kWh/yr)	Overall Savings	
					(kWh/yr)	(kWh/yr/ft^2)
20409	Eltopia	1120	2500	???	2500	2.2
20459	Cosmopolis	625	4430	-40	4390	7.0
99925	Bay Center	1739	6440	-340	6100	3.5
99940	Monmouth	2701	6300	-670	5630	2.1
20686	Libby	224	1150	0	1150	5.1
99928	Libby	1360	5340	???	5340	3.9
Average					4185	4.0

Note: Cooling energy use and savings are often ambiguous. In each of the "???" cases, there was no change or a decrease in cooling.

Table 11 shows most of the submetered loads encountered in the study. They are reported as annualized numbers over the entire project. Some loads, such as additional window AC units, were submetered but their consumption is too small to be of interest. Only two sites had walk-in coolers. Not all sites had electric resistance heaters after the DHP installation. The table highlights the difference between the restaurants and the other sites. At the restaurants, the two process loads of water heating and refrigeration are much more significant than space conditioning. The table also shows the residual, non-metered load consisting of the total building usage minus the known, individual end-uses. The total building usage is the "Service Total" column. The "non-HVAC" column shows the all of the energy used in the building apart from heating or cooling. That energy has the potential to end up as an internal heat gain to the space depending on what device uses the energy and where it is located. The final column is the fraction of the total energy that is not used for space conditioning.

Table 11. Small Commercial, Annualized Submetered Usage Across all Sites

Site ID	DHP Heating (kWh/yr)	DHP Cooling (kWh/yr)	Electric Resistance (kWh/yr)	Water Heating (kWh/yr)	Walk-In Cooler (kWh/yr)	Residual, non-submetered (kWh/yr)	Service Total (kWh/yr)	non-HVAC (kWh/yr)	non-HVAC %
20409	2,432	969	3,995	720	-	11,998	20,232	12,773	63%
20459	3,835	42	3	1,084	-	1,578	6,562	2,662	41%
20686	979	17	-	120	-	2,771	3,960	2,951	75%
21726	6,200	-	6,600	1,960	-	11,383	-	-	-
99520	1,221	1,601	1,084	13,366	5,486	27,104	61,311	57,375	94%
99925	3,471	353	2,874	700	-	6,956	14,728	7,998	54%
99926	3,475	97	181	2,521	-	2,192	8,498	4,713	55%
99928	4,279	432	-	986	-	13,343	19,081	14,329	75%
99932	3,740	2,848	-	7,090	12,393	26,344	53,541	46,154	86%
99940	2,374	670	2	-	-	235,241	-	-	-

3.2.1 Office: Site 20409

Site 20409 is a small office building in Eltopia, Washington. It is occupied 8:00am to 5:00pm Monday through Friday year round, and on Saturdays in the summer. The existing HVAC system consisted of electric resistance baseboards and two window AC units. The single-zone DHP was installed to serve the main office space of the building. The baseboards were left in place but one of the AC units was removed. The billing analysis shows a reduction in heating energy use of 2,500 kWh/yr (weather-normalized). At the same time, the total bills increased likely due to some increase in other, unknown loads.

The office runs the DHP nearly year round for 4,380 hours in heating, 2,180 hours in cooling, and 2,000 hours in fan-only mode. The total submetered cooling energy use for the DHP was 1,000 kWh/yr. There is undoubtedly cooling in the pre-installation case, but the post-installation cooling use could potentially pose an increase in energy use overall. The data loggers recorded a paltry 10 kWh/yr of use on the remaining window AC unit, indicating it is no longer used.

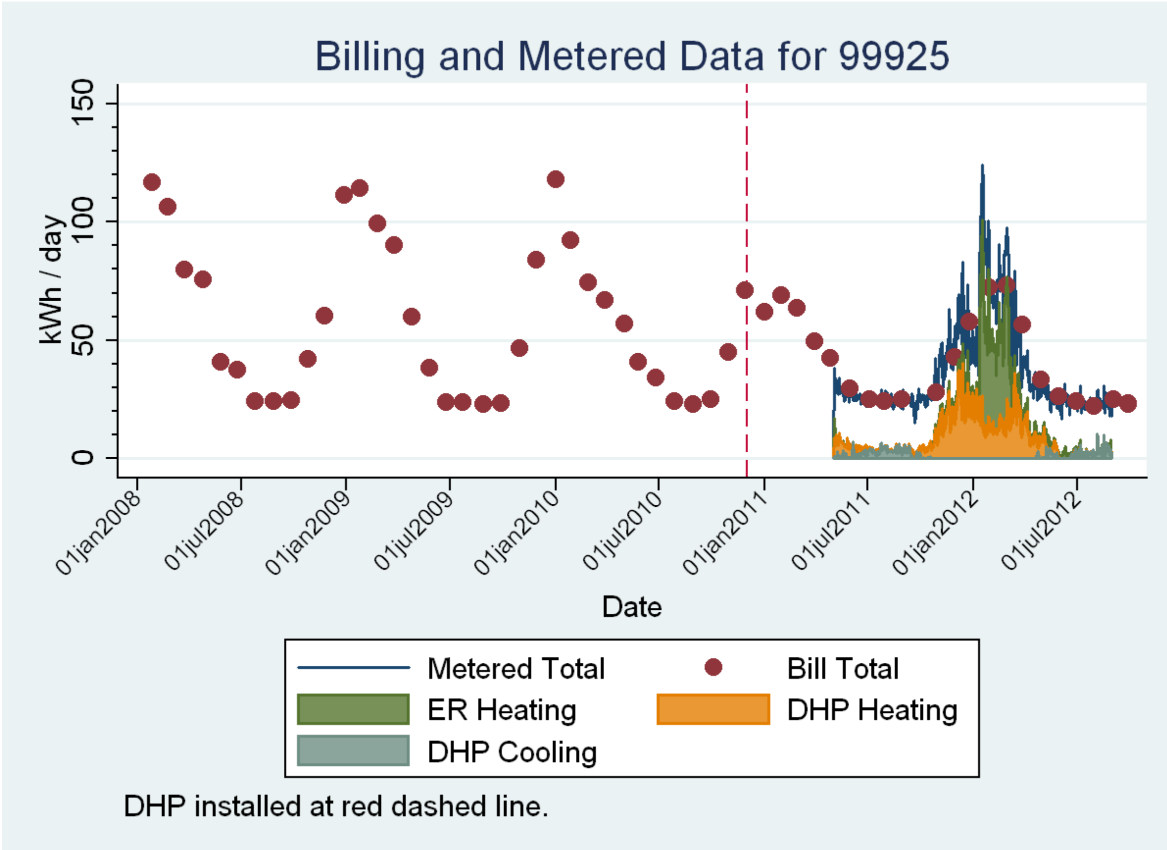
A 1-ton DHP was installed at this site. It is in heating zone 1 and cooling zone 3.

3.2.2 Office: Site 99925

Site 99925 is an office within a wood-frame house in Bay Center, Washington. Its 1.5 full time employees use the space 8:00am to 5:00pm Monday through Friday. An exceptionally clear heating signature can be extracted from the billing data – clearer than at any other site in this study. The heating energy shows regular behavior with respect to outdoor temperature. Figure 3 shows the billing data history and submetered energy use for the site. In the three heating seasons prior to DHP installation in December 2010, the monthly average energy use regularly climbs to 120 kWh/day. In the summertime, it drops to a base load of approximately 20 kWh/day. The bills show the immediate effect of installing the DHP in December 2010. Instead of climbing to over 100 kWh/day, energy use stays level at 70 kWh/day. In the next heating season, the pattern repeats.

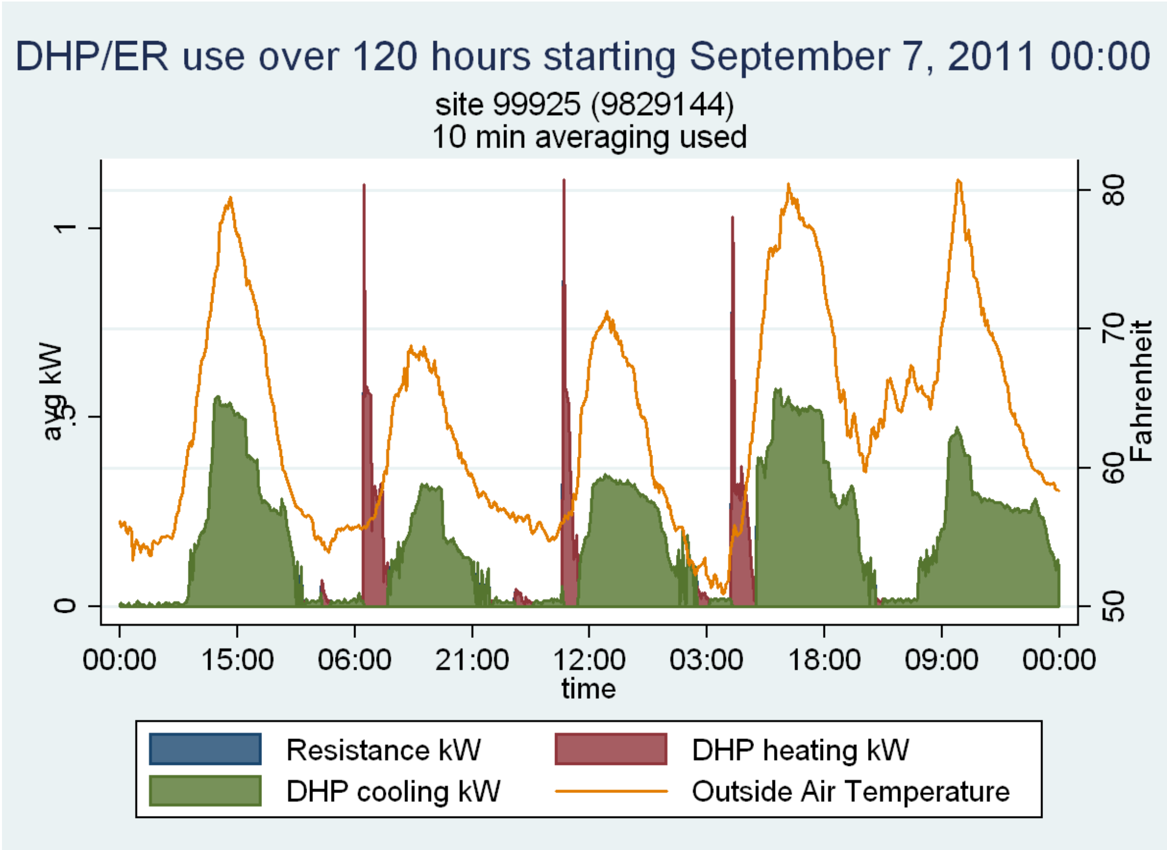
The submetering began in May 2011 and is also plotted in Figure 3. The total daily submetered energy use is the blue line. As expected, it closely tracks the bills. The submeters reported an average cooling energy use of 350 kWh/yr. This is a new load because there previously was no cooling system. There is both significant DHP and electric resistance heating use. The site begins the season with the DHP providing all the heat, but around January 2012, the occupants apparently turn on the electric resistance electric resistance heaters for additional heat. Interestingly, the increased electric resistance electric resistance usage results in reduced DHP usage. This suggests that the electric resistance heaters influence the space temperature of the DHP zone. That reduces the effective load on the DHP. Conceivably, the site could increase overall DHP runtime and savings by lowering the electric resistance set point relative to the DHP set point.

Figure 3. Data for Office Site 99925



Close inspection of Figure 3 shows the DHP is used for heating and cooling on the same day. Figure 4 shows three such days in September. The DHP provides some initial heat in the cool morning hours before switching to cooling to maintain a constant temperature inside the space as the outside temperature rises. The use of both heating and cooling in the same day turned out to be extremely rare in all sites across the study.

Figure 4. Same Day Heating and Cooling



Overall, this is the picture-perfect site in the study. The regular occupancy and thermostat settings make it possible to quantify the savings by billing analysis. Additionally, that regularity in thermostat settings makes it possible to save energy with the DHP. The site reduced its heating load by 6,440 kWh/yr with the DHP installation and only added back 340 kWh/yr in cooling, creating a net weather-normalized savings of 6,100 kWh/yr.

This site installed a 1 1/4-ton (15,000 BTU/h) DHP. It is located in heating zone 1 and cooling zone 1.

3.2.3 Office: Site 20686

Site 20686 is a very small office, 224 ft^2, in the cold climate of Libby, Montana. It is occupied by two to three people from 8:00am to 5:00pm Monday through Friday. The pre-installation HVAC system was a single wall heater and a window AC unit. The pre-installation bill analysis showed an existent, yet incredibly weak, heating signature. This was due to the site having lots of process loads relative to space heating needs. In the submetering period, the data loggers recorded only 1,000 kWh/yr of DHP usage, which is a surprisingly small number for such a cold climate. The building is small and well insulated, however. The billing analysis estimated 2,150 kWh/yr in the base case producing a savings of 1,150 kWh/yr after DHP installation.

The heating usage as reported by the bills increased dramatically after the DHP was installed. From that alone, one would conclude the DHP was providing much more heat to the building. By comparing the submetered DHP energy to the change in billed energy, however, we know the increase in energy usage was not due to that particular DHP. It appears the occupants added some other heating-dependent load to their building complex. Therefore, in this case, the best estimate of change in energy use due to the DHP comes from the difference in pre-bills to post-submeters: a reduction of 1,150 kWh/yr.

This site installed a 3/4-ton DHP. It is in heating zone 2 and cooling zone 1.

3.2.4 Office: Site 99940

Site 99940, in Monmouth, Oregon, is another building with office occupancy characteristics. There are two to five employees working 8:00am to 5:00pm Monday through Friday. Prior to the DHP installations, the site was heated with electric resistance wall heaters. In all, over the course of three years, three different DHPs were installed inside the 2,700-ft^2 building. The first DHP, installed in 2007, consisted of two indoor heat exchangers. The second DHP, installed in July 2009, also had two indoor heat exchangers totaling 2.5 nominal tons of output capacity. The equipment provides the heating for 1,700 ft^2 of the office. With two indoor heat exchangers, it covers two distinct zones separate from the other DHPs on site. A third DHP was installed in summer 2010 as part of a small addition to the building.

At this site, we were unable to obtain billing records prior to late 2007, so were unable to determine a baseline of energy use without any DHPs installed. The only DHP for which it was possible to estimate a heating baseline was the second two-head system. The bills show two distinct heating seasons prior to installation and three after installation. The submetering onsite monitored both of the two-unit DHPs as well as a subpanel for the 2010 addition. In this way, it was possible to differentiate the new load from the previous bills. The best estimate of energy savings, for both heating and cooling, in this case comes from comparing adjusted billing totals, which suggest a savings of 5,630 kWh/yr for the second system. The savings estimate includes the DHP cooling energy use takeback of 670 kWh/yr.

This site is in heating zone 1 and cooling zone 1.

3.2.5 Retail: Site 99928

Site 99928 is a computer retail and repair store in Libby, Montana. It has four to six employees working 9:00am to 5:00pm Monday through Friday and occasional Saturdays. The baseline HVAC system consisted of baseboard heaters in the showroom with plug-in space heaters as needed plus a window AC unit for cooling. Overall, due to the electronics used in the building, the store has significant levels of internal gains. Although the business is retail and repair, this site looks a lot like a heavily occupied office similar to the other offices in this study. It is a wood-framed building with regular, weekday occupancy. Therefore, it is useful to group it with the other offices.

Comparing the pre-installation heating use to the post-installation heating use, submetering shows that the site reduces consumption by 5,340 kWh/yr (weather-normalized). Although the cooling signature regression is weak, the billing history shows a slight bump in energy use in August every year, which is likely cooling energy. In the pre-installation period, the bills show that the window AC unit uses roughly 10 kWh/day for 60 days or 600 kWh/yr for cooling. In the post-installation period, the submeters logged 430 kWh/yr of DHP cooling energy use. Because the cooling energy use estimate in the pre-installation period is only approximate, it is difficult to say if the DHP produced cooling savings, but it is possible to say that it did not add to the cooling load. A notable item on the heating system operation for this site is that after the DHP was installed, the baseboard heaters were no longer used. All of the heating and cooling energy now comes from the DHP and possibly some plug-in electric resistance space heaters. At this site, we submetered total energy use, hot water, and the DHP. The plug loads and lighting, which we refer to as the residual submetered amount, are the difference between total energy, hot water, and DHP. The residual amount shows a clear temperature dependence for the site (0.25 kWh per degree day at a 48˚F base), which suggests that the occupants use supplemental, plug-in space heaters. The supplemental heating is a small amount and can be seen in Figure 5. Still, for most of the winter, the space heating load is met by the DHP alone.

Table 11 provides insight into the levels of internal gains present in the building. The table shows that of the total 19,000 kWh/yr used on site, 14,000 kWh/yr, or 75%, are used for process loads including some water heating. Relative to the other office sites, 99928 has high process loads, nevertheless, there are distinct energy savings achieved with DHP installation. This is a significant finding suggesting that all retail and office locations, even those heavily occupied with people and electronics, can show energy reductions with a DHP retrofit.

In contrast, Table 11, shows that the two restaurant sites, 99520 and 99932, have enormous non-HVAC loads which dwarf any of the space heating needs. Although much of the non-HVAC energy use may not end up as internal gains (much of the water heating energy goes down the drain and the walk-in coolers have refrigeration heat exchangers outside the building envelope), the non-HVAC loads are so large that even if a small fraction of that ends up inside the envelope, it will considerably offset heating needs.

Figure 5. Data for Retail Site 99928

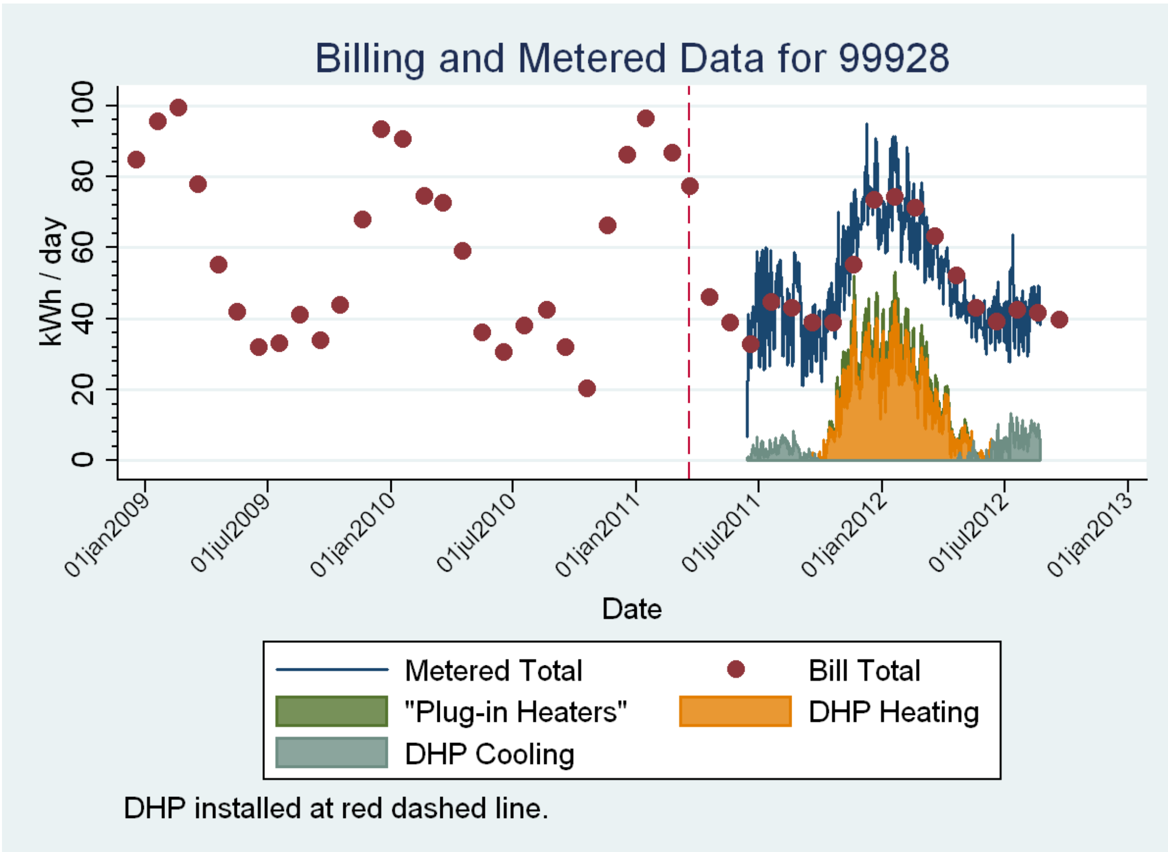
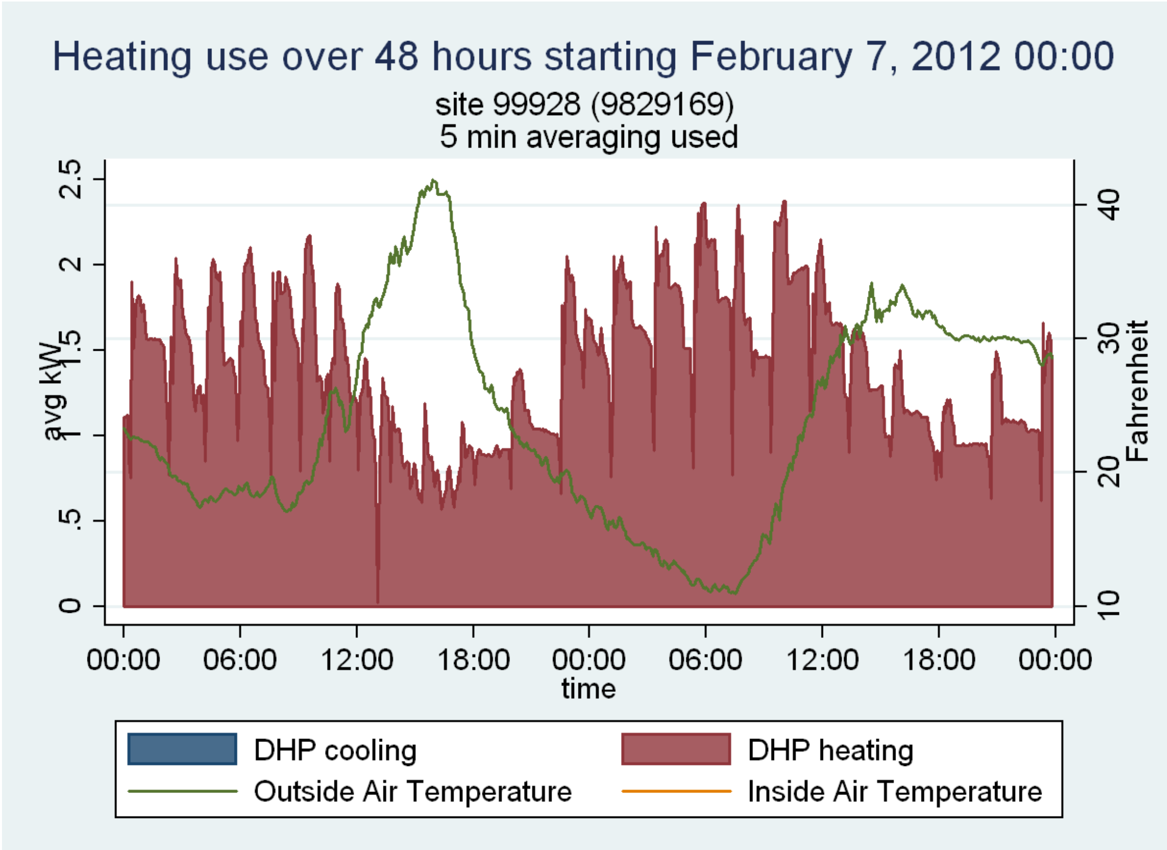


Figure 6 shows the operation of the DHP at the site over a cold, 48-hour period and demonstrates just how it is possible to carry the entire building load. At the lowest outdoor temperatures, the DHP, a Mitsubishi FE12NA, is running at its maximum output. Previous field and lab work showed the operational COP of this particular unit between 10˚F-20˚F is approximately 2 (Ecotope, 2011; Baylon et al., 2012). Therefore, the DHP is supplying about 2-4 kW/hr of heat at the lower temperatures, which is plenty given the estimated heat loss rate of the building at 250-300 Btu//hr-˚F (75-90W/˚F). Figure 6 shows the DHP engaging in defrost cycles every 1.5 hours. Those are indicated by the decrease in power to approximately 0.75 kW followed by a surge in power draw and output over the next 10- to 30-minute period.

Figure 6. 48-Hour Heating Use at Site 99928



This site installed a 1-ton DHP. It is in heating zone 2 and cooling zone 1.

3.2.6 Day Care: Site 20459

The day care facility has more in common with the office and retail spaces in this project than with other school facilities. The site occupies a wood-framed building in Cosmopolis, Washington. It operates on an 8:00am to 5:00pm Monday through Friday schedule with 2 adults and 12 children. At 625 ft^2, the building is densely occupied, leading to relatively high levels of internal gains. In some sense, this makes the building similar to the retail space at 99928. The baseline heating system at the site was a set of electric resistance baseboard heaters. When the DHP was installed, the baseboard heaters were left in place but the submetering shows that they were never used. In other words, all the heating and cooling needs for the site were provided by the DHP.

The weather-normalized pre- to post- bill analysis shows that the site reduced its heating energy use by 4,430 kWh/yr. The submeters recorded only a slight amount of cooling use at 40 kWh/yr, which is a tiny new load at the site.

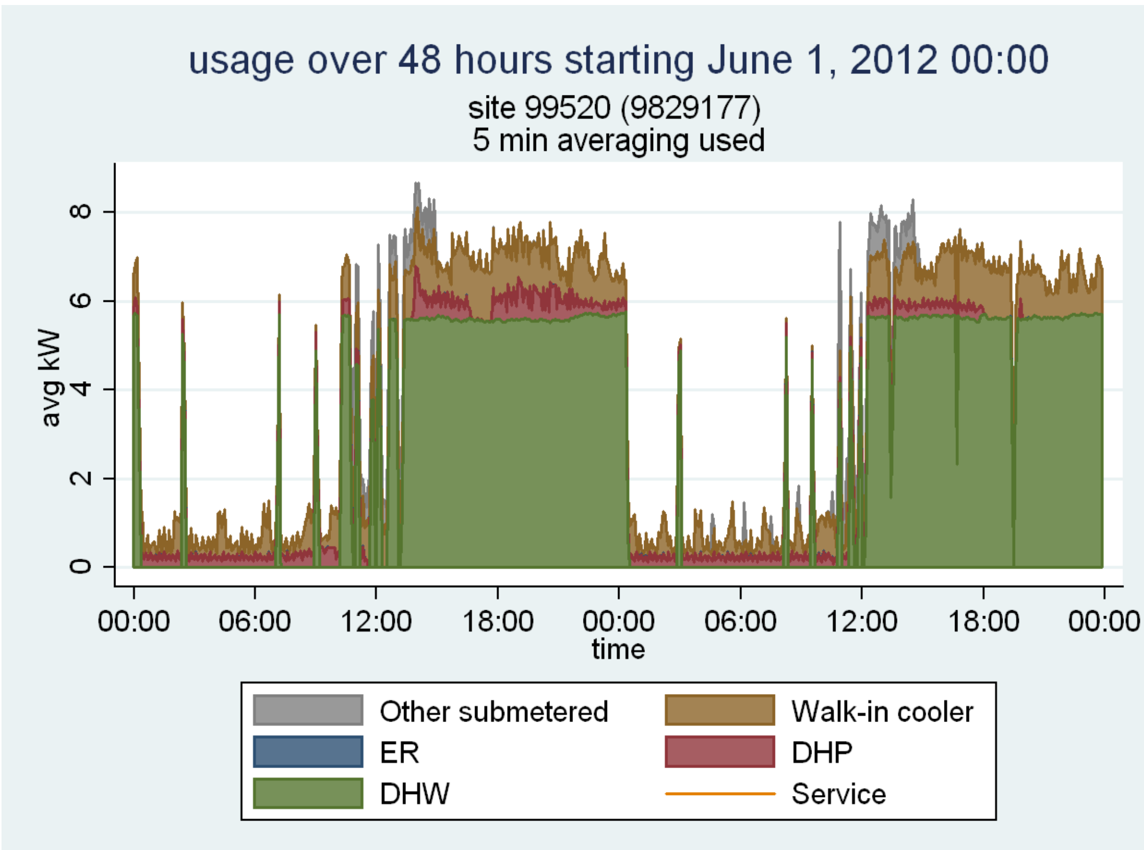
This site installed a 1-ton DHP. It is in heating zone 1 and cooling zone 1.

3.2.7 Restaurants: Sites 99520 and 99932

Both the restaurants proved to be too complex for this study design to handle. It was not possible to determine a significant space heating or cooling signature from the pre-DHP installation bills. At site 99520, the VBDD regression suggested that the site used less heating energy when the outside temperature decreased, which is purely nonsensical. At site 99932, the pre-DHP heating signature was existent albeit extremely weak but the post-DHP bills and metering show an increase in energy use completely unrelated to the DHP or any other submetered load. In neither case did the analysis show a cooling signature. Taken together, all of these findings preclude estimating the change in energy use due to the DHP. Put another way, the heating and cooling energy uses do not rise above the aggregate noise of the other process loads on site.

Figure 7 illustrates the issue at site 99520. In June, the DHP is in cooling mode but the other loads on site dominate the total energy use. The figure shows a walk-in cooler constantly running, some usage on a circuit labeled as “make-up air heaters” but apparently also including additional loads, and a hot water heater running from noon to restaurant close. Instead of a DHP, this site would be better served by a commercial heat pump water heater or upgraded cooler.

Figure 7. 48-Hours of Process Loads at Restaurant Site 99520



Even though it was not possible to directly estimate changes in DHP energy, Baylon et al. (2012) have shown it is possible to indirectly estimate the DHP coefficient of performance (COP) and therefore compare it to a known baseline COP. This allows an implicit estimation of energy savings by answering the question: Given the heat energy input and output of the DHP in the post-installation case, what would have been the input heating energy requirement for the pre case-installation heating system?

For site 99520, the submeters show 1220 kWh/yr of heating energy use and 1600 kWh/yr of cooling energy use. Using known DHP performance curves, we estimated the annual COP in heating to be 3.7. The previous system had a COP of 1. That indicates a potential savings of up to (3.7-1)*1220 kWh/yr or 3300kWh/yr of heating savings. With cooling, the previous system was a PTAC with a SEER less than 10. The DHP SEER is 20, a two-fold increase in efficiency. Therefore, we estimate a reduction in cooling energy of 1600 kWh/yr. Overall, the DHP may be saving 4900 kWh/yr of energy onsite. Nevertheless, the only way to confirm this amount is with submetering in both the pre- and post-DHP periods.

For site 99932, there is a similar story. Estimates of heat output and performance differences indicate a potential savings of 9,000 kWh/yr for heating and 2,800 kWh/yr for cooling. Direct measurements on site for some time *before* the DHP was installed are needed to confirm this.

Site 99520 is served by a 2.5-ton DHP; site 99932 is using a 3-ton DHP. Both are in heating zone 1 and cooling zone 1.

3.2.8 Gathering Hall: Site 21726

There are three buildings on this site all on the same utility billing meter. The DHP was installed in the gathering hall within the largest of the buildings. At the outset of the submetering, it appeared possible to individually submeter the total usage of all three buildings and then subtract out the unwanted building energy consumption from the pre- and post-period bills. Upon analysis of the data, it was determined that the occupancy and use characteristics changed too much over the course of the billing and submetering period to make any reliable calculations. To put it in perspective, the gathering hall, which may have only been occupied two days per week in some years, would only need to change to three days per week in another year to render our understanding of the data incomplete.

Using the heat output and COP estimation method, the DHP could have saved 6,000 kWh/yr over the baseline electric resistance system. Like the restaurant case, the only way to know is to submeter both the baseline and new systems.

This site installed 3 2-ton DHPs. It is in heating zone 1 and cooling zone 1.

3.2.9 Transitional Housing: Site 99926

This site slipped into the study because the bills were going to a commercial address although the occupancy of the building was clearly residential in its use pattern. Over the course of a few years, the site houses a changing number of occupants, which makes it impossible to compare heating usage patterns from year to year. As in the previous three cases, it is possible to estimate a DHP savings from the submetered data alone with the heat output and COP method. Such a method estimates 7,600 kWh/yr in savings. The occupants used only 100kWh/yr in cooling. Even with such an estimate, the wide differences in occupancy from year to year rendered the analysis inconclusive.

A 1-ton DHP was installed at this site. It is in heating zone 2 and cooling zone 1.

3.3 Conclusions and Recommendations

The field monitoring and analysis of ten small commercial sites showed that six of the sites exhibited regular occupancy and scheduled thermostat behavior and therefore reliable estimates of energy savings due to DHP installation could be calculated. The other four sites either displayed no central tendencies or proved too complex to analyze so no formal conclusions about them can be drawn. In each case, the submeters logged DHP usage but occupancy changes or a non-existent heating signature prior to installation precluded a savings estimate. For those sites, particularly restaurants, a new field study submetering both pre- and post- DHP installation periods could likely determine the energy savings.

The six sites where an analysis was possible all exhibited the following characteristics:

- Representative of either office or retail occupancies
- Stand-alone structures but well-insulated with low heat loss rates
- Wintertime heating loads
- Occupied at least 9:00am-5:00pm, 5 days per week
- Heavy reliance on the DHP to heat the space (up to 90% of the annual heating needs)

The analysis shows that a prescriptive installation program of DHPs in small office and retail spaces has the potential to reduce energy use. Six relatively well-behaved sites showed an average of 4,185 kWh/yr of savings.

In developing a prescriptive program, the target buildings should exhibit the characteristics mentioned above with the following additions. The structures need not be stand-alone. The heat loss rates of some of the metered buildings were so small that they suggest adjoined units in strip malls would also be good candidates for a retrofit. Further, it is not possible to predict heavy usage of the DHP from pre- installation data; however, program materials could be developed to encourage the occupants to set the thermostats to favor DHP usage.

The modeling work of Larson and Heater (2011) showed that the DHP retrofit energy savings depend on the type of commercial activity and amount of internal gains associated with a building. This study evaluated sites with a wide range of internal gains (a lightly occupied office in Eltopia to a heavily occupied day care center in Cosmopolis), suggesting that all office and retail type occupancies are candidates for a prescriptive DHP retrofit measure. Classifying a site as an office or retail space places enough limits on the internal gains to leave enough heating load in place for the DHP. In contrast, a restaurant or convenience store (with all of their refrigerated cases and other unusual end uses) typically has process loads that greatly offset heating demand.

Due to the small study size and diversity of climates, it is not possible to make generalizations about heating and cooling energy use across different Pacific Northwest climate zones with the metered data. To be sure, although there are two offices with energy savings in Libby, it’s not clear that they represent typical small offices in Libby let alone Western Montana or all of Heating Zone 3. To generalize the results from this project, a possible method is to create calibrated simulations. Using EQuest or SEEM, it would be possible to show the simulations could predict energy use at the six office and retail sites. From there, the simulations could be run on a prototypical set of buildings across heating and cooling climate zones thereby providing a grounded energy use estimate. Such simulation frameworks already exist (Larson and Heater, 2011).

Assigning a measure cost in the commercial sector is difficult but a rough estimate is $4000 for a one indoor head system. It is likely the installed cost is less than this for simpler installations so using $4000 is a conservative approach. Assuming a 16 year measure life and a real discount rate of 4%, the levelized cost of the DHP savings is $0.074/kWh, well under the NWPCC ceiling of $0.101/kWh.

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Appendix A. Cross-Sectional Regression Results

Two separate but related data sets are available for the task of selecting appropriate specifications for cross-unit regressions. The 12 submetered units have relatively rich characteristic and consumption data, but the small number of units (four of which received no exit interviews due to the unavailability of occupants) constrains the complexity of the analysis. On the billing data side monthly consumption data from all 188 units are available, but potential explanatory variables are few. Variables which can be inferred from billing data alone are prior total consumption levels, prior heating levels as estimated via VBDD, and changes in electricity account number, which are a reasonable proxy for an occupancy change.[11]

[11] Most complete occupancy changes in fact imply *two* account changes, prior occupant to house account, and house account to new occupant.

Table 12 and Table 13 display results of the two most fruitful specifications for cross-sectional regressions, one ("metered units only") estimated over the 12 submetered units, the other ("all units") estimated over all 188 units.

Table 12 depicts results of the “all units” regression. The dependent variable is weather-adjusted change in annual kWh, estimated from bills. Aside from a constant term, the sole explanatory variable is pre-installation annual kWh consumption. To ease interpretation of the coefficients, the annual prior kWh used as an explanatory variable was mean-corrected by subtracting the overall 188-unit sample mean of prior consumption from each observation. This mean-correction procedure does not alter the value or explanatory power of the estimated response coefficient, but does change the value and interpretation of the estimated constant term. The estimated response coefficient on prior kWh is highly significant, and has the interpretation that every kWh increase in prior annual consumption increases the estimated savings by 0.34 kWh. The constant term coefficient is also highly significant, and (given that all other explanatory variables are mean-corrected) has an interpretation of the expected savings for a unit with a prior consumption exactly at the sample mean of all 188 units’ prior consumption. Available potential explanatory variables tried and rejected as insignificant include occupancy changes/yr (as proxied by account number changes), unit size, and site affiliation (Jadwin or Oakwood).

Table 13 depicts results of the “metered units only” regression. The dependent variable is weather-adjusted change in annual input heating kWh, estimated using submetered data. In addition to a constant term, two explanatory variables are used: the first is the same explanatory variable used in the first regression (mean-corrected pre-installation annual kWh, from bills); the second (resistance fraction) is the fraction of post-installation input heat accounted for by all forms of resistance heating. Over the twelve submetered sites, this fraction ranges from zero to (very nearly) one.

Despite being estimated using a data set of only twelve records, both explanatory variables have statistically significant coefficients. The inverse relation between the resistance heating fraction and savings is particularly strong; the implied savings increase in expected consumption for every percent decrease in resistance fraction is 40 kWh/yr. It is of course consistent with basic engineering reasoning that, all else being equal, a greater percent shift from resistance to DHP heat implies greater savings. The coefficient of -0.295 on pre-installation annual kWh is marginally significant at 10%, and similar in magnitude to the -0.343 coefficient estimated in the “all units” regression. Given the size of the standard error on -0.295, the hypothesis that the two estimates are in fact equal cannot be rejected. The -0.295 coefficient has the same interpretation as in the previous regression, that is, a 1 kWh increase in prior consumption implies a 0.295 kWh increase in expected savings. In this regression the constant term coefficient has the interpretation of the expected change in consumption given that the resistance fraction is zero (complete conversion to DHP heat) and prior kWh annual consumption is equal to the sample mean prior consumption of all 188 sites.

Table 12: Regression Specification - All Units

Explanatory Variable	Est Coefficient	Std Error	t-statistic	P>|t|	[95% Confidence Interval]	
Pre-installation kWh, adjusted & centered	-.343	.057	-6.02	0.00	-.455	-.230
Constant term	-962.37	160.43	-6.00	0.00	-1278.9	-645.9

kWh change, adjusted (dependent var)	pre-to-post change in annual weather-adjusted total kWh
Pre-installation kWh, adjusted & centered (explanatory var)	estimated weather-adjusted prior total annual kWh re-centered at prior adjusted kWh mean for all 188 sites

Overall Regression statistics	
Number of obs	188
R-squared	0.16
Adj R-squared	0.16

Table 13: Regression Specification - Submetered Units Only

Explanatory Variable	Est Coefficient	Std Error	t-statistic	P>|t|	[95% Confidence Interval]	
Pre-installation kWh, adjusted & centered	-0.295	0.162	-1.82	.10	-.66	.07
Resistance fraction	3975.9	1184.5	3.36	.008	1296.3	6655.45
Constant term	-2412.6	471.8	-5.11	.001	-3479.93	-1345.33

Input heat change (dependent var)	Submetered input heat (DHPH+ER+resid.heat from table CXX) minus weather-adjusted pre-installation heat, estimated using VBDD on just submetered unit's billing data
Pre-installation kWh, adjusted & centered (explanatory var)	Estimated weather-adjusted prior total annual kWh re-centered at prior adjusted kWh mean for all 188 sites
Resistance fraction (explanatory var)	Estimated fraction of total submetered post-installation input heat which is resistance heat

Overall Regression statistics	
Number of obs	12
R-squared	0.61
Adj R-squared	0.52

Appendix B. Site Screening and VBDD Analysis

Ecotope expended considerable resources in screening potential submetering sites. This discussion covers our approach to single-family homes, but the process also applies to multifamily and simple small commercial structures. Evaluation of potential conservation measures depends on a sizable pre-measured “signal”—in this case, electric resistance heating. Site submetering is quite expensive in terms of the initial installation of equipment, tending of data, and final analysis. Therefore, it is very desirable to target sites that actually display significant amounts of electric heating energy. Sites that use wood heat or are infrequently occupied (vacation homes, for example) would be expected to use limited electrical heat and would therefore show little or no change in electric heat usage even if a DHP were installed. Potential sites were drawn from utility incentive lists, either through the large database curated by Fluid Market Strategies or from individual utilities or homeowners. Utility bills extending back at least one year (and often two years) were requested for all of these sites and re-shaped as needed (in terms of number of days in billing period, back-to-back bill errors, etc.) for review.

Each house was assigned a weather site based on its location and climate. In general, the weather sites were assigned on the basis of geographical proximity. After these assignments, National Weather Service (NWS) data were collected for each site. The NWS data included the high and low temperatures for each day of the year. A computer program was written to calculate degree-days based on these high and low temperatures. Using the billing periods specified in the bills, complete temperature records were assigned to each bill. In a few cases, this assignment was not possible due to missing values in the NWS records, and in such cases, information from nearby weather sites was used to supplement data.

The characterization of climates and heating requirements is based on the construction of heating degree-days (HDDs) for each site. The degree-day is a construct of the NWS, and is calculated according to the following equation:

$$DD = T_{BASE} - (T_H + T_L)/2$$

where:

DD : Daily Degree Days

T_{BASE} : Degree-Day Reference Temperature

T_H : Daily High Temperature

T_L : Daily Low Temperature

The NWS and virtually all climate summaries use a T_{BASE} of 65° F for calculating HDDs. This base temperature has been an established part of NWS reporting for more than 70 years, and was designed to roughly describe the factors that predict space heat in residential buildings. However, as homes have become better insulated and have more internal gains (due to appliances, lights, etc.), base 65° F degree-days are less and less useful as a space heat predictor. In relatively well insulated houses with typical modern appliances, the T_{BASE} can easily fall below 55° F. Homeowner preference on how they operate their heating equipment will also obviously influence the degree-day base (also called the balance point).

The central assumption in screening sites by using utility bills is that the amount of space heating in a single month is strongly related to outside temperature. This relationship can be derived by relating overall energy use to outside temperature and estimating space heat energy by reviewing usage patterns over the year.

There are several methods for assessing and estimating home heat use. The most common of these techniques is the Princeton Scorekeeping Method (PRISM) analysis (Fels, 1986). The method used in this report is adapted from PRISM, and relies on a variable base degree day (VBDD) method in which individual bills are paired with the average temperature conditions for the billing period, expressed as degree-days. A regression is established using these points, and the fit indicates the relationship between space heating and weather conditions. The actual procedure consists of an iterative process; degree-days are calculated to various bases between 50° F and 72° F. A separate regression is run for each degree-day increment, and the best fit is selected.

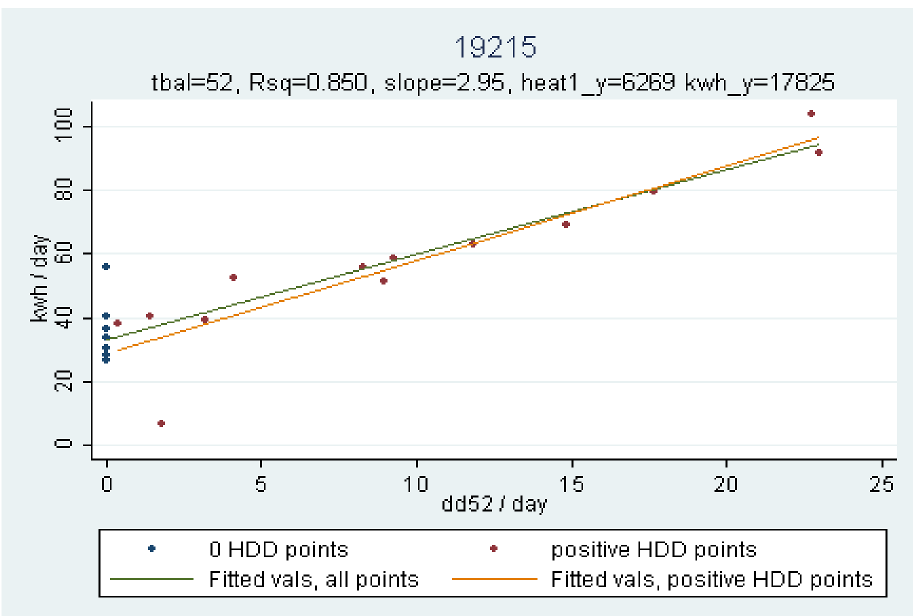
For most Pacific Northwest weather sites, there are months in which no degree-days occur and no space heating occurs. In western Washington and Oregon, for example, it is not unusual for space heating to be completely absent between May and October in well-insulated homes. Ecotope’s regression algorithms derive space heating estimates only for those months in which HDDs occur. The remaining bills are used to derive non-space-heating energy usage (also known as baseload).

A balance-point degree-day base is selected from the best fit of energy use to degree-days. The regression against degree-days to this base produces a slope that expresses heating requirements in kilowatt hours per degree-day (kWh/DD) as the heat loss rate for the house. An intercept is also produced, representing the point at which the HDDs and heating load equal zero. The intercept represents home energy use when no space heat is present. When multiplied by the number of months in the analysis, this becomes a first-order estimate of the home's non-space-heating energy use.

One difficulty associated with this method is that non-space-heating usage actually varies seasonally, depending upon outdoor temperature and hours of sunlight. The impact of these seasonal non-heating variations is well documented in Roos and Baylon (1993). The 150 homes in that study were submetered so that non-space-heating load variations were monitored and could be studied. Other researchers have observed similar effects and have attempted to provide solutions to this problem in evaluating regression-based billing analyses. The method proposed by Fels et al. (1986) is to fit a cosine function using the regression constant. The constant (*y*-intercept) represents the minimum seasonal value of appliance usage, and the maximum value is described by a cosine function with an amplitude of approximately 1.15. Another complication is that some homes use mechanical cooling. Cooling will also occur (at least for the most part) during zero-HDD periods. If a house is known to have mechanical cooling, and if it is likely it operates, we should expect to see increased usage during summer months. Depending on how this usage is accounted for, it can either be included in baseload or parsed out as mechanical cooling.

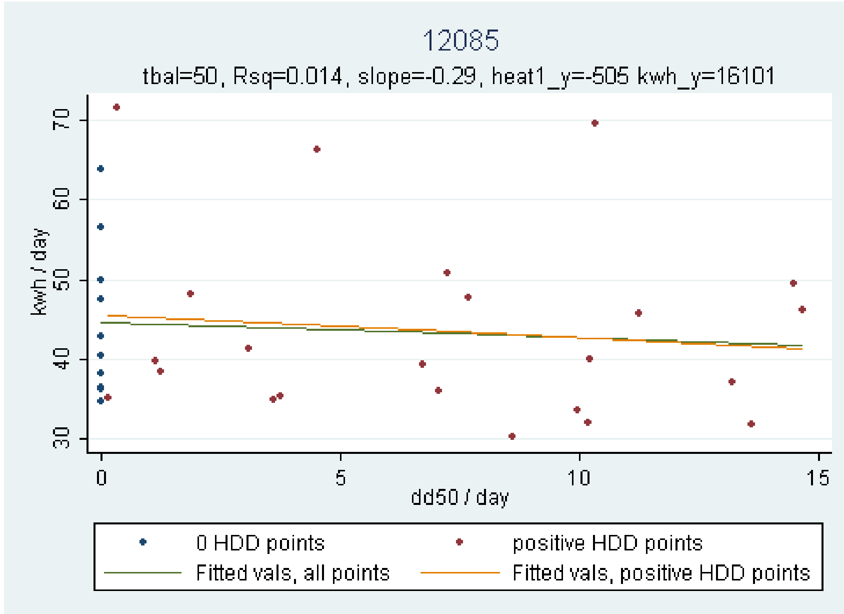
Figure 8 shows a site that exhibits a well-behaved relationship between electricity usage (kWh/day, on y-axis) and outdoor temperature (degree days, on x-axis). The VBDD process finds that the best-fit degree day base is 52° F and estimates an annual heating energy usage of 6,269 kWh/year. In Figure 8, the blue dots show usage during zero-HDD days, and some of this usage (for points above the regression line) is possibly mechanical cooling. The site is located in Benton County (eastern Washington Tri-Cities), so cooling is not unlikely.

Figure 8. VBDD Regression with Strong Seasonal Relationship



A second example illustrates a common problem with sites that include a DHP: likely usage of wood or another non-electric heating fuel. Ideally, a DHP would not be installed in this site because it would not offset heating electricity. Figure 9 shows no apparent relationship between electricity usage (red dots) and the best-fit regression line. The correlation coefficient is effectively 0, indicating mathematically that there is no relationship between electricity usage and winter (heating) conditions.

Figure 9. VBDD Regression with Weak Seasonal Relationship



The VBDD is a necessary first step, but it is not always sufficient to identify a good candidate. A second billing analysis is typically conducted by using another strategy. In this case, no regression analysis was conducted. We used the billing procedure developed by Kennedy (1994). The procedure begins with the selection of the three lowest bills of an annual billing cycle. The median of these three bills is then selected as a first-order estimate of non-space heating consumption. The Roos and Baylon (1993) adjustment is applied, and the result is the monthly estimate of the home's non-space-heating energy usage. The difference between this result and the total bill for the month becomes the monthly space heating estimate. A multiplier of about 1.1 can be used on the middle low bill, if desired, to account for seasonality of the baseload.

The median low bill approach is relatively quick and can be used by those not equipped to run VBDD routines. However, any temperature-based variation is not directly measured, because this procedure does not normalize by temperature or degree-days. This procedure is less complex than the regression analysis, but it cannot be easily applied across climate zones and different years' weather conditions.

Appendix C. Weather-Adjusted Energy Use and Savings Estimates

Weather plays a defining role in heating energy use. In fact, it is the single natural driver determining the heating load on a building. Colder weather years will require more energy use than warmer ones. When comparing heating energy use across years, it is important to account for changes in weather. For instance, in a hypothetical case with no change in heating equipment, an abnormally warm year in the post-period could masquerade as energy savings. Likewise, an abnormally cold year, coupled with a change in heating system, could act to suppress the actually savings estimates if not properly accounted for.

Throughout the report, three distinct weather possibilities are mentioned. The first is the “raw” weather or simply the weather “as is” for the measurement period. The second is “adjusted” weather. The third is “normalized” weather.

For the first (raw) case, when comparing energy use from different time periods, no attempt is made to account for temperature differences. This may be the best approach in years where the heating degree days vary no more than a few percent from one another.

The second case, the “weather-adjusted” technique, is generally the best approach to compare energy use between the pre- and post-installation cases. It relies on the least amount of data manipulation. The process involves creating a linear model of heating use for the pre-installation period and then calculating the model outputs using the post-installation weather. In that case, only the pre-period data is altered (to match the post-period weather).

The third weather analysis technique is to prepare “weather-normalized” comparisons. This is useful when making predictions about general and future savings trends. Normalized weather is said to be the typical weather encountered at a given location over a multiple decade time span. To calculate weather normalized energy uses, one has to normalize the data for both the pre- and post-installation periods. Further, one needs to use weather station data and not temperature data collected on site. The weather stations, often located 50 or more miles from a site, can experience different temperatures than those at the site. Using the weather station temperatures introduces another level of uncertainty in the calculations. Combined with the need to create two heating models (one for each side of the installation period), the weather normalization process alters three different data streams in contrast to the single alteration necessary for the weather adjustment strategy. It increases the uncertainty significantly. Nevertheless, normalization is powerful because it can generalize the results.

A reason for caution in weather-normalizing or weather-adjusting energy consumption data is that the models used assume a linear relationship between heating energy use and observed weather degree-days. This linear response assumption is reasonable in many cases, but is problematic in situations of intermittent occupancy, of changing heating set points, and also in the presence of compressor-driven space-heating technology. Heat pump COPs which vary with outside temperature violate this linearity assumption. If heat pumps are present only in the post-installation period, weather-adjusting to post-installation weather can be used to avoid having to linearize heat pump energy use data.

Throughout the main body of the report, the weather-normalized results are presented. The weather-adjusted results are presented here for completeness.

Table 14. Estimated Multifamily Per-Unit Heating Savings Across Units (Weather-Adjusted)

Site	# units	Avg. unit size	Pre-install heat (adj)	Post-install heat (adj)	kWh change (adj)
Jadwin	116	865	3062	2292	-975
Oakwood	72	750	2230	1353	-663

Table 15. Estimated Multifamily Per-Unit Cooling Savings Across Units (Weather-Adjusted)

Site	# units	Pre-install cool (adj)	Post-install cool (adj)	kWh change (adj)
Jadwin	116	709	160	-402

Table 16. Energy Savings at Six Small Commercial Sites (Weather-Adjusted)

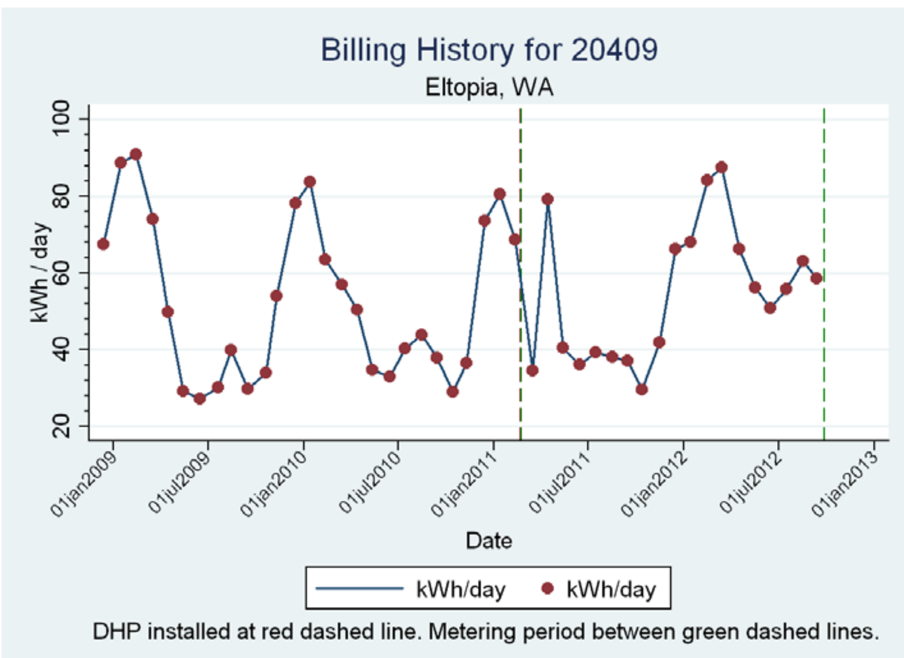
Site ID	City	Floor Area (ft^2)	Heat Savings (kWh/yr)	Cool Savings (kWh/yr)	Overall Savings	
					(kWh/yr)	(kWh/yr/ft^2)
20409	Eltopia	1120	2700	???	2700	2.4
20459	Cosmopolis	625	4600	-40	4560	7.3
99925	Bay Center	1739	7000	-350	6650	3.8
99940	Monmouth	2701	3990	-670	3320	1.2
20686	Libby	224	1200	0	1200	5.4
99928	Libby	1360	4900	???	4900	3.6
Average					3888	4.0

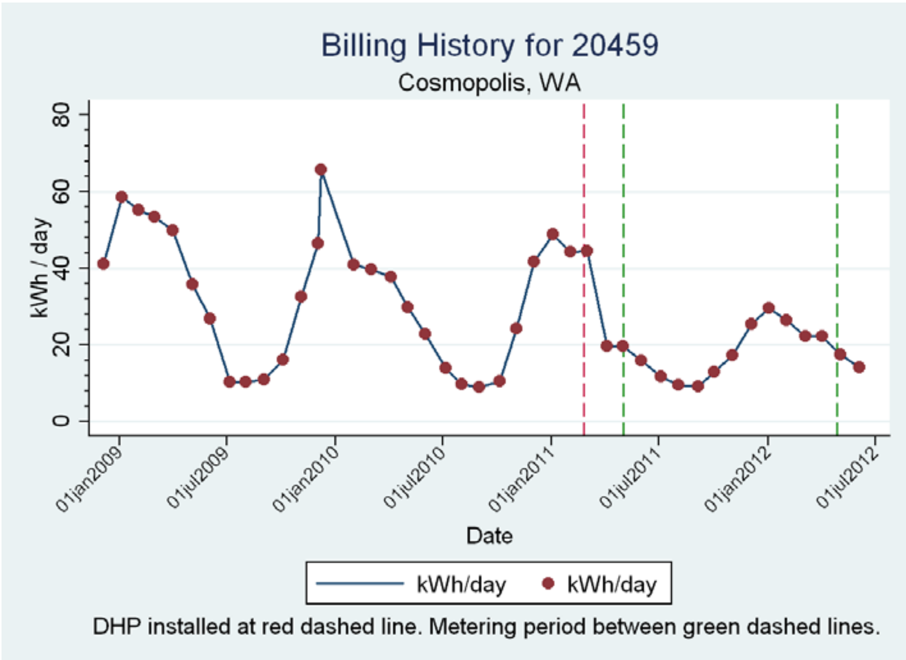
Appendix D. Small Commercial Site Billing Data History Graphs

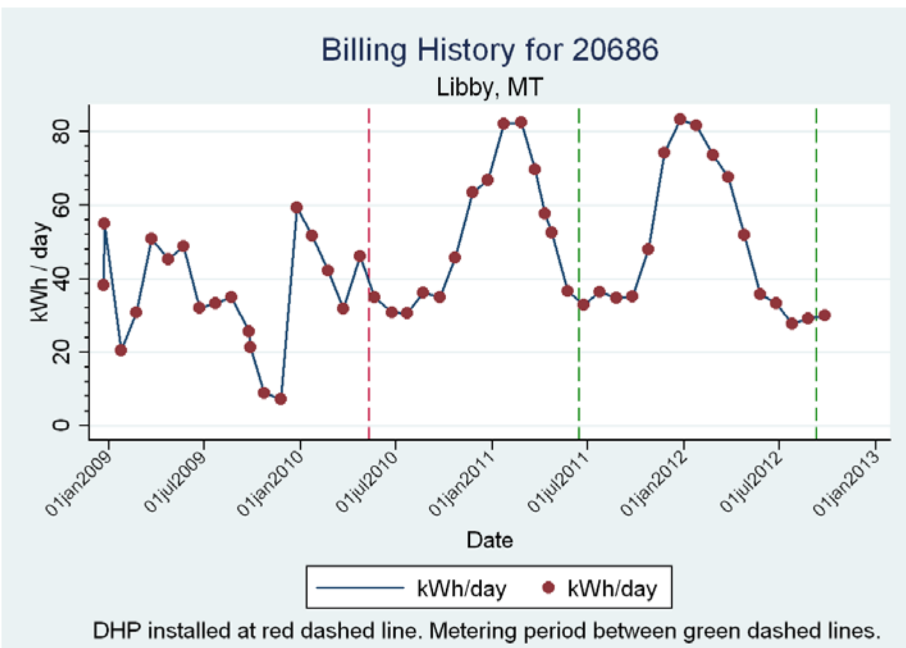
This appendix contains graphs of the billing data history for all ten sites. On the graphs, the blue line shows the trend of total energy used in kWh/day while the red points call out the day of the meter read. The vertical, red dashed line shows the date of the DHP installation. The time between the vertical, green dashed lines shows the field monitoring period. Note that none of the data are weather normalized.

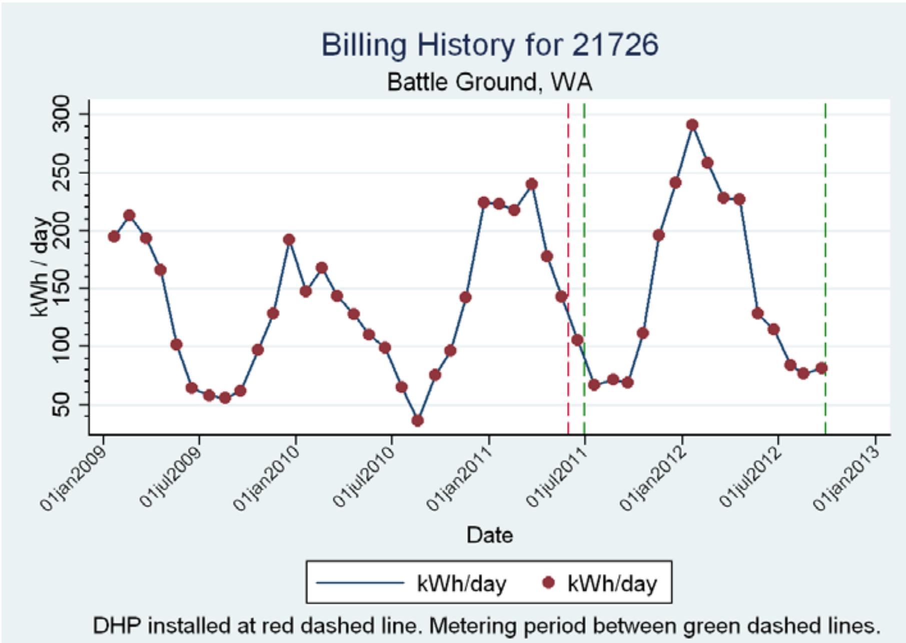
Most of the graphs show a distinct, seasonal increase in total electricity usage which corresponds to the heating signature. The two restaurants are the exceptions. Site 99520 shows fairly erratic energy use over the year. The only noticeable trend occurs in February where we learned from the occupant survey that the restaurant shuts down every year. Site 99932, another restaurant, shows a "W" shaped space conditioning signature. It has two low points in total energy use occurring in the spring and fall shoulder seasons. The restaurant both heats and cools heavily except when the outside conditions are moderate.

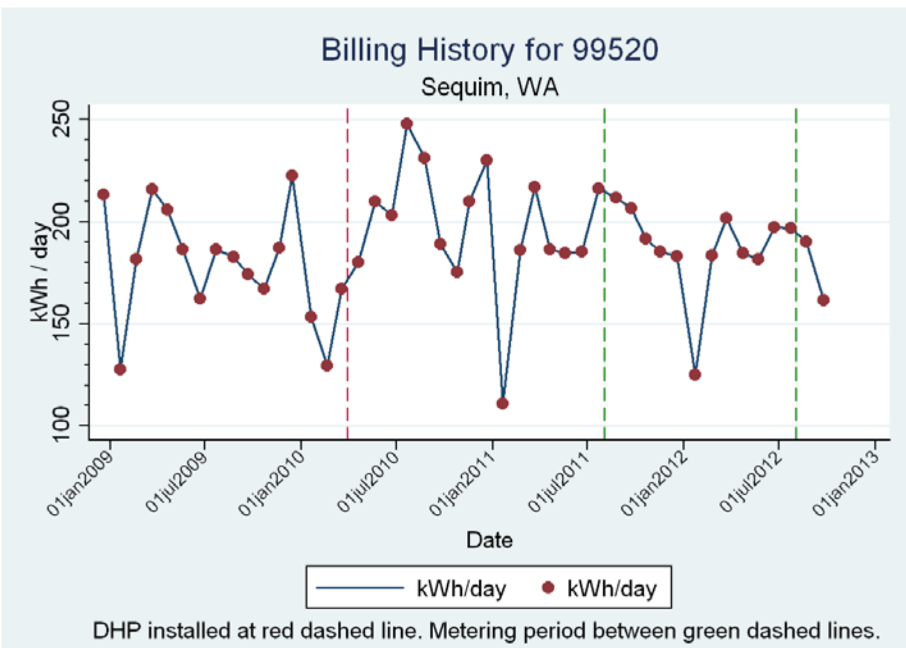
Site 99925, an office in Bay Center, Washington, is a perfect example of a thermostated heating load where the DHP installation greatly reduces energy use. The graph clearly shows three seasons of higher heating energy use before the DHP installation and two seasons of much lower use after the installation. In contrast, site 99926 demonstrates the challenges of using billing data as a baseline for energy use. The graph shows total energy use after the DHP installation increased significantly; however, this is likely due to a change in occupancy. Last, at site 99940, a collection of offices in Monmouth, OR, a multi-zone DHP was installed in the summer of 2009. This led to significant heating savings in the subsequent three seasons.

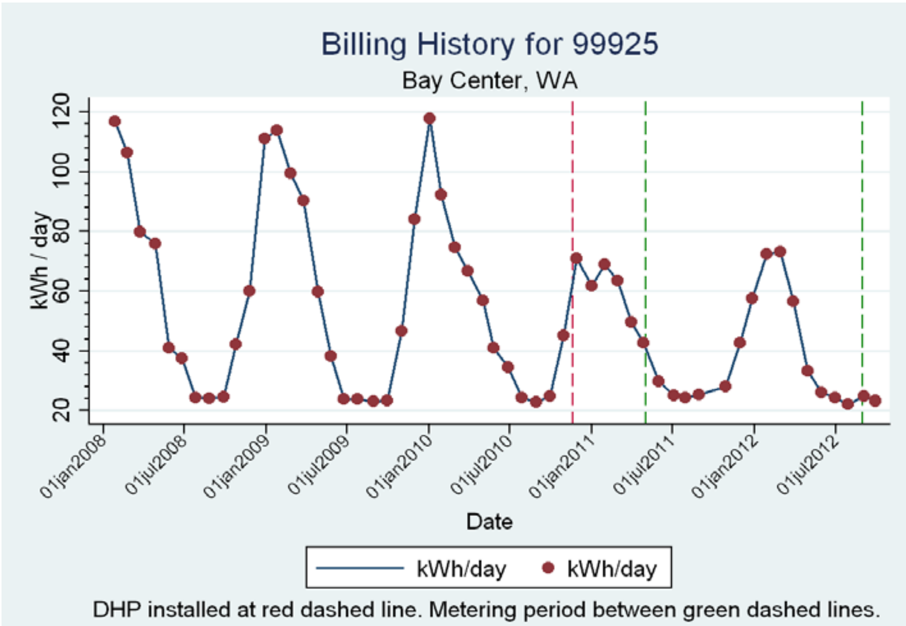


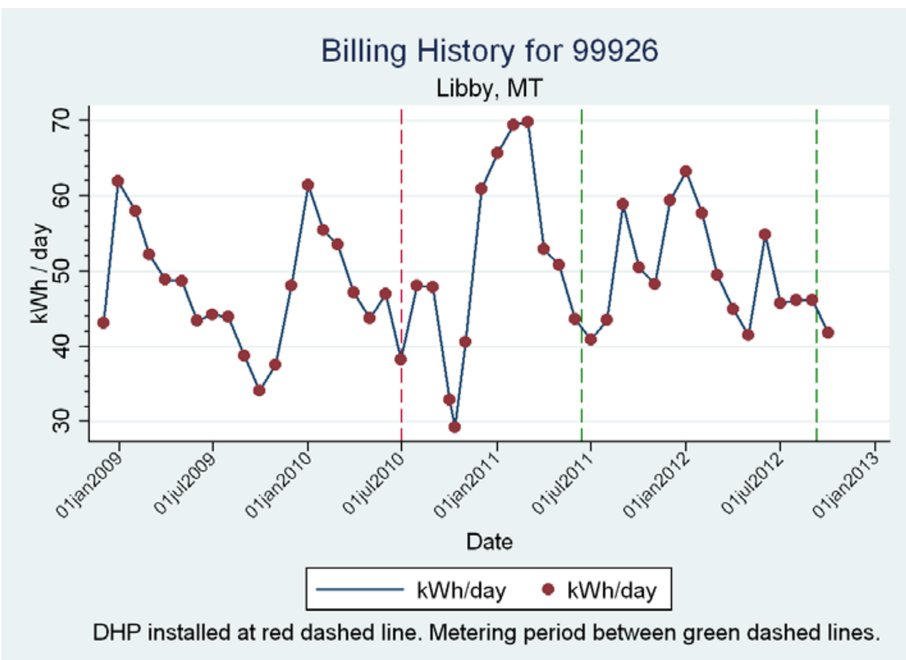

Billing History for 20459
Cosmopolis, WA
kWh / day
0
20
40
60
80
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.

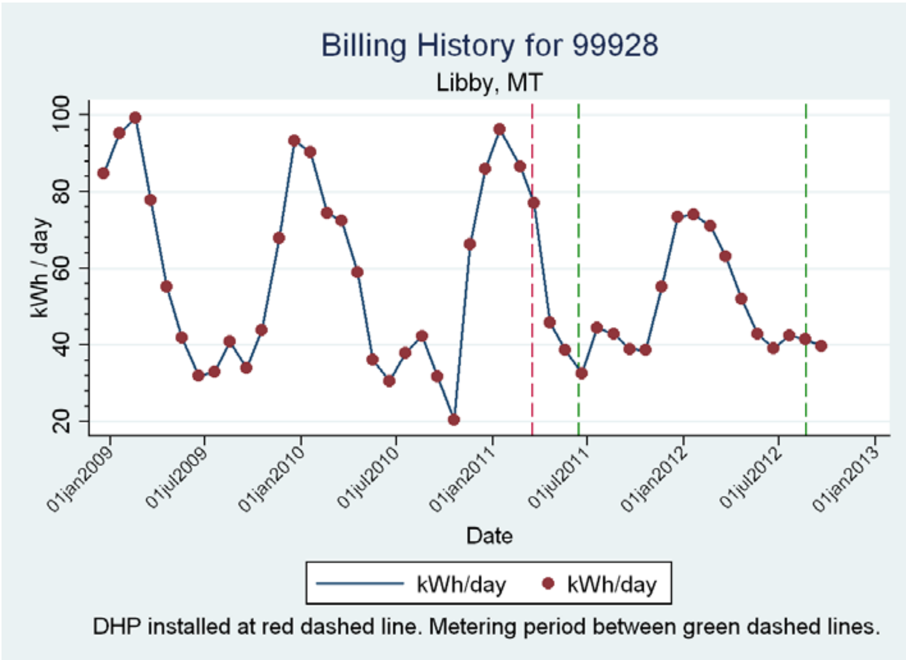

Billing History for 20686
Libby, MT
kWh / day
0
20
40
60
80
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.

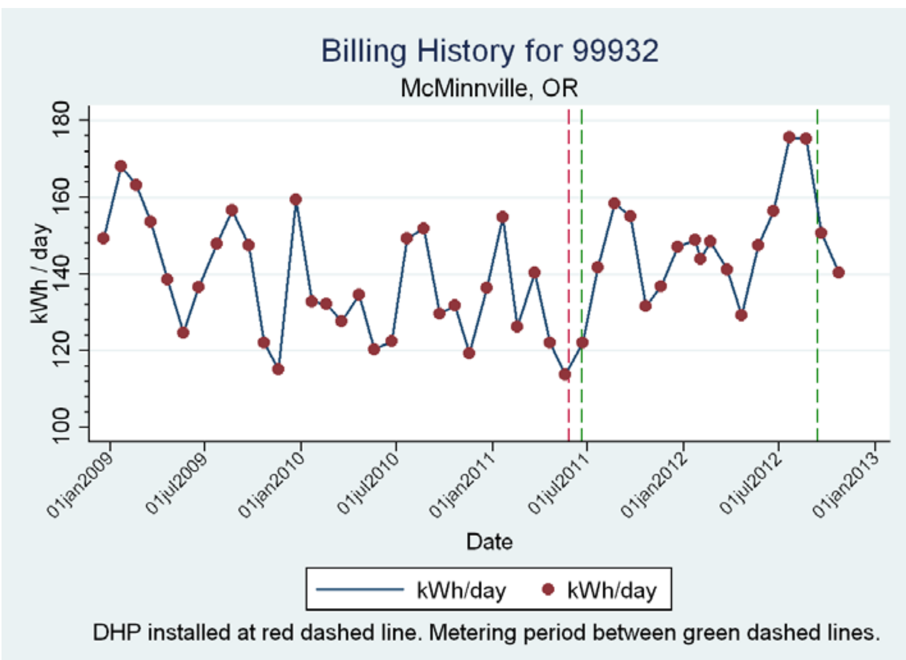

Billing History for 21726
Battle Ground, WA
kWh / day
300
250
200
150
100
50
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.

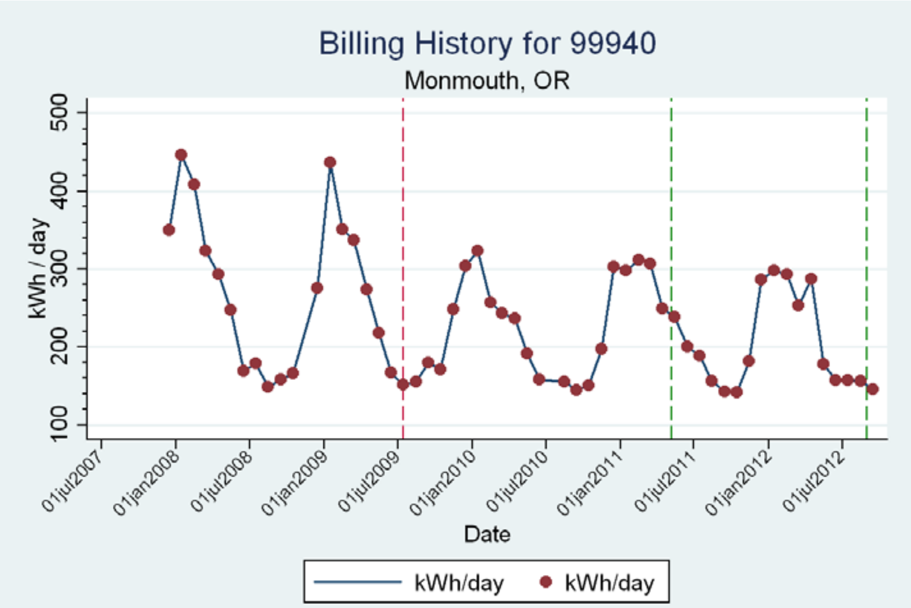

Billing History for 99520
Sequim, WA
kWh / day
250
200
150
100
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99925
Bay Center, WA
kWh / day
20
40
60
80
100
120
01jan2008
01jul2008
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99926
Libby, MT
kWh / day
30
40
50
60
70
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99928
Libby, MT
kWh / day
20
40
60
80
100
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99932
McMinnville, OR
kWh / day
100
120
140
160
180
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.



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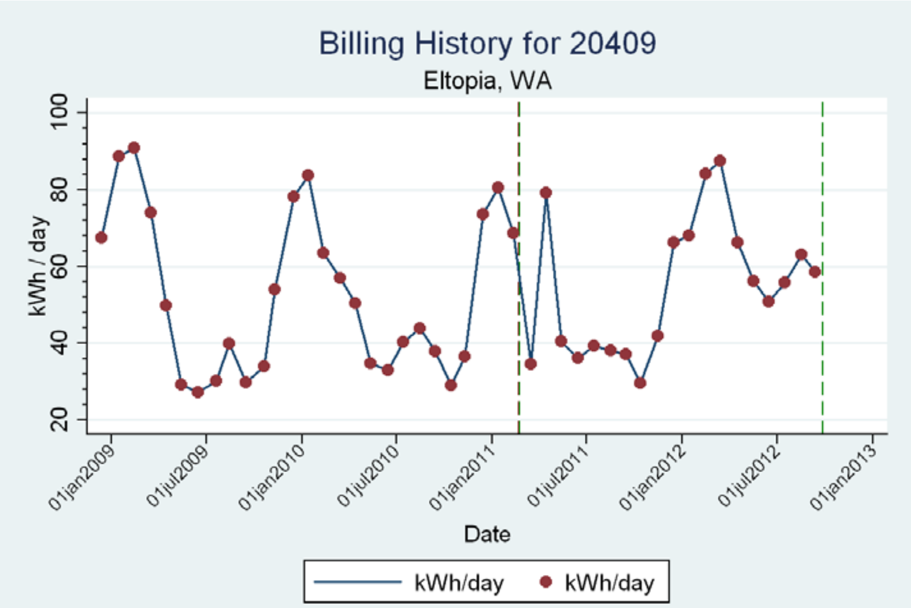
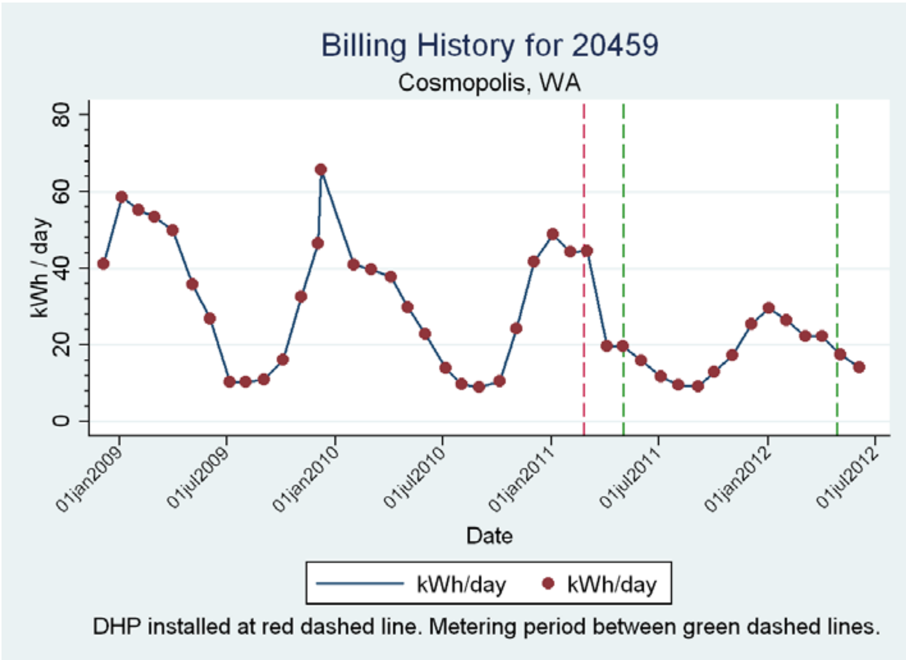
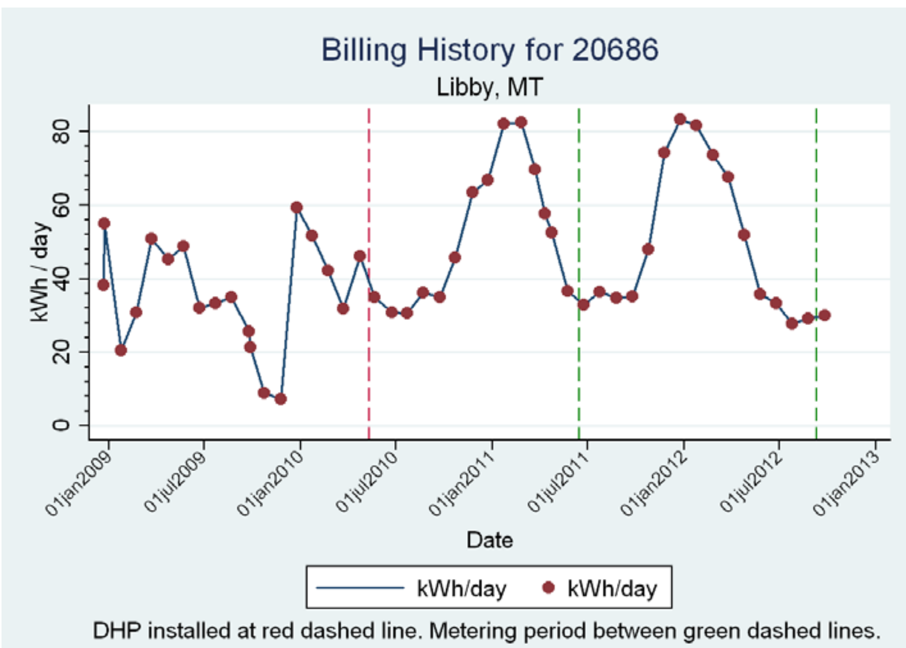


DHP installed at red dashed line. Metering period between green dashed lines.



Billing History for 20459
Cosmopolis, WA
kWh / day
0
20
40
60
80
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.



Billing History for 20686
Libby, MT
kWh / day
0
20
40
60
80
01jan2009
01jul2009
01jan2010
01jul2010
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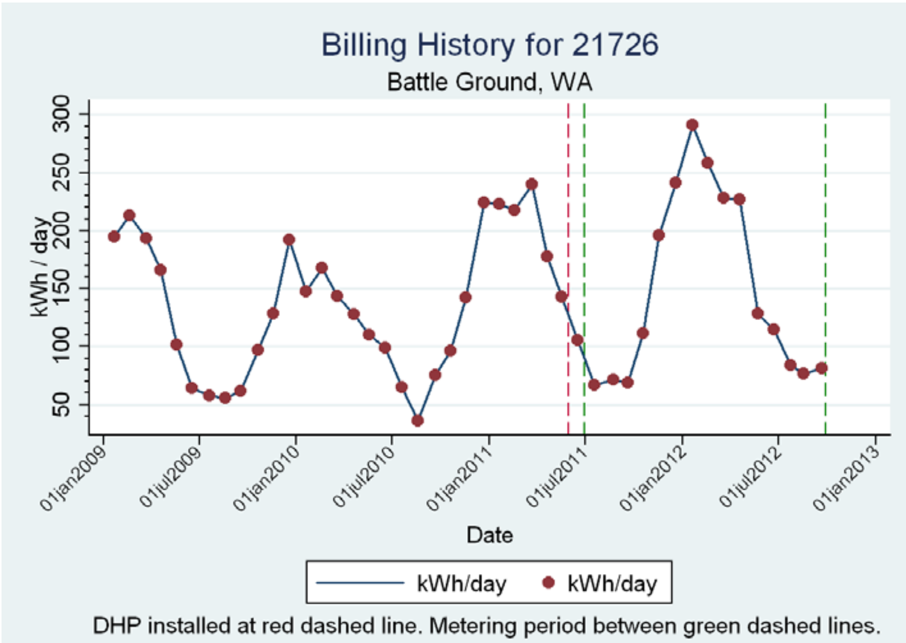
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 21726
Battle Ground, WA
kWh / day
50
100
150
200
250
300
01jan2009
01jul2009
01jan2010
01jul2010
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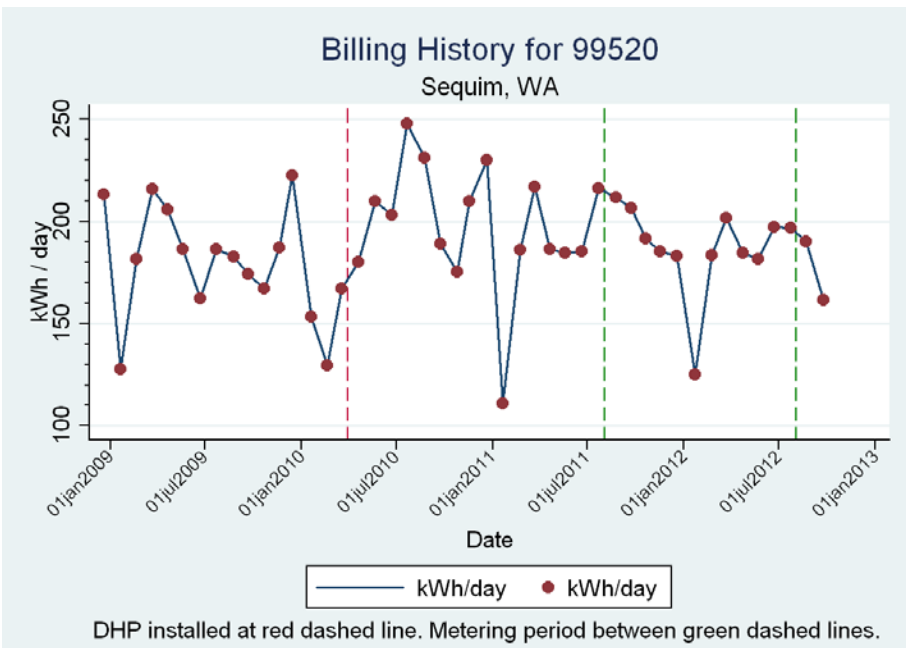
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99520
Sequim, WA
kWh / day
100
150
200
250
01jan2009
01jul2009
01jan2010
01jul2010
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Date
kWh/day
kWh/day
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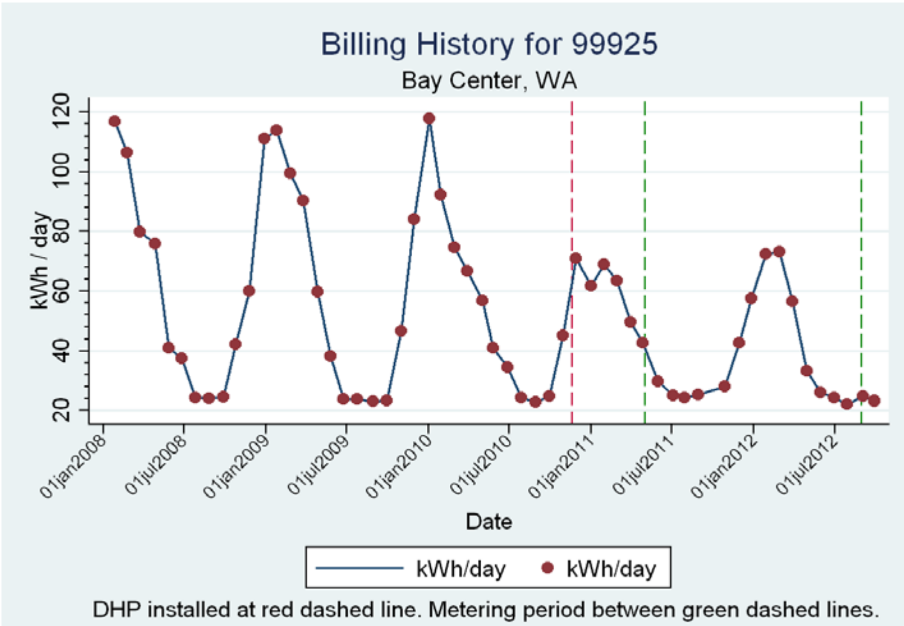
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Bay Center, WA
kWh / day
20
40
60
80
100
120
01jan2008
01jul2008
01jan2009
01jul2009
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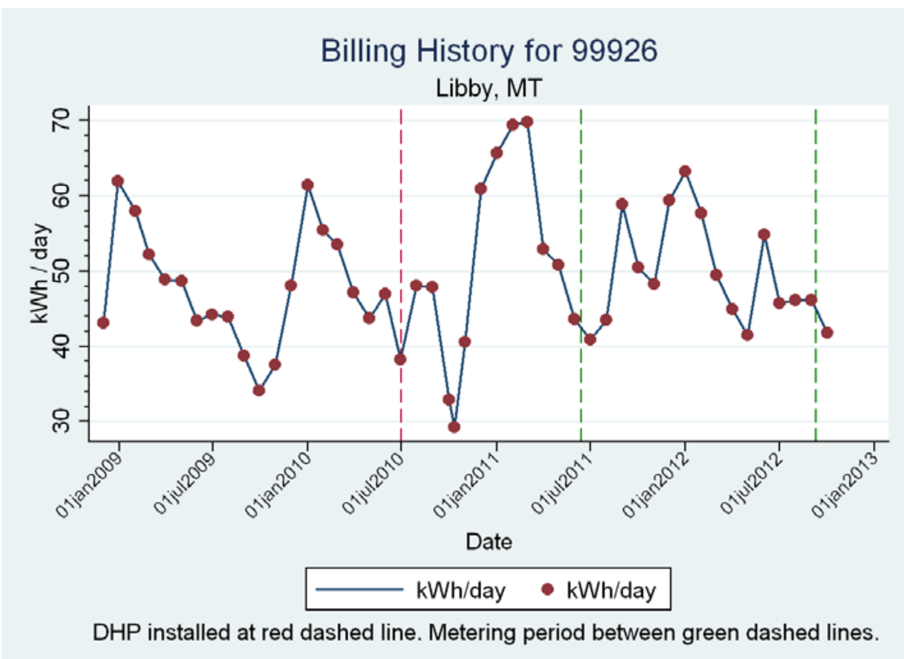
01jul2012
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.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Libby, MT
kWh / day
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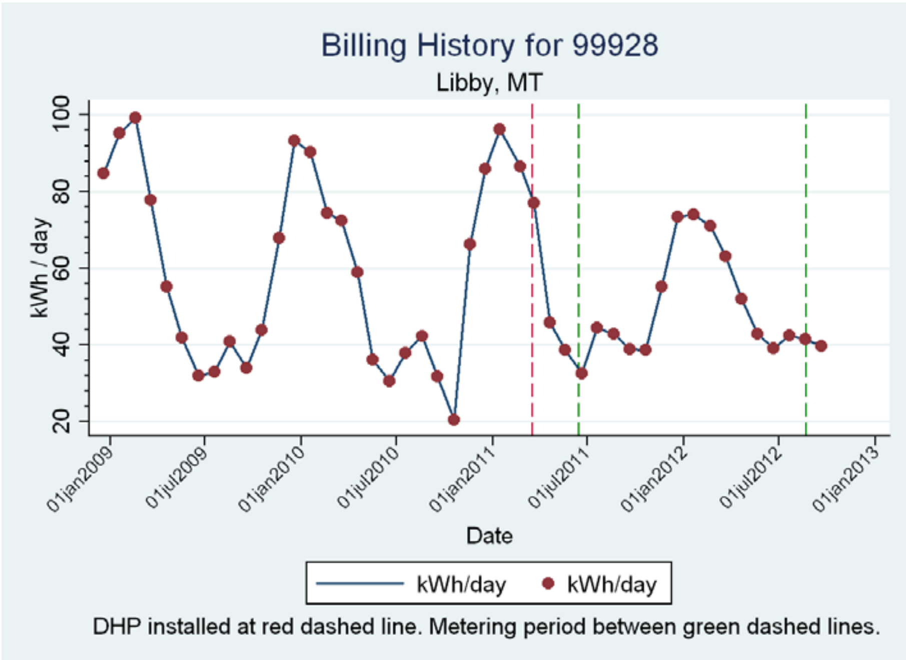
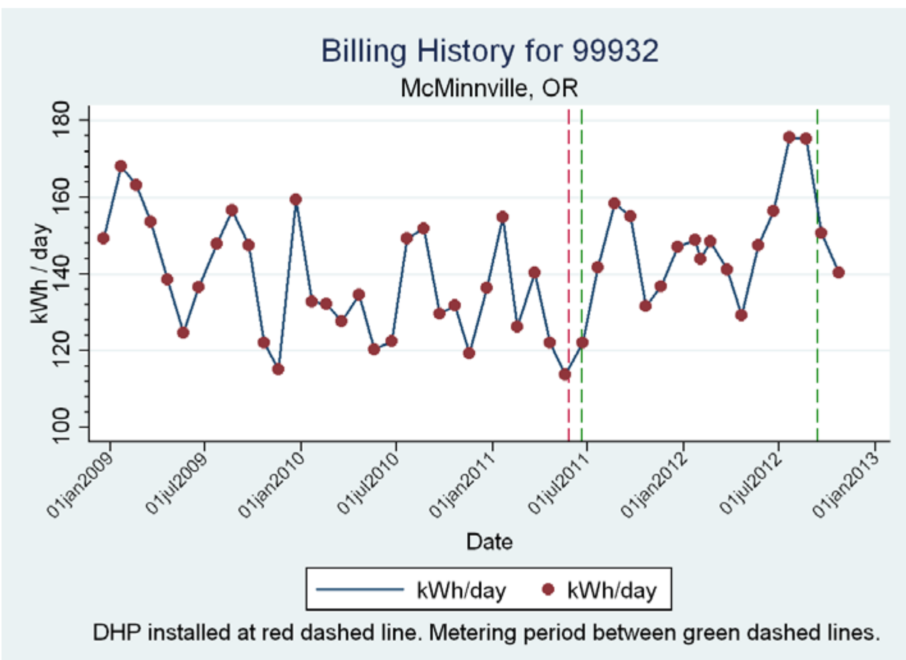
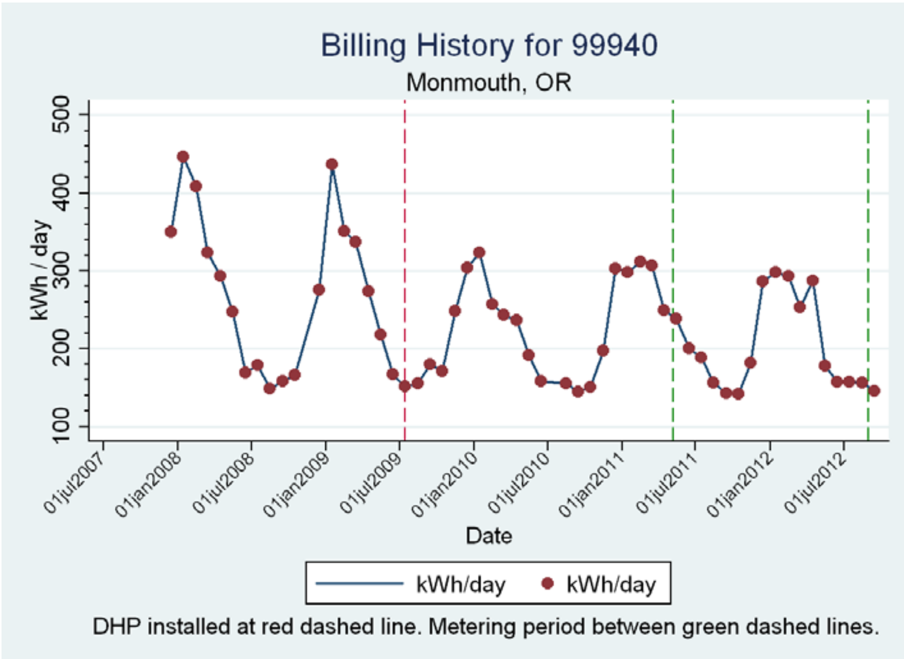
40
50
60
70
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99928
Libby, MT
kWh / day
20
40
60
80
100
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99932
McMinnville, OR
kWh / day
100
120
140
160
180
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
01jan2013
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.


Billing History for 99940
Monmouth, OR
kWh / day
100
200
300
400
500
01jul2007
01jan2008
01jul2008
01jan2009
01jul2009
01jan2010
01jul2010
01jan2011
01jul2011
01jan2012
01jul2012
Date
kWh/day
kWh/day
DHP installed at red dashed line. Metering period between green dashed lines.

BONNEVILLE POWER ADMINISTRATION
DOE/BP-4493 • February 2013