BONNEVILLE POWER ADMINISTRATION

Ductless Heat Pump Cold Climate Performance Evaluation

January 3, 2013

A Report of BPA's Energy Efficiency Emerging Technologies Initiative

Prepared for
Kacie Bedney, Project Manager
Mark Johnson, Project Manager
Bonneville Power Administration

Prepared by
Ben Larson
Benjamin Hannas
Poppy Storm
David Baylon

Ecotope Inc.
4056 9th Avenue NE
Seattle, WA 98105

Table of Contents

GLOSSARY OF ACRONYMS III

EXECUTIVE SUMMARY V

1. INTRODUCTION 1

1.1. OBJECTIVES 2

2. METHODOLOGY 3

2.1. SITE SELECTION 3
2.2. METERING DESIGN AND DATA COLLECTION 5
2.2.1. Metering Goals 5
2.2.2. Metering Specifications 5
2.2.3. On-Site Audits and Interviews 6
2.2.4. Data Collection and Assembly 6
2.2.5. Error Checking and Data Quality Control 7
2.3. BILLING AND WEATHER DATA ASSEMBLY 8
2.4. ON SITE CHARACTERISTICS 8
2.5. ANALYSIS APPROACHES 8
2.5.1. Weather Normalization vs. Weather Adjustment 9
2.5.2. Metered Savings Calculations 10
2.6. STUDY LIMITATIONS 10

3. HOME CHARACTERISTICS 12

3.1. AUDIT CHARACTERISTICS 12
3.1.1. House Envelope and Size Characteristics 12
3.1.2. DHP Installation 13
3.2. OCCUPANT SURVEYS 14
3.2.1. Demographics of Occupants 14
3.2.2. Cooling Use 14
3.2.3. Supplemental Fuel 15

4. METERED FINDINGS AND OBSERVATIONS 16

4.1. HEATING ENERGY USE 16
4.2. COOLING USE AND OFFSETS 16
4.3. DHP RUNTIME, OUTPUT, AND COP 17
4.3.1. DHP Runtime 17
4.3.2. COP Metering Results 18

5. ENERGY SAVINGS ANALYSIS 22

5.1. BASE CASE HEATING USE 22
5.2. COP-BASED SAVINGS 25
5.3. SEEM MODELING OF METERED HOMES 26
5.4. BILLING ANALYSIS AND SAVINGS ESTIMATES 32
5.4.1. Billing Analysis and Weather Adjustments 33
5.4.2. Metered Savings Estimates 36
5.4.3. Savings – Fraction of Total Heating 38

6. CONCLUSIONS 39

7. REFERENCES 41

List of Tables

Table 1. Conditioned Floor Area 12
Table 2. Blower Door Results 13
Table 3. Heat Loss Rates by Group 13
Table 4. DHP Installations, Metered Sites 14
Table 5. Occupancy Distribution, Number of Occupants 14
Table 6. Cooling Equipment by Group 14
Table 7. Percent of Sites Reporting Wood Use 15
Table 8. Metered Space Heating 16
Table 9. DHP Cooling Use 16
Table 10. Annual Equipment Runtime by Mode 17
Table 11. DHP Heating Input and Output Energy 19
Table 12. Average Heating COP, Seasonal 19
Table 13. Fraction of House Heated by DHP by Group 21
Table 14. Base Energy Use (Unadjusted Bills) 24
Table 15. Base Energy Use (Normalized Bills) 24
Table 16. Base Energy Use (Adjusted Bills) 25
Table 17. Total Heating Savings 26
Table 18. Base Heating Energy Use - Bills and SEEM (Weather-Normalized) 28
Table 19. Measured and Modeled Normalized Heating Energy Use 30
Table 20. Modeled Heating Energy Savings Estimates 32
Table 21. Billing Data and Heating Energy Estimated via VBDD (Unadjusted) 34
Table 22. Energy Savings Billing Data and Heating Energy (Unadjusted) 34
Table 23. Billing Data and Heating Energy Estimation via VBDD Adjusted to Post-Install Year 34
Table 24. Energy Savings Billing Data and Heating Energy – Adjusted 35
Table 25. Weather-Normalized Billing Data Heating Energy Estimation via VBDD 35
Table 26. Weather-Normalized Energy Savings for Billing Data Heating Energy Estimate 35
Table 27. Metered Savings Heating Only 36
Table 28. Final Savings Calculation 38
Table 29. Space Heating Saving Fraction 38

List of Figures

Figure 1. Final Site Distribution for Cold Climate DHP Sites 4
Figure 2. DHP Performance at Low Temperatures 18
Figure 3. Pre-Installation Energy Use – Bills vs. SEEM Estimates 29
Figure 4. Post-Installation Energy Use - Meters vs. SEEM Estimates 31
Figure 5. Comparison Billing Analysis and Metered Heating (Post-Installation) 33

Glossary of Acronyms

AC	air conditioning
ACH	air changes per hour
ACH50	air changes per hour at 50 pascals of pressure
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BPA	Bonneville Power Administration
Btu	British thermal unit
Btu/hr	British thermal units per hour
COP	coefficient of performance
CT	current transducer
DHP	ductless heat pump
DHW	domestic hot water
ER	electric resistance
ISO	International Organization for Standardization
kWh	kilowatt hours
kWh/yr	kilowatt hours per year
MEL	miscellaneous electric load (not space-conditioning or DHW loads)
n	number of observations
NCDC	National Climatic Data Center
NEEA	Northwest Energy Efficiency Alliance
NPCC	Northwest Power and Conservation Council
NREL	National Renewable Energy Laboratory
NWE	NorthWestern Energy

NWS	National Weather Service
PRISM	PRInceton Scorekeeping Method
RMS	root mean square
RTF	Regional Technical Forum
R-value	thermal resistance value
SD	standard deviation of the population
SEEM	Simple Energy and Enthalpy Model
TMY	Typical Meteorological Year
UA	The sum of the thermal transfer coefficient (U) times the area (A) of the components of the building. Also includes convective losses from infiltration.
U-value	thermal conductivity
V	volt
VBDD	variable base degree day
VLT	vapor line temperature (of the refrigerant—indicates cooling or heating mode)

An Emerging Technologies for Energy Efficiency Report

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

BPA does not endorse specific products or manufacturers. Any mention of a particular product or manufacturer should not be construed as an implied endorsement. The information, statements, representations, graphs and data presented in these reports are provided by BPA as a public service. For more reports and background on BPA's efforts to "fill the pipeline" with emerging, energy-efficient technologies, visit the E3T website at http://www.bpa.gov/energy/n/emerging_technology/.

Executive Summary

Ductless mini-split heat pumps (DHPs) have been gaining in popularity in the Northwest. Previous research has identified significant energy savings from displacing zonal electric resistance in single-family homes (Baylon et al., 2012)[1]. The savings estimates in theses larger pilot projects were focused on the western climate zones where more mild heating conditions prevail. NorthWestern Energy (NWE), the Bonneville Power Administration (BPA), and the Northwest Energy Efficiency Alliance (NEEA) all wished to specifically explore DHP installations in the colder Heating Zone 3 climate and commissioned Ecotope to conduct a supplemental study.

Using procedures and methods established under the NEEA DHP evaluation to monitor 95 houses, Ecotope monitored six sites in NWE service territory in western Montana and four sites for BPA in Idaho Falls. Taken together, with the 10 sites from the NEEA study of 95 sites, there are 20 sites in cold climates. This report presents analysis and findings for each of these DHP metered samples separately and in aggregate (20 sites total). All DHP sites for these metered samples were single-family homes with electric zonal heat.

The same DHP equipment model was installed at the 10 new sites. It has been marketed as a well-performing unit for cold climates. Ecotope observed very good performance from other DHP models installed at the previous 10 sites as well. To increase the sample size and predictive power, Ecotope rolled all 20 sites together in this report.

A fundamental question for the NEEA evaluation was the performance of DHPs in cold climates. The field monitoring in eastern Idaho demonstrated that DHPs performed well even in cold climates. The measured, annual, coefficient of performance (COP) at the 10 new sites was found to be 3.0. Further, the instrumentation showed the DHPs continued to operate at outdoor temperatures as cold as -15˚F, providing 100˚F air to the house at a COP between 1.5 and 2 in

---

[1] For more information on the larger DHP pilot project and evaluation see the Ductless Heat Pump Impact and Process Evaluation: Field Metering Report see: http://neea.org/docs/reports/ductless-heat-pump-impact-process-evaluation-field-metering-report.pdf?sfvrsn=18

these conditions. The meters showed the occupants used the DHP for a substantial number of hours in the year providing, on average, 68% of the heat at the 10 sites.

This study quantified energy savings in two distinct ways parallel to the previous metering study. The first was a billing analysis looking at heating energy use both before and after the DHP installation. The second was directly measuring the DHP heat output and input. The billing analysis of the pre- installation period provides the base case energy use estimate while the meters provide the direct measurement of post- installation energy use. The billing analysis found an average savings of 3,000 kWh/yr at the NWE sites, 3,300 kWh/yr at the BPA Eastern Idaho sites, and 3,300 kWh/yr at the NEEA Eastern Idaho sites for an average savings of 3,241 kWh/yr. Due to incomplete billing records or seemingly random use of the thermostat in the pre-billing period, three of the sites were excluded from the savings averages. Essentially, there was no reliable way to determine base case heating energy used in those sites.

In contrast to the bills, the direct COP measurement of DHP heat output and input at the site showed significantly larger energy savings. The metered COP analysis found an average savings of 7,000 kWh/yr at the NWE sites, 5,600 kWh/yr at the BPA Eastern Idaho sites, 3,900 kWh/yr at the NEEA Eastern Idaho sites, and an average savings of 5,200 kWh/yr at all 20 cold climate locations. These results suggest that the participants actually “took back” increased comfort and other benefits in an amount that represented about 40% of the heat produced by the DHP. This phenomenon was observed in the previous study but the overall effect in this climate was more than twice the regional average.

Although the two methods appear at odds with one another, they suggest the finding that the sites are using more heat from electrically derived sources in the post-installation period than they were in the pre-installation period. Occupant surveys support this finding. The surveys showed some sites used more wood heat prior to the DHP installation and several sites discontinued wood use altogether. Further, the surveys collected information indicating the occupants were intentionally setting the thermostat significantly lower prior to the DHP in an attempt to reduce heating costs. As a whole, the sites saved energy, burned less wood, and were kept warmer after the DHP installation.

In sum, the study demonstrated the feasibility of using DHPs in cold climates. Several brands and models of DHPs stand out in particular as high performers. They operated with COPs above 1 even at sub-zero temperatures. Moreover, the study billing analysis showed that DHPs can save a substantial amount of energy in cold climates—in excess of 3,000 kWh/yr. The detailed metering analysis showed the DHPs saved more than 5,000 kWh/yr and that the occupants shared some of that savings with the utility in the form of a higher indoor temperature setpoint and by burning less wood.

This study focused on homes with very little supplemental wood heat. In the cold climate zones this is unusual. Nevertheless, the benefits of this technology, in both comfort and economical operation, would make this an attractive option in Heating Zone 3 climates. Given the impact of supplemental fuels, utilities may need to consider either reduced net savings from the measure (and increased comfort for their customers) or a very rigorous screening process that limits the amount of supplemental fuel used in eligible homes.

1. Introduction

NorthWestern Energy (NWE) commissioned the Northwest Energy Efficiency Alliance (NEEA)[2] to implement a small ductless heat pump (DHP) field monitoring study in the colder climates in NorthWestern Energy's service territory. The study was conducted as a supplement to a larger DHP pilot project and evaluation launched by NEEA in the fall of 2008. NEEA hired Ecotope, Inc., supported by Research Into Action, Inc., and Stellar Processes to evaluate the Northwest Ductless Heat Pump (DHP) Pilot Project. The DHP field monitoring in the NEEA DHP evaluation included 95 sites in various climate zones across the Northwest (Baylon et al., 2012).[3] Ecotope has conducted the NorthWestern Energy cold climate field monitoring study (NWE study) using the same metering protocol and analysis methods developed in the larger metering report. The analysis presented here is an extension of that report focused on the Heating Zone 3 climate that characterizes the NorthWestern Energy service territory.

The main goal of the NWE study was to assess the performance of DHPs in Heating Zone 3 climates in western Montana. In order to provide a more comprehensive picture of DHP performance in cold climates, this report also includes analysis and findings for 14 additional cold climate DHP sites from two related DHP metered samples: the NEEA DHP pilot evaluation (10 cold climate sites) and a Bonneville Power Administration (BPA) DHP sample (four cold climate sites):

- **NWE Montana (6 sites).** Metered sites from the NorthWestern Energy supplement to the NEEA DHP evaluation. All sites were located in Heating Zone 3 climates in Helena, Great Falls, Belgrade, or Cascade, Montana. The sites were metered in February 2011 and decommissioned in April 2012, providing approximately 13 months of metered data.
- **BPA Eastern Idaho (4 sites).** Metered sites from a BPA DHP evaluation. All sites were installed in Heating Zone 3 in Idaho Falls, Idaho in December 2010 and January 2011. The sites were metered in December 2010 and decommissioned in April 2012, providing approximately 15 months of metered data.
- **NEEA Eastern Idaho (10 sites).** Metered sites from the NEEA DHP evaluation. Nine of the sites were located in Idaho Falls, Idaho. The tenth site was located in Black Foot, Idaho. All sites were in Heating Zone 3. The sites were metered in October and November 2009 and were decommissioned in April 2011, providing approximately 16 months of metered data.

---

[2] See www.neea.org

[3] For more information on the larger DHP pilot project and evaluation see the Ductless Heat Pump Impact and Process Evaluation: Field Metering Report see: http://neea.org/docs/reports/ductless-heat-pump-impact-process-evaluation-field-metering-report.pdf?sfvrsn=18

This report presents the methodology, analysis, and key findings of the detailed field monitoring of six cold climate DHP installations in the NWE service territory, and findings for each of these additional cold climate metered samples separately and in aggregate (20 sites total). All DHP metered sites for these three metered samples were single-family homes with electric zonal heat

1.1. Objectives

The objectives of this DHP field study were to:

- Describe the total energy use of the heat pump as it operates in each home, including the effective heat output and the total heating energy required.
- Determine the total cooling use of the equipment.
- Establish the offset to space heating brought on by this equipment.
- Develop the climate and occupancy parameters needed to explain the savings observed.
- Summarize the non-space heating energy uses across the systems monitored.

To meet these objectives a metering package was deployed in each home. The metering package consisted of "quad-meter" approach, including:

- A detailed meter documenting watt-hour consumption by the DHP.
- A watt-hour meter documenting the consumption of the electric baseboard heating throughout the home.
- A watt-hour meter documenting electricity use of the domestic hot water (DHW) system.
- A watt-hour meter documenting total electricity use of the home at the service drop.

In addition, Ecotope measured the indoor and outdoor temperatures and installed a temperature sensor on the DHP vapor line to determine whether the heat pump was in cooling or heating mode during operation.

For all NWE Montana and BPA Eastern Idaho sites, and six NEEA Eastern Idaho sites, Ecotope also installed a supplemental metering package that measured air flow and temperature at the air handler unit and allowed the calculation of a coefficient of performance (COP) for the units.

For this study the base case heating use could not be metered before the installation of the metering package. The base case was derived from billing records collected by the utility for a period prior to the DHP installation. A set of comparison bills was also collected to correspond to the monitoring period after the installation of the DHP.

2. Methodology

The methodologies for the NorthWestern Energy and the BPA cold climate DHP sites directly mirror the methodology for the NEEA DHP evaluation. The methodology involves four separate steps:

1. Site selection in the NWE service territory supplemented by samples drawn from eastern Idaho
2. A quad metering protocol, some degree of COP measurement, an onsite audit and blower door and duct leakage test, and daily cellular data downloads and "real-time" error checking.
3. A billing analysis on about three years of data including both the DHP pre- installation period and the post-installation period.
4. A series of site characteristics collected on site during the metering installation

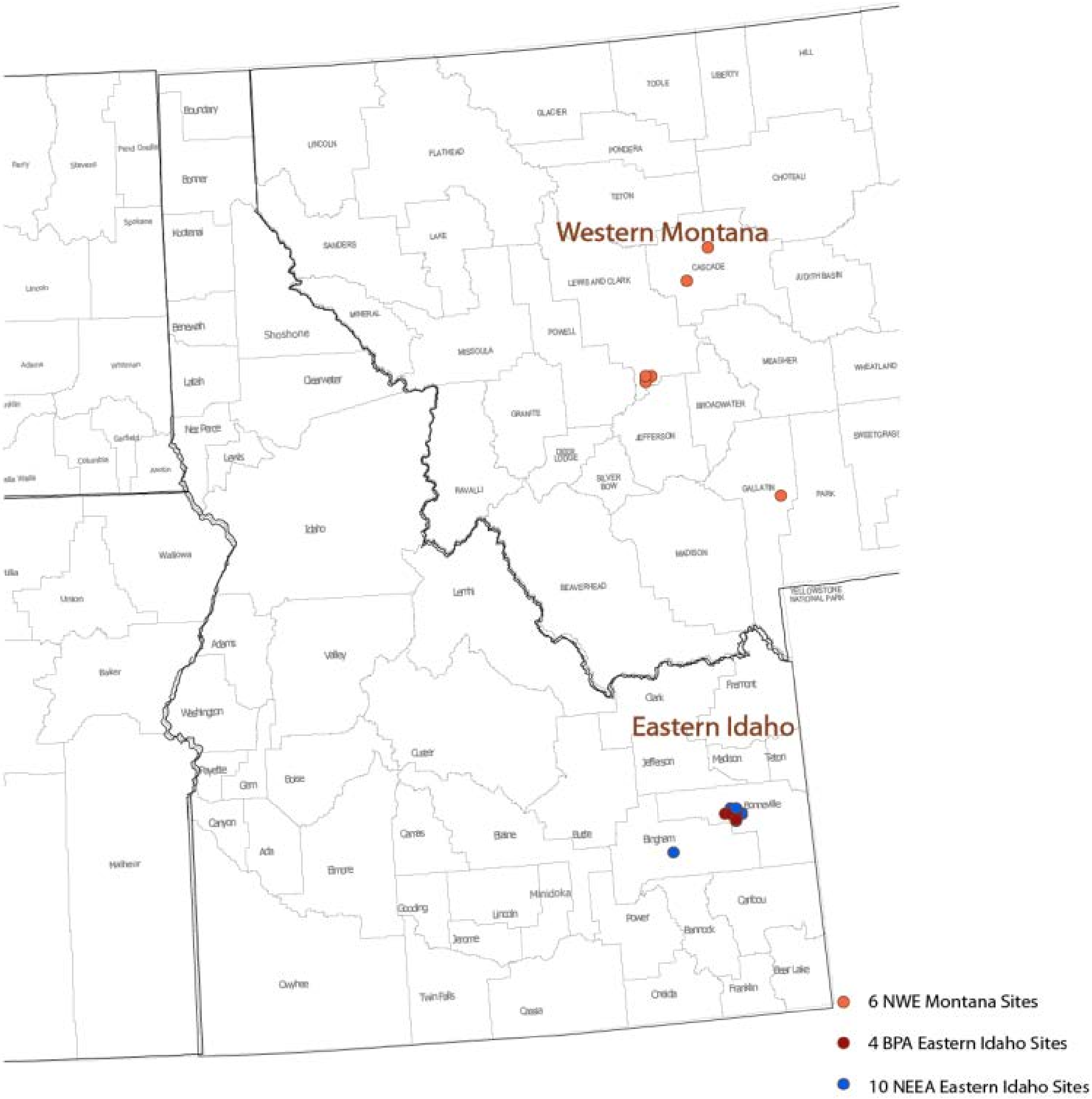
2.1. Site Selection

To minimize the extent to which the analysis would be compromised by supplemental (non-electric) heating fuels that could not be directly measured, all potential metered sites were screened. The screening took the form of a variable base degree day (VBDD) assessment of the bills collected for the period before the installation of the DHP. This methodology allowed an assessment of the electric heating use of the home based on month-to-month changes in consumption predicted by outdoor temperature.[4] The screening process had the effect of increasing the potential electric savings from the sample. Figure 1 presents the final distribution of sites that passed the bill screening, were metered, and had sufficient data for analysis.

---

[4] This analysis is often referred to as a "PRISM" (PRInceton Scorekeeping Method)-type analysis after the method for evaluating weather sensitivity in utility bills in the 1970s (see Fels, 1986). The methods used here are a variation of this method that is explained in more detail in Appendix A.

Figure 1. Final Site Distribution for Cold Climate DHP Sites



2.2. Metering Design and Data Collection

2.2.1. Metering Goals

The metering design had five goals:

1. Meter heating system energy use after installation of the DHP. This was accomplished by metering the DHP and separately metering all the resistance loads in the zonal electric heating system that was displaced (but not removed).
2. Meter the performance and operating patterns of the DHP, including the interaction with the occupant.
3. Meter the DHW usage. This required a meter on the large resistance load associated with the DHW tank.
4. Meter the total electric energy usage of the home by metering the service drop for the whole house. This measurement had the effect of giving a sum check on the other meters and, with subtraction, allowed a picture of the (MELs) electric loads in the home.
5. Measure the COP of the units on-site, in real time. This system used temperature sensors at the indoor unit as well as a low mass anemometer to measure air flow. The instruments had to be calibrated on-site. Space limitations on the datalogger usually resulted in insufficient channel space to monitor more than one indoor unit.

2.2.2. Metering Specifications

To achieve the DHP metering goals, Ecotope customized a “quad-metering” system to measure four key categories of energy usage:

1. **DHP channel** measured with a combination of split-core current transducer (CT), true root mean square (RMS) watt transducer, and pulse counter.
2. **House electric service drop** measured with the same combination of equipment.
3. **Electric resistance (ER) heaters** measured with a simple CT.
4. **DHW tank** measured with a current transformer and true-RMS conversion module.

In addition to the energy use of the home, several other auxiliary data streams were measured:

- **Outdoor (ambient) temperature.** A standalone, weatherproof temperature sensor/datalogger was placed in a shaded location near the metered home and recorded hourly average temperature. These data were compared with National Weather Service (NWS) weather site data and also used in COP analysis.
- **Indoor central zone temperature where the DHP was installed.** This logger collected the average hourly temperature for the entire metering period. Indoor temperature data were downloaded at the end of the metering period and synchronized to the time/date stamps in the metered data set. The purpose of this measurement was to give the analyst an idea of the comfort in the main area of the home during the heating season.

- **Vapor line temperature (VLT) of the refrigerant line from the DHP to the indoor air handler.** The VLT was used in conjunction with the recorded outside temperature to determine whether the DHP was in heating or cooling mode. The DHP energy was then separated into those two categories based on this determination in each five-minute data collection interval.
- **COP measurements.** Six of the NEEA Eastern Idaho sites and all of the NWE Montana sites and BPA Eastern Idaho sites were metered with additional points that would allow the estimate of an in-situ system's efficiency, the COP. Two temperature sensors were added (to measure change in temperature across the indoor unit), and a small vane anemometer was installed to provide a proxy measurement for airflow.[5]

2.2.3. On-Site Audits and Interviews

Each site received a detailed physical energy audit (including a measurement of house air-tightness). The audit's primary purpose was to generate a heat loss rate for the home. The primary site occupant was interviewed twice during each study. The first interview occurred when metering equipment was installed, and focused on satisfaction with the DHP equipment as well as occupancy patterns in the period before DHP installation.

The second interview was conducted during the decommissioning. This interview again focused on satisfaction with the DHP equipment and also upon what changes in the occupancy and house thermal shell occurred during the metering period. Finally, several specific questions were asked about supplemental heating from wood or other fuels. Unlike the first interview, the occupant was also asked about the household's use of low-voltage (110-volt [110V]) space heaters.

Wherever possible, these audits and interviews became explanatory variables that could be used in the analysis of the observed metered data.

2.2.4. Data Collection and Assembly

Depending on the meter installation schedule for various metered samples, 13 to 16 months of metered data were collected for the DHP sites. The NWE Montana and BPA Eastern Idaho sites were metered for a nearly parallel timeframe; winter of 2010/2011 through April 2012. The NEEA Eastern Idaho sites were metered approximately one year earlier; late autumn 2009 through April 2011.

---

[5] The COP is the ratio of heating (or cooling) output from the DHP to the power needed to run the compressor and indoor and outdoor fan. Another way of expressing the COP is in efficiency percentage, with a COP of 1 meaning 100% efficiency. The COP measurement is very useful for comparison to laboratory test results (Larson, et al, 2011), AHRI-rated performance (from the manufacturer), and to inform the development of inputs for simulation assessment of the DHP (also used to determine savings from application of the ductless technology).

“Annualized” datasets was used throughout the analysis. In addition to variables representing the four directly measured energy use channels (total service, DHP, 240V ER heat, and DHW), a “residual” variable was calculated representing the energy use left over after all metered channels (DHW, ER, DHP) were subtracted from the total service energy. This residual was summarized on the same time scale as the remaining metered channels.

The bulk of these data were downloaded to the Ecotope file server on a nightly basis using a cellular 3G connection. Because the instruments had substantial data storage capacity, short-term interruptions in cell phone service were easily remedied in a subsequent download period. When this failed, a site visit could be arranged to reset the datalogger. In most cases, such an intervention ensured a continuous data record.

2.2.5. Error Checking and Data Quality Control

The data handling and data quality were developed to ensure a high-quality data stream throughout the field monitoring. Each stage of the installation was addressed:

- A field installation guide was developed. Site installation managers were required to fill out a detailed site protocol, including types of sensors and individual sensor serial numbers (because these are the primary identifiers of sensors after data returns from the datalogging vendor).
- The datalogging vendor offered a "web services" interface by which Ecotope’s server could directly retrieve data from the data warehouse. Ecotope used the automatic calling functions to deliver site data to the local Ecotope repository.
- Ecotope’s datalogging system automatically retrieved all new site data from the warehouse once a day via command-driven batch files, and subjected the data to range and sum checks. Because one of the site-monitoring channels was total service power consumption, Ecotope analysts were able to compare service consumption against the sum of metered power consumption channels.
- The above processes were supplemented with field visits when data quality or downloads failed. This happened rarely except for the sites where no cell phone coverage resulted in a failure of the automated systems. In these cases, the data were downloaded manually approximately every three months. In some cases, sensor or logger failure was observed in the data downloads, and a technician was dispatched to download or repair the site.

Data from the COP installations were downloaded with the power and temperature data. The review of these data was done manually on a periodic basis. Generally, this was not a continuous data stream but rather data series that covered the range of temperatures that could be used to generate seasonal COP. The consequences of errant measurements at the COP sites are not as critical as for the year-long accumulation sites, because the performance is described in relation to outdoor temperature bins rather than accumulated over the entire year.

2.3. Billing and Weather Data Assembly

Utility billing data from the metered sites were analyzed to establish the base case (pre-installation) heating energy consumption. Utility bills were evaluated using VBDD methods to establish an estimate of seasonal heating loads. Although such an estimate is only approximate as the metering protocol did not allow monitoring before the DHP was installed. Even with detailed metering, there is some uncertainty in the base space heating energy use.

In addition to billing data, the record for each home included daily minimum and maximum outdoor temperatures recorded at a nearby weather station. The weather stations used were selected individually for each site from those available through the National Climatic Data Center (NCDC). All were either NWS stations or members of the NWS's Cooperative Station Network. The daily minimum and maximum temperatures were used to construct daily heating-degree and cooling-degree estimates to various bases at each site.

2.4. On site characteristics

During the process of installing the metering the technicians interviewed the homeowner and developed an extensive database on the home characteristics. These included a complete energy audit of the home sufficient to develop a detailed heat loss for the home including a blower door assessment of the envelope tightness. In addition the survey asked the homeowner detailed questions about supplemental fuel use and occupancy patterns. This information was used to characterize the home so that a SEEM[6] estimate of heating and cooling loads could be developed.

The characteristics also provided an opportunity to evaluate savings determinants. In the previous study (Baylon et al., 2012) the larger sample size provided more flexibility for multivariate analysis. In this cold climate study the site characteristics were used sparingly to understand the observed savings and energy use characteristics of the home.

2.5. Analysis Approaches

The primary goal of this analysis was to develop a savings estimate to assess the use of the DHP technology in cold climates. Several strategies were used to meet this objective:

- Assess heating energy savings from actual energy use, both before and after the installation of the DHP. The detailed metered data from the DHP was compared to the ER heating.

---

[6] SEEM consists of an hourly thermal, moisture, and air mass balance simulation that interacts with duct specifications, equipment, and weather parameters to calculate the annual energy requirements of the building. It employs algorithms consistent with current American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), Air-Conditioning, Heating, and Refrigeration Institute (AHRI), and International Organization for Standardization (ISO) calculation standards. SEEM is used extensively in the Northwest to estimate conservation measure savings for regional energy utility policy planners.

- Construct a simulation model that is calibrated against the results of the billing and metered analyses that can be used to predict the savings from a more widespread application of the DHP program throughout the region.
- Provide implications that can be used to inform the development of a utility program to support the installation of DHPs in cold climates.

The datasets assembled for these metered samples enabled a variety of methodological approaches to measuring changes in space-conditioning energy consumption. These approaches fall into three main categories:

- Those that rely only on billing data and weather station data. The great advantage of billing-data-only methods is that the exact same method can be used to calculate consumption in both periods. Known biases in consumption estimates can have little consequence on savings estimates because the biases are present both before and after installation.
- Those that rely on short-interval metered data and site temperature data for the post-installation period. This method depends on detailed metering of the DHP and a direct assessment of its output without reference to the previous conditions in the house.
- Mixed methods using short-interval metered consumption data, site temperature data for the post-installation period, and billing and weather station data for the pre-installation period. This method provides detailed insight into the operation of the DHP and the overall heating and cooling energy of the home but requires careful consideration and estimation of potential biases both before and after installation.

2.5.1. Weather Normalization vs. Weather Adjustment

"Weather normalization" entails casting weather-sensitive consumption or savings results in terms of a long-term average or "normal" weather. This has the effect of eliminating biases in estimating space heat savings since all the estimates are expressed in terms of a common weather year. VBDD regression provides an established method of estimating heating energy use in any particular year and adjusting that estimate to an alternative year as long as the temperature profile is known. When we present weather normalized results the heating is expressed in terms of the "long-term average" from NCDC for a site's chosen weather station.

"Weather-adjustment," as we define it, means casting consumption or savings results in terms of some specific reference weather period. In this report, the specific reference weather period is the post-installation period for which we have detailed metered data. All the post-installation metered data were gathered during the chosen reference weather period; hence there is no need to adjust the measurements to another reference period. Pre-installation, temperature-sensitive consumption can be expressed in terms of this weather year using the same procedure as the normalization discussed above.

In this report, we present some results in weather-normalized form, but in general we prefer to present weather-adjusted results (expressed in terms of recorded post-installation weather). This is largely due to the fact that we cannot estimate the VBDD regression without aggregating the metered data to at least daily intervals. Much of the fine detail of the data is lost in the process. In addition other elements of our analysis dataset such as the questionnaire data (e.g., use of supplemental fuels and periods of low occupancy) cannot be readily time-shifted limiting their use as explanatory variable in any cross sectional analysis.

2.5.2. Metered Savings Calculations

There were separate heating savings estimates for each base case method (normalized and adjusted). Ecotope combined metered channels and residuals to calculate savings estimates that accounted for the biases observed in each metering record. Several separate savings estimates were developed:

- In general, the method selected in most of the cases was based on the on-site temperature data (the post-installation weather period). The billing analysis was adjusted to that temperature record. The savings were estimated using the difference between the space heating estimate from the post installation period and the adjusted heating estimate based on the pre-installation period.
- In some cases the bills were erratic or had missing data. In those cases, the billing analysis used the difference between the total consumption derived from the post-installation period and the total consumption in the pre-installation period adjusted to the post-installation weather.

The metered results allow the assessment of the runtime of each DHP in each metering period (generally five minutes). As a result, the COP monitoring data and the laboratory testing (Larson et al., 2011) could be applied to the observed runtime, and an estimate of the heat output of the DHP was made. Section 4 discusses this approach and the resulting savings estimates.

Finally, a goal of this study was to adapt the results of the metering to the SEEM model used in assessing energy savings for future programs and program planning. The Regional Technical Forum (RTF) and the Northwest Power and Conservation Council (NPCC) use the SEEM model to estimate residential energy savings. For this analysis, some modifications were made to the basic model to accommodate the fact that the DHP provides only a fraction of all the space heat required by the home. This analysis used the long-term weather files developed as the Typical Meteorological Year (TMY). This weather record closely resembles the normalization period discussed above. This approach is discussed in Section 4.

2.6. Study Limitations

There were several sources of known bias that influenced our analysis. Notable sources were:

- The use of supplemental fuels (such as wood) to offset some of the space heating requirement. This has the effect of biasing the space heating estimate wherever it occurs. In at least one case the consequences were so severe that the site was not used in the final analysis.
- Changes in operating approaches to the heating system, especially the increase in thermostat settings.

- Changes in occupancy, especially changes in the number of occupants or the period of occupancy during the year.
- The presence of large (and seasonal) loads that are not part of the heating system of the home but would appear as part of the space heating estimate in a conventional billing analysis.

3. Home Characteristics

This section presents home characteristics findings from the DHP metered sites. A detailed audit of each home was conducted at the outset of the metering. This audit included take-offs of the overall square footage of the conditioned floor area, the areas and insulation of all envelope components, window types, and a blower door test (to estimate the impact of air leakage). In addition, two occupant surveys were conducted; one done at the time of installation of the metering equipment and one done at the conclusion of the metering, as the meters were being decommissioned. The first survey was designed to start a record of each participant in the metering study. The second survey focused on occupancy patterns associated with DHP use during the year the meters were installed. These two interviews provided a picture of the energy use and space heating patterns of the participants. The results of the audits and the occupant surveys are summarized in this section and are used to refine and understand the savings from the DHPs as installed and operated.

3.1. Audit Characteristics

3.1.1. House Envelope and Size Characteristics

Table 1 shows the distribution of house area by geographic group. Data for the metered sites were measured by the Ecotope field team at the time of the audit. The average floor area across groups varies quite a bit, from 1,834 in NWE Montana to 2,695 in BPA Eastern Idaho. Most houses in this small sample had basements, and the Montana houses were simply smaller than the other two locations.

Table 1. Conditioned Floor Area

	Computed from Audit Measurements	
Group	**Sq. Ft.**	**n**
NWE Montana	1834	6
BPA Eastern Idaho	2695	4
NEEA Eastern Idaho	2316	10
Average/Total	2247	20

Notes: Sq. Ft. – square feet; n – number of observations

A blower door test of the envelope tightness was conducted on all homes. Table 2 summarizes the results of these tests. The table also translates the blower door results into an effective natural infiltration rate in four different ways. The first uses an old rule of thumb that an effective infiltration rate is the blower door test output of air changes per hour at 50 Pa of pressure (ACH50) divided by 20. The last three estimates are made using the SEEM simulation program with individual models for each house. The simulation calculates infiltration on an hourly basis by using house height, the blower door results, and weather data including outdoor temperature and wind speed, and then outputs annual, heating season, and heating design day ACH averages. The overall average heating season ACH of this sample is consistent with findings from comprehensive Northwest region infiltration studies from the 1980s on ER-heated houses (Palmiter, 1991).

Table 2. Blower Door Results

	Blower Door Results		Natural Infiltration Estimates				
				SEEM ACH Outputs			
Group	ACH50	SD	ACH50 / 20	Annual Average	Heating Season Average	Heating Design Day	n
NWE Montana	5.6	0.6	0.28	0.21	0.22	0.33	5
BPA Eastern Idaho	4.0	1.2	0.20	0.13	0.13	0.17	4
NEEA Eastern Idaho	4.8	1.1	0.24	0.15	0.17	0.22	10
Average / Total	4.8	1.1	0.24	0.16	0.17	0.24	19

Note: SD – standard deviation of the population

Table 3 shows the distribution of heat loss rate across the homes measured by the sum of the heat loss rate of the envelope components and air infiltration (UA). When the overall heat loss rate is normalized by house size, the heat loss from one group to the next is fairly consistent, with Montana being slightly higher than the other two groups.

Table 3. Heat Loss Rates by Group

	UA Total		UA/Sq.Ft.		
Group	Mean	SD	Mean	SD	n
NWE Montana	463	325	0.268	0.080	5
BPA Eastern Idaho	525	147	0.194	0.038	4
NEEA Eastern Idaho	532	131	0.236	0.050	10
Average/Total	512	191	0.236	0.060	19

3.1.2. DHP Installation

Most of the sites in the study have only one DHP outdoor unit and one DHP indoor unit. This factor results from the prevailing installation type in the DHP pilot and the limitations of the meter equipment (which can accommodate a single outdoor unit and up to two indoor units). Systems with more than two indoor units or more than one outdoor unit were not metered. Table 4 shows the average size (measured by capacity) of the installed DHP equipment by group as well as the number of homes with two indoor heads.

The nominal heating output capacity in the NWE and BPA groups is nearly uniform because only one particular DHP model was installed. The Mitsubishi MUZFE12NA has a rated heating capacity of 13,600 Btu/hr. At one of the BPA sites, the home owner opted to install another MUZFE09NA as well in a totally independent zone of the house giving them two DHPs on site. For the NEEA Eastern Idaho sites, the previous generation to the “FE”, the MUZFD12NA, was common, as well as the nominal one-ton Fujitsu 12RLS (rated capacity of 16,000 Btu/hr in heating).

Table 4. DHP Installations, Metered Sites

Group	Tons	2 Indoor Heads	n
NWE Montana	1.13	0	6
BPA Eastern Idaho	1.36	1	4
NEEA Eastern Idaho	1.33	1	10
Average/Total	1.27	2	20

3.2. Occupant Surveys

Occupant surveys were used to inform the base case energy use. These interviews focused on supplemental fuel use, cooling loads, thermostat settings, etc. The homeowner was interviewed at two points in the metering process: once during the installation of the metering system and energy audit and again when the metering equipment was removed (decommissioning).

3.2.1. Demographics of Occupants

Table 5 shows the distribution of occupancies across the three groups. As the Table 5 shows, the average occupancy is about 2.4 occupants per household.

Table 5. Occupancy Distribution, Number of Occupants

Group	Age Categories				Total	n
	Under 12	12 to 18	19 to 65	Over 65		
NWE Montana	0.5	0.0	0.7	0.7	1.8	6
BPA Eastern Idaho	0.8	0.0	2.0	0.0	2.8	4
NEEA Eastern Idaho	0.6	0.0	1.3	0.6	2.5	10
Total	0.6	0.0	1.3	0.5	2.4	20

3.2.2. Cooling Use

About one-third of the occupants reported some sort of compressor-based cooling as part of their summer conditioning. Virtually all of this equipment consisted of window air conditioning (AC) units. Table 6 shows the distribution of cooling equipment reported by occupants when interviewed at the installation of the metering system.

Table 6. Cooling Equipment by Group

Group	None	Cooling	n	% with Cooling
NWE Montana	3	2	5	40%
BPA Eastern Idaho	3	1	4	25%
NEEA Eastern Idaho	7	3	10	30%
Total	13	5	19	26%

3.2.3. Supplemental Fuel

Table 7 summarizes the wood heat use estimates of the occupants when interviewed during the meter installation. The initial interview was conducted one to six months after the DHP installation and focused on the wood heat usage before DHP installation (“Pre DHP”). The estimates made during the decommissioning interview (at the end of the metering period) are reported as “Post DHP” and reflect the current wood heat usage at that time after at least one heating season with the DHP. For this small sample there was an 80% decline in the use of any supplemental wood heat in the period after the DHP installation. The categories were derived from the interview comments of the home owner:

- “Occasional” wood use is less than one cord of wood a year.
- “Some Heating” implies up to two cords or an occupant that reported some heating from wood heating.
- “Supplemental” wood heat is a category for an owner that uses more than two chords and notes that the wood heat is a substantial part of their heating system.

Table 7. Percent of Sites Reporting Wood Use

Wood Use	Pre DHP	Post DHP
None	73.7%	95.0%
Occasional	15.8%	5.0%
Some Heating	10.5%	0.0%
Supplement	0.0%	0.0%
Total Cases	19	20

The amount of wood burned is important because it displaces heating requirements that would otherwise be met with electric sources. The wood use is based on self-reported occupant surveys. Our recent experience has shown such self-reported information to be highly unreliable; however, we have included in this report as a general indication of wood use. It is difficult to quantify the amount of wood burned, let alone the heat supplied to the house from that wood. In examining billing data, it is likely that some of the sites burned wood in the pre-installation period and that those same sites burned less post- installation. This finding occurred even though we heavily screened sites to exclude those with suspected wood use. Nevertheless, the change in wood use in some homes has the impact of reducing the potential savings from the DHP in those homes.

4. Metered Findings and Observations

The metering instruments were programmed to collect information at five-minute intervals so the major electric loads in each home could be carefully characterized. The equipment accumulated these uses on a true (RMS) power basis.

4.1. Heating Energy Use

Energy use by both existing 220V heaters and the DHP were measured at five-minute intervals. The data were aggregated into daily and monthly summaries and used to generate space heating measurements that could be compared to the billing analysis to generate estimates of DHP impact on home heating energy requirements.

Table 8 summarizes the space heating use by group, indicated by kilowatt hours per year (kWh/yr). The striking feature of this summary is the increase in DHP energy usage in the BPA sites and again in the NWE sites over the NEEA sites. In the Montana sites in particular, the large DHP usage points towards the possibility of large energy savings.

Table 8. Metered Space Heating

Group	DHP (kWh/yr)		ER (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	3388	927	3705	3830	6
BPA Eastern Idaho	2738	875	6746	3006	4
NEEA Eastern Idaho	2260	938	7361	3715	10
Average/Total	2694	1007	6141	3816	20

4.2. Cooling Use and Offsets

In the metered DHPs, an additional temperature sensor was added to the vapor line of the split system. This sensor allowed the analysis to distinguish electric energy used for cooling from all other energy uses of the DHP. As a result, an accurate assessment of cooling energy use was assembled. Table 9 summarizes the cooling energy used by the DHPs. The mean cooling energy is virtually the same across all the groups given they are located at high elevations and have relatively cool summers. It is also a small portion of the total energy consumed in the house.

Table 9. DHP Cooling Use

Group	DHP Cooling Use (kWh/yr)		n
	Mean	SD	
NWE Montana	202	235	6
BPA Eastern Idaho	275	235	4
NEEA Eastern Idaho	211	208	10
Average/Total	221	211	20

The cooling energy use shown in Table 9 is not new cooling energy. It is a combination of cooling provided to homes that did not previously use mechanical cooling and homes that now offset a previous inefficient cooling system with the DHP. As described in Section 3, about one-third of the sample had pre-existing cooling equipment. In fact, the billing data at some sites clearly showed some summertime cooling use in the pre-installation period. Therefore, the DHP represents a reduction in cooling energy.

4.3. DHP Runtime, Output, and COP

The DHP technology is somewhat different than conventional split-system heat pumps. Apart from the lack of a centralized ducting system and the attending losses to leakage and buffer spaces, this equipment operates at high COPs well in excess of 4 during the warmer parts of the heating season and averages about 3 over the entire heating season, even in these cold climate sites with very cold outdoor temperatures during much of the heating season.

4.3.1. DHP Runtime

The pilot project sizing strategy (displacement model) of selecting equipment to heat the main house zone but not meet the entire load, combined with the relatively low part-load ratios seen in other sites (Larson et al., 2011), results in the DHP operating for longer periods of time. The longer runtime does not necessarily result in more or less energy use; rather, it reflects the equipment control strategy, which acts to maintain steady output and space temperature.

Table 10 displays the metered annualized operational time for the ER heaters in each site and the DHP runtime categorized by mode. We used the VLT sensor and equipment power consumption to determine if the DHP was in heating, cooling, or fan-only mode. We identified heating when the VLT was above the outside temperature, cooling when the VLT was below the outside temperature, and fan-only when the VLT was similar to outside temperature and power consumption was below 100 watts. Table 10 reflects the consistent operating pattern of the DHP installation: occupants tend to run the unit continually, and in many cases ER is reduced to only a fraction of the time. As outdoor temperature falls (especially in the colder climates), the DHP continues to produce useable heat but at a reduced COP and thus a reduced total output.

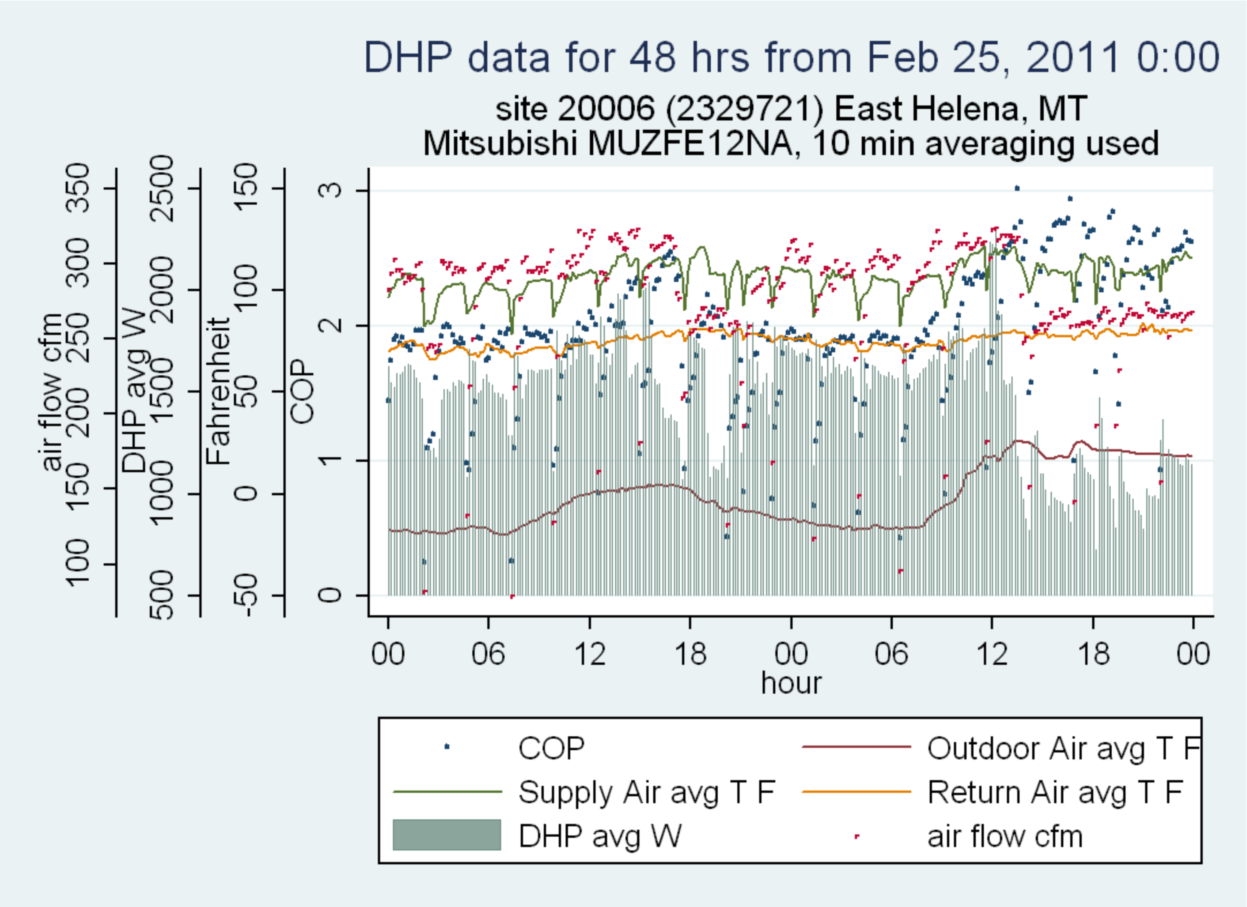
Table 10. Annual Equipment Runtime by Mode

Group	Annual Runtime by Type and Mode (hours)				n
	ER	DHP Heat	DHP Cool	DHP Fan	
NWE Montana	1660	4404	472	1322	6
BPA Eastern Idaho	2918	3690	572	1182	4
NEEA Eastern Idaho	3717	4197	612	954	10
Average/Total	2940	4157	562	1110	20

4.3.2. COP Metering Results

Figure 2 presents a graph of the data recorded by the COP monitoring instrumentation. Logged at five-minute intervals, the data show the average over the each interval: the DHP power usage, the supply air temperature, the return air temperature, the indoor unit airflow, and the outside air temperature. COP is calculated as the difference in supply and return air temperatures, multiplied by the mass flow rate of air and divided by the equipment input power. The Figure 2 shows operating responses to extremely cold temperatures (between -15°F and +15°F).[7]

Figure 2. DHP Performance at Low Temperatures



---

[7] The equipment running in steady state maintains COPs near 2 even at very cold temperatures. Whenever the outdoor temperature rises, as expected, so does the COP. The nearly periodic fluctuation in power and airflow stoppage are the indicators that a defrost cycle is occurring. Notably, the DHP maintains supply air temperatures in excess of 100°F in the plotted period.

The COP measurements conducted on the metered homes allowed the development of an estimate of COP based on the data presented in Figure 2 across the entire heating season. Using the aggregation of the measurements into 5°F temperature bins, an in-situ COP was generated. These data covered a range of outdoor operating temperatures and indoor loads. Due to the challenging nature of the measurements, especially airflow, not all sites produced useable data for the full metering period. Ecotope carefully scrutinized the useable data to construct an in-situ performance curve for the MUZFE12NA. Given there were 10 metered sites all with this unit, the dataset is particularly robust.

To construct the COP analysis, each observation (at the five-minute data interval) was placed into a temperature bin based on measured outdoor temperature at the house. Within each bin, there was a range of COPs for each observation as a result of the equipment operating at variable capacity levels and cycling up and down in speed (and therefore also varying airflow). The mean value within each bin was used for the analysis. Although COP is known to vary with power drawn by the equipment, the approach taken here is to use a simple average that accounts for the variation in power and other effects, such as defrosting and on/off cycling over the course of the year.

Table 11 shows the COP metering results for 16 sites that produced useable data over the course of the study. The table shows both the measured input energy (electrical input) and the measured output energy (house heating).

Table 11. DHP Heating Input and Output Energy

Group	DHP Heating Input Energy (kWh/yr)		DHP Heating Output Energy (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	3388	927	10402	2771	6
BPA Eastern Idaho	2738	875	8365	2512	4
NEEA Eastern Idaho	2336	1187	6380	3288	6
Average/Total	2831	1065	8385	3265	16

Table 12 shows the average COP of all units for which this calculation could be made. Because of the control approach used by this equipment, the COP remains high even for very cold temperatures. The standard deviation (SD) for the NWE and BPA sites is very small because the equipment across all those sites was identical and the climates similar.

Table 12. Average Heating COP, Seasonal

Group	Average Heating COP		n
	Mean	SD	
NWE Montana	3.16	0.03	6
BPA Eastern Idaho	3.07	0.03	4
NEEA Eastern Idaho	2.81	0.34	6
Average/Total	3.01	0.25	16

BONNEVILLE POWER ADMINISTRATION

January 2013

Using the heat output of the DHP and the metered energy input to the ER system (making the standard assumption that ER energy input equals heat output), we can determine the total heat supplied to the house. The fraction supplied by the DHP is then calculated by dividing DHP heat output by total house heat. Table 13 summarizes the observed fraction of the house heated by the DHP for each group. The nature of the measurement and analysis constrained us to estimating the heating fractions only for single-indoor units. The tables suggest that although the DHPs provide a substantial amount of heat in these houses, the remaining ER heating energy use is still significant because it is being delivered at roughly three times the energy input of the DHP system (assuming an average DHP COP of 3). Clearly, then, there are still significant savings to be achieved if the rest of the space heating could be provided by a DHP system with similar COPs.

Table 13. Fraction of House Heated by DHP by Group

Group	DHP Heating Fraction		n
	Mean	SD	
NWE Montana	0.76	0.2	6
BPA Eastern Idaho	0.56	0.14	4
NEEA Eastern Idaho	0.45	0.18	10
Average/Total	0.57	0.22	20

5. Energy Savings Analysis

Energy savings from the DHP installations were developed around a base case derived from utility bills and occupant survey information. The detailed metering of the DHP allowed an assessment of the amount of space heating that the unit provided (as an upper limit for the savings of the DHP itself). The metering system also produced separate estimates of space heat from ER heat systems and supplemental sources. These three data streams were combined to arrive at an overall picture of the savings from the installation of the DHP systems.

5.1. Base Case Heating Use

The metered data were collected from the period after the DHP installation. As a result, the base case heating use that occurred before the installation had to be inferred from a VBDD billing analysis of that period. Although this analysis is much less detailed than the metered data, it does provide the basis for estimating the savings from the DHP. For purposes of this section of the report, the term “heating energy” refers to the estimates from the VBDD billing analysis. Because the VBDD method identifies only correlation in total billed electric consumption with outdoor temperature, it will necessarily include portions of other end-uses such as lighting or water heating that may also be at least partially correlated with outdoor temperature. The analysis of the estimates of pre-installation heating use was conditioned, where possible, by the insights gathered from the occupant interviews and the metering results.

During the meter installation and energy audit, the homeowners were asked to complete a billing release so a complete set of electric bills could be collected from their utility. The utility had already provided bills for one to two years prior to the installation of the DHP; these bills were used to screen potential metering participants. At the end of the metering period, the utilities were again asked to provide bills for the period after the DHP installation through decommissioning. In most cases, this record included bills from about 15 months for both the pre-installation and post-installation periods. These two billing data sets became the basis for the development of the base heating estimates for the individual home as well as a check on the savings evaluations derived from the metered data and analysis. The steps for this analysis included:

- Assemble a billing record that extended over the pre-installation period using data gathered during the screening and recruiting.
- Assemble a billing record from the post-installation period.
- Develop a VBDD analysis for each site using all the available data, with a separate analysis for the period before and after the DHP installation. Typically this involves at least three years of data.
- Results from the pre-installation period were then assembled into a base heating estimate against which the DHP savings were calculated.

The weather-normalization procedures (VBDD) used in this billing analysis are designed to compensate for temperature differences in the various billing periods and to provide a basis for extending the savings and baseload information to an arbitrary weather record.

BONNEVILLE POWER ADMINISTRATION

January 2013

For this analysis, two separate normalizations were done:

- A long-term average of the most representative weather site was used for each home. Typically about 15 years (most recent period) of weather data were used for this normalization.
- All of the heating estimates were adjusted according to recorded post-installation weather. Thus, for engineering or other estimates that could not be easily adjusted for climate, the billing analysis could be compared to detailed metered results using this weather year.

Table 14 shows the total and heating-only energy usage in the pre-installation period derived from the billing analysis.

Table 14. Base Energy Use (Unadjusted Bills)

Group	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	19774	5250	10496	2724	6
BPA Eastern Idaho	26699	5566	14445	5133	4
NEEA Eastern Idaho	23447	7173	14708	4443	10
Average/Total	22995	6542	13392	4388	20

The savings are calculated from the base heating usage developed in this billing analysis. Because the weather changes from year to year, one function of the billing analysis is to allow the heating estimate to be adjusted based on changes in weather at a particular site. Table 14 was developed using the actual weather in the pre-installation period. Table 15 shows the result for a "normal" weather year. For this analysis, 15 years of weather (ending in spring 2012) were averaged to arrive at a long-term normalized weather dataset. When normalized, the decrease in energy use suggests our metering period was slightly warmer than the typical weather.

Table 15. Base Energy Use (Normalized Bills)

Group	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	19346	5477	10144	2970	6
BPA Eastern Idaho	26419	5298	14358	5185	4
NEEA Eastern Idaho	22862	6471	13453	4197	10
Average/Total	22519	6213	12641	4224	20

The impacts of the DHP installations are calculated for the weather that was observed during the post-installation period, which means the pre-installation heating estimates were applied to the post-installation weather data and compared to the post-installation usage data. This was done largely to account for the "heating bill" derived from the billing analysis being an estimate based on the portion of the bill that changes with outdoor average monthly temperature. We have observed that other factors are at play in this estimate, such as seasonal loads that are not related to space heating, and space heating for outbuildings that are not part of the home heating system. In general, the metering system did not include those uses, so it was important for the billing analysis heating estimates to be adjusted to the weather in the post-installation period. Table 16 shows the base case space heating estimates as adjusted to the post-installation period.

Table 16. Base Energy Use (Adjusted Bills)

Group	Heating Energy (kWh/yr)		n
	Mean	SD	
NWE Montana	9797	3962	6
BPA Eastern Idaho	13894	4724	4
NEEA Eastern Idaho	13881	4300	10
Average/Total	12658	4484	20

These transformations of the pre-installation billing analysis are used as appropriate in developing the savings estimates and calibrating the simulation in the remainder of this section.

5.2. COP-Based Savings

One approach to estimating the electricity savings of operating the DHP vs. baseboard ER heat is to directly measure the energy outputs and inputs of the equipment. The approach asserts that the heating output of the DHP would otherwise be met with ER heat. Therefore, the energy saved by the DHP is equal to the energy output minus energy input. A distinct advantage of this approach to estimating savings is that it uses data from the post-installation period directly and does not depend on data from the pre-installation period. In particular, it can be analyzed separately from some behavioral issues such as the occupants using non-electric, supplemental heat in the pre-installation period and offsetting that fuel use with DHP use in the post-installation period.

The COP-based savings estimates are calculated in several steps. The first is to use metered data to create a map of equipment COP vs. outside temperature. The second step is to sum the annual DHP input energy for a given site by a given set of outdoor temperature bins. The third step multiplies the COP maps by the input energy in a given temperature bin to determine the total annual heating output and electric savings.

The DHP energy use profiles were created over the same 5°F temperature bins as the COP maps. Taken from the metered period and split into heating, cooling, or fan-only usage categories, they represent a direct measure of the total energy used by the DHP when the outside temperature was in a given temperature bin for a given category. The total energy varied across bins based on occupant and climate. To determine annual electric savings in heating mode for a site, the energy input in a bin is multiplied by (COP – 1), which is the efficiency improvement over ER heat and summed over all temperature bins.

Table 17 shows the results of the energy-output-based procedure. As presented in Section 5.4 below, the savings calculated from the direct output of the DHP are consistently higher than the savings calculated using the metering and billing analysis. On average, savings calculated in this way are 62.2% higher than the “net” savings from the meters and the whole house VBDD billing analysis. The difference between the savings calculation can be attributed as extra heat that is actually offsetting other energy sources or providing added heating and comfort to the occupants.

Table 17. Total Heating Savings

Group	Savings from COP (kWh/yr) Mean	SD	n
NWE Montana	7015	1845	6
BPA Eastern Idaho	5627	1638	4
NEEA Eastern Idaho	3924	1767	10
Average/Total	5259	2174	20

5.3. SEEM Modeling of Metered Homes

To examine the energy savings from another perspective, Ecotope carried out an extensive modeling exercise of all the houses in the metered sample. The exercise produced predictions of heating energy in both the pre- and post-installation periods. In this case, modeling energy use offers several advantages. First, through modeling, it is possible to separate the effects of occupant behaviors from the operation of the equipment. Second, it is possible to examine, in detail, the effect of changing certain building or operating characteristics on energy use. Third, with a calibrated model, it is also possible to make reasonable predictions about energy use in a more general population of houses including analytical prototypes for regional planning.

The modeling process consists of several broad steps:

- Create a unique simulation representing each individually metered house.
- Calibrate all the simulations to the heating base case (or pre-installation) energy to establish a constant set of modeling inputs using the base case heating system of zonal ER heat.
- Using the inputs calibrated to the base case, run the simulations again with DHP heating systems to represent the post-installation case.
- Calibrate the post-installation simulations to post-installation metered energy use by adjusting as few of the modeling inputs as possible.

For the modeling tool, Ecotope used the SEEM thermal simulation model. Developed at Ecotope, SEEM is an hourly numerical simulation that predicts annual heating and cooling energy use in residential structures. The SEEM simulation inputs consist of several categories, including occupancy settings like thermostat setpoint and schedule, equipment descriptions, ducts (not used in this case of ductless and zonal equipment), envelope dimensions and insulation levels, foundation type/description, and infiltration and ventilation parameters.

The audits provided the necessary data to describe the physical characteristics of the house including dimensions, insulation levels, and a two-point blower door test to measure the air infiltration rate. Each house is then described with a unique set of dimensions and characteristics like floor, wall, and window area and the corresponding insulating thermal resistance values (R-values) and conducting values (U-values). In lieu of an in-depth lighting, appliance, and plugload audit, Ecotope used a formula based on house size and occupancy to calculate the internal heating gains for each house.[8] The larger the house and the greater the number of occupants, the higher the input internal gains value is for each house. Each simulation was set up to use the TMY weather data that most closely approximates each individual site.[9]

With the set of simulation descriptions complete, Ecotope set out to calibrate the output to the pre-installation heating energy use. The goal of the process was to match the weather-normalized heating energy use obtained from the billing records (as discussed in Section 5.1) to the (inherently) weather-normalized SEEM output. The house audits and survey data described the physical characteristics of the house well, constraining those input parameters. Therefore, in the calibration process we adjusted the thermostat setpoints (the simulation input that represent more behavioral aspects of how building heating systems are used).

Field technicians queried occupants on what thermostat settings they used in the base case period. The answers included settings for the main living space and bedrooms, but we found this information to be too general and unreliable to use directly in the modeling. It was unclear which temperatures applied to which zones in the house and how big those zones were. Thus, we sought to use a single setpoint for all 20 houses. For a particular house, the setpoint is meant to represent the average temperature of all zones in the house.[10]

Using this adjustment approach, the SEEM simulation subsumes most of the occupant “takeback” effects even if they are not related to temperature. The calibration matches the SEEM output to the observed space heat, so the combination of loads, thermostat settings, and supplemental fuels are represented in this final calibrated result.

Ecotope ran the entire simulation data set at several setpoints and found the one that produced the heating energy use that most closely matched the pre-installation data. The setpoint used for the pre-installation case was 66.8°F. Table 18 shows both the normalized pre-installation billing data heating energy use and the SEEM-predicted energy use. Note the close agreement of the overall mean to which the simulations were tuned.

---

[8] Hendron, Robert. *Building America Research Benchmark Definition Updated December 20, 2007*. NREL/RP-550-42662.NREL. Golden, CO. January 2008.

[9] TMY3. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/. For example, houses in Belgrade, MT, were simulated using the Bozeman, MT, TMY3 data.

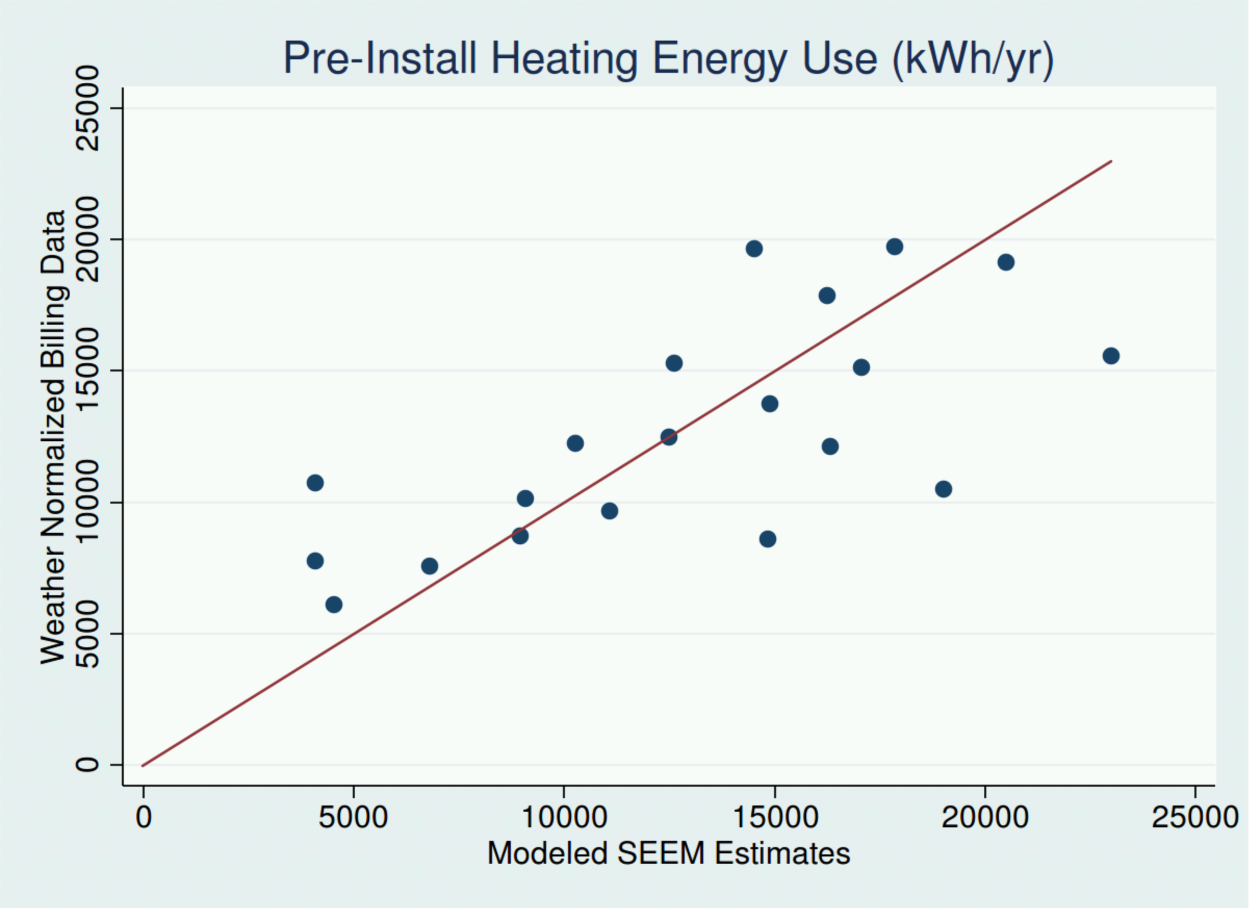
[10] SEEM is a single-zone model. Some occupants reported keeping the bedroom thermostats at a lower setting than the main living space. The input to SEEM, then, roughly represents a weighted average of zone temperatures and zone floor areas.

Table 18. Base Heating Energy Use - Bills and SEEM (Weather-Normalized)

Group	Billing Data (kWh/yr) Mean	Billing Data (kWh/yr) SD	SEEM Estimates (kWh/yr) Mean	SEEM Estimates (kWh/yr) SD	n
NWE Montana	10144	2970	10991	8061	6
BPA Eastern Idaho	14358	5185	13568	4157	4
NEEA Eastern Idaho	13453	4197	13807	4296	10
Average/Total	12641	4224	12914	5500	20

There is a high degree of variation in heating energy use patterns among all the houses in the sample, which is evident by the differences between groups. Figure 3 plots the pre-installation billing data and the SEEM pre-installation prediction. The red line is the 1:1 line. Due to the high variability in the data, we assert that the mean energy use across all the houses is the most relevant comparison for this study. In fact, we never expect the simulation to predict energy use for each individual house, but we expect that, on the whole, the averages will match. One method to get closer correspondence between the pre-installation bills and SEEM predictions is to individually vary the thermostat settings for each house. We elected not to pursue this path because we are ultimately interested in the mean energy use across categories and the typical parameters with which to model these houses. Modeling with a uniform setpoint meets that goal.

Figure 3. Pre-Installation Energy Use – Bills vs. SEEM Estimates



With the base case simulation parameters established, the next step in the modeling exercise is to run the batch of simulations with DHPs as the heating source. More appropriately, the simulations are run using a combination of DHP and ER heating, which represents how the houses operated—the displacement model. Ecotope developed DHP performance models at three different DHP efficiency levels specifically from the data in this project (see the laboratory assessment of the DHPs for a more detailed discussion [Larson et al., 2011]). These laboratory-based performance curves, coupled with the field-based COP measurements, were generalized across the entire range of equipment in the metered sample. This became a SEEM input, which could be varied depending on the particular equipment in the home. For the BPA and NWE sites, the simulations were conducted with a performance model specifically for the DHP at those sites (it is the same across all sites).

Besides the heating system, no other changes were made to the simulation parameters except to explore a range of thermostat setpoints. Again, the goal of looking at various setpoints was to match the simulation output to the observed data. In the post-installation case, we can match the simulation outputs to the metered heating energy use described in Section 4. Table 19 displays the comparison in average metered energy use to average modeled energy use. Post-installation simulation results show the best agreement with the metered data for a thermostat setpoint of

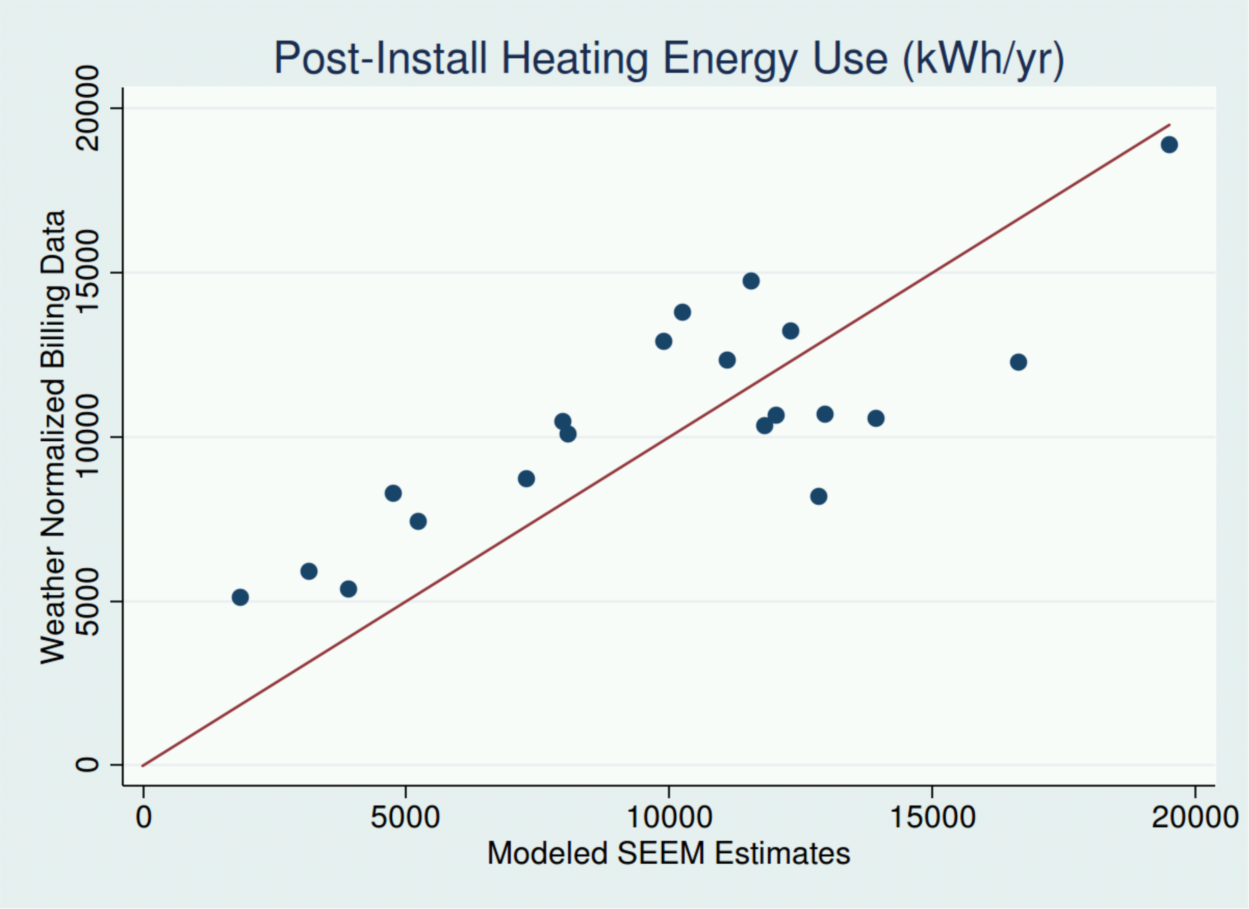
69.5°F. The post-installation simulations were also run with the 66.8°F setpoint, the value used for the pre-installation simulations.

Table 19. Measured and Modeled Normalized Heating Energy Use

Method	Heating Energy (kWh/yr)		n
	Mean	SD	
Pre-Installation Billing Data	12641	4224	20
Pre-Installation SEEM 66.8°F Setpoint	12914	5500	20
Pre-Installation SEEM 69.5°F Setpoint	14785	6043	20
Post-Installation Metered Data	10558	3989	20
Post-Installation SEEM 66.8°F Setpoint	8683	4109	20
Post-Installation SEEM 69.5°F Setpoint	9850	4579	20

The post usage in Figure 4, like the pre usage in Figure 3, plots the post-installation DHP and ER metered energy use and the SEEM estimated energy use for each house. The red line, again, shows the 1:1 line where the meters and simulation are equal. As with the pre-installation case, the graph shows a significant amount of scatter and variation in usage patterns. Therefore, we chose to use the mean values of the simulations and predictions for comparison.

Figure 4. Post-Installation Energy Use - Meters vs. SEEM Estimates



The simulation results show the best match to the pre-installation bills and the post-installation meters for differing setpoints between the two study periods. To match the measured data, we increased the heating setpoint by 2.7°F for every house in the sample from the pre-installation to post-installation period. This has the effect of increasing the underlying heat demand in the house in the post-installation period. There are two likely explanations. First, the occupants could be heating the space to a higher setpoint than before. Second, the occupants could be using supplemental, non-electric, non-metered heating sources less in the post-installation period than before.

Table 20 presents the modeled savings estimates in three different ways based on the thermostat heating setpoints used in the simulations. The pre-installation 66.8°F setting vs. post-installation 69.5°F setting most closely matches the billing and metered data, respectively. The pre-installation 66.8°F setting vs. post-installation 66.8°F setting represents the scenario where the occupant does not change operational patterns from the pre-installation to post-installation periods. The pre-installation 69.5°F setting vs. post-installation 69.5°F setting represents the scenario where the occupants' behavior in the post-installation period with the higher thermostat setpoint is assumed to be the simulation baseline. The former case more closely approximates the heating output based savings measurements discussed in Section 5.2 above. Overall, the mean savings increases with each method by 700–1,200 kWh/yr based on the occupants' heating equipment usage patterns.

Table 20. Modeled Heating Energy Savings Estimates

Group	Pre 66.8°F – Post 69.5°F (kWh/yr)		Pre 66.8°F – Post 66.8°F (kWh/yr)		Pre 69.5°F – Post 69.5°F (kWh/yr)		n
	Mean	SD	Mean	SD	Mean	SD	
NWE Montana	3108	1820	4247	2818	4831	2281	6
BPA Eastern Idaho	4115	2669	4938	2826	6084	3069	4
NEEA Eastern Idaho	2618	948	3939	1283	4538	1467	10
Average/Total	3064	1661	4231	2069	4935	2059	20

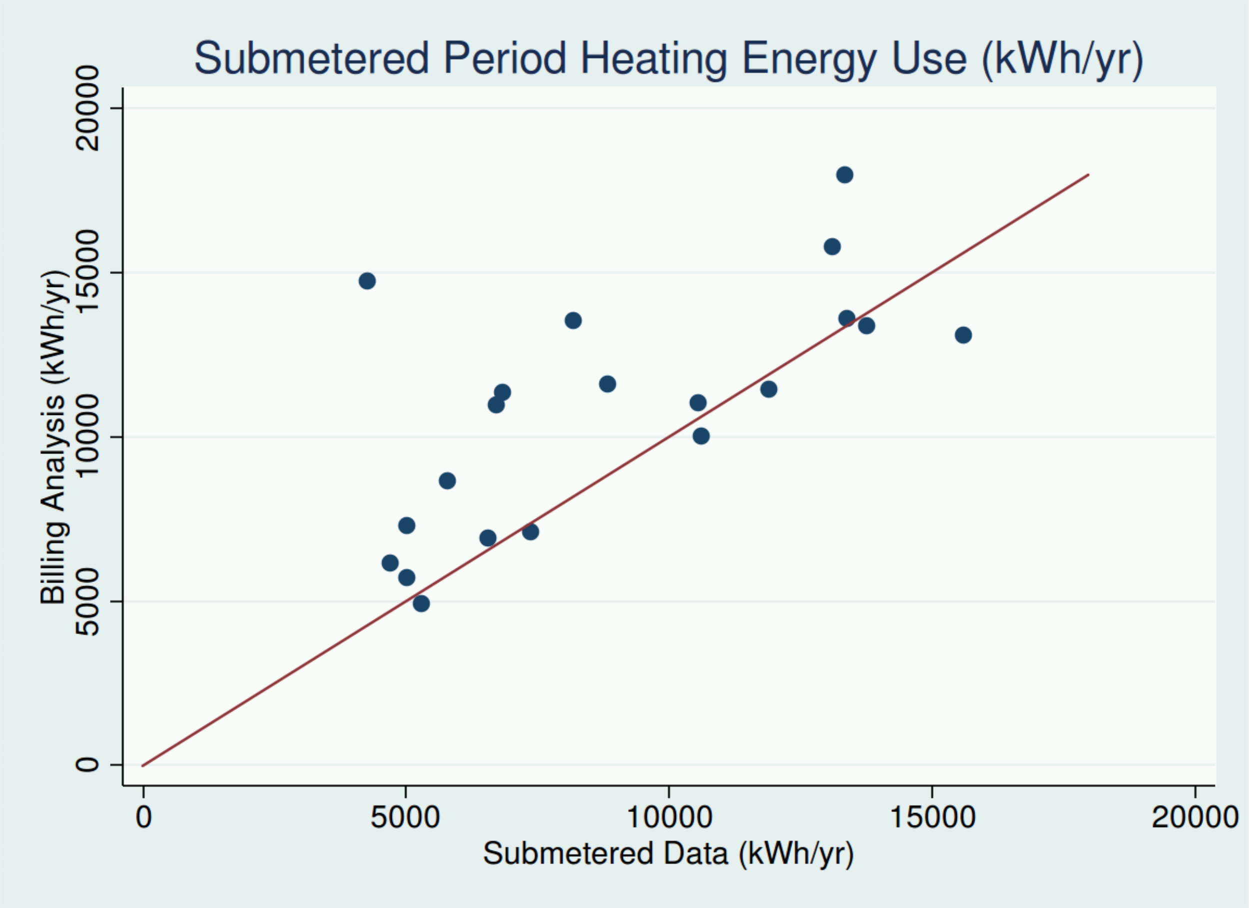
The "pre 69.5°F **–** post 69.5°F" scenario most closely resembles the heating output and COP-based savings estimate presented in Section 5.2 above. They are measurements or calculations of the heating system as the occupant is using it in the post-installation period.

The difference in savings between the "pre 66.8°F **–** post 69.5°F" and "pre 69.5°F **–** post 69.5°F" scenarios quantifies the amount of additional heat put into the house through an electric source. This means the occupant is enjoying the comfort benefits of a higher indoor temperature or has switched from non-electric heating sources (e.g., wood stoves or propane fireplaces). To get the same change in interior conditions and usage patterns with the pre-installation setup, an all-ER system would require an increase in consumption of approximately 1,870 kWh/yr. Thus, this modeling exercise is able to quantify the heating "takeback" of the sample.

5.4. Billing Analysis and Savings Estimates

The metered space heating across the entire sample was compared with the billing analysis for the same time period. This was done to demonstrate comparability between measured space heat and space heat derived from a billing analysis for the same period. Figure 5 shows the relationship between the billing analysis and the metering analysis. This analysis ignored the residual calculations and shows the underlying relationship between these two datasets.

Figure 5. Comparison Billing Analysis and Metered Heating (Post-Installation)



5.4.1. Billing Analysis and Weather Adjustments

The information presented in this section summarizes the energy use of the houses derived from billing data in both the pre- and post-installation periods. The energy use for the pre-installation period is presented in Section 5.1 above. For comparison purposes, it is also presented in more detail here. To estimate the heating energy use from the billing data, Ecotope used the VBDD regression technique discussed in Section 2.

This section presents data in several ways. The first is the “raw” bills and the associated heating energy. The “raw” bills are simply the annualized bills in the pre- and post-installation periods. If there are multiple years of billing data, they are “annualized” into an average year. The heating signature is extracted from the bills via the VBDD technique. With the bills for both periods, it is possible at this point to compare energy use to estimate a change due to the DHP. The difference in energy use between the two periods constitutes an estimate of energy savings based on billing analysis. Table 21 and Table 22 show the total billing energy use, heating energy use, and savings in this way. The bills, however, reflect the specific weather conditions occurring during the billing periods and therefore should not be directly compared without adjusting or normalizing the heating estimates to the weather in a common period. By this method, we can compare energy uses for similar outdoor temperatures for a given set of periods.

Table 21. Billing Data and Heating Energy Estimated via VBDD (Unadjusted)

Group	Pre-Installation Period				Post-Installation Period				n
	Total (kWh/yr)		Heating (kWh/yr)		Total (kWh/yr)		Heating (kWh/yr)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
NWE Montana	19774	5250	10496	2724	17109	7308	8313	4811	6
BPA Eastern Idaho	26699	5566	14445	5133	21969	3283	11459	2507	4
NEEA Eastern Idaho	23447	7173	14708	4443	22094	6393	11952	2618	10
Average/Total	22995	6542	13392	4388	20573	6367	10762	3615	20

Table 22. Energy Savings Billing Data and Heating Energy (Unadjusted)

Group	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	2665	2659	2183	2969	6
BPA Eastern Idaho	4729	3514	2986	2730	4
NEEA Eastern Idaho	1353	3245	2756	2777	10
Average/Total	2422	3246	2630	2692	20

To correctly compare the billing data between the two different periods, the heating estimate adjusted the pre-installation data to the post-installation weather. The calculation amounts to adjusting for the difference in heating degree days between the periods. Table 23 presents the adjusted energy uses from the billing data. Note that, as is expected, the total bills in the post-installation period do not change from Table 21.

Table 24 presents the change in energy for both total energy and heating energy with the data adjusted to the post-installation period weather.

Table 23. Billing Data and Heating Energy Estimation via VBDD Adjusted to Post-Install Year

Group	Pre-Installation Period				Post-Installation Period				n
	Total (kWh/yr)		Heating (kWh/yr)		Total (kWh/yr)		Heating (kWh/yr)		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
NWE Montana	18999	5986	9797	3962	17109	7308	8313	4811	6
BPA Eastern Idaho	25955	5651	13894	4724	21969	3283	11459	2507	4
NEEA Eastern Idaho	23420	6615	13881	4300	22094	6393	11952	2618	10
Average/Total	22600	6482	12658	4484	20573	6367	10762	3615	20

Table 24. Energy Savings Billing Data and Heating Energy – Adjusted

Group	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	1890	1799	1484	2266	6
BPA Eastern Idaho	3986	4055	2435	3142	4
NEEA Eastern Idaho	1326	2485	2508	2682	10
Average/Total	2027	2729	2186	2558	20

In terms of the weather used, adjusting the bills to the post-installation period makes the most sense because that corresponds to the period of metering. Therefore, the adjusted bills and the metered use can be compared. It is also of interest to "normalize" the data to typical long-term weather. Weather-normalized data can then be compared across metered samples and, most importantly, the calibration of the SEEM simulation program uses this normalized weather to correspond to the long-term weather used in the simulations. Table 25 presents the weather-normalized bills and heating energy.

Table 26 presents the weather-normalized savings between the pre- and post-installation periods. Only the heating energy portion, not the total bill, is weather-normalized. The normalized data are not strictly comparable to the analysis with the meter data, but are provided here for comparison to the modeling (Section 5.3 above). Note that the heating energy use does not differ drastically between the "adjusted" and "normalized" tables.

Table 25. Weather-Normalized Billing Data Heating Energy Estimation via VBDD

Group	Pre-Installation Heating (kWh/yr)		Post-Installation Heating (kWh/yr)		n
	Mean	SD	Mean	SD	
NWE Montana	10144	2970	8961	5020	6
BPA Eastern Idaho	14358	5185	11552	2379	4
NEEA Eastern Idaho	13453	4197	10987	2457	10
Average/Total	12641	4224	10492	3390	20

Table 26. Weather-Normalized Energy Savings for Billing Data Heating Energy Estimate

Group	Heating Energy (kWh/yr)		n
	Mean	SD	
NWE Montana	1184	3012	6
BPA Eastern Idaho	2805	2962	4
NEEA Eastern Idaho	2465	2594	10
Average/Total	2149	2720	20

5.4.2. Metered Savings Estimates

In contrast to the billing analysis, metering directly measures the space heat consumption. This process does not measure heating system components that are not on the main space heating circuits. These loads (when they occur) are seasonal loads that appear in the billing analysis as space heating. Likewise, the estimation of heat savings from the metering system must take those loads into account.

To begin this process, the base case billing analysis was compared to the measured space heat using the metered DHP and ER circuit loads. This comparison subsumes some of the changes in occupancy that reflect on the savings. These effects include changes in non-electric supplemental heat, increased temperature, especially in the zones heated by the DHP, and changes in occupancy such as increases in number of occupants or reductions in time of occupancy (e.g., “snow birds”). Table 27 shows the results of this comparison.

Table 27. Metered Savings Heating Only

	DHP Metered Savings (kWh/yr)		
Group	Mean	SD	n
NWE Montana	3316	2771	4
BPA Eastern Idaho	5452	6666	3
NEEA Eastern Idaho	4260	3335	10
Average/Total	4248	3707	17

In the case of a pre- and post- installation billing comparison, both sides of the analysis should account for the residual heating. When savings from the billing analysis are compared to the metered heating contribution of the DHP, savings estimates differ by a factor of two. To resolve this difference, a separate set of savings estimates was developed. These savings estimates used the metered data but allowed the quantification of the bias introduced by supplemental heating and large loads present in the sample. This approach has the effect of correcting for occupant behavior that is not captured in the metering and could be interpreted as space heating by a VBDD billing analysis.

Several efforts were made to account for these effects in the metered data. These efforts included a review of the billing graphs for obvious unoccupied months and a review of occupant survey responses to discern changes in occupancy. The VBDD outputs were also scrutinized for obvious bad fits. Three of the sites were excluded from the final tables due to incomplete billing records or seemingly random use of the thermostat in the pre-installation period. For these three sites there was no reliable way to determine the base case heating energy of the site.

Because of the variety of space-heating estimates and estimating procedures used through the report, a variety of savings were estimated. Seven separate heating-savings estimates were made using various treatments of weather adjustment and seasonal load adjustments. The estimates for all the procedures were similar, although individual cases showed quite divergent savings. To resolve this, each estimate was reviewed to establish a most-likely estimate of savings analysis. These were generally based on the quality of the temperature regression fit and, in a few cases, the occupant questionnaire. Table 28 summarizes the final savings by individual group for the metered sample.

Table 28. Final Savings Calculation

Group	DHP Savings – Final Adjustment (kWh/yr)		n
	Mean	SD	
NWE Montana	3001	1072	4
BPA Eastern Idaho	3339	3046	3
NEEA Eastern Idaho	3307	3230	10
Average/Total	3241	2695	17

Table 28 represents the best estimate of savings from the pre-installation heating estimates (electric heat signature) in each of the metered houses. The estimates include a combination of actual reductions in heating energy due to DHP use and other adjustments that take into account occupant behavior not directly measured by the metering system. Comparison to the savings developed in Sections 5.2 and 5.3 above suggest the impact of supplemental fuels and thermostat increases account for about 42% of the savings generated by the DHP.

5.4.3. Savings – Fraction of Total Heating

The final savings presented in Table 28 were evaluated against the base case heating estimates. Table 28 shows a relatively uniform savings across all the climates reviewed in this study, with Montana slightly higher than the other two groups. Table 29 presents the savings as a fraction of the pre-installation space heating.

Table 29. Space Heating Saving Fraction

Group	DHP Savings – Space Heating Savings Ratio		n
	Mean	SD	
NWE Montana	0.34	0.05	4
BPA Eastern Idaho	0.21	0.14	3
NEEA Eastern Idaho	0.22	0.22	10
Average/Total	0.25	0.18	17

6. Conclusions

Overall, much like the larger NEEA report on 95 DHPs across the Northwest (Baylon et al., 2012), this metering study suggests a successful technology when applied to buildings heated with zonal ER systems. Additionally, the savings measured at the new Heating Zone 3 sites in the NWE and BPA groups were similar to previous work adding to the robustness of the finding. The DHPs at all the sites kept operating throughout the entire heating season and through the coldest parts. Even at the most challenging conditions, the DHP was providing 100˚F air to the occupants at a COP near 2.

In these heating dominated climates, the cooling from the DHP used an insignificant amount of energy. Some sites used the DHP in cooling mode at the height of summer but the occupant surveys and pre-installation bills suggests this is not a new electric load. Previously, many of the houses had window air conditioning (AC) units. If anything, the DHPs likely provided a small amount of cooling energy savings.

The study quantified energy savings in two distinct ways. The first was a billing analysis looking at heating energy use both before and after the DHP installation. The second was directly measuring the DHP heat output and input. The billing analysis found an average savings of 3,000 kWh/yr at the NWE sites, 3,300 kWh/yr at the BPA Eastern Idaho sites, and 3,300 kWh/yr at the NEEA Eastern Idaho sites for an average savings of 3,241 kWh/yr. Due to incomplete billing records or seemingly random use of the thermostat or large amount of un-reported wood heat in the pre-billing period, three of the sites were excluded from the savings averages. Essentially, there was no reliable way to determine the site's base case heating energy.

In contrast to the bills, the direct COP measurement of DHP heat output and input at the site showed significantly larger energy savings. The metered COP analysis found an average savings of 7,000 kWh/yr at the NWE sites, 5,600 kWh/yr at the BPA Eastern Idaho sites, 3,900 kWh/yr at the NEEA Eastern Idaho sites, and an average savings of 5,200 kWh/yr at all 20 cold climate locations. This represented on average a 60% increase in savings over the savings measured in the billing analysis.

Although the two methods appear at odds with one another, they suggest the finding that the sites are using more heat from electrically derived sources in the post-installation period. Occupant surveys support this finding. The surveys showed some sites used more wood heat (to which a billing analysis is blind) prior to the DHP installation. Further, the surveys collected information indicating the occupants were intentionally setting the thermostat significantly lower prior to the DHP in an attempt to reduce heating costs prior to the installation of the DHP. As a whole, the sites saved energy, burned less wood, and were kept warmer after the DHP installation. These factors taken together suggest that the DHP provided substantial benefits to the participants beyond the energy savings that they realized.

The sites included in the DHP metering were selected, in part, to focus on houses that showed a strong correlation of pre-installation electricity usage with outdoor temperature. This process of screening for an "electric heat signature" tends to ensure that the savings estimates from the metered DHP installations are more likely to be significant than in the population as a whole. This screening process is necessary in order to establish a base case heating energy use estimate without metering the house pre-DHP installation. Lastly, the energy savings from a utilitysponsored conservation program designed to mimic this selection process would act to maximize the utilities’ savings potential.

In the colder climates there is a clear tradeoff between greater customer satisfaction and greater savings to the home owner and the utility. The tradeoff relates to increased occupant comfort and savings in areas where substantial amounts of wood heat are a traditional heating source. The degree to which the utility screens for this effect is the degree to which larger net savings at the meter could be realized.

This cold climate study demonstrated DHPs are a feasible heating technology in cold climates and that conservation programs can be built around their use. Any program should account for occupant behavior that may include offsetting wood or adding to increased comfort in the home. Even with those offsets, the technology showed substantial savings.

7. References

Baylon, D, L. Larson, P. Storm, and K. Geraghty. 2012. Ductless Heat Pump Impact & Process Evaluation: Field Metering Report, Energy Efficiency Alliance. Portland OR.

Fels, M. 1986. PRISM: An Introduction. Energy and Buildings, Volume 9 (1986), pp. 5-18.

Fels, M., J. Rachlin, and R. Socolow. 1986. Seasonality of Non-Heating Consumption and Its Effect on PRISM Results. Energy and Buildings, Volume 9 (1986), pp. 139-148.

Hendron, R., Building America Research Benchmark Definition Updated December 20, 2007. NREL/TP-550-42662. National Renewable Energy Laboratory (NREL). Golden, CO. January 2008.

Larson, B., D. Baylon, and P. Storm, 2011, Ductless Heat Pump Impact & Process Evaluation: Lab-Testing Report, Northwest Energy Efficiency Alliance, Portland OR.

Palmiter, L. S., I.A. Brown, and T.C. Bond. Measured Infiltration and Ventilation in 472 All-Electric Homes. *ASHRAE Transactions*, Vol. 97 Part 2. 1991. American Society of Heating Refrigeration and Air-Conditioning Engineers. Atlanta, GA.