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Ductless Heat Pump Impact & Process Evaluation: Field Metering Report

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Table of Contents

GLOSSARY OF ACRONYMS V

EXECUTIVE SUMMARY VII

1. INTRODUCTION 1

1.1. The Ductless Heat Pump Efficiency Measure 1
1.2. The DHP Pilot Project 3
1.3. Integrated Evaluation of the DHP Pilot Project 4
1.4. DHP Field Metering Evaluation 5

2. METHODOLOGY 6

2.1. Sample Design 6
2.2. Metering Design and Data Collection 10
2.2.1. Metering Goals 10
2.2.2. Metering Specifications 10
2.2.3. Coefficient of Performance (COP) Measurements 11
2.2.4. On-site Audits and Interviews 12
2.2.5. Data Collection and Assembly 12
2.2.6. Error Checking and Data Quality Control 13
2.2.7. Decommissioning 13
2.2.8. Billing and Weather Data Assembly 14
2.3. Analysis Approaches 14
2.3.1. Weather Normalization vs. Weather Adjustment 16
2.3.2. Metered Savings Calculations 17

3. HOME CHARACTERISTICS 18

3.1. Audit Characteristics 18
3.1.1. House Envelope and Size Characteristics 18
3.1.2. DHP Installation 20
3.2. Occupant Surveys 21
3.2.1. Demographics of Occupants 21
3.2.2. Thermostat Setting 22
3.2.3. Cooling Use 23
3.2.4. Supplemental Fuel 23
3.2.5. Supplemental Heating (110V Space Heaters) 24
3.2.6. Large Loads and Outbuildings 26

4. METERED FINDINGS AND OBSERVATIONS 27

4.1. Heating Energy Use 27
4.1.1. Space Heating Residual 27
4.2. Interior Temperature 30
4.3. Cooling Use and Offsets 32
4.4. Domestic Hot Water Usage 32
4.5. DHP Runtime, Output, and COP 33
4.5.1. DHP Runtime and Fractional Capacity 33
4.5.2. COP Metering Results 35

5. ENERGY SAVINGS ANALYSIS 42
  5.1. BASE CASE HEATING USE 42
  5.2. COP-BASED SAVINGS 44
  5.3. SEEM MODELING OF METERED HOMES 45
  5.4. BILLING ANALYSIS AND SAVINGS ESTIMATES 52
    5.4.1. Billing Analysis and Weather Adjustments 53
    5.4.2. Metered Savings Estimates 55
    5.4.3. Savings – Fraction of Total Heating 57
6. NET SAVINGS APPROACH AND ANALYSIS 58
  6.1. CDA/SAE REGRESSION ANALYSIS 58
  6.2. SAVINGS DETERMINANTS 59
    6.2.1. Regression Results 59
    6.2.2. Climate and Capacity 60
    6.2.3. Occupant-Determined Savings 62
    6.2.4. Savings Comparisons 63
7. CONCLUSIONS AND RECOMMENDATIONS 66
  7.1. DHP SAVINGS 66
    7.1.1. Total Savings 66
    7.1.2. Net Savings 67
    7.1.3. Calibrated Simulation Savings 68
  7.2. PROGRAM IMPLICATIONS 68
    7.2.1. Supplemental Heat 69
    7.2.2. Thermostat Setting and Take-Back 69
    7.2.3. House Characteristics 69
    7.2.4. DHP Capacity and Multiple Indoor Units 70
    7.2.5. Secondary Observations and Findings 70
  7.3. OVERALL CONCLUSIONS AND NEXT STEPS 72
8. REFERENCES 73
APPENDIX A – VBDD METHODOLOGY 74
APPENDIX B – DETAILED DISCUSSION OF MEASUREMENT AND DATA DELIVERY/ERROR CHECKING PROCEDURES 78
APPENDIX C – ON-SITE AUDIT PROTOCOL 85
APPENDIX D – SEEM DHP MODIFICATIONS 91
APPENDIX E – DETAILED ALTERNATIVE SAVINGS TABLES 94
APPENDIX F – REGRESSION SPECIFICATIONS AND RESULTS 98

List of Tables

TABLE 1. SAMPLE DISTRIBUTION OF DHP METERED SITES 7
TABLE 2. COMPARISON, METERED SAMPLE TO ALL PARTICIPANTS 18
TABLE 3. CONDITIONED FLOOR AREA....19
TABLE 4. BLOWER DOOR RESULTS....20
TABLE 5. HEAT LOSS RATES BY CLUSTER 20
TABLE 6. DHP INSTALLATIONS, METERED SITES 21
TABLE 7. OCCUPANCY DISTRIBUTION, NUMBER OF OCCUPANTS 22
TABLE 8. REPORTED CHANGE IN THERMOSTAT 23
TABLE 9. COOLING EQUIPMENT BY CLUSTER 23
TABLE 10. PERCENT REPORTING WOOD USE 24
TABLE 11. PERCENT REPORTING ANY WOOD HEAT 24
TABLE 12. USE OF 110V SPACE HEATERS 25
TABLE 13. LARGE LOADS (PERCENT ALL PARTICIPANTS) 26
TABLE 14. METERED SPACE HEATING....27
TABLE 15. ESTIMATED NON-METERED SPACE HEAT (KWH/YR) 30
TABLE 16. AVERAGE NON-METERED SPACE HEAT FULL SAMPLE (KWH/YR) 30
TABLE 17. AVERAGE WINTER TEMPERATURE AND SETBACK....31
TABLE 18. DHP COOLING USE....32
TABLE 19. DHW USE BY OCCUPANT TOTAL 33
TABLE 20. CAPACITY RATIO, SELECTED SITES....34
TABLE 21. ANNUAL EQUIPMENT RUNTIME BY MODE....35
TABLE 22. DHP HEATING INPUT AND OUTPUT ENERGY FOR 23 SITES....38
TABLE 23. DHP HEATING INPUT AND OUTPUT ENERGY FOR 69 SITES....39
TABLE 24. AVERAGE HEATING COP, SEASONAL 39
TABLE 25. FRACTION OF HOUSE HEATED BY DHP BY CLUSTER....40
TABLE 26. FRACTION OF HOUSE HEATED BY DHP BY HEATING CLIMATE ZONE 40
TABLE 27. BASE ENERGY USE (UNADJUSTED BILLS))....43
TABLE 28. BASE ENERGY USE (NORMALIZED BILLS)) 43
TABLE 29. BASE HEATING ENERGY USE (ADJUSTED BILLS) 44
TABLE 30. TOTAL HEATING SAVINGS....45
TABLE 31. BASE HEATING ENERGY USE – BILLS AND SEEM (WEATHER-NORMALIZED)....47
TABLE 32. MEASURED AND MODELED NORMALIZED HEATING ENERGY USE 49
TABLE 33. MEASURED AND MODELED ANNUAL COP 50
TABLE 34. MODELED HEATING ENERGY SAVINGS ESTIMATES....51
TABLE 35. BILLING DATA AND HEATING ENERGY ESTIMATION VIA VBDD (UNADJUSTED) 53
TABLE 36. ENERGY SAVINGS BILLING DATA AND HEATING ENERGY (UNADJUSTED) 53
TABLE 37. BILLING DATA AND HEATING ENERGY ESTIMATION VIA VBDD ADJUSTED TO POST-INSTALL YEAR AND FOR DHW ...54
TABLE 38. ENERGY SAVINGS BILLING DATA AND HEATING ENERGY - ADJUSTED 54
TABLE 39. WEATHER-NORMALIZED BILLING DATA HEATING ENERGY ESTIMATION VIA VBDD 55
TABLE 40. WEATHER-NORMALIZED ENERGY SAVINGS FOR BILLING DATA HEATING ENERGY ESTIMATE....55
TABLE 41. METERED SAVINGS HEATING ONLY....56
TABLE 42. FINAL SAVINGS CALCULATIONS....57
TABLE 43. SPACE HEATING SAVING FRACTION 57
TABLE 44. PREDICTED DHP SAVINGS....59
TABLE 45. COOLING ENERGY USE....63

TABLE 46. NET-SAVINGS RATIOS....64
TABLE 47. COMPARATIVE TOTAL SAVINGS....67
TABLE 48. WEATHER-NORMALIZED NET SAVINGS....68

List of Figures

FIGURE 1. MAPPED DISTRIBUTION OF DHP METERED SITES....8
FIGURE 2. OCCUPANCY TYPES FOR METERED SITES....22
FIGURE 3. EXAMPLE OF 120V HEAT....25
FIGURE 4. LARGE LOAD RESIDUAL LOAD PATTERN....28
FIGURE 5. LOW-VOLTAGE SPACE HEATING RESIDUAL LOAD PATTERN....29
FIGURE 6. TEMPERATURE RECORDS FOR TWO METERED SITES....31
FIGURE 7. HEATING PART LOAD OPERATION FOR 25 SITES....34
FIGURE 8. DHP PERFORMANCE AT LOW TEMPERATURES....36
FIGURE 9. HEATING MODE COP MEASUREMENTS, SITE 12411....37
FIGURE 10. LABORATORY TESTING RESULTS COMPARED TO FIELD COP MEASUREMENTS....38
FIGURE 11. PRE-INSTALLATION ENERGY USE – BILLS VS. SEEM ESTIMATES....48
FIGURE 12. POST- INSTALLATION ENERGY USE – METERS VS. SEEM ESTIMATES....50
FIGURE 13. COMPARISON BILLING ANALYSIS AND METERED HEATING (POST-INSTALLATION)....52
FIGURE 14. SAVING COMPARED TO SAVINGS FRACTION....61

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
CDA	conditional demand analysis
CFM	cubic feet per minute
COP	coefficient of performance
CT	current transducer
DD	degree day
DHP	ductless heat pump
DHW	domestic hot water
ER	electric resistance
GSM	global system for mobile communications
HDD	heating degree days
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air conditioning
ISO	International Organization for Standardization
kW	kilowatt
kWh	kilowatt hours
kWh/yr	kilowatt hours per year

MEL	miscellaneous electric load (not space-conditioning or DHW loads)
MPER	market progress evaluation report
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
NWS	National Weather Service
PRISM	PRInceton Scorekeeping Method
R^2	coefficient of determination
RMS	root mean square
RTF	Regional Technical Forum
R-value	thermal resistance value
SAE	statistically adjusted engineering model
SD	standard deviation of the population
SEEM	Simple Energy and Enthalpy Model
SOAP	Simple Object Access Protocol
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)

Executive Summary

NEEA hired Ecotope, Inc., supported by Research Into Action, Inc., and Stellar Processes to evaluate the Northwest Ductless Heat Pump (DHP) Pilot Project. The pilot project ran from October 2008 to December 2009. The DHP evaluation includes a tiered analysis of five components of technical performance and market acceptance: market progress and evaluation, lab testing, field monitoring, billing analysis, and cost-effectiveness.

The program was built on a "displacement" model in which the DHP equipment was designed to supplement an existing zonal electric heating system. This model for the DHP pilot project leaves more of the occupant interaction to chance; i.e., the occupant is able to reset the equipment, adjust the thermostat remotely, and change the load on the equipment through the use of the electric resistance (ER) heating or a supplemental heating system. Detailed field monitoring was necessary to distinguish performance impacts related to occupant actions (e.g., thermostat adjustments) from those resulting from the efficiency and performance of the DHP equipment as installed by contractors under the pilot program.

This report focuses on the detailed metering portion of the evaluation. Ecotope installed metering equipment on a total of 95 homes selected from the participants in the DHP pilot project. The metered sites were analyzed to develop the determinants of energy savings of the DHP systems as they operated across a variety of climates and occupants. The results of this report will contribute to a more comprehensive understanding of DHP performance and applicability as an energy efficiency measure in the Northwest.

The objectives of the DHP field metering are:

1. 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.
2. Determine the total equipment cooling use across cooling climates throughout the region.
3. Establish the offset to space heating brought on by this equipment and the cost-savings impact of the incremental cooling from the equipment.
4. Develop the climate and occupancy parameters needed to explain the observed savings.
5. Summarize the non–space-heating energy uses across the monitored houses.

To meet the first objective, Ecotope installed a detailed instrumentation package to measure DHP electricity input and thermal output. Table ES-1 shows the DHPs performed extremely well, generating heat with an annual coefficient of performance (COP) of 3 across all metered sites.

Table ES-1. Ductless Heat Pump Performance

Cluster	DHP Heating Input Energy (kWh/yr)		DHP Heating Output Energy (kWh/yr)		DHP Heating Seasonal COP		N
	Mean	SD	Mean	SD	Mean	SD	
Willamette	1876	962	6048	2872	3.40	0.32	20
Puget Sound	1823	708	5549	2570	3.05	0.56	20
Inland Empire	2492	1097	5637	2126	2.41	0.59	12
Boise/Twin	2256	1274	6440	3040	2.96	0.30	8
Eastern Idaho	2188	978	6112	2675	2.84	0.30	9
Average / Total	2052	969	5886	2602	3.00	0.55	69

Notes:

kWh/yr – kilowatt hours per year

SD – standard deviation of the population

N – number of observations

The metering equipment also recorded the energy each DHP used for space cooling. Table ES-2 demonstrates that little energy was used. In fact, in the more significant cooling climates of the Inland Empire and Boise/Twin, house audits showed that the DHP cooling often replaced far less efficient window air-conditioning units, likely resulting in net cooling energy savings.

Table ES-2. DHP Cooling Energy Use

Cluster	DHP Cooling Use (kWh/yr)		N
	Mean	SD	
Willamette	156	134	26
Puget Sound	72	76	25
Inland Empire	408	260	16
Boise/Twin	306	184	15
Eastern Idaho	211	208	10
Average/Total	208	204	92

Ecotope implemented two approaches develop final savings estimates for the DHP metered sample. The approaches are divided into a total savings estimate and a net savings estimate:

1. **Total savings** indicated by overall net heat output of the DHP as measured by the metering (Table ES-3). This approach relies on the metered heating output of the DHP regardless of the other heating systems in the house. We used a COP estimate as well as the runtime and power draw of the equipment throughout the year to generate these savings estimates. In this calculation, the cooling impacts of the DHP are not taken into account.

Table ES-3. Total Savings, Metered

Cluster	Savings from COP (kWh/yr) Mean	Savings from COP (kWh/yr) SD	N
Willamette	4148	2061	18
Puget Sound	3812	1981	19
Inland Empire	3264	1470	11
Boise/Twin	4184	1871	8
Eastern Idaho	3924	1767	9
Total	3887	1844	65

2. **Net savings** are calculated from the change in space heat consumption between the pre-installation period and the metered space heat after the DHP is installed (Table ES-4). This approach is complicated by the uncertainty in the base case but includes occupant "take-backs" such as increased indoor temperature and reduced supplemental fuel use.

Table ES-4. Net Heating Savings, Metered

Cluster	DHP Savings (kWh/yr) Mean	DHP Savings (kWh/yr) SD	N
Willamette	3316	2121	26
Puget Sound	3043	2357	25
Inland Empire	1882	1580	16
Boise/Twin	3628	2985	16
Eastern Idaho	3307	3230	10
Average/Total	3049	2424	93

The ratio between the two saving calculations is about 80%. This suggests that almost 20% of the heat produced by the DHP is used to provide other benefits (beyond energy savings) to the occupant.

The metered results and billing records were used to calibrate the Simple Energy and Enthalpy Model (SEEM) simulation. This proved very successful once the performance curves for the DHP equipment were integrated into the program. The results were within 5% of metered performance measurements.

The last metering objective was to collect information on non–space-conditioning energy use in the houses. Table ES-5 summarizes the metered water heating energy use by number of occupants per house.

Table ES-5. Domestic Hot Water Energy Use, Metered

Occupants	Metered DHW Use (kWh/yr) Mean	SD	N
1	1824	831	17
2	3049	1005	51
3	3201	1688	14
4	4436	1067	8
5+	6538	1375	3
Average/Total	3080	1430	93

Table ES-6 summarizes the net residual load derived from the difference between the heating, cooling, and DHW uses and the total metered space heating load. The total of the "other" electric loads sources is expressed as the total of the miscellaneous electric loads (MELs). The low-voltage and other heating derived from the metering analysis is included the table as a separate column. This use represents about 7% of the MELs in this sample.

Table ES-6. Miscellaneous Electric Loads

Cluster	Total MELs Total	Heat	Other	N
Willamette	13729	787	12942	26
Puget Sound	10103	565	9538	25
Inland Empire	13382	842	12540	16
Boise/Twin	13631	1171	12460	16
Eastern Idaho	13488	1209	12279	10
Total	12652	849	11803	93

To ascertain how the components of the system, the characteristics of the house, and the behavior of the occupants interact, a multivariate conditional demand analysis (CDA) was developed using regression estimating procedures. The goal was to establish the variables that explained the final net savings and the degree to which those variables were predictive of the DHP performance. This analysis added insights that were used to assess the DHP pilot program, develop conclusions, and provide recommendations:

The metering results provide insights into the DHP/ER system operation, including:

- Supplemental heat from other fuels has less overall impact on savings than was originally expected. Overall supplemental heat has little or no impact on DHP savings if the initial electric heat signature is strong.
- The analysis strongly indicates that increased temperature results in lower savings. The effect is small (less than 10% of measured savings) but, throughout the sample, evidence indicates that the occupants, on average, are opting for slightly higher temperatures once the DHP is installed.

- The use of the displacement model is far less sensitive to the characteristics of the home than would be expected in a conventional heating system. The DHP offsets a fairly uniform amount of ER heat while that source makes up any shortfall.
- The second indoor air handler (head) allows another zone to be conditioned. In colder regions, the effect is to offset the load more effectively and reduce the time that the ER operates. The effect is much smaller in warmer regions.

Secondary evaluation findings include:

- The occupant acceptance of this equipment is quite good. There is almost uniform satisfaction with the DHP within the metered sample.
- The impact of DHP efficiency ratings on overall performance or overall savings appears somewhat minimal. The study encompassed a wide variation in efficiency ratings, but the savings were more correlated to the system operation and occupant control.
- In no climate did the cooling from the DHP exceed or even approach the levels of heating savings.

Overall, the impact of the metering on this sample suggests a successful technology when applied to buildings heated with zonal electric systems. The impact of the DHP displacement model appears to deliver significant savings for a minimal amount of capital equipment.

It is important to note that the houses selected for this study were all screened to determine that the pre-DHP installation electricity usage indicated a strong correlation with outdoor temperature. This screening for an “electric heat signature” was conducted to ensure the best possible calculation of “baseline” electricity usage for comparison of post-installation whole-house energy bills and comparison of pre-bills against the metering results. This screening, however, was not generally conducted on the rest of the pilot project population of 3,899 houses. This limits the direct comparability of the “net savings” results with the rest of the sample since this metric relies on pre-installation electricity bill screening.

Houses without a strong relationship between pre-installation electricity usage and outdoor temperature are far more likely to have supplemental heating sources such as wood stoves that make it difficult to ascertain net savings. The lack of a strong electric heat signature, however, does not necessarily imply that “total savings” (i.e., heat delivered to the house by the DHP) would be reduced compared to the results of the direct metering observed in the sample. From this study, total savings appears to be primarily a function the existing ER heat and a number of factors including climate, ER and DHP heating setpoints, and number of indoor heat exchangers.

Upcoming DHP Impact and Process Evaluation reports, including billing analysis and cost-effectiveness analysis of the overall pilot project, will build upon the field metering analysis included in this report. All analysis from the DHP evaluation will be integrated into a final report with a comprehensive summary of findings, conclusions, and recommendations. Findings from this review of the metered sample will be used to inform the billing analysis and the cost-effectiveness of the larger pilot project.

1. Introduction

The Northwest Energy Efficiency Alliance (NEEA) is a non-profit organization working to maximize energy efficiency to meet future energy needs in the Northwest. NEEA is supported by, and works in collaboration with, the Bonneville Power Administration (BPA), Energy Trust of Oregon and more than 100 Northwest utilities on behalf of more than 12 million energy consumers.[1]

NEEA hired Ecotope, Inc., supported by Research Into Action, Inc., and Stellar Processes to evaluate the Northwest Ductless Heat Pump (DHP) Pilot Project. The pilot project ran from October 2008 to December 2009. Ecotope is conducting the DHP Pilot Project Impact and Process Evaluation from October 2008 to December 2012. The DHP evaluation includes a tiered analysis of five components of technical performance and market acceptance: market progress and evaluation, lab testing, field monitoring, billing analysis, and cost-effectiveness.

This report presents the results of the detailed field monitoring of a sample of DHPs from the pilot project. The report focuses on the determinants of consumption and energy savings as these systems operate across a variety of climates and occupants. The results of this report will contribute to a more comprehensive understanding of DHP performance and applicability for energy savings in the Northwest.

This introduction provides a background of DHPs as an energy-efficiency measure in the Northwest, the DHP pilot project, the core activities included in the DHP evaluation, and key objectives of the DHP field monitoring and analysis.

1.1. The Ductless Heat Pump Efficiency Measure

In the summer of 2007, the Regional Technical Forum (RTF), at the behest of NEEA, began the process of assessing the use of a modernized “mini-split” heat pump technology. These systems had long been used in East Asia and had a limited market in the Northwest in supplying heating, ventilation, and air-conditioning (HVAC) systems to small inconvenient zones in commercial building applications. Until 2006, these systems had been designed to provide spot cooling in individual zones, with very little potential for any application that required heating.

Beginning in 2006, a new generation of this equipment was introduced. The upgrades were largely the result of the increases in Federal Standards for heat pumps and air conditioning introduced at the beginning of that year. Over the next year, several manufacturers introduced

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[1] See the website at www.neea.org.

entirely redesigned systems focusing on inverter-driven variable-speed compressor technology and multi-speed fans. Like the previous generation of mini-splits, these systems used small wall-mounted air handlers with direct refrigerant supply from a compressor located outside. The system excelled at providing high-efficiency heating and cooling to a single zone or multiple zones through individual air handlers.

As the new generation of equipment was introduced, it was apparent that this equipment would be substantially more efficient than conventional split-system heat pumps with central air handlers and a central ducting system. Moreover, such systems were low enough in cost and were flexible enough to be considered as a measure to offset electric resistance (ER) zonal heating systems, which are not easily retrofitted with ducting systems.

The RTF reviewed a provisional measure using these new technologies. At that point, the measure was renamed ductless heat pump (DHP). The RTF used several assumptions to make preliminary savings estimates:

- The equipment would be installed in main living zones without actually replacing the existing electric heating. This approach became known as the “displacement” heating model.
- Occupants would usually select this heating source over their existing system because of its efficiency and convenience.
- The DHP would provide up to 60% of the space heat and result in a 30–40% reduction in space heating energy requirements.
- Interaction with wood and other supplemental heating would be minimized by restricting the measure to homes that do not use substantial amounts of wood heat.
- Mechanical cooling usage, especially in the region’s western climates, would not be large enough to offset the heating benefits in these climates and may provide added cooling benefits in the eastern climates with larger cooling loads.
- The systems could be delivered in any climate in the Northwest, although there was some concern that the DHP technology might not perform in the coldest weather. The displacement model was thought to mitigate the risk associated with this scenario.

In 2007, based on these assumptions, the RTF approved a provisional savings and cost/benefit analysis that suggested that a system could be designed to provide cost-effective regional efficiency resources.

Homes with zonal ER space heating systems have been the target of utility energy efficiency programs for most of the last 30 years. About half a million such homes are currently served by the region's electric utilities. These homes typically use a variety of zonal electric heat (including wall heaters, baseboards, or electric cable), do not use ducts, and are controlled in each room individually. The savings potential for these homes has typically been based on reducing the heat loss rate of the building through retrofit insulation and window upgrades. These efforts reduced the heating demands of the house and thus the electric heat bill.

From the electric heat customer's point of view, the options available to save energy and heating bills were more limited:

- Some customers would retrofit their homes with a duct system and convert the heating to natural gas or an electric heat pump.
- Other customers have sought to reduce their electric heating requirements through the installation of supplemental heat such as wood stoves. In these cases, the home nominally remains electrically heated but with reduced electric energy requirements. Although the distribution of this supplemental heat is uneven throughout the Northwest, it represents a significant amount of space-heating offset in several parts of the region.
- Finally, some customers reduced the thermostat setpoint of the home in some or all rooms to reduce the costs of the electric heating system.

To address this market with a cost-effective DHP measure, the systems were thought to be optimized with a single outdoor compressor and one or two indoor air handlers. This configuration represents a relatively low-cost way to supply the needs of a major portion of the heating load without actually requiring the introduction of a full distribution system that serves several zones.

To ensure that the pilot was as cost-effective as possible, the general approach for the pilot was to market the system as a "displacement" technology—that is, a technology that would offset the existing space heating without replacing the existing ER space heaters. The other attractive aspect of the "displacement" approach is that it leaves in place the existing zonal electric heat, thereby not risking adverse home comfort.

1.2. The DHP Pilot Project

Beginning in the autumn of 2008, NEEA, the BPA, and a number of cooperating utilities in the Northwest introduced a pilot project to market this DHP technology to customers with zonal electric heat. The principal goal of the pilot was to show that DHPs could interact with the homes of individual owners and provide savings that justify the relatively significant cost of adding a split system to an individual zonal electrically heated house. From the outset, the project targeted customers who were most likely to accept this technology and who were most likely to have significant electric energy savings. Potential participants were asked about supplemental fuel use, and (in some utilities) certain customers were restricted from the project based on such usage or based on overall electric energy use patterns.

In the pilot project, NEEA and the regional utilities could install these systems and evaluate their performance over a significant number of installations. The DHP pilot project included several goals important to developing the DHP technology as viable efficiency measure:

- Develop an approach to marketing this technology based on introducing the product to residential HVAC contractors that could sell and install the product to the local markets throughout the region.
- Install at least 2,500 units (a total of 3,899 units were installed under this pilot by the end of 2009) across the region using a combination of an integrated market strategy and substantial utility incentives sponsored by BPA and regional utilities.

- Use the installations from the pilot project to evaluate and assess the market acceptance of the DHP technology. This evaluation was designed to address the market and delivery process developed in the pilot project.
- Design an impact evaluation to mimic the approach to the central heat pump programs operating throughout the region. The impact evaluation includes both detailed assessment of field performance (including measurement of the field coefficient of performance [COP]) and the aggregate impact on billed consumption.
- Validate a simulation approach to predicting energy savings using the regional residential analysis tool, Simple Energy and Enthalpy Model (SEEM).[2] This model would be used in the future to establish the electric savings associated with various DHP installation programs.

1.3. Integrated Evaluation of the DHP Pilot Project

To quantify the savings from increasing the efficiency of the zonal heating system, the pilot included an integrated project evaluation. This evaluation includes five components:

- **Market Progress Evaluation.** Assessment of pilot project participants' use of DHPs, their use of other heating and cooling equipment, and their satisfaction with the DHPs. The market progress evaluation also reported on the evolving experiences and perspectives of manufacturers, utilities, and NEEA, as well as those of program implementation staff and their opinions about the suitability of DHPs as an efficiency measure in markets other than those targeted by the pilot. The evaluation explored responses to the technology and pilot, and intentions to install DHPs among participating and nonparticipating installers (McRae et al., 2011).
- **Lab Testing and Analysis.** Detailed laboratory testing that established the efficiency of the DHP technology. The lab testing sought to establish the efficiency and performance of the equipment at various outside temperatures (Larson et al., 2011). DHP lab performance was compared to *in-situ* metered performance.

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[2] 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.

- **Field Monitoring and Analysis.** Detailed metering of the equipment installed in a sample of single-family homes throughout the Northwest. This effort was meant to establish the results of occupant approaches to using the DHP in the context of the existing heating system (which remained intact in most cases).
- **Billing Analysis.** An impact analysis using the results of the billing changes in the customers using the DHP. This was designed around a large sample of participants across the region and was meant to capture the overall impacts of DHP use.
- **Cost-Effectiveness Analysis.** An analysis that integrates the impact evaluation with costs and benefits collected from the process interviews, the program reviews, and the impact evaluation.

1.4. DHP Field Metering Evaluation

This report focuses on the detailed metering portion of the evaluation. Ecotope metered a total of 95 homes across the Northwest. These homes were sampled from the participants in the DHP pilot project in 2008 and 2009.

The objectives of the DHP field metering are:

- 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 across a variety of cooling climates throughout the region.
- Establish the offset to space heating brought on by this equipment and the cost-savings impact of the incremental cooling from the equipment.
- Develop the climate and occupancy parameters needed to explain the savings observed.
- Summarize the non-space heating energy uses across the systems monitored.

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 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.

A COP supplement to the basic metering package was installed in 35 homes. The *in-situ* COP measurement was incorporated into the study design in order to compare findings with the lab testing and analysis.

2. Methodology

2.1. Sample Design

The DHP field monitoring sample design required that a sufficient number of homes be metered in most Northwest climates to allow a reliable assessment of the performance of the DHP equipment in the climates tested. Pilot participants were divided into eight climate clusters. These clusters reflected marketing clusters that were part of the contractor marketing program developed in the pilot program and provided some geographic continuity.

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 (explained further in Appendix A) allowed an assessment of the electric heating use of the home based on month-to-month changes in consumption predicted by outdoor temperature.[3] The screening process had the effect of increasing the potential electric savings from the sample. The results from the metering should be generalized, with attention paid to the potential bias in the metering sample.

The sampling process included:

- A review of the bills collected from the pre-installation billing records.
- A VBDD-type screening to establish that the homes used electric heating (not wood or some other supplemental heating).
- A random sample of the available homes that passed the screening. The number of homes to be metered in each of two of the clusters was set at 25. The screening resulted in about 25% attrition in the sample frame.
- The remaining three clusters in the eastern parts of the region were selected from a very limited pool to be those homes with an acceptable heating signature even if there was evidence of supplemental space heating from wood or other fuels.
- The early installations in Western Montana were screened as part of the early assessment of the eastern climate zones. This group resulted in only about 35% of the cases with a

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[3] 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.

credible electric heat signature, and all of those had evidence of wood or some other supplemental fuels.

- Recruitment of the samples, with potential sites offered an incentive to allow meters to be placed in the home over the course of 14 to 18 months.

The eight climate zones are summarized in Table 1, including the total number of sites ultimately used in each climate zone. Figure 1 shows the geographic distribution of the final metered sample. Table 1also shows the fraction of homes in each cluster that were excluded during the bill screening. In the Boise/Twin cluster, some of the homes were also excluded because of multi-head DHP installations.

Table 1. Sample Distribution of DHP Metered Sites

	Sites			
Cluster	Total	Meters	COP Meters	Screening Fraction
Willamette	2,219	27	9	26%
Puget Sound	797	25	11	15%
Coastal	308	0	0	N/A
Inland Empire	167	17	5	27%
Boise/Twin	128	16	4	42%
Eastern Idaho	92	10	6	20%
Tri-Cities	60	0	0	N/A
Western Montana	128	0	0	92%
Total	3,899	95	35	26%*

*Does not include Montana screening results

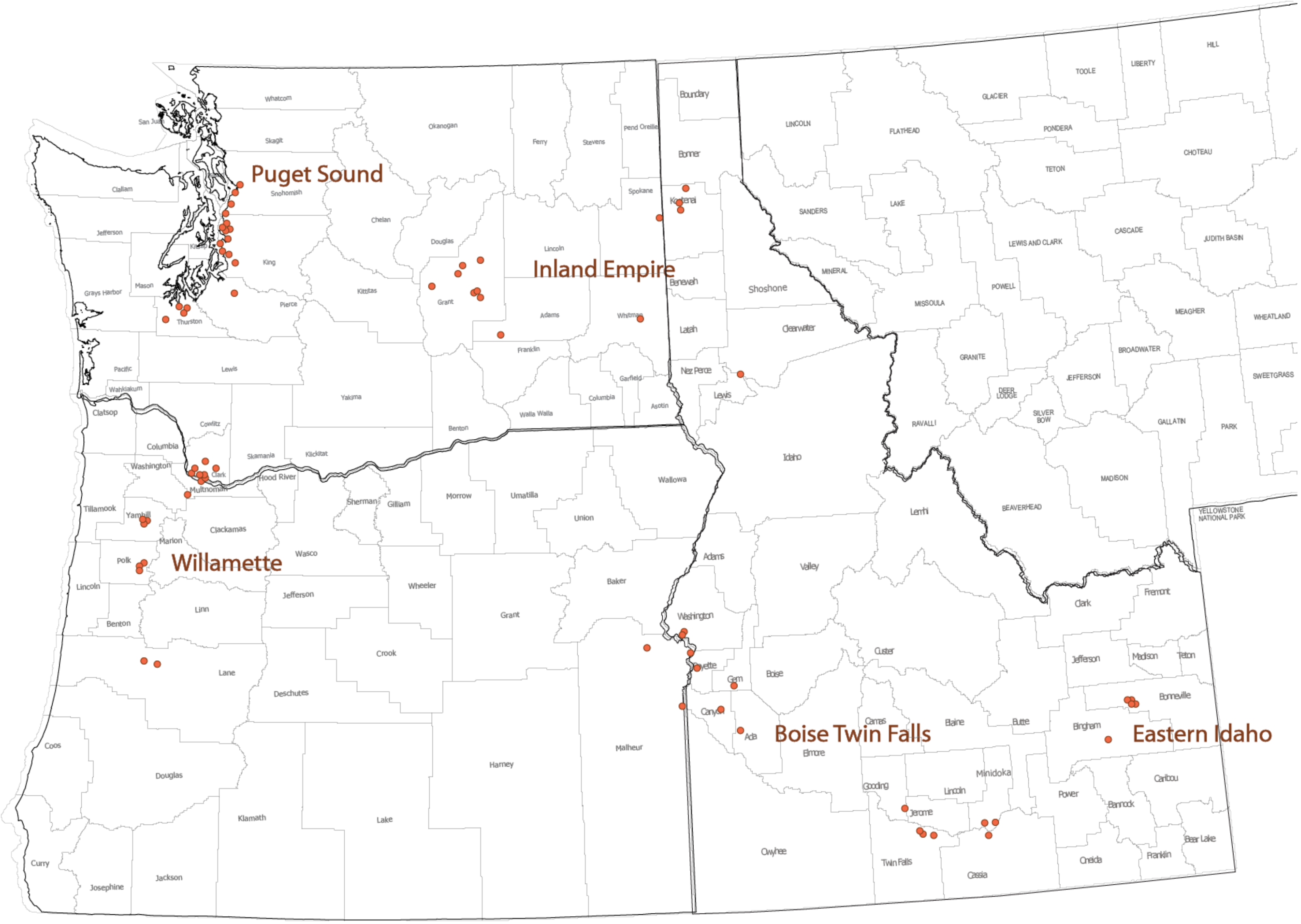
The sample was designed around five of the eight climate clusters. The savings evaluated in this report are characterized by these clusters, and are meant to characterize the distinctly separate climates that are represented by these geographic clusters.

In two of these clusters, the Willamette and the Puget Sound, the sample was a random sample from a relatively large number of available DHP installations. These samples were designed to be simple, random samples that were subsequently “screened” to determine the appropriate participants for the metering.

The Willamette cluster roughly includes the area from Cowlitz County, Washington, in the north to Lane County, Oregon, in the south along the Interstate 5 corridor. The Puget Sound cluster includes, essentially, the four counties in western Washington surrounding Seattle and was largely represented by four utilities: Puget Sound Energy, Snohomish County Public Utility District, Seattle City Light, and Tacoma Power.

In the remaining clusters, the number of DHPs that were installed was considerably smaller. It became apparent early in the process that it would not be possible to draw a random sample because so few homes were available (even with a reduced sample size).

Figure 1. Mapped Distribution of DHP Metered Sites



The Inland Empire cluster includes the area from the Columbia River to the Idaho/Montana border and from the Canadian border south approximately 200 miles to include most of Northern Idaho and Northeastern Washington. The next cluster, the Boise/Twin Falls cluster, is represented by the western Snake River Plain, from Twin Falls, Idaho, north into the Ontario, Oregon, area. This cluster includes all but the easternmost fraction of the Idaho Power service territory. These clusters correspond, roughly, to the Heating Zone 2 climate zone used by the Northwest Power and Conservation Council (NPCC) in the regional power plan.

The final cluster used in the metering is the Idaho Falls area, which includes the areas between Blackfoot, Idaho, and Idaho Falls, Idaho, which are among the coldest climates in Idaho and are typically characterized as Zone 3 climates in the NPCC regional power plan.

The other clusters in the eastern part of Montana, the coastal areas, and the Tri-cities area of Washington and Oregon either were too small or had a much more extensive use of supplemental wood heat, making site selection impractical.

In addition, as the screening process was initiated, it became apparent that much more supplemental wood heat was used in these eastern localities than was identified through bill screening in the Willamette and Puget Sound clusters. Thus, the screening removed many more homes (more than 50%). Furthermore, there was a substantial probability that some amount of supplemental heat was present, even where electric space heat was determined as the primary heating system in the billing analysis. Once it was realized that the random sample of participants was unrealistic, an engineering sample of convenience was designed to cover these eastern climates and geographic areas.

The samples that were selected in each of these eastern clusters were determined largely by eligibility (after passing a somewhat relaxed screening test) and willingness to participate. Virtually every home that met those criteria was recruited and scheduled, if it was at all possible. Even so, the sampling goals in each of these localities were not met, with substantially fewer than 20 homes in any of these clusters. Nevertheless, the sample did include a wide variety of homes in climate zones two and three, including several areas in the western Snake Plain and eastern Washington where significant cooling loads would be anticipated.

Table 1 shows the distribution of the sample throughout the various clusters. Within the main metered sample, which included 95 homes, 35 of those homes received a supplemental metering package that measured air flow and temperature at the air handler unit and allowed, in theory at least, the calculation of a COP for the unit in real time.

The COP data were to be included with savings estimates so that the actual COP of the unit and the effective savings associated with that COP could also be part of the savings estimate. Because this metering protocol required sensors wired and placed in full view at the air handler, the COP samples were based on that subset of people willing to participate (across all five climate zones) and, thus, is a reasonably arbitrary sample across a variety of manufacturers and equipment types.

Because of the nature of these samples, although standard errors and confidence intervals were calculated in every case, the impact of a fairly arbitrary sample in the eastern clusters should be considered when interpreting these statistics. In addition, two sites were removed after meters were installed. These were in the Inland Empire and the Willamette clusters and were lost as a result of failures in the metering system.

2.2. Metering Design and Data Collection

The Ecotope field team began installing the DHP metering equipment in the spring of 2009 and continued through mid-January 2010. The metering equipment remained in place for all but two sites through March 2011. Thus, for all sites more than a year of data was collected, and for some sites almost two years of data were available, including most of two heating seasons. Appendix B provides greater detail of the metering system as installed.

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 domestic hot water (DHW) usage to help establish regional planning assumption based on metering done in the early 1990s. 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 miscellaneous electric loads in the home. Like the DHW, this load was metered in the early 1990s, and no similar data set had been accumulated since that time.
5. Develop a method to measure the COP of the units on-site, in real time. This system was devised in the early stages of the meter installation and 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. **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 stand-alone, 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.

The decision to measure VLT was based on preliminary metering in another small DHP pilot in the Northwest (Geraghty and Baylon, 2009). This previous research suggested that the cooling signal determination using only indoor temperature was very problematic, and the analyst was left to guess when cooling was occurring in the swing seasons of late spring and early autumn. The controls for the DHP equipment are very interactive, and it is possible for simultaneous cooling and heating to occur. Measuring the VLT allows the analyst to know when the unit is cooling and allows a direct accumulation of the total cooling load and the conditions where cooling is supplied while ER heat is also used.

The data collected in the metering process were recorded at either five-minute or one-minute intervals. Some of the COP sites were set to log at a one-minute interval. After six months, a review of the data resulted in a decision that this extra precision was not helpful, and the metering interval was reset to five minutes. These data were available from Ecotope's automated download process and included all the energy use and most of the temperature information collected.

2.2.3. Coefficient of Performance (COP) Measurements

Thirty-five of the sites were metered with additional points that would allow the estimate of an *in-situ* system's efficiency, the COP. 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. Output is converted from British thermal units per hour (Btu/hr) to kilowatts (kW) so that the numerator and denominator are in the same units. 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 AHRI-rated performance, and to inform the development of inputs for simulation assessment of the DHP (also used to determine savings from application of the ductless technology).

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. This device accumulated pulses in a manner similar to that for the electric energy current transformers/watt transducers. Different pulse rates could be compared with a one-time calibration to determine cubic feet per minute (CFM) of airflow. The product of temperature split and airflow is thermal output in heating or cooling. Because energy usage/power of the DHP and outdoor temperature are also unknown, system COP can be calculated as a function of outdoor temperature bins. With this level of on-site data, considerable insight was available both on system performance and as a check in real time of laboratory measurements (Larson et al., 2011). See Appendix B for details of this instrumentation design.

2.2.4. 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 protocol for this audit is in Appendix C.

The primary site occupant was interviewed twice during the 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 previous interview, the occupant was also asked about the household's use of low-voltage (110-volt [110V]) space heaters. This was identified as an important variable in a previous DHP evaluation (Ecotope, 2010), and we anticipated finding similar issues in this study.

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

2.2.5. Data Collection and Assembly

Depending on the meter installation schedule for various clusters, one to two years of metered data were collected for the DHP sites. The metered installations were complete by January 2010, and data were collected for nearly the full suite of sites through March 2011. As a result, a full common year of data was gathered for each site in the sample. Except for small data gaps in the manual download sites and two sites where the occupants insisted on removing the meters, all sites in the analysis data had at least 14 months of data; the median number of data-days per site for the entire sample was 569.

The "annualized" data set 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 3G connection (cell phone). 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.

2.2.6. Error Checking and Data Quality Control

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

- A field installation guide was developed in the early stages of field installation. 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 computers 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. This process resulted in several site visits across the sites in an effort to get a useable amount of COP data from the metered sites. The COP measurements depended on a very sensitive anemometer, which was subject to dust and required precise field calibration. About 75% of the sites with COP meters produced some amount of useful data. 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 and could be applied to laboratory testing results (Larson et al., 2011). 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.

2.2.7. Decommissioning

The field team decommissioned the DHP meters during April and May 2011. In two cases, the participants requested early removal of the metering equipment. In one case, less than a year of data was collected and the site was not used. In the other case, a full year was collected, and the information collected was useable even though somewhat abbreviated.

The decommissioning process included the retrieval of the temperature loggers that recorded temperature hourly in the main living space. In addition, the automated cellular data download failed at three sites, and the data were retrieved during the decommissioning. The datalogger has a storage capacity for about six to seven months of data, so the sites were visited at least twice before the final decommissioning. In especially remote sites, this was problematic and resulted in some data loss. In general, these sites were salvaged and useable data were available.

2.2.8. Billing and Weather Data Assembly

Utility billing data from the metered sites were analyzed to establish the baseline (pre-DHP) 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, 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 general, the billing record extended (at least) from the beginning of 2007 (about two years before the beginning of the monitoring year and at least 12 months before any installations) to the end of the monitoring period, March 2011. The pre-installation billing record was assembled from approximately 14 to 24 months of bills collected before the installation of the DHP. The post-installation period included a minimum of approximately 15 months of bills.

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.

2.3. Analysis Approaches

The primary goal of this analysis was to develop a savings estimate to assess the use of the DHP technology. 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.
- Develop a picture of the determinants of those savings using secondary data collected from the occupants and from the metered data.
- 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 insights that can be used in future billing analysis to inform the overall savings from a more general evaluation of the DHP pilot program.
- Provide implications that can be used to inform the development of a utility program to support the installation of DHPs as an energy-efficiency resource.

To support these strategies, the following data sets were developed over the course of the pilot project:

- Electric bills collected from the utilities servicing these homes. The billing data included an average of two years of consumption before the installation of the DHP and up to 30 months of data after the installation. For the analysis, we averaged about 18 months of post-installation billing.
- Metered data for four power channels and three temperature channels at five-minute intervals and a pendent temperature logger at one-hour intervals.
- Full energy audit data detailing the heat loss rate of the home, including a blower door test to inform the air infiltration component.
- Three separate surveys taken of the occupants: the first by the installation contractor at the time of the installation of the DHP; the second by the instrumentation team when the meters were installed and the energy audit was conducted; the third at the time of decommissioning the metering system after at least 15 months of data collection.

The rich data sets assembled for this project enabled a variety of methodological approaches to measuring changes in space-conditioning energy consumption. These approaches fall into three main categories:

1. 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.
2. 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.
3. 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.

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.
- 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.

- An unexpected complication in the metered space heating, which appeared during the metering phase of the project. We noted the issue of unsuspected apparent space heat hidden in the residual load (the non-metered portion of domestic electric consumption) in a previous report (Ecotope, 2010).

All of the 220V circuits used to power resistance zonal heaters were separately metered as the "ER" channel, but any use of plug-in 110V heaters in convenience outlets throughout the home was not separately measured. The approach to this problem was to apply the VBDD regression machinery to all *residual* loads in determining heating signatures. This approach allowed an estimate of "space heat" otherwise hidden in the residual loads. However, this approach also captured other seasonal loads correlated to heating degree days (HDDs) such as partially heated outbuildings, spas, and hot tubs. These uses introduce added biases, but those biases probably appear in the pre-installation period so it is important to account for them when calculating savings using only pre-installation billing analysis as the basis of the savings estimate.

Specific measurement approaches for residual heat could be any of the following, depending on the site:

1. Ignore any degree day (DD) response in residual load and set residual heat to "0" (in cases where we could confidently ascribe the apparent heat to some other end use not present in the pre-installation period).
2. Employ the VBDD technique used in Geraghty and Baylon (2009).
3. Sort residual energy use by month, take the fourth-largest month as a "base," and assume that usage over this base amount in the three largest months is space heat. This approach applies in cases where space heat is suspected but, because of irregular usage, the VBDD technique fails to produce plausible estimates.
4. Use DD regressions but fix the balance point exogenously (e.g., DD rather than VBDD).

In practice, we used approach No. 3 for most sites.

2.3.1. 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. If space heat energy is assumed to be linear in HDDs, and if this linear response coefficient can be estimated, weather normalization is a straightforward matter of multiplying this response coefficient by long-term average annual HDDs. VBDD regression provides an established method of estimating the DD response coefficient. In the context of this report, "long-term average" means all the data available from NCDC for a site's chosen weather station. This varies from station to station, but averages about 15 years (ending in mid-2011) for the stations used here.

"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. Post-installation metered data were gathered during the chosen reference weather period and hence need no alteration. Pre-installation temperature-sensitive consumption can be expressed in terms of reference period weather using the same procedure as the normalization discussed above.

We present some results here in weather-normalized form, but in general we prefer to present weather-adjusted results (expressed in terms of recorded post-installation weather). We adopt this approach partly because DD response coefficients for metered data can be estimated only by aggregating it to at least daily aggregation intervals. Much of the fine detail of the data is lost in the process. In addition, weather normalization via VBDD assumes linearity in DD response, and heat pumps, because of temperature-dependent COPs, do not satisfy this linearity requirement. Finally, other elements of our analysis data set such as the questionnaire data used in cross-sectional analysis cannot be readily time-shifted.

2.3.2. Metered Savings Calculations

There were separate heating savings estimates for each baseline 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 about 85% 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. This approach allowed more flexibility in deriving the savings by using the appropriate combination of estimations from the metering period. In these cases, the residual calculated from the residual analysis was used to modify the metered space heat and actually reduce the apparent savings.
- In a few cases (4%), the metered data included large loads that were metered. This was rare because the instrumentation often was fully used in the quad-metered specification. In those cases, however, the seasonal biases from the extra loads were removed from the base, and the savings were calculated using the adjusted results.
- In about 10% of cases, the space heating was erratic or had missing data. In those cases, the billing analysis for the post-installation period was used if an adequate billing record could be assembled. The billing data were adjusted to the weather for the post-metering period in those cases.

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 could be applied to the observed runtime, and an estimate of the heat output of the DHP was made. Section 5 discusses this approach and the resulting savings estimates.

Finally, a goal of this project was to adapt the results of the metering and lab testing to the SEEM model used in assessing energy savings for future programs and program planning. The RTF and the 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 5.

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 component of heat loss/gain associated with air infiltration). 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 one to two years that 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

The average size of the homes in the metered sample is reasonably comparable to the average size of homes in the larger pilot of 3,899 sites. Table 2 shows a comparison of the metered sample to all pilot participants. Data for the pilot project participants were collected with a homeowner participation form. The estimates on the homeowner form were typically collected by the contractors and are probably estimates made by the homeowners during the application. Data for the metered sites were measured by the Ecotope field team at the time of the audit.

Table 2. Comparison, Metered Sample to All Participants

	Pilot Participants		**Metered Participants**	
Cluster	Sq. Ft.	N	Sq. Ft.	N
Willamette	1531	2219	1503	27
Puget Sound	1594	797	1395	25
Inland Empire	1734	167	1393	17
Boise/Twin Falls	1711	128	1966	16
Eastern Idaho	2156	92	2316	10
Average/Total	1595	3899	1618	95

Notes:
Sq. Ft. – square feet
N – number of observations

Table 3 shows the distribution of house area across the different clusters for the floor area estimated by the homeowner or contractor at intake and the measured area taken from the detailed audit. A lot of variation exists between these two groups. Despite the variance, the average floor area across clusters is consistent. This variance was largely due to several cases where basements, although conditioned, were not counted in the square-footage area in the original assessment.

Table 3. Conditioned Floor Area

	Reported by Intake Form		Computed from Audit Measurements	
Cluster	Sq. Ft.	N	Sq. Ft.	N
Willamette	1524	27	1503	27
Puget Sound	1335	25	1395	25
Inland Empire	1386	17	1393	17
Boise/Twin Falls	1599	16	1966	16
Eastern Idaho	1926	10	2316	10
Average/Total	1504	95	1618	95

A blower door test of the envelope tightness was conducted on all homes. Table 4 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 air changes per hour (ACH) at 50 pascals of pressure (ACH50) blower door test 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 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 4. Blower Door results

Cluster	Blower Door Results		Natural Infiltration Estimates				N
	ACH50	SD	ACH50 / 20	ACH Annual Average (SEEM)	ACH Heating Season Average (SEEM)	ACH Heating Design Day Average (SEEM)	
Willamette	9.5	2.5	0.48	0.24	0.28	0.35	27
Puget Sound	10.7	5.4	0.54	0.28	0.32	0.41	25
Inland Empire	8.8	3.6	0.44	0.22	0.26	0.35	17
Boise/Twin	7.9	4.0	0.39	0.20	0.24	0.31	16
Eastern Idaho	4.8	1.1	0.24	0.15	0.17	0.22	10
Average / Total	8.9	4.1	0.45	0.23	0.27	0.35	95

Note:

SD – standard deviation of the population

Table 5 shows the distribution of heat loss rate across the homes measured by the sum of the heat loss rate of the homes envelope components and air infiltration (UA). When the overall heat loss rate is normalized by house size, the heat loss from one cluster to the next is quite consistent. It is likely that the overall size and insulation level is typical of small electrically heated homes throughout the region. Only in the coldest climate, eastern Idaho, was there a deviation from this norm, with appreciably lower heat loss rates per square foot.

Table 5. Heat Loss Rates by Cluster

Cluster	UA Total		UA/Sq. Ft.		N
	Mean	SD	Mean	SD	
Willamette	503	165	0.336	0.055	27
Puget Sound	500	172	0.366	0.115	25
Inland Empire	459	200	0.332	0.083	17
Boise/Twin Falls	580	198	0.331	0.135	16
Eastern Idaho	532	131	0.236	0.050	10
Average/Total	511	177	0.332	0.099	95

Note:

UA – The sum of thermal transfer coefficient (U) time the area (A) of the components of the building. Also includes convective losses from infiltration.

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 one outdoor unit were not metered. In the entire pilot study, about 34% of the DHP installations had more than a single indoor air handler (head).

In this sample, only 18% had two indoor heads. Table 6 shows the average size (measured by capacity) of the installed DHP equipment by cluster as well as the number of homes with two indoor heads.

Table 6. DHP Installations, Metered sites

Cluster	Tons	2 Indoor Heads	Total Metered
Willamette	1.76	3	27
Puget Sound	1.20	1	25
Inland Empire	1.79	4	17
Boise/Twin	1.51	8	16
Eastern Idaho	1.33	1	10
Total	1.53	17	95

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).

The first of these interviews addressed the occupant characteristics and their operational choices. For the most part, the occupants had had only a few months of experience with the equipment prior to the installation of the metering. In no case had a DHP been installed through an entire cooling or heating season. The questions focused on the demographics of the household, the thermostat and ventilation operation of the home, and the use of wood or other supplemental fuels for space heating.

The second interview was conducted as the metering equipment was decommissioned. In all cases, the occupants had at least 18 months of experience with the DHP. In some cases (especially in the western climates), the DHP had been installed for well over two years. This interview included revisiting several questions including the use of wood or other supplemental fuels after the DHP installation. In addition, any changes in occupancy or operations were addressed.

3.2.1. Demographics of Occupants

The occupancy of the metered sites reflected the overall demography of the pilot installation. This sample was dominated by one- or two-adult households with no children. Approximately half of the participants in this category are over 65. Figure 2 shows the distribution of these household characteristics.

Figure 2. Occupancy Types for Metered Sites

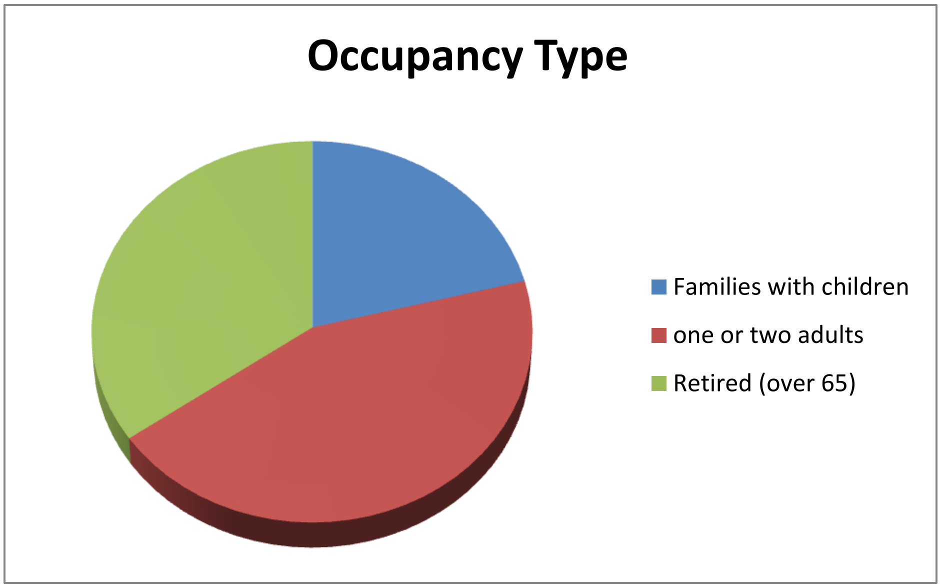


Table 7 shows the distribution of occupancies across the five sampling clusters. As the table shows, the average occupancy is about 2.3 occupants per household. The average age is 47.6 years old, indicating an overall older demographic. For the overall pilot project participants, the average occupancy is about 2.2 occupants per household and average age is 45.3 years. As such, the overall occupancy patterns in the metered sample closely reflect the overall occupancy patterns in the pilot study.

Table 7. Occupancy Distribution, Number of Occupants

Cluster	Under 12	12 to 18	19 to 65	Over 65	Total	Mean Age (yrs)	N
Willamette	0.2	0.3	1.3	0.5	2.3	43.9	27
Puget Sound	0.2	0.2	1.2	0.6	2.2	45.4	25
Inland Empire	0.2	0.0	1.0	0.9	2.1	53.2	17
Boise/Twin	0.4	0.1	0.8	1.1	2.4	53.5	16
Eastern Idaho	0.6	0.0	1.3	0.6	2.5	44.4	10
Total	0.3	0.1	1.1	0.7	2.3	47.6	95

3.2.2. Thermostat Setting

In this sample, the overall thermostat setting for the main living zone was said to be the same as the ER heating. This question was asked both in the installation interview and again at decommissioning. Table 8 summarizes the reported thermostat settings from both interviews.

Table 8. Reported Change in Thermostat

Thermostat change	N	%	Mean (Δ°F)
Down	9	9.68	-3.0
No change	65	69.89	0.0
Up	19	20.43	2.8
Total	93	100	0.3

In a few of these cases (20%), occupants reported thermostat changes that were larger than 3°F. Given the accuracy of line voltage thermostats, the reported change is probably within the error of the ER thermostats.

3.2.3. Cooling Use

About 45% 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 9 shows the distribution of cooling equipment reported by occupants when interviewed at the installation of the metering system. Approximately 55% of the occupants had no cooling equipment prior to the installation of the DHP. Only about 25% of the occupants in the western climates (the Willamette and Puget Sound clusters) had cooling equipment. In the eastern climates, on the other hand, cooling equipment is the norm, with almost 80% of those cases reporting window AC units.

Table 9. Cooling Equipment by Cluster

Cluster	None	Cooling	Total	% with Cooling
Willamette	18	9	27	33.3%
Puget Sound	21	4	25	16.0%
Inland Empire	2	15	17	88.2%
Boise/Twin	5	11	16	68.8%
Eastern Idaho	7	3	10	30.0%
Total	53	42	95	44.2%

3.2.4. Supplemental Fuel

Table 10 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. In this group, there was a 50% decline in the use of any supplemental wood heat in the period after the DHP installation.

Table 10. Percent Reporting Wood Use

Wood Use	Pre DHP	Post DHP
None	63.2%	84.2%
Occasional	27.4%	10.5%
Some Heating	5.3%	3.2%
Supplement	4.2%	2.1%
Total Cases	95	95

The amount of wood burned is very important. The wood use here is based on self-reported occupant surveys. Occupants may have reported wood use if they used only three fires per year, but that will not show up as a change to heating. There is a significant difference in the amount of wood burned in any of these categories that we are not able to quantify.

Table 11 shows the distribution of wood heat across the clusters. For simplicity, all categories of wood use are combined. The table shows a drop in the use of wood in all the clusters except the Inland Empire cluster (which is dominated by more rural residences).

Table 11. Percent Reporting Any Wood Heat

Cluster	Pre DHP	Post DHP	N
Willamette	44.4%	25.9%	27
Puget Sound	40.0%	8.0%	25
Inland Empire	17.6%	17.6%	17
Boise/Twin	37.5%	12.5%	16
Eastern Idaho	40.0%	10.0%	10

3.2.5. Supplemental Heating (110V Space Heaters)

The metering system captured all of the 220V circuits used to power the baseboards or other zonal heaters in the home. The platform was not designed to measure plug-in 110V heaters. If there were significant 110V heaters mentioned during the second occupant interview (conducted at the decommissioning of the instruments), the temperature-based regression on the residual was added to the total space-heating calculation along with the DHP and the 220V ER circuits. At other sites, where some auxiliary heat was clearly observable (e.g., in an adjacent workshop) and the results of this VBDD assessment showed a significant seasonal variation, we assumed that this variation was attributed to space heating, even though it was not directly metered. Figure 3 illustrates this point. The occupant in this home uses only the DHP and low-voltage (120V) space heating. The meters captured only the DHP space heat, and the later analysis of the residual revealed the space heat from the low-voltage plug-in heaters.

Figure 3. Example of 120V Heat

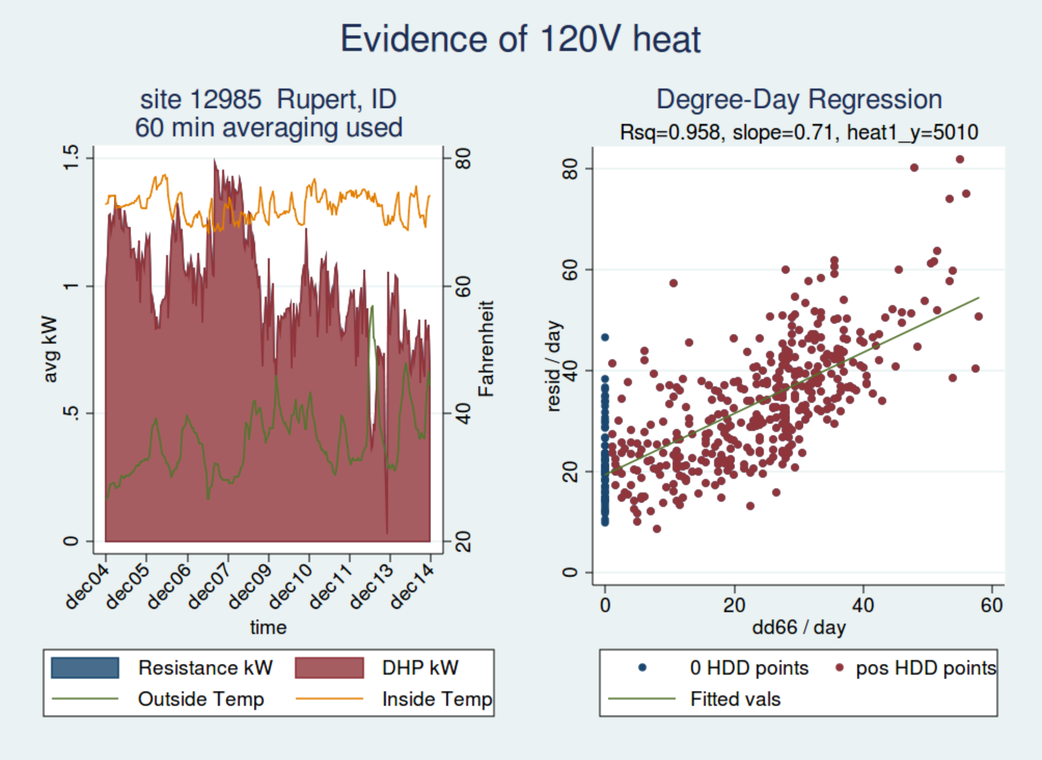


Table 12 shows the distribution of supplemental 110V electric heat across the individual sampling clusters. Because this question was asked only at decommissioning, the results should be interpreted as the actual use of this equipment during the metering period. As with the wood heat use, we do not always know the degree to which the occupants used the space heaters. Infrequent use of the heaters would typically not be detected in the residual analysis or the billing analysis.

Table 12. Use of 110V Space Heaters

Cluster	% 110V Heaters	N
Willamette	33.3%	24
Puget Sound	62.5%	24
Inland Empire	25.0%	16
Boise/Twin	37.5%	16
Eastern Idaho	37.5%	8
All Cases	37.5%	88

3.2.6. Large Loads and Outbuildings

The occupant questionnaire included such items as hot-tub spas, auxiliary shop, or other buildings that were on-site and on the meter but were not part of the house itself. These areas were generally thought to be heated, and in some cases, we were able to meter that heat separately from the rest of the heating circuit.

In all of these cases, we argue that the auxiliary heating or heating-like signatures are present in both the base and metering periods. Thus, the VBDD regressions capture that usage in the base period and, in order to get an accurate assessment of the total heating, they had to be included in the heating estimates for the metering period as well.

Table 13 shows the distribution of these loads across the sample clusters. The prevalence of well pumps in the eastern clusters is expected. The well pumps (and irrigation pumps) do not have an impact on the base heating load or the DHP savings estimates. Heated shops and spas often do have an impact on seasonal loads and thus on space heat estimates.

The "Other" category is a mixture of large loads. Many of these loads do not affect the seasonal evaluation of heating loads. These include seasonal swimming pools, irrigation pumps, continuous computer loads, etc. About two-thirds of these loads are similar to well pumps and have no impact on base space heat estimates.

Table 13. Large Loads (Percent All Participants)

Cluster	Well Pump	Shop	Spa	Other	All Cases
Willamette	7.4%	3.7%	11.1%	18.5%	33.3%
Puget Sound	4.0%	8.0%	8.0%	12.0%	20.0%
Inland Empire	23.5%	11.8%	23.5%	17.6%	52.9%
Boise/Twin	56.3%	37.5%	6.3%	18.8%	62.5%
Eastern Idaho	10.0%	10.0%	10.0%	0.0%	20.0%

4. Metered Findings and Observations

The metering instruments were designed to collect information at five-minute intervals so that 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 14 summarizes the space heating use by sampling cluster, indicated by kilowatt hours per year (kWh/yr). The striking feature of this summary is the size of the DHP use relative to the ER circuits.

Table 14. Metered Space Heating

	DHP (kWh/yr)		**ER (kWh/yr)**		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	2044	974	1767	1943	26
Puget Sound	1978	878	2400	1931	25
Inland Empire	2861	1284	3606	3402	16
Boise/Twin	3289	1463	4443	4110	15
Eastern Idaho	2260	938	7361	3716	10
Average/Total	2395	1186	3303	3291	92

As noted in Section 3, there were additional sources of electric zonal heat from plug-in 110V space heaters. In some cases, these sources contributed a significant amount of unmetered space heat during the monitoring period. These heat sources are not included in the Table 14 heating summaries.

4.1.1. Space Heating Residual

In addition to the heating circuits, the metering system recorded the DHW use and total electrical service to the home. This allowed a "residual" channel to be calculated by subtracting the DHW and combined heating (ER and DHP) channels from the total service drop. The "residual" includes the entire plug load, lighting, and other auxiliary loads in the home. This channel was then evaluated with the same VBDD procedure as the heating channels. In some cases, the residual displayed some seasonal slope. When this slope was large and well-determined, the seasonal portion of the "residual" load was treated as residual space heat.

Figure 4 and Figure 5 illustrate this point. In Figure 4, there is a substantial residual load that is almost completely the result of a heavily used spa/hot tub. The pattern of use is much more erratic than the pattern in Figure 5, where the occupants use plug-in 110V space heating as their only source of back-up heat. Thus, even though the residual has substantial scatter, there is a fairly strong relationship to temperature throughout the entire heating season.

Figure 4. Large Load Residual Load Pattern

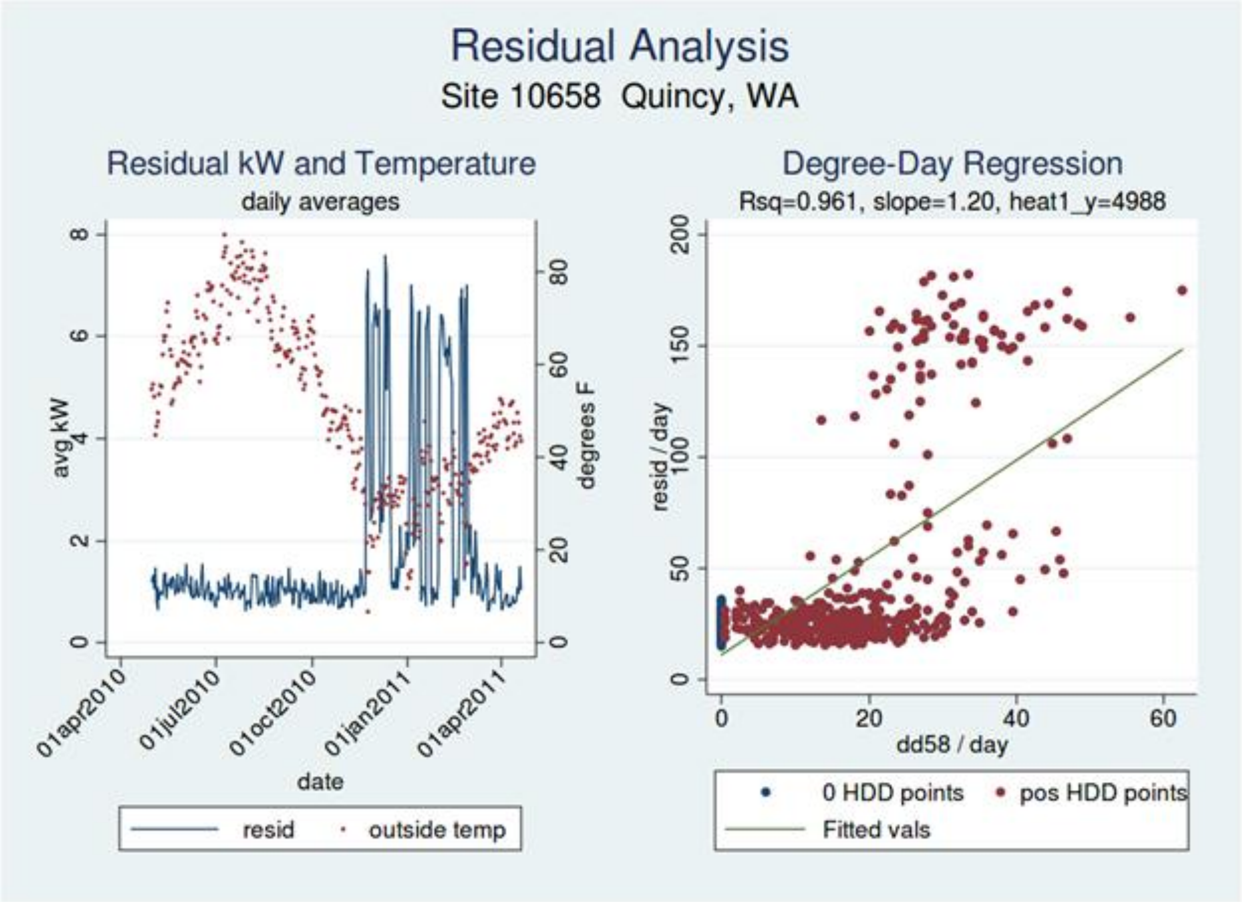
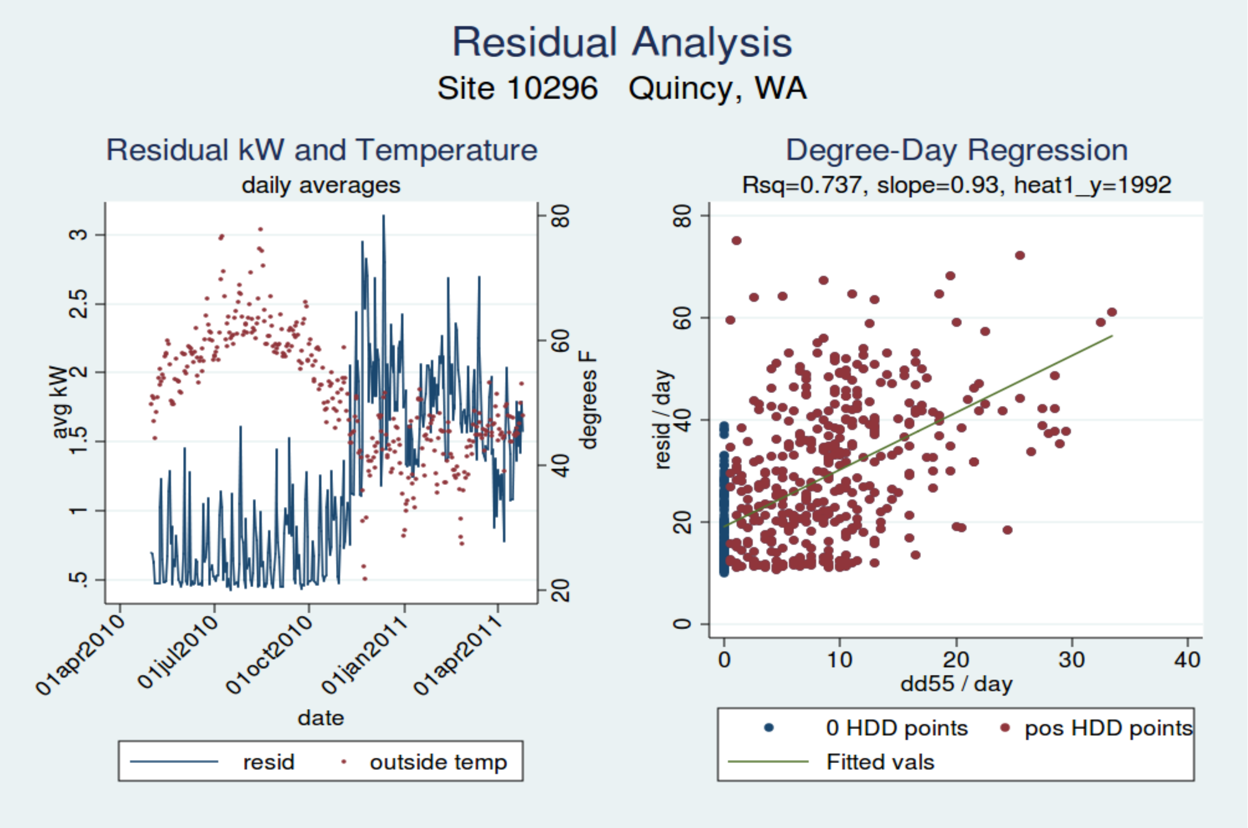


Figure 5. Low-Voltage Space Heating Residual Load Pattern



Both of these cases receive an adjustment to the metered heating to make it commensurate with pre-installation billing analysis. In the case of site 10296 (Figure 5), adjustment was to include actual space heat not captured in the meters. In the case of site 10658 (Figure 4), the spa usage was assumed to be present in the pre-installation heat estimate, and a correction was made to make it comparable to the metered heating.

There are 32 such homes among the metered sample. In this group, 75% mentioned that they used electric (110V) supplemental heat (see Figure 5). The remaining cases were generally traced to a shop, spa, or some other outbuilding (see Figure 4). The DHP savings and performance must take this usage into account because a load must be adjusted before the savings are calculated. Table 15 summarizes the residual for the 32 cases identified. Table 16 shows the impact of this calculation across the entire sample.

Table 15. Estimated Non-Metered Space Heat (kWh/yr)

Cluster	Mean	SD	N
Willamette	2459	1662	8
Puget Sound	1413	905	10
Inland Empire	4490	2584	3
Boise/Twin	2342	1501	8
Eastern Idaho	4031	3992	3
Total	2441	1955	32

Table 16. Average Non-Metered Space Heat Full Sample (kWh/yr)

Cluster	Mean	SD	N
Willamette	756	1453	26
Puget Sound	565	898	25
Inland Empire	842	2041	16
Boise/Twin	1171	1586	16
Eastern Idaho	1209	2708	10
Total	840	1627	93

4.2. Interior Temperature

During the metering period, the temperature pendant was placed in the central zone at about five feet above the floor. This pendant recorded the temperature hourly for the entire metering period. The results were downloaded during decommissioning, and the temperature record was synchronized with the remaining data collected and placed in the data record for each home. It is important to remember that this temperature record corresponds to the actual temperature in this space, but no temperature data are available from the pre-installation period.

The review of the temperature records across the entire sample shows a very low level of setback behavior during the heating season. In fact, only two homes showed day-to-night temperature differences during the heating season that exceeded 2°F. Figure 6 illustrates this pattern. In this case, the two sites are both located in Northern Idaho. Site 11362 became a wood heat site about two months after the metering was installed. As indicated by the yellow line, the temperature in this case varies 10°F or more largely as a function of the wood burning incidents. Site 13087, on the other hand, shows a more typical pattern where temperature varies only slightly on a daily basis, and then within a range of less than 5°F.

Figure 6. Temperature Records for Two Metered Sites

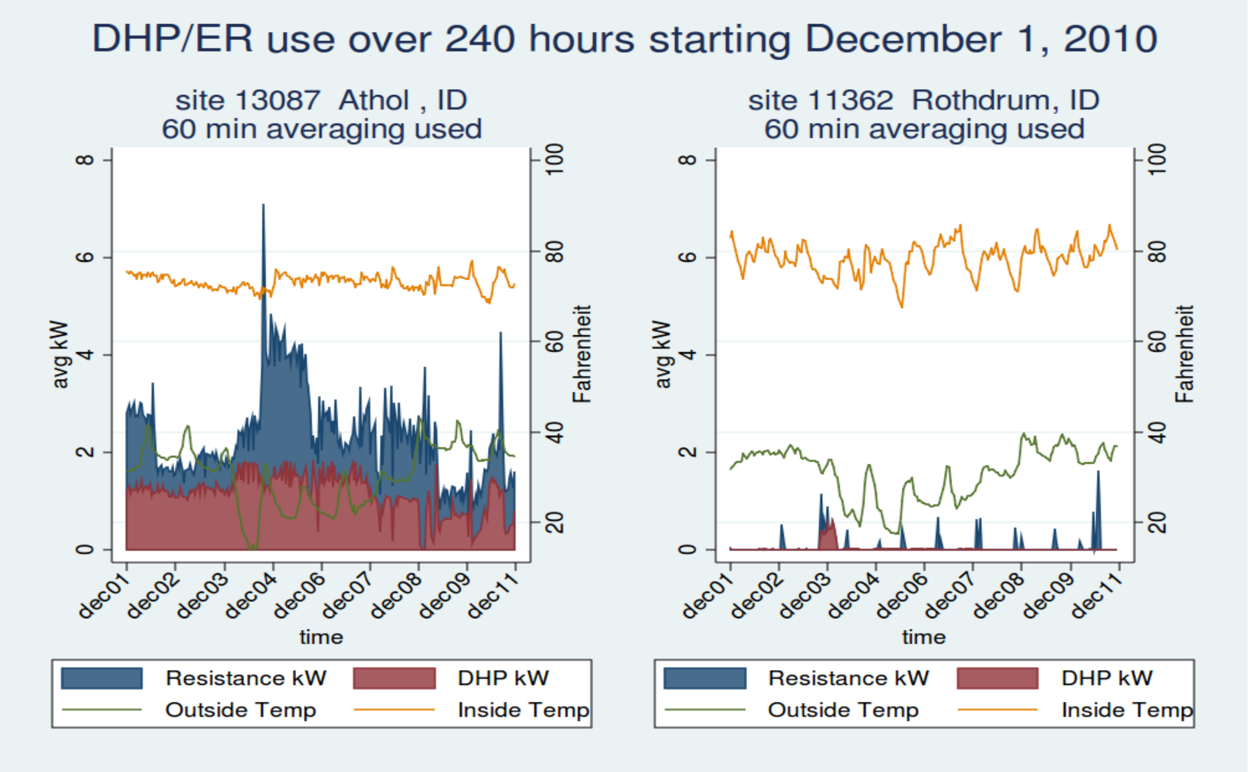


Table 17 shows the average temperature conditions during the winter season. These values were developed using the temperature record from November through February.

Table 17. Average Winter Temperature and Setback

	Average Day/Night Temperature		Average Temp.	
Cluster	Night	Day	Mean	**N**
Willamette	69.6	69.5	69.5	25
Puget Sound	69.0	69.1	69.1	23
Inland Empire	72.7	73.0	72.9	16
Boise/Twin	73.1	73.3	73.2	15
Eastern Idaho	69.9	70.4	70.2	8
Total	70.7	70.8	70.7	87

The error bound on these temperatures is about 0.75°F at 95%. As the table indicates, the pattern of these occupants is to arrive at a particular setpoint and maintain that throughout the heating season. We suspect that this partly results from the use of the line voltage thermostats that are typical of electric zonal heating.

4.3. 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 evaluation 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 18 summarizes the cooling energy used by the DHPs included in this sample. The table distinguishes between the climates of eastern Washington and Idaho (where summers are considerably warmer) from the climates of western Oregon and Washington, which are characterized by mild summer weather with occasional transients into warm temperatures that would suggest a cooling load.

Table 18. DHP Cooling Use

Cluster	**DHP Cooling Use (kWh/yr)** Mean	SD	**N**
Willamette	156	134	26
Puget Sound	72	76	25
Inland Empire	408	260	16
Boise/Twin	306	184	15
Eastern Idaho	211	208	10
Average/Total	208	204	92

The cooling energy use shown in Table 18 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 45% of the sample had pre-existing cooling equipment, mostly in the eastern clusters.

4.4. Domestic Hot Water Usage

The DHW usage in this sample was influenced substantially by the nature and occupancy of the homes. Occupancy in this sample is less than the average at about 2.3 occupants per home.[4] In only rare cases, there were families larger than four people. Moreover, more than 30% of all occupants are over 65 year of age, while only 19% of all occupants are under 18 (as noted in

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[4] According to the U.S. Census Bureau's American Housing Survey, the average single-family occupancy in the Northwest is 2.47 people per house.

Section 3 and Table 7). This reflects a consistent pattern in the pilot study for an older population.

Table 19 shows the hot water consumption metered in each of these homes.

Table 19. DHW Use by Occupant Total

Occupants	Metered DHW Use (kWh/yr)		Expected DHW Use based on Q_{HW} (kWh/yr)	Ratio	N
	Mean	SD			
1	1824	831	1793	1.02	17
2	3049	1005	2962	1.03	51
3	3201	1688	4131	0.77	14
4	4436	1067	5300	0.84	8
5+	6538	1375	7638	0.86	3
Average/Total	3080	1430	3276	0.97	93

When this usage is compared to the results of the metered analysis from the early 1990s (Roos & Baylon, 1993; Quaid et al., 1991) the overall results are about 3% lower consumption. This comparison uses the equation from Roos:

$$Q_{HW}=624+1169*Occ$$

Where Q_{HW} is the total DHW energy requirement and *Occ* is the total number of occupants in the home.

As can be seen, this is near the expected value for absolute consumption. We suspect that the demographics of this group actually elevate the per capita DHW consumption and thus over-estimate the total energy use from DHW relative to a more demographically representative sample.

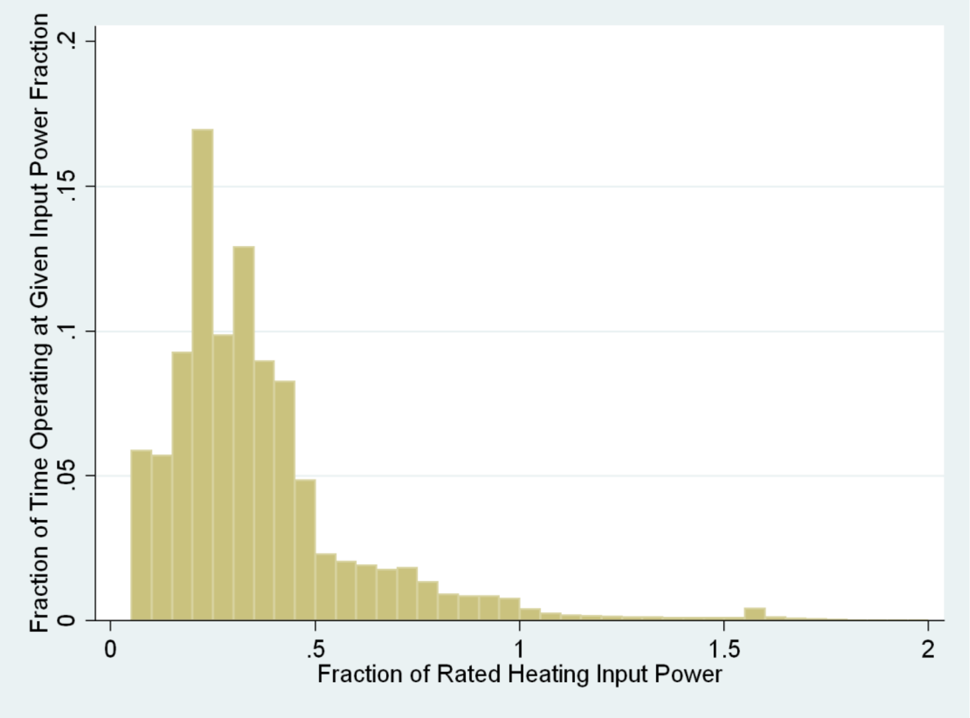
4.5. DHP Runtime, Output, and COP

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 surprising COPs well in excess of 4.0 during the warmer parts of the heating season and averages about 3.0 over the entire heating season, even in climates with very cold outdoor temperatures during much of the heating season.

4.5.1. DHP Runtime and Fractional Capacity

Another aspect of this technology during heating operation is that it tends to operate at 30% to 40% of rated capacity. Except during periods of defrost or sudden adjustments in the thermostat, the DHP operates at relatively low part load. The observed COPs are in part a result of this control strategy. Figure 7 summarizes the field data from 25 units with one indoor heat exchanger across the sample to demonstrate that, for the majority of hours of operation, the DHP is running at one-third of its rated input power.

Figure 7. Heating Part Load Operation for 25 Sites



When the performance of the DHP unit is examined in detail across the entire sample, it is clear that this equipment operates in part load conditions throughout the heating season. Table 20 shows the fraction of rated capacity that is developed by this equipment.

Table 20. Capacity Ratio, Selected Sites

Cluster	Average Capacity Ratio	SD	N
Willamette	0.26	0.08	19
Puget Sound	0.32	0.11	19
Inland Empire	0.21	0.06	11
Boise/Twin	0.36	0.12	8
Eastern Idaho	0.30	0.07	9
All Cases	0.29	0.10	66

The pilot program 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, 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 21 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. Briefly, 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 21 reflects the consistent operating pattern of the DHP installation: occupants tend to run the unit continually. 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 21. Annual Equipment Runtime by Mode

	Annual Runtime by Type and Mode (hours)				
Cluster	ER	DHP Heat	DHP Cool	DHP Fan	**N**
Willamette	1411	4354	494	1248	27
Puget Sound	1889	4603	259	1915	25
Inland Empire	2599	4402	768	1483	17
Boise/Twin	2844	4918	742	1519	16
Eastern Idaho	3718	4198	612	955	10
Average / Total	2234	4507	535	1481	95

Table 21 shows the striking difference in ER versus DHP heating runtime as well as the expected variation in heating system runtime between climates.

4.5.2. COP Metering Results

Figure 8 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 shows a typical operating pattern in cold conditions (between 0°F and 20°F).[5]

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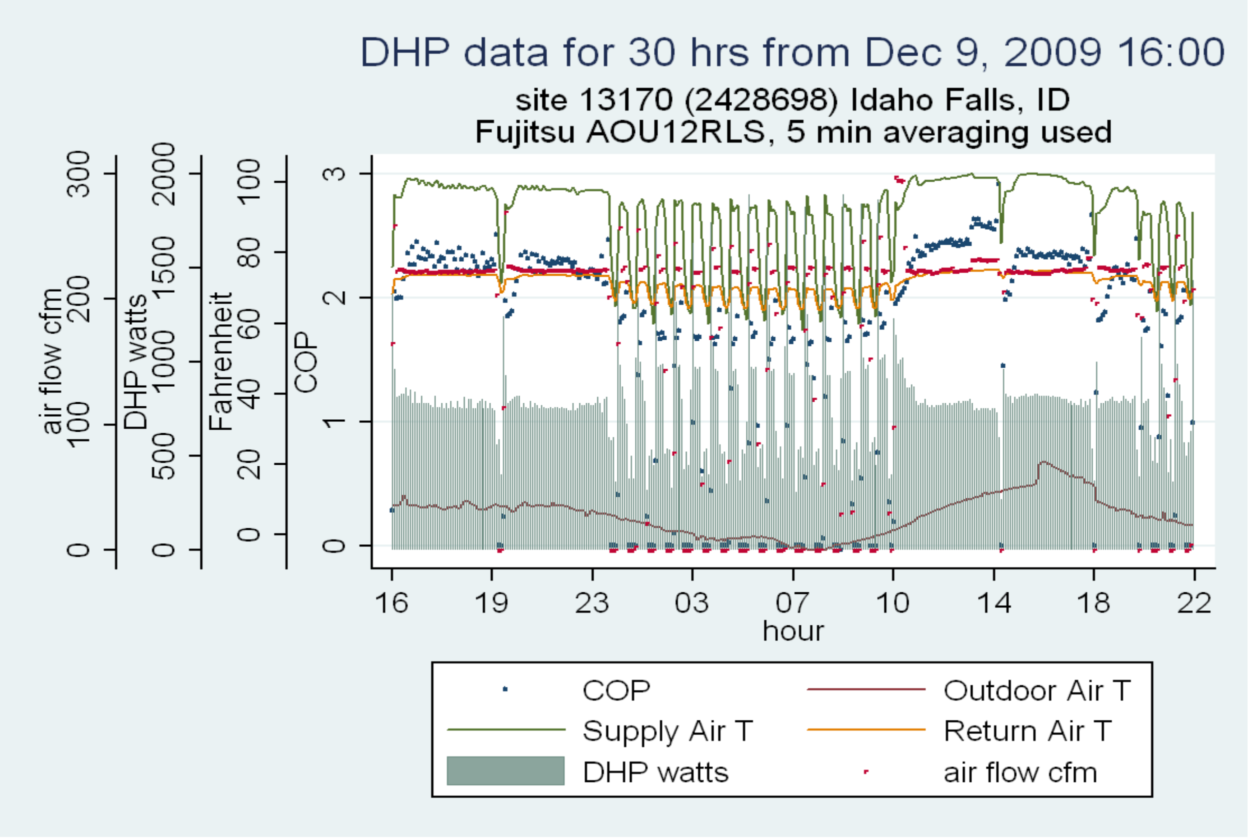
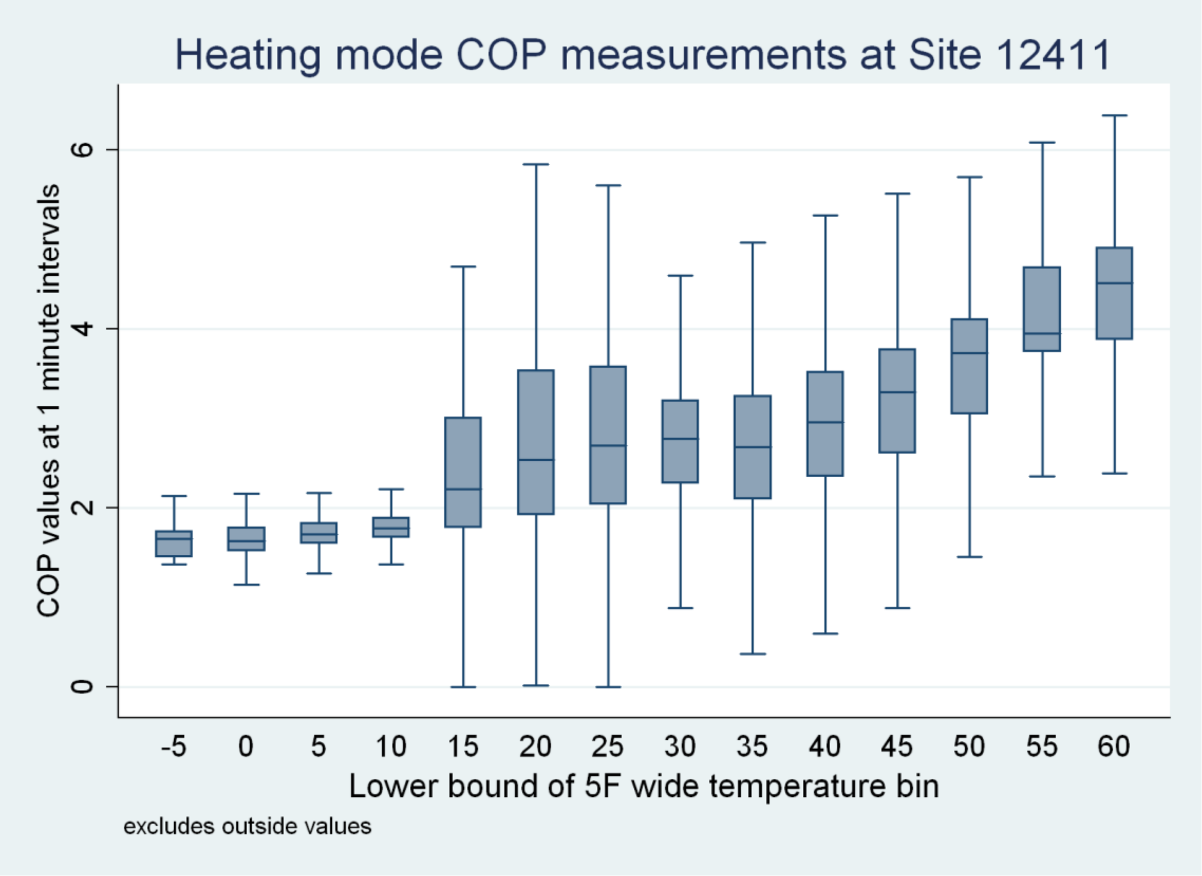
[5] The equipment runs in steady state most of the time with occasional defrost cycles. With the overnight temperature drop, there are about two defrost cycles per hour from hours 24 to 10. The fluctuation in power and airflow stoppage are the indicators that a defrost cycle is occurring. This equipment has a nominal rating of 16,000 Btu/hr with a nominal peak energy draw of 2.2 kW. Figure 8 indicates that even under these circumstances, the peak draw almost never uses the full capacity of the compressor, and, on average, the equipment is running at only about 40% of capacity. This control strategy seems to be held in common among all the DHPs tested in this pilot. One possible intent of this strategy is to maintain reserve in case of sudden changes in thermostat setpoint and to maintain control over the output temperature so that the equipment seldom emits cool output air (which might annoy the occupant).

Figure 8. DHP Performance at Low Temperatures



The COP measurements conducted on 35 of the metered homes allowed the development of an estimate of COP based on the data presented in Figure 8 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. Of all the houses metered, the data provided useable measurements at 23 sites spanning nine different equipment models. Ecotope carefully scrutinized the useable data to construct an *in-situ* performance curve for each equipment type. Figure 9 shows one such curve for a unit commonly found in the project. The figure uses box and whisker plots for COP measurements, with the middle line of each box representing the median value in that temperature bin; the top and bottom of each box are the 75th and 25th percentile values, respectively.

Figure 9. Heating Mode COP Measurements, Site 12411



To construct the COP maps, 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 is used for the map. 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.

In an earlier phase of this DHP Impact and Process Evaluation, two units were tested under a variety of laboratory test conditions (Larson et al., 2011). The tests spanned a range of compressor operating speeds in an effort to understand how the equipment might operate in the field. When the results of these tests were compared to field monitoring of COPs, the results were surprisingly consistent. Figure 10 shows this relationship for one of the pieces of equipment metered and the results of the lab testing on that same equipment.

Figure 10. Laboratory Testing Results Compared to Field COP Measurements

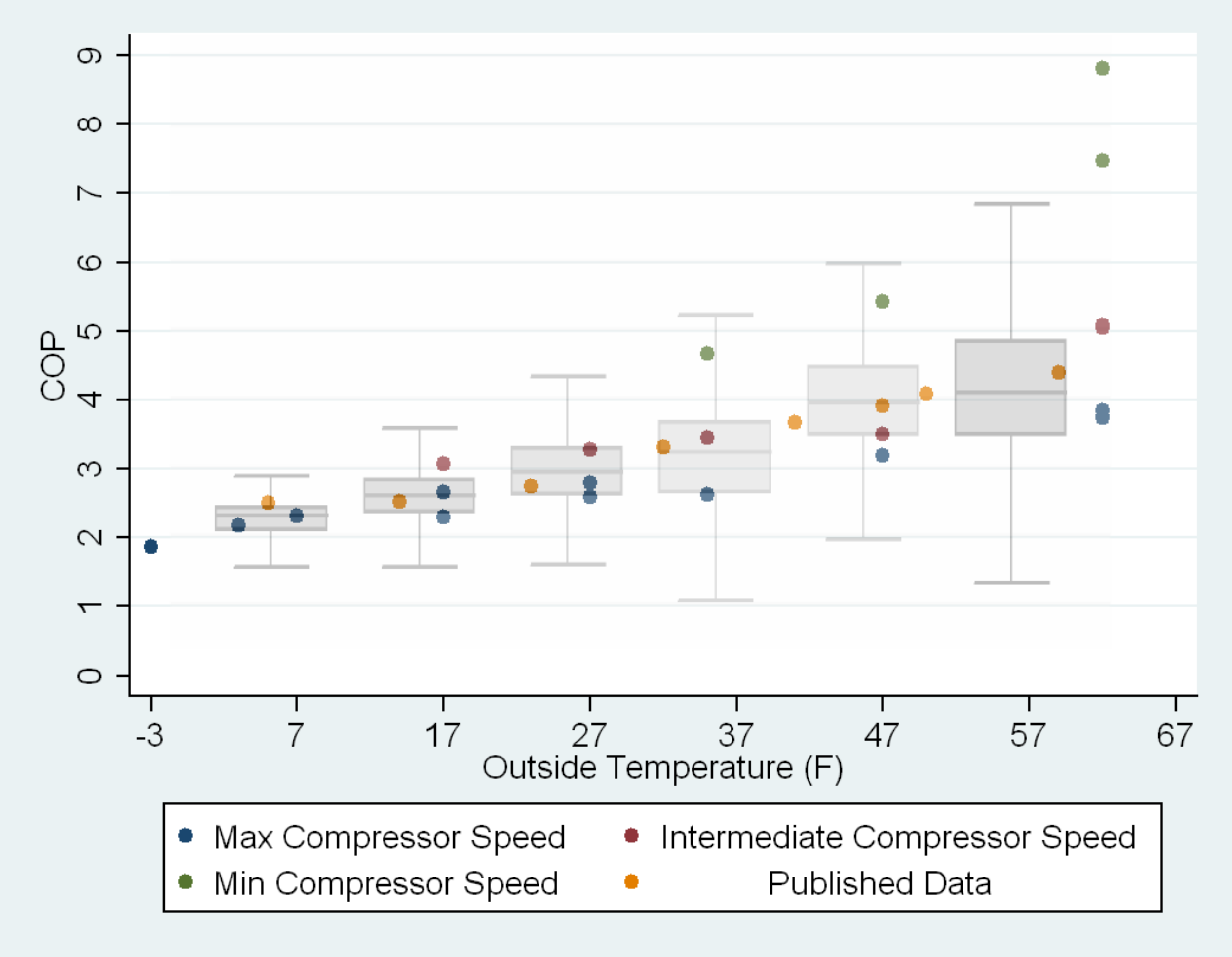


Table 22 shows the COP metering results for 23 sites that produced useable data over the course of the study. The table shows both the measured input energy (electrical input) and the measured output energy (house heating).

Table 22. DHP Heating Input and Output Energy for 23 Sites

	DHP Heating Input Energy (kWh/yr)		DHP Heating Output Energy (kWh/yr)		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	1943	776	6248	2319	6
Puget Sound	1569	590	4794	2950	5
Inland Empire	2590	1140	6454	2111	4
Boise/Twin	1637	682	4935	2125	2
Eastern Idaho	2297	1175	6380	3288	6
Average / Total	2040	924	5888	2567	23

To more broadly inform the results, Ecotope expanded the use of the direct COP measurements. The nine unique COP maps by equipment type associate heating efficiency (and heating output) with the measured input power and outdoor temperature. All of the metered sites measured power and temperature that, using the COP maps, could be used to predict performance in cases where it was not directly measured. Sites were assigned a COP map in two types of instances: (1) if they used the exact equipment for which there was an existing map; and (2) if they matched the heating season performance factor (HSPF) and model line (but were a different size) of a known model. Due to difficulties in predicting performance of multiple indoor head systems, all 17 sites with two indoor air handlers were excluded from the analysis. The remaining sites not matched (nine in all) had equipment from manufacturers for which we did not have field measurements. In all, the field-based determination of COP was expanded from 23 sites to 69 sites with similar equipment characteristics.

Table 23 shows the results of the extended COP-based metering results for a total of 69 sites. The average energy input in Table 23 is lower than for the entire sample in Table 14 because the COP based analysis was restricted to units with only one indoor heat exchanger. The units with two indoor heat exchangers were somewhat more commonly installed in colder climates and larger houses, therefore meeting a larger heating load.

Table 23. DHP Heating Input and Output Energy for 69 Sites

	DHP Heating Input Energy (kWh/yr)		DHP Heating Output Energy (kWh/yr)		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	1876	962	6048	2872	20
Puget Sound	1823	708	5549	2570	20
Inland Empire	2492	1097	5637	2126	12
Boise/Twin	2256	1274	6440	3040	8
Eastern Idaho	2188	978	6112	2675	9
Average / Total	2052	969	5886	2602	69

Table 24 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.

Table 24. Average Heating COP, Seasonal

	Directly Metered Sites			Expanded Sites		
	COP			COP		
Cluster	Mean	SD	**N**	Mean	SD	**N**
Willamette	3.40	0.28	6	3.40	0.32	20
Puget Sound	3.04	0.95	5	3.05	0.56	20
Inland Empire	2.64	0.38	4	2.41	0.59	12
Boise/Twin	3.01	0.05	2	2.96	0.30	8
Eastern Idaho	2.81	0.34	6	2.84	0.30	9
Average / Total	3.00	0.55	23	3.00	0.55	69

Table 24 indicates that there are significant differences between the colder zones and the warmer western zones. These differences probably account for the reduced COP in those climate clusters, but as the data indicate, the variation across sites in any of these climates is small by comparison to the natural variation. Only the Inland Empire cluster is significantly different. At least part of this effect is that there are some units in this population that are less efficient than the typical units in the remaining clusters.

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 put into the house. The fraction supplied by the DHP is then calculated by dividing DHP heat output by total house heat. Table 25 summarizes the observed fraction of the house heated by the DHP for each cluster. Table 26 summarizes similar information but for the Northwest Climate Heat Zones.[6] The nature of the measurement and analysis constrained us to estimating the heating fractions only for single-indoor units. The tables show a clear change in the heating fraction by climate zone. In addition, 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 three). 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 25. Fraction of House Heated by DHP by Cluster

Cluster	Mean	SD	N
Willamette	0.76	0.17	20
Puget Sound	0.71	0.17	20
Inland Empire	0.68	0.21	12
Boise/Twin	0.58	0.28	8
Eastern Idaho	0.45	0.18	9
Average/Total	0.67	0.22	69

Table 26. Fraction of House Heated by DHP by Heating Climate Zone

Heating Zone	Mean	SD	N
1	0.73	0.17	40
2	0.64	0.24	20
3	0.45	0.18	9

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[6] http://www.nwcouncil.org/rtf/**zones**/regional_hot.pdf

To understand how the fraction of home heating can change with climate, imagine the case of a house heated only with the DHP in the central living zone. In heating, the central zone will be at setpoint, but the outer zones will be at lower temperatures. As the outside temperature decreases, the outer zones will get colder while the central zone is maintained at setpoint. The DHP now has less influence on the peripheral zones, so they must be heated more often with the ER heaters in those zones. In the most extreme case, in cold climates, the DHP may not meet the load required of it for the central zone, in which case the ER heat in that main zone could be used to maintain the setpoint. In the field study, we observed this situation very infrequently. In a similar way, better-insulated houses could have a more uniform heat distribution and potentially more DHP heating than less well-insulated houses. Our sample was not sufficient, however, to allow any observation of this effect. Taken together, these effects lead to the differing DHP heating fractions.

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 output by 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 that 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 May 2011. In most cases, this record included bills from about 18 months. 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 include:

- 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 ending in May 2011.
- 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 and in most cases much longer.
- Results from the pre-installation period were then assembled into a base heating estimate against which the DHP saving 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.

For this analysis, two separate normalizations were done:

- Long-term average at the particular 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 27 shows the total and heating-only energy usage in the pre-installation period. This energy use was derived from the billing analysis for both the base period and the post-installation period. This is shown for each sampling cluster.

Table 27. Base Energy Use (Unadjusted Bills))

Cluster	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		N
	Mean	SD	Mean	SD	
Willamette	18759	6000	9052	3665	26
Puget Sound	16597	5579	9620	3300	25
Inland Empire	23945	7444	10566	4265	16
Boise/Twin	26453	9759	11737	3540	16
Eastern Idaho	23447	7173	14708	4443	10
Average/Total	20898	7842	10535	4053	93

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 27 was developed using the actual weather in the pre-installation period. Table 28 further adjusts this result to a "normal" weather year. For this analysis, 15 years of weather (ending in spring 2011) were averaged to arrive at a long-term normalized weather.

Table 28. Base Energy Use (Normalized Bills))

Cluster	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		N
	Mean	SD	Mean	SD	
Willamette	18757	6000	7815	3572	26
Puget Sound	17240	4659	8272	3099	25
Inland Empire	23945	7444	9208	3847	16
Boise/Twin	26453	9759	11075	3271	16
Eastern Idaho	23447	7173	13453	4197	10
Average/Total	21112	7606	9344	3897	93

The impacts of the DHP installation are calculated against the weather that was observed during the metering period as adjusted using the pre-installation heating estimates applied to that weather. This was done largely to account for the fact that the "heating bill" derived from the billing analysis is 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 metering period. Table 29 shows the base case space heating estimates as adjusted to the post-installation period.

Table 29. Base Heating Energy Use (Adjusted Bills)

	Heating Energy (kWh/yr)		
Cluster	Mean	SD	**N**
Willamette	7944	3531	26
Puget Sound	8234	3251	25
Inland Empire	9379	3881	16
Boise/Twin	11699	3464	16
Eastern Idaho	13881	4300	10
Average/Total	9553	4051	93

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 metering period directly and does not depend on data from the pre-DHP 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. Second, because most sites did not have *in-situ* COP measurements, those maps, where appropriate, are assigned to the larger set of field sites. The third step is to sum the annual DHP input energy for a given site by a given set of outdoor temperature bins. The fourth 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 purpose. 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 30 shows the results of the energy-output-based procedure. As presented in Section 5.4, 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 about 27.5% of 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 30. Total Heating Savings

Cluster	Savings from COP (kWh/yr) Mean	SD	N
Willamette	4148	2061	18
Puget Sound	3812	1981	19
Inland Empire	3264	1470	11
Boise/Twin	4184	1871	8
Eastern Idaho	3924	1767	9
Total	3887	1844	65

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, individual, metered house.
- Calibrate all the simulations to the heating base (or pre-installation) case 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 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 plug-load audit, Ecotope used a formula based on house size and occupancy to calculate the internal heating gains for each house.[7] 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.[8]

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 baseline 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 95 houses. For a particular house, the setpoint is meant to represent the average temperature of all zones in the house.[9]

Using this adjustment approach, the SEEM simulation subsumes most of the occupant “take-back” effects even if they are not related to temperature. The calibration matches the SEEM

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

[8] TMY3 http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
For example, houses in Soap Lake, WA were simulated using the Ephrata, WA TMY3 data.

[9] 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.

output to the observed space heat, so the combination of loads, thermostat settings, and supplemental fuels are represented in this final calibrated result.

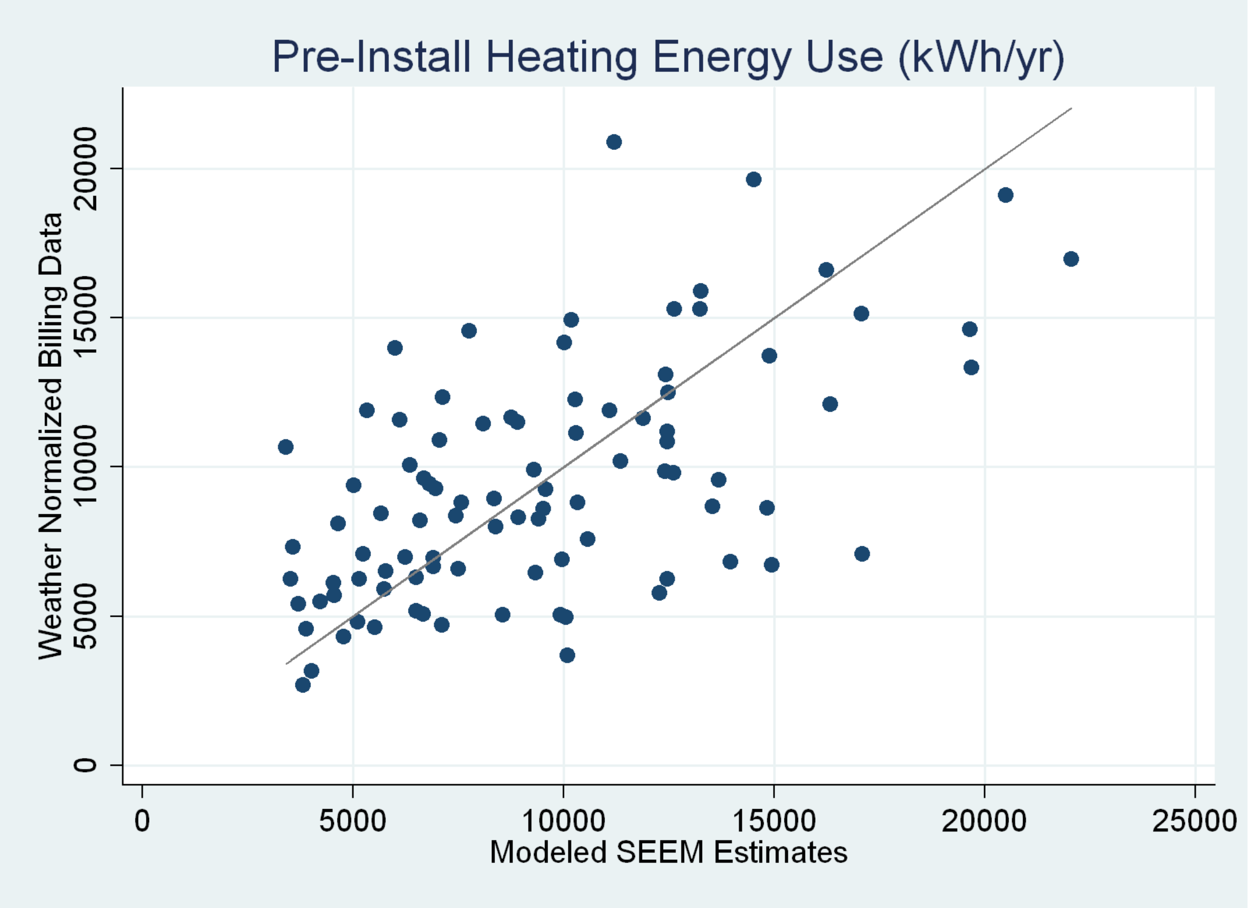
Ecotope ran the entire simulation data set at several setpoints and found the one that produced the heating energy use that most closely matched the pre-installation data. The best match setpoint was 66.8°F. Table 31 shows both the normalized pre-installation billing data heating energy use and the SEEM-predicted energy use. Note the close agreement of the overall mean to which the simulations were tuned.

Table 31. Base Heating Energy Use – Bills and SEEM (Weather-Normalized)

	Billing Data (kWh/yr)		**SEEM Estimates (kWh/yr)**		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	7923	3602	7591	3172	25
Puget Sound	8272	3099	7904	3453	25
Inland Empire	8932	3815	9030	2935	15
Boise/Twin	11075	3271	11763	4484	16
Eastern Idaho	13453	4197	13807	4296	10
Average/Total	9347	3892	9331	4135	91

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 clusters. Figure 11 plots the pre-installation billing data and the SEEM pre-installation prediction. The gray 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 11. 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. See Appendix D for more discussion.

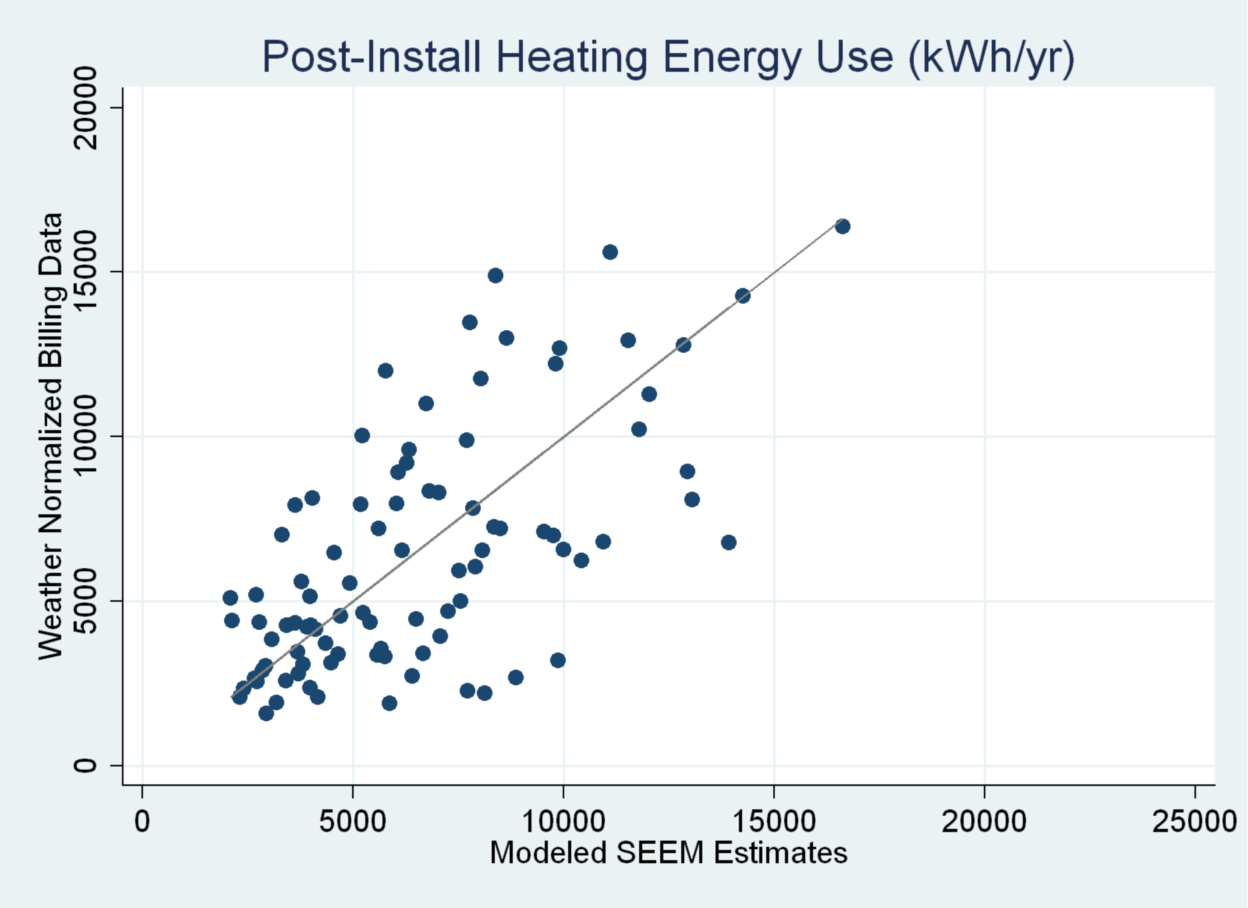
The simulations were conducted with three DHP performance levels and three house heating fractions. Ecotope divided the house simulations into three equipment performance categories based on the installed equipment HSPF rating over the ranges: 7.7–9.3, 9.4–11.3, and 11.4 or greater. Those categories were modeled with a heat pump approximating an HSPF of 8.5, 10.5, or 12 respectively. We assigned DHP house heating fractions by climate zone using the percentages found in Table 26.

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 32 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. Figure 12, like Figure 11, plots the post-installation DHP and ER metered energy use and the SEEM estimated energy use for each house. The gray line, again, shows the 1:1 line where the meters and simulation are equal. As with the pre-installation case, the graph shows lots of scatter and variation in usage patterns. Therefore, we chose to use the mean values of the simulations and predictions for comparison.

Table 32. Measured and Modeled Normalized Heating Energy Use

	Heating Energy Use (kWh/yr)		
Method	Mean	SD	**N**
Pre-Installation Billing Data	9347	3892	91
Pre-Installation SEEM 66.8°F Setpoint	9331	4135	91
Pre-Installation SEEM 69.5°F Setpoint	11181	4693	91
Post-Installation Metered Data	6484	3894	91
Post-Installation SEEM 66.8°F Setpoint	5428	2815	91
Post-Installation SEEM 69.5°F Setpoint	6466	3151	91

Figure 12. Post- Installation Energy Use – Meters vs. SEEM Estimates



As a way to verify the operation of the model, Table 33 shows the comparison between the annualized, measured COP on-site and the modeled COP by SEEM. The annual COPs show good agreement on average and for the Inland Empire, Boise, and Eastern Idaho clusters. The table shows that the simulation overestimates COPs for the Puget Sound cluster by as much as it underestimates them for the Willamette cluster. Overall, however, the agreement is good, suggesting that the simulation provides a reasonable model of field conditions.

Table 33. Measured and Modeled Annual COP

	SEEM Modeled COP		**Metered COP**		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	2.87	0.71	3.40	0.32	20
Puget Sound	3.49	0.46	3.05	0.56	20
Inland Empire	2.57	0.56	2.41	0.59	12
Boise/Twin	2.91	0.48	2.96	0.30	8
Eastern Idaho	2.88	0.37	2.84	0.30	9
Average/Total	3.00	0.63	3.00	0.55	69

For the houses in this study, the simulation worked equally well for two indoor heat exchanger systems as it did for single heat exchangers. Only those houses with the single units (the vast majority of houses in the study) had the COP monitoring rig so it was only possible to calibrate the heating output of the simulations to those houses. The annualized COP summary in Table 33 shows the agreement between measured and modeled efficiency for the single indoor unit sites. When the simulation is extended to the houses with two indoor heat exchangers, the agreement is not quite as good, but the sample size is much smaller (see Section 3). Interestingly, the DHP house heating fraction appears to be similar between the one- and two-headed systems. Importantly, the houses with two exchangers have a larger floor area by over 20%. This suggests the second heat exchanger is used to cover that additional floor area and does not contribute to a higher percentage of the house heated by the DHP. Overall, if only one indoor unit was installed in these houses, the DHP heating fraction would actually decrease relative to the houses with less floor area. Further studies with larger sample sizes of multi-head units could explore this issue more completely.

The simulation results show the best match to the pre-installation bills and the post-installation meters for differing setpoints. 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 34 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 occupant's behavior in the post-installation period with the higher thermostat setpoint is assumed to be the baseline. The former case more closely approximates the heating output based savings measurements discussed in Section 5.2. Overall, the mean savings increases with each method by 800–1,000 kWh/yr based on the occupant's heating equipment usage patterns.

Table 34. Modeled Heating Energy Savings Estimates

	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)		
Cluster	Mean	SD	Mean	SD	Mean	SD	**N**
Willamette	2435	1227	3424	1480	4242	1801	27
Puget Sound	3073	1521	4015	1809	4998	2189	25
Inland Empire	2724	1485	3719	1754	4376	2056	17
Boise/Twin	3742	1695	4874	2007	5738	2316	16
Eastern Idaho	2618	948	3939	1283	4538	1467	10
Average/Total	2894	1460	3931	1732	4748	2047	95

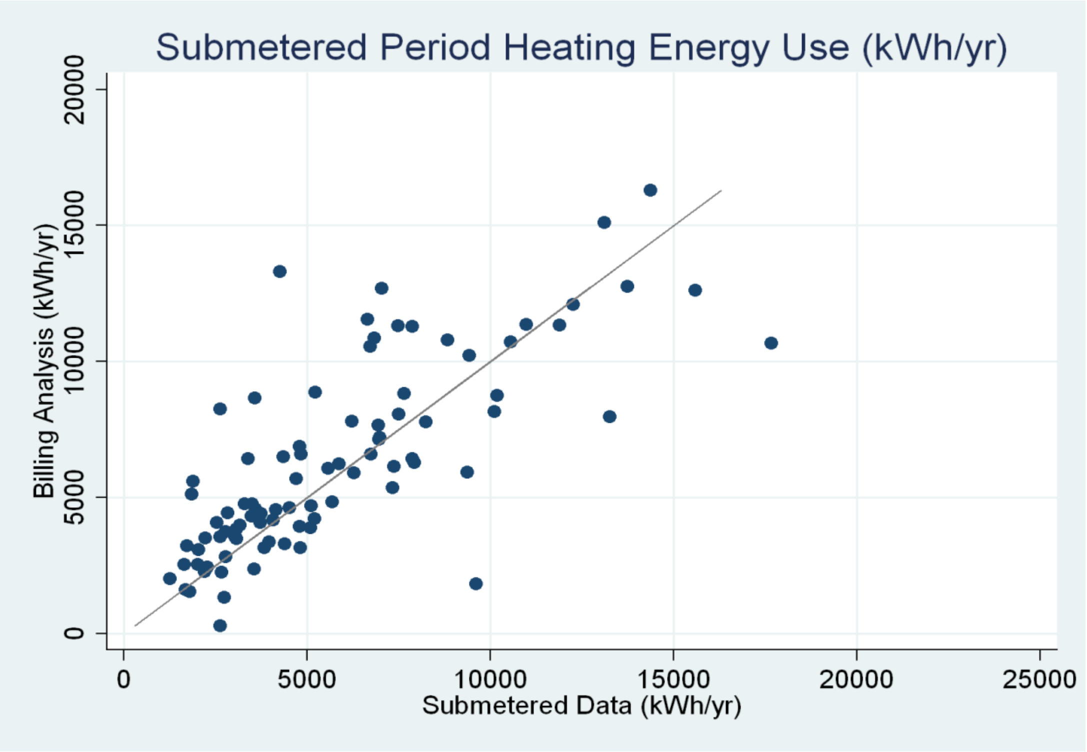
The "pre 69.5°F / post 69.5°F" scenario most closely resembles the heating output and COP-based savings estimate presented in Section 5.2. They are measurements or calculations of the heating system as the occupant is using it in the post-installation period.

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 that 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 old, an all-ER system would require an increase in consumption of approximately 1,850 kWh/yr. Thus, this modeling exercise is able to quantify the heating "take-back" 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 period. This was done to demonstrate that the relationship between measured space heat and space heat derived from a billing analysis for the same period was comparable. Figure 13 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 data sets.

Figure 13. 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 above in Section 5.1. 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 and Appendix A.

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 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 35 and Table 36 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 35. Billing Data and Heating Energy Estimation via VBDD (Unadjusted)

	Pre-Installation Period				Post-Installation Period				
	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		Total Energy (kWh/yr)		Heating Energy (kWh/yr)		
Cluster	Mean	SD	Mean	SD	Mean	SD	Mean	SD	**N**
Willamette	18759	6000	9052	3665	14880	5307	4738	2535	26
Puget Sound	16597	5579	9620	3300	13608	3843	5178	1956	25
Inland Empire	23945	7444	10566	4265	21820	7130	7484	3920	16
Boise/Twin	26453	9759	11737	3540	22850	10014	8517	3291	16
Eastern Idaho	23447	7173	14708	4443	22094	6393	11952	2618	10
Average/Total	20898	7842	10535	4053	17879	7521	6755	3616	93

Table 36. Energy Savings Billing Data and Heating Energy (Unadjusted)

	Total Energy (kWh/yr)		Heating Energy (kWh/yr)		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	-3879	4728	-4314	4059	26
Puget Sound	-2989	3463	-4442	3070	25
Inland Empire	-2125	4196	-3082	2316	16
Boise/Twin	-3603	3825	-3221	3237	16
Eastern Idaho	-1353	3245	-2756	2777	10
Average/Total	-3019	4025	-3781	3275	93

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. In addition, we made an additional correction to the heating energy estimate to account for the seasonality of DHW energy use. Use patterns and colder incoming water temperatures in the winter than in the summer give a temperature-sensitive response to the DHW energy that often leads to an overestimated prediction of heating energy use. Through the use of the metered DHW channel in the metering period, it is possible to determine the temperature-sensitive signal and subtract it from both the pre- and post-installation periods. We assert that the DHW energy use is invariant across periods.

The use of the metered DHW data is a departure from standard billing analysis, which traditionally has access only to the monthly utility bills. The use of the metered DHW data in both the pre- and post-installation periods leads to a significant improvement in the VBDD estimate. This is necessary given that, in the metering period, we collect data specifically on heating equipment in the house, so for comparison purposes, it is important that the base case constitute only space heating energy sources. The heating energy estimate for the pre-installation period adjusted for DHW consumption and to post-installation period weather does just that.

Table 37 presents the adjusted energy uses from the billing data. Note that, as is expected, the total bills in the post-DHP period do not change from Table 35. Table 38 presents the change in energy for both bill totals and heating energy with the data adjusted to the post-installation period weather.

Table 37. Billing Data and Heating Energy Estimation via VBDD Adjusted to Post-Install Year and for DHW

	Pre-Installation Period				**Post-Installation Period**				
	Total Energy (kWh/yr)		**Heating Energy (kWh/yr)**		**Total Energy (kWh/yr)**		**Heating Energy (kWh/yr)**		
Cluster	Mean	SD	Mean	SD	Mean	SD	Mean	SD	**N**
Willamette	17818	5686	7944	3531	14880	5307	4262	2273	26
Puget Sound	15897	4946	8234	3251	13608	3843	4875	1888	25
Inland Empire	22609	7055	9379	3881	21820	7130	7101	3756	16
Boise/Twin	26068	9605	11699	3464	22850	10014	8303	3366	16
Eastern Idaho	23420	6615	13881	4300	22094	6393	11373	2479	10
Average/Total	20147	7574	9553	4051	17879	7521	6375	3523	93

Table 38. Energy Savings Billing Data and Heating Energy - Adjusted

	Total Energy (kWh/yr)		**Heating Energy (kWh/yr)**		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	-2938	4674	-3682	3896	26
Puget Sound	-2289	2718	-3360	3100	25
Inland Empire	-789	3867	-2278	1890	16
Boise/Twin	-3218	3841	-3396	3137	16
Eastern Idaho	-1326	2485	-2509	2682	10
Average/Total	-2269	3751	-3178	3130	93

In terms of the weather used, adjusting the bills to the post-installation period makes the most sense because that is the period that is also metered. 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 studies 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 39 presents the weather-normalized bills and heating energy. Table 40 presents the weather-normalized savings between the pre- and post-installation periods. Only the heating energy portion and 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). Note that the heating energy use does not differ drastically between the "adjusted" and "normalized" tables.

Table 39. Weather-Normalized Billing Data Heating Energy Estimation via VBDD

	Pre-Installation Period		**Post-Installation Period**		
	Heating Energy (kWh/yr)		**Heating Energy (kWh/yr)**		
Cluster	Mean	SD	Mean	SD	**N**
Willamette	8093	3635	4358	2350	26
Puget Sound	8272	3099	4957	1874	25
Inland Empire	9208	3847	6960	3719	16
Boise/Twin	11075	3271	7857	3299	16
Eastern Idaho	13453	4197	10987	2457	10
Average/Total	9422	3884	6282	3388	93

Table 40. Weather-Normalized Energy Savings for Billing Data Heating Energy Estimate

	Heating Energy (kWh/yr)		
Cluster	Mean	SD	**N**
Willamette	-3735	3914	26
Puget Sound	-3314	3015	25
Inland Empire	-2248	1855	16
Boise/Twin	-3218	2940	16
Eastern Idaho	-2465	2594	10
Average/Total	-3141	3076	93

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 41 shows the results of this comparison.

Table 41. Metered Savings Heating Only

Cluster	DHP Savings – Metered Results (kWh/yr)		N
	Mean	SD	
Willamette	4017	2582	25
Puget Sound	3857	3058	25
Inland Empire	2186	3084	16
Boise/Twin	4451	5464	16
Eastern Idaho	4260	3335	10
Average/Total	3757	3519	92

In the case of a pre- and post-DHP 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 about 20%. 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 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 residual energy use for seasonal signatures and a review of occupant survey responses to discern changes in occupancy. The most useful formulation was a "median low bill" technique developed as an alternative to VBDD (Kennedy, 1994). This approach used the deviation from the median low residual consumption from the four months of summer usage to establish a base residual use and calculated the increase from that level in the heating season to establish the impact of the seasonal heating loads embedded in the residual use. Other methods were also used including a VBDD fit to the residual and an attempt to adjust the baseline billing analysis from results of detailed evaluation of the metered residual behavior.

Because of the variety of space-heating estimates and estimating procedures used here, a variety of savings was estimated. These estimates are shown in Appendix E. Nine separate heating-savings estimates were made using various treatments of weather adjustment, residual space heating, 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 42 summarizes the final savings by individual cluster for the metered sample.

Table 42. Final Savings Calculations

Cluster	DHP Savings -- Final Adjustment (kWh/yr) Mean	DHP Savings -- Final Adjustment (kWh/yr) SD	N
Willamette	3316	2121	26
Puget Sound	3043	2357	25
Inland Empire	1882	1580	16
Boise/Twin	3628	2985	16
Eastern Idaho	3307	3230	10
Average/Total	3049	2424	93

Table 42 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 suggest that the impact of supplemental fuels and thermostat increases account for about 25% of the savings generated by the DHP.

5.4.3. Savings – Fraction of Total Heating

The final savings presented in Table 42 were evaluated against the base case heating estimates. This assessment will be used to compare to the single percentage savings used by the RTF. Table 42 shows a relatively uniform savings across all the climates reviewed in this study. The only exception here is the Inland Empire. Table 43 presents the savings as a fraction of the pre-installation space heating. In Table 43, the effect of climate is more apparent. The displacement model leads to this result in the colder climates unless there is the addition of a second indoor unit or a larger capacity compressor. Either change can add substantially to the unit cost.

Table 43. Space Heating Saving Fraction

Cluster	DHP Savings -- space heating savings ratio Mean	DHP Savings -- space heating savings ratio SD	N
Willamette	0.43	0.22	26
Puget Sound	0.34	0.20	25
Inland Empire	0.24	0.22	16
Boise/Twin	0.29	0.20	16
Eastern Idaho	0.22	0.22	10
Average/Total	0.33	0.22	93

6. Net Savings Approach and Analysis

The relationship between the savings observed in the metered sample and the characteristics of the occupants, the home, and the energy consumption provide the basis for understanding the savings from the DHP. Savings analysis for the DHP installation using the displacement model is complicated by various “take-backs” as well as by the need to interact with an existing heating system. To ascertain how these components of the system and the characteristics of the house interact, a multivariate analysis was developed using regression estimating procedures. The goal of this analysis was to establish the determinants of the savings and the degree to which those determinants were predictive of the DHP performance.

The sample included an effort to minimize some of these interactions by screening potential participants based on the evidence of a strong electric space heat signal from the billing analysis done on the pre-installation electric bills. Although this effort did not completely eliminate the anomalies based on the use of wood or other supplemental fuels, it did ensure that a substantial fraction of the home’s space heating could be attributed to ER heating. The advantage of this approach is to provide insights on the determinants of consumption and savings from the DHP. The disadvantage is that numerous factors and interactions with supplemental fuels are observable in this group.

6.1. CDA/SAE Regression Analysis

Throughout this report, various characteristics of the individual participants have been shown. These characteristics such as house size, heat loss, and auxiliary loads all have an effect on the savings estimates calculated. Most of this analysis used a conditional demand analysis (CDA) to explore the relationship between observed or surveyed characteristics and the energy use or energy savings from the DHP installation. The general procedure was to create binary or dummy variables which took the value 0 or 1. These variables were then used as indicator variables that are placed in a regression. For this purpose, the t-statistic needed to be at least 1.64 (10% significance criteria) to be used in further analysis.

A more traditional regression analysis using continuous variables that could explain (and later be used to predict) the size of the savings observed was explored in parallel with the CDA analysis. This approach is generally called a “statistically adjusted engineering model” (SAE). Like the CDA, this approach can develop only limited statistical significance due to the small sample size. Ultimately, this DHP analysis combined the two methods to yield a regression specification that can provide effective explanation. Appendix F shows the results of this regression analysis. Overall, the regression model had a coefficient of determination (R^2) of about 0.36. This coefficient of determination was increased to 0.75 when the regression was specified without a constant term. Section 6.2 provides further explanation of savings determinants derived from this analysis. Table 44 summarizes the results of the regression fit on the savings predicted across the entire sample.

When compared to Table 42, the mean savings has been recovered within 1% but some variations between the observed savings in the Idaho clusters are apparent. This is likely due to the large number of multi-head systems in this group, which is under-predicted by the regression. The number of indoor air handlers was used in the original regression specification, but in this sample the coefficient did not meet the significance criteria. In this event, the one cluster where this specification is problematic is the Boise/Twin Falls cluster, where more than half of the installations include multiple indoor heat exchangers.

Table 44. Predicted DHP Savings

Cluster	DHP Savings – SAE Prediction (kWh/yr) Mean	DHP Savings – SAE Prediction (kWh/yr) SD	N
Willamette	3193	1507	26
Puget Sound	3265	1075	25
Inland Empire	2058	1257	16
Boise/Twin	2989	1352	16
Eastern Idaho	4051	1566	10
Average/Total	3074	1419	93

6.2. Savings Determinants

As shown in Section 5, there are numerous methods that yield savings estimates. The metered results and the billing results are comparable across the entire sample. Although this suggests the veracity of a billing analysis as a base for calculating savings, a true understanding of the energy savings delivered requires the introduction of additional elements. The challenge in this analysis is to separate the apparent savings derived from the billing analysis and the metered space heat from the savings that would have been predicted if the conditions in the home were held constant.

6.2.1. Regression Results

The regression results offer one set of estimates of the savings available from these installations. The regression recovers the mean of the original savings variable. The structure of this analysis is instructive, however. The regression analysis showed statistical significance for only four variables:

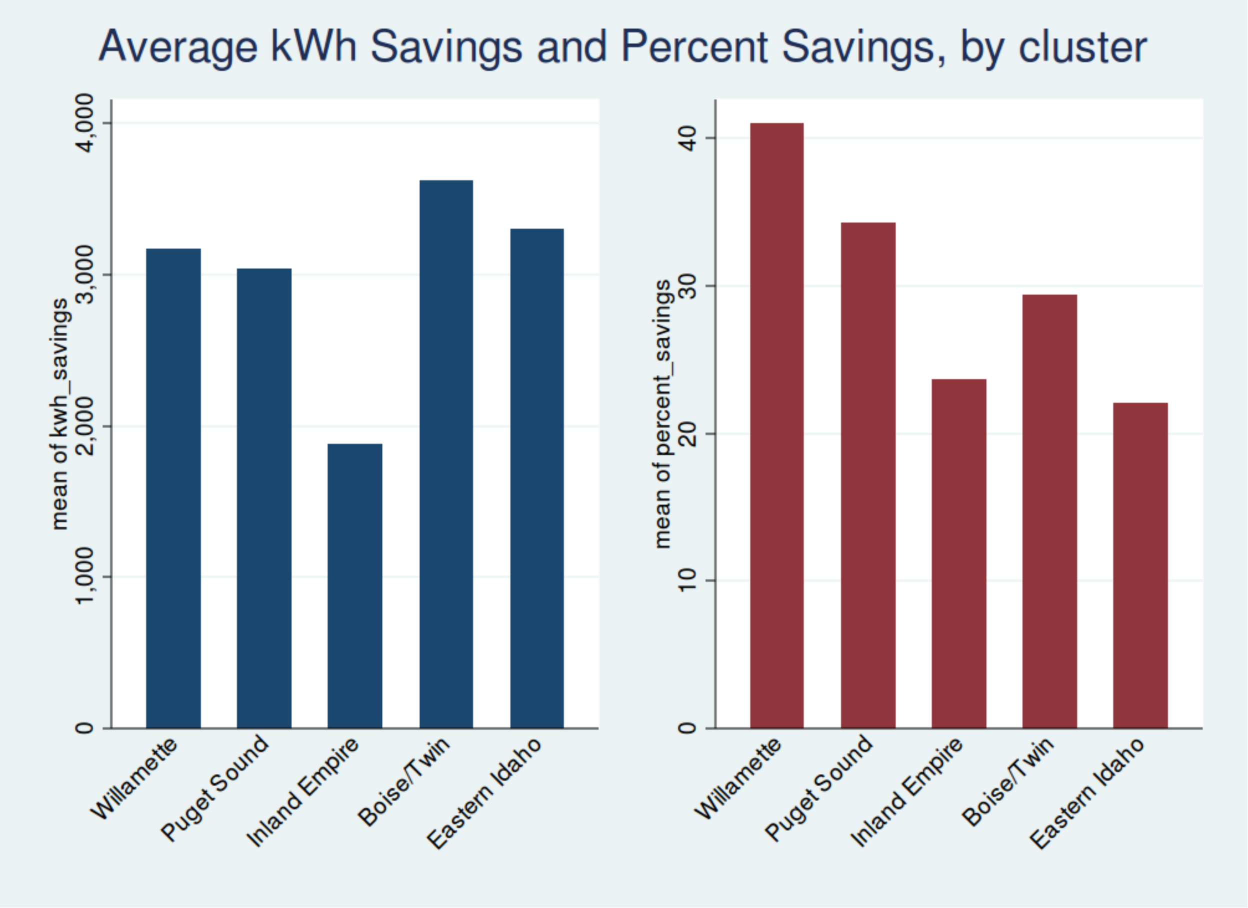
- **Pre-installation heating energy estimates:** This variable was derived from the billing analysis of the utility bills from the period before the installation of the DHP (see Section 5.1). The analysis showed a strong and significant relationship between estimated savings and this variable. The regression predicted that the DHP would save about 32% of the pre-installation space heat estimate. An equally significant finding was that when the regression was specified for the western climates (Puget Sound and the Willamette Valley) separately, the differences in saving percentages were apparent. In the western climates, the saving estimates were 47% of the initial space heat estimate, and in the eastern climates (Inland Empire, Boise/Twin Falls and Eastern Idaho), the percent saving fell to 24% of the space heat estimate. This finding suggests the nature of the displacement model, which tended to install a single DHP compressor and indoor heat exchanger regardless of the size of the peak heating load. In the colder eastern climates, this seemed to limit the savings fraction considerably. The impact on absolute savings, however, was less striking. When the regression was re-specified for the entire sample, the coefficient on the pre-installation heating use was about .32. This finding suggests that the underlying saving fraction across all climates in this sample is about 32%.

- **Climate:** As would be expected from the findings above, when climate is specified in an overall regression with all cases, the coefficient is also significant. The size of this coefficient suggests that there is about an 877-kWh reduction in absolute savings in the eastern climates.
- **Wood heat use:** The reported use of wood prior to the installation of the DHP has a positive influence on savings throughout the sample. It is important to remember that, in developing this sample, we carefully screened the participants to avoid wood heat as much as possible. When some wood was used, however, in the resulting sample those participants saved an additional 1,108 kWh each. This suggests that the wood heat itself was largely irrelevant but that the occupants were interested in offsetting their large space heating requirements and not particularly their small amount of wood burned sporadically through the heating season.
- **Indoor temperature:** The metering system included a temperature monitor that was placed in the space where the DHP was installed. Section 4.2 discusses these data. To use the temperature data in the regression, a variable was constructed such that the average temperature for the entire sample was subtracted from the average temperature for each case. This had the effect of normalizing the indoor temperature so that the coefficient could be expressed as a variation in temperature. The effect of this transformation was to make the coefficient reflect the impact of a single degree of temperature difference between the homes in the sample. In this analysis, the impact of a one-degree increase in temperature on the overall savings was a reduction of 125 kWh.

6.2.2. Climate and Capacity

With any conventional heating system, the heating capacity is designed to meet the loads imposed on the house by the efficiency of the building envelop and the severity of the climate. With the DHP displacement model used in this program, the link between the heating load and the equipment size was broken. This is reflected in the relatively similar absolute savings in each cluster but the ever-decreasing fractional savings. Figure 14 illustrates this effect.

Figure 14. Saving Compared to Savings Fraction



There has been substantial variation in savings due to climate when the savings ratio is reviewed. In the SAE model, the coefficient predicting the impact on the pre-existing space heating was significantly different between the milder climates in the western sample clusters and the eastern sample clusters, which stretched from the Columbia River to the Rocky Mountains. As a fraction of pre-existing space heating, the savings were 51% larger in the western climates. This is a very small sample, so the impact of the more rural areas could explain some of this difference. Overall, however, it seems clear that the eastern climates have a lower fractional impact on their space heat.

The size of the DHP installation was fairly similar in all regions. Because the capacity was not scaled to the climate, it is reasonable to expect that the savings fraction would go down. One mitigating feature of our sample is that the eastern zones had 76% of the units with multiple indoor heads. This feature leads to somewhat larger compressors and increased the house area covered directly by the DHP system.

The case of the Boise/Twin Falls cluster in Figure 14 is instructive. This cluster had the largest-capacity units installed and the largest number of multi-head units of any group in the metered sample. Indeed this pattern carries over into the entire pilot program. As a result, the saving percentages are higher compared to a similar climate in the Inland Empire cluster. In addition, these homes are larger than the homes in the other clusters, but even so the heating savings fraction is much larger than the other cooler eastern climates.

6.2.3. Occupant-Determined Savings

With all heating systems, the occupant determines many of the major components of consumption.

With the DHP systems in this program, the occupant has an added level of flexibility. In no case is the DHP a system designed to fully condition the home, and so the occupant can adjust the ratio of the DHP contribution to all other heating sources at will. It is apparent here that most occupants set the DHP at a particular temperature and allowed the rest of the heating system to operate as needed.

The other “supplemental” fuel is unmetered ER space heat. This source is used throughout the sample, but because of its portability and the convenience of using 110V outlets, they were not metered by the quad-metering system. In reality, these sources are in the base heating load (although we are unable to discern how much). Our savings calculations have taken it into account, but the overall effect of this bias appears to be about 20% of the estimated energy savings from the DHP.

Thermostat settings are said to be fairly constant. It is doubtful, however, that the temperature is exactly the same. At least one occupant commented that the DHP seemed to make the space warmer and more comfortable. One suspects that the line voltage thermostats that controlled the ER heat actually maintained a lower effective temperature and that the estimate of no change in thermostat setting, although true, may not actually reflect the actual temperature in the living area. It is apparent from the SEEM runs that at least one obvious calibration of SEEM output to observed performance is an increase of more than 2.7°F in the average indoor temperature. The regression coefficient suggests that a 2.7°F increase in temperature would result in a reduction of about 340 kWh/yr.

One goal of this study was to assess the impact of cooling consumption on the DHP heating savings. The metered sites in the western climates were largely without cooling prior to the installation. Many of these occupants commented on the cooling benefit as a major factor in their satisfaction with the DHP. Although this may have been a significant factor in the purchase of this equipment, it was not a major factor in the overall energy use of the DHP. Because we measured the cooling from the DHP separately, we can be certain of the amount of energy used for cooling under all circumstances.

Across all climate zones, this amounted to less than 10% of the total energy consumed by the DHP, and in the western zones (where there was very little existing cooling equipment), the size of the cooling load was less than 150 kWh/yr. In the eastern zones (except Idaho Falls) the saturation of pre-existing cooling equipment (and therefore cooling energy use) was 78%. Some or all of the cooling provided by the DHP served to offset cooling previously provided by window units or other zonal cooling. When compared to heating savings, even without accounting for the pre-existing cooling equipment, overall impacts are about 7%. Table 45 shows the relationship between cooling and heating savings. In the eastern clusters, the actual adjustment is much smaller or an improvement in overall heating savings.

Table 45. Cooling Energy Use

	DHP Energy Use (kWh/yr)		
Cluster	Heating Savings	Cooling Use	Ratio
Willamette	3316	154	0.05
Puget Sound	3043	72	0.02
Inland Empire	1882	428	0.23
Boise/Twin	3628	306	0.08
Eastern Idaho	3307	211	0.06
Total	3049	208	0.07

The case of the Inland Empire should be noted. This part of the sample showed the least saving of any group. Part of the large cooling fraction in this group is the result of the heating savings being half the size of the other Zone 2 sites in the Boise/Twin cluster. Even at that, this group used more cooling than any other cluster. The small sample size precludes further exploration of the anomalies of this portion of the sample.

Occupancy in the total sample is dominated by two-person households. The few cases with larger households did not seem to use the DHP differently. Indeed, those tended to be larger homes and were consistent with the pattern of fairly constant DHP use offsetting a somewhat higher heating bill.

The variations are further complicated when a third system is introduced (generally, a wood or pellet stove). Because the efforts to screen out such customers were largely successful, the ability of this sample to address the interaction between wood heat and a DHP is very limited and probably misleading.

6.2.4. Savings Comparisons

In principle, the results from the COP savings analysis (Table 30) could be considered the *ex ante* savings estimates.[10] This is because the COP analysis reflects all the heating benefit developed by the DHP in each home before the occupants took back some of these savings. In effect, by comparing Table 30 and Table 42, net-savings ratios can be calculated. Table 46 summarizes these net-savings ratios.

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[10] *Ex ante* savings estimates are the result of the initial prediction for the savings from a particular energy efficiency program or measure. In this case, the simulation is serving as the engineering analysis, although in practice such an estimate would be made using prototypical analysis applied to standardized climates.

Table 46. Net-Savings Ratios

Cluster	Savings (kWh/yr) Adjusted Net	Savings (kWh/yr) COP Total	Ratio
Willamette	3316	4148	0.80
Puget Sound	3043	3812	0.80
Inland Empire	1882	3264	0.58
Boise/Twin	3628	4184	0.87
Eastern Idaho	3307	3924	0.84
Total	3049	3887	0.78

There are several factors that contribute to these net-savings ratios. For the most part, these factors are determined by the particular conditions and decisions made by the occupants. There are several determinants of these results. During the installation of the metering system, and again during the decommissioning of the meters, the occupants were asked about the operation of their DHP as well as the general occupancy conditions of the home:

- **Thermostat setpoints:** In a zonal electric system, each room would typically have an independent thermostat. About 20% of the occupant interviews indicated that they had adjusted their thermostat. Unfortunately, the thermostat that controls the electric heat is a line voltage device that is notoriously inaccurate. Although the DHP thermostat is much more reliable, field technicians often heard from occupants that it was difficult to program. The interviews and the temperature records both confirm that these occupants did not generally use the setback capabilities in the DHP.
- **Supplemental fuels:** Occupants used supplemental fuels throughout the sample. The occupant interviews identified some amount of wood heating (usually described as minimal). Nevertheless, about 37% of all occupants reported the use of wood heat before the installations of the DHP. Interviews after the metering period indicated that the incidence of wood heat had fallen to about 15%. This should have had the effect of increasing the heating load in the homes. The results of the regression analysis, however, suggest that the presence of wood heat is not a cause for reduced savings from the DHP.
- **Large loads:** Some metered sites had outbuildings with seasonal (heating) loads that are not measured in the metered heating circuits but are included in the total energy use. In the uncorrected base case heating estimate obtained from billing analysis alone, these loads were included and undoubtedly biased the base heating estimate (in our project with the metering, we correct for the known large loads in the base case). The presence of large loads did not impact the CDA regression. Because it represented only about 11% of an already small sample, this is not surprising or conclusive.
- **Low-voltage space heating:** A feature of the metering design is that the 220V heating circuit is completely metered. In many cases, there are additional portable space heaters that are used to supplement the heating in the home. For this analysis, it was not possible to separate large seasonal loads and supplemental low-voltage space heating. These two loads are combined in the “residual adjustment” developed in Section 4. In the regression analysis, however, the presence of this sort of space heat was not statistically significant in predicting overall savings.

These loads have the effect of depressing the apparent savings from the DHP when compared to an engineering analysis. In the sample, the detailed metering allowed these biases to be corrected, but in a larger billing evaluation, the data would not be available to correct for these loads.

7. Conclusions and Recommendations

7.1. DHP Savings

Ecotope implemented two approaches to the development of final savings estimates for the DHP metered sample:

1. Savings related to the overall heat output of the DHP as measured by the metering. Using a temperature bin method, Ecotope extended the directly measured heat output at 23 sites to 69 total sites, a majority of houses in the study. The method uses the COP measurement, runtime, and equipment power draw in each bin to estimate a total, annual heating energy output.
2. Savings related to the change in space heat consumption between the pre-installation period and the observed metered heating. This approach is complicated by the uncertainty in the base case as a result of deriving the base heating load from billing analysis.

These two approaches yield different answers and have different implications to overall savings and the potential to assess the gross and net savings associated with the DHP installation.

7.1.1. Total Savings

The total impact of the DHP can be described in two ways. The first is to use the output of the DHP and assign the net energy produced as a benefit that would be available to the home. It is apparent that the occupants actually reduce this apparent energy benefit by using some amount of “take-back.” To establish the total savings, however, two methods were used:

- The total heating benefit was measured at several DHP installations and projected to like installations throughout the sample. This analysis used the actual runtime of the DHP as measured on-site and the measured heating COP to establish this impact.
- The SEEM model was developed to provide a calibrated estimate of the heating savings when the inputs were held constant. This took the form of calibrating the SEEM runs to a particular indoor temperature setting and holding that setting constant to establish the savings had the occupancy conditions remained constant.

Table 47 shows the comparison between the metered total savings and the SEEM-calculated total savings. The occupant has shared these savings with the utility by taking some of this increased heat output and improving the comfort of at least one zone in their home. For this reason, we have chosen to call the results of these data and calculation the “total” heating savings.

Table 47. Comparative Total Savings

Cluster	Savings from COP (kWh/yr)			Savings from SEEM (kWh/yr)		
	Mean	SD	N	Mean	SD	N
Willamette	4148	2061	18	3424	1480	27
Puget Sound	3812	1981	19	4015	1809	25
Inland Empire	3264	1470	11	3719	1754	17
Boise/Twin	4184	1871	8	4874	2007	16
Eastern Idaho	3924	1767	9	3939	1283	10
Average/Total	3887	1844	65	3931	1732	95

The analysis of total equipment saving was limited to sites where we had reliable COP measurement within the sample. We believe that this estimate is somewhat reduced by the fact that all the installations of multiple indoor units were not included because we had no reliable COP data from those types of installations. The SEEM saving estimates used a constant thermostat setting calibrated to the pre-installation condition and constant occupancy gains.

7.1.2. Net Savings

The net savings are the savings actually delivered by the DHP in the context of the heat pump performance and the occupant interaction and take-backs with that equipment. It is clear from this analysis that the impact of occupant take-back on overall heating performance was about 25% of the savings estimated from the total output of the DHP. The calculations of savings based on the actual heating load observed by the metering system took into account the ER zonal heating and the supplemental electric heating that the occupant may have used. About 30% of the sample used supplemental electric heat (usually portable heaters) that was not metered.

In this analysis, the other sources of seasonal load that could appear in the base case were also estimated. Net savings were derived from using two methods:

- A normalized billing analysis from both the pre-installation period and the post-installation period.
- An adjusted pre installation billing analysis and an evaluation of the metered data adjusted for residual space heat load.

Table 48 compares these two approaches. As the table indicates, the totals are essentially identical (within 3%). The variance in the savings estimate is large, particularly in the billing analysis.

Table 48. Weather-Normalized Net Savings

Cluster	Billing Analysis (kWh/yr)		Adj. Metered Result (kWh/yr)		N
	Mean	SD	Mean	SD	
Willamette	3735	3914	3316	2121	26
Puget Sound	3314	3015	3043	2357	25
Inland Empire	2248	1855	1882	1580	16
Boise/Twin	3218	2940	3628	2985	16
Eastern Idaho	2465	2594	3307	3230	10
Average/Total	3141	3076	3049	2424	93

7.1.3. Calibrated Simulation Savings

The SEEM program is a standard analysis tool used by the RTF to evaluate residential efficiency measures. To use this program for the DHP evaluation, Ecotope made some modifications to account for the operation and performance of the DHP systems. The calibrated runs suggest that the modifications to SEEM reflect the actual operation of the homes in this sample. The net savings estimates were about 5% lower than the values derived from the meters and billing directly. This savings estimate was based on an equivalent thermostat adjustment meant to account for the “take-backs” observed in the metered analysis.

Total savings, on the other hand, as shown in Table 47, compared quite well with the metered saving measures from the DHP runtime and performance. The total savings estimate was about 1% higher than the calculation from the observed equipment output. These two comparisons provide a good indication that the SEEM program can be used to assess the savings of a DHP installation program across the entire region.

7.2. Program Implications

The role of a detailed metered sample in the overall assessment of the DHP as a regional energy efficiency measure is to provide insights into interaction of this technology with occupants and home characteristics. The displacement model for the DHP pilot project leaves more of this interaction to chance (i.e., the occupant is able to reset the equipment, adjust the thermostat remotely, and change the load on the equipment through the use of the electric heating or a supplemental heating system).

In order to maximize the value of this detailed monitoring on the equipment, we took steps to obviate several variables. These actions included a substantial effort to reduce the effects of supplemental fuel (non-electric heat). As a result, the findings of this metering study have limits in their application to the overall savings observed in the 3,899 pilot installations. The results of the metering, however, do provide insights into the operation of the DHP system.

7.2.1. Supplemental Heat

The analysis shows that supplemental heat from other fuels has somewhat less of an impact on overall savings than was originally expected. Overall, supplemental heat has little or no impact on DHP savings *if the initial electric heat signature is strong*. This is true even in climates where there is only a moderate heating load. In this sample, the impact of the DHP seems to concentrate on the electric heating load and not on the supplemental fuel load.

This finding provides a fairly significant insight into how a utility program might screen to ensure appropriate savings levels. It is apparent that the important variable is not whether the particular household uses wood heat, but rather whether it uses electric heat and uses it at levels that are at least consistent with a thermostated space heating load. To implement this screen, the utility would need to only review the billing history and ensure an adequate seasonal heating estimate.

7.2.2. Thermostat Setting and Take-Back

There is a complex relationship with DHP thermostat settings and observed savings. It is apparent that under some conditions, occupant temperature adjustments can actually increase the apparent savings from an installation. When the DHP temperature settings go up, the DHP offsets ER loads in the outer zones more successfully, because the temperature differences that allow heat to transfer to these adjacent bedrooms or other zones is now warmer and, thus, more effective.

Nevertheless, the analysis strongly indicates that increased temperature results in lower savings. This is a small effect, but throughout the sample there is evidence that the occupants are opting for slightly higher temperatures once the DHP is installed. This phenomenon seems to have an effect on net savings of about 10% on average across the sample.

7.2.3. House Characteristics

The use of the displacement model is far less sensitive to the characteristics of the home than would be expected in a conventional heating system upgrade, such as a split-system heat pump or some other central heating system.

Because of the nature of the zonal heating, the zone where the DHP is located is more important than the particular heat loss characteristics of the building, at least within the limits of our current sample. The overall heat loss of the house and the overall size of the house all appear to have relatively little, if any, impact on savings delivered by the DHP system. For utility program design, this is a relatively important finding, because the utility may not need to be concerned about building characteristics in order to achieve the savings that are reviewed here.

Thus, a building that is relatively new, with high levels of insulation, is as likely to deliver the savings shown here as a building with low levels of insulation, as long as the other two conditions exist—namely, that there is an ER zonal heating system and that the home itself delivers a strong electric heating signature when the bills are reviewed. Indeed the one consistent home characteristic that explains most of the savings variance in this sample is the size of the electric heat estimate derived from the bills in the pre-installation period.

7.2.4. DHP Capacity and Multiple Indoor Units

The dominant installation in this sample, and in the pilot installations as a whole, is single outdoor compressors with a single indoor air handler (head). In this configuration, the savings observed did not change appreciably with increased capacity. It is apparent that in colder climates (especially in the Idaho clusters), the savings from the DHP was a lower fraction of the overall heating requirements than in the more mild climates.

In this sample, about 20% of the sites used multiple heads. Because of the limitation of the metering equipment, a few installations with more than two heads were screened out and not monitored. The majority of these cases were in the southern Idaho clusters. It is apparent from this group that the impact of multiple heads combined with added compressor capacity can have a significant impact of total savings.

The second head allows another zone to be conditioned. With extra capacity, this has the effect of better distributing the heat to outer zones. When outside temperatures are cold, the effect is to offset the load more effectively and reduce the time that the ER system operates. The effect of a second head seems to be less significant in the more mild climates, presumably because the heating loads in these outer zones are seldom significant so their offset does not result in an overall energy savings.

The extra head does add to the cost of the installation of the DHP system. Whether this extra cost is justified by the added performance will be assessed as the detailed cost/benefit analysis is developed in later stages of this DHP evaluation.

7.2.5. Secondary Observations and Findings

The primary determinants of savings of this equipment are mentioned above, but there are secondary issues that came up during the analysis that should be noted.

Occupant Acceptance

By and large, the occupant acceptance of this equipment is quite good. According to the decommissioning interviews, there is almost uniform acceptance and satisfaction with the DHP within the metered sample. This finding is consistent with the market progress evaluation report (MPER) interviews conducted earlier in this study (McRae et al., 2011). There are, of course, several cases where owners were quite dissatisfied. Those cases centered on mechanical issues with the equipment itself. These issues included installation issues such as mis-charging, out-of-specification line length, etc., as well as equipment deficiencies such as ineffective defrost control. It is clear that some of the installations in this sample had both lower-efficiency equipment and poorer installation. These seemed to be reflected in the savings observed.

Another complaint was that people in these homes were accustomed to radiant heating systems, and found the blowing of air to be distracting and uncomfortable. This was fairly rare but in a few cases the DHP unit seems to have been used less as a result of this problem.

A third complaint was that changing the filters was inconvenient and that a self-cleaning filter should be developed. We have no opinion about this, other than it is true that filter maintenance is important to the overall performance of this equipment, and in homes that have a large amount of particulates in the air, such as homes where smokers reside, the need to emphasize the maintenance of filters is very important.

Equipment Efficiency

The efficiency of DHP equipment varies, even within an individual manufacturer's product group. This is especially true in one case where the product line was upgraded in the midst of the pilot installations. However, the impact of the efficiency ratings on overall performance or overall savings seems to be less important than other factors. In other words, efficient units that can achieve COPs of 3.0 or more, even during part of the year, seem to be able to deliver consistent amounts of savings when compared to units that have more efficient HSPF ratings. The correlation between efficiency ratings and observed savings is tenuous at best. In a couple of cases, the installations had much lower HSPF ratings on average. Those cases did have reduced savings, but several factors such as supplemental fuels and larger heat loads were also present so the small sample size made any real inference impractical.

If the occupant is using the heat pump extensively and offsetting space heating during that time, it is likely that even moderately efficient units will deliver savings similar to the most high-efficiency models.

Fortunately, as models evolve, many of the main manufacturers are delivering ever-higher-efficiency compressors and control systems. Within limits, this should not be considered a major issue in assessing the individual manufacturers in the program. In a few cases, especially older units with HSPFs that are dramatically lower (less than 9.0) seem to have reduced performance. But this equipment is relatively rare in the metered sample. In general, we are impressed by the consistency of performance beyond the HSPF ratings.

Cooling

In no climate did the net cooling from the DHP exceed or even approach the levels of savings that were generated from the heating side. The implication of this analysis is that the cooling energy effect is sufficiently small that it can and should be ignored in calculating the net impact of this equipment. Only in a few climates did this appear to be inaccurate. In those climates, the impact of the DHP cooling probably increased (slightly) the net savings.

Moreover, in those climates where relatively large cooling loads were observed, there was, generally, some reason to believe that pre-existing cooling loads from relatively low-efficiency window AC units were the norm. In some cases, these units remain, but for the most part these units were not apparent at either installation (May 2009 to January 2010) or decommissioning (April and May 2011) of these meters.

The DHP offers a considerable improvement in efficiency and control over the window AC units. Although the amount of displacement of these inefficient cooling loads could not be quantified, the window AC units were largely abandoned by the time of the decommissioning interview, more than a year after the original installation.

To the extent that equipment with the efficiency of a DHP can be used for zonal cooling in any climate, utilities will be far better off than if cooling is left to more typical window AC units or portable AC units with COPs much lower than the typical cooling performance of the DHP systems.

7.3. Overall Conclusions and Next Steps

Overall, the impact of the metering on this sample suggests a successful technology when applied to buildings heated with zonal ER systems. The impact of the DHP displacement model appears to preserve the maximum amount of performance for the minimum amount of capital equipment. In most cases, there is equivalent performance between houses with larger multiple-zone systems and the smaller, single-zone systems typical in this sample. Therefore, it is our view that occupants should have the option of installing a larger system. However, the displacement model has proven to produce desirable savings numbers and is likely to be among the most cost-effective efficiency measures available to utility customers across the region.

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 program population as a whole. Therefore, the energy savings from a utility-sponsored conservation program designed to mimic this selection process would act to maximize the savings potential.

Upcoming DHP Impact and Process Evaluation reports, including billing analysis and cost-effectiveness analysis of the overall pilot project sample frame (3,899 participants), will build upon the field metering analysis included in this report. All analysis from the DHP evaluation will be integrated into a final report with a comprehensive summary of findings, conclusions, and recommendations. Findings from this review of the metered sample will be used to inform the billing analysis of the larger pilot program and the cost-effectiveness analysis.

8. References

Ecotope, Inc, 2010, Residential Ductless Mini-Split Heat Pump Retrofit Monitoring: 2008-2010 Analysis, Bonneville Power Administration, 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.

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

Geraghty, K. and D. Baylon, 2009, Residential Ductless Mini-Split Heat Pump Retrofit Monitoring, Bonneville Power Administration, Portland, OR.

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

Kennedy, M. 1994. Energy Exchanger Program: Heat Load Estimating Procedures. Ecotope, Inc. for Washington Water Power, Spokane, WA.

McRae, M, N. Harris, and A. Armstrong, 2011, Northwest Ductless Heat Pump Pilot Project: Market Progress Report #2, 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.

Quaid, M., R. Kunkle, and B. Lagerberg, 1991, RCDP Cycle II Appliance Analysis, Washington State Energy Office, Olympia, WA.

Roos, C. and D. Baylon, 1993. Non-Space Heating Electric Consumption in Manufactured Homes, RCDP Cycle II, Ecotope, Inc., Seattle, WA.

Appendix A – VBDD Methodology

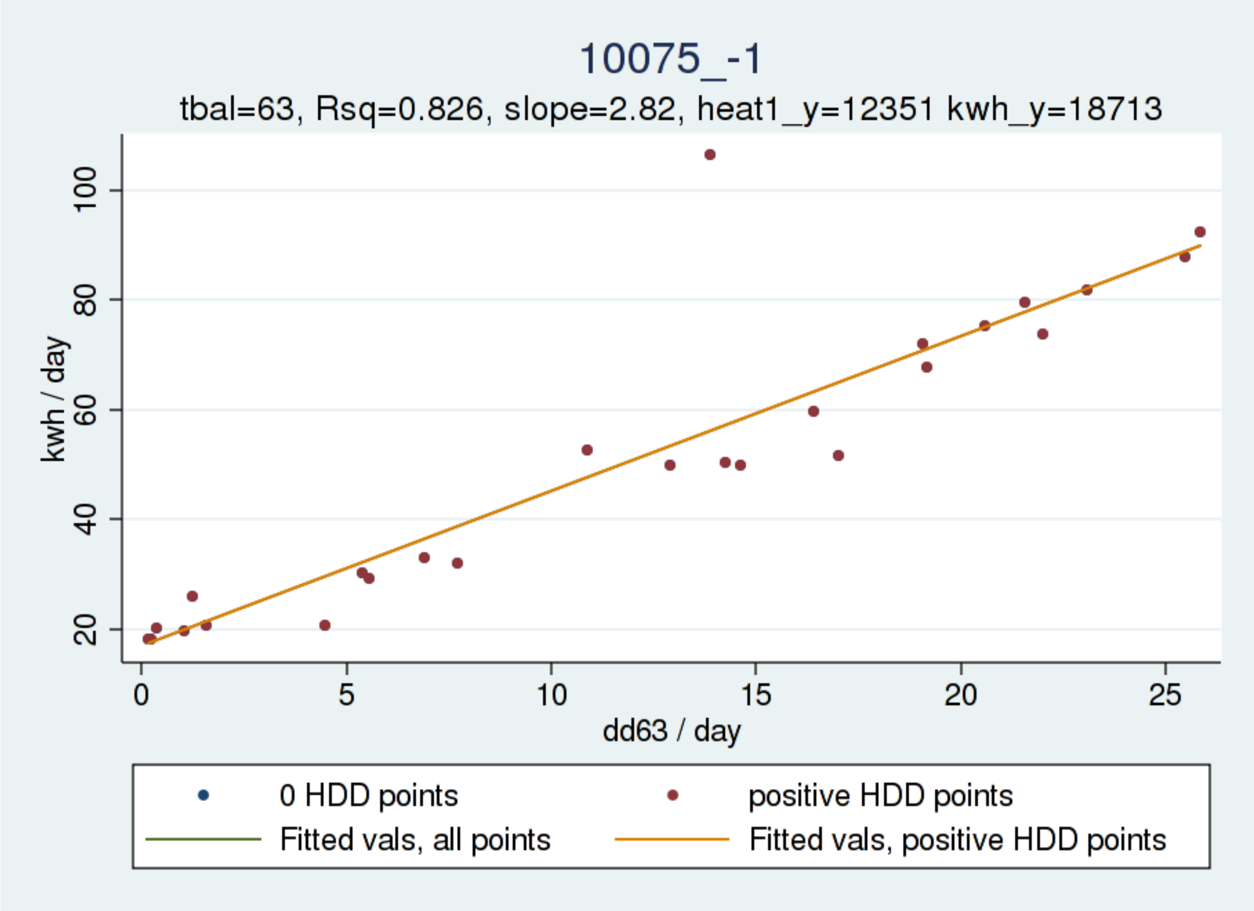
To put the "pre-installation" and "post-installation" periods (referring to installation of the ductless heat pumps [DHPs] for this study) on an equal weather footing, we fit standard variable-base degree-day (VBDD) regressions to the pre-installation metered bills for each of the sites for which we have at least 12 months of pre-installation bills. Where we had more than one year, the bills for all available months were included in the regression with the appropriate weather data. This step led to a more reliable fit to the temperature data and a better estimate of the heating energy before the DHP installation.

The VBDD regression methodology simultaneously estimates a house balance point (heating degree-day base), a slope coefficient of linear energy consumption response to heating degree-days, and a constant term that has an interpretation as unvarying monthly baseload (i.e., the sum of all non-space-conditioning loads such as water heat and appliances). The "balance point" refers to the coldest temperature at which no space heating is required. The regression estimates this value and uses it as part of estimating the overall space-heating load.

Figures A-1 and A-2 display typical scatter plots that illustrate this analysis. Site 10075 was analyzed comparing monthly kilowatt hours per day (kWh/day) consumption (generated from electric bills) against degree-days per day (generated from local weather station data for the pre-installation period) to balance point for that site (63°F). Two graphs are depicted, one using billing data from the pre- installation period (10075_-1; Figure A-1), and the second using data from the post-installation period (10075_1; Figure A-2). The ascending straight line is the fitted regression line that captures the response of monthly kWh to heating degree-days (HDDs). In fact, two separate lines are plotted for each graph, one with zero HDD months included, the other with them excluded. In this case, the exclusion has virtually no effect on the regression line, so the lines overlay one another and only one line is visible. Estimated coefficients and degree-day (DD) base (balance point) from these regressions provide a way to disaggregate billed consumption into heating (HDD-sensitive consumption) and "other." They also offer a way to predict heating consumption given the change in the weather data and a new set of temperature data. The regression coefficient of determination (R^2) for this site is typical of these homes and shows a good relationship between weather conditions and heating energy consumption. We applied the coefficients estimated using the pre-installation period data to the weather data experienced in the post-installation submetering period to estimate the hypothetical heating consumption that would have occurred in the post-installation period without the DHP installation.

The study regressed billing period consumption on billing period DDs using a slight modification of the standard VBDD method pioneered by Fels (1986). Under the Fels PRISM method, also known as VBDD regression, the HDD base and the regression response coefficient of energy consumption to DDs are jointly estimated by finding the HDD base that maximizes "goodness of fit" as measured by R^2. Using R^2 as a criterion effectively maximizes the proportion of total variation in consumption explained by a linear response to HDDs. In a single-zone structure (like a manufactured house) heated with an electric resistance (ER) furnace and a seasonally unvarying baseload, the linear coefficient has the interpretation of house U-value multiplied by area (UA), and the regression intercept has the interpretation as a seasonally constant average baseload not dependent on space heating demand. The DD base estimated by this procedure has an interpretation as the house balance point. Balance point is not thermostat setpoint, but rather is the lowest outside temperature at which the setpoint temperature can be maintained without space heating—where house internal and solar gains precisely match heat loss. Except in the special and implausible case where house internal and solar gains are zero, balance point is lower than thermostat setpoint. Although 65ºF is a plausible thermostat setpoint, it is not a reasonable balance point for the vast majority of houses. Varying solar gains and thermostat setpoint changes have the effect of changing the balance point, so that the actual heating input data (the bills) in fact reflect some random mix of effects of HDDs to different bases.[11]

Figure A-1. Typical VBDD Assessment, Pre-Installation



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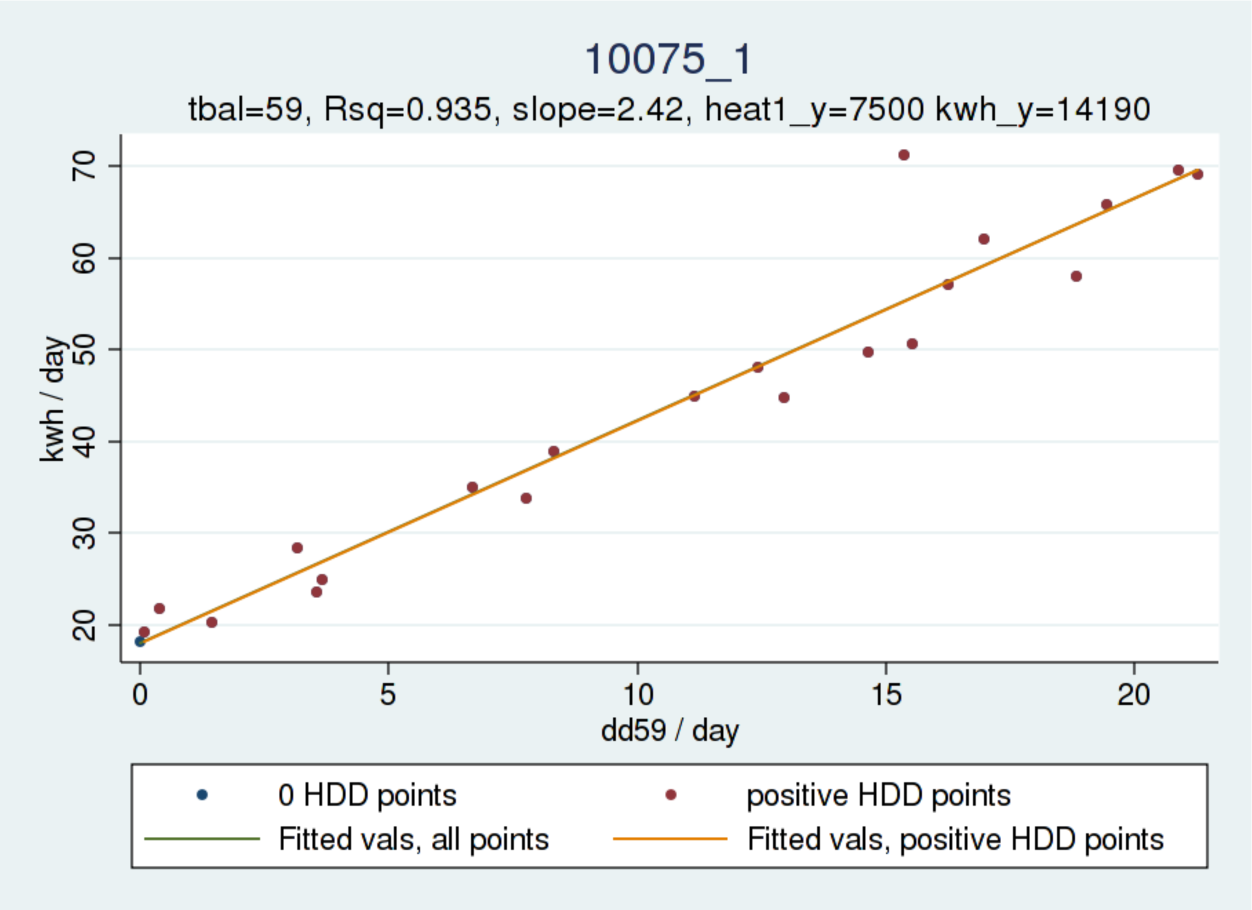
[11] Note: The U-value is thermal transmittance of a material, incorporating the thermal conductance of the structure along with heat transfer resulting from convection and radiation.

Figure A-2. Typical VBDD Assessment, Post-Installation



The “Ecotope modification” to the Fels PRISM procedure involves excluding data points from a regression estimation where the billing interval’s HDDs to that base are zero. Empirically, this serves to insulate the estimated HDD slope coefficient and constant from the influence of summertime cooling loads, which certainly exist for some of our sites.

Given a VBDD fitted regression coefficient and estimated balance point, a straightforward estimate of heating load for a given month is the product of the regression coefficient with HDD to that balance point base for that month. An accompanying estimate of annual non–heating-related base load is simply the fitted regression constant times 12 months. A problem with this simplest of approaches is that it is well established from submetered data that non–space-heat load components do have seasonal variation, notably electric light (with length of day) and hot water heat (with seasonally varying intake water temperature), and without adjustment these seasonally varying base load components are imputed to heating load. An adjustment method first proposed by Fels et al. (1986) is to fit a cosine function using the regression constant. Following the Fels approach, we adjust our heating estimate using a trigonometric function of the estimated regression “base load” constant α as follows:

Heat for month m = $Max(\beta \cdot HDD - \alpha \cdot (.1 + .1 \cdot \cos(2\pi m/12)),0)$

Where β is the estimated regression slope coefficient, *HDD* is calculated heating degree-days for month m to the chosen base, and α is the estimated regression constant. In effect, some of the seasonally varying load is taken away from the heating estimate $\beta \cdot HDD$ and given to the base load estimate α.

Given estimated coefficients, the above formula can be used to predict heat consumption given a new set of HDD data—not the HDD data which were used in the actual coefficient estimation. This is how we derive our estimates of the heating consumption that would have occurred in the post-installation period had the old heating system not been replaced by a DHP. The parameters estimated in the pre-installation period are applied to the post-installation period's HDD in the above formula. Although external temperature is one of our post-installation submetered data streams, and could optionally be used as a basis for post-installation period HDD calculation, we chose to continue with the same cooperative weather station temperature data stream that was used to estimate the pre-installation billing data regressions.

Appendix B – Detailed Discussion of Measurement and Data Delivery/Error Checking Procedures

This appendix describes aspects of a measurement plan used in an ongoing evaluation of ductless mini-split heat pumps (95 sites). The primary goals of the field monitoring are to characterize energy usage, ambient temperature, and main living space interior temperature. The main research question is to determine the amount of offset to straight electric resistance (ER) heating provided by the ductless heat pump (DHP) technology. Secondary goals are to measure non-heating usage in the home (hot water/base load) and to place heating usage (and cooling usage) into context as a function of house heat loss rate and house type. The datalogging system needs to be able to measure true root mean square (RMS) power and integrate properly to accumulate electricity consumption over at least one year's time.

Measurement Design

The measurement design incorporated four objectives:

1. Deliver heating system energy use once the DHP is installed. This was accomplished by metering the DHP and separately metering all the resistance loads in the zone electric heating system that was displaced (but not removed).
2. Meter the performance and operating patterns of the DHP as it relates to the various determinants of consumption for this type of equipment. This was done on about one-third of the sites (coefficient of performance [COP] evaluation).
3. Meter the domestic hot water (DHW) usage to help establish regional planning assumption based on submetering done in the early 1990s but not repeated. This required a submeter 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 had the effect of giving a sum check on the other meters and (with subtraction) allowed a picture of the miscellaneous electric loads in the home. Like the DHW, this load was submetered in the early 1990s and no similar data set had been accumulated since.

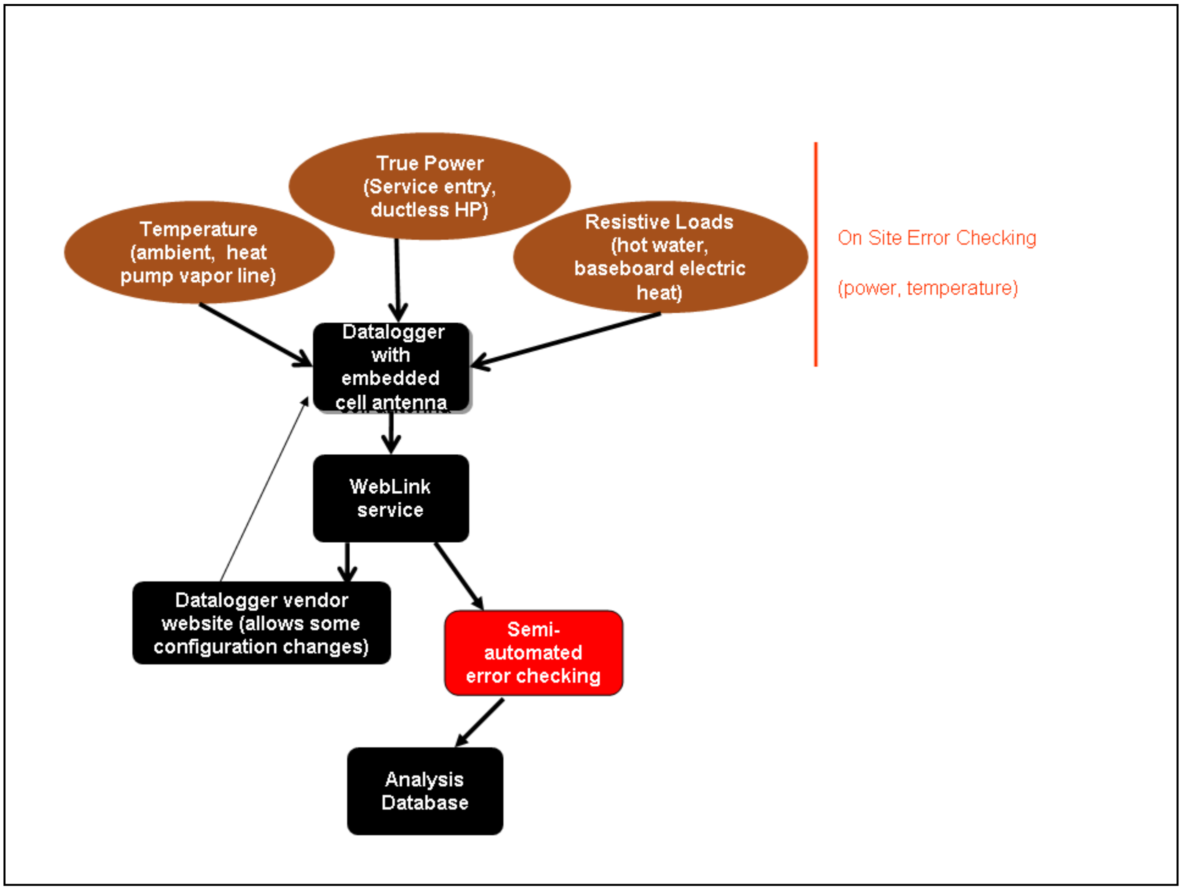
The metering approach designed to respond to these goals was called a quad-metering system. The DHP and house service loads were monitored with true power meters. The ER heaters and DHW tank were monitored with simple current transformers (CTs). Three temperatures were measured in the basic metering plan: outdoor ambient, indoor zone where the DHP was installed, and vapor line temperature at the heat pump itself.

Preliminary metering in a small pilot suggested that the cooling signal determination using only indoor temperature was very problematic, and the analyst was left to guess when cooling was occurring in the swing seasons of late spring and early autumn. The controls for the DHP equipment are very interactive, and it is possible for simultaneous cooling and heating to occur. Measuring the vapor line temperature allows the analyst to be sure when the unit is cooling and allows a direct accumulation of the total cooling load and the conditions where cooling is supplied while ER heat is also used.

Metering Equipment

To reliably measure whole-house electricity usage, hot water usage, and heating usage (including DHP) over a year's time, the metering equipment needed to be well-designed, durable, and weather-resistant. The hardware selected included industry-standard CTs, wired thermistors, watt transducers, and pulse counters. Details for two of the instruments used in the project are found in the references (Continental Control Systems, 2008; Onset Computer Corporation, 2008). The equipment was designed to be installed outdoors, if needed. Data were sampled every five seconds and averaged into five-minute averages. Storage was made into a solid-state datalogger equipped with internal global system for mobile communications (GSM)-type communication technology. Data were uploaded automatically every six hours to a web-based server. From this point, data were screened for anomalous readings through a custom automated process (described in detail below).

Figure B-1. Schematic of Data Collection Process



From the perspective of a year-to-several-years-long data gathering effort such as the one discussed in this paper, the principal advantage of near real-time data retrieval – as opposed to long-term accumulation onsite and one-time retrieval – is to provide an early-warning system for data production or quality problems, so that timely corrections or repairs can be made. With nearly 100 sites in the field producing data at five- or one-minute intervals (roughly an aggregate

300,000 data points per day), this early warning system needed to be highly automated in order not to overwhelm human monitors.

On-Site Error-Checking Procedure

Error checking is not delayed until after data have been recovered. At each field site, approximately 10 sensing elements (CTs, temperature sensors, etc.) were deployed to measure temperatures and electricity consumption. A field installation guide was developed in the early stages of field installation, and it covered most elements of the installation activities. Onsite 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 once data return from the datalogging vendor). Because the work was geographically dispersed, five different field installers (and six different electricians) were involved in installations. This meant that it was likely problems would occur despite careful attention to the installation protocol.

The most complicated part of the installation is the group of equipment that measures power usage by the house and DHP. After this hardware was installed and the datalogger initialized, the field installers were instructed to check apparent power readings against handheld measurements to determine reasonable equivalence. “Reasonable” means that, depending on which load was measured, the handheld measurement would not necessarily be exactly that of the datalogger, given the fact that the power factor was not always measured by the handheld device. Key to making this process less confusing was selection of the proper logging interval; with the combination of CTs (typically 50 amp for the DHP or 100 amp for the whole-house service) and a 30-second logging interval, the checkout math became very straightforward and helped minimize setup problems because the site installer could see quickly if datalogger measurements corresponded to the handheld measurements.

Temperature measurements were not monitored as closely. Partly this is because one of the measurements (heat pump vapor line temperature) is used as an indicator of mode of operation (heating or cooling); the actual temperature measured is less important than the divergence in temperature from ambient temperature. (That is, if the vapor line temperature is considerably above ambient temperature, the unit is in the heating mode; if the reverse is true – vapor line is very cold – the unit is in cooling mode.) This indicator is important as a delineator of heating/cooling energy usage.

This situation is different in about one-third of the sites. In these sites, the accuracy of the temperature measurements is critical, because it is directly tied to unit thermal output and accuracy. Unfortunately, no systematic checkout procedure was used at the time of installation (more attention being paid to the much more intricate device used to measure airflow), and we learned after reviewing data that one of the thermostats displayed nonlinear response (about 15% of sites). These sensors were replaced, but in some cases there had been months of delay. These are non-accumulation sites (meaning the total usage over a desired time interval is not the objective of the measurement), but focus on unit performance at different outdoor temperature bins; nevertheless, it would have been much better to have performed a careful checkout of sensors at installation. More discussion of this issue follows the main error-checking discussion.

Overview of Data Management

The datalogging vendor offered two interfaces for clients to gather and interact with site data remotely once they had been delivered to the web-server data warehouse: first, a website interface; and, second, a "web services" interface where our computers could directly retrieve data from the data warehouse using the Simple Object Access Protocol (SOAP) internet web services protocol (Onset Computer Corporation, 2009). We used the latter method.

The system we established 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 our site monitoring channels was total service power consumption, we were able to compare service consumption against the sum of submetered power consumption channels (usually ER, DHW, and DHP). The difference between the service load and the sum of these submetered loads, constituting lighting, kitchen appliances, and plug loads, should of course never be negative. In practice, this summing constraint proved to be one of the most useful ways of detecting data quality problems.

We checked each batch of new data for the expected time gap between successive observations (five minutes or one minute, depending on the site). We also took the opportunity to check the timeliness of the most recent data obtained in our retrieval request. Given that the site loggers call to transfer accumulated data to the warehouse every six hours, a "most recent time" significantly in excess of six hours indicates trouble. The daily retrieval and data-checking process took about two hours to run each night.

Error-Checking Details

As stated above, the automated error checking focused on both temperature and energy readings. A program was written that could search each site data file quickly and identify sites with anomalous readings.

Temperature error-checking was straightforward. Reasonable temperature ranges were assigned to the ambient (outdoor) and heat pump vapor line sensor channels; it was possible to look through what would eventually become several dozen sites to notice whether problems were occurring with these channels. It would be more accurate to say, however, that really only very high or very low temperatures would be identified as issues because the range of possible ambient temperatures was expected to be between -15ºF and 110ºF, and the range of possible vapor line temperatures was expected to be between 25ºF (cooling operation or defrost) and 150ºF (heating operation).

Checking electricity usage was more involved, but the basic concept is simple: compare all submetered usage with the total service entry usage over each logged period to make sure the sum of submetered usage does not exceed the service entry usage. In actuality, it would be impossible for this to happen unless there is a measurement or data collection problem.

Most of the data problems originate with the dataloggers themselves rather than the data transfer mechanism. Dataloggers are temperamental and not straightforward to install and configure correctly. Timely data retrieval and scrutiny are essential for detecting and attending to subtle configuration problems, and logger-originated data quality issues, such as data corrupted by electromagnetic interference, cannot be mitigated in all cases.

The dataloggers have a web-based remote management interface that permits the resolution of some problems without repeated site visits (e.g., mistaken data averaging intervals). At regularly scheduled data upload intervals, there is a window of opportunity to send configuration instructions to the datalogger, and to execute those instructions. In addition, problems that are essentially ones of interpretation (e.g., incorrect sensor serial number, incorrect pulse count multiplier applied to power consumption data) can also be corrected remotely. But there remain certain problems that can be addressed only with site visits. The following table summarizes important site interventions:

Table B-1. Site Interventions

Total sites	95
Datalogger replaced	8
Other critical interventions requiring a site visit	3
Important configuration issues resolved using remote interface	7
Other critical first-week data quality issues cleared up without site visit	6
Site visits to fix signal interference problems (desirable, not essential (in most cases))	23

It is apparent that without the feedback provided by timely data monitoring, about 20 of our 95 sites would not have produced useable data. Final data quality in the remaining sites also will benefit from the data-monitoring effort. The wide scope of signal interference problems, for example, was evident to us only because of automated data monitoring, and this in turn permitted us, in concert with the vendor, to develop a strategy to reduce signal interference in ongoing data collection. We think this adds up to a compelling case for a strategy of investing carefully in near real-time data monitoring, with its attendant expenses. Given all the costs of recruitment, equipment purchases, and installation, a site failure rate of over 20% is simply too high in most field monitoring situations.

There is a second important reason to develop such near-real-time monitoring machinery, and that is that it enables much faster learning and response to problems on the part of all participants, including both Ecotope and the datalogging vendor. It cannot be stressed too much that successfully executing a long-term datalogging program should be thought of as a process of adaptive learning. Ecotope's installation procedures and rates of problem site occurrence improved over the course of the project. Thanks to systematic data monitoring, we were able to bring a number of equipment problems to the vendor's attention rapidly and forcefully, which was useful to the vendor and for us. There is no ready-made template for large-scale projects of this sort. All participants need to adapt, and to learn, and a systematic and well-thought-out system for timely data monitoring and analysis allows that to occur.

Coefficient of Performance (COP) Measurements

As mentioned above, about one-third of the sites were used to estimate *in-situ* system efficiency (coefficient of performance, or COP). 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. (Output is converted from British thermal units per hour [Btu/hr] to kilowatts [kW] so that the numerator and denominator are in the same units). 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 Air-Conditioning, Heating, and Refrigeration Institute (AHRI)-rated performance, and also to inform a parallel analysis of utility bills (also used to determine savings from application of the ductless technology).

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. (This device accumulated pulses in a manner similar to that for the electric energy CTs/watt transducers. Different pulse rates could be compared with a one-time calibration to determine cubic feet per minute [CFM] of airflow.) The product of temperature split and airflow is thermal output in heating or cooling. Because energy usage/power of the DHP and outdoor temperature are also unknown, system COP can be calculated as a function of outdoor temperature bins.

Conclusion

Monitoring systems were installed in a total of 95 residences in three Northwest states over the course of eight months. Installations were completed by several installers and electricians, resulting in varying installation quality. Mistakes in configuration and data collection occurred and continued to occur over the remaining months, but a standardized review process has minimized data loss.

Critical elements of minimizing data loss are:

- Ability to keep track of the data streams as they are uploaded via automated processes from the datalogging company to local computers
- Understanding of reasonable data values in the data streams via error checking and graphical analysis
- Ability to quickly make simple changes in analysis problems (to process data that appear to be bad but that are merely a result of scaling factor problems, etc.)
- Quick response by field personnel to fix persistent field problems with sensors/dataloggers

It is critical to review the error file daily and flag problem sites for quick investigation. The site might be having problems, but apparent errors could be the result of internal software glitches, or could be short-term quasi-problems that are solved during the next data upload. On each end of the project, the personnel involved need to understand the equipment and be able to fix problems reliably and quickly.

What is an acceptable error level? The accuracy of one-time measurements depends on the technician’s experience, understanding of what is to be measured, and equipment calibration. For longer-term projects, with more moving parts and intermediate steps, some amount of data pollution and loss must be assumed. But having a way to ascertain there is a problem, and do it regularly, is crucial to minimizing data loss.

References

Continental Control Systems. 2008. WattNode Advanced Pulse Installation and Operation Manual. Revision 2.34, July 21, 2008.

Northwest Power and Conservation Council (NWPPC). 2010. 6th Northwest Power Plan (supporting data spreadsheet). Portland, OR. Pre-publication edition, February, 2010.

Onset Computer Corporation. 2008. Hobo U30 Station User’s Guide. Document D-12269-D.

Onset Computer Corporation. 2009. Hobolink Web Services Developer’s Guide. Document 12789-A.

Appendix C – On-site Audit Protocol

Name:	**Date:**
Address:	**Technician(s):**
Phone:	**Organization:**
Utility:	

Homeowner Acknowledgment:
I acknowledge that I have given permission for Ecotope, Inc. or its representative to test my heat pump system and house as part of the Northwest Energy Efficiency Alliance Ductless Heat Pump Project. Ecotope and its subcontractors are covered by $1 million professional liability insurance. Ecotope will repair or cause to be repaired any damage caused as the result of the testing.

_______________________________________ _____________
Homeowner signature Date

By signing below, I allow Ecotope, Inc. to request and use utility billing information to evaluate the energy performance of heat pumps. The information will be kept strictly confidential and only used for pooled summaries of results.

_______________________________________ _____________
Homeowner signature Date

Electric utility account #(if available):_________________

Account holder name (if different from above): _______________________________

House type:	Rambler 2 story Split level attached Garage Other (specify):	**Year house built**	
		Indicate major remodel details/dates (especially if weatherization occurred):	
		Location of DHP: LR DR FamRm Other:	

Homeowner interview:

How many people live here full-time? Adults (age 12 or over):_____Children (under 12):______

Does your house experience brownouts or other power problems? Y N
How many times/year?_________

How much wood do you burn in a typical winter?_________

What is your water heat fuel _______________________________________

Does the house have a LPG fireplace ____ or stove/oven _______ or dryer _____?
About how many gallons of LPG do you use per year?_______

Other auxiliary electric loads: well pump____ extra refrig/freeze ________ shop equipment ____
Spa/hot tub ______
Other____
*
Do you have a whole house ventilation system? ___yes ___no
If yes, what type: ____spot fan on timer ___other whole house fan ___AAHX other________________

Do you have any problems to report with your DHP heating system?

Which of the following types of improvements have you made to your home during the past year?

( ) refurbished the outside of your home
( ) updated your kitchen
( ) updated a bathroom
( ) added a room or more living space
( ) none of the above

Which of the following energy reduction measures did you make during the past year?

( ) added insulation
( ) installed more energy efficient windows or doors
( ) replaced an appliance or appliances with energy efficient appliances
( ) installed new energy efficient light bulbs
( ) caulked windows and doors
( ) installed solar panels
( ) other: ________________________________

Have you participated in any other energy-related programs in the last year, such as a home audit or incentives for an energy-efficient purchase? [If yes, describe] _______________________________
____

Before the DHP installation, approximately what temperature did you set:

The main living space _______°
The bedrooms ________°
Other spaces________________°
___________________________°
___________________________°
___________________________°

Since the DHP installation, approximately what temperature do you set:

The main living space _______°
The bedrooms ________°
Other spaces________________°
___________________________°
___________________________°
___________________________°

How many window air conditioner units do you have in your home, if any?
____________ # OF WINDOW AC UNITS
In the year prior to the DHP installation, in which months did you use your air conditioner? ____

Though you just recently installed your DHP, I'd like to know how your experience has been with DHP so far. Please rate your satisfaction of the following aspects using a 5-point scale, where 1= "very dissatisfied," 3= "neither dissatisfied nor satisfied," and 5= "very satisfied."

DHP	**1**	**2**	**3**	**4**	**5**	**DK**
More energy efficient than regular electric heat						
Indoor unit(s) is quiet						
Reducing your energy bill						
More comfortable than traditional electric heat						
Provides heating and air conditioning in a single unit						

Record house UA (no infiltration) here: ___________________Btu/ft^2 ºF

Record heated floor area here: _______________ ft^2

Record house volume here: _________ft^3

2-Point Blower Door Test

Depressurize to near 50 and 25 Pa with respect to outside. **Note the house pressure WRT outside doesn't have to be exactly 50 or 25 Pa; the actual values will be corrected to 50 Pa during analysis.**

Make and model of blower door used

____

Blower Door (BD) Depressurization Test Procedure:

1. *Close all windows and doors to the outside. Open all interior doors and supply registers.*
2. *Close all dampers and doors on wood stoves and fireplaces. Seal fireplace or woodstove as necessary to prevent ash disaster.*
3. ***Make sure furnace and water heater cannot come on during test. Put water heater and/or gas fireplace on "pilot" setting. Make sure all exhaust fans and clothes dryer are off. Make sure any other combustion appliances will not be backdrafted by the blower door**.*
4. ***Make sure doors to interior furnace cabinets are closed**. Also make sure crawlspace hatch is on, even if it is an outside access. Check attic hatch position. Put garage door in normal position.*
5. *Set fan to depressurize house. Run pressure tap out through door shroud.*
6. *Depressurize house to –50 Pa or thereabouts. Record house pressure, BD flow pressure, and BD ring (below). If you cannot reach –50 Pa, get as close as possible and record information.*
7. *Now take the house down to –25 Pa WRT outside and record information.*

Blower Door Tests	House P near 50 Pa (P_{50})	BD fan pressure	BD Ring	BD flow near 50 Pa (Q_{50})	House P near 25 Pa (P_{25})	BD fan pressure	Ring	BD flow near 25 Pa (Q_{25})
Test 1								
Test 2								

8. *To check test, calculate the flow exponent, n. Use the following formula,* $n = \ln(Q_{50}/Q_{25})/\ln(P_{50}/P_{25})$. *Note* Q_{50} *and* Q_{25} *are the flows through the blower door at the testing pressures (which are denoted* P_{50} *and* P_{25}. *Depending on the test, you may not get the house to exactly –50 or –25 Pa WRT outside. Use the exact* ΔP *you measure when checking the flow exponent. For example, if the house gets to –48 Pa for the high* ΔP*, use this as the* P_{50} *in the equation. If the flow exponent is not between 0.50 and 0.75, repeat the test.*

Note testing conditions (if windy, inaccessible room(s), garage door open or closed, etc):

METERING DETAILS

Note this should be the multiplier you use to confirm the U30 data matches the one-time power measurement.

DEVICE	S/N	NOTES
U30	Record device keycode#:	39
WattNode Model# _____________		Service entry CT size__________ A Parallel _____ or series ______
WattNode Model# ____________		
Temp. Sensor 1 (OAT)		
Temp. Sensor 2 (VLT)		
Temp Sensor 3 (RAT) (COP)		
Temp Sensor 4 (SAT) (COP)		
Pendant (IDT)		
Pulse 1 (serv entry)		
Pulse 2 (hot water)		
Pulse 3 (DHP)		
TRMS		

DHP outdoor unit make/model:

ID unit make/model:

More notes on installation (CT connections, extra panels, 120V heater circuits, etc.):

Appendix D – SEEM DHP Modifications

Modeling ductless heat pumps (DHPs) presents a unique challenge. Traditional split-system heat pumps run at a constant speed, and so their performance is uniquely determined by the ambient conditions. The inverter-driven ductless mini-splits, however, may vary their compressor speed, changing input power, output capacity, and efficiency even while outdoor temperature and indoor temperature remain constant. In addition, the indoor fan speed may also vary, further confounding the modeling exercise.

Originally, laboratory testing was intended to fully inform a DHP performance model for the simulation. Unfortunately, the added dimensionality of variable compressor frequency and fan speed rendered lab data curve fits finicky and unstable. In sparse regions of the space, curve fits were unduly influenced by a handful of points not completely indicative of standard performance. Deriving a thorough characterization of operation at all possible conditions would require more data than originally anticipated, owing to the high dimensionality of the space. Even then, the modeling exercise would remain difficult, as different combinations of compressor speed and fan speed allow the DHP to provide the same heating output at the same ambient conditions but with differing efficiency, changing based on control logic of the unit. Modeling a DHP from only laboratory data would require, in addition to performance curve fits, extremely detailed knowledge of standard equipment control logic, user-settable control logic, and exactly what settings the user chose. This is impractical. A more tractable approach was to implement a model built from a combination of lab data and field data.

The most reliable information garnered from the lab testing was the characterization of maximum input power and maximum output capacity. These curve fits were accurate and indisputable. As such, they form the basis of the SEEM model, and are supplemented by coefficients of performance (COP)s measured in the field.

The primary difficulty of model development was extracting COP functions from the field data. Because we lacked sufficient information to characterize COP at all possible compressor frequencies, the most desirable outcome was to use mean observed COPs from the field data which implicitly contain the range of compressor and fan operating speeds. These were not always obvious in the field data. Some conditions showed multi-modal COPs, where the DHP preferred one of several distinct types of operation. Others showed a more uniform distribution of efficiency, where at a fixed outside temperature the observed COPs ranged between 2 and 6, with little preference shown to any particular COP. Under these circumstances, asserting a single COP is not a well-defined proposition; although it is possible to calculate an arithmetic mean, that mean is not necessarily indicative of performance. If at 50 degrees outside air the COP distribution for a monitored unit has modes at 2 and 4, does that mean it operates with a COP of 3? No, that means it operates with a COP of either 2 or 4, depending on the load requested and the control logic of the DHP.

To develop COP curve fits, we chose three equipment models for which data were most abundant – the Fujitsu 12RLS, Mitsubishi FD12NA, and Mitsubishi A24NA – and at each temperature bin censored data to include only those points for which the COP distribution contained a single, unambiguous mode. Curves were fit to these data. The idea was to develop a mapping between outdoor temperature and COP that subsumed the complexity of variable speed compressors and fans; if our idea were to map a single temperature to a single “expected” COP, then we could reasonably attempt this only when a justifiable correspondence exists, (i.e. the distribution of observed COPs at that temperature cluster around a single mode).

Inside SEEM, the DHP model works in this manner:

- At each hour, given ambient conditions, equipment type, and equipment size, the COP and maximum capacity are calculated (COP from the field data curve fits and max capacity from the lab data curve fits).
- The load requested of the DHP is then compared to the maximum output.
- If the DHP has sufficient capacity to the meet the requested load, then it does so with field COP.
- If the DHP cannot meet the requested load, then it runs at full capacity as characterized in the lab testing.

Assessing the load requested of the DHP also bears mention. A DHP provides zonal heat, but SEEM is a single-zone model. To reconcile this difference, the mini-split is assumed to serve a constant fraction of the house load. Typical values for that fraction were informed by the field monitoring, with mean heat pump load fraction varying with climate. During the simulation, SEEM calculates the heating load on the house in each hour. The appropriate fraction of that load is passed to the DHP, and the remainder is met through electric resistance heat.

Apportioning some constant fraction of the house load to the DHP worked well for heating, because it is assumed that a supplemental system, with a constant COP of one meets the remainder of the load. In cooling, no such assumption can be reasonably made. This prompted further modifications, as the house-load-fraction paradigm breaks down when no supplemental system intervenes. In cooling mode, the DHP would meet its obligation for a given load fraction while the rest of the house temperature would float upwards. The following paragraph describes the situation by way of example.

Suppose that for some house the cooling setpoint is 74°F and that, at a given hour, the cooling load is 10,000 Btu/hr. Additionally, suppose that the DHP serves 60% of the house. The DHP would then provide 6,000 Btu/hr of cooling, and the remaining 4,000 Btu/hr would be added to the house as heat, with a corresponding increase in temperature. Because it is assumed that the DHP only serves some fraction of the house (even if that fraction is close to one), the total cooling load is rarely met, even if the DHP has sufficient capacity. In general, the house temperature would float upwards all day, and the DHP would continue working into the evening long after the outdoor temperature fell. While it is realistic to assume that, due to zoning effects, the DHP cannot fully meet the cooling load and parts of the house heat beyond comfort, once nighttime temperatures fall below the house setpoint it seems reasonable to assume that the prudent homeowner opens windows. Allowing the DHPs to chug away in the simulation generated unrealistically high values for cooling energy usage not representative of anything observed in this study. This prompted the addition of a pseudo-economizer mode to be used with the DHP equipment type.

The pseudo-economizer mode disallows cooling energy when the outside temperature is below some user-set threshold. The assumption is that, if the air outside is cooler than the inside air, people are more likely to open windows than operate a mechanical system. The amount of heat removed from the space, for purposes of temperature calculation, is the same as would have been removed by the DHP, only it is assumed that the homeowner removed that heat through non-mechanical means. The method is admittedly inexact, but represents our best attempt at modeling cooling for the DHPs and generates reasonable output.

Appendix E – Detailed Alternative Savings Tables

The procedures for evaluating the pre-installation bills and the post-installation metered consumption resulted in several possible combinations of savings estimates. In general, the differences among these estimates results from three sources:

1. The results of the variable base degree day (VBDD) were developed for a particular weather record. These results were then normalized to long-term weather and adjusted to the weather (temperature) recorded by the field meters. Both the heating estimates and the total energy use (in kilowatt hours per year [kWh/yr]) could be modified in this way.
2. The post-installation period also generally included a billing record that was at least 12 months. In two cases, the billing record for the post-installation period was incomplete, and a billing analysis was not conducted on the post-installation period for those sites.
3. The metering included a direct measure of space heat from both the electric resistance space heat and from the DHP. These two channels were combined to give a metered "total" space heat. This total could be processed with the measured site temperature and allow a VBDD normalization to be done.

It was observed in some cases that there was space heating (or at least a seasonal consumption pattern) in the metered total electric service when the heating and domestic hot water (DHW) channels were removed. Specific adjustment approaches to account for residual heat could be any of the following, depending on the site:

- Ignore any degree-day response in residual load and set residual heat to 0 (in cases where we could confidently ascribe the apparent heat to some other end use not present in the pre-installation period).
- Employ the VBDD technique used in Geraghty and Baylon (2009). Referred to as normalized residual.
- Sort residual energy use by month, take the fourth-largest month as a "base" and assume that usage over this base amount in the three largest months is space heat. (This approach applies in cases where space heat is suspected but, because of irregular usage, the VBDD technique fails to produce plausible estimates.) Referred as the alternative residual calculation.

Savings were calculated for most combinations of these heating estimates. Generally, these savings are within a fairly tight range. It is the purpose of this appendix to show the various saving summaries generated from these combination of pre- and post-installation heating estimates. Each table represents an alternative savings calculation. The savings used in the final report represents a careful review of each site to ensure that the observed consumption patterns are properly accounted. Three sites had customer adjustments that were used in the final analysis and are not summarized here. Two sites have been removed and were not used in these summaries or in the saving analysis presented in the main report.

Table E-1. Savings From Pre-Installation and Post-Installation Total Billings, No Adjustments

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	3879	4728	26
Puget Sound	2989	3463	25
Inland Empire	2125	4196	16
Boise/Twin	3603	3825	16
Eastern Idaho	1353	3245	10
Total	3019	4025	93

Table E-2. Savings From Pre-Installation and Post-Installation Billing Analysis Adjusted to the Metering Year

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	3682	3896	26
Puget Sound	3360	3100	25
Inland Empire	2278	1890	16
Boise/Twin	3396	3137	16
Eastern Idaho	2509	2682	10
Total	3178	3130	93

Table E-3. Savings From Pre-Installation and Post-Installation Billing Analysis Adjusted to the Normalized Long-Term Weather Year

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	3735	3914	26
Puget Sound	3314	3015	25
Inland Empire	2248	1855	16
Boise/Twin	3218	2940	16
Eastern Idaho	2465	2594	10
Total	3141	3076	93

Table E-4. Pre-Installation Heating Estimate Adjusted to the Metering Weather Year and Compared to the Metered Space Heating Only

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	4017	2582	25
Puget Sound	3857	3058	25
Inland Empire	2186	3084	16
Boise/Twin	4451	5464	16
Eastern Idaho	4260	3335	10
Total	3757	3519	92

Table E-5. Pre-Installation Heating Estimate Adjusted to the Metering Weather Year and Compared to the Metered Space Heating Adjusted Using the Alternate Residual Calculation

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	3230	2181	25
Puget Sound	3291	2998	25
Inland Empire	1344	2217	16
Boise/Twin	3280	5633	16
Eastern Idaho	3050	3344	10
Total	2908	3361	92

Table E-6. Pre-Installation Heating Estimate Adjusted to the Metering Weather Year and Compared to the Metered Space Heating Adjusted Using the VBDD Residual Calculation Without Modification

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	2795	2495	25
Puget Sound	3071	2881	25
Inland Empire	902	2393	16
Boise/Twin	2896	6067	16
Eastern Idaho	2028	2928	10
Total	2475	3508	92

Table E-7. Normalized Pre-Installation Heating Compared with Normalized Metered Heating, with VBDD Calculated Residual

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	2937	2606	25
Puget Sound	3132	2739	25
Inland Empire	761	2422	16
Boise/Twin	2013	4560	16
Eastern Idaho	2049	2976	10
Total	2354	3127	92

Table E-8. Normalized Pre-Installation Heating Compared with Normalized Metered Heating, with Alternative Residual Calculation

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	3375	2243	25
Puget Sound	3311	2924	25
Inland Empire	1493	2005	16
Boise/Twin	2569	4568	16
Eastern Idaho	2895	3229	10
Total	2838	3031	92

Table E-9. Savings Used in Final Analysis Chosen from Available Savings Methods

Cluster	DHP Savings (kWh/yr)		N
	Mean	SD	
Willamette	3316	2121	26
Puget Sound	3043	2357	25
Inland Empire	1882	1580	16
Boise/Twin	3628	2985	16
Eastern Idaho	3307	3230	10
Total	3049	2424	93

Appendix F – Regression Specifications and Results

The regression analysis developed from the engineering and statistical calculation presented in Section 5 is potentially useful to understand the optimum strategy for developing savings in a DHP program based on the displacement model. The use of regression techniques known as conditional demand analysis (CDA) has been developed in several contexts, but in this study its power is limited by the relatively small sample size. Only the most powerful associations can be identified. This analysis used two sets of variables:

- **Indicator or dummy variables derived from the occupant surveys conducted both at installation and during the site visits used to install and decommission the metering equipment.** These variables are specified as logical variables that take the value 1 if the characteristic is present and 0 if it is not. Most of the explanatory variables derived from the survey data were not statistically significant in this specification either alone or with other variables. This was partly due to the relatively small size of the sample and partly due to the variance in occupant behavior in using the DHP.
- **Continuous variables that could describe a continuous relationship between the savings estimates and the characteristic.** These variables include building heat loss rate, house area, heat pump capacity, and estimates of electric space heat prior to the installation of the DHP. These variables had surprisingly little relationship to the estimated energy savings from the DHP. In general, the displacement model very likely removes much of the relationship between building envelope characteristics and actual DHP saving and performance. Because the DHP system is small relative to the peak heating load, almost all of its potential output is used and the savings are derived from the offset in the much less efficient electric zonal heat.

Table F-1 shows the results of these regressions (both CDA indicator variable and statistically adjusted engineering [SAE] continuous variables). In these regressions, the savings estimates developed in Section 5 were the dependent variable. The coefficient of the continuous variables (pre-installation heating estimate) could be interpreted as the fraction of the pre-DHP heating usage reduced by the DHP savings. The coefficient of the indicator variables are the contribution to the total savings associated with the particular characteristic. For example, the savings associated with the eastern climates (on average) is reduced by 877 kWh.

In addition, Table F-1 shows the results of the regression applied to the entire sample as well as the separate evaluation of the warmer clusters (1 and 2) and the cooler clusters (4, 5, and 6). Only the estimated heating from the pre-installation period was significant when the sample was broken into these two climates. This result points to the limitations of this sample size in establishing a complex regression model. Even where variables such as heat pump capacity should be significant, the natural variation in occupant behavior overwhelms any underlying relationship.

The coefficient of determination (R^2) for the final regression was .36 with a very small constant term. When the regression was re-specified without a constant term, the R^2 increased to .75. The coefficients remained essential unchanged in these two specifications.

Table F-1. CDA/SAE Regression Results

Variable	Type	Range	Units	Description	Coefficient			
					Significant	Total	Western	Eastern
PRE_HEAT_BILLS	Continuous	2884-20700	kWh	Heating estimate derived from pre-installation bills	Yes	0.320	0.470	0.240
TOT_OCCUPANTS	Integer	1 to 6	People	Reported occupancy at residence	No			
FLOOR_AREA	Continuous	448-3607	Sq. Ft.	Conditioned floor area of residence	No			
HOUSE_UA	Continuous	165-927	Btu/°F-hr	Whole house UA including infiltration	No			
TOT_CAPACITY	Continuous	9000-36000	BTU/hr	DHP capacity rating (from installation records)	No			
CLIMATE	Logical			Western or Eastern Climates (Eastern=TRUE)	Yes	-877		
NUMB_INDOOR	Logical			One or two indoor heads (two heads=TRUE)	No			
BWOOD	Logical			Wood used prior to DHP installation (some wood use =TRUE)	Yes	1108		
AIAT_	Continuous	60-79	°F	Average Temperature from the DHP zone	Yes	-125		
DMAIN	Logical			Thermostat adjusted after DHP installation (increased=TRUE)	No			

It should be noted that the expected sign of the wood heat variable is not what we see here. In fact, the presence of wood heat seems to increase the apparent savings. This could be the result of the careful screening that ensured that all participants had a strong electric heat signal. As a result, the amount of wood in most of this sample is probably trivial, and the apparent savings amount is an artifact of the particular sensibility of the occupants that reported wood heating.

The temperature variable was normalized to a variance from a constant temperature of 70.7°F. This temperature was selected as the average of the observed temperature across all homes. This transformation has no effect on the coefficient, but it normalizes the temperature so that the regression does not generate a large constant term. In effect, the temperature coefficient is the amount of savings reduction for each degree of temperature rise (or vice versa). This variable was statistically significant and suggested that the apparent increase predicted by the SEEM analysis (section 5.3) is at least consistent with these regressions results.

The analysis also explored many other variables. These included auxiliary loads (spas, shops, etc.), normalized heat loss rates, reported thermostat adjustments, occupant satisfaction with the equipment, etc.

The variables that appeared significant in this analysis are much easier to gather in a utility program. They depend on little specific information about the home other than the space heat estimate derived from the bills. The input variables needed for a SEEM simulation, on the other hand, would not be available to evaluate a DHP installation program without substantial audit information collected during installation.

The CDA/SAE analysis may be more useful in a large-scale billing analysis. In effect, gross savings from the installation would be possible using the data from the COP categories presented in Section 5 and the predicted savings from the regression equation suggested in Table F-1. The results from such an analysis would tend to use the remaining electric heat as a base and calculate savings potential from that base. The proposed methods here build on the metered data and the saving calculations but attempt to simplify the process so that data collected at an installation or program level can be used to generate the total savings estimates associated with the DHP operation. This analysis also suggests the overriding importance of an initial electric heat indication in the billing record. The other variables (notably wood heat) seem to be far less important once a reasonable electric heat usage is established.