BONNEVILLE POWER ADMINISTRATION

Ductless Heat Pump Engineering Analysis:

Single-Family and Manufactured Homes with Electric Forced-Air Furnaces

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A Report of BPA Energy Efficiency's Emerging Technologies Initiative

Prepared for
Kacie Bedney, Project Manager
Bonneville Power Administration

Prepared by
David Baylon
Bob Davis
Kevin Geraghty
Lucinda Gilman

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An Emerging Technologies for Energy Efficiency Report

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

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David Baylon is the Principal and President of Ecotope. He has been active in the field of energy conservation and energy efficiency since 1975. He has authored or coauthored many of the key studies that have informed the Northwest's approach to energy conservation in both the residential and commercial building sectors. Since 1987, Mr. Baylon has managed several reviews of energy codes and standards in the Northwest, including reviews of residential energy codes for the BPA, the Northwest Power and Conservation Council, the State of Oregon, and various jurisdictions in the State of Washington. He served as a principal in the development of field evaluation for five commercial baseline projects, four field reviews of the region's manufactured housing demand-side management (DSM) programs, three residential duct sealing and performance projects, two heat pump field evaluations, and several field evaluations of BPA residential initiatives in the early 1990s.

Bob Davis is the Director of Measurement and Verification for Ecotope. He has served as Project Manager for heating, ventilation, and air conditioning (HVAC) equipment performance and duct research conducted in light commercial buildings and in single-family and manufactured homes for BPA, the Electric Power Research Institute (EPRI), the Eugene Water and Electric Board (EWEB), the Northwest Energy Efficiency Alliance (NEEA), Puget Sound Energy (PSE), Portland General Electric, and the Oregon Department of Energy. He has written numerous field protocols, instrumented many homes with automated data collection systems, conducted dozens of technical training sessions, and has extensive experience troubleshooting packaged rooftop units, gas furnaces/appliances, and heat pumps.

Kevin Geraghty is an analyst and statistician at Ecotope. His primary focus is sampling, database development, impact evaluation, and regression analysis. His work has included creating numerous sample designs for program verification, conducting nonresidential and residential energy use studies, coauthoring a number of verification studies of utility conservation programs in California, and carrying out the statistical analysis on measure persistence studies as well as standard regression-based demand-side management (DSM) evaluations using billing and load research data. In addition, he is skilled at several database-management formats, including *Access*, *Stata*®, and *SAS*®.

Lucinda Gilman is a project manager at Ecotope. She manages metering projects for NEEA and BPA. She has been managing program and technology pilots since 2008.

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Abstract

This study evaluated the impact of ductless heat pumps (DHPs) on single-family and manufactured homes with forced-air furnaces (FAFs). The study found savings of about 5,500 kilowatt hours (kWh) resulting from the use of DHPs. The driver of these savings was the occupant's FAF and DHP control strategy: occupants who made the DHP their primary heat source saved considerably more energy than those who retained the FAF as their primary heat source. The savings resulted from a combination of DHP efficiency, reduced energy waste from duct losses, and a change from heating the whole house to keeping the main part of the house comfortable with the DHP.

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Glossary of Acronyms and Abbreviations

AC	air conditioning
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/ft^2	British thermal units per square foot
CFM	cubic feet per minute
COP	coefficient of performance
CT	current transducer
DHP	ductless heat pump
DHW	domestic hot water
DSM	demand-side management
E3T	Emerging Technologies for Energy Efficiency
EPRI	Electric Power Research Institute
ER	electric resistance
EWEB	Eugene Water and Electric Board
FAF	forced-air furnace
HDD	heating degree days
HVAC	heating, ventilation, and air conditioning
ISO	International Organization for Standardization
kW	kilowatt
kWh	kilowatt hours
kWh/yr	kilowatt hours per year
MH	manufactured homes
NAC	normalized annual consumption
NCDC	National Climatic Data Center
NEEA	Northwest Energy Efficiency Alliance
NPCC	Northwest Power and Conservation Council
NWS	National Weather Service
Pa	Pascals
PRISM	PRInceton Scorekeeping Method
PSE	Puget Sound Energy
R^2	coefficient of determination

RMS	root mean square
RTF	Regional Technical Forum
R-value	thermal resistance value
SD	standard deviation
SEEM	Simple Energy and Enthalpy Model
SF	single-family homes
sq.ft.	square feet
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
VBDD	variable base degree day
VLT	vapor line temperature (of the refrigerant—indicates cooling or heating mode)

Executive Summary

The Pacific Northwest has embarked on a long-term effort to study the impacts of small split-system heat pumps that are designed to provide zone-level heating and cooling. The impact of ductless heat pumps (DHPs) on single-family homes with existing zonal heat (such as baseboard units) is fairly well understood. The Bonneville Power Administration (BPA) hired Ecotope, Inc., to study other use cases: single-family units with forced-air furnaces (FAFs), multifamily units, manufactured homes with FAFs, cold climate sites, and small commercial applications. This add-on study started in September 2010 and will be completed at the end of 2012. This report summarizes field results from a set of 20 homes originally heated with forced-air electric furnaces. Half of the study set consists of site-built homes, and the other half is manufactured homes.

From 2007 through 2011, at the request of the Regional Technical Forum (RTF), BPA developed an initial pilot study (the Monmouth study) to provide basic information on the energy savings potential of DHP technologies. That study included 14 sites, all existing single-family homes with zonal electric heat. The study concluded that the initial savings estimate associated with this technology in single-family zonal electric homes is about 4,000 to 4,500 kilowatt hours (kWh) per year (Geraghty et al., 2009; Geraghty et al., 2010; Baylon et al., 2012).

In October 2008, BPA and the Northwest Energy Efficiency Alliance (NEEA) initiated a DHP pilot program targeting 2,500 single-family, site-built homes with zonal electric heating systems. NEEA's DHP pilot captured billing history data from up to 2,500 individual homes with DHPs, submetered 92 of these sites, and added data loggers and 30 coefficient of performance (COP) submeters to an additional 35 sites. This study drew from a broad base of sites across the Pacific Northwest and found average savings of approximately 3,049 to 3,850 kWh per year (depending on measurement technique) across three heating climate zones (Baylon et al., 2012).

The program from which all these sites were drawn was built on a "displacement" model, in which the DHP equipment was designed to supplement an existing electric heating system. The model used in this study leaves more of the occupant interaction to chance. 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.

The objectives of the field submetering are:

- Develop energy savings estimates for each application.
- Assess and explain the determinants of consumption in each application, explain the interaction between these conditions and the installed DHP system, and obtain and summarize feedback from the occupants of these submetered sites on their use of and satisfaction with the DHP in their homes.
- Develop and/or modify any deemed savings calculations that might be presented to the RTF.

To meet these objectives, Ecotope installed a detailed instrumentation package to measure DHP electricity input and thermal output. This package measured the electricity consumption of the DHP, electric FAF, domestic hot water and total house load. It also tracked indoor and outdoor temperatures and the temperature of the DHP vapor line (to distinguish whether a system was in heating or cooling mode).

Sites were recruited either from NEEA's database of incentivized installations or from a BPA pool. Recruiting took longer than expected due to the need to establish and promote this pool. Further challenges arose during the prequalification procedure, when houses were evaluated for a strong electric heat signature. As is common in these studies, not all homes showed a strong heat signature. Sites were screened using the variable base degree day (VBDD) analysis used in other DHP studies (see

Appendix B for a description of this procedure). All sites were located in Heating Zone 1, which is defined as having fewer than or equal to 6,000 heating degree days (HDD), in Oregon and Washington. Sites were distributed across Cooling Zones 1 through 3, with the majority in Cooling Zone 1.[1]

Occupant demographics and building characteristics were roughly comparable to the main NEEA DHP study as well. Cooling was not a major factor in this study. Approximately half of the homes had some form of cooling before DHP installation, but those were mostly window AC units, and homeowners reported that they did not use them often. Wood heat was a factor in two homes. Many homes used a supplemental 120-volt heater in a back room.

The primary goal of the 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 assembled from the utility billing records of each house.
- Evaluate the heating impact of the DHP from the submetered energy use and the empirically derived COP (Baylon et al., 2012).
- Construct a simulation model using the regional residential analysis tool, Simple Energy and Enthalpy Model (SEEM) [2] that is calibrated against the results and that provides an estimate of distribution efficiency in the furnace system.
- Develop a picture of the savings using a typology of FAF and DHP control strategies.

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

- Electric bills collected from the utilities servicing these homes
- Metered data for four power channels and three temperature channels
- Full energy audit data
- Three separate surveys taken of the occupants

The pre-installation total and heating energy consumption for the homes in this study are shown in Table 13 in the main body of this report. Savings analysis from this base consumption was conducted, estimating two separate overall savings impacts:

- Difference in overall consumption between the pre-installation period and the post-installation period;
- Difference in heating estimates from bills collected in the pre-installation and post-installation periods.

These are approximately similar to the analysis done in the previous studies based on zonal (baseboard) electric heat, but the presence of the FAF and ducting system significantly changes some of the analysis steps. Table 1 shows the heating savings estimates for the two billing analyses used in this sample.[3]

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[1] Cooling zone 1 is defined as fewer than 300 cooling degree days; cooling zone 2 has 300-600 cooling degree days; and cooling zone 3 has more than 600 cooling degree days. Heating and cooling zone definitions are set by the Northwest Power and Conservation Council (NPCC), www.nwcouncil.org.

[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.

[3] The same table appears as Table 14 in the main body of the report.

Table 1. Savings Estimates from Billing Analysis

House Type	Savings, Pre/Post DHP Installation(kWh/yr)			
	Total Bills		VBDD Heating Estimates	
	Mean	Standard Deviation (SD)	Mean	SD
Manufactured Homes (MH)	6022	2833	4147	2268
Single-Family Homes (SF)	5214	2541	2710	2541
Total	5618	2652	3429	2457

There is a very significant difference between the savings derived from the heating estimates and the savings derived from the total bills. This result contrasts with the previous analysis where the normalized space heat estimates became the basis for the space heat savings and the total savings generally agreed within a few percentage points with the heating savings from the billing analysis (Baylon et al., 2012).

The difference between the results of the two savings analyses shown in Table 1 indicates a potential problem with the VBDD analysis in this sample. This method assumes that the underlying components of the heating system remain the same. In this analysis, installation of the DHP produces fundamental changes in the heating system. A large fraction (in some cases *all*) of the space heating is provided by a zonal heating system after the DHP installation. That is, the DHP becomes the main source of heat in the house, and the furnace is rarely used. Only a few of these homes used extensive zonal heating before the DHP installation, and that was typically provided by a 120-volt plug-in heater. As a result, the incremental impact of space heating is a combination of the reduced energy requirement from the more efficient DHP *and* the reduction in distribution (duct) losses associated with the furnace and duct system. These changes could bias the heating estimate in the post-installation case and account for the disagreement in the two savings estimates.

To evaluate this problem, the submetered data were used. Because the DHP operation and the furnace operation were submetered throughout this period, it is possible to describe exactly how much space heat the DHP equipment provided and to compare this result with the observed consumption changes in the billing record. This analysis used the performance curves and COP estimates developed in the main NEEA zonal DHP study. Table 2 summarizes the savings from the DHP contribution calculated directly from the submetered results. [4]

Table 2. Savings Estimate from Submetering

House Type	Total Savings (kWh/yr)	

[4] The same table appears as Table 15 in the main body of the report.

	Mean	SD
MH	6105	2511
SF	4715	2224
Total	5373	2405

The billing analysis that focused on the total consumption change is consistent with the results of the total savings analysis from the submetered data. This summary finds total savings within 4% for the whole sample and within 10% for each housing type.

These findings are significantly different from the results of NEEA's larger regional study, which showed savings in the range of 4,000 to 4,500 kWh/yr. The primary drivers of this difference are the lack of duct losses and the control strategies employed by the residents. Control strategies fell into three categories:

- The DHP is the primary heating source. This case is relatively common and is the result of the occupant essentially turning off the furnace except under very limited circumstances. This control strategy often includes supplemental 120-volt heaters in back rooms of the home.
- The furnace remains primary. This condition is rarer but is the result of the occupant maintaining the central thermostat at a temperature close to the apparent DHP setpoint.
- The heating load is shared. The third case is a hybrid of the above 2 strategies, in which the occupant uses the DHP in most mild weather but switches to the heating system for a fraction of the time. This mode of operation preserves some of the benefits of the DHP on offsetting distribution losses but does not allow the DHP to provide as much space heating as it might otherwise.

Table 3 shows the distribution of control strategies among the two housing types. [5]

Table 3. Control Strategies, Submetered Systems

House type	Control Strategy			
	DHP Prime	FAF Prime	Shared	All
MH	5	0	5	10
SF	3	4	3	10

This combination of strategies led to a high fraction of the total heat energy of the home coming from the DHP – an average across all sites of 77.3%. When the DHP is primary, it supplies well over 90% of the heat. Prequalification for this study was not as rigorous as it was for the main NEEA DHP study, so it is likely that this result will be robust across the general population.

A SEEM analysis was conducted to determine whether the current SEEM implementation could be used in this application. The goal is to eventually provide BPA and the RTF with a framework for developing an

[5] The same table appears as Table 16 in the main body of the report.

incentivized DHP measure for homes with electric FAFs. Table 4 shows the savings results from this simulation exercise. [6] Because the VBDD analysis proved problematic, the savings estimate from the billing totals was calibrated against the SEEM run for the post-installation conditions. As with the base case calibration, the comparison between the billing analysis and SEEM is quite close, with about a 4% difference overall.

Table 4. Calibrated SEEM Savings Comparisons

House Type	Savings, Heating Consumption (kWh/yr)			
	SEEM Savings Results		Billing Savings Results	
	Mean	SD	Mean	SD
MH	6231	3268	6022	2833
SF	5479	2240	5214	2541
Total	5855	2754	5618	2652

Finally, the cooling load was evaluated. On average, the DHP used approximately 167 kWh/yr in cooling mode. It should be emphasized that this is not entirely new cooling energy, considering that some homes had existing AC before the study, and it likely was less efficient than the DHP.

The results of this analysis show a significant electricity savings when a ductless heat pump is installed in a single-family or manufactured home heated by a forced-air electric furnace. Table 5 shows the total savings from the billing analysis and total savings as measured by the heat output of the DHP from the submetered analysis. [7] Although these two estimates differ somewhat, the agreement is quite striking and there is no statistical difference between the two. Overall savings of about 5,500 kWh/yr is a reasonable estimate.

[6] The same table appears as Table 22 in the main body of the report.
[7] The same table appears as Table 26 in the main body of the report.

Table 5. Final Savings Results

House Type	Savings, Heating Consumption (kWh/yr)			
	Submetered Savings Results		Billing Savings Results	
	Mean	SD	Mean	SD
MH	6105	2511	6022	2833
SF	4715	2224	5214	2541
Total	5373	2405	5618	2652

The savings determinant in this sample is the control strategy used by the occupant. This factor drives the overall percentage of the heating load that the DHP covers and the amount of duct losses that are offset.

1 Introduction

The Pacific Northwest has embarked on a long-term effort to study the impacts of small split-system heat pumps that are designed to provide zone-level heating and cooling. The impact of ductless heat pumps (DHPs) on single-family homes with existing zonal heat (such as baseboard units) is fairly well understood. The Bonneville Power Administration (BPA) hired Ecotope, Inc., to study other use cases, specifically:

- Single-family units with forced-air furnaces (FAFs),
- Multifamily units,
- Manufactured homes,
- Cold climate sites (sites with more than 9,000 heating degree days [HDDs]), and
- Small commercial applications.

This ongoing study started in September 2010, and submetering installations remain in the field for multifamily and small commercial sites.

This report on the first group of sites covers single-family residences with FAFs and manufactured homes. It summarizes the results of detailed field monitoring from a set of 20 homes originally heated with forced-air electric furnaces. Half of the study set consists of site-built homes, and the other half is manufactured homes. The report discusses the differences between DHPs in single-family zonal homes, single-family homes with FAFs, and manufactured homes. These differences arise primarily from the different control strategies required to manage backup heat and (in the case of manufactured homes) a lower average square footage.

1.1 Background

From 2007 through 2011, at the request of the Regional Technical Forum (RTF),[8] BPA developed an initial pilot study (the Monmouth study) to provide basic information on the energy savings potential of DHP technologies. This pilot study used modern submetering technology to ascertain the performance of these systems in end-users' homes. The target customer group for that study included 14 existing single-family homes with zonal electric heat. The goals of the study were to provide early verification of the RTF's energy savings assumptions, to gain experience to inform a larger review of DHP retrofits in zonal electrically heated homes, and to review data collection procedures and refine the instrumentation protocol. The study concluded that the initial savings estimate associated with this technology in single-family zonal electric homes is about 4,000 to 4,500 kilowatt hours (kWh) per year (Geraghty et al., 2009). Later reports (Geraghty et al., 2010; Baylon et al., 2012) confirmed these savings persisted in the second and third year after DHP installation.

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

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[8] The RTF is run by the Northwest Power and Conservation Council (NPCC) and is responsible for evaluating and approving new energy efficiency measures in the Northwest.

Until recently, heating, ventilation, and air conditioning (HVAC) measures for homes with forced-air electric furnaces have been limited to air-source heat pumps. If DHPs could be proven to be an effective alternative, they could be a good option for many. They are often less expensive and more efficient than regular heat pumps and do not have the associated duct heat loss issues. The DHP measure was designed in a similar fashion to the single-family zonal measure, where the focus was on installing a DHP to cover the main heating zones while retaining backup heating for secondary areas. This approach is known as the “displacement, not replacement” model.

The program from which the sites in this study were drawn was built on this model. The model used in this study leaves more of the occupant interaction to chance than in the zonal study; 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 forced-air electric furnace. 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.

The submetered 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.

For single-family homes with FAFs, a primary focus of the analysis is the interaction between the DHP and the overall heating system because it can largely determine the extent of energy savings. The central system thermostat setpoint should be set significantly lower than the DHP setpoint in winter and higher in summer (if central air conditioning [AC] is present) in order to maximize the DHP’s contribution to space heating and cooling. In addition, because the DHP does not heat back rooms as effectively as a ducted system, it was necessary to investigate whether participants reported comfort complaints or used plug-in 120-volt heaters or other means to deal with these rooms.

The control issue for manufactured homes is similar to that of site-built homes. In the Pacific Northwest, at least 90% of manufactured homes are heated by electric FAFs, and only about 15% have central AC paired with this furnace. Manufactured homes tend to be smaller than single-family homes on average and, depending on their age and insulation level, may have lower heating loads. Therefore, the question is whether the heating load is big enough, and whether the DHP can offset enough of the furnace energy use, to merit a measure.

The research goals of this pilot for these two groups are:

- Develop energy savings estimates for each application, based on the submetered and billing data and other parameters of the DHP equipment developed from the NEEA and BPA studies.
- Assess and explain the determinants of consumption in each application; explain the interaction between these conditions and the installed DHP system, including any offsetting interactive effects; and ascertain the installation factors that drive these determinants, and whether there should be limitations on systems incentivized by a utility-based DHP program.
- Obtain and summarize feedback from the occupants of these submetered sites on their use of and satisfaction with the DHP in their homes.

- Develop and/or modify any deemed savings calculations that might be presented to the RTF as applied to the DHP installations evaluated in this pilot using the regional residential analysis tool, Simple Energy and Enthalpy Model (SEEM). [9]

1.2 The Ductless Heat Pump Efficiency Measure

In the summer of 2007, the RTF, at the behest of NEEA, began the process of assessing the use of a modernized "mini-split" heat pump technology. 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 AC introduced at the beginning of that year. Over the next year, several manufacturers introduced entirely redesigned systems focusing on inverter-driven, variable-speed compressor technology and multi-speed fans. Like the previous generation of mini-split systems, these systems used small, wall-mounted air handler/coil units with direct refrigerant supply from a compressor located in the outdoor unit. They 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 flexible enough to be considered as a measure to offset electric resistance (ER) zonal heating systems, which are not easily retrofitted with ducted heating systems.

The RTF reviewed a provisional measure that used these new technologies. 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 (the "displacement, not replacement" 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% to 40% reduction in space heating energy requirements.
- The interaction with wood use 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.

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[9] 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.

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.

The model for single-family homes with FAFs and manufactured homes adopted the same assumptions but also anticipated different issues surrounding interaction between the central furnace (thermostat and ducts) and the DHP. It is this model that was promoted and evaluated in this study.

1.3 DHP Field Metering Evaluation

Ecotope submetered a total of 10 single-family and 10 manufactured homes in Washington and Oregon. The single-family homes and some of the manufactured homes were drawn from the NEEA DHP pilot project, and the balance of the manufactured homes was drawn from a pool created by BPA for the purposes of this study.

The objectives of the DHP field submetering were:

- 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 resulting from use of 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.

2 Methods

2.1 Site Selection

Single-family homes were gathered from NEEA's database of approved installations and screened in the same way that single-family zonal systems were screened for the main NEEA study. This iterative process ran from late November 2010 through late February 2011. Lists of qualifying sites were obtained from the database, and bills were requested from the utilities. We were unable to recruit an adequate number of manufactured homes from this database because there was no incentive for manufactured homes, although a few cases apparently had been included in the database even without any incentives. To reach more manufactured homes, BPA issued a custom pool of 50 incentives to develop a recruiting list. These incentives were then promoted to utilities, and the resulting sites were screened in the same way as the single-family sites. The need for the custom incentive pool extended the recruitment timeframe considerably, with site recruiting beginning in late November 2010 and continuing through the end of March 2011.

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 submetered 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 Geraghty et al., 2009, andAppendix B) allowed an assessment of the electric heating use of the home based on month-to-month changes in consumption predicted by outdoor temperature.[10] The screening process had the effect of increasing the potential electric savings from the sample.

[10] 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 method used here is a variation of this method. Appendix B provides more background.

Ecotope then contacted sites that passed this screening to evaluate whether they were good candidates for the study and, if so, recruit them.

More than 50 single-family and 50 manufactured home sites were evaluated for inclusion in the study to get 10 participants in each pool. Many sites were not good candidates for a variety of reasons. Table 6 lists the primary reasons that potential sites were rejected. Some sites were not good candidates for submetering due to physical issues with the site; some sites were not good candidates because their bills did not show a significant heating load and others had access or equipment problems (electrical panel configuration, etc.).

Table 6. Most Common Reasons for Disqualification

	Single-Family	Manufactured Homes
Physical issues prevented installation of submetering equipment	4	3
Heating signature not clearly evident	12	7
Home or heating system did not qualify	4	2
Furnace replaced or removed altogether as part of DHP installation	1	4

2.2 Final Site Distribution

All sites were located in Heating Zone 1, which is defined as less than or equal to 6,000 HDDs. Sites were distributed across Cooling Zones 1 through 3, with the majority in Cooling Zone 1.[11] Most sites were in Washington, and the rest were in Oregon. Table 7 shows the distribution of sites by Cooling Zone, and Table 8 shows the distribution of sites by state.

Table 7. Sites by Cooling Zone

	Cooling Zone		
	1	2	3
Manufactured Homes (MH)	7	1	2
Single-Family (SF)	5	4	1

[11] Cooling Zone 1 is defined as fewer than 300 cooling degree days; Cooling Zone 2 has 300 to 600 cooling degree days; and Cooling Zone 3 has more than 600 cooling degree days. Cooling Zone 1 covers Seattle and coastal areas; Cooling Zone 2 covers Portland and most of the I-5 corridor; Cooling Zone 3 covers Spokane, Boise, and other inland cities. Heating and cooling zone definitions are set by the Northwest Power and Conservation Council (NPCC), www.nwcouncil.org.

Table 8. Sites by State

	Oregon	Washington
MH	2	8
SF	3	7

2.3 Metering Design and Data Collection

The Ecotope field team installed the DHP submetering equipment from December 2010 through March 2011, and decommissioning took place in April 2012. Thus, more than a year of data was collected for each site.

2.3.1 Metering Goals

The submetering design had four goals:

- Submeter heating system energy use after installation of the DHP. This was accomplished by submetering the DHP and separately submetering the forced-air electric heating system.
- Submeter the domestic hot water (DHW) usage to help adjust regional DHW usage (given the last DHW submetering was done in the early 1990s.)
- Meter the total electric energy usage of the home (at the service drop). This measurement facilitated a sum check on the submetered loads.
- Measure and log the temperature of the main living space, the outdoor temperature, and the DHP vapor line temperature.

2.3.2 Metering Specifications

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

- **DHP channel,** measured with a combination of split-core current transducer (CT), true root mean square (RMS) watt transducer, and pulse counter.
- **Total house electric service drop (SERV),** measured with the same combination of equipment.
- **240-volt electric resistance heaters,** measured with the same combination of equipment.
- **Domestic hot water tank,** measured with a current transformer and RMS electric current 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/data logger was placed in a shaded location near the submetered home and recorded hourly average temperature. These data were compared with National Weather Service (NWS) weather site data.
- **Indoor central zone temperature where the DHP was installed.** This logger recorded the average hourly temperature for the entire submetering period. Indoor temperature data were downloaded at the end of the period and synchronized to the time/date stamps in the submetered 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 DHP.** 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 submetering in BPA's Monmouth study. This previous research suggested that determining the cooling signal using only outdoor 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 electric resistance heat is also used.

The data collected in the submetering process were recorded at five-minute intervals, and these averages were based on measurements taken every five seconds.

2.3.3 On-site Audits and Interviews

Each site received a detailed physical energy audit, including a measurement of the air-tightness of the house. The audit's primary purpose was to determine a heat loss rate for the home. The protocol for this audit is in Appendix C.

The primary site occupant was interviewed three times during the study. The first interview occurred when submetering 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 a detailed phone survey conducted in April 2012. The interviewer asked participants detailed questions about their satisfaction with and use of the equipment. The third interview was conducted during the decommissioning. This interview focused on setpoints and control strategies as well as any changes to the home during the monitoring period (significant energy efficiency improvements, new appliances, occupancy, etc.). Finally, several specific questions were asked about supplemental heating from wood or other non-electric fuels. The occupant was also asked about the household's use of 120-volt space heaters. This was identified as an important variable in previous DHP evaluations (Geraghty et al., 2010; Baylon et al., 2012), 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 submetered data.

2.3.4 Data Collection and Assembly

As noted above, the submetered installations were complete by the end of March, 2011, and data were collected for the full suite of sites through March, 2012. As a result, a full common year of data was gathered for each site in the sample.

An "annualized" data set was used throughout the analysis. In addition to variables representing the four directly measured energy use channels (SERV, DHP, 240-volt electric resistance heat, and DHW), a "residual" variable was calculated representing the energy use left over after all submetered channels were subtracted from the SERV. This residual was summarized on the same time scale as the submetered channels.

The bulk of these data was downloaded to the Ecotope file server on a nightly basis using a 3G cellular connection. Because the data loggers had substantial storage capacity, short-term interruptions in cellular service were easily remedied in a subsequent download period. When downloads failed, a site visit was arranged to reset the data logger.

2.3.5 Error Checking and Data Quality Control

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

- A field installation guide was written before fieldwork began and then revised 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 are downloaded from the datalogging vendor).
- The datalogging vendor offered a "web services" interface by which Ecotope's computers could directly retrieve data from the vendor's 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 each 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 submetered power consumption channels.
- The above processes were supplemented with field visits when data quality or downloads failed. Such failures were rare, except for one site where no cell phone coverage resulted in a failure of the automated systems. In this case, the data were downloaded manually approximately every six 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.

2.3.6 Decommissioning

The field team decommissioned the DHP submeters during April, 2012. The decommissioning process included the retrieval of the temperature loggers that recorded temperature hourly in the main living space. In addition, for the one site where the automated cellular data download failed, the data were retrieved during decommissioning.

2.3.7 Billing and Weather Data Assembly

Utility billing data from the submetered 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, it is the only pre-DHP heating energy estimate because submeters were installed only for the post-DHP period.

In general, the billing record extended from the beginning of 2009 (about two years before the beginning of the monitoring year) to the end of the monitoring period, March 2011. The pre-installation billing record was assembled from approximately 12 to 24 months of bills collected before the installation of the DHP. The post-installation period included 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.

2.4 Home Characteristics

This section presents the physical characteristics of the 10 single-family and 10 manufactured home sites and, where data are available, compares these characteristics to the characteristics of the submetered homes in the NEEA zonal DHP pilot.

Thermal audits were performed at the time of installation of the DHP submetering equipment. The thermal audits encompassed house heat loss rate, shell air leakage, and duct leakage/insulation/location.

Most sites are located within 30 miles of Interstate 5, but two sites are coastal sites. These sites are almost totally devoid of any cooling load. Three sites are located in the Tri-Cities area of Washington State and have similar overall heating requirements to the other sites. However, depending on the local effects, substantial cooling usage could be expected in these sites. The remaining sites are characterized as western climates in Heating Zone 1.

2.4.1 Shell Characteristics

The audit measured conditioned floor area (shown in Figure 1), duct leakage, and house air-tightness and calculated an overall heat loss rate. The supply duct leakage is of primary interest because it has the largest contribution to heating load outside of the house heat loss rate (UA,[12] shown in Figure 2). Although overall UA is higher for the single-family homes than for the manufactured homes, it is lower on a UA per square foot basis (shown in Figure 3). The supply leakage fraction (shown in Figure 4) is found by dividing the supply leakage at a test pressure of 25 Pascals (Pa) to outside by measured air handler flow. The main point of comparison between the NEEA DHP pilot sites (all site-built single family sites (no manufactured homes)) and the homes in this study is the UA. On average, it is relatively similar, but houses in this study have ducts, and some of the ducts have significant leakage. This factor explains some of the increased savings potential for a centrally-ducted system compared to the NEEA DHP homes, which all had zonal (non-ducted) electric heat. Table 9 summarizes these numbers and shows the mean, median, and standard deviation (SD). The box plots in the figures visually show the distribution of data. The mid-line in the box plot is the median value, and the top and bottom of the shaded box describe the 75th and 25th percentile, respectively, of the data points (so the box in effect represents the "middle 50%" of the data).

Figure 1. Conditioned Floor Area

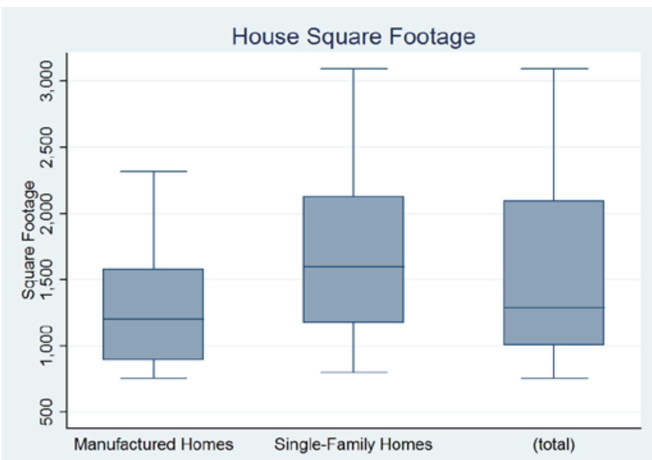
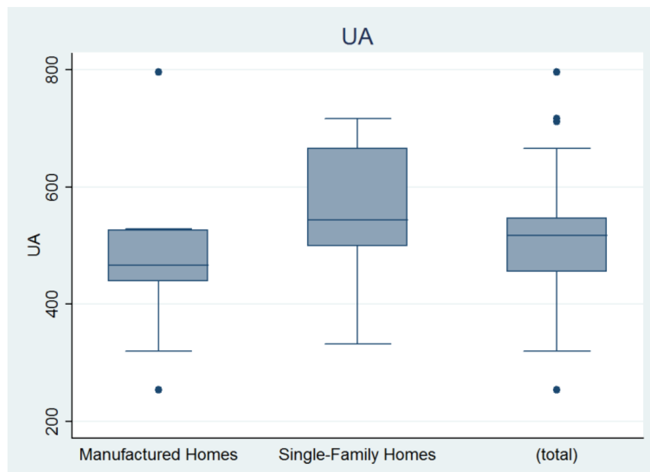


Figure 2. House Heat Loss Rate (UA)



[12] The UA is the sum of the thermal transfer coefficient (U) times the area (A) of the components of the building, and it includes an infiltration component (estimated from the blower door test).

Figure 3. UA per square foot

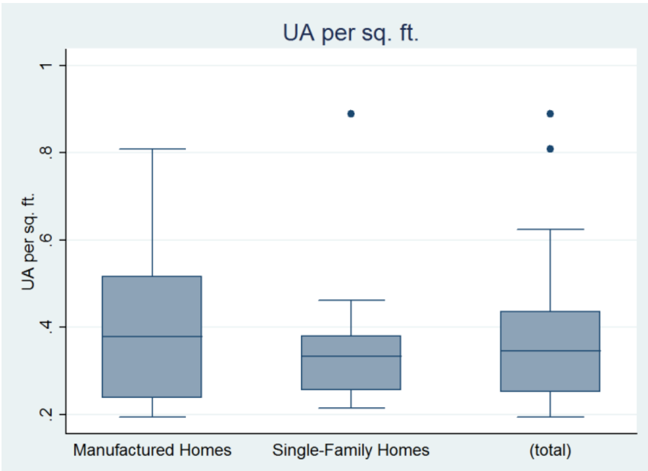


Figure 4. Duct Supply Leakage Fraction

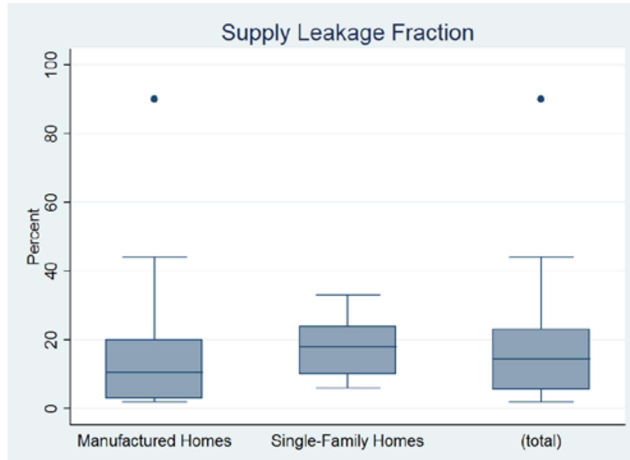


Table 9. Aggregated Building Characteristics

	Conditioned Floor Area (Sq. Ft.)			UA			UA/Sq. Ft.			Supply-side duct leakage[13]		
	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
MH	1318	1205	543	475	466	143	0.361	0.387	0.194	20.4%	10.2%	27.7%
SF	1686	1597	684	556	544	117	0.330	0.341	0.234	16.9%	14.1%	9.8%
NEEA DHP pilot[14]	1618			511		177	0.316		0.099	n/a		n/a

2.4.2 Cooling

Just over half of the participants did not have any AC before purchasing the DHP, as shown in Table 10. All participants in Cooling Zone 3 had AC. After installing the DHP, only one participant reported that they continued to use their old cooling. Participants with prior cooling reported using their previous cooling between half a month and five months per year. They were unable to specify how often they use the DHP in cooling mode; this uncertainty may be because most set the unit to automatic, which adjusts between heating and cooling as needed.

[13] Supply-only leakage to outside measured at 25 Pa divided by the measured air handler flow.
[14] There were 95 homes in this study and 92 had an intact submetering dataset that could be evaluated.

Table 10. Air Conditioning Prior to DHP

	Manufactured Homes	Single-Family	Total
None	2	7	9
Window	5		5
Central	2	1	3

2.4.3 Supplementary Heat

The submetering system captured all of the 240-volt circuits used to power the baseboards or other zonal heaters in the home. The platform was not designed to measure plug-in 120-volt heaters. Six single-family and six manufactured home participants reported using 120-volt plug-in heaters to supplement the DHP. As explained in Section 3.4, it was possible to estimate plug-in heater usage during the billing analysis.

2.4.3.1 Wood use

Table 11 shows that wood heat usage was low in this sample. Only two of the twenty participants reported significant use of wood heat. Sites that used significant non-electric heat were screened out during recruiting in most cases, but as long as the screening found a healthy heating signature, the site was a viable candidate.

Table 11. Wood Heat Usage

	None	Wood use
Manufactured Homes	9	1: 1/8 cord
Single-Family	7	2: A couple of logs at the holidays 1: 2 cords

2.4.4 Large Loads and Outbuildings

The occupant questionnaire included such items as a spa, auxiliary shop, or other buildings that were on-site and on the utility meter but not part of the house itself. These areas were generally thought to be heated, although we were unable to submeter that heat directly. In this study, two single-family homes reported having spas. None of the other participants reported large loads or outbuildings.

2.5 Occupant Characteristics

This section presents details about the occupants of the homes in the study taken from the three surveys performed.

Information was gathered for all twenty participants during the installation and decommissioning surveys, and seventeen participants were reached for the phone interview conducted in February 2012. The phone survey was more extensive than the interviews that were performed on decommissioning. Together, the surveys show the participants' use of space heaters and room or central AC, overall satisfaction with the DHP, and thermal performance of the home. The installation survey also asked participants about energy efficiency program participation and other energy reduction measures.

Survey information was collected on thermostat setpoints and changes in setpoints after installation of the DHP. However, these reported changes were found to have no relationship to the control strategies observed in the submetered data and described in Section 3. Previous studies similarly found occupant-reported setpoint data to be somewhat unreliable.

2.5.1 Demographics

Generally, there were slightly more people living in the single-family homes than the manufactured homes. An average of 2.7 people (including children) lived in the single-family homes, and an average of 2.0 people lived in the manufactured homes. This is perhaps not surprising given the slightly smaller average square footage of manufactured homes. The average for the main DHP pilot was 2.3 people per home. The United States Census Bureau cites an average of 2.45 people per home for Oregon and 2.49 for Washington.[15] Two homes had occupancy changes over the course of the study; both had one occupant move out.

2.5.2 Satisfaction with the DHP

Overall, DHPs are working well for participants with FAFs. Three participants reported that the DHP did not meet their needs when it was very cold out. One reported that the DHP did not work below freezing, one below 20 degrees, and one "on the coldest days of winter." Only the first of those participants rated themselves as dissatisfied with the DHP, however.

Participants were asked to rate their satisfaction with the DHP on a scale of 1 to 5, with 1 meaning "very dissatisfied" and 5 meaning "very satisfied". All participants except one were satisfied or very satisfied with the comfort of the new heat, and all were satisfied or very satisfied with the comfort of the new cooling. There was no bias in terms of cooling satisfaction based on cooling zone. Satisfaction with the electricity bill was a little lower, with three participants reporting themselves as less than satisfied. Likewise, three participants were less than satisfied with the sound level of the indoor unit. All participants rated themselves as satisfied or very satisfied with the level of maintenance required. There were no significant differences between the single-family and manufactured home participants, so Table 12 presents combined results.

Table 12. Participant Satisfaction with DHP

(1=very dissatisfied; 5=very satisfied)

	1	2	3	4	5
Sound level of the indoor unit			3		14
Electricity bill since the DHP was installed			3	6	8
Comfort of the new heat			1	5	11
Comfort of the new cooling				2	15
Maintenance the DHP requires				2	15

[15] Oregon and Washington QuickFacts from the Census Bureau, http://quickfacts.census.gov/qfd/states/41000.html and http://quickfacts.census.gov/qfd/states/53000.html.

2.6 Analytic Approaches

The primary goal of this analysis was to develop a savings estimate to assess the DHP technology in homes with electric FAFs. Four strategies were used to meet this objective:

- Assess heating energy savings by using the utility billing records of each house.
- Derive the heating impact of the DHP from the submetered energy use and the empirically-derived COP (Baylon et al., 2012).
- Construct a simulation model using SEEM that is calibrated against the field results and that provides an estimate of distribution efficiency in the furnace system.
- Explain the savings using a typology of furnace and DHP control strategies.

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 19 months of consumption before the installation of the DHP and about two years of data after the installation. In three sites, the billing record for the pre-installation period was less than a full year; in those cases, an annualized usage was developed using the VBDD technique. This allowed an estimate of pre-DHP heating usage.
- Metered data for four power/energy channels and two temperature channels (outdoor and DHP vapor line) at five-minute intervals and indoor temperature 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 and a duct leakage test/duct insulation assessment to estimate distribution efficiency.
- Three separate surveys taken of the occupants, as described above in section 2.3.3.

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

- The overall change in consumption was calculated by examining the electric utility bills collected at each site. This approach used a variable-base degree day (VBDD) analysis to normalize consumption for climate variation but evaluated the savings based on the change in total normalized annual consumption (NAC)[16] in the pre-installation and post-installation periods.
- The space heat was derived from the VBDD analysis in both the pre-installation and post-installation periods. This change in the normalized space heat was an estimate of the savings from the DHP operation.
- The heating impact was derived from submetered data. For this analysis, the impact of the DHP was derived from the duty cycles of the equipment as measured and the COP for the equipment as derived from previous laboratory and empirical results (Baylon et al., 2012). This method allows a direct estimate of the total heating contribution of the DHP as it operates in the house.

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

- Changes in occupant control and operation of the heating system. Many occupants selected the DHP as their primary heating system and either turned off their furnace for virtually all of the heating season or in two cases disconnected it altogether. In these cases, the change in the heating system is so dramatic that the ability of the VBDD billing analysis to produce a reliable space heat estimate is compromised.

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[16] The normalized annual consumption (NAC) is the result of using the output of the VBDD analysis (heating requirements and base electric load) and expressing the total in terms of the long term weather at the site. This allows the analyst to avoid biases that might occur in abnormally warm or cold years and express savings estimates in terms of more typical weather.

- Duct leakage, duct location, and conductive loss. These vary across each home and also vary based on how much of the heating load the DHP offsets.
- Use of 120-volt space heaters. In some cases, this usage, along with a switch to the DHP as the primary heating source, changed the home from a central forced-air system to a zone-heated and zone-controlled system. In those cases, the absence of duct losses reinforces the savings from the DHP, although the real situation is a change in the nature of the heating system enabled by the DHP.
- The presence of large (and seasonal) loads that are not part of the heating system of the home. This factor can create a bias because these loads would appear as part of the space heating estimate in a conventional billing analysis.

The estimation of base (pre-DHP) heating consumption in this group required some adjustments. In particular, the heating estimates from the VBDD analysis were inconsistent, and estimates of parameters such as house balance point and non-space heating baseload varied in the same house between the pre-installation and the post-installation periods. The analytical approach included an attempt to constrain the VBDD fit so that the post-installation measurements were informed by the submetered data. This constraint took the form of a restricted balance point that was allowed to vary much less in the post-installation period. The effect of this constraint on the overall results of either predicted heating or predicted savings was minimal, and the remainder of the analysis effort was designed to compensate for this bias. As a result, the development of VBDD base heating consumption was abandoned in favor of the overall consumption for the pre-installation period. Savings were then developed on the changes in *total* consumption between the pre-installation and post-installation periods. The submetering confirmed these savings by using measured heat output.

The SEEM simulation program was employed using the results of the pre-installation billing analysis. The results of the duct leakage tests and the duct audit were used as part of the overall calibration of the SEEM simulation. This process resulted in a secondary savings estimate that was comparable to the change in total consumption from the billing analysis and the total heat savings from the submetered DHP performance.

2.6.1 VBDD Analysis

The VBDD procedure seeks to separate space heating from the total utility bill based on the usage changes in response to outdoor temperature, as indicated by the bills. The general approach is to iteratively find the best fit between the billing records and the average temperature (typically from a nearby weather station). The results include:

- The home's balance point
- The slope of the regression line that describes the temperature response (usually interpreted as an estimate of the heat loss rate of the house).
- A coefficient of determination (R^2) statistic to describe the quality of the fit between electricity consumption and outside temperature.

This analysis is done on both a period of more than one year prior to the installation of the DHP and again on a period of at least one year after the installation. These are two separate analyses with two separate space heating estimates. The savings from the billing analysis alone constitute the change in space heating or consumption. In no case, however, was any separate submetering done of space heating or water heating load in the period prior to the installation of the DHP. Thus, the base case for purposes of calculating savings must be extracted from the billing analysis conducted on the data for the period before the installation of the DHP.

The VBDD procedure allows the heating estimates and the overall energy consumption estimates to be normalized to a long-term weather station rather than be responsive to the particular year in which the data were collected. Appendix D lists the weather stations used in this analysis.

2.6.2 Weather Normalization

"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 have a linear relationship to HDDs, and if this linear response coefficient can be estimated, weather normalization is a straightforward matter of multiplying this response coefficient. The normalization process applied to the total NAC used this heating adjustment to ensure the comparability of billing totals across the analysis periods. In the context of this report, "long-term average" means all the data available from the NCDC for a site's chosen weather station. The length of time for available data varies from station to station, but averages about 16 years (ending in mid-2011) for the stations used here.

This report presents results in weather-normalized form. Individual submetered comparisons, where developed, were also normalized to the outdoor temperature recorded on-site. Savings were calculated by comparing submetered energy use to metered temperature, which allowed us to normalize the energy use channels against recorded weather data. This technique allowed us to establish a final savings number with confidence that we had correctly represented the performance at each home.

2.6.3 DHP COP curves

During the previous studies, especially the regional NEEA study, a set of laboratory tests and performance estimates were made on a variety of DHPs. These were designed to develop an *in situ* performance curve that could be used to predict performance of the equipment under a variety of circumstances. Two of the units were tested in detail in a laboratory and other units were submetered *in situ*. This method allowed a fairly complete set of COP curves to be made to assess performance of the heat pump (Ecotope, 2011). The outcome of this approach is that the submetered run time and performance of the DHP can be translated into a heating output that is comparable to the heating contribution of the DHP during its operation.

3 Findings

The following subsections describe the findings of the study, including submetered results, DHP heating and cooling fractions, and total savings.

3.1 Base Case Energy Consumption

The evaluation of this set of DHP installations began with VBDD analysis. The pre-installation total and heating energy consumption for the homes in this study are shown in Table 13. In all cases, these consumption numbers have been normalized to long-term weather. The heating estimate does not take into account supplemental heat such as wood. The sample included two homes that used at least some wood, but the data do not include a direct estimate of this fuel use. Occupants stated that there was not a significant change in wood use after the DHP was installed. Thus, in the billing analysis, the overall heating savings would not be affected because the same conditions prevail for the pre-installation and post-installation periods. Table 13 shows the base consumption for the two groups and the total for the entire sample of 20 homes. Overall space heating consumption is not affected significantly by the different climates represented here, because the number of HDDs and underlying heating load in all these climates are similar.

Table 13. Weather-Normalized Base (pre-DHP) Consumption

House Type	Base Consumption			
	Total (kWh/yr)		Heating (kWh/yr)	
	Mean	SD	Mean	SD
MH	19747	5889	10586	3678
SF	21641	6153	9185	3311
Total	20694	5941	9886	3481

Savings analysis from this base consumption was conducted, estimating two separate overall savings impacts:

- Difference in overall consumption between the pre-installation period and the post-installation period.
- Difference in estimates of heating usage from bills collected in the pre-installation and post-installation periods.

These estimates are approximately similar to the analysis done in the previous studies based on zonal (baseboard) electric heat, but the presence of the FAF and ducting system significantly changed some of the analysis steps. Table 14 shows the heating savings estimates for the two billing analyses used in this sample.

Table 14. Savings Estimates from Billing Analysis

House Type	Savings, Pre/Post DHP Installation(kWh/yr)			
	Total Bills		VBDD Heating Estimates	
	Mean	SD	Mean	SD
MH	6022	2833	4147	2268
SF	5214	2541	2710	2541
Total	5618	2652	3429	2457

There is a very significant difference between the savings derived from the heating estimates and the savings derived from the total bills. This result contrasts with the previous analysis where the normalized space heat estimates became the basis for the space heat savings and the total savings generally agreed within a few percentage points with the heating savings from the billing analysis (Baylon et al., 2012).

The difference between the results of the two savings analyses shown in Table 14 indicates a potential problem with the VBDD analysis in this sample. This method assumes that the underlying components of the heating system remain the same. However, because there is a central system that is now partly offset by a DHP installed in one zone of the house, it appears that the VBDD approach does not work reliably at these sites. Savings in the post-installation period are a combination of the reduced energy requirement from the more efficient DHP *and* the reduction in distribution losses associated with the furnace and duct system. These changes could bias the heating estimate in the post-installation case and account for the disagreement in the two savings estimates.

3.2 Metered Results

A reduction in FAF use is not the only reason why the overall consumption patterns might change. Other reasons include changes in occupancy, changes in occupant behavior patterns, and related effects. Periodic occupant interviews indicated that occupancy patterns were unchanged across all except two sites in this study. This suggests a different, more systematic discrepancy.

To evaluate this problem, the submetered data were used. The goal of the site submetering is to inform the savings calculations made from the billing analysis and thereby determine a more accurate and defensible saving analysis than is provided by the billing analysis alone. Because the DHP operation and the furnace operation were submetered throughout this period, it is possible to describe exactly how much space heat the DHP equipment provided and to compare this result with the observed consumption changes in the billing record.

In this study, the submetering system reports both the kWh use of the DHP during its operation and the actual hours of operation during the submetering period. This information, in turn, is combined with the known COP curves developed in previous studies (Baylon et al., 2012) and correlated to measured outdoor temperature to establish heating output at each temperature bin. The approach allows the analysis to predict the total heating contribution of the DHP to the house and to assess the savings associated with that contribution.

In the case of the zonal-heated homes in previous DHP studies, a fraction of the heating output calculated this way was returned to the home in the form of increased interior temperature, thus reducing the total heating energy savings from the DHP. This factor resulted in about 20 percent reduction in space heating savings between the actual submetered results and the results from the direct performance of the DHP. The COP analysis is repeated in this sample, using essentially the same procedures. In this sample with the FAF heating systems, the impact of this sort of savings reduction was minimal and probably not statistically significant. Table 15 summarizes the savings from the DHP contribution calculated directly from the submetered results.

Table 15. Total Savings, DHP Operation

House Type	Total Savings (kWh/yr)	
	Mean	SD
MH	6105	2511
SF	4715	2224
Total	5373	2405

The billing analysis that focused on the <u>total</u> consumption change is consistent with the results of the total savings analysis from the submetered data. This summary finds total savings within 4% for the whole sample and within 10% for each housing type.

3.3 Savings Determinants

Comparing the results of this study with the results of the previous NEEA and BPA studies finds significant differences. Savings in the previous studies were in the range of 4,000 to 4,500 kWh (Geraghty et al., 2009; Geraghty et al., 2010; Baylon and Geraghty, 2012; Baylon et al., 2012). This result can be attributed to several factors, but the principal effect is the choice of occupant control strategy and its effect on the fraction of space heat provided by the DHP.

A significant factor at least in some cases is the duct leakage and thus the reduction in delivered heating efficiency of the electric FAF. On average, the ducts' leakage and conductivity result in a reduction of 25% in the heat delivered to the house. When the DHP is operating and the furnace is off, this loss is removed and the efficiency difference between the electric FAF and the DHP is increased considerably.

3.3.1 DHP Control Strategies

A review of submetering data for these homes shows three distinct strategies for controlling the central heating system once a DHP is installed.

- The DHP is the primary heating source. This case is relatively common and is the result of the occupant essentially turning off the furnace except under very limited circumstances, usually morning warm-up in cold temperatures. The result is that for the most part the heating requirements are provided by the DHP. This strategy is more common in manufactured homes than in single-family homes, but it is nevertheless used in both these groups and results in a system that substitutes the high-efficiency DHP technology for a lower-efficiency central furnace (which includes significant duct losses in some cases). The net result is to offset not only the energy used by the furnace, but also the additional duct losses. We also noted the likelihood of some 120-volt plug-in electric heater usage with this control scenario.
- The FAF remains primary. This condition is rarer but is the result of the occupant maintaining the central thermostat at a temperature close to the apparent DHP setpoint. In some cases, the DHP is allowed to fill in during milder outside temperatures. During colder weather, however, the furnace and ducts provide the bulk of the heating needs. This control strategy results in lower savings, and indeed in some cases, the DHP has minimal impact on overall heating energy requirements. The more common condition in this control strategy is that the occupant makes a conscious changeover away from the central thermostat as the outdoor temperature permits, and the DHP provides significant space heat during those periods.
- The heating load is shared. The third case is a hybrid of the above two strategies, in which the occupant uses the DHP in most mild weather but switches to the central heating system for a fraction of the time. . The switch can happen when using the DHP mostly or exclusively for morning warm-up in the main part of the house, or when using the FAF as the primary heating source for a small fraction of the heating season when the temperatures are quite low. This mode of operation preserves some of the benefits of the DHP on offsetting distribution losses but does not allow the DHP to provide as much space heating as it might otherwise. As a result, the savings is in between the DHP-primary case and the FAF-primary case.

The three approaches to controls then become the basis for further analysis of the submetered space heat. Table 16 shows the distribution of control strategies between the two housing types.

Table 16. Control Strategies, Submetered Systems

House type	Control Strategy DHP Primary	Shared	FAF Primary	All
MH	5	5	0	10
SF	3	3	4	10

3.4 DHP Heating Fraction

Table 17 shows the distribution of DHP heating as a fraction of the total heat energy delivered by the furnace system and the DHP. In some cases, there are supplemental sources such as 120-volt plug-in heaters and wood stoves. The billing analysis results take the electric supplemental sources into account. The other supplemental fuels may affect one or two cases but have been ignored for this analysis. For the DHP, the heat delivered is defined as the electricity measured by the submeter on the DHP channel times the COP for the DHP derived from previous studies. The control categories shown in Table 17 follow those used in Table 16.

Table 17. Fraction of Space Heat Delivered by DHP (averages)

House type	Control Strategy			
	DHP Prime	Shared	FAF Prime	All
MH	99.1%	68.2%		83.7%
SF	97.6%	78.6%	45.3%	71.0%
Total	98.5%	72.1%	45.3%	77.3%

When the DHP is primary, it provides in excess of 90% of the heat. For this group (40% of the sample), the occupant has essentially abandoned the central furnace system. In many of these cases, a residual space heat component exists that was not directly submetered, although it is accounted for in the total bill analysis. In addition, there are two cases where wood heat was present. In these cases, the occupant used the wood heat as a supplement to the DHP rather than using the furnace. For the shared cases, an average of about 70% of the space heating was attributable to the DHP. Where the FAF is primary, the contribution of the DHP to the overall space heating is less than 50%. In this group (four of the single-family homes), the contribution of the DHP varies substantially, between less than 20% and more than 60% of the space heat total.

3.5 Total Savings Distribution

Table 18 shows the DHP output by housing type and control strategy. Systems using the DHP as primary heat have more than twice the savings of those continuing to use the FAF as their primary heat source.

Table 18. Total Savings by Control Strategy

House Type	Primary Heating			
	DHP	Shared	FAF	All
MH	7295	5152		6105
SF	6308	5381	3021	4715
Total	6872	5238	3021	5373

Table 19 shows the distribution of savings generated from the billing analysis using the same distribution by control strategy and housing type. A comparison with Table 18 shows a remarkable agreement between the results of the submetered output of the DHP and the results of the billing analysis.

Table 19. Distribution of Billing Analysis Savings Results

House Type	Primary Heating			
	DHP	Shared	FAF	All
MH	7893	3888	-	5890
SF	7592	4592	4369	5403
Total	7721	4252	4144	5618

The total savings estimated in this way is quite similar to the total reduction in kilowatt hours observed in the billing analysis, and quite *dissimilar* from the heating estimates provided by the VBDD method. We view this as confirmation that use of the VBDD method for the combination of DHP and central forced-air systems can lead to a misleading result. However, the total bill reduction in combination with the submetered results does provide a good overall estimate of the contribution of the DHP.

Given the difference between the FAF operation in the manufactured homes and the single-family homes in this analysis, where the difference is more apparent than in the billing analysis, we suspect that a great deal of the impact of DHPs on manufactured home heating usage is due in part to the size of the homes relative to the DHP heating capacity. Although regression analysis on this point was unsuccessful, it does seem that the DHP is much more reliably selected as a space heating source in smaller manufactured homes than in larger single-family homes. This may mean that a DHP is more likely to be able to meet the entire heat demand for these smaller homes (which also typically have a open floor plan for the main living area of the home). Even so, the homes that use the DHP as the primary heat source drive the savings in the site-built group. These homes have approximately twice as much savings as homes where the FAF continues to be the primary heating system.

3.6 SEEM Calibration

Using the information collected during the installation and summarized in section 2.4, a SEEM analysis was conducted to determine whether the current SEEM implementation (which was developed using the results of the NEEA DHP study) could be used in this application. The point of this exercise is to eventually provide BPA and the RTF with a framework for developing an incentivized DHP measure for these building types heated with a central FAF.

To develop an estimate of the heating system distribution efficiency, a calibrated SEEM simulation was developed. The procedure involves calibrating the SEEM simulation to the observed heating signature derived from the VBDD analysis of the electric bills before the DHP installation. Thermostat settings were used from the occupant interviews to provide a calibrated base case. Table 20 shows the results of the base case calibration. Overall, the initial runs agree within about 8% of the heating energy estimated by the billing analysis. Although there are some cases that are considerably different, the importance of individual occupant behavior makes this result quite acceptable.

Table 20. SEEM Calibration to Base Case Heating Estimates

House Type	Base Heating Consumption (kWh/yr)			
	SEEM Heating Results		Billing Analysis Results	
	Mean	SD	Mean	SD
MH	12053	4941	10586	3678
SF	9101	2742	8823	2690
Total	10577	4173	9704	3264

This calibration was used to develop the SEEM savings prediction. Table 21 shows the savings results from this simulation exercise. Post-installation calibration was not possible because the VBDD analysis did not produce a reliable space heating estimate. Instead, the savings estimate from the billing totals was calibrated against the SEEM run for the post-installation conditions. The empirically derived heating fraction from the DHP (see Table 17) and the duct leakage calculated from the duct blaster test were used to calibrate the savings analysis in the SEEM runs. The post-installation simulations used the same temperature setpoints used in the initial runs. As with the base case calibration, the comparison between the billing analysis and SEEM is quite close, with about a 4% difference overall.

Table 21. Calibrated SEEM Savings Comparisons

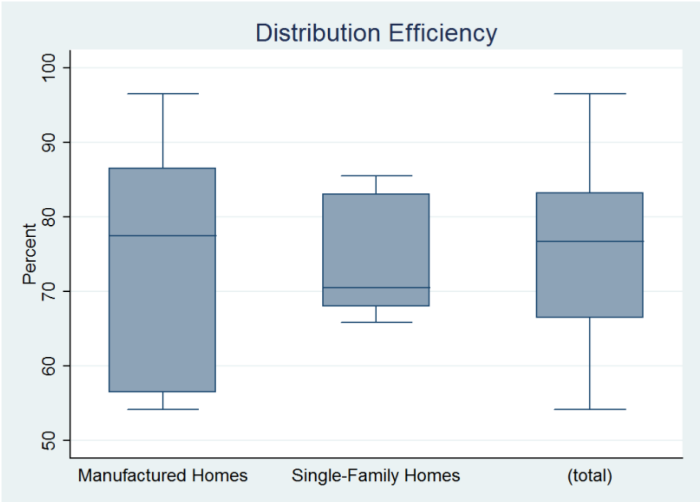
House Type	Savings, Heating Consumption (kWh/yr)			
	SEEM Savings Results		Billing Savings Results	
	Mean	SD	Mean	SD
MH	6231	3268	6022	2833
SF	5479	2240	5214	2541
Total	5855	2754	5618	2652

During the submeter installation, a detailed duct leakage test was done along with a measurement of system airflow and supply plenum and return plenum (where appropriate) static pressures. This procedure results in a calculated duct efficiency shown in Table 22 and Figure 5. Note site-by-site estimates are found in Appendix A.

Table 22. Duct Distribution Efficiency

House Type	Distribution Efficiency	
	Mean	SD
MH	75.0%	15.2%
SF	77.0%	11.1%
Total	76.0%	12.9%

Figure 5. Duct System Distribution Efficiency



3.7 Cooling Analysis

More than half of the sites used some sort of compressor-based cooling equipment before the DHP was installed. These systems were mostly window AC units that were installed during the cooling season and stored during the remainder of the year. The cooling results have been summarized using the Northwest Power and Conservation Council (NPCC) cooling climate zone assignments. Cooling Zone 1 consists of the Puget Sound area and the coastal areas in both Washington and Oregon. Cooling Zone 2 includes all of the lower Willamette Valley and the southwest Washington counties adjacent to the Portland metro area (Cowlitz and Clark counties). Cooling Zone 3 consists of the two counties that compose the Tri-Cities region of eastern Washington (Franklin and Benton counties).

Table 23 shows the distribution of cooling equipment reported by occupants when interviewed at the installation of the submetering system. Approximately 40% of the occupants had no cooling equipment prior to the installation of the DHP. About 53% of the occupants in the western climates (the Willamette and Puget Sound clusters) had cooling equipment. All these homes had one or two window AC units in use only in hot weather. In the eastern climates (Tri-Cities), on the other hand, cooling equipment is the norm, with all homes reporting cooling, two with a central AC system and one with window AC units.

Table 23. Homes with Cooling Equipment by Climate

Cooling Zone	Cooling Type		% with Cooling
	Zonal	Central	
Zone 1	4	0	40.0%
Zone 2	5	0	71.4%
Zone 3	1	2	100.0%
Total	10	2	60.0%

As discussed above, a vapor line temperature sensor was used to distinguish between DHP heating and cooling operation at the submetered sites. As a result, an accurate assessment of cooling energy use was assembled. Table 24 summarizes the cooling energy used by the DHPs included in this sample. The table distinguishes 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 warmer temperatures that would suggest a cooling load.

Table 24. DHP Cooling Use

Cooling Zone	DHP Cooling Use (kWh/yr)		n
	Mean	SD	
Zone 1	106	116	9
Zone 2	91	74	7
Zone 3	527	433	3
Total	167	233	19

The cooling energy use shown in Table 24 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. About 60% of the sample had pre-existing cooling equipment. Table 25 shows the cooling provided by the DHP in the cases where no previous cooling existed. This cooling could be interpreted as new load, but the size of this load is so small that we elected to ignore it in the final savings calculation.

Table 25. DHP Cooling Use, No Pre-Installation Cooling

Cooling Zone	DHP Cooling Use (kWh/yr)		n
	Mean	SD	
Zone 1	39	47	6
Zone 2	113	107	2
Zone 3	0	0	
Total	57	66	8

4 Conclusions

The results of this analysis show a significant electricity savings when a DHP is installed in a single-family or manufactured home heated by a forced-air electric furnace (FAF). The occupants in this study tended to favor the DHP over the FAF in most cases, and indeed chose to operate the DHP to the exclusion of the FAF in many cases. The interaction is surprising because it is quite clear that the furnace, if it were allowed to operate on its own thermostat, would overwhelm the DHP and result in essentially no savings. In the great bulk of this sample, however, that did not occur. The overall impact is about a 45% increase over the observed savings from the NEEA DHP study (Baylon et al., 2012), and a similar improvement over the previous BPA Monmouth study

(Geraghty et al., 2009; Geraghty et al., 2010; Baylon and Geraghty, 2012). Cooling energy use in this group, as in other groups evaluated in past studies, was insignificant. Table 26 shows the total savings from the billing analysis and total savings as measured by the heat output of the DHP measured from the submetered data. Although these two estimates differ somewhat, the agreement is quite striking, and there is no statistical difference between the two. Overall savings of about 5,500 kWh/yr is a reasonable estimate.

Table 26. Final Savings Results

House Type	Savings, Heating Consumption (kWh/yr)			
	Submetered Savings Results		Billing Savings Results	
	Mean	SD	Mean	SD
MH	6105	2511	6022	2833
SF	4715	2224	5214	2541
Total	5373	2405	5618	2652

The savings determinants in this sample are largely focused on the control strategies used by the occupants in managing the DHP and the rest of their heating system. In cases where the occupant favors the DHP to the exclusion of most other heating sources, savings are dramatically higher. This result is fairly predictable. However, in this study, 40% of the occupants made this selection. It should be pointed out that the recruitment of these sites was not as selective as previous studies, so it is reasonable to suspect that this 40% may be fairly robust across other samples.

In addition, another 40% used the DHP as a fairly equal partner with the furnaces, producing up to 75% of the space heating required by the home. The furnace is used intermittently in these cases, usually in colder temperatures and/or during limited periods of morning warm-up. The thermostat pattern for this case is that the occupant manually turns on the furnace for some period of time, and then turns it off again whenever those conditions are no longer present.

The FAF remained the primary heating source in only about 20% of the cases. In those cases, savings were driven down, although only to levels similar to those observed in the zonal electric-heated homes.

The impact of creating a zonal heating system, even a partial one, on these homes is, we believe, the decisive impact of this technology when paired with a central ducted system. In homes where the DHP becomes the primary heating source, the duct losses associated with the furnace are greatly curtailed. Any time the DHP is operating in lieu of the FAF, these additional savings, which account for about 25% of the apparent heating energy use or the apparent heating output, are actually an accumulated savings, even though the DHP is not producing that heat directly.

In order to minimize the use of the FAF while maintaining occupant comfort, several strategies can be employed. These all focus on getting heat to the back rooms.

- 120-volt space heaters could be supplied to occupants for some or all of these rooms. In this study, most participants used one space heater for supplemental heat.
- The thermostat for the FAF could be moved to one of the back rooms so that it activates the furnace only when the DHP cannot keep up.

- A second FAF thermostat could be installed in a back room and wired in parallel with the main thermostat. This way, either thermostat could activate the FAF.
- The registers in the area of the home heated by the DHP could be closed or blocked off.

In addition to the above strategies, occupants should be educated to establish a main FAF thermostat heating setpoint significantly lower than the DHP thermostat.

The use of supplemental heat in this sample seems to be fairly minimal. In two cases, occupants mentioned space heating from wood heat or pellet stoves. In both these cases, the occupants said that they continued to use these stoves in the manner that they had previously used them. In both cases, these were supplemental sources that provided a fraction of the heat, and it appears that these sources continue to provide roughly the same amount of heat even after the addition of the DHP.

Temperature increase in the central zone could not be measured because we have no previous data on the interior temperature of the home. However, from interview data, it is apparent that at least some of the occupants operate the DHP to maintain a higher central living space temperature than had been maintained by the furnace. This factor does not appear to have the kind of impact that it has in the zone-heated houses because the extra temperature in the central zone serves to make the outer zones more comfortable, and thus reduces the probability that the occupants will turn on the furnace. There are no separate thermostats in those zones in a central furnace home, so in general, the higher temperature in the central zone is probably counter-balanced by reduced temperatures in the outer zones.

Finally, it should be noted that these homes were selected based on participation in the NEEA DHP pilot program and, in a few cases, in focused programs that individual utilities ran at the behest of BPA in order to get additional FAFs for this study. Screening was done minimally, although in the DHP program, occupants were generally required not to use wood heat, either before or after the installation of the DHP. Although this secondary heat varied somewhat throughout the region, it is apparent that in this sample fairly few of the homes used wood heat, and indeed, most of these homes had substantial electric heating loads prior to the installation of the DHP.

The overall impact of this analysis suggests that the DHP technology applied in FAF homes can provide significant space heating and provide occupants with a space heating option that provides measurable and noticeable savings in their electric bills. The next step should be to develop a set of SEEM runs on appropriate prototypes so that a range of expected savings can be generated in the context of a regional program for forced-air electric homes.

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Appendix A. Full Site Building Characteristics

Table 27. Manufactured Home Building Characteristics

Customer ID	Heating Zone[1]	Cooling Zone	Number of Occupants	Conditioned Floor Area (ft²)	Total House Heat Loss Rate (UA) F)	UA/ ft²	Supply-side Duct Leakage Fraction[2]	Infiltration Rate (Air changes/hr)[3]	Duct Efficiency[4]
10289	1	1	3	1577	526	0.333	3.1%	0.45	77.2
18520	1	1	2	2316	450	0.194	2.0%	0.65	74.0
18594	1	1	2	2139	509	0.238	5.8%	0.47	96.5
19235	1	2	2	784	320	0.409	4.6%	0.49	55.4
19236	1	3	2	986	796	0.808	89.9%	0.11	90.8
20167	1	1	2	1323	528	0.399	44.2%	0.50	56.5
20369	1	1	2	1188	254	0.214	14.6%	0.58	82.0
99907	1	1	1	756	472	0.624	17.9%	0.18	86.5
99909	1	1	1	891	460	0.516	1.8%	0.41	54.2
99919	1	3	2	1222	439	0.359	20.3%	0.47	77.7

[1] Heating zone 1 is defined as having fewer than or equal to 6,000 heating degree days (HDD). Cooling zone 1 is defined as fewer than 300 cooling degree days; cooling zone 2 has 300-600 cooling degree days; and cooling zone 3 has more than 600 cooling degree days. Heating and cooling zone definitions are set by the Northwest Power and Conservation Council (NPCC), www.nwcouncil.org.

[2] Supply leakage to exterior divided by measured air handler flow

[3] Blower door flow at 50 Pa test pressure/20.

[4] As estimated by SEEM

Table 28. Single-Family Building Characteristics

Customer ID	Heating Zone[1]	Cooling Zone	Number of Occupants	Conditioned Floor Area (ft^2)	Total House Heat Loss Rate (UA F)	UA/ ft^2	Supply-side Duct Leakage Fraction[2]	Infiltration Rate (Air changes/hr)[3]	Duct Efficiency[4]
10542	1	1	1	1607	499	0.310	9.6%	0.52	76.7
10571	1	1	2	2062	716	0.347	33.0%	0.41	85.5
10584	1	1	2	1587	546	0.344	24.1%	0.33	68.6
10611	1	1	1	1247	474	0.380	14.1%	0.28	100.0
10687	1	2	2	800	711	0.889	22.3%	0.56	68.0
11700	1	1	4	2126	526	0.247	6.3%	0.52	65.9
11776	1	2	2	1173	542	0.462		0.60	70.6
12395	1	2	2	1027	332	0.324	8.9%	0.48	83.0
12868	1	2	1	2140	548	0.256		0.29	83.2
13516	1	3	4	3092	666	0.215	n/a	0.48	66.5

[1] Heating zone 1 is defined as having fewer than or equal to 6,000 heating degree days (HDD). Cooling zone 1 is defined as fewer than 300 cooling degree days; cooling zone 2 has 300-600 cooling degree days; and cooling zone 3 has more than 600 cooling degree days. Heating and cooling zone definitions are set by the Northwest Power and Conservation Council (NPCC), www.nwcouncil.org.

[2] Supply leakage to exterior divided by measured air handler flow

[3] Blower door flow at 50 Pa test pressure/20.

[4] As estimated by SEEM

Appendix B. Site Screening and VBDD Analysis

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

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

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

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

where:

- DD : Daily Degree Days
- T_{BASE} : Degree-Day Reference Temperature
- T_H : Daily High Temperature
- T_L : Daily Low Temperature

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

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

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

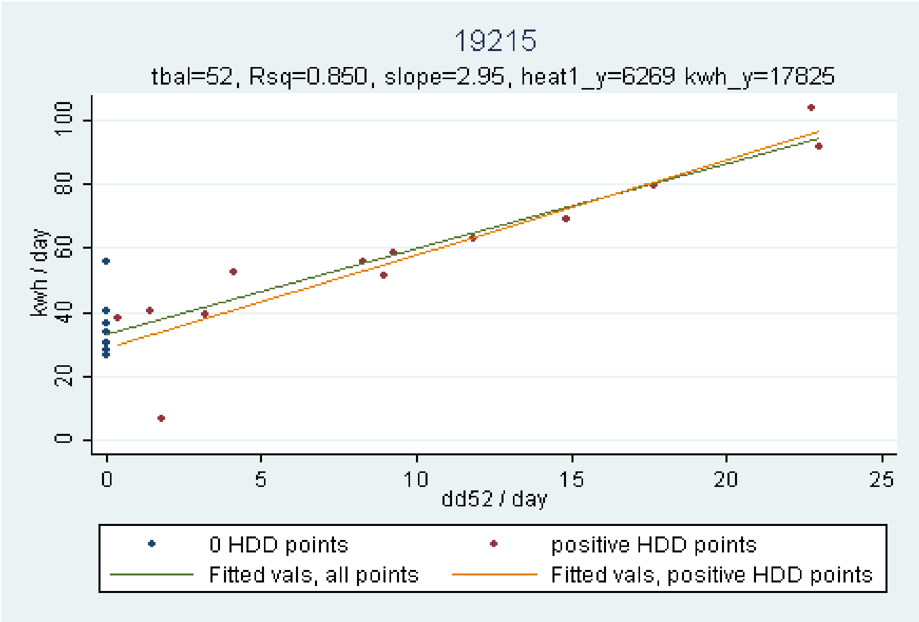
For most Pacific Northwest weather sites, there are months in which no degree-days occur and no space heating occurs. In western Washington and Oregon, for example, it is not unusual for space heating to be completely absent between May and October in well-insulated homes. Ecotope's regression algorithms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

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

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

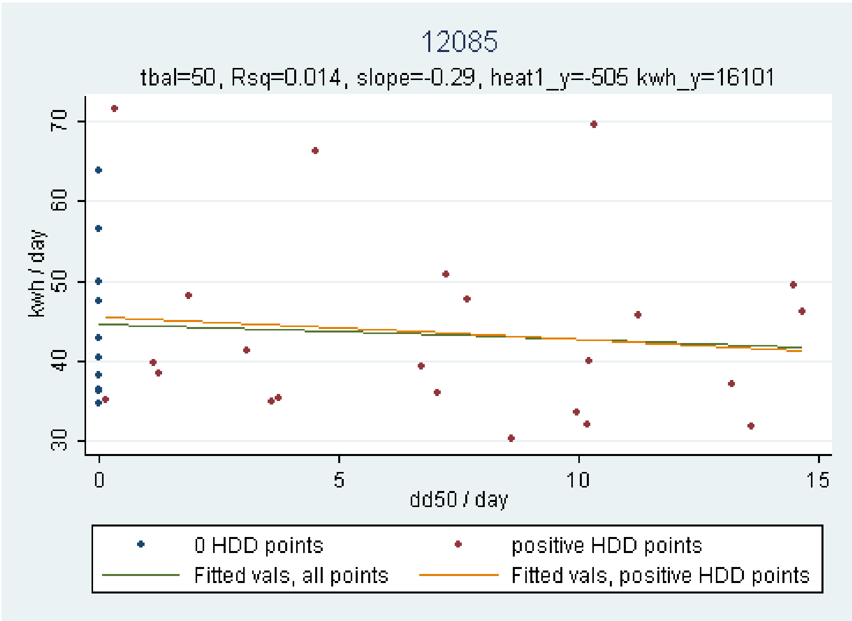
Figure 6 shows a site that exhibits a well-behaved relationship between electricity usage (kWh/day, on y-axis) and outdoor temperature (degree days, on x-axis). The VBDD process finds that the best-fit degree day base is 52° F and estimates an annual heating energy usage of 6,269 kWh/year. In Figure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

Figure 6. VBDD Regression with Strong Seasonal Relationship



A second example illustrates a common problem with sites that include a DHP: likely usage of wood or another non-electric heating fuel. Ideally, a DHP would not be installed in this site because it would not offset heating electricity. Figure 7 shows no apparent relationship between electricity usage (red dots) and the best-fit regression line. The correlation coefficient is effectively 0, indicating mathematically that there is no relationship between electricity usage and winter (heating) conditions.

Figure 7. VBDD Regression with Weak Seasonal Relationship



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

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

Appendix C. Metering Protocol (Forced-Air Furnace Sites)

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 Manufactured Other:	Year house built	
		Indicate major remodel details/dates (especially if weatherization occurred):	
Location of EFA furnace Garage Inside Crawl Attic Other	Does site have central AC? Yes No	Location of DHP(s): 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/freezer ________

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, what temperature did you set the thermostat for <u>heating</u> during occupied times_______° (if central AC): for <u>cooling</u> during occupied times______º

What setback temperatures/times did you use? Heating_______________   Cooling____________

Since the DHP installation, what temperature did you set the thermostat for <u>heating</u> during occupied times_______° (if central AC): for <u>cooling</u> during occupied times______º

What setback temperatures/times do you use? Heating_________________   Cooling____________

If your DHP has been installed within the last 18 months, your answers to the following questions will help us more accurately interpret the data we collect as well as help us help you to optimize the DHP's performance.

The DHP controller is set to:

( ) HEAT

( ) COOL

( ) I'm not sure

The DHP fan setting is set to:

( ) AUTO

( ) Usually quiet

( ) Low

( ) Medium

( ) High

What is the current DHP temperature setting? ____________

How often do you change the temperature setting?

( ) When I want the temperature warmer/colder.

( ) I don't change the setting.

Is the DHP left on during the day? ___________ If not, when is it on:

Is the DHP left on overnight? _______________

Where do you spend the majority of your waking hours in the home? _________________________

How do you heat/cool the spaces in the home you use less frequently?_________________________

What is the status of your back-up heating system (furnace, resistance heaters, other pre-DHP)?

Are you satisfied with the control strategy? ______ yes ______no
If not, what problems are you having (cold rooms?)
____

Are you going to try different control as a result of this audit? If so describe____________________

How often do you clean the DHP filter? ______________

How many window air conditioner units do you have in your home, if any? _______________

In the year prior to the DHP installation, in which months did you use your air conditioner?
____

Do you still use any room air conditioners? If so, how many? _____________________________________

Do you regularly use 120v plug-in heaters??____ yes ____no If yes, how often and in which room(s)?____

Has your plug in heater usage changed since DHP installation?____
____

Though you just recently installed your DHP, I'd like to know how your experience has been with the 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						

House heat loss rate calculation (note spreadsheet can also be used if desired)

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

Record heated floor area here: ______________ ft^2

Record house volume here: _________ft^3

Ducts/Airflow

We need enough information to estimate the system efficiency of the ducts. This means getting the length and diameter and insulation level of the ducts in unconditioned spaces such as garage, attic and crawlspace. If the ducts run between-floors, also note this. **Ducts fully inside the conditioned space do not need to be measured.** Measure diameters to nearest inch and lengths (overall) to nearest 3'. Estimate as needed to save time by pacing off runs inside the house, using stud spacing as an estimating device, etc. If insulation is damaged or missing, note as needed. **Describe both supply and return sides of system. Make sketch/notes as needed.**

Supply ducts (list all unique dimensions/insulation levels)

Duct type (metal/flex)	Duct Zone Location (garage, attic, crawl, other)	Dimension (LxW or inside diameter if round)	Length (feet)	Area (ft^2) (convert dimension to ft first)	Insulation (best guess on R-value)*	UA to Duct Zone

*R-value/inch is about 3 for fiberglass; derate if damaged or missing

Return ducts (list all unique dimensions/insulation levels)

Duct type (metal/flex)	Duct Zone Location (garage, attic, crawl, other)	Dimension (LxW or inside diameter if round)	Length (feet)	Area (ft^2) (convert dimension to ft first)	Insulation (best guess on R-value)*	UA to Duct Zone

*R-value/inch is about 3 for fiberglass; derate if damaged or missing

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:

Close all windows and doors to the outside. Open all interior doors and supply registers.

Close all dampers and doors on wood stoves and fireplaces**.** Seal fireplace or woodstove as necessary to prevent ash disaster.

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 back drafted by the blower door.

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.

Set fan to depressurize house. Run pressure tap out through door shroud.

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.

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								

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):

TrueFlow test

Set-up: Turn on air handler (by using fan-only switch or by turning on heat/AC). Drill access hole as needed and point hooked end of static tap into airflow**. Do not drill into the duct at any point where you are concerned with hitting something.**

Measure pressure in supply plenum. Record pressure below as Normal System Operating Pressure (NSOP). Also measure pressure in return plenum and record:__________

Place appropriate plate and spacers into filter slot. Turn on air handler and record supply static pressure with TrueFlow in place (TFSOP) and pressure drop across plate.

Plate used (14 or 20) _______________

Normal System Operating Pressure (NSOP) _____Pa

True Flow System Operating Pressure (TFSOP) _____Pa

Correction Factor* √(NSOP/TFSOP) __________

Plate pressure drop ________Pa

Raw Flow (CFM)________

Corrected Flow ________CFM

Exterior Duct Leakage Test

Performing exterior duct leakage test:

Exterior house doors and garage doors should be closed for exterior duct leakage test.

Pressurize the house to about 50 Pascals WRT outside.

Pressurize tested part of duct system to about 50 Pascals with smallest flow ring possible.

Measure pressure of ducts WRT house. Make sure blower door flow does not impinge on pressure tap measuring house pressure.

Adjust duct tester speed controller so that duct pressure WRT house is zero or very close.

Re-check pressure of ducts WRT outside.

Measure duct tester fan pressure. Look up flow in table, use gauge **(make sure gauge is paired with the right duct tester)** or use flow equation. Record duct pressure WRT out, DB fan pressure, DB fan ring.

If you cannot reach 50 Pa or 25 Pa, test to the highest pressure you can reach and enter this in the 50 Pa column. Use a test pressure of half this pressure for the low pressure test.

Repeat steps 2-7 with house and ducts at about 25 Pa WRT outside.

Check flow exponent (as above).

Note any unusual testing conditions (wind, etc.):

Duct Leakage to Outside Data (note duct pressure WRT outside may not be exactly 50 or 25 Pa)

	Both sides		Supply or Return (circle one)	
	50 Pa	25 Pa	50 Pa	25 Pa
Duct P	____	____	____	____
Ring	____	____	____	____
Fan P	____	____	____	____
Flow	____	____	____	____

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.

DEVICE	**S/N**	**NOTES**
U30	S/N: Record device keycode#:	

WattNode Model# ____________		
Temp. Sensor 1 (OAT)		
Temp. Sensor 2 (VLT)		
Pendant (IDT-main)		
Pendant (IDT-back)		
Pulse 1 (SERV)		Service entry CT size__________ A Parallel _____ or series ______
Pulse 2 (FAF)		CT size(s)__________ A Parallel (if picking up OD unit)______
Pulse 3 (DHP)		CT size__________ A
TRMS (DHW)		CT size__________ A

Note: to check out SERV on 30 sec avg with 100A CTs in parallel, multiplier to compare with clamp-around is 200. DHP multiplier (assuming 50 A CT) is 100. FAF multiplier (assuming 100 CT(s)) is either 200 or 400 (if 2 100A CTs installed in parallel to get FAF/CAC circuit(s)).

DHP outdoor unit make/model:

ID unit make/model:

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

Appendix D. Weather Stations Used in Billing Analysis

Weather Station	Housing Type		
	Manufactured Home (MH)	Single-Family (SF)	Total
OR Brookings	1	0	1
OR Eugene	1	0	1
OR McMinnville	0	1	1
OR Salem	0	2	2
WA Mount Vernon	1	0	1
WA Fort Lewis	1	0	1
WA Hoquiam	1	0	1
WA Kelso	2	0	2
WA Olympia	1	0	1
WA Pasco	2	1	3
WA Seattle	0	5	5
WA Vancouver	0	1	1
All Sites	10	10	20

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