Performance of Ductless Heat Pumps in the Pacific Northwest

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ABSTRACT

The advent of small, inverter-driven compressors—the mini-split or ductless heat pump (DHP)—creates a possible retrofit opportunity for single-family homes heated with electric resistance zonal heating. This is a significant technological improvement that could triple heating efficiency, greatly improve cooling efficiency, and be applicable to electric heating systems throughout the country. Pacific Northwest utilities embarked on a multiyear pilot program to install, monitor, and evaluate this technology. The first phase of the pilot was conducted on fourteen homes in Oregon and Washington. This sample was submetered with a "quad-metering" protocol, which assessed four channels of energy use (DHP, electric heat, hot water, and total use).

This paper will report on the evaluation of the sub-metered data collected on these homes. All homes used zonal electric resistance heating. Energy savings were derived from hourly data collected over one year in each of these homes. Base-case heating and normalized energy use estimates were derived from a billing analysis which was calibrated with the submetered data. This procedure allowed the development of weather-normalized savings estimates for each home using a Variable Base Degree Day analysis.

Overall savings indicated by this research suggest that with a small DHP (<24 kBtu), savings of 44% of the heating energy was observed (on average). With a very simple installation, this level of savings implies a cost-effective measure for Pacific Northwest utilities and customers. The dataset also indicates limitations and further requirements crucial to developing the metering protocol for a larger submetered sample, currently underway on 95 homes in the region.

Introduction

The ductless heat pump (DHP), or mini-split heat pump, is a technology used extensively in Asia, and in various sectors of North America, for at least 30 years. This technology is based on small compressors with single or double air handlers, mounted onto walls or ceilings to provide direct space heating and cooling. Historically, these heat pumps have been relatively inefficient and, more importantly, poor at providing heat especially below 40°F (outdoor temperature). With the advent of new federal standards in 2006, several manufacturers from East Asia introduced an inverter-driven compressor technology that allows much better performance across all temperature bins. This technology is coupled with a multispeed or inverter-driven fan. The output from these modern compressors and fan systems is fairly impressive, and their efficiencies are improved by the ability of the equipment to match loads and temperature requirements with simple controls.

As these new technologies became available, their potential as a retrofit technology in the Pacific Northwest became of increasing interest. From preliminary market assessment (NEEA

2009) it was decided that such technology could be used in retrofitting electric zone heated homes. This approach offered a significant market with large savings opportunities.

About 575,000 existing homes in the four states of the region (Washington, Oregon, Montana, and Idaho) have electric resistance zonal heating. Over the last three decades the regional utilities embarked on numerous weatherization programs to upgrade the insulation levels in these homes, with reasonable success; however, few additional improvements were available without replacing the HVAC system. It has been historically difficult to upgrade the HVAC systems in these homes because of the lack of existing ductwork. Furthermore, the cost of such a retrofit has been generally prohibitive, especially for low- and middle-income families.

The DHP system, while not particularly inexpensive, promises the ability to improve a single zone (or two zones) in the main living area of the house with a heat pump that could operate at a coefficient of performance (COP) well above 2.0 and provide a significant fraction of the space heating requirements of the house without installing a central heating and ducting system into the house. Such a technique would provide significant savings over the electric resistance units (baseboards or wall heaters) typical of the zonal heating systems.

Pacific Northwest DHP Pilot Study

Beginning in 2007, the Pacific Northwest, through the Regional Technical Forum (RTF), a technical review body for utility energy efficiency programs throughout the region, developed a standard to be used as a preliminary estimate of savings for DHPs in the absence of any experience in the interaction between this equipment and electric zonal heat systems. Since the DHP system would retrofit into an existing system, it would *displace* the heat provided in some, but not all, zones of a house. The occupants themselves would control whether or not the equipment was used. Therefore, the system would have to maintain a level of even heat and comfort, as well as a level of control attractive to occupants, offsetting an existing electric baseboard system. In addition, cost considerations dictate a focus on a single zone (single compressor) in order to preserve the cost-effectiveness of the DHP as an energy-efficiency measure.

Under the guidance of the RTF a multiyear pilot program was designed and funded through the Bonneville Power Administration (BPA). The first phase of this pilot program was aimed at a small number of electric-resistance heated homes where DHP units were installed.

The goals of this initial pilot study were to:

1. Provide proof of concept for the “quad-metering” protocol using real-time monitoring of kWh energy use and temperature. The measurements are logged in real time and are designed to separate the consumption of the DHP system from the remaining electric resistance zonal heating system.
2. Assess the viability of using billing data collected from a period prior to the installation of the DHP system to provide the baseline consumption used for calculating changes in space-conditioning consumption. This approach included the use of classic weather-adjustment procedures on billing data to develop weather-compatible consumption estimates for purposes of estimating heating energy savings.
3. Develop changes in the metering protocol and data collection that would enhance the confidence and veracity of energy savings estimates from these metering and analysis procedures.

4. Summarize consumption characteristics from homes metered in this initial project and assess the heating energy savings from the installation.
5. Review and assess cooling energy impacts on the final energy savings from the DHP installation.

Methodology

Three small utilities in the BPA service territory participated, and a total of 14 electric-resistance zonal houses were retrofit. In all cases, an individual compressor and an individual air handler were installed as the primary retrofit in a central living zone. Once the heat pump was installed, a “quad-metering” system was also placed in the house. This included four current transducers subdividing the electric load of the house. The circuits metered using the “quad-metering” protocol were: the DHP itself; the remaining space heating equipment; the domestic hot water (DHW) heater; and the total energy use for the house. In addition, outdoor and indoor temperature measurements were included. The metering system began operation in or around February 2008, and continued for one year. This metering system became the basis for evaluating the potential savings from this technology as it applies to this population of residential space heat customers.

Generalizing performance from a small group is problematic, but the installations and metering results provide a very useful engineering overview of the potential for these systems. Furthermore, this study was an experiment meant to develop and refine an initial approach to DHP metering and energy savings analysis. These efforts informed the methodology for the larger and more systematic evaluation study currently underway. There are some data deficiencies, such as no measurements to distinguish heating and cooling loads in these DHPs, no logged whole-house consumption on two sites, and imprecise installation dates. On the positive side, the research has provided savings estimates for this group and invaluable insight into the types of data that must be collected to distinguish between heating and cooling operation. The methodology proceeded in the following steps:

1. The bills for each house were gathered for a period up to three years prior to the installation of the DHP. In two homes these bills were missing or unreliable, and those homes received only a partial analysis or were abandoned.
2. The results of the submetered data were collected over the course of a 13-month period from February 2008 to March 2009. This data included the space heat channels for the electric resistance space heat, the DHP, the domestic hot water, and the total electricity supplied to the house at the main service. The data was logged on a five-minute average which included true power corrections for the heat pump and the main and current transducers for the other two power channels
3. A variable-base degree-day (VBDD) regression analysis was conducted on the bills from the pre-period to evaluate a predicted heating load and to provide a basis for weather normalizing this load for comparison to the observed submetered data.

Heating energy savings were calculated comparing the estimates of space heating requirements from the billing analysis and the metered space heating in the year of DHP operation.

Variable-Base Degree-Day Billing Analysis

The study regressed billing period consumption on billing period degree-days using a modification of the standard variable-base degree-day method pioneered in the 1980s (Fels 1986). Under the PRISM method, also known as variable-base degree-day regression, the heating degree-day (HDD) base and the regression response coefficient of energy consumption to degree-days are jointly estimated by finding the heating degree-day base which maximizes the regression coefficient of determination (R^2). In a single-zone structure the linear coefficient has the interpretation of house UA, and the regression intercept has the interpretation as a seasonally-constant average baseload not dependent on space heating demand. The degree-day base estimated by this procedure has an interpretation as the house balance point; that is, the lowest outside temperature at which the home does not require space heating. Although 65ºF is a plausible thermostat set point, it is not a reasonable balance point for the vast majority of houses. Varying solar gains and thermostat set point changes have the effect of changing the balance point, so that the actual heating input data (the bills) in fact reflect some random mix of effects of heating degree-days to different bases.

The "Ecotope modification" to the PRISM procedure involves excluding data points from a regression estimation where the billing interval's heating degree-days to that base are zero. Empirically, this serves to insulate the heating estimates from the influence of summertime cooling loads, which certainly exist for some of our sites.

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

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

Where β is the estimated regression slope coefficient, *HDD* is calculated heating degree-days for month *m* to the chosen base, and α is the estimated regression constant. In effect, some of the seasonally-varying load is taken away from the heating estimate $\beta \cdot HDD$ and given to the base load estimate α. Given estimated coefficients, the above formula can be used to predict heat consumption given a new set of HDD data—not the HDD data used in the actual coefficient estimation.

This procedure was then used to derive estimates of the heating consumption that would have occurred in the "post" period had the old heating system not been replaced by a DHP. The parameters estimated from the bills in the "pre" installation period are applied to the "post" period's HDD in the above formula. In this analysis we used the weather data to develop the post-installation and pre-installation heating estimates.

Weather

Raw comparisons of energy consumption over different time periods can be misleading if the weather over the two periods is significantly different. Table 1 reports "pre" and "post" heating degree-day comparisons for National Weather Service Cooperative Station Network sites that best matched the 14 house locations. There is a consistent pattern of increase in annual heating-degree-days (increase in heating requirements) between the pre-installation period and the post-installation period. This increase occurred independent of the particular locality and of the calculation base from which the climate was evaluated. Thus the weather in all the sites was significantly colder in the period in which the DHP was evaluated than in the previous periods used to generate the base-case heating estimates,

Table 1. Weather Station Heating-Degree-Day Summary

Weather station	Periods	Base 55ºF	Base 60ºF	Base 65ºF
Monmouth	2006-2007 Pre	2,169	3,370	4,744.5
	2008-2009 Post	2,444	3,671	5,082
	% Change	+12.7%	+8.9%	+7.1%
Moses Lake	2003-2006 Pre	3,329	4,425	5,689
	2007-2008 Post	4,077	5,224	6,499
	% Change	+22.5%	+18.1%	+14.2%
Tacoma	2005-2007 Pre	2,505	3,790	5,343
	2007-2008 Post	2,716	4,058	5,632
	% Change	+8.4%	+7.1%	+5.4%

Source: Ecotope, Inc. 2009

Energy Consumption

Up to three years of utility billing data were collected for the pre-installation period. The most recent pre-installation period usually ended in the fourth quarter of 2007. A composite "annualized" total consumption was constructed to collapse these multiyear pre-installation bills into a single "pre" billing year. For the comparison post-installation period, the metered one-year total from the quad-meter system was used, rather than utility bills, since at the time of the analysis insufficient post-installation bills were available.

Table 2 is a raw comparison of these before-and-after installation total kWh consumption figures for each of 13 sites, uncorrected for any differences in weather from year to year. The "pre" figures are derived from monthly bills; the "post" figures from aggregated hourly logged data. Two missing values (MosesLake 1 and 2) in the post period reflect the absence of whole-house data logging in those two cases. Even without any total use information, these sites can be evaluated for heating energy savings using the regression analysis on the pre-bills and the observed total space heat developed from the metering system. A final sub-metered site, Monmouth 3, is not shown because it had less than a full year of available "pre" bills at the time of the analysis. The aggregate change, for the 11 sites with both figures available, shows a decrease in electrical energy consumption of 2,800 kWh per household (12% decline) when the actual un-normalized consumption is compared.

It is important to note that the comparison in Table 2 does not account for the significant changes in weather that occurred between the base years and the post-installation period. Thus weather normalization is essential to assess the space conditioning energy savings that could be attributed directly to the DHP installation.

Table 2. Total Whole House Annualized Consumption (kWh/yr)

	Consumption		
	Pre-bills	**Post (logged use) 2008-2009**	**Raw Savings**
Monmouth 1	26,332	23,062	3,270
Monmouth 2	20,836	19,633	1,203
Monmouth 4	22,382	23,723	-1,341
Monmouth 5	16,703	13,733	2,970
Monmouth 6	23,451	19,997	3,454
Monmouth 7	20,410	19,193	1,217
Monmouth 8	32,631	28,912	3,719
Monmouth 9	20,139	21,171	-1,032
Monmouth 10	37,162	25,102	12,060
Monmouth 11	23,829	21,330	2,499
MosesLake 1	12,162	--	--
MosesLake 2	29,244	--	--
Tacoma 1	15,483	12,779	2,704
Average (of 11)	**23,578**	**20,785**	**2,793**
Median (of 11)	**--**	**--**	**2,704**

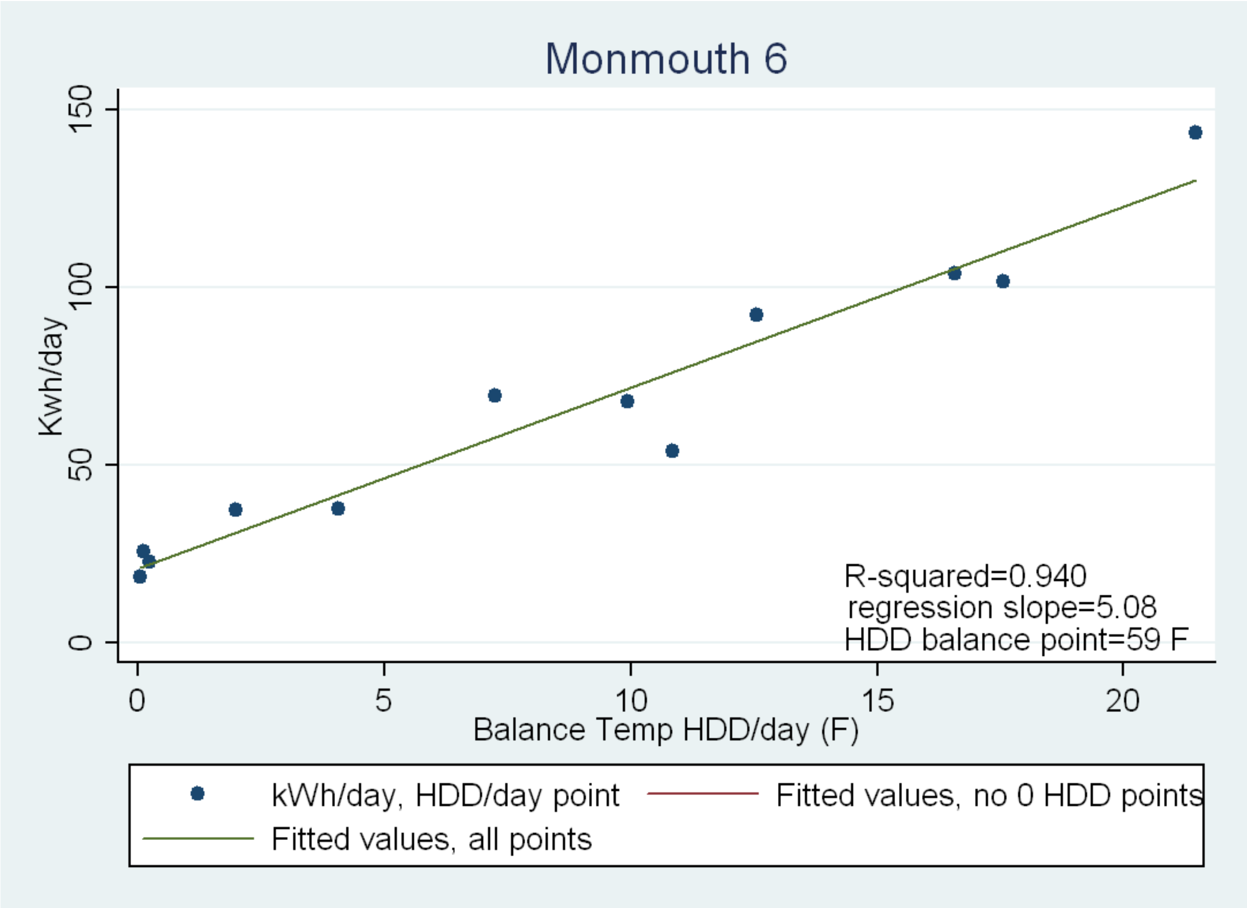
Source: Ecotope, Inc. 2009

Weather Normalization

To put the "pre" and "post" periods on an equal weather footing, we fit VBDD regressions to the "pre" metered bills for each of the 13 sites for which we have at least 12 months of "pre" bills. Where we had more than one year, the bills for all available months were included in the regression with the appropriate weather data.

Figure 1 displays a typical scatter plot that illustrates this analysis. This site (Monmouth 6) was analyzed comparing monthly kWh/day consumption (generated from electric bills) against degree-days per day (generated from the Salem, OR weather data for the pre-installation period) to balance point for that site (59°F). The ascending straight line is the fitted regression line that captures the response of monthly average kWh per day to monthly average heating degree-days per day. Estimated coefficients and degree-day base (balance point) from these regressions provide a way to disaggregate billed consumption into heating (HDD-sensitive consumption) and "other" consumption. They also offer a way to predict heating consumption given a new set of temperature data from a subsequent period. The R^2 for this site is typical of these homes and shows a good relationship between weather conditions and heating energy consumption. We applied the coefficients estimated using the "pre" period data to the temperature data recorded in the "post" submetering period to estimate the hypothetical heating consumption that would have occurred in the "post" period without the DHP installation.

Figure 1. Point Scatter and VBDD Regression Lines for a Representative Site



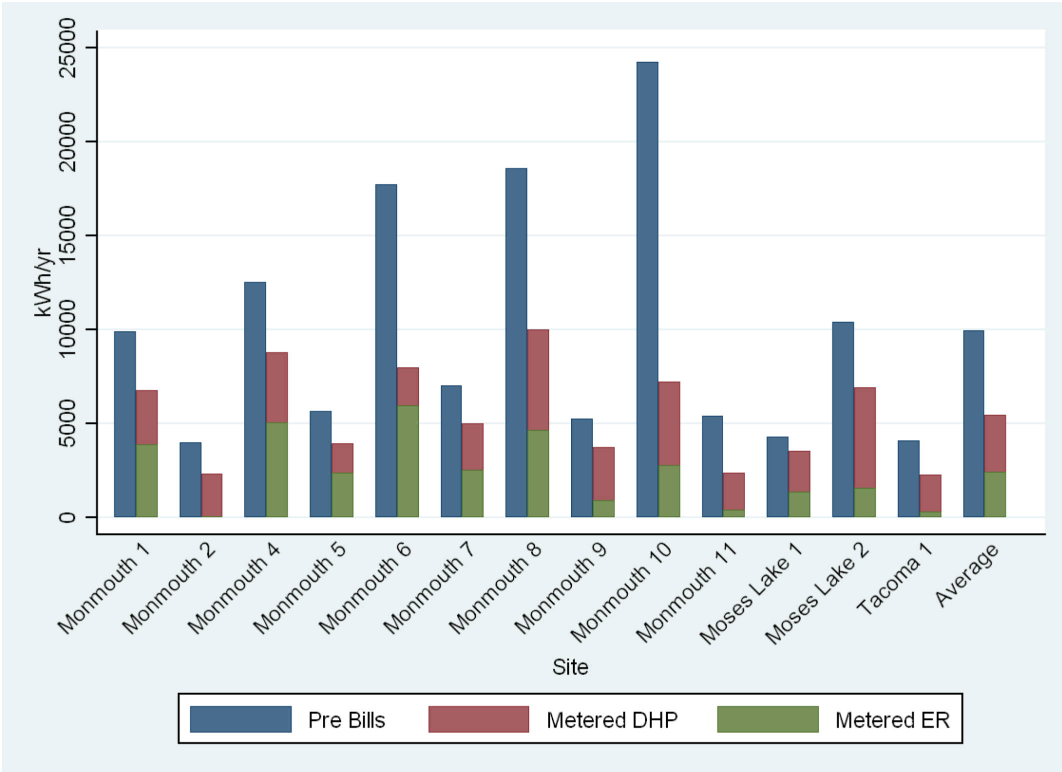
Source: Ecotope. Inc. 2009

Savings Analysis

Figure 2 compares the estimated weather-normalized space heat consumption from the billing VBDD analysis (pre-installation coefficients applied to post-installation year temperatures) with the actual observed space conditioning consumption in the post-installation year. The blue bar in each pair shows the VBDD-derived weather-normalized heating consumption for each site in the pre-installation period. The red-green bar in each pair shows the directly-measured accumulated space-conditioning consumption for the post-installation year. The red portion of a red-green bar represents the total energy used by the DHP, and the green portion shows the energy used by zonal electric space heaters.

In Figure 2, it is possible to make the relevant comparisons with 13 sites, rather than 11 from Table 2, since the two sites which lack logged whole-house "post" consumption have logged DHP and resistance "post" heating consumption. The average savings represented by these sites is about 4400 kWh for the entire year. This is about 44% of the space heating estimated by the billing analysis when averaged over the houses metered.

Figure 2. Heating Energy Savings by Site



Source: Ecotope. Inc. 2010

Cooling

The presence of summertime cooling load poses challenges for the VBDD methodology. Cooling reduces the apparent heating savings by increasing the submetered DHP usage. Cooling can also bias the VBDD methodology by inflating the baseload estimate, thereby reducing the apparent heat load throughout the heating season. One response to this problem is our practice of excluding zero-HDD data points when estimating VBDD regressions.

An alternate approach employed in significant cooling climates is to complicate the VBDD model by adding cooling degree-days (CDD) as an explanatory variable. This action adds two parameters to the three-parameter model: the CDD base, and the CDD response coefficient. Usage of window AC units (the predominant cooling mechanism in houses with resistance heat) does not, however, have a very consistent relationship to cooling degree-days, since such units are typically not regulated by a thermostat. Consequently, CDD coefficients estimated from bills reflecting window AC usage are often unstable, with little explanatory power. We did not pursue this approach.

Roughly half the sites in our study group had window AC units prior to the DHP installation, and we can assume that some cooling occurred during much of the sample, both before and after DHP installation. Prior bills, and post-installation logged data, provide clues that cooling load has occurred. In most of the sample, those clues suggest cooling load that is nonexistent or very small relative to annual heating load.

Cooling load also poses problems for interpreting the submetered logged DHP usage data. We were unable to develop a reliable method of assigning all hourly DHP usage to heating or cooling based on indoor and outdoor hourly temperature alone. Approximately 85% of hours where some DHP usage was logged could be assigned with confidence to heating or cooling, but the remaining 15% were ambiguous. Additional state information appears necessary to assign this residual 15% to heating or cooling. Nonetheless, it is possible to detect approximate cooling loads in a few of our sites, based on seasonal usage. In three sites there was evidence of cooling in the VBDD regression; the remaining 11 sites, which had no obvious cooling signature before, continue to show a pattern of minimal or no cooling.

There is no apparent evidence, based on the current data, that the installation of DHPs has created a significant new cooling load. Sites that had a notable pre-installation cooling load evident in bills continue to have it in DHP usage, but the sites that did not have much cooling before do not seem to use their DHPs much in cooling mode. More detail can, and should, be added to this picture when the technical means are in place in the field to reliably distinguish DHP heating and cooling usage. Such a specification is used in the phase two metering currently underway.

Conclusions

Given the nature of this study as a series of case studies without a strong relationship to any population, this review has provided many valuable insights and hypotheses that can influence future DHP research and programs:

- The fact that these installations did not have metering before the installation of the DHP system meant that the savings and changes in electric consumption depend on a billing analysis in the year prior to installation. This analysis has been assisted by the use of more than one year of pre-consumption data. As a result, these homes have a consistently high correlation between the balance temperature and heating loads and reasonable estimates of space heating prior to installation.
- Only very limited occupant characteristics data were collected and available. As with the billing data, more data may have explained some of the details of the metered and billing data used here and provided insights that would be helpful in the analysis of energy savings. It is our recommendation that a structured interview protocol be included. This would be part of a more detailed energy audit. Such an approach would aid in understanding occupant behavior patterns (such a thermostat settings or the use of supplemental fuels) as well as providing sufficient data on the home itself to estimate the underlying heating requirements. This would allow more validation of the base-case billing analysis results and more direct estimation of the impacts of the DHP installation.
- The most significant insight was identification of the metering package required to provide an effective dataset for understanding the performance of the DHP systems. Because of the accessibility of thermostat set points in these installations, it is very difficult to determine when the heat pump is in cooling mode. This problem was thought to be easily resolved by the use of outdoor temperature. It has proven ambiguous at a level that makes any estimate of cooling offsets problematic. The resulting recommendation is the introduction of vapor line temperature to act as a surrogate for the cooling signal.

While there are important caveats that should be placed on this analysis, there are several additional observations that can be thought of as preliminary indication of the potential impact of DHP installations on the heating requirement of electric resistance heated homes in the Pacific Northwest:

- Initial saving estimates suggest that the savings associated with this technology is approximately 4,500 kWh per year with a greater than 40% reduction in overall space heating. This estimate compares favorably with the estimates used by the RTF in assessing this technology as an energy-savings measure.
- The data suggests that the use of cooling in this group is not increased by the introduction of the DHP technology.
- The use of the DHP as a displacement heating system has the effect of generating savings independently of initial house size. Since this strategy provides a uniform capacity in a single zone, the size of the remaining zones in a particular house is less important. Presumably, the overall efficiency of the house envelope will have an effect on the savings estimates but that hypothesis will require more characteristics data and a more representative sample.

Many of these observations will be reviewed in the course of ongoing research on this technology. At this writing the DHP systems reviewed here provide a promising indication of a viable future savings measure for existing electric zonal heated homes.

This analysis served as an excellent precursor to the large study current underway. In that scope about 95 sites were metered, and approximately 4,000 sites will receive a billing analysis, including at least one year of consumption both before and after the installation of the DHP. We expect in that analysis to be able to include a comparison between a billing analysis and the submetering results. The metering begun in this cohort of homes is ongoing and a second year of data is currently being down loaded for an update on this analysis.

A topic for further study in this area would be the use of supplemental fuels (especially wood). Homes in this pilot project had very little wood heat either before or after the DHP installation. In the larger sample the screening for supplemental fuels was less rigorous and we assume that some of the study homes will have supplemental fuel. We expect that this supplemental heating will have the effect of reducing the apparent savings from those homes if the homeowner uses the DHP as a substitute for the solid fuel.

This DHP measure has become a very important component in BPA's residential program. The pilot project lays the groundwork for determining cost and energy savings data necessary to determine if DHPs provide reliable, cost-effective energy savings. The results of this study provided the support BPA needed to expand its reimbursements and incentives for additional applications in other types of residential heating systems and building types. BPA is now trying to encourage DHP installations in manufactured homes and multifamily housing. BPA will follow up with measurement and verification on manufactured homes and multifamily housing from its current reimbursement offerings, and is considering other applications for DHP, such as small commercial buildings and homes with central ducted forced-air furnaces.

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