The Heat is On! Understanding the Savings Potential of Heat Pumps

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ABSTRACT

This paper presents findings from an impact evaluation of residential ducted air source heat pump (ASHP) and variable speed heat pump (VSHP) conversion measures from electric resistance heat based on billing regression analysis in the Pacific Northwest. The analysis used post-only with comparison group (POCG) regression models to evaluate the impact of installing these measures and variable-based degree-day (VBDD) analysis to examine the distribution of changes in electricity use among participants. The study also included a drivers analysis to show reasons for variance in savings.

Table 1 shows the evaluated savings based on the POCG regression analysis, with average savings ranging from 1,711 kWh per year for VSHPs installed in manufactured homes in heating zone 1 up to 5,075 kWh per year for VSHPs installed in single-family homes in heating zone 1. The evaluated savings were similar to recently updated savings values by the Regional Technical Forum (RTF), an organization in the northwest which develops measure savings estimates.

Table 1. Evaluated savings

Heat pump type	Home type	Heating zone(s)	Average annual savings (kWh)
ASHP	Single family	2/3	3,315
	Manufactured home	2/3	2,256
VSHP	Single family	1	5,075
	Manufactured home	1	1,711
	Single family	2/3	2,527
	Manufactured home	2/3	3,753

The drivers analysis identified the following key drivers of savings:

- Participants with the highest baseline usage experienced the greatest savings.
- Single-family homes in heating zone 1 that did not have AC increased their electricity usage after installation of a VSHP.
- Manufactured homes had lower savings due to lower electricity usage.

Introduction

Heat pump technologies are increasingly being relied upon to provide cost effective energy savings nationwide. Many states and regions promote heat pumps as part of their standard energy efficiency program offerings.

Bonneville Power Administration (BPA) acquires energy savings from its utility customers that result from certain measures, including heat pumps. For ducted ASHPs (the focus of this paper), BPA acquires energy savings from standard compressors and variable speed compressors.

In order for BPA to ensure the reliability of its energy savings achievements, measure specification and savings estimates must be approved by the Northwest Regional Technical Forum (RTF) to become "BPA Qualified." For Unit Energy Savings (UES) measures, the RTF categorizes the measures into either "proven" (reliable savings estimates) or "planning" (requiring additional research to move to proven).

Currently, ASHP conversions in heating zones 2 and 3 and VSHP conversions in all heating zones (1, 2, and 3)[1] are classified as planning measures. This paper covers an impact evaluation of these residential ASHP and VSHP conversion measures. The savings estimates developed through billing analysis would help move these measures from planning to proven.

Methodology

Billing Analysis

The impact evaluation included billing analysis using two main regression model methods, which are detailed in this section:

1. A post-retrofit only with comparison group regression model
2. Pre- and post-retrofit without comparison group using the variable-base degree-day (VBDD) regression model

A post-retrofit only with comparison group model. We developed a comparison group for each energy efficiency measure evaluated through the billing analysis. The comparison group did not meet the standards for a control group under a randomized controlled trial (RCT) experimental design but did provide a baseline from which to measure the impact of installing each respective energy efficiency measure.

Customers in a comparison group play an important role in the estimation of electricity savings impacts from an energy efficiency program. Without a comparison group, any change in energy consumption between the pre- and post-periods that is not associated with differences in electricity use in the pre-period or temperature (as represented by heating degree-day [HDD] and cooling degree-day [CDD]) is assumed to be due to the installation of the energy efficiency measure. However, changes in energy consumption between the pre- and post-periods may be due to one or more systematic factors unrelated to the measure, such as changes in the economy, supply shocks within the regional electricity market, or society-wide changes in residential energy use.

By including comparison sites in the billing regression model that are similar to participant sites with respect to geographic location, electricity usage, and participation in the same energy efficiency program (at either an earlier or later date), the evaluation accounted for the existence of any systematic external factors that might have affected electricity usage, as well as eliminated initial group differences as an explanation for post-installation changes in electricity usage by program participants. Assignment of a residential customer to the comparison group was not random, but rather determined based on one or more criteria (e.g., monthly energy consumption). Because of this, this paper refers to the analysis as a quasi-experimental design, thereby acknowledging that the comparison group did not meet the standard of a control group within an RCT experimental design.

While all the customers that installed one of the five energy efficiency measures offered through any of the 23 utilities that provided data for this project are program participants, for the purpose of the

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[1] Heating zone 1 defines a mild region with less heating demand, heating zone 2 includes moderate heating areas, and heating zone 3 has the highest heating demands.

billing analysis, the team segmented customers into one of two groups based on the number of months of billing data before and after installation of the energy efficiency measure:

1. The "participant" group included customers with at least 12 months of billing data prior to installation of the energy efficiency measure and at least 12 months of billing data after installation.
2. The "comparison" group included customers with at least 24 months of billing data prior to installation of the energy efficiency measure or at least 24 months of billing data after installation of the energy efficiency measure.

We matched each customer in the participant group to a customer in the comparison group based on how closely the monthly electricity usage of the two customers aligned during the 12 months prior to the participant installing the energy efficiency measure.

We used a POCG regression model to evaluate the impact of installing any of the HVAC measures in the homes of residential customers that participated in one or more of the energy efficiency programs sponsored by a Northwest utility served by BPA. The POCG model is appropriate for study designs, such as impact evaluations of energy efficiency programs, where individuals self-select into the program and analysis of the energy impacts is conducted after ("post") installation of the measure. In addition, the customers comprising the comparison group are similar to participants in that they are from the same geographic area, are similar with respect to (monthly) electricity use, and they participated in the same or a similar energy efficiency program, either at an earlier or later date.[2]

The study POCG model is as follows:

$$kWh_{i,t} = \beta_1 CDD_{i,t} + \beta_2 HDD_{i,t} + \sum_{j=1}^{12} \beta_j Mt_t \times kWh_{i,t-12} + \sum_{k=1}^{12} \beta_k Mt_t \times kWh_{i,t-12} \times Pt_i + \varepsilon_{i,t}$$

Where:

$kWh_{i,t} = Average\ daily\ kWh\ of\ customer\ i\ in\ month\ t\ of\ the\ post\text{-}period$

$CDD_{i,t} = Average\ cooling\ degree\ days\ for\ participant\ i\ in\ month\ t$

$HDD_{i,t} = Average\ heating\ degree\ days\ for\ participant\ i\ in\ month\ t$

$Mt_t = Indicator\ variable\ that\ equals\ 1\ for\ month\ t, else\ 0$

$Pt_i = Indicator\ variable\ that\ equals\ 1\ if\ customer\ i\ is\ a\ participant, else\ 0$

$kWh_{i,t-12} = Average\ daily\ kWh\ of\ customer\ i\ in\ month\ t\ of\ previous\ year$

$\beta_1, \beta_2, … = Parameters\ to\ be\ estimated\ in\ the\ model$

$\varepsilon_{i,t} = Random\ error\ term$

By specifying the model with an array of monthly indicator variables (Mt_t) that interact with the pre-period electricity usage variable ($kWh_{i,t-12}$) and an indicator variable for participant (Pt_i), we estimated energy impacts for the program for each calendar month.

Variable-base degree-day (VBDD) regression model. The VBDD modeling approach differs from the POCG regression model in that it fits individual regression models for each customer's pre-installation billing

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[2] This is in contrast to a designed experiment, such as RCT, where information is known about the individuals before they begin participating in the study and the subjects of the study are randomly assigned to either a participant or control group.

data and the customer's post-installation billing data. This means that this evaluation estimated two regression models for each customer in the participant group.

The VBDD model is specified as follows:

$$kWh_m = \alpha + \beta_1 CDD_{T,m} + \beta_2 HDD_{T,m} + \varepsilon_m$$

Where:

$kWh_m = Average\ daily\ kWh\ in\ month\ m$

$CDD_{T,m} = Average\ cooling\ degree\ days\ at\ reference\ temperature\ T\ in\ month\ m$

$HDD_{T,m} = Average\ heating\ degree\ days\ at\ reference\ temperature\ T\ in\ month\ m$

$\alpha = Estimated\ parameter\ representing\ daily\ baseload\ electricity\ usage$

$\beta_1, \beta_2 = Parameters\ to\ be\ estimated\ in\ the\ model$

$\varepsilon_m = Random\ error\ term$

Using the estimated coefficients from each customer's pre- and post-period models, we computed the weather normalized average consumption for the pre- and post-periods using weather station data retrieved from the National Oceanic and Atmospheric Administration (NOAA). The team then computed the difference between the pre- and post-period weather normalized average consumption for each participant customer.[3]

The primary purpose of estimating VBDD models for program participants was to examine the distribution of changes in daily electricity use among participants. Whereas the post-only model provides estimates of the program level impact of installing a specific piece of equipment (as well as the impact for the average participant), the VBDD model simply measures the change in average daily electricity use for each participant while controlling for differences in temperature between the pre- and post-periods. Any change in electricity usage for an individual participant may be due entirely or in part to energy savings associated with installing the measure. However, because the VBDD model precludes the use of a comparison group, it is not possible to attribute a change in electricity use to the installation of the energy efficiency measure.

Drivers Analysis

To conduct the drivers analysis, we used the VBDD model calculated during billing analysis. The output of the VBDD modeling process is the weather normalized change in electricity usage for each program participant between the pre-installation and post-installation periods, which serves as the dependent variables for the drivers analysis. These changes in electricity usage can be positive, negative, or zero.

The explanatory variables considered for the drivers analysis include average monthly electricity use prior to installation of the ASHP or VSHP, characteristics of the homes, previous HVAC equipment, and characteristics of the installed equipment (e.g., Seasonal Energy Efficiency Ratio [SEER] and Heating Seasonal Performance Factor [HSPF]) to try to understand what factors impact savings. All variables except

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[3] Since each VBDD model is estimated using data for a single home (i.e., a "sample of one"), we did not differentiate the estimated change in daily electricity usage for each comparison home from the estimated change in daily electricity use for each participant home.

for pre-period usage, which was calculated using utility data, are from the Performance Tested Comfort System (PTCS) registry that contains installation data entered directly by contractors.

Findings

The overall results for BPA's residential ASHP and VSHP impact evaluation showed that evaluated savings were similar to the RTF's assumptions (which were based on evaluation results from 2021), with realization rates of 110 percent, 86 percent, and 78 percent for the three heating zone and measure categories shown in Table 2 below. Table 2 shows evaluation results compared to savings assumptions, BPA's reported savings (based on savings results prior to 2021), and 2021 RTF values.

Table 2. Realization rates compared to 2021 RTF UES values

Measure	Heating zone	Home type	Program population	Sample	2021 RTF values (kWh)	Evaluated savings rate (kWh)	Realization rate
ASHP conversion	HZ 2/3	SF	232	172	430,716	570,200	132%
		MH	113	85	293,371	191,763	65%
		Subtotal					110%
VSHP conversion	HZ 1	SF	895	459	2,320,480	2,329,544	100%
		MH	246	149	714,609	254,879	36%
		Subtotal					86%
	HZ 2/3	SF	144	105	350,948	265,319	76%
		MH	31	23	98,232	86,321	88%
		Subtotal					78%

The drivers analysis identified baseline usage as a key driver of savings, with participants who had the highest pre-installation usage experiencing the greatest savings. This explains why manufactured homes generally had lower savings than single-family homes – they typically have lower baseline electricity usage.

The team also calculated the 90 percent confidence interval for average annual evaluated savings for each measure, heating zone, and home type. For four of the six measure combinations, the RTF savings fall within or below the 90 percent confidence interval of the estimated evaluated savings.

Error! Reference source not found. Figure 1 below displays the evaluated savings and their associated 90 percent confidence intervals (the blue dot with the blue bracket) compared to the RTF values (green dot). As shown in the figure, RTF values for three of the six categories fall within the confidence intervals, one is below (where the evaluated savings are statistically higher than the RTF value), and the remaining two are above (where the evaluated savings are statistically lower than the RTF value).
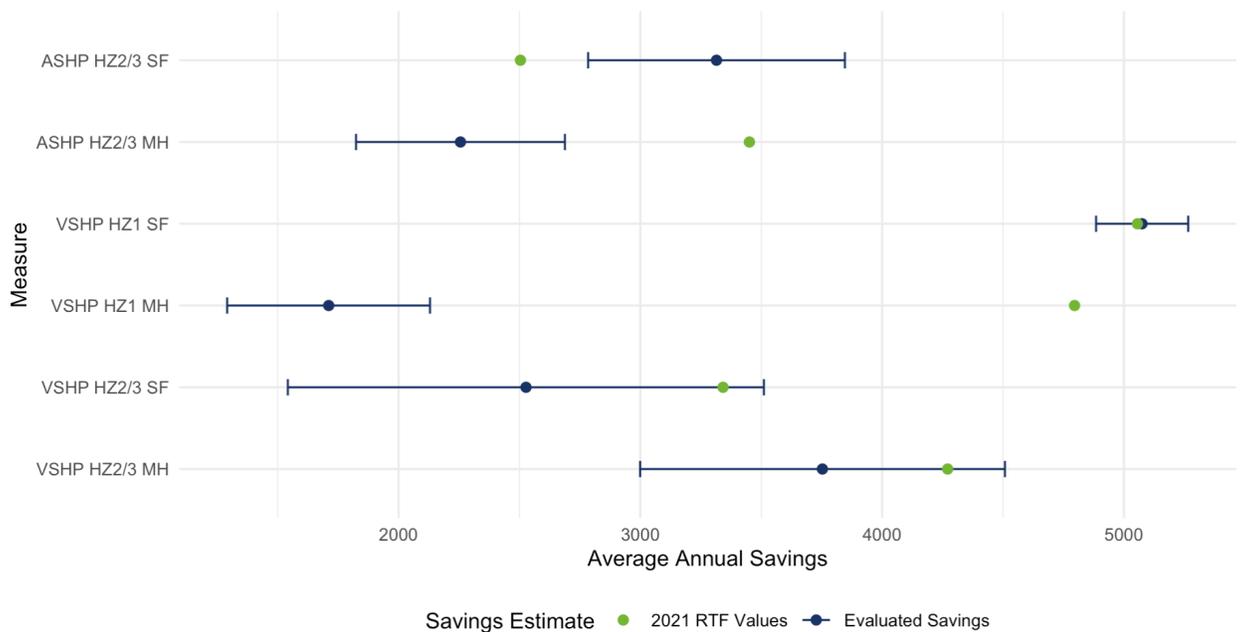
Figure 1. Confidence intervals for average annual change in electricity use (in kWh) after installation

Table 3 provides the numeric values associated with the confidence intervals, with an asterisk indicating savings values that fall within or below the evaluated savings estimates.

Table 3. Confidence intervals for average annual change in electricity use (in kWh) after installation

| Measure | Heating zone | Home type | Evaluated savings | | | 2021 RTF values |
			Lower bound	Evaluated savings	Upper bound	
ASHP conversion	HZ 2/3	SF	2,784	3,315	3,846	2,504**
		MH	1,824	2,256	2,688	3,451
VSHP conversion	HZ 1	SF	4,885	5,075	5,266	5,506*
		MH	1,291	1,711	2,130	4,796
	HZ 2/3	SF	1,542	2,527	3,511	3,342*
		MH	2,999	3,753	4,508	4,271*

* Savings value is within the 90 percent confidence interval
** Savings value is below the 90 percent confidence interval

Potential Reasons for Lower-than-Expected Savings

While the billing analysis results were similar to RTF savings values from 2021, they are lower than earlier assumed savings values. The earlier savings estimates for heat pumps have not been realized.

Three earlier studies were reviewed to identify potential reasons why savings have been lower than expected:

- **2018-2019 Residential HVAC Impact Evaluation Final Report (BPA 2020).** This impact evaluation conducted billing analysis to estimate the savings for heat pump measures. This study included billing analysis and a customer survey for customers with ductless heat pumps. The customer

survey findings are relevant to this research because both ductless and ducted heat pumps face similar issues regarding the addition of cooling.

- **Northwest Energy Efficiency Alliance Residential Building Stock Assessment II (NEEA 2019).** The residential building stock assessment characterized the building stock for different home types.
- **Bonneville Power Administration Air Source Heat Pump Commissioning, Controls & Sizing Baseline Field Study Report (BPA 2019)**. This study collected data to inform the current baseline model for residential ASHP commission, controls, and sizing in the Pacific Northwest.

A summary of the reasons why savings may not be as high as initially assumed are discussed below. A survey of customers who installed VSHPs and ASHPs (which BPA is considering) would help confirm whether these issues are relevant for this particular study.

Snapback

Snapback, also known as a rebound effect, occurs when an end user installs a higher efficiency measure and then uses it more to increase comfort or derive other benefits as a result of the lower operating costs (Greening, 2000). Snapback with the use of heat pump conversions typically occurs when the occupants heat and/or cool their home to more comfortable temperatures since the efficiency of the unit is greater than what they had before.

Addition of Air Conditioning

Based on program data, 81 percent of participants did not have air conditioning before installing the evaluated heat pumps. By converting their previous heating system to a heat pump, end use customers essentially added cooling capability, which adds to overall energy usage, which may or may not be offset by the efficiency savings achieved by using the heat pump for heating. The regression analysis showed that participants experienced large savings during the winter months, but experienced reduced savings or even increased consumption during summer months.

BPA's 2018 evaluation of ductless heat pumps (DHPs) indicated that a substantial percentage of households that installed DHPs did not have AC beforehand, but reported that had they not installed a DHP, they would have planned to add central AC at a later date. If the baseline for heat pumps accounted for a central AC baseline for homes that did not already have cooling, heat pumps might show more realized savings as they offset future purchases and use of much less efficient central AC.

The UES values provided did not differ significantly by whether the baseline included AC or not. For example, ASHPs installed in single-family homes in heating zones 2 and 3 expected site savings of 2,842 kWh per year for homes with AC and 2,454 kWh per year for homes without AC. For VSHPs, the UES values were the same for homes with and without AC.

Contractor Design Choices

As a way to reduce customer complaints, contractors may favor comfort for the participant over efficiency. A past market study commissioned by BPA in 2019 found that contractors may "lock out" heat pump compressors at higher temperatures so that homes heat up faster, but may rely more on less efficient electric resistance back-up heating (which leads to less efficient equipment operation). This means that heat pumps will not turn on until higher temperatures are reached when they should be allowed to operate until the internal thermostat tells them to stop (typically at 5ºF or lower). Electric resistance will turn on at higher temperatures than intended (they typically should not operate at a temperature higher than 35ºF). While the participant operates the heat pump, it may rely on less efficient

heating using electric resistance, leading to lower savings. Of the participant sites where we have this data, 58 percent retained a backup heating system. In addition, the heat pump may not be operating even when it is able to efficiently do so.

Based on the prior impact evaluation of DHPs, this anecdotally is done to provide higher temperatures at the register, which gives the impression that the system is doing well, even though a system may still be heating effectively at a lower supply temperature. Contractors may also oversize equipment. Their motivation is to have a satisfied customer and not have to go back to homes and address issues; for that reason, they typically err on the side of ensuring comfort over efficiency.

Displacement of Non-Electric Heat

The baseline equipment may include non-electric heating fuels such as wood and/or gas. If heat pump measures are used to offset some of the wood and/or gas heating, electric pre/post savings may show added load or negative savings. The 2019 Norwest Energy Efficiency Alliance (NEEA) Residential Building Stock Assessment (RBSA) reported that 65 percent of residences in Washington, Idaho, Oregon, and Montana have primary heating systems that are non-electric. A customer survey could help clarify the use of wood and gas heating.

Conclusions and Recommendations

The billing analysis of ASHP and VSHP conversions conducted in the Northwest showed average annual savings ranging from 1,711 kWh per year for VSHPs installed in manufactured homes in heating zone 1 (the mildest of the region) up to 5,075 kWh per year for VSHPs installed in single-family homes in heating zone 1. Realization rates were higher for ASHPs in heating zones 2 and 3 (110%) versus VSHPs (86% for heating zone 1 and 78% for heating zones 2 and 3). Key drivers of savings included total electricity usage, home type, and heating zone. Single-family homes in heating zone 1 that did not have AC increased their electricity usage after installation of a VSHP, which may suggest that some households were using the heat pump to cool their home. While the billing analysis results were similar to RTF savings values from 2021, they were lower than earlier assumed savings values that BPA and other program administrators had assumed based on data prior to 2021.

To better understand the reasons for lower-than-expected savings for ASHP and VSHP conversions, we offered a consideration regarding additional data collection:

- **Consider conducting a customer survey** to explore the issues raised in the report that reduce realized savings, both to confirm and understand the magnitude of the various issues. The survey could explore more in-depth concurrent participation in other energy efficiency programs and behavioral habits of households. This evaluation appended PTCS data onto the regression models to estimate drivers of savings. In future evaluations, PTCS data will not be available, as the program has closed.

We also had some considerations regarding viewing heat pump savings more broadly, allowing one to consider more than pre/post electric savings benefits.

- **Consider baseline assumptions for homes that do not already have AC.** There could be certain geographic areas based on cooling degree days that assume eventual AC installation. The baseline assumptions for homes that are most likely to install AC assume less efficient AC versus no cooling. Since a pre-post billing analysis compares energy use before and after heat pump

installation, it does not capture the energy savings compared to homes that would have otherwise installed separate AC systems.

- **Consider baseline assumptions for homes that reduced supplemental heating.** Pre-post monthly electricity billing analyses do not capture reductions in supplemental heat, as that does not show up on a monthly electricity bill. For households in the study that reduced their supplemental heating usage in the post-period, it is possible that they would have reduced their supplemental heating usage even if they only installed a baseline-level heat pump. Consider characterizing any post-period increase in usage with like-baselines.
- **Consider real world household occupant usage patterns.** Households that install high-efficiency heat pumps may have different usage patterns than households with electric resistance heat, as their heating costs are now much cheaper, they desire to be more comfortable, or they keep their house at safer temperatures. It is possible that households that convert from electric resistance heat to baseline-level heat pumps may also change their usage patterns. Consider assessing households' actual usage patterns after heat pump conversion, accounting for any changes in usage after installation, health and safety benefits, and using like-baselines.

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