Energy Trust of Oregon

Utility Billing Analysis of 2013-2014 Multifamily Ductless Heat Pump Retrofits

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EXECUTIVE SUMMARY

Energy Trust of Oregon's Multifamily program launched a pilot to test Ductless Heat Pumps (DHPs) in multifamily buildings beginning in 2009. The measure was moved out of pilot status in 2016 after a preliminary analysis by Lockheed Martin corroborated the initial savings estimates. However, due to challenges in obtaining quality site information and utility billing data, and in conducting billing analysis in multifamily buildings, the energy savings were not rigorously evaluated until now. This study examines electric savings resulting from the installation of DHP systems in electrically heated multifamily buildings in Oregon, using utility billing analysis, across a wide variety of building sizes, vintages and installation scenarios. We quantified the average annual electric savings per DHP system and attempted to determine if there were any differences in energy savings between different types of buildings and DHP systems, especially between small (2-4 unit) and large (5-20 unit) multifamily structures. We selected 148 multifamily buildings that received DHPs in 2013 and 2014 as the treatment group and then selected a comparison group of 174 electrically heated multifamily buildings that participated in the Multifamily program in 2016.

After removing buildings that were unsuitable for analysis, we analyzed 112 treatment buildings and 136 comparison buildings. Treatment buildings used an average of 9,067 kWh per unit per year in the pre-treatment period, while comparison buildings used 8,828 kWh on average. Eighty-two percent of treatment buildings were small, while only 62 percent of comparison buildings were small. Thus, building size was an important difference that we attempted to account for in the analysis. In addition, roughly half of buildings in the study sample were owner-occupied and three-quarters were located in the Portland Metro area.

Several different analysis techniques were used to quantify energy savings using monthly electricity billing data. Electricity savings were found to be 1,768 kWh per year (±757 kWh) per DHP, on average. This equates to 20 percent overall electric savings and 47 percent heating savings. Although, this represents substantial energy savings for multifamily dwelling units, it is significantly lower than the deemed savings values used during the 2013 and 2014 program years, resulting in a 62 percent realization rate.

Differences in energy savings were found based on building sizes, vintages and installation scenarios. Small buildings appeared to have lower savings than large buildings, contrary to our hypothesis at the outset of the study. Buildings where less than 25 percent of units received a DHP had savings far exceeding that of buildings where 25 percent or more of units received a DHP. Buildings with high baseline electric usage per unit had significantly higher savings per DHP than buildings with lower usage per unit, presenting a good opportunity for targeting. Ownership type also had a major impact on savings per DHP, with owner-occupied condos showing electric savings that were more than eight times higher than renter-occupied buildings. Geographic region also had significant influence, with Portland Metro area buildings saving roughly five times more electricity than non-metro area buildings. On the other hand, DHP systems with multiple indoor heads had very similar electric savings to single head systems. There was also no statistically significant difference between high efficiency DHP systems and lower efficiency systems.

We recommend that Energy Trust use the electric savings of 1,768 kWh per DHP to true-up savings for past program years and to recalibrate the current deemed savings values. In

addition, the amount of variation in savings observed in this study is somewhat concerning. We recommend conducting an additional study to see if energy savings are changing over time, and to determine the sources of variability in savings. We recommend another billing analysis with a larger sample of multifamily buildings and more recent DHP projects installed from 2015 to 2017. This study would allow us to produce a more stable savings estimate using a larger sample size and to conduct a more robust analysis of the driving factors influencing DHP savings.

INTRODUCTION

Energy Trust of Oregon's Multifamily program launched a pilot to test the energy savings and market acceptance of Ductless Heat Pumps (DHPs) in multifamily buildings beginning in 2009. Initially, the pilot measure was based on the savings assumptions for DHPs in single-family dwellings, which were established through studies by the Northwest Energy Efficiency Alliance (NEEA) and others[1]. The deemed savings for DHPs in single family were scaled down based on multifamily heating loads and initially estimated to be 2,504 kWh per DHP per year for multifamily buildings in heating zone 1 and 3,881 kWh per DHP per year for buildings in heating zone 2. The working assumption was that the vast majority of DHPs installed in this setting would displace zonal electric resistance heating and that they would provide about 60 percent of the space heating[2].

Due to the difficulties of obtaining quality site information and billing data, and in conducting billing analysis in multifamily buildings, DHP energy savings were not immediately evaluated at the beginning of the pilot. However, Energy Trust continued to support DHPs for multifamily buildings to develop the market, with the assumption that the initial savings estimates, based on engineering analysis, were reasonable and that costs would come down as the market advanced.

In 2015, Energy Trust's Program Management Contractor (PMC) Lockheed Martin conducted an initial pre- and post-billing analysis of multifamily units that received DHPs in 2013 and 2014. This information was used in a measure approval document[3] (Appendix A). The analysis results showed a 2,583 kWh per unit per year reduction in electricity usage in western Oregon on average for a one ton DHP (Appendix A, table 2). Larger reductions in electricity use were observed east of the Cascades. These estimates roughly aligned with the original savings estimates for the pilot, providing some confidence in the savings and a good rationale to continue to offer incentives for DHPs in multifamily buildings. At this point, the measure was moved out of the pilot phase and approved for use as a standard, deemed savings measure in the Multifamily program in 2016.

As we looked more deeply at this measure, the savings results of the Lockheed Martin study appeared high, based on the average multifamily dwelling unit electric load of 9,188 kWh per year, as computed in NEEA's 2011 Residential Building Stock Assessment (RBSA) and referenced in previous measure development work[4]. The proportion of electricity used for heating in Northwest homes is 38 percent, as reported in the RBSA Metering Study[5].

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[1] NEEA. (2014). Final Summary Report for the Ductless Heat Pump Impact and Process Evaluation. Retrieved from http://neea.org/docs/default-source/reports/e14-274-dhp-final-summary-report-(final).pdf?sfvrsn=8

[2] Energy Trust of Oregon. (2008). Cost-Effectiveness Calculator for Ductless Mini-Split Heat Pumps in Multifamily Pilot. Internal document.

[3] Energy Trust of Oregon. (2016). Measure Approval Document for Ductless Heat Pumps in Existing Multifamily.

[4] NEEA. (2013). Residential Building Stock Assessment: Multifamily Characteristics and Energy Use. Retrieved from http://neea.org/docs/default-source/reports/residential-building-stock-assessment--multi-family-characteristics-and-energy-use.pdf

[5] NEEA. (2014). Residential Building Stock Assessment: Metering Study. Retrieved from http://neea.org/docs/default-source/reports/residential-building-stock-assessment--metering-study.pdf

Considering these regional data points, we would expect multifamily heating loads to be about 3,500 kWh per year on average. Thus, DHP savings of 2,583 kWh per year would equate to a roughly 70 percent reduction in heating energy usage per multifamily unit, a very aggressive savings target. In addition, other regional studies of DHPs in multifamily have shown much lower electricity savings[6], although they were conducted in larger facilities that do not represent the size of Energy Trust's Multifamily program participants. Lastly, Energy Trust's Existing Homes program estimated electricity savings of just 2,153 kWh for single-family homes with electric heat[7], which have higher heating loads on average. Based on these factors, we hypothesized that electricity savings from DHPs installed in multifamily buildings in Oregon would be lower than previously estimated.

Evaluation Goals

The primary goal of this billing analysis was to confirm the annual electric savings resulting from the installation of DHP systems in electrically heated multifamily buildings. Through this analysis, we quantified the average annual electric savings per DHP system. We also attempted to determine if there were any differences in energy savings between different types of buildings and DHP systems, especially between small (2-4 unit) and large (5-20 unit) multifamily structures. Ultimately, the results of the analysis will determine whether Energy Trust should continue to support and promote DHPs in multifamily buildings.

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[6] BPA. (2016). Assessment of Ductless Mini-Split Heat Pump Energy Savings in Stack House Apartments. Retrieved from https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Pages/Assessment-of-Ductless-Mini-Split-Heat-Pump-Energy-Savings-in-Stack-House-Apartments.aspx

[7] Energy Trust of Oregon. (2015). Measure Approval Document for Ductless Heat Pumps in Single Family Homes.

METHODS

Sample Selection

We began the sample selection by identifying 210 participating multifamily buildings that received DHPs in 2013 and 2014 from Energy Trust's Project Tracking database, ranging from 2-4 unit structures, to large assisted living facilities and condominium towers. Of these, we deemed 148 buildings eligible for evaluation, meaning that we could physically locate them, we could determine the number of units and configuration, and the percent of units that received a DHP was large enough that we could analyze the energy impact. These sites became our treatment group. The majority of treatment group sites were 2-4 unit small multifamily structures. Condominium towers were screened out of the treatment sample due to their relative rarity, unique characteristics and very low percentage of treated units.

We then selected a comparison group of similar electrically heated multifamily buildings that participated in the Multifamily program in 2016, using the Project Tracking database. These "future participants" installed major electric heating measures, including DHPs, heat pumps, packaged terminal heat pumps, windows and insulation after the analysis period of this study. By selecting electrically-heated buildings that participated in the Multifamily program in future years, we were able to ensure a degree of comparability to the pre-treatment condition of the participant buildings.

We found 174 future participant buildings across Oregon that met these criteria and had sufficient information to include in the analysis. These sites became our comparison group. We did not attempt to screen out treatment or comparison buildings that installed other incidental efficiency measures during the analysis period, since these data were difficult to match when going from individual units to the building-level. However, we believe that these incidental measures were evenly distributed between the treatment and comparison groups, given their similar propensity to participate in the program. We checked the frequency of major efficiency measures installed during the analysis time period in a sample of sites and found them to be relatively uncommon in both study groups.

Next, we identified all electric utility dwelling units associated with each of the treatment and comparison buildings. For each dwelling unit, we extracted the history of monthly billing data from Energy Trust's Utility Customer Information (UCI) database from 2010 to 2016. Monthly electric meter reading data were cleaned, including removing duplicate and estimated meter readings, and removing readings with very short or very long time intervals. We then shifted the meter readings to align with calendar months by prorating the average daily electric usage, based on the number of days of overlap with each month. Once the meter readings were organized by month, we aggregated all monthly electric usage data to the building level. We assessed the completeness of monthly building-level data and removed monthly observations where more than one-quarter of the unit-level observations were missing or incomplete.

Next, we defined pre- and post-treatment study periods, and an analysis blackout period for each treatment building, based on the installation dates of the DHP systems. The blackout period began in the month prior to the first DHP installed in the building. It ended the month after the last DHP was installed in the building. Utility data in the blackout period were not analyzed. The pre-treatment period encompassed the 24-months before the blackout period, and the post-treatment period consisted of the 12 months following. Proxy installation dates were developed for each comparison building to determine the pre- and post-treatment periods to be analyzed. To do this, we created building strata based on geographic region and number of dwelling units. Within each stratum, we identified the range of DHP installation dates for the treatment buildings and assigned a random proxy installation date within that range to each comparison group building. This procedure was repeated for each stratum until all comparison buildings were assigned a proxy installation date. The goal was to produce a distribution of analysis periods that were relatively similar between the treatment and comparison groups, especially within groups of similar buildings.

Once we completed cleaning and aggregating electric usage data, we began to assess outliers and determine characteristics of sites that were unsuitable to analyze. The following screening criteria were applied to identify and remove sites from the analysis:

- A small number of new multifamily buildings, constructed since 2010, which were dissimilar from the rest of the sample. In addition, some of these sites did not have sufficient pre-treatment usage data for us to properly analyze.
- Buildings with more than 20 units were deemed outliers in the sample, in terms of structure size.
- Buildings with insufficient usage data, specifically those with fewer than 18 observations pre-treatment or fewer than nine observations post-treatment.
- Buildings with large swings in raw annual electric usage, from pre- to post-treatment, where electric usage more than doubled or decreased to less than half.
- Outliers in pre-treatment annual electric usage—based on the top and bottom 1 percent of the treatment group distribution.
- Treatment group buildings where less than one DHP was installed for every 10 dwelling units, to ensure the DHP effect would be detectable.

Table 1 provides detailed attrition numbers with sample size and average pre-treatment annual electric usage at each step in the analysis for each group. After attrition, there were 112 treatment buildings and 136 comparison buildings available for the analysis, with average annual electric usage per dwelling unit of 9,067 kWh per year and 8,828 kWh per year, respectively.

Table 1: Sample attrition.

	Treatment Buildings			Comparison Buildings		
Analysis Step	N	%	Pre-Tx Raw Annual kWh Per Unit	N	%	Pre-Tx Raw Annual kWh Per Unit
Initial sample of evaluable buildings	148	100	--	174	100	--
Matched to billing data	137	93	8,386	170	98	8,981
Remove buildings with billing data quality issues	136	92	8,388	168	97	8,980
Remove new buildings constructed since 2010	133	90	8,456	167	96	8,995
Remove large buildings with > 20 units	130	88	8,505	143	82	8,986
Remove buildings with insufficient billing data in pre- or post-period	127	86	8,686	141	81	9,076

Remove buildings with large changes in pre-to-post electric usage	121	82	8,905	139	80	9,091
Remove extreme outliers in pre-treatment electric usage	121	82	8,905	136	78	8,828
Remove treatment buildings with low proportion of treated units	112	76	9,067	136	78	8,828

Modeling Approaches

Using several different regression modeling techniques, we analyzed monthly electricity usage data to estimate DHP energy savings. The outputs from each model were used to determine the difference in pre-to-post change in electricity usage between treatment and comparison buildings; and second, to isolate the energy savings attributable to each DHP system. The primary outcome variable in each model was the average daily electric usage per building in each calendar month. Treatment and comparison group buildings were modeled using a study group indicator variable. Another indicator variable flagged the pre- and post-treatment study periods for each building. In the more complex models described below, we attempted to remove the influence of unrelated factors by accounting for changes in weather and differences in building size, using additional variables and interaction terms. To estimate the average building-level electric savings—the difference-in-differences in annual electric usage per building—we used interaction terms between the study group and the study period (and in some models weather variables and building size). The average electric savings per treatment building were divided by the average number of DHPs installed per building. This calculation allowed us to arrive at the average savings per DHP system installed.

The following sections provide descriptions of the various models used in the analysis.

- Simple linear regression model
- Multivariate linear regression model
- Fixed effects panel regression model
- Multilevel panel regression model
- Building-level variable base degree-day models

Detailed information about each regression model, including the regression equations and the savings calculation methods, are included in Appendix B.

<u>Simple linear regression model.</u> First, we created a simple linear regression model using the Generalized Linear Model (GLM) function in Stata[8], predicting average daily usage per building with the study group indicator, the study period and the difference-in-differences interaction term. The GLM model accounted for clustering of observations by building in the error estimates. We multiplied the coefficient of the difference-in-differences interaction term by 365 days, and divided by the average number of DHPs installed per treatment building, to achieve the annual savings estimate per DHP.

<u>Multivariate linear regression model.</u> Next, we built up a linear regression model using GLM with a more explanatory set of covariates and interaction terms, to control for differences in weather and building size. Average daily electric usage per building was predicted using the study group, the study period, average daily heating degree-days (HDDs) and cooling degree-days (CDDs),

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[8] StataCorp LLC. (2017). Stata: Data Analysis and Statistical Software. www.stata.com

the number of dwelling units, and the interaction terms between these variables. We utilized fixed reference temperatures of 60ºF for heating and 70ºF for cooling. This GLM model also accounted for the clustering of observations by building when computing the error terms. We calculated the annual savings estimate per DHP using the linear combination of the five difference-in-differences interaction terms listed below and dividing by the average number of DHPs installed per treatment building.

Fixed effects panel regression model. We used the Fixed Effects Linear Model function in Stata to create a panel regression model with building-level fixed effects, to account for the longitudinal nature of the data within each building. In this type of model, a separate intercept term is computed for each building and included with the other fixed independent variable coefficients. While this type of model is standard practice in utility billing analysis, it has the downside of limiting the explanatory variables that can be included in the model. All time-insensitive building characteristics become collinear with the building-level fixed effects, and cannot be analyzed without being included in an interaction term. Thus, we created a fixed effects model with a subset of the explanatory variables and interaction terms used in the multivariate linear regression model to estimate the average daily electric usage per building. We utilized fixed reference temperatures of 60ºF for heating and 70ºF for cooling. We calculated the annual savings estimate per DHP using the linear combination of the five difference-in-differences interaction terms listed below and dividing by the average number of DHPs installed per treatment building.

Multilevel panel regression model. We used the Multilevel Mixed Effects Linear Model function in Stata to create a multilevel panel regression model with random building-level effects, to properly account for the longitudinal nature of the data within each building. Robust standard errors were calculated. The fixed effects portion of this model uses the same explanatory variables as the multivariate linear regression model to estimate the average daily electric usage per building. The random effects portion of the model creates an intercept and slope coefficients for the HDD and CDD variables for each individual building. We first created the model with the same HDD and CDD reference temperatures as above (HDD60 and CDD70), but also created a model with optimal reference temperatures for the study sample. To optimize the HDD and CDD reference temperatures, we re-ran the model using all combinations from 45 to 85ºF where the CDD reference was greater than or equal to the HDD reference. The best-fit model, based on the fit statistics[9], used a reference temperature of 58ºF for HDD and 78 ºF for CDD and was used to calculate the energy savings. We calculated the annual electric savings estimate per DHP using the linear combination of the five difference-in-differences interaction terms listed below and dividing by the average number of DHPs installed per treatment building.

Building-level variable base degree-day models. The last analysis technique we used was similar to PRISM (PRInceton Score-keeping Method[10]), using a building-level, Variable Base Degree-Day (VBDD) regression modeling approach. A weather normalization procedure is used to estimate weather-normalized annual energy usage for each building in each study period. The energy savings are estimated with a differences-in-differences calculation using the normalized energy usage outputs. First, we fit separate weather regression models for each

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[9] Akaike, H. (1974). A New Look at the Statistical Model Identification. IEEE Transactions on Automatic Control, 19, 716-723. Retrieved from http://ieeexplore.ieee.org/document/1100705/

[10] Fels, M. (1986). PRISM: An Introduction. Energy and Buildings, 9, 5-18. Retrieved from http://www.marean.mycpanel.princeton.edu/~marean/images/prism_intro.pdf

building in each study period, using HDD and CDD variables. We used Stata's Linear Regression procedure to create these models. We re-ran each building-level model using all combinations of HDD and CDD reference temperatures from 45 to 85ºF where the CDD reference was greater than or equal to the HDD reference. We also ran separate heating-only models for each building using the same range of reference temperatures. Any model with a negative HDD or CDD coefficient was excluded. The model with the overall highest adjusted R-squared for each building and study period was selected to calculate the weather-normalized annual usage, using the TMY3 long-run HDDs and CDDs. However, if the model R-squared was less than 0.25, then we assumed the building was insensitive to weather and used the raw annual usage for the analysis.

Next, we calculated the change in normalized annual electric usage for each building as the difference between the pre- and post-treatment normalized annual usage. To determine the average electric savings per building, we created a linear regression model where the treatment variable, combined with a variable for building size, predicted the average change in normalized annual usage. We used the Linear Regression procedure in Stata with robust standard errors. We calculated the annual electric savings estimate per DHP using the linear combination of the two treatment terms listed below and dividing by the average number of DHPs installed per treatment building.

Subgroup Analysis

In addition to the overall savings per DHP, we were interested to see if there were differences in savings based on different subgroups of buildings within the sample. One subgroup we tested was based on size of multifamily buildings, where the sample was split between small multifamily structures (2-4 units) and larger ones (5-20 units). We hypothesized that small multifamily buildings could have higher energy savings because they had larger units, fewer shared walls, higher heating loads, and would be relatively similar to single-family homes (which have estimated DHP savings of 2,153 kWh in heating zone 1[11]). We tested this difference by splitting the study sample (treatment and comparison buildings) into two subgroups and re-running the VBDD analysis separately for each one. We recomputed annual electric savings per DHP for each subgroup, using the procedure described above.

We were also interested to see if there were differences in savings by annual electric usage category, geographic region, building ownership type, installation year, installer and DHP make and efficiency level. We used each of these characteristics to break the sample into two or more subgroups, which we analyzed and compared using the same method. For factors associated exclusively with the treatment group, such as DHP efficiency level, we simply divided the treatment group into subgroups and compared each subgroup to the entire comparison group. Lastly, we tested the impact of removing treatment buildings that had multi-head DHP systems or less than 25 percent of dwelling units treated. We qualitatively compared the differences in savings estimates by assessing the magnitude of the difference, the sample size of each subgroup and the overlap between the confidence intervals.

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[11] Energy Trust of Oregon. (2015). Measure Approval Document for Ductless Heat Pumps in Single Family Homes.

RESULTS

Sample Characteristics

The final analysis sample contained 112 treatment buildings with 193 DHPs installed from 2013 to 2014. There were 136 electrically-heated comparison buildings that participated in Energy Trust's Multifamily program in 2016. There were a total of 393 dwelling units in the treatment buildings and 660 dwelling units in the comparison buildings.

Table 2 lists some of the basic characteristics for buildings in the sample. Treatment buildings contained an average of 3.5 dwelling units and used 31,743 kWh per year, or 9,067 kWh per unit, on average. Comparison buildings had an average of 4.9 dwelling units and used 39,992 kWh per year, or 8,828 kWh per unit, on average. Treatment and comparison buildings were similar in terms of age and geographic distribution. Treatment buildings more frequently consisted of owner-occupied units, while the comparison group had more market rate apartment buildings. Comparison buildings tended to be slightly larger on average, with a higher proportion of buildings with five or more dwelling units. We attempted to control for this difference in our analysis by including a variable for the number of dwelling units in the regression models used to estimate savings. There was also slightly lower pre-treatment annual electric usage per unit in the comparison group, most likely a result of the higher number of dwelling units per building.

Table 2: Basic characteristics of multifamily buildings in the final analysis sample.

	Treatment		Comparison	
Characteristic	N	% or Mean	N	% or Mean
Number of Units Per Building	112	3.5	136	4.9
Duplex	51	46%	40	29%
Tri/Quad-Plex	41	37%	44	32%
5+ Unit Building	20	18%	52	38%
Year Built	98	1970	93	1973
Pre-1950	14	13%	7	5%
1950-1979	50	45%	64	47%
1980-2010	34	30%	22	16%
Unknown	14	13%	43	32%
Multifamily Market				
Owner Occupied	58	52%	60	44%
Market Rate Apts.	50	45%	71	52%
Affordable Apts.	4	4%	2	1%
Unknown	0	0%	3	2%
Geographic Region				
Portland Metro	78	70%	108	79%
Willamette Valley	16	14%	15	11%
Southern Oregon	6	5%	6	4%
Central Oregon	7	6%	6	4%
Eastern Oregon	2	2%	0	0%
Oregon Coast	3	3%	1	1%

Electric Utility				
Portland General Electric	79	71%	101	74%
Pacific Power	33	29%	35	26%
Pre-Tx Annual kWh per Unit	112	9,067	136	8,828
<10,000 kWh per Year	72	64%	94	69%
10,000+ kWh per Year	40	36%	42	31%
Pre-Tx Annual kWh per Bldg.	112	31,743	136	39,992

We further assessed how well the comparison group represented the treatment group by comparing the distribution of proxy installation dates with treatment group installation dates. As described in the Methods section, the installation dates were used to define the study periods used in the analysis of electric usage data. We also directly compared the time periods of electric usage data included in the pre- and post- periods for each study group. Ideally, a representative comparison group will have pre- and post-treatment time periods that are very similar to the treatment group. These comparisons of the time periods analyzed for each study group are displayed in the distribution plots in Figure 1.

The data show that, generally, the analysis time periods used in the comparison group follow the treatment group relatively closely. However, the treatment group contains a higher proportion of installation dates in late 2014 and higher proportion of usage data from late 2015, while the comparison group contains a higher proportion of installation dates in early 2014 and higher proportion of usage data in mid-2014.

Figure 1: Comparison of analysis time periods between study groups.

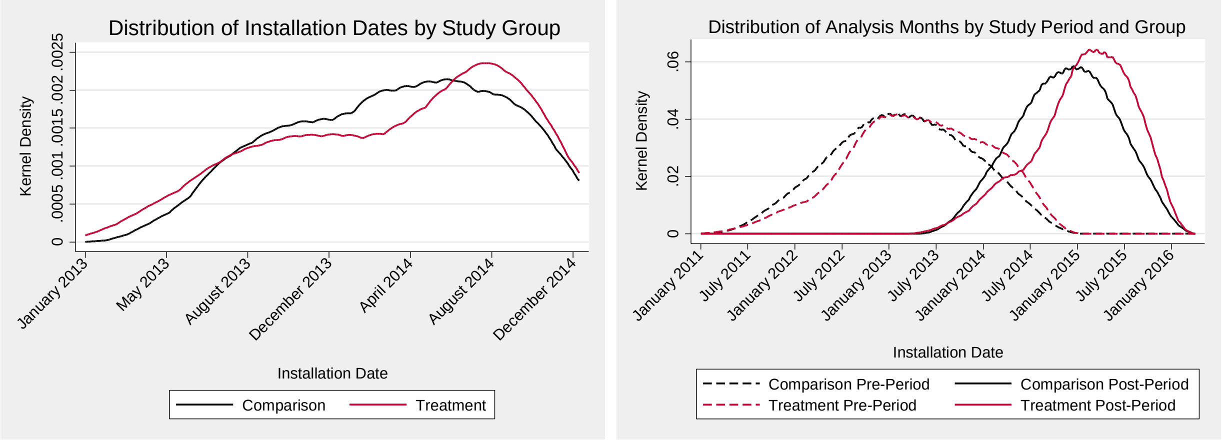


Table 3 summarizes some of the basic characteristics of the DHP systems installed in the treatment buildings. The majority of treatment buildings in our analysis sample had DHPs installed in 2014, with an average of 1.7 DHPs per building (median of 1.0) and an average of 55 percent of dwelling units treated with a DHP (median of 50 percent). The average number of indoor units per DHP system was 1.3 (median of 1.0) with 73 percent of treatment buildings having installed 1:1 systems.

Two manufacturers dominated the market in 2013 and 2014, representing 81 percent of DHP projects in the sample, with a few other manufacturers making up the remaining systems. The average Heating Season Performance Factor (HSPF) was 10.5, with a median of 10.6. The top three contractors installed DHPs in 29 percent of treatment buildings. The average installation cost per DHP across the treatment buildings was $4,643, although this average contains outliers that drove up the average, particularly systems with more than one indoor head. The median provides a more balanced assessment of the typical DHP installation cost, which was $4,208. The mean cost for systems with only one indoor head was $3,888 (median of $3,985). The average deemed electricity savings per DHP claimed by Energy Trust was 2,852 kWh per year (median of 2,916 kWh).

Table 3: Basic characteristics of DHP systems installed.

Characteristic	N	% or Mean
Installation Year		
2013	25	22%
2014	87	78%
Number of DHPs Per Building	112	1.7
1 DHP System	73	65%
>1 DHP System	39	35%
Dwelling Units with DHPs	112	55%
Number of Indoor Units per DHP	108	1.3
1 Indoor Unit	82	73%
>1 Indoor Unit	26	23%
Unknown	4	4%
HSPF	111	10.5
Make		
Manufacturer A	58	52%
Manufacturer B	33	29%
Manufacturer C	9	8%
Other/Unknown	12	11%
Installers		
Contractor A	14	13%
Contractor B	10	9%
Contractor C	8	7%
Other/Unknown	80	71%
Installation Cost Per DHP	112	$4,643
Savings Claimed Per DHP (kWh)	112	2,852

Raw Treatment Effect

To get a rough estimate of the energy impact of DHPs in treatment buildings, we compared the pre- and post-period raw annual electricity usage between the treatment and comparison buildings. The results are summarized in Table 4. As discussed above, the treatment group pre-period raw annual usage was slightly higher per dwelling unit than the comparison group, while it was significantly lower per building. This was due to the difference in building size, with comparison buildings containing significantly more dwelling units on average. In the post-treatment period, both groups had substantially lower raw annual electricity usage per building, but the treatment buildings reduced their usage by 1,654 kWh (90 percent confidence interval: ±1,594) more than the comparison buildings, on average. A t-test of the change in electric usage between groups confirmed that this difference was borderline statistically significant (t=1.71, p=0.088).

Table 4: Raw annual electricity usage per building, by study group and period.

		Pre-Period Annual kWh		Post-Period Annual kWh		Change in kWh	
Group	N	Mean	SE	Mean	SE	Mean	SE
Treatment	112	31,743	1,914	26,364	1,408	-5,379	767
Comparison	136	39,992	1,804	36,267	1,642	-3,725	587
Difference	**248**	**-8,249**	**2,630**	**-9,903**	**2,163**	**-1,654**	**966**

If we divide the building level treatment effect by the average number of DHPs installed per treatment building (1.72), we can estimate the raw annual electric savings per DHP, using the equation below. The result was 960 kWh per year reduction per DHP installed. This estimate of the effect has a large amount of uncertainty, as seen in the wide confidence interval, and does not account for important differences in weather or the differences in building size between the study groups.

$$\frac{1{,}654\ kWh\ reduction}{1\ building} * \frac{1\ building}{1.72\ DHPs} = 960\ kWh\ reduction\ per\ DHP\ (90\%\ CI \pm 927)$$

Figure 2 graphically displays the distribution of raw annual electricity usage per building among treatment and comparison buildings for each study period. The reduction in raw usage from the pre- to post-treatment period is clearly visible in both groups. Figure 3 displays the distribution of changes in raw annual electric usage per building for each study group. These graphs demonstrate that the reductions in usage were generally much larger in the treatment buildings.

Figure 2: Distribution of raw annual electricity usage per building, by study group and period.

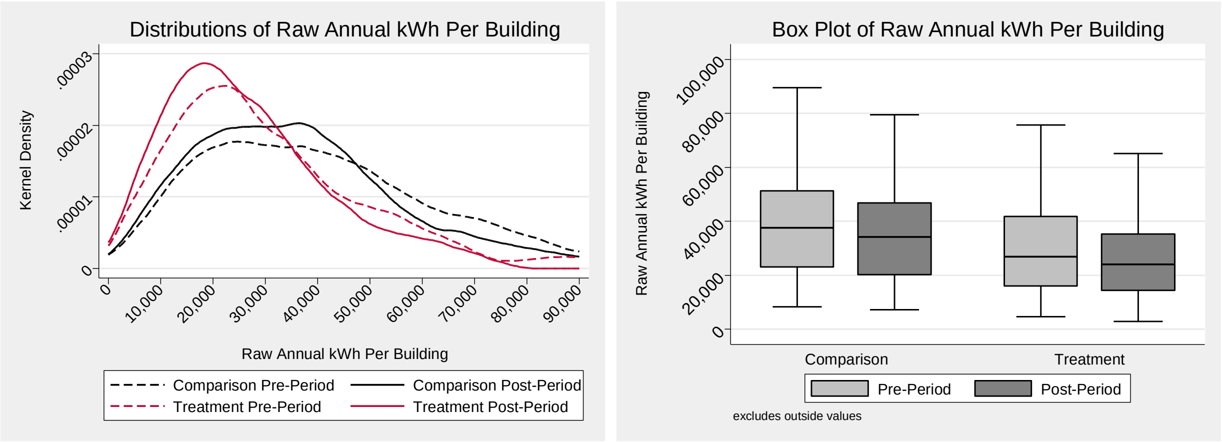
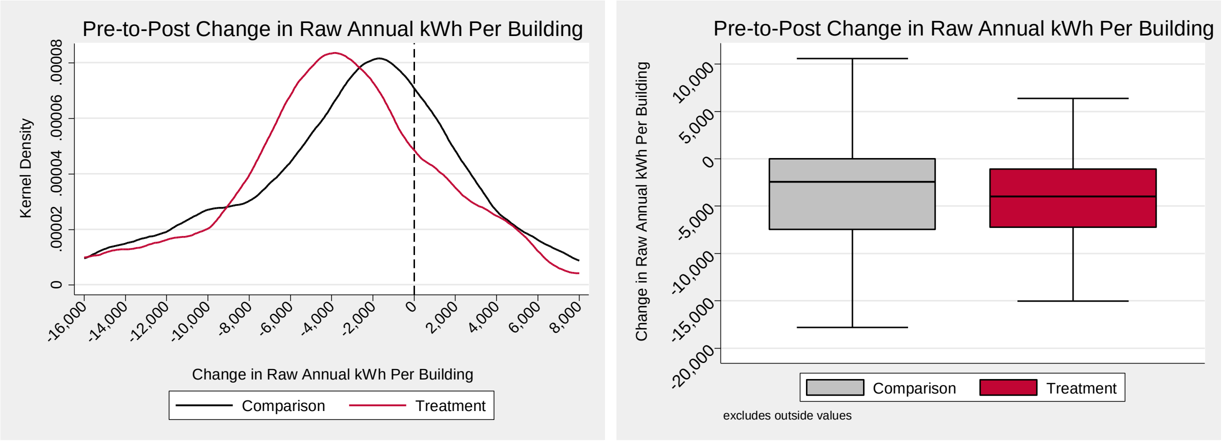
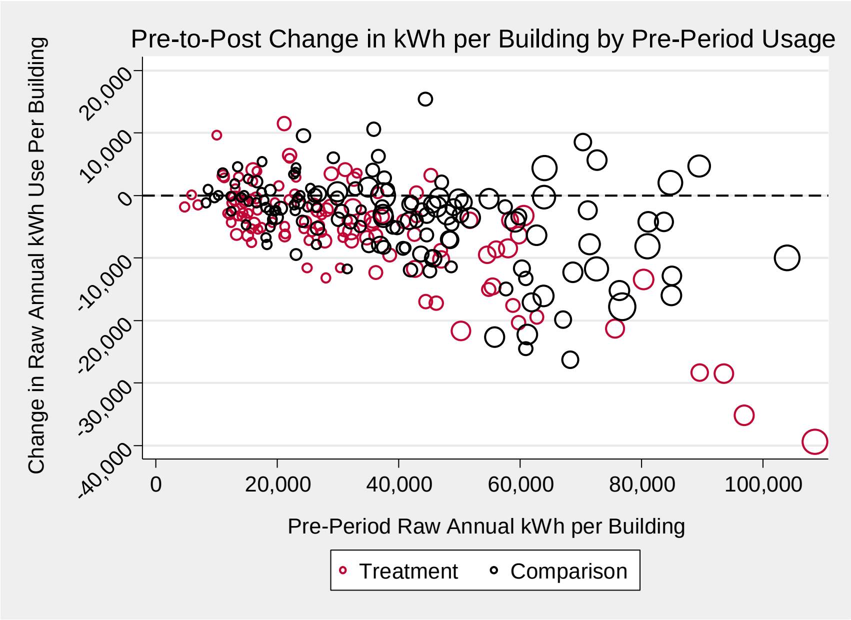


Figure 3: Distribution of changes in raw annual electricity usage per building, by study group.



Similarly, Figure 4 shows the scatter of changes in raw annual electric usage for each building in the study sample versus their pre-period annual electric usage. This plot illustrates that treatment buildings tended to have larger reductions in electric usage than comparison buildings. However, many comparison buildings, especially larger ones with relatively high pre-period usage, experienced substantial reductions in electric usage as well.

Figure 4: Scatterplot of changes in electricity usage for each building, by pre-period electric usage, study group, and building size.



Note: Marker size illustrates the relative size of each building, based on the number of dwelling units.

Energy Savings

Table 5 summarizes the estimated annual energy savings and energy usage resulting from each of the models we used in the analysis. Table 5 also summarizes the pre-treatment average annual electric usage and heating usage predicted by each model. We provide the results of the raw treatment effect (described above) and the simple linear regression model for comparison purposes only. We do not consider them accurate assessments of savings because they omit important factors. The results from the other methods were very consistent with one another, varying by less than 50 kWh per year. In the end, we report a final savings estimate based on the VBDD method, which will be used for program planning purposes.

Simple linear regression model. This model provided us with the most basic energy savings estimate with no adjustment for weather or building size. Using the simple linear regression model, the unadjusted annual energy savings per DHP were 1,120 kWh. This equates to 12 percent of the average pre-treatment, raw annual electric usage per dwelling unit of 9,067 kWh. The 90 percent confidence interval of the savings estimate was ±916 kWh, and relative precision was 82 percent, indicating a high degree of uncertainty.

Multivariate linear regression model. The multivariate linear regression model controlled for the effects of weather and building size, allowing for a more accurate estimate of typical energy savings. Using this model, the adjusted annual energy savings per DHP were 1,797 kWh. The average pre-treatment, adjusted annual usage per dwelling unit was 9,025 kWh, with annual heating usage of 3,268 kWh and annual cooling usage of 36 kWh. Thus, the savings estimate equates to 20 percent overall electric savings and 55 percent heating savings. The 90 percent confidence interval of the savings estimate was ±771 kWh, and relative precision was 43 percent, indicating a moderately high degree of uncertainty.

Fixed effects panel regression model. The fixed effects panel model better handled variance between and within buildings than the multivariate regression model, while controlling for weather and building size. The adjusted annual energy savings per DHP were 1,755 kWh. The average pre-treatment, adjusted annual usage per dwelling unit was 9,804 kWh, with annual heating usage of 3,492 kWh, and annual cooling usage of 33 kWh. This equates to 18 percent overall electric savings and 50 percent heating savings. The 90 percent confidence interval of the savings estimate was ±762 kWh, and relative precision was 43 percent, indicating a moderately high degree of uncertainty.

Multilevel panel regression model. Similar to the fixed effects panel model, the multilevel panel model provided a more accurate estimate of typical energy savings by controlling for weather and building size, as well as properly accounting for variations in energy usage within and between buildings. Using the consistent HDD and CDD reference temperatures of 60 and 70, the adjusted annual energy savings per DHP were 1,750 kWh. The average pre-treatment, adjusted annual usage per dwelling unit was 9,085 kWh, with annual heating usage of 3,592 kWh and annual cooling usage of approximately 45 kWh. Thus, the savings estimate equates to 19 percent overall electric savings and 49 percent heating savings. The 90 percent confidence interval of the savings estimate was ±760 kWh, and relative precision was 43 percent, indicating a moderately high degree of uncertainty.

We also conducted a search for the optimal HDD and CDD reference temperatures, which we found to be 58 and 78, respectively. When we re-ran the multilevel panel model with these HDD and CDD variables, the difference in the point estimate and error term were trivial. However, there were notable differences in the estimated pre-treatment annual electric usage and heating and cooling components. The average pre-treatment, adjusted annual usage per dwelling unit was 9,104 kWh, with annual heating usage of 3,264 and annual cooling usage of 12 kWh. This results in 19 percent overall electric savings and 54 percent heating savings.

Building-level VBDD models. The building-level VBDD weather normalization method is the standard procedure used for residential utility billing analysis[12]. It provided an accurate estimate of energy savings based on building science principles by modeling each building's relationship with weather individually in each study period. The advantage of this method is that each building is assigned its own heating and cooling reference temperatures based on individual model fit. The adjusted annual energy savings per DHP were 1,768 kWh. The average pre-treatment, adjusted annual usage per dwelling unit was 9,014 kWh with annual heating usage of 3,801 kWh and annual cooling usage of 159 kWh. This results in 20 percent overall electric savings and 47 percent heating savings. The 90 percent confidence interval of the savings estimate was ±757 kWh, and relative precision was 43 percent, indicating a moderately high degree of uncertainty.

Table 5: Estimated annual electric savings per DHP, by analysis method.

Analysis Method	Annual kWh Savings per DHP	90% Conf. Interval	Rel. Precision @ 90% Conf.	% Savings	% Heating Savings	Annual kWh Usage Per Unit	Heating kWh Usage Per Unit
Raw treatment effect	960	±927	97%	11%	--	9,069	--
Simple linear model	1,120	±916	82%	12%	--	9,067	--
Multivariate linear model	1,797	±771	43%	20%	55%	9,025	3,268
Fixed effects panel model	1,755	±762	43%	18%	50%	9,804	3,492
Multilevel panel model	1,750	±760	43%	19%	49%	9,085	3,592
Building-level VBDD models	**1,768**	**±757**	**43%**	**20%**	**47%**	**9,014**	**3,801**

Building-Level VBDD Model Results

Below we provide additional detail about the results of the VBDD building-level models. Table 6 provides a summary of the building-level models themselves, including the number of buildings where a valid weather model was selected, the mean HDD and CDD reference temperatures selected, and the mean R^2 value of the weather models. The treatment group had a slightly lower proportion of buildings where a valid weather model was selected, especially in the pre-treatment period. In these cases, a poor model fit resulted in the use of the raw annual electric usage, rather than the normalized annual electric usage. In addition, the weather models that were used in the treatment group had slightly lower R^2 values than the comparison group. On average, the reference temperatures selected for the VBDD models were very similar to the temperatures used in the pooled models, described above.

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[12] NEEA. (2013). Residential Building Stock Assessment: Multifamily Characteristics and Energy Use. Retrieved from http://neea.org/docs/default-source/reports/residential-building-stock-assessment--multi-family-characteristics-and-energy-use.pdf

Table 6: Summary of building-level VBDD models, by study group and period.

Group	N	Study Period	Buildings with Weather Model	% Buildings with Weather Model	Mean HDD Reference Temp	Mean CDD Reference Temp	Mean Model R^2
Treatment	112	Pre	101	90%	59.8	71.0	0.81
		Post	108	96%	59.7	73.1	0.86
Comparison	136	Pre	133	98%	59.8	72.7	0.85
		Post	132	97%	59.7	73.1	0.89

Figure 5 shows the distribution of HDD and CDD reference temperatures for the building-level weather models used. Many of the weather models did not utilize a CDD variable, so the sample sizes are smaller.

Figure 5: Distributions of VBDD building-level model HDD and CDD reference temperatures, by study group and period

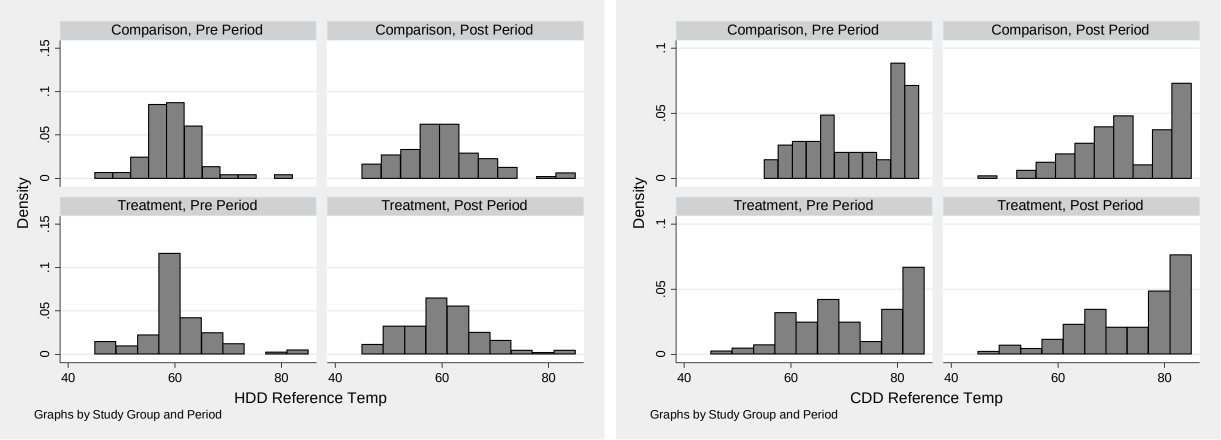


Table 7 provides the mean VBDD model-estimated weather-normalized annual electricity usage per building for each study group and study period. Table 7 also shows the mean differences in annual usage between the study groups in each period, the changes in annual usage within each group and the difference in the changes in annual usage. Treatment buildings reduced their usage substantially on average, while the comparison building usage only changed slightly. The treatment buildings reduced their weather-normalized annual electric usage by 2,588 kWh more than the comparison buildings on average. If we divide this results by 1.72, the number of DHPs installed per treatment building, we get 1,502 kWh, which represents the reduction in electric usage per DHP. This rough estimate of savings is similar to the final result without the adjustment for building size.

Table 7: Normalized annual electric usage per building, by study group and period.

Group	N	Pre-Period Annual kWh		Post-Period Annual kWh		Change in kWh	
		Mean	SE	Mean	SE	Mean	SE
Treatment	112	31,521	1,899	27,863	1,498	-3,658	707
Comparison	136	39,672	1,792	38,602	1,716	-1,070	558
Difference	**248**	**-8,151**	**2,611**	**-10,740**	**2,278**	**-2,588**	**901**

Figure 6 shows the distributions of weather-normalized annual electricity usage per building for the treatment and comparison groups in each study period. Figure 7 graphically displays the building-level treatment effect by comparing the distributions in the change in weather-normalized annual electric usage per building between the treatment and comparison groups.

The difference between the two study groups is readily apparent. The mode of the comparison group distribution of change in electric usage is close to zero kWh, indicating relatively small changes in energy usage for most of these buildings. Conversely, the treatment group distribution has a mode near -2,000 kWh, indicating a substantial reduction in energy usage for most treatment buildings.

Figure 6: Distribution of normalized electric usage per building, by study group and period.

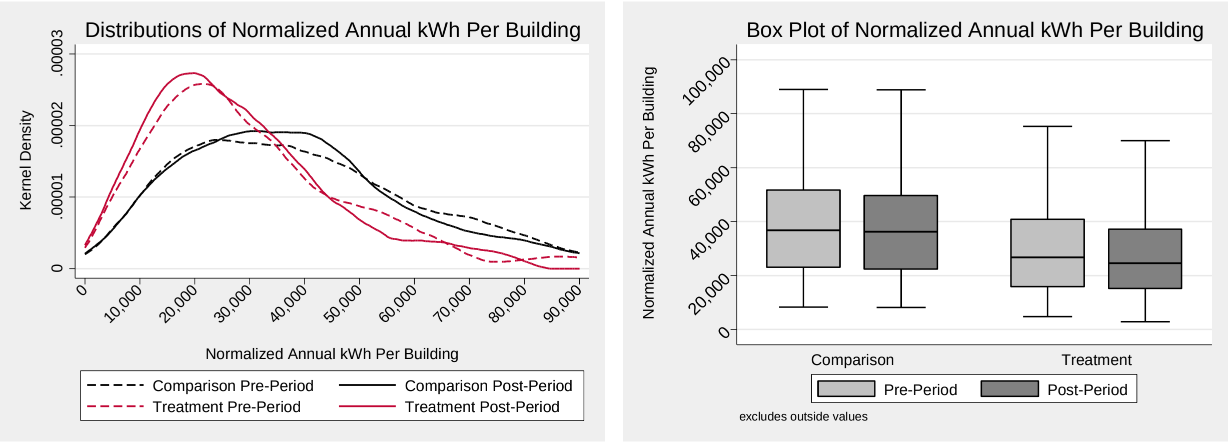


Figure 7: Distribution of change in normalized electric usage per building, by study group.

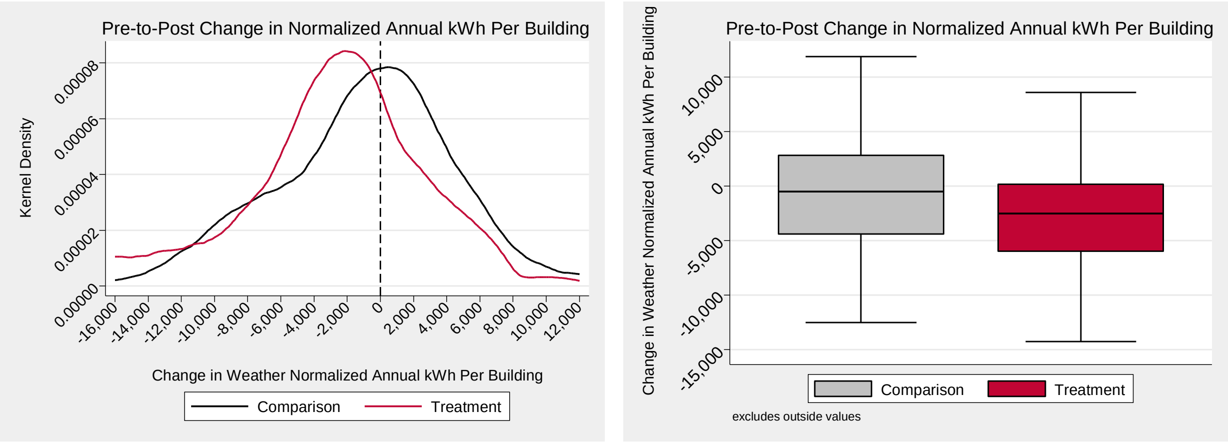
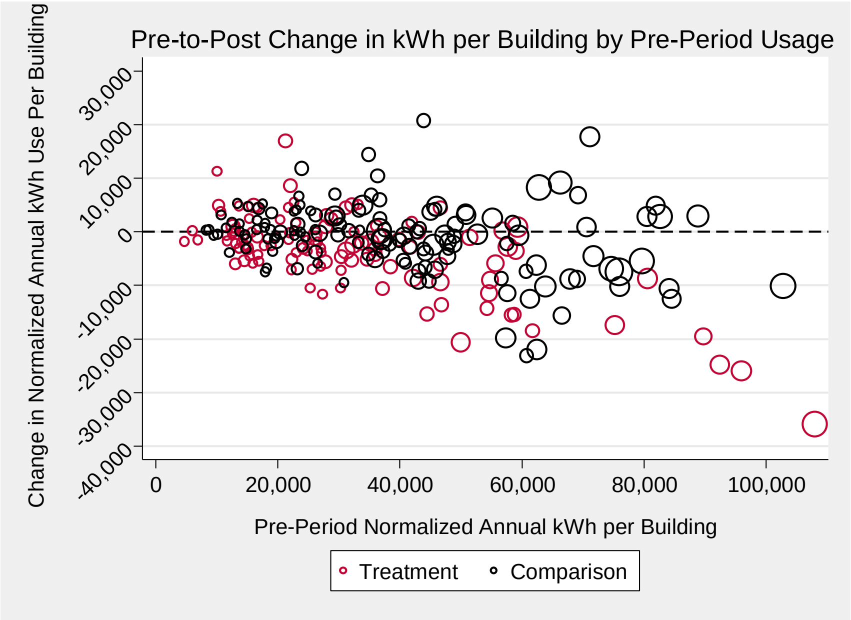


Figure 8 displays the variability in pre-to-post changes in weather-normalized annual electric usage as a function of the pre-period annual electric usage. The reference line indicates zero change in usage. This figure shows that reductions in treatment group normalized electric usage were much more frequent than increases. In addition, the reductions tended to be larger for buildings with higher pre-treatment usage. Changes in usage in the comparison group were more evenly distributed around zero, with a few obvious outliers.

Figure 8: Scatterplot of changes in normalized electricity usage per building, by pre-period electric usage, study group, and building size.



Note: Marker size illustrates the relative size of each building, based on the number of dwelling units.

Subgroup Analysis Results

As previously discussed, we conducted subgroup analyses to understand the effect of a number of factors on DHP electric savings in multifamily buildings. We analyzed the potential impact on savings of the following building characteristics: building size, pre-treatment annual usage per unit, geographic region and ownership of units. We also analyzed the impact of the following treatment variables: DHP manufacturer, average HSPF level, install year, installation contractor, percent of units treated, and number of indoor heads per system.

This analysis does not prove any causal links between particular subgroups and energy savings. Rather, it is suggestive of factors where differences in savings may have occurred. Further, a number of the factors we analyzed were moderately correlated with one another, making it difficult to determine which ones were most influential. Table 8 shows the correlation coefficients between the building characteristics variables we investigated.

Not surprisingly, larger buildings with more units had higher total annual electric usage and lower annual usage per unit. There was a slight association between the larger buildings in the sample and buildings with owner-occupied units. There was also a slight association between buildings in the Portland Metro area and owner-occupied units.

Table 8: Pearson correlation coefficients for associations between building variables.

Subgroup Variable	Number of Units	Buildings with 5+ Units	Annual kWh per Building	Annual kWh per Unit	High annual usage	Portland Metro Region	Owner-Occupied
Number of units	1.00						
Buildings with 5+ Units	0.83	1.00					
Annual kWh per building	0.81	0.72	1.00				
Annual kWh per unit	-0.22	-0.17	0.31	1.00			
High annual usage (10,000+ kWh per unit)	-0.17	-0.15	0.25	0.81	1.00		
Portland Metro region	0.19	0.18	0.23	0.06	0.00	1.00	
Owner-occupied units	0.28	0.22	0.29	-0.04	-0.03	0.36	1.00

Table 9 shows the correlation coefficients between the treatment variables we investigated as potential influences on savings. There was a moderately strong correlation between single-head DHP systems and higher HSPF levels.

There was also a minor association between the top three installers and higher HSPF levels. After further investigation, we discovered that the installers appeared to have moderately strong relationships with particular DHP manufacturers. Cross-tabulations revealed that the top three installers were slightly more likely to install DHP systems from Manufacturer A (62 percent of buildings) than other installers (48% of buildings), although this difference was not statistically significant. In addition, the DHPs installed by the top three installers had significantly higher HSPF ratings than those installed by other contractors (p<0.001), with averages of 11.3 versus 10.2.

Table 9: Pearson correlation coefficients for associations between treatment variables.

Subgroup Variable	Low proportion of units with DHPs	Single head DHPs	Higher HSPF (10.5+)	Install Year	Top 3 Installers
Low proportion of units with DHPs	1.00				
Single head DHPs	-0.21	1.00			
Higher HSPF (10.5+)	-0.16	0.52	1.00		
Install Year	-0.04	0.06	0.03	1.00	
Top 3 Installers	-0.02	0.17	0.36	0.01	1.00

Table 10 presents the estimated weather-normalized annual electric savings results for each subgroup in the analysis, based on the VBDD building-level models. For each subgroup, the table displays the treatment group sample size, the annual savings estimate, the 90 percent confidence interval, the relative precision at 90 percent confidence, the savings as a percent of mean annual electric usage per unit, the mean normalized annual electric usage per unit, and the mean number of dwelling units per building. The results for subgroups with sample sizes below 30 are flagged as unreliable and should be interpreted with caution. In addition, it is important to look at the magnitude of the confidence interval and relative precision to understand the reliability of each estimate. The results of each subgroup can be compared to the overall results in the first row to better understand the magnitude of variations. We flagged factors where the difference in savings estimates between subgroups were statistically significant at the 10 percent level. In many cases, the absolute values for the subgroup savings estimates presented below, and differences between them, may not be that meaningful; however, the differences are indicative that certain factors may have a real effect on DHP electric savings. Alternatively, some of these differences may be due to random chance or to other factors that are correlated with those listed below. More discussion and interpretation of the subgroup findings are provided below.

Table 10: Estimated annual electric savings per DHP, by subgroup.

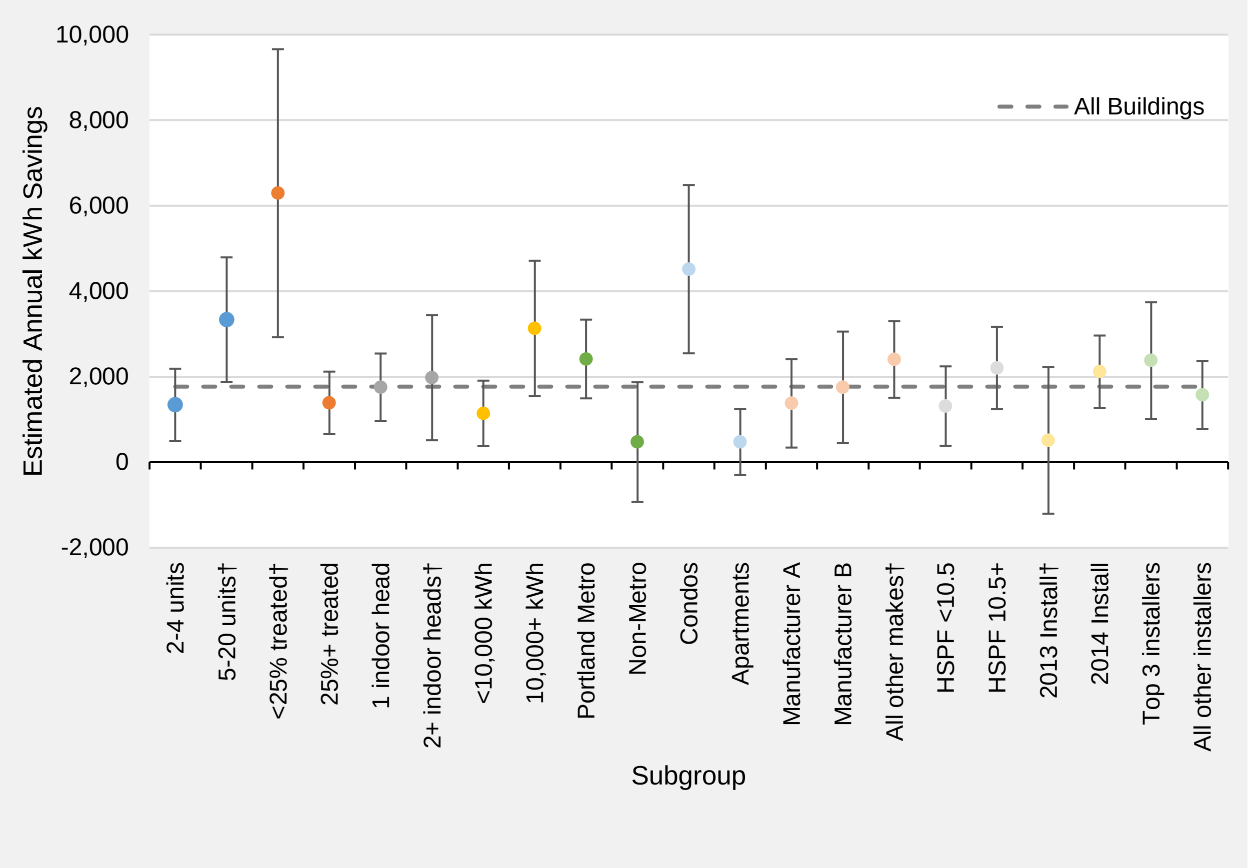
Factor	Subgroup	Tx N	Annual kWh Savings	90% Conf. Interval	90% Rel. Precision	% Savings	Annual kWh Usage	# of Units
Overall	**All buildings**	**112**	**1,768**	**±757**	**43%**	**20%**	**9,014**	**3.5**
Building size*	2-4 units	92	1,340	±848	63%	15%	9,012	2.8
	5-20 units†	*20*	*3,335*	±1,456	44%	*37%*	*9,023*	*6.8*
% of units with DHPs*	*<25% treated†*	*15*	*6,291*	±3,369	54%	*67%*	*9,373*	*6.4*
	25%+ treated	97	1,387	±732	53%	15%	8,958	3.1
Number of indoor heads	1 indoor head	82	1,752	±791	45%	20%	8,833	3.5
	2+ indoor heads†	*26*	*1,977*	±1,464	74%	*21%*	*9,453*	*3.7*
kWh usage per unit*	<10,000 kWh	73	1,143	±765	67%	16%	7,085	3.6
	10,000+ kWh	39	3,130	±1,582	51%	25%	12,625	3.3
Region*	Portland Metro	78	2,414	±921	38%	26%	9,395	3.8
	Non-Metro	34	471	±1,398	297%	6%	8,139	2.8
Ownership type*	Condos	58	4,515	±1,969	44%	49%	9,260	3.9
	Apartments	54	475	±770	162%	5%	8,749	3.1
DHP make	Manufacturer A	58	1,377	±1,034	75%	16%	8,633	3.2
	Manufacturer B	33	1,755	±1,300	74%	18%	9,529	3.7
	All others†	*21*	*2,405*	±896	37%	26%	*9,257*	*4.1*
Efficiency rating	HSPF <10.5	52	1,314	±928	71%	15%	9,035	3.8
	HSPF 10.5+	59	2,204	±963	44%	25%	8,891	3.3
Installation year	*2013†*	25	*512*	±1,715	335%	6%	*8,810*	*3.3*
	2014	87	2,118	±845	40%	23%	9,072	3.6
Installer	Top 3 installers	32	2,378	±1,362	57%	25%	9,503	3.5
	All others	80	1,572	±799	51%	18%	8,818	3.5

† The sample size of treatment group buildings was very small for this subgroup, so the results may not be reliable.

* The difference between subgroups was statistically significant at the 10% level for this factor.

Figure 9 graphically displays the estimated weather-normalized, annual electric savings results for each subgroup with 90 percent confidence intervals. This bar chart provides a sense for the magnitude of differences, relative to the amount of error in each estimate. All subgroup estimates are compared to a reference line, representing the overall electric savings estimate for the entire sample of treatment buildings.

Figure 9: Estimated annual electric savings per DHP, by subgroup, with 90% confidence intervals.



† The sample size of treatment group buildings was very small for this subgroup, so the results may not be reliable.

Building size. The number of dwelling units in a building appeared to have a significant impact on the estimate of annual electric savings per DHP. Larger buildings with 5-20 units had a savings estimate nearly 2,000 kWh higher than the estimate for 2-4 unit buildings. Not only were the absolute savings higher but the percent electric savings were also higher. At the outset of this study, we hypothesized that smaller buildings would have higher DHP electric savings, because they tend to have higher heating loads per unit and more closely resemble single-family homes. These results suggest that the opposite may be true. Although the difference was statistically significant, the sample size of larger buildings was very small, calling into question the reliability of these results and whether there is a real difference.

Proportion of dwelling units with DHPs. One concern we had with this analysis was that buildings with low proportions of units treated with DHPs would be difficult to analyze because their savings signal could be overwhelmed by noise in the energy usage data. To address this concern, we compared buildings where less than 25 percent of the units received a DHP with buildings where 25 percent or more of the units received a DHP. Note that buildings where less than 10 percent of units received a DHP were removed from the analysis during screening because of this concern. Buildings with less than 25 percent of units treated had a savings estimate far exceeding the estimate for buildings with 25 percent or more of units treated. Although the difference was statistically significant, the sample size of buildings with a low proportion of treated units was very small, so the savings estimate for this subgroup may not be reliable.

<u>Number of indoor heads.</u> In previous DHP studies[13] it has been shown that DHP systems with multiple indoor heads have a performance penalty and do not necessarily save more electricity than a single head system installed in the same home. Flat savings, combined with substantially higher equipment and installation costs for multi-head systems, negatively impact the cost-effectiveness of the technology. We compared buildings with single-head DHP systems to those with multi-head systems and obtained results consistent with past research. Buildings with single-head systems had an annual electric savings estimate very similar to buildings with multi-head systems. This small difference was not statistically significant. In addition, the number of buildings with multi-head DHP systems was very small, so the savings estimate for this subgroup may not be reliable.

<u>Electric usage per unit.</u> Buildings with 10,000 kWh per unit or more of annual electric usage in the pre-treatment period had a savings estimate per DHP that was nearly 2,000 kWh more than buildings with lower usage per unit. Not only were the absolute savings higher, but the percentage of electric savings was also higher. This difference was statistically significant. This is a fairly typical finding when analyzing utility bill impacts of residential measures and aligned with our expectation for the effect of household energy consumption on DHP savings. It supports the argument that targeting multifamily buildings with high electric usage per unit would improve the overall cost-effectiveness of DHPs.

<u>Region.</u> Due to the limited sample size of DHP projects outside the Portland Metro area, we could only compare buildings in the Portland Metro area with buildings in the rest of Oregon (primarily Western Oregon). Even so, the geographic region had a very significant impact on the estimate of electric savings per DHP. Buildings in the Portland Metro area had a savings estimate that was nearly 2,000 kWh higher than the estimate for non-Metro buildings. Geographic region is related to climate, which can drive differences in savings, but it may also be associated with other factors more directly tied to DHP performance and savings. In addition, the savings estimate for non-Metro buildings had very poor precision, so this value should be interpreted with caution.

<u>Ownership type.</u> The analysis sample contained a fairly even split of treatment buildings that were owner-occupied condos versus renter-occupied apartments. Renter-occupied buildings were primarily market rate apartments, but also contained a few affordable housing and assisted living buildings. Ownership type had a very significant impact on the estimate of electric savings per DHP. Owner-occupied condo buildings had an electric savings estimate that was 4,000 kWh higher than the estimate for apartment buildings. Not only were the absolute savings much higher, but the percentage electric savings were also higher. However, the savings

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[13] NEEA. (2014). Final Summary Report for the Ductless Heat Pump Impact and Process Evaluation. Retrieved from http://neea.org/docs/default-source/reports/e14-274-dhp-final-summary-report-(final).pdf

estimate for apartment buildings was somewhat uncertain, with relatively poor precision, so this value should be interpreted with caution. Also, it is likely that building ownership is related to many other building factors, such as configuration, occupancy, equipment, and operation, which may more directly influence DHP performance and electric savings.

DHP make. Treatment buildings in the analysis sample predominantly received DHP systems from Manufacturer A, while Manufacturer B was the second most common. The remaining buildings were split between several other well-known DHP makes. While DHP brand appeared to have an effect on the estimate of electric savings per DHP, the differences were not statistically significant. In addition, the savings estimates for the Manufacturer A and B subgroups had relatively low precision, and the sample size for the other DHP make subgroup was very small.

Efficiency rating. Treatment buildings were relatively evenly split between DHPs with low efficiency ratings (HSPF of <10.5) and high efficiency ratings (HSPF of 10.5+). It is logical to assume that the buildings with higher efficiency DHPs installed would realize higher electric savings, which is what we observed. However, the difference in the savings estimates between the low and high efficiency subgroups was not statistically significant. In addition, the savings estimate for the low efficiency subgroup had relatively high uncertainty.

Install year. We wanted to investigate whether there were differences in DHP savings over time, but very few DHPs were installed through the Multifamily program in 2013. A much larger number was installed in 2014. Although it appeared that the electric savings estimate per DHP was much lower for 2013 projects, the difference was not statistically significant. In addition, the sample size of 2013 DHP projects was very small, so the savings estimate for this subgroup may not be reliable.

Installation contractor. DHPs were installed in treatment buildings by dozens of contractors, with no single contractor predominating in the analysis sample. To see if there were important differences, we looked at the top three contractors and compared them to all other contractors in the sample. The subgroup of DHP projects completed by the top three contractors appeared to have somewhat higher savings than DHP projects completed by all other contractors. However, this difference was not statistically significant.

CONCLUSIONS AND RECOMMENDATIONS

On average, low-rise multifamily buildings in Oregon with two to 20 dwelling units that installed one or more DHP systems from 2013 to 2014 realized electricity savings of 1,768 kWh (±757) per DHP per year. This represents 20 percent overall electricity savings per treated dwelling unit and 47 percent heating savings. The evaluated savings estimate is statistically different from the average deemed savings claimed by Energy Trust's Multifamily program in 2013 and 2014, of 2,852 kWh per DHP. This resulted in a realization rate of 62 percent. In 2017, the program claimed average deemed savings of 2,916 kWh per DHP for buildings with zonal electric resistance heat. The electric savings estimated in our study are similar to, but slightly lower than, DHP electric savings demonstrated in previous studies of single-family homes in the Northwest[14]. Past studies of DHPs in multifamily buildings have found much lower electric savings from DHPs, although those studies focused on much larger, renter-occupied buildings, which are not directly comparable[15] to our analysis sample. This leads us to conclude that the electric savings estimated in this study, for multifamily buildings in Oregon, is within a plausible range.

We observed substantial variation in building-level changes in electric usage in the analysis sample. This variability caused lower than expected precision in the overall DHP electric savings estimate. The relative precision, at 90 percent confidence, was 43 percent, compared to the typical target of 10 percent for energy efficiency impact evaluations. We identified a number of factors that appeared to explain some of the variability in DHP electric savings within the analysis sample. However, these results should be interpreted with caution, because many of the subgroups we analyzed had relatively small sample sizes or low precision, so we do not have high confidence in the savings estimates. In addition, many of the factors we identified are correlated with one another, so we don't necessarily know which ones are the primary drivers of differences in savings.

One of the interesting subgroup analysis findings was that larger buildings with more units realized significantly higher electric savings than smaller buildings. This was counterintuitive because we assumed that larger buildings with smaller dwelling units and smaller heating loads would achieve lower electric savings. An alternative explanation is that DHPs installed in smaller dwelling units in larger buildings may more effectively displace a higher proportion of the electric heating load. In addition, larger buildings were associated with a lower proportion of dwelling units treated with a DHP. In this case, a single DHP system may partly serve the heating load of more than one dwelling unit or common area within the same building envelope, thus saving more energy per DHP than in a building with a high proportion of treated units. However, it is equally possible that these differences in savings resulted from other factors related to building size or from random variations related to the small subgroup sample sizes.

In our analysis sample, owner-occupied buildings tended to be larger than the renter-occupied buildings on average. The higher savings observed in larger buildings may partly explain the

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[14] NEEA. (2014). Final Summary Report for the Ductless Heat Pump Impact and Process Evaluation. Retrieved from http://neea.org/docs/default-source/reports/e14-274-dhp-final-summary-report-(final).pdf
[15] BPA. (2016). Assessment of Ductless Mini-Split Heat Pump Energy Savings in Stack House Apartments. Retrieved from https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Pages/Assessment-of-Ductless-Mini-Split-Heat-Pump-Energy-Savings-in-Stack-House-Apartments.aspx

relatively high savings estimate for condo buildings compared to apartment buildings. Conversely, condo units often have more open floor plans than apartments, which may contribute to higher savings in larger buildings, by allowing the DHP to serve a larger portion of the electric heating load. Condo buildings were also associated with slightly higher annual electric usage per unit, which was in turn related to higher electric savings per DHP. The finding that buildings with higher electric usage per unit have higher savings is not surprising, since these buildings have more opportunity for savings.

DHPs installed in buildings in the Portland Metro area had significantly higher electric savings than those installed outside the Portland area. While this could be due to differences in climate or installation practices, there are some interesting differences in building characteristics that could partly explain the difference. Portland Metro buildings were more likely to be condos and they had higher electric usage per unit, on average. Since these two factors were associated with higher electric savings, they may be partly driving the higher Portland Metro area savings. There may also be underlying factors that we did not study that are the true drivers of the observed differences in DHP savings. It is also possible that these differences are simply due to random variability in the sample. In any case, these associations between building characteristics and savings are noteworthy and require further investigation.

There are several potential limitations to this study, which may reduce the validity or generalizability of the results. We decided early in the study to conduct our analyses at the building level rather than the dwelling unit level. Using this approach, we captured and analyzed whole building energy consumption, which allowed us to properly account for space conditioning interactions that occur between dwelling units and common areas within a structure. The potential downside is that the natural variability in energy usage for the entire building may obscure the energy savings to some degree, particularly when only a small portion of dwelling units are treated. However, this study provided some evidence that DHPs influenced space heating beyond the treated unit, which can only be captured through a building level analysis.

The comparison group selected for this study was created from buildings that went on to participate in the Multifamily program in a future year (2016). The working assumption was that the most comparable sites to program participants are other program participants. They tend to share building characteristics, tenant characteristics and propensity to do other energy efficiency measures. We also had relatively good information about them to use in the analysis. Unfortunately, since we did not match the comparison group to our treatment group based on energy usage or building characteristics, the groups were somewhat similar but not identical. For instance, the comparison buildings tended to be larger, used more total electricity per year, used less electricity per dwelling unit and were less likely to be condos. However, for this analysis the most important factor was how similar the comparison buildings were to the treatment buildings in terms of year over year changes in electric usage, minus the DHP effect.

Several potentially influential factors we were not able to analyze may have played a role in the observed energy savings. We were unable to obtain information about other incidental efficiency measures installed in the treatment and comparison buildings during our analysis period, including those incentivized by the Multifamily program. We assumed that the treatment and comparison buildings had a similar propensity to install efficiency measures because they were all program participants. However, large projects in either group could have skewed the results in one direction or the other.

Another characteristic with incomplete information was heating fuel. We selected only treatment and comparison buildings with electricity listed as the primary heating fuel. However, we did not have information about the use of supplemental fuels, particularly wood and gas. If there was significant supplemental heating in the analysis sample, then it could have skewed the results towards zero.

Considering all the strengths and potential limitations, we believe that this analysis provides the basis for a reasonable energy savings estimate of DHPs installed in two to 20 dwelling unit multifamily buildings in Oregon. Given the relatively large sample size of this analysis and the insensitivity of results across numerous model specifications, **we recommend that the Multifamily program use the electric savings we found, of 1,768 kWh per DHP to recalibrate the deemed savings that Energy Trust claims.** In addition, **we recommend that this savings value be used to true-up DHP electric savings claimed in past program years.**

In addition, the amount of variation in savings within the analysis sample and between subgroups is somewhat concerning. **We recommend conducting an additional study to see if the energy savings are changing over time, and to determine the sources of variability in savings. We recommend another billing analysis with a larger sample of multifamily buildings and more recent DHP projects installed from 2015 to 2017.** This study would allow us to produce a more stable savings estimate using a larger sample size and see if there was a trend in savings over time. In addition, **we recommend collecting more detailed data on building characteristics, occupant information, and short-interval electric usage data from a wide variety of different buildings with recent DHP installs.** This would allow for a more robust analysis of the driving factors influencing DHP electric savings and a more precise quantification of their impacts.

APPENDIX

Appendix A: Preliminary Evaluation of Ductless Heat Pumps Installed in Oregon Multifamily Properties

Measure Approval Document for Ductless Heat Pumps in Existing Multifamily

Valid Dates:

January 1, 2017 to December 31, 2017

End Use

Ductless heat pump (DHP) systems in existing multifamily, replacing electric resistance heat units.

Program Applicability

Based on the referenced analysis and associated cost-effectiveness screening, the measures described below are approved on a prospective basis for use in the following programs:

- Existing Multifamily

Cost Effectiveness

Table 1 Cost Effectiveness Calculator DHP in existing multifamily buildings

Measure	Measure Life (years)	Savings	Costs	Maximum Incentive	Utility BCR at Max Incentive	TRC BCR
		kWh				
DHP in existing multifamily (Portland) 3/4 ton	18	1,937	$2,207	$1,975	1.00	0.90
DHP in existing multifamily (Bend) 3/4 ton	18	3,252	$2,207	$1,975	1.68	1.50
DHP in existing multifamily (Portland) 1 ton	18	2,583	$2,596	$1,975	1.33	1.01
DHP in existing multifamily (Bend) 1 ton	18	4,336	$2,596	$1,975	2.24	1.70
DHP in existing multifamily (Portland) 1.5 ton	18	3,875	$3,374	$1,975	2.00	1.17
DHP in existing multifamily (Bend) 1.5 ton	18	6,504	$3,374	$1,975	3.36	1.97
DHP in existing multifamily (Portland) 2 ton	18	5,166	$5,192	$1,975	2.67	1.01
DHP in existing multifamily (Bend) 2 ton	18	8,672	$5,192	$1,975	4.48	1.70

Exceptions

Cost effectiveness is listed in Table 1. The smallest expected size DHP is not cost effective in the Portland climate zone. This size accounted for less than 5% of installations during the pilot.

Energy Trust has requested a cost effectiveness exception from the OPUC, which was approved on 10/19/2016. This exception is based on UM-551 criteria D. This measure will help increase participation in a cost effective program. If smaller sizes were excluded, contractor and participant confusion may decrease participation as building owners replace multiple units within a property at the same time. The OPUC also considered the passing overall TRC of the mix of expected sizes as a consideration in approving the exception. OPUC staff has requested an update in September 2017 or before, verifying that the mix of sizes of DHP in multifamily does not change from projections such that DHP overall fails the TRC. In the event that this measure is updated prior to September, the updated analysis will be shared.

Program Requirements

Qualification for the offering requires:

- Installation of an inverter driven DHP and HSPF 9.0 or greater,
- DHP must have a 5-year minimum compressor warranty.
- Replacing electric resistance (Electric furnace, electric baseboard or in-wall unit).
- Must collect and record, total tons, number of indoor units, number of outdoor units.

Savings and Baseline

A pilot study was conducted to measure actual savings from DHPs replacing electric resistance-heated units in existing multifamily. The pilot analysis included systems installed from March 2011– August 2014. A total of 396 DHP systems (494 tons of capacity with 471 heads) were installed at 130 unique sites across both climate zones. The final pilot impact evaluation is not complete in time for 2017 measures, so an interim savings calculation was completed by Lockheed Martin.

Pilot measurement and verification analysis was conducted in accordance with:

- ASHRAE Guideline 14-2002 – Measurement of Energy and Demand Savings
- U.S. DOE Uniform Methods Project[16]
- International Performance Measurement and Verification Protocol (IPMVP) Option C.

Monthly electricity usage data from 2010 through 2014 was extracted from Energy Trust's utility billing database for all properties participating in the pilot. Usage data for each unit was matched to the treatment and control group units using the address and unit number or meter number. Dwelling units

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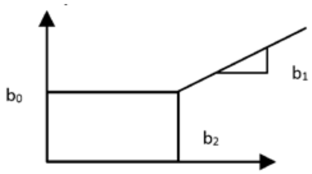
[16] http://www1.eere.energy.gov/wip/pdfs/53827-8.pdf

that could not be matched to utility data, with unidentifiable areas, with other energy conservation measures, or with natural gas consumption were dropped from the analysis. Electric billing records with missing values, duplicates, or with billing periods that were too long or too short were removed from the analysis. The final attrition step in the analysis was to remove units with fewer than three electric usage observations either before or after the heater retrofit was completed. Next, raw daily average electric usage for each billing period for each unit was computed. Daily usage became the primary unit for the analysis. Unit-level energy consumption was examined in a simple linear regression versus HDD.

To determine the energy savings attributable to the ductless heap pumps, the change in monthly electricity usage from the pre- to post-installation period was compared, while controlling for square footage, DHP capacity, and weather (heating degree-days). Weather data from two Oregon weather stations (Portland and Bend) were obtained online from the National Climatic Data Center. Each multifamily building was matched to the nearest weather station based on its zip code. Daily average heating degree-days (HDD) for each billing period for each dwelling unit were calculated. HDD variables were computed for a reference temperature of 61°F to be consistent with other pilot studies[17]. Average daily HDD variables were directly compared with the average daily electric usage.

The comparison in usage was made using the steady-state, single-variate, three-parameter change point linear regression model applied to utility billing data. Utility bill data was normalized to the lowest common denominator by dividing by: number of days in billing period, square footage of the dwelling unit, and capacity of DHP system (tons). Normalized electric use was modeled as a function of average daily HDDs. The following figure and formula describe the resulting linear regression model[18]:



$$E = b_0 + b_1(HDD)$$

Figure 1 Regression Model Methodology

Where:

- E is the estimated energy consumption during the heating season
- b_0 is the non-heating base load energy consumption

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[17] Rubado, D. (2015). Multifamily Program Cadet Energy Plus Heater Pilot, Billing Analysis of Electric Energy Usage. 9pp. Energy Trust of Oregon.

[18] 2013 ASHRAE Handbook - Fundamentals

- b_1 is the slope coefficient for the relative increase in energy consumption per unit heating degree day
- b_2 is the change point for the defined heating season (3 HDD / day)

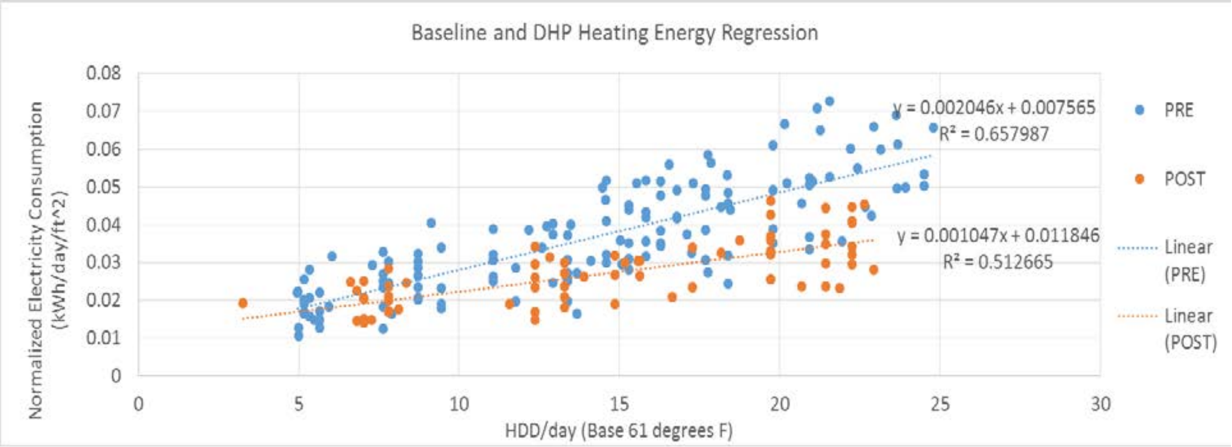

Figure 2 Regression Model Results

The difference of the slope coefficient, b_1, for pre- and post-installation consumption describes the average daily energy savings for data normalized for dwelling area, and per ton of DHP capacity. The post installation base load coefficient, b_0, was set to equal the pre-installation coefficient at the assumed change point for heating season (b_2 = 3 HDD/day) to remove any variation in non-heating energy consumption. A linear combination of pre- and post-installation regression models was computed to estimate the weather normalized average electric savings per dwelling unit and per ton of DHP capacity, as follows:

$$E_{savings/ton} = \left(b_{1\ pre-installation} - b_{1\ post-installation}\right) * HDD_{TMY} * Area_{average\ dwelling}$$

Where:

- $b_{1\text{ pre-installation}}$ is the pre-installation slope coefficient
- $b_{1\text{ post-installation}}$ is the post-installation slope coefficient
- HDD_{TMY} is the 20 year (1995 – 2014) average HDDs for each weather station
- $Area_{\text{average dwelling}}$ is the average dwelling unit area (ft^2) for the pilot group

A compliance analysis was conducted using standardized statistical tests and error thresholds described in ASHRAE Guideline 14 to evaluate the model compliance.

Table 2 Weather and Energy Savings Data by Climate Zone

Climate Zone	20 Year Average HDD (1995-2014)	Energy Savings per Ton (kWh/yr)
Portland	3,172	2,583
Bend	5,325	4,336

Measure Life

The measure lifetime is 18 years and is the same lifetime used for ductless heat pumps in other Energy Trust programs.

Cost

Cost data was collected for DHP systems during the pilot period for 396 units installed at 130 different properties across the territory. On a case by case basis, the cost of DHP systems is dependent on the installed capacity (tons) and the number of indoor heads. The added benefit of room air conditioning is not considered in the cost analysis. A multivariate regression analysis was conducted on pilot cost data to obtain accurate cost per ton and per head. The regression resulted in an R^2 value of 0.983 with the cost coefficients in Table 3.

Table 3 Cost Coefficients for System Capacity and Number of Heads

Cost Component	Cost estimate
DHP cost per ton	$1,556
DHP cost per head	$1,040

The estimated installed cost can be estimated by the following equation for any system configuration:

$$DHP\ Installed\ Cost = \$1{,}556\ x\ Tons + \$1{,}040\ x\ Heads$$

Incentive Structure

While savings are structured by capacity, incentives will be structured per outdoor unit. The maximum incentive is $1975/unit. *The maximum is for reference only and is not a suggested incentive.*

Follow-Up

Savings should be revised with the results of the final pilot evaluation at the earliest opportunity. If pilot results are available in advance of the 2017 program year, this memo should be updated prior to 2017.

Costs should be reviewed at next revision.

An update will be provided to the OPUC on or before September 2017 regarding the overall TRC of installed projects based on 2017 mix of DHP tonnages.

Version History and Related Measures

Table 4 Version History

Date	MAD ID	Reason for revision
5/12/11	70	Approve single family DHP for small multifamily
8/8/13	97.x	Pilot approval for multifamily
6/20/14	187	Extend and modify terms of pilot approval
10/20/16	97.x	Transition from pilot to standard measure, supersedes earlier versions of MADs 97, and 187.

Table 5 Related Measures

Measures	MAD ID
DHP in new homes	177
DHP in existing single-family homes	70
DHP in manufactured homes	41
DHP in new construction multifamily and lodging	192

Approved and Reviewed by

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Appendix B: Detailed Regression Model Methods and Equations Used to Determine DHP Energy Savings in Multifamily Buildings

Simple Linear Regression Model

The following formulae describe the regression model and savings calculation:

$$Usage_{ij} = \beta_0 + \beta_1(Post_{ij}) + \beta_2(Tx_i) + \beta_3(Post_{ij} * Tx_i) + \epsilon_{ij}$$

Average Annual Savings per DHP = $(365 * \beta_3)/DHPs$

Where:

i = the building indicator,
j = the month indicator,
$Usage_{ij}$ = the average daily electric usage for building *i* during month *j*,
β = the fixed effect model coefficients for each variable,
β_0 = the fixed model intercept, which can be interpreted as the pre-treatment, comparison group average daily electric usage per building,
$Post_{ij}$ $\{0,1\}$ = dummy variable where (1) indicates that building *i* is in the post-treatment period during month *j*,
Tx_i {0,1} = dummy treatment variable where (1) indicates that building *i* is in the treatment group and (0) indicates the comparison group, which is static across all months,
ϵ_{ij} = unexplained model error term for building *i* during month *j*, and,

$DHPs$ = Mean number of DHPs installed per treatment building.

Multivariate Linear Regression Model

The following formulae describe the regression model and savings calculation:

$$\begin{aligned} Usage_{ij} = {} & \beta_0 + \beta_1(Post_{ij}) + \beta_2(Tx_i) + \beta_3(Post_{ij} * Tx_i) + \beta_4(HDD60_{ij}) + \beta_5(Post_{ij} * HDD60_{ij}) \\ & + \beta_6(Tx_i * HDD60_{ij}) + \beta_7(Post_{ij} * Tx_i * HDD60_{ij}) + \beta_8(CDD70_{ij}) \\ & + \beta_9(Post_{ij} * CDD70_{ij}) + \beta_{10}(Tx_i * CDD70_{ij}) + \beta_{11}(Post_{ij} * Tx_i * CDD70_{ij}) \\ & + \beta_{12}(Units_i) + \beta_{13}(Post_{ij} * Units_i) + \beta_{14}(Tx_i * Units_i) \\ & + \beta_{15}(Post_{ij} * Tx_i * Units_i) + \beta_{16}(Units_i * HDD60_{ij}) \\ & + \beta_{17}(Post_{ij} * Units_i * HDD60_{ij}) + \beta_{18}(Tx_i * Units_i * HDD60_{ij}) \\ & + \beta_{19}(Post_{ij} * Tx_i * Units_i * HDD60_{ij}) + \beta_{20}(Units_i * CDD70_{ij}) \\ & + \beta_{21}(Post_{ij} * Units_i * CDD70_{ij}) + \beta_{22}(Tx_i * Units_i * CDD70_{ij}) \\ & + \beta_{23}(Post_{ij} * Tx_i * Units_i * CDD70_{ij}) + \epsilon_{ij} \end{aligned}$$

$$\text{Average Annual Savings per DHP } = \frac{365*\beta_3 + LRHDD60*\beta_7 + LRCDD70*\beta_{11} + AvgUnits*\beta_{15} + LRHDD60*AvgUnits*\beta_{19} + LRCDD70*AvgUnits*\beta_{23}}{DHPs}$$

Where:

i = the building indicator,

j = the month indicator,

$Usage_{ij}$ = the average daily electric usage for building *i* during month *j*,

β = the fixed effect model coefficients for each variable,

β_0 = the fixed model intercept,

$Post_{ij}$ $\{0,1\}$ = dummy variable where (1) indicates that building *i* is in the post-treatment period during month *j*,

Tx_i $\{0,1\}$ = dummy treatment variable where (1) indicates that building *i* is in the treatment group and (0) indicates the comparison group, which is static across all months,

$HDD60_{ij}$ = average daily heating degree-days, with 60^{o}F reference temperature, for building *i* during month *j*,

$CDD70_{ij}$ = average daily cooling degree-days, with 70^{o}F reference temperature, for building *i* during month *j*,

$Units_i$ = the number of dwelling units in building *i*, which is static across all months,

ϵ_{ij} = unexplained model error term for building *i* during month *j*,

$LRHDD60$ = long-run annual HDDs, with 60^{o}F reference temperature, for each weather station averaged across the treatment buildings, derived from the Typical Meteorological Year 3 (TMY3) dataset, and,

$LRCDD70$ = long-run annual CDDs, with 70^{o}F reference temperature, for each weather station averaged across the treatment buildings, derived from the TMY3 dataset,

$AvgUnits$ = mean number of dwelling units per treatment building, and,

$DHPs$ = mean number of DHPs installed per treatment building.

Fixed Effects Panel Regression Model

The following formulae describe the regression model and savings calculation:

$$\begin{aligned} Usage_{ij} = {} & \beta_0 + \beta_i + \beta_1(Post_{ij}) + \beta_2(Post_{ij} * Tx_i) + \beta_3(HDD60_{ij}) + \beta_4(Post_{ij} * HDD60_{ij}) \\ & + \beta_5(Tx_i * HDD60_{ij}) + \beta_6(Post_{ij} * Tx_i * HDD60_{ij}) + \beta_7(CDD70_{ij}) \\ & + \beta_8(Post_{ij} * CDD70_{ij}) + \beta_9(Tx_i * CDD70_{ij}) + \beta_{10}(Post_{ij} * Tx_i * CDD70_{ij}) \\ & + \beta_{11}(Post_{ij} * Units_i) + \beta_{12}(Post_{ij} * Tx_i * Units_i) + \beta_{13}(Units_i * HDD60_{ij}) \\ & + \beta_{14}(Post_{ij} * Units_i * HDD60_{ij}) + \beta_{15}(Tx_i * Units_i * HDD60_{ij}) \\ & + \beta_{16}(Post_{ij} * Tx_i * Units_i * HDD60_{ij}) + \beta_{17}(Units_i * CDD70_{ij}) \\ & + \beta_{18}(Post_{ij} * Units_i * CDD70_{ij}) + \beta_{19}(Tx_i * Units_i * CDD70_{ij}) \\ & + \beta_{20}(Post_{ij} * Tx_i * Units_i * CDD70_{ij}) + \epsilon_{ij} \end{aligned}$$

$$\text{Average Annual Savings per DHP } = \frac{365*\beta_2 + LRHDD60*\beta_6 + LRCDD70*\beta_{10} + AvgUnits*\beta_{12} + LRHDD60*AvgUnits*\beta_{16} + LRCDD70*AvgUnits*\beta_{20}}{DHPs}$$

Where:

i = the building indicator,

j = the month indicator,

$Usage_{ij}$ = the average daily electric usage for building *i* during month *j*,

β = the fixed effect model coefficients for each variable,

β_0 = the overall fixed model intercept for all buildings,

β_i = the fixed model intercept for building *i*,
$Post_{ij}$ $\{0,1\}$ = dummy variable where (1) indicates that building *i* is in the post-treatment period during month *j*,
Tx_i $\{0,1\}$ = dummy treatment variable where (1) indicates that building *i* is in the treatment group and (0) indicates the comparison group, which is static across all months,
$HDD60_{ij}$ = average daily heating degree-days, with 60ºF reference temperature, for building *i* during month *j*,
$CDD70_{ij}$ = average daily cooling degree-days, with 70ºF reference temperature, for building *i* during month *j*,
$Units_i$ = the number of dwelling units in building *i*, which is static across all months,
ϵ_{ij} = unexplained model error term for building *i* during month *j*,
$LRHDD60$ = long-run annual HDDs, with 60ºF reference temperature, for each weather station averaged across the treatment buildings, derived from the Typical Meteorological Year 3 (TMY3) dataset, and,
$LRCDD70$ = long-run annual CDDs, with 70ºF reference temperature, for each weather station averaged across the treatment buildings, derived from the TMY3 dataset,
$AvgUnits$ = mean number of dwelling units per treatment building, and,
$DHPs$ = mean number of DHPs installed per treatment building.

Multilevel Panel Regression Model

The following formulae describe the regression model and savings calculation:

$$\begin{aligned} Usage_{ij} = \beta_0 &+ \beta_1(Post_{ij}) + \beta_2(Tx_i) + \beta_3(Post_{ij} * Tx_i) + \beta_4(HDD60_{ij}) + \beta_5(Post_{ij} * HDD60_{ij}) \\ &+ \beta_6(Tx_i * HDD60_{ij}) + \beta_7(Post_{ij} * Tx_i * HDD60_{ij}) + \beta_8(CDD70_{ij}) \\ &+ \beta_9(Post_{ij} * CDD70_{ij}) + \beta_{10}(Tx_i * CDD70_{ij}) + \beta_{11}(Post_{ij} * Tx_i * CDD70_{ij}) \\ &+ \beta_{12}(Units_i) + \beta_{13}(Post_{ij} * Units_i) + \beta_{14}(Tx_i * Units_i) \\ &+ \beta_{15}(Post_{ij} * Tx_i * Units_i) + \beta_{16}(Units_i * HDD60_{ij}) \\ &+ \beta_{17}(Post_{ij} * Units_i * HDD60_{ij}) + \beta_{18}(Tx_i * Units_i * HDD60_{ij}) \\ &+ \beta_{19}(Post_{ij} * Tx_i * Units_i * HDD60_{ij}) + \beta_{20}(Units_i * CDD70_{ij}) \\ &+ \beta_{21}(Post_{ij} * Units_i * CDD70_{ij}) + \beta_{22}(Tx_i * Units_i * CDD70_{ij}) \\ &+ \beta_{23}(Post_{ij} * Tx_i * Units_i * CDD70_{ij}) + u_{0i} + u_{1i}HDD58_{ij} + u_{2i}CDD58_{ij} + \epsilon_{ij} \end{aligned}$$

$$\text{Average Annual Savings per DHP } = \frac{365*\beta_3+LRHDD60*\beta_7+LRCDD70*\beta_{11}+AvgUnits*\beta_{15}+LRHDD60*AvgUnits*\beta_{19}+LRCDD70*AvgUnits*\beta_{23}}{DHPs}$$

Where:

i = the building indicator,
j = the month indicator,
$Usage_{ij}$ = the average daily electric usage for building *i* during month *j*,
β = the fixed effect model coefficients for each variable,
β_0 = the fixed model intercept,
$Post_{ij}$ $\{0,1\}$ = dummy variable where (1) indicates that building *i* is in the post-treatment period during month *j*,

Tx_i $\{0{,}1\}$ = dummy treatment variable where (1) indicates that building *i* is in the treatment group and (0) indicates the comparison group, which is static across all months,
$HDD60_{ij}$ = average daily heating degree-days, with 60ºF reference temperature, for building *i* during month *j*,
$CDD70_{ij}$ = average daily cooling degree-days, with 70ºF reference temperature, for building *i* during month *j*,
$Units_i$ = the number of dwelling units in building *i*, which is static across all months,
u_{0i} = the random intercept for building *i* which is independent from ϵ_{ij},
u_{1i} = the random slope coefficient of HDD60 for building *i* which is independent from ϵ_{ij},
u_{2i} = the random slope coefficient of CDD70 for building *i* which is independent from ϵ_{ij},
ϵ_{ij} = unexplained model error term for building *i* during month *j*,
$LRHDD60$ = long-run annual HDDs, with 60ºF reference temperature, for each weather station averaged across the treatment buildings, derived from the Typical Meteorological Year 3 (TMY3) dataset,
$LRCDD70$ = long-run annual CDDs, with 70ºF reference temperature, for each weather station averaged across the treatment buildings, derived from the TMY3 dataset,
$AvgUnits$ = mean number of dwelling units per treatment building, and,
$DHPs$ = mean number of DHPs installed per treatment building.

Building-level Variable Base Degree Day Models

The following model specifications describe the weather normalization procedure for each building and study period:

$$Usage_j = \beta_0 + \beta_1(HDD_j(\tau_h)) + \beta_2(CDD_j(\tau_c)) + \epsilon_j$$

Or,

$$Usage_j = \beta_0 + \beta_1(HDD_j(\tau_h)) + \epsilon_j$$

$$Normalized\ Annual\ Usage = 365 * \beta_0 + LRHDD(\tau_h) * \beta_1 + LRCDD(\tau_c) * \beta_2$$

$$Normalized\ Annual\ Heating\ Usage = LRHDD(\tau_h) * \beta_1$$

Where:

j = the month indicator,
$Usage_j$ = the average daily electric usage for a given building and study period during month *j*,
β_0 = the model intercept, which represents the estimated average daily "base load" usage for a given building and study period,
β_1 = the model predicted heating slope for a given building and study period,
$HDD_j(\tau_h)$ = the average daily HDDs at heating reference temperature τ_h during month *j*,
β_2 = the model predicted cooling slope for a given building and study period,
$CDD_j(\tau_c)$ = the average daily CDDs at cooling reference temperature τ_c during month *j*,
ϵ_j = unexplained model error term for month *j*,
$Normalized\ Annual\ Usage$ = the weather normalized annual electric usage for a given building and study period,
$Normalized\ Annual\ Heating\ Usage$ = the weather normalized annual electric heating usage for a given building and study period,

$LRHDD(\tau_h)$ = the long-run annual HDDs at reference temperature τ_h, for each weather station averaged across the treatment buildings, derived from the TMY3 dataset and,
$LRCDD(\tau_c)$= the long-run annual CDDs at reference temperature τ_c, for each weather station averaged across the treatment buildings, derived from the TMY3 dataset.

The following formulae describe the overall regression model, used to quantify the difference-in-differences, and the final savings calculation:

$$Change_i = \beta_0 + \beta_1(Tx_i) + \beta_2(Units_i) + \beta_3(Tx_i * Units_i)$$

$$\text{Average Annual Savings per DHP} = (\beta_1 + AvgUnits * \beta_3)/DHPs$$

Where:

i = the building indicator
$Change_i$ = the weather normalized annual change in electric usage from the pre- to post-treatment period for building *i*,
β_0 = the model intercept,
β = the fixed effect model coefficients for each variable,
$Tx_i\ \{0,1\}$ = dummy treatment variable where (1) indicates that building *i* is in the treatment group and (0) indicates the comparison group, which is static across all months,
$Units_i$ = the number of dwelling units in building *i*,
$AvgUnits$ = mean number of dwelling units per treatment building, and,
$DHPs$ = mean number of DHPs installed per treatment building.