A Look Inside the Eye on the Wall: Sub-metering Data Analysis and Savings Assessment of the Nest Learning Thermostat

Phillip Kelsven, Bonneville Power Administration

Robert Weber, Bonneville Power Administration

ABSTRACT

Thermostats are the hot topic in energy efficiency right now, and rightfully so. It is rare for a ubiquitous and fairly boring device to undertake such a radical transformation in technology, capabilities, and human interaction. We bring new and interesting data to the conversation.

Smart thermostat evaluations are providing a robust research portfolio showing consistent energy savings. However, much of this research does not delve into how smart thermostats actually control heating and cooling systems, and how people are interacting with these devices. Bonneville Power Administration and Franklin Public Utility District have installed Nest Learning Thermostats in 176 homes with heat pumps. Metering devices were installed in 13 homes to better understand how the Nest controls heat pumps. Metering devices tracked the energy consumption of the heat pump compressor, air handler, and backup resistance heat as well as indoor and outdoor temperature at one minute intervals. This data provides some insight from a small sample of homes on what the Nest is actually doing.

The metering data reveals reductions in average indoor temperature and heat pump run times. The data also suggests that the Nest employs a control tactic that changes the cycling pattern of heat pumps. The data also reveal that individuals behavior with their thermostat changes after having a smart thermostat. People choose to both increase and decrease their temperature settings showing a behavior change after installing a smart thermostat. The savings assessment indicates that there are significant savings in the average home, but there is wide variation in savings across all homes in the pilot.

INTRODUCTION

Bonneville Power Administration (BPA) and Franklin Public Utility District (FPUD) located in Pasco, Washington conducted a Nest Learning Thermostat™ field pilot study starting in the summer of 2013 thru the fall of 2015. The Nest thermostat was selected because of the ability to learn and self-program to maximize energy savings and comfort. The pilot study aimed to evaluate the device’s ability to control residential air-source heat pump (ASHP) operation and realize electricity savings. 176 Nest Thermostats were installed in single-family residences. In addition, electricity sub-metering devices were installed in 13 homes to better understand how the Nest optimizes heat pump operation.

To determine the annual kWh thermostat energy saving performance, BPA staff utilized utility billing data on the larger sample of pilot participants. The sub-meter data analysis provided insight into Nest control tactics.

Key features and findings of the pilot include:

- Recruitment of pre-screened homes was relatively easy because participating customers were provided a free $250 Nest thermostat. FPUD partnered with a HVAC contractor to provide free professional installation.
- The installed thermostat was configured with the Heat Pump Balance and Max Savings options enabled. Heat Pump Balance is a unique setting in the Nest thermostat for homes with heat pumps that optimizes the use of the backup resistance heat element in the heat pump. There are three efficiency levels; Max comfort allows the backup heat element to come on the most to maximize comfort, balance may provide slightly less comfort but more energy savings, and max savings limits the use of backup heat the most to provide the most energy savings.
- At the time of installation, the HVAC installer confirmed that the existing heat pump, household wiring, and wireless router were compatible with the Nest device. As a requirement of participation, the homeowner contractually agreed that FPUD could obtain data from their thermostat, and would not change their assigned thermostat password for at least two weeks. This was a very effective means to provide low cost assurance of installation and proper thermostat setup.

METERING DEVICES

BPA installed metering devices in Nest participant homes in order to better understand how the Nest was interacting with the heat pump, home, and its occupants. Metering equipment was installed in 13 of the 176 Nest participant homes, and collected data for a period of over one year, from January 2014 to March 2015. One-minute interval average amperage draw data was collected from three circuits, including the outdoor heat pump unit, the indoor air handler, and the backup electric resistance heat. Onset temperature sensors were also placed near the thermostat in each home and recorded average indoor air temperature at one-minute intervals. One outdoor temperature sensor was affixed to the exterior of one home to record outdoor air temperature at one minute intervals. The metered homes were located close together in and around Pasco, WA so the outdoor temperature at one home will be very close to the outdoor air temperature at all other metered homes. The outdoor air temperature logger was protected from direct sunlight, wind, and precipitation.

The logging equipment installed consisted of an Onset Hobo U30 logger installed at the main panel of each home. Each leg of the breaker for the above circuits was tracked with a 50-amp Dent Mini-Hinged HSC-20 transformer. The data from the U30 logger was sent to an Onset Flex Smart TRMS Module. Data was sent via satellite to the Onset website where the data was collected.

Most of the metering devices were installed in January and February 2014, with four homes having meters installed November 2013. The metering devices were removed by March 2015. The Nest installations occurred in February to March of 2014. Most of the metered sites only had two to four weeks of metering before the Nest installation. While the metering occurred during cold weather when we expect most of the Nest savings to occur, there were not many very cold days in the metering period. 2014/2015 was a warmer-than-normal winter in the Northwest with 4,627 heating degree days (base 65) compared to a long run 15 year average of 4,960 in Pasco, WA. 2014 was thus 7% warmer than normal in terms of heating degree days.

The final metering sample consists of 8 sites with useable data during the cold weather period. The data that was analyzed for this analysis for most sites is January 2014 through April 2014 by which time most of the cold weather occurred. One site appears to have supplemental heat or there were errors in data collection as data indicates that indoor air temperature is maintained on several occasions with no heat pump power draw. Four other sites were thrown out due to missing data and data anomalies in matching up the metered data to the associated circuit for outdoor compressor unit, indoor air handler, and backup heat.

METERING DATA ANALYSIS METHODOLOGY

While the metering data cannot be used to estimate Nest energy savings, it does provide a valuable look into the how the Nest changes the basic operation of a heat pump, as well as how people interact with the Nest. The data tells a story about the strategy Nest appears to use to more efficiently heat and cool a home using less energy. The metering data also provides valuable insight into how people’s interaction with their thermostat changes after a smart thermostat is installed. The metering data suggests that energy savings is likely, but may be attributable to a different source than BPA or other program administrators expect.

There are several reasons why conclusions should not be drawn from the sub-metering analysis. The pre Nest install metering period was very short providing a limited sample of time to compare with the post Nest metering data. This is a small sample of homes in which some of people living in them worked for or were friends with people who work for Franklin PUD, possibly biasing the sample. The weather conditions analyzed are not reflective of the weather conditions throughout four seasons of a year, and also not reflective of a typical year’s winter. The average temperature in the pre period was 38.1 degrees while the average temperature throughout the year in Pasco, WA is about 54 degrees. Despite these downfalls, there is still value and insight in these data.

This analysis attempts to estimate heat pump compressor and resistance back up heat run time differences pre and post Nest installation during relatively similar weather conditions. This is a challenging task due to the paucity of data and weather conditions in the pre-treatment period. In order to estimate run time differences post treatment, it is necessary to isolate heat pump run times during similar outdoor air temperature conditions. Two different methods are used to calculate differences in run time between pre and post Nest install. One method assesses heat pump compressor and backup heat run time in ten different bins of outdoor air temperature. Another method assesses heat pump run time in ten different bins of delta-t, or the difference between outdoor and indoor temperature.

The first method referred to as the outdoor air temperature (OAT) method. The “OAT Method” allows for indoor temperature settings to float given a set outdoor temperature. The second method referred to as the “delta-t method” measures compressor and back up heat run time when the home faces similar heating needs from pre to post Nest install. The main difference between the two methods is that the OAT method measures run time differences regardless of what the indoor temperature is or what the chosen thermostat set point is, and the delta-t method measures run time differences from pre to post within a relatively constant difference between indoor air temperature (IAT) and OAT.

The OAT method calculates the heat pump compressor and backup heat run time in ten different outdoor air temperature (OAT) bins. Temperature bins are created from 25 to 65 degrees at four degree intervals resulting in ten OAT bins. Percent run time for each bin is calculated by aggregating the number of minutes the heat pump was drawing power when the home was exposed to the OAT in each bin and then dividing into the total amount of minutes the home was exposed to the OAT in each bin. Since all of the heat pump units in the metering sample are single speed heat pumps, the power draw is very similar across time when the unit is drawing power. Only one heat pump appeared to be drawing a small amount of power nearly all the time and this threshold was accounted for in the run time calculation. The run time for the backup heat was calculated in a similar manner. The average indoor air temperature (IAT) is also reported to assess any changes in IAT. This method allows us to study changes in run time that may or may not be due to changes in the temperature setting of the thermostat. In this sense the homes heating need may be different from pre to post given the same OAT.

The Delta-t analysis method holds fairly constant the heating need of the home. The difference between outdoor and indoor temperatures is referred to as “delta – t”, the difference or “delta” between the outdoor and indoor temperatures. To illustrate this concept, if outdoor air temperature is 36 degrees and indoor air temperature is 70 degrees, the delta-t is 34. In theory when the heat pump is exposed to similar delta-t conditions at two points in time it must work just as hard to maintain the indoor air temperature (IAT) despite absolute differences in outdoor or indoor air temperatures.

Similar to the OAT method, the delta-t method analyzes differences in run times in ten different delta-t bins. Four degree delta-t bins are created from delta-t 10 to delta-t 50. Four degree delta-t bands are small enough to ensure that similar climate conditions occurred pre and post, but also large enough to get a moderately sized sample of time when the home was exposed to those weather conditions. Similar to the OAT method, the metric used in the delta-t method is percentage run time. The run time was calculated by summing the number of minutes when the outdoor heat pump compressor unit was drawing power. The number of minutes are aggregated in each bin and divided into the number of minutes the home was exposed to each 4 degree delta-t band of weather conditions. The result is a percentage run time calculation.

METERING DATA ANALYSIS RESULTS

Results from both analysis methods indicate a reduction in both heat pump compressor and back up heat run times post Nest install. Figure 1 shows the aggregate run time changes for all 8 sites from the OAT method, and figure 2 shows changes in the average IAT from the OAT method. The aggregate pre Nest compressor run time for the OAT method is 26% compared to 13% post Nest install. The aggregate pre Nest backup heat run time for the OAT method is 1.5% compared to 0.6% post Nest install. Run time reductions are greater when the OAT is lower and run time reductions decrease as OAT increases. The average IAT across all OAT bins was 70.52 degrees in the pre period compared to 69.66 degrees in the post period for an overall IAT reduction of 0.86 degrees.

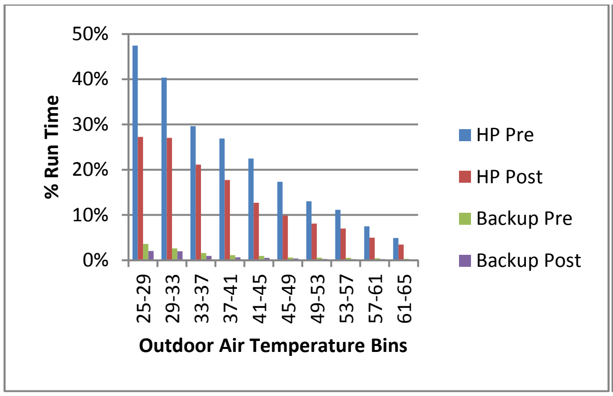

Figure 1: Run time by OAT bins

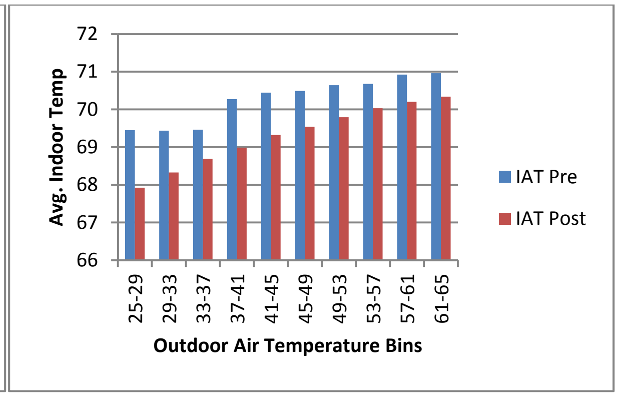

Figure 2: Average IAT by OAT bins

The delta-t analysis method shows similar results to the OAT method. Figure 3 shows there were compressor run time reductions in all delta-t bins, however there were run time increases in back up heat in the two coldest weather delta-t bins. The aggregate compressor run time for all sites in the pre-period was 28%, compared to a run time of 14% post Nest install. The aggregate back up heat run time was 2% in the pre period and 1% in the post period. Contrary to what was found in the OAT method, the two coldest weather delta-t bins experienced increases in back up heat run time post Nest install. This is likely due to more aggressive temperature setbacks observed during the night time post Nest install. The OAT method does not account for the chosen temperature set point or IAT, so the effect of a lower set point at some sites during set back periods such as during the night time will show up as run time decreases at coldest OATs. The delta-t method does account for IAT and chosen set points, so these results suggest that when the home faces a similar heating need in the pre and the post at the coldest temperatures, the back up heat runs more to accommodate that heating need in this sample of homes.

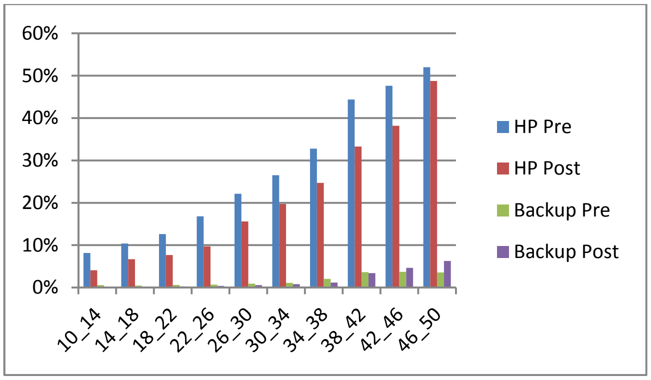

Figure 3: Run Time by Delta-t Bin

All of the individual sites experienced heat pump compressor run time reductions. Some homes experienced back up heat run time reductions while others had no reductions in back up heat run times. Table 1 shows the pre and post run times for both analysis methods as well as the pre and post average IAT. Both methods show similar results at the individual site level as well as in aggregate. In total, both compressor and back up heat run times were cut in half on average. As mentioned previously, the run time reductions should not be confused with possible energy savings. These results are derived from a sample of the weather conditions throughout a typical year and suffer from a cold weather pre metering period that was only a couple weeks long and from a warmer than average winter.

Table1: Individual Site Run Time and IAT Differences for OAT and Delta-t Methods

Site	1	2	3	4	5	6	7	8	Total
OAT Method									
Compressor Run Time Pre	38%	28%	40%	24%	21%	9%	18%	29%	**26%**
Compressor Run Time Post	15%	18%	9%	14%	12%	3%	9%	8%	**13%**
Back Up Heat Run Time Pre	6.25%	0.81%	0.01%	1.53%	0.14%	0.00%	1.02%	2.76%	**1.51%**
Back Up Heat Run Time Post	2.11%	0.84%	0.00%	0.88%	0.00%	0.00%	0.10%	0.45%	**0.63%**
Delta-t Method									
Compressor Run Time Pre	39%	31%	38%	27%	25%	9%	22%	32%	**28%**
Compressor Run Time Post	16%	19%	11%	15%	13%	3%	10%	9%	**14%**
Back Up Heat Run Time Pre	6.31%	1.03%	0.02%	1.76%	0.13%	0.00%	1.73%	3.11%	**1.71%**
Back Up Heat Run Time Post	2.24%	1.02%	0.00%	0.94%	0.00%	0.00%	0.11%	0.54%	**0.71%**
IAT Pre	72.04	69.62	68.65	69.33	70.14	73.58	70.99	70.16	**69.80**
IAT Post	72.63	68.69	66.44	68.91	68.81	71.27	71.96	69.93	**69.31**

Home characteristics and observed changes in temperature setting either from manual manipulation or Nest features explain some of the differences between homes. Site 3 had the largest reduction in compressor run time but also had the second largest decrease in average IAT (2.21 degrees) largely due to a four degree decrease in set-back temperature. Prior to Nest install site 3 was setting back at night consistently to 64 degrees, however after Nest install was setting back to 60 degrees. Site 6 has an abnormally low compressor run time to begin with and also had the largest decrease in average IAT (2.31 degrees). Site 6 likely has a much more efficient shell as it is a 2,067 square foot home built in 2007. It is interesting to note that even homes that experienced an average increase in IAT had reductions in compressor and back up heat run times, suggesting that something else besides a reduction in IAT may be causing run times to decrease.

Analysis of the overall changes in indoor air temperature inform the effectiveness of the Nest thermostat at producing energy savings. Analysis indicates that there is an average reduction in IAT of about 0.5 degrees, but this difference is not statistically significant. Analysis of the distributions if IAT indicate that the post install IAT distribution is less skewed to the right with a more normal distribution and also has a longer left tail, indicating a trend toward lower set-back temperatures.

Time series trends on indoor air temperature provide insight into how people are interacting with thier Nest, and what the Nest is doing to them. Site #1 is a good example of how the Nest is changing temperature control strategies and achieving run time reductions despite an increase in average IAT. Figures 4 and 5 show that before Nest install, they appeared not to have a set control schedule. Heating set points were between 73 and 76 degrees with no apparent order other than the temperature was set back every night to between 68 and 70 degrees. The first 10 days after Nest install saw a similar pattern followed by a very distinct change in control settings. Ten days after Nest install, the set point is consistently set at 75 degrees and sets back to 71 every night. This site increased their upper and lower temperature settings but still managed to decrease compressor and back up heat run times in all but the two coldest OAT bins, and all but the one delta-t band with the coldest weather. Every temperature bin in both the OAT and delta-t methods showed slight reductions in back up heat run time at site #1

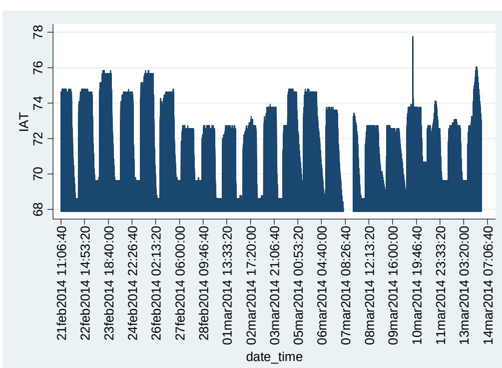

Figure 4: Site # 1 indoor air temperature pre

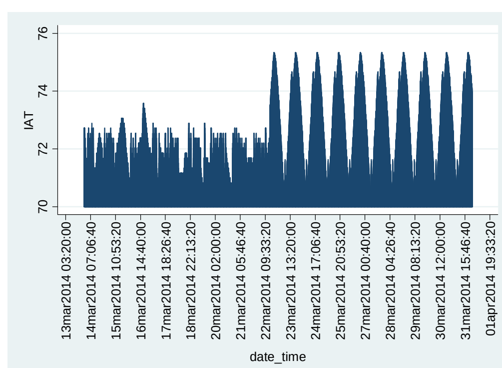

Figure 5: Site #1 indoor air temperature post

Site # 1 is a good example of what was observed in the 7 other sites. A host of different strategies were observed, some where upper set points increased but with a set-back that had not previously existed, some where there was no clear pattern difference between pre and post Nest, and some where there were clear examples of the auto-away function working regularly during extended non-occupied days. Some households had regular daily patterns after the Nest install, while others had more random set-point patterns. The point to take away from this is that the Nest was able to reduce run times in nearly all of the sites despite the diversity of control strategies and behavior changes.

Some of the most interesting findings from this analysis are from examining the heat pump cycling patterns before and after the Nest was installed. In order to see these, similar weather days must be isolated in the pre and post periods. Due to the limited number of days with data in the pre-period, this was a challenging task. A similar weather day is defined as a day where the high and low outdoor air temperatures were within five degrees of each other. Five degrees is not an insignificant difference but does not take away from the significantly different cycling patterns observed after Nest install.

There appear to be noticeable changes in the heat pump cycling patterns in similar weather days from pre to post Nest install. Figures 6 and 7 are from Site #1 and display the indoor air temperature at the top, with the outdoor air temperature below that; the bottom of the graphs show heat pump compressor runs and the spikes are resistance back-up heat runs. Very clear differences are evident from comparing the compressor run cycles. In the pre-period day there are 55 short cycles that are frequently in the 6-8 minute range with a couple 30-45 minute cycles in the morning. In the post-period day there are only 8 cycles in the entire day with each cycle running about 30-45 minutes each with one backup heat cycle at the end or middle of the cycle. The result of these different cycling strategies is a compressor run time reduction of 155 minutes (436 minutes on 3/8/2014, 181 minutes on 3/28/2014). The backup heat is reduced from 72 minutes to 43 minutes. There are two more sites where similar weather days could be isolated with very similar looking cycling differences.

Analysis of the individual cycle run times in all 8 homes indicates that the average pre-install run time was 13.6 minutes, and the average post-install run time was 29.8 minutes. The average cycle run time more than doubles after installation of the Nest despite warmer weather during the post period. Is it possible that Nest is not merely saving energy in heat pumps by minimizing the use of back up heat and reducing the average IAT? It is possible that the Nest could simply be taking advantage of the fact that a heat pump's coefficient of performance (COP) increases the longer a heat pump cycle runs (Green, 2012). Heat pumps use a lot of energy just powering up for a cycle run, so elongating the heat pump cycle run time produces efficiencies in performance. There may also be a little physics at work. Nest may also be taking advantage of a term in physics referred to as thermal inertia. The large mass of materials in homes take a long time to absorb heat, and the longer you heat them the more heat they can retain for longer. Therefore longer heat pump cycle runs may be building up thermal inertia which maintains IAT between cycle runs.

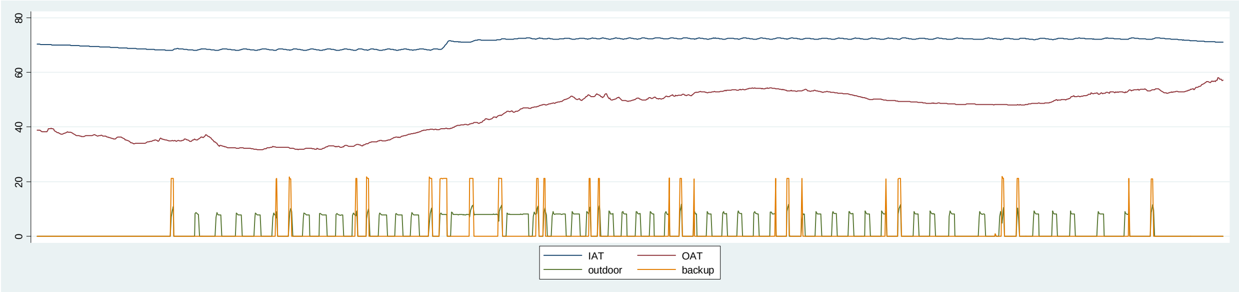

Figure 6: Heat pump cycle runs with indoor and outdoor temperature, pre-install

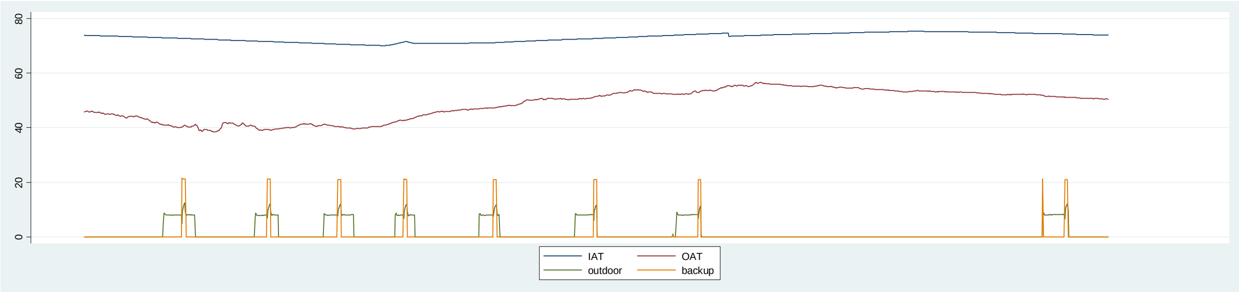

Figure 7: Heat pump cycle runs with indoor and outdoor temperature, post install

BILLING ANAYSIS

Two billing analysis were performed on the Nest participant sites to estimate annual pilot program energy savings. A pre – post Normalized Annual Consumption (NAC) model (UMP, 2013) including Variable Base Degree Days (VBDD) was estimated on 169 Nest program participants. A pooled Fixed and Random Effects model was also estimated on 169 Nest program participants. The same pre and post consumption periods are used for all homes in the treatment and comparison group. The pre-treatment period is February 2013 through January 2014 and the post period is September 2014 through August 2015. A small comparison group of 40 homes that previously participated in the Franklin PUD energy efficiency program and are known to have heat pumps was formulated to correct for any systematic changes in energy consumption not due to the Nest thermostat.

PRE-POST NAC MODEL

The method used to estimate annual kWh savings is a pre/post, treatment/comparison method employing monthly consumption data. The method used to calculate annual electric use regresses kWh per day during each billing period against heating and cooling degree days per day to derive the heating, cooling, and base consumption slopes. A variable-base degree-day (VBDD) method was employed using variable base reference temperatures for heating degree-day calculations. Reference temperatures between 40 and 70 degrees were used to calculate heating degree days in multiple regression runs for each site. The regression model with the highest r-squared is chosen for each site. This method excludes results from sites where there is a low correlation between consumption and heating degree days. Savings are explored as a function of r-squared with the final results using sites with r-squared greater than .70. Final results are reported net of the comparison group savings adjustment.

DATA SCREENING – PRE-POST NAC MODEL

Extreme observations that are considered to be unlikely to represent any program-induced changes were excluded from the final analysis to reduce uncertainty of the overall savings. Such outliers can be due to changes in occupancy or some other household factors or may be due to extremely small or large annual consumption that indicates a data error or represent an unoccupied home. Data screening was applied to each site which has complete pre and post consumption data. The following data screens were used:

- Sites with 0 kWh monthly readings were removed (2 sites)
- Duplicate meter reads were removed
- Final savings employs sites whose regression R-Squared from either the pre or post periods is < .70 (70 sites)
- Sites whose post consumption increased or decreased by more than 50% were removed (4 sites)

RESULTS – PRE-POST NAC MODEL

The results of the pre-post NAC VBDD model indicate statistically-significant energy savings, though with relatively high uncertainty in the magnitude of the savings due to the fairly small study group size. As Table 2 shows, the average total household energy savings at sites with a good model fit (>= .70 r-squared) is 1,103 kWh per year. The 95% confidence interval of these savings are between 599 and 1,607 kWh per year. If the r-squared criteria is loosened, the average savings are 855 kWh per year with a 95% confidence interval of 381 to 1,388 kWh per year. The comparison group had average savings of 262 kWh per year and is applied to the final results. The average savings generally increases for homes with higher pre-treatment energy consumption. Sites with good model fit were grouped into quintiles of pre-treatment energy consumption. The third and fifth quintile has a couple outliers that pull down the average energy savings, however as expected homes that use more energy also save more energy from installing a Nest thermostat.

Table 2: Pre-Post NAC Model Billing Analysis Results

N	Total Annual Savings (kWh)	95% Lower C.I.	95% Upper C.I.	R-Squared Criteria	Pre Install Consumption	% Total Savings
167	885	381	1388	All	21804	4.06%
130	824	314	1333	>= .50	21016	3.92%
115	959	419	1498	>= .60	20930	4.58%
97	1103	599	1607	>= .70	21110	5.23%

Table 3: Final Savings Results

R-Squared Criteria	N	Mean Total Annual Savings (kWh)	95% Lower C.I.	95% Upper C.I.	Mean Pre Install Consumption	% Total Savings	Mean Pre Install Heating & Cooling Consumption	% Savings of Estimated Heating & Cooling Load
>= .70	97	841	337	1345	21110	3.98%	6811	12.35%

POOLED FIXED AND RANDOM EFFECTS MODEL

A common model used for estimating energy savings for smart thermostats is a pooled fixed or random effects regression model. A similar model was used in the Energy Trust of Oregon evaluation (Apex 2014) as well as Nest's own white paper (Nest 2015). This approach involves using multiple variations of a single linear regression model with customer-specific fixed and random effects. Each month is treated as its own observation but each site has a unique intercept for a site-specific fixed effect. The best fit model controls for and includes variables for heating and cooling degree days, a post-period identifier, as well as home square footage. A random effect was then added that models the fact that there is a grouping structure to the data as well as another random effect that models the relationship between heating degree days, square footage and energy consumption. The result is a "mixed effects" model. The model was estimated in Stata software (Statacorp LP, College Station, TX) using the "mixed" command. The coefficients from the model are directly used to calculate estimated savings.

Several different model variations were tested and the best fit model formula is of the following form: $\boldsymbol{kWhperday_{ij}} = \beta_0 + \beta_1 HDDperday_{ij} + \beta_2 CDDperday_{ij} + \beta_3 Post_j + \beta_4 SQFT_i + u_{oi} + u_{1i} HDDperday_{ij} + \varepsilon_{ij}$

Where: $\boldsymbol{kWhperday_{ij}}$ = The average daily kWh usage for home *i* during month j
$\boldsymbol{\beta_0}$ = Fixed intercept for all homes
$\boldsymbol{HDDperday_{ij}}$ = Heating Degree Days for home *i* during month *j*
$\boldsymbol{CDDperday_{ij}}$ = Cooling Degree Days for home *i* during month *j*
$\boldsymbol{Post_j}$ = Dummy variable where 1 indicates post Nest period and 0 indicates pre Nest install
$\boldsymbol{SQFT_i}$ = Square footage for home *i*
$\boldsymbol{u_{oi}}$ = Random intercept for site *i* independent of ε_{ij}
$\boldsymbol{u_{1i}HDD_{ij}}$ = Random slope coefficient of HDD for site *i* and independent of ε_{ij}
$\boldsymbol{\varepsilon_{ij}}$ = Model error for site *i* during billing period *j*

The savings are estimated by multiplying the coefficients by their average values (UMP, 2013). The following function estimates Nest savings:

$$\text{Savings} = \beta_1(12.71) + \beta_2(1.523) + \beta_3(365.25) + \beta_4(2{,}040)$$

Six different model specifications were estimated and the results are presented in Table 4. The results are all fairly similar across all model specifications except for the model including an HDD random effect with year built in the model. Every model with year-built in the specification indicates that year-built has a very low p-value, indicating that the variable is not significant in the model. Therefore model specification 2 should be considered an outlier. The estimated savings from the fixed and random effects models are between 955 and 970 kWh per year. The results of the pooled fixed and random effects model are similar to results from the pre-post NAC VBDD model.

Table 2: Fixed and Random Effects Billing Analysis Model Results

Model Specification	Annual kWh Savings
1. Pure Fixed Effects with year built	970
2. Random with HDD Random Effect, with year built	884
3. Random without HDD Random Effect, with year built	965
4. Random with HDD random Effect, no year built (*best fit model)	955 (95% C.I. 606, 1304)
5. Random without HDD Random Effect, no year built	969
6. Random with Square feet Random Effect with year built	971

CONCLUSION

This paper presents sub-meter data on the operation of heat pumps in 8 homes after installing a Nest Learning Thermostat as well as an assessment of energy savings in 176 homes. Findings suggest that compressor and back up heat run times during the weather conditions that the homes were exposed to are reduced on average by one half across a range of outdoor air temperatures and delta-t. The average run time reductions should not be considered a proxy for potential energy savings due to the small sample and limited pre install metering period. The compressor run time reductions are partly due to an average decrease in indoor air temperature over the post metering period. However, significant differences in heat pump cycling patterns in similar weather days are observed. The Nest may be harnessing the advantage of increased heat pump performance efficiencies from longer cycle runs. We also speculate that longer heat pump cycles can increase thermal inertia and provide warmth to the home between the more infrequent cycles. The savings assessment estimates energy savings at 841 kWh per year which is about 4% of the average homes energy consumption and 12% of heating and cooling consumption.

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