B O N N E V I L L E   P O W E R   A D M I N I S T R A T I O N

Assessment of Ductless Mini-Split Heat Pump Energy Savings in Stack House Apartments

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About the Report

The study described in the following report was conducted under contract to Bonneville Power Administration (BPA) to provide an assessment of energy savings in multi-family buildings from ductless mini-split heat pump technology.

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Abstract

This project examined energy use and savings of ductless heat pumps in a new, mid-rise multifamily building in Seattle. Of the 279 apartments in the complex, 93 had DHPs and 186 did not. The analysis compared the energy use between the two groups using industry-standard temperature-energy regression techniques. The project found very low overall energy use which led to challenges in the analysis. Nevertheless, the best estimates of heating energy showed 500 kWh/yr for studios, 1,000 kWh/yr for one bedrooms, and 1,500 kWh/yr for two bedrooms. The corresponding best estimate for savings showed 350 kWh/yr. In addition to the heating energy savings, the occupants used the DHPs for cooling which added to the overall energy and reduced overall savings.

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Executive Summary

Ductless, mini-split heat pumps (DHPs) have been shown to offer substantial energy savings throughout the Pacific Northwest in single family and manufactured homes (Baylon 2012). Previous work has examined energy savings in specific subset of multifamily houses (Larson & Geraghty 2012). That work on multifamily buildings studied low-rise, “walk-up” style apartments. The multifamily sector also consists of mid- and high-rise buildings which differ enough in construction techniques to suggest the energy usage patterns of DHPs will differ between them and low-rise. This study examines the energy use and savings of DHPs installed in a new, mid-rise multifamily building in Seattle.

This project offered an opportunity to observe energy use in the Stackhouse Apartments, a new, urban mid-rise multifamily building. The building contained apartments both with and without DHPs allowing us to compare energy between the two types. DHPs have also been installed as retrofits to displace existing resistance heating systems but this building allows the simultaneous comparison of energy use between the 279 apartments in the complex. Of those units, 93 had DHPs and 186 did not. During the building design phase, in response to projected higher cooling loads, the developer elected to place DHPs in the south and west facing apartments on upper floors. This complicates the comparison between the types. An ideal experimental design would be to scatter the DHPs randomly throughout the building but the practical aspects of using a multi-million dollar building as the study site constrained the experiment. As a result, Ecotope made cautious and careful comparisons between the apartment types and encourages such interpretation by the reader.

Starting from utility billing data, the main tool for assessing the heating and cooling energy use is temperature-energy regression. Our approach used the “change-point” method to identify temperature-correlated and non-temperature-correlated portions of the total energy load. The parsed relationship was then extended to a Typical Meteorological Year weather file to estimate generalized savings. That usual approach encountered challenges in this project for three reasons: bi-monthly data, high tenant turnover, and low space conditioning loads.

A significant finding of the project is that the heating loads on the units are simply low. Our best estimates of annual heating requirements were 500 kWh/yr for studios, 1,000 kWh/yr for one bedrooms, and 1,500 kWh/yr for two bedrooms. Roughly, the average total energy use was 3,000 kWh/yr per apartment.[1] The corresponding best estimate of weather normalized, DHP savings per unit was 350 kWh/yr. The analysis showed that DHPs do save energy over their non-DHP counterparts in the heating season. It also showed that, as might be expect, the DHPs were used to provide cooling in the summer. This use of mechanical cooling offsets some of the energy saved by the DHP in heating.

Important lessons learned from this project include that having bi-monthly data for this type of analysis is extremely challenging. Obtaining daily energy use total by apartment would provide a richer data trove which would offer up more explanatory power. That finer resolution data would provide more insight in to DHP cooling use. At the same time, the inevitable occupant turnover and low heating loads in mid-rise multifamily buildings will continue to challenge current billing analysis techniques.

The project also suggests that the value of comfort cooling should not be underestimated. Builders in Seattle continue to select ductless heat pumps in their multifamily buildings seemingly regardless of energy use or incentives. The prospect of comfort cooling for tenants is a powerful marketing tool. Consequently, because there is the opportunity for some heating savings and because alternative cooling technologies use more energy, it is worthwhile investigating further how utilities can continue to support these equipment choices.

[1] Note that water heating is excluded from this value because it is provided centrally and metered separately (approximately it is 1,000 kWh/yr).

1 Introduction

1.1 Stack House Apartments and Supply Laundry Development Project

The Stack House Apartments and Supply Laundry in Seattle's South Lake Union neighborhood – a mixed use development in the rapidly densifying, former industrial district – opened to tenants in late 2013. Developed by Vulcan and designed by Runberg Architects, with mechanical design assistance from Ecotope, the full block consists of three buildings: two seven story apartments and the adaptive reuse of the historic Supply Laundry Building into commercial space. The award-winning project includes many green features, including an innovative central heat pump water heating plant, a bioswale to treat storm water runoff into South Lake Union (the "Swale on Yale"), rooftop gardens, and a rainwater cistern for irrigation.

Figure 1 shows the building from the courtyard perspective while Figure 2 provides an aerial photo. Note in Figure 2 the outdoor units for the heat pumps scattered about the roof. Also note the non-rectilinear building shapes and the shadows cast by some parts of the complex on to the others. These diverse angles and shading create a mix of solar heating orientations which tends to muddy some of the later comparisons between units in the complex.

Figure 1, Stack House Apartments Courtyard

Figure 2, Stack House Apartments Aerial

1.2 Heat Loss and Energy Efficiency Characteristics

The Stack House apartment buildings were constructed with the so-called “five over one” construction of many similar Seattle developments, timber framing atop a concrete pedestal. Table 1 shows the heat loss characteristics of the upper-level, wood-framed apartments in question for this analysis. The envelope characteristics are basically those required to meet the energy code, which is to say that other mid-rise buildings are being built with similar shell characteristics.

Table 1, Heat Loss Characteristics of Stack House Apartments

Stack House Apartments Heat Loss Characteristics	
Walls	R-21
Roof	R-38
Floor	R-30
Windows	Vinyl Double Low-E w/ Thermal Breaks (U-0.29, SHGC-0.22)

The apartments feature all LED lighting, Energy Star appliances, and exhaust fans for ventilation. A central heat pump water heating system (reverse cycle chiller) serves domestic hot water needs, so water heat does not show up in individual unit bills. The building corridors are ventilated to meet code requirements but not excessively so. This lower amount of ventilation is another design feature leading to low, overall building energy use.

For space conditioning, units received a mix of King KCE electric resistance wall heaters and ductless mini-split heat pumps. Apartments on the upper three levels facing south or west received Mitsubishi MSZ-GE series ductless mini-split heat pumps in the living area, with nominal capacity ranging between 9,000 and 24,000 Btu/hr depending on load calculations for specific units. This was in all cases a single head system. The MSZ series holds rated SEER of 21, EER of 13.6, and HSPF of 10 (Mitsubishi Heat Pump Model Specifications). All other apartments received King KCE electric wall heaters in the main living area, which are convectors rather than forced fan heaters. The main living area in all apartments was controlled by a 7-day programmable thermostat. The bedrooms in all cases contained the electric wall heaters, controlled by a dial on the heater itself. The electric wall heaters ranged in capacity from 500W to 2500W depending on the load calculation for the space in question.

Note that the DHP apartments with at least one bedroom then also contained electric wall heaters in the bedroom(s), although the DHPs were sized to provide capacity for the entire apartment.

1.3 Context and Press Clippings

Also notable, Stack House made the pages of The Atlantic's CityBlog for an article on urban gardening (Holt 2015), and saw reference from local independent media outlet Crosscut on the changing landscape for artists in Seattle, frequently priced out of redeveloping neighborhoods in favor of tech transplants who can afford the newly expensive rents (Roth 2016).[2] These details, while seemingly unrelated to energy efficiency analysis, help set the table for possibly surprising findings later in the report. This building has been heavily acclaimed and marketed, and lies within the suddenly trendy Seattle neighborhood of South Lake Union: ground zero for high wage, high tech transformation of the Emerald City. Keeping in mind this context may help when reviewing the occupant behavior and startlingly low energy use profiles.

2 The Units

The two residential buildings of the development mostly consist of one bedroom and studio apartments. Townhomes and lofts exist on the first and second floors, along with common and recreation areas. For the purposes of energy analysis we will only examine the apartments on floors three through seven. None of the lower story townhomes or lofts received DHPs, and their floor plans are distinct from the upper level apartments that did receive DHPs.

Table 2 exhaustively displays the profile of apartments by building level, number of bedrooms, and DHP status.

Table 2, Apartment breakdown by size, building level, and DHP status

	Bedrooms						
	0	1	1+	2	2+	3	Total
Level	No DHP						
7	8	4	3	3	0	0	18
6	8	4	3	3	0	0	18
5	8	4	3	3	0	0	18
4	15	20	6	5	2	0	48
3	15	19	6	6	1	1	48
1	1	18	0	17	0	0	36
Total No DHP	55	69	21	37	3	1	186
Level	DHP						
7	7	16	3	2	2	1	31
6	7	16	3	2	2	1	31
5	7	16	3	2	2	1	31
4	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
Total DHP	21	48	9	6	6	3	93
Overall Total	76	117	30	43	9	4	279

Out of 279 total units, 93 received DHPs and 186 did not. The units receiving DHPs were all located on levels five through seven, and predominantly one bedroom or studio layouts. Of 117 total one bedroom apartments in the

[2] At the time of writing, available listings for Stack House apartments viewed on Seattle Craigslist showed 23 apartments for lease: eight studios ranging from $1429 to $1804 per month; nine one bedrooms ranging from $1708 to $2494 per month; and six two bedrooms ranging from $2481 to $3084 per month.

development, 48 contain DHPs and 69 do not; of 76 total studio apartments 21 contain DHPs and 55 do not. The upper three floors each hold 49 apartments, 31 of which received DHPs and 18 did not.

For the sizes of those apartments by number of bedrooms, the studio apartments range in heated floor area from roughly 400 to 600 square feet, one bedroom apartments from 580 to 780 square feet, and two bedroom apartments typically around 1000 square feet. The floor plans also feature “1+” and “2+” layouts, with the corresponding number of bedrooms along with an additional room. Figure 3 shows the distributions of square footage by number of bedrooms in the Stack House apartments.

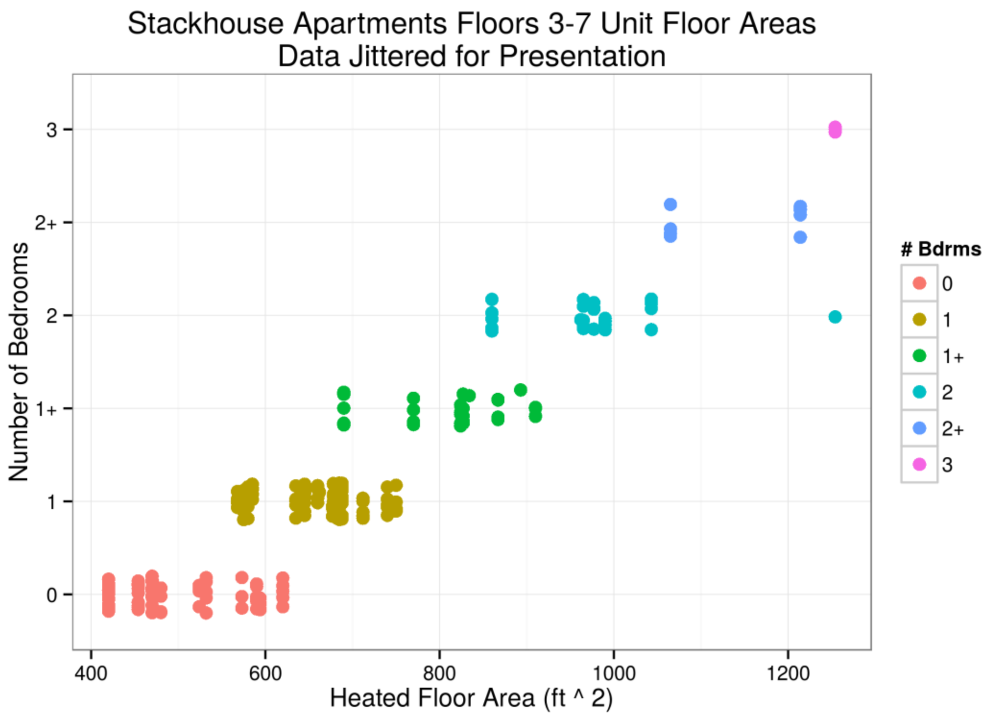

Figure 3, Apartment size distributions

Since we will largely concern ourselves with heating and cooling in this report, it is also helpful to consider the heat loss characteristics. Most notably, in an apartment building of this size, individual apartments have very little exterior surface area. Figure 4 shows the distribution of exterior surface area by apartment size. Notably, the studio apartments below the top floor contain at most 200 square feet of external surface area. A single 25’ long wall may be the only surface of the apartment exposed to the outdoors: the other walls either abut adjacent apartments or the corridor. With wall insulation and good windows we already suspect that the heating load for such a space –with less than 200 square feet of surface area to outside – should be minor at best. (The top floor apartments obviously have much more exterior surface area by way of the ceiling to the roof.) The typical heat loss rates of the units range from 55 Btu/hr/F for studios to 185 Btu/hr/F for the 3 bedrooms – all are remarkably small.

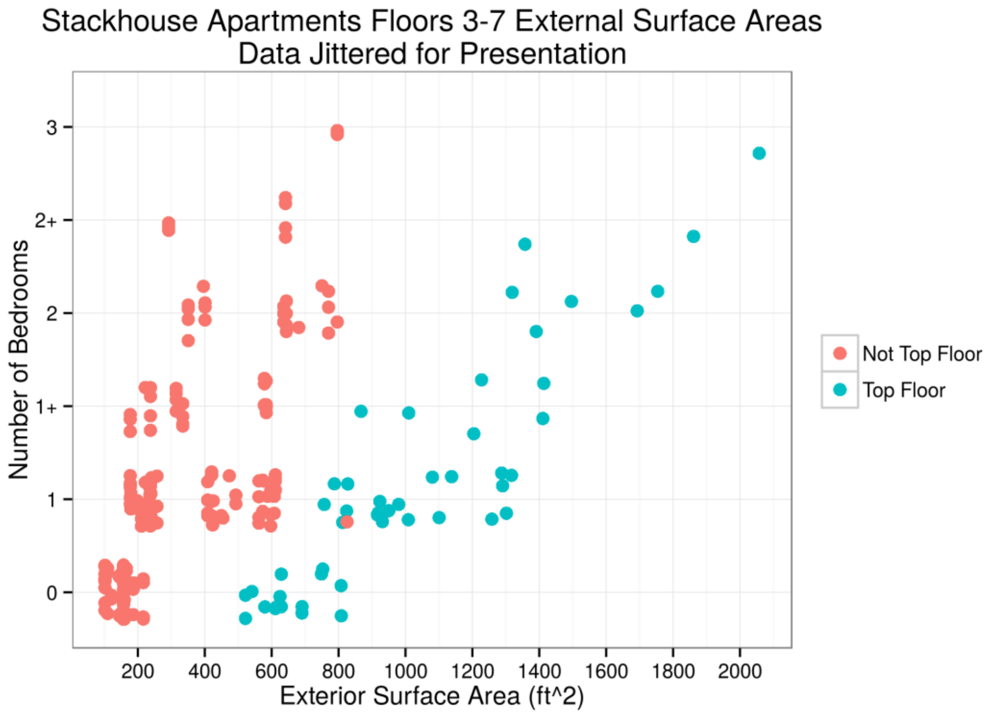

Figure 4, External surface areas of apartments in Stack House

In addition to the apartment areas, another notable topic concerns tenant turnover. In an analysis of single family homeowners, occupancy generally continues uninterrupted. Disruptions and oddities occur, of course, but they (hopefully) prove the exception rather than the rule. In contrast, the Stack House apartments are occupied by renters rather than owners and a building of this nature likely sees much higher occupant turnover and much higher occupant variation than among the single family homeowners we often analyze for savings estimation.

Using customer identifiers to parse tenancy (and also identify periods of vacancy for individual apartments), it becomes clear that occupant turnover will in fact present issues for the energy savings analysis. Table 3 shows the stay length by tenant, using all data from fall 2013 to present. Only about one in five tenants remained in their unit for at least 2 years in the time span for analysis. Two in five tenants occupied their apartment for between one and two years, and the same less than one year. With an already weak space conditioning signal due to the size and thermal characteristics of the apartments, this will pose problems for the savings analysis.

Table 3, Stay length by tenant, fall 2013 to present

Stay Length by Unique Tenant (3rd-7th floor apartments for analysis)		
# of Years	Total	Percent
<1	173	39%
1-2	182	41%
2+	94	21%
	449	100%

For another view, Table 4 shows, by apartment, the number of distinct tenants during the roughly three years of record. About one third of apartments were occupied by the same tenant(s) during the entire analysis period. The other roughly two thirds saw either two or three distinct sets of tenants. One particular apartment saw five different lessees over the three year period. This does not bode well for delicately extracting a signal of temperature dependence from low load apartments, since different tenants often use energy in different ways. This variation can swamp the temperature-dependent space conditioning signal in the data.

Table 4, Number of distinct tenants by apartment

Number of Distinct Tenants by Apartment (3rd-7th floor apartments for analysis)		
# of Tenants	Total	Percent
1	77	32%
2	109	45%
3	51	21%
4	4	2%
5	1	0%
	242	100%

3 Descriptive Statistics

An initial, useful step for analysis is to simply tally the observed energy use, regardless of any temperature-based adjustments. Table 5 shows average energy use by apartment size and DHP status during calendar years 2014 and 2015. Two observations leap off the page. First, the overall usage is extremely low, on the order of six kWh/day for a studio and nine kWh/day for a one bedroom. On an annual basis this implies that most apartments in the building use only a few thousand kWh per year, *total*. Second, the average daily energy usage changes little between DHP and non-DHP apartments. For occupied studio and one bedroom apartments the energy use was virtually identical. For larger floor plans, with admittedly many fewer instances, the DHP apartments actually used more energy than their DHP deficient counterparts.

Table 5, Descriptive Statistics. Average kWh/day by number of bedrooms and occupancy during calendar years 2014-2015

	Number of Units		Occupied kWh/day		Unoccupied kWh/day		Total kWh/day	
Bedrooms	No DHP	DHP	No DHP	DHP	No DHP	DHP	No DHP	DHP
0	53	21	6.6	6.3	4.9	4.6	6.4	6.0
1	51	48	9.1	9.0	7.4	7.0	9.0	8.8
1+	21	9	10.6	12.9	7.9	8.2	10.0	12.4
2	20	6	12.1	12.5	10.0	12.6	11.9	12.5
2+	2	6	11.4	15.4	8.4	9.4	10.0	14.5
3	1	3	14.9	13.3	24.5	8.1	15.7	12.1

First off, what might explain the extremely low overall energy use? The two contributing factors are assuredly the building's insulation level and the occupant demographics. A well-insulated building shell along with small amounts of external surface area for individual apartments implies a low space conditioning load. Recall that with central heat pump hot water heating, domestic hot water is not included in these billed totals. Energy Star appliances and LED lighting further reduce the billed load. Efficiency alone, though, likely does not result in a 3000 kWh/year home. Plausibly the occupant characteristics constitute the other piece of the puzzle: young, urban professionals, more likely to work long hours, eat out, and not have families. Ecotope saw a similar effect in detailed analysis of another recent multifamily building near central Seattle – Sunset Electric on Capitol Hill – where in that case the occupants used a fraction of hot water as anticipated by design guidelines (Heller & Oram 2015). We believe the current demographics of new construction, multifamily buildings in trendy Seattle neighborhoods skew towards young professionals who lightly occupy the apartments.

Second, why might the DHP apartments use similar energy to the non-DHP apartments? Systematic differences exist between the non-DHP and DHP apartments. The DHP apartments largely reside in the more luxurious west building, on higher floors with better views. We do not have hard evidence for this assertion but the conventional wisdom has suggested that the DHP apartments are on average more expensive. The comparison in Table 5 is therefore not exactly fair and direct for estimation of energy savings, but does indicate at a broad level that the presence of a ductless heat pump may not deliver game-changing energy savings in the new, multi-family building segment.

To look beyond averages by category and see the entire range of daily average kWh for individual apartments, Figure 5 shows the distributions of daily kWh by apartment size. Studio apartments mostly used between 3 and 11 kWh/day. One bedroom apartments mostly used between 5 and 15 kWh per day. These totals occur regardless of DHP status, but we saw in Table 5 that systematic differences did not particularly exist in mere average kWh/day.

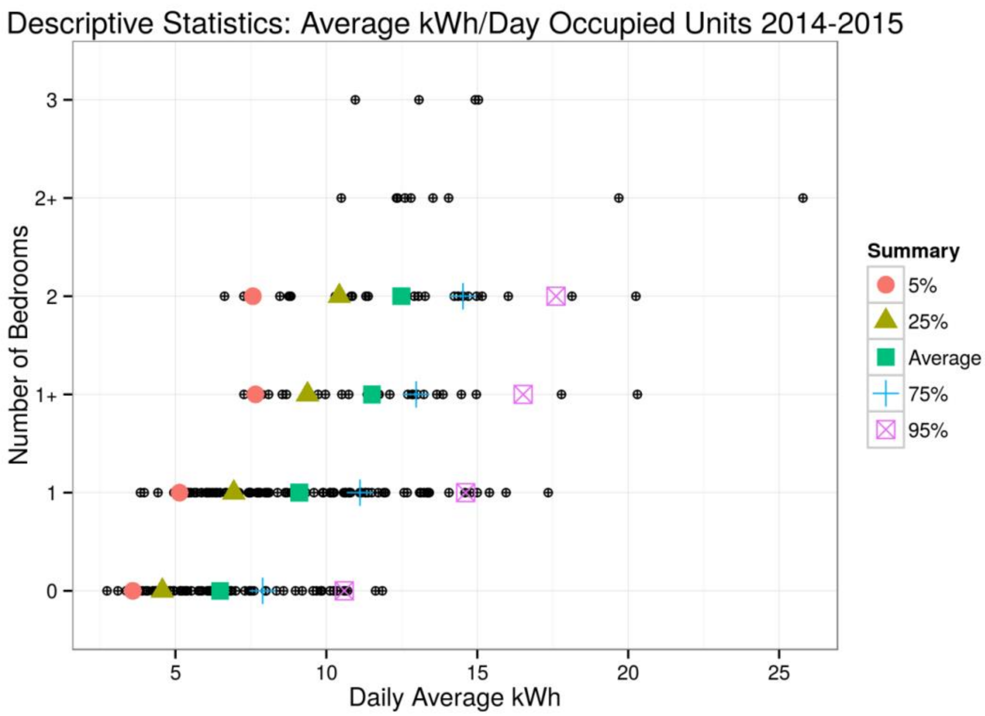

Figure 5, Distribution of average kWh / day by apartment size and DHP status

4 Temperature Dependent Energy Use

4.1 Regression Methodology

Before we start looking at regression analysis of temperature dependent energy use, we should point out that all analysis was carried out using the RStudio interface for the popular, open-source statistical software R. Regressions of energy use on outdoor temperature were conducted using the “rterm” package, a developmental library for R hosted on Ecotope’s github account.[3] Regressions were conducted using a change point analysis methodology, where average daily kWh is taken as a piecewise linear function of average outdoor temperature,

[3] Please contact the authors for details on downloading or using the rterm package

with possible “elbows” for heating and cooling depending on whether the usage profile was correlated with cold outdoor temperatures, warm outdoor temperatures, or both.

4.2 Parsing Unit Bills for Temperature Dependence

Typically, an HVAC savings analysis relies on these or similar regression techniques to identify temperature-correlated and non-temperature-correlated portions of the total energy load. The parsed relationship is then extended to a Typical Meteorological Year weather file to estimate generalized savings. That usual approach doesn’t work as well in this setting for three reasons:

1. Bi-Monthly Data
2. High tenant turnover
3. Low space conditioning loads.

This study represents a perfect storm of factors for obfuscating temperature dependence. Bi-monthly data makes it extremely difficult to parse energy use for temperature dependence, and necessitates long stretches of contiguous occupancy to have any confidence whatsoever in the results. What’s more, systematically looking for cooling in the marine climate of Seattle (where strong cooling requirements may last only a month at most) with only bi-monthly resolution is challenging at best. High tenant turnover prevents long stretches of consecutive occupancy, and low space conditioning loads in the first place magnifies the impact of occupant randomness: these factors conspire with the bi-monthly records to essentially invalidate the utility of any usual analysis method with individual bill streams.

Some examples of individual apartments follow to demonstrate the outlook for unit-based temperature regressions:

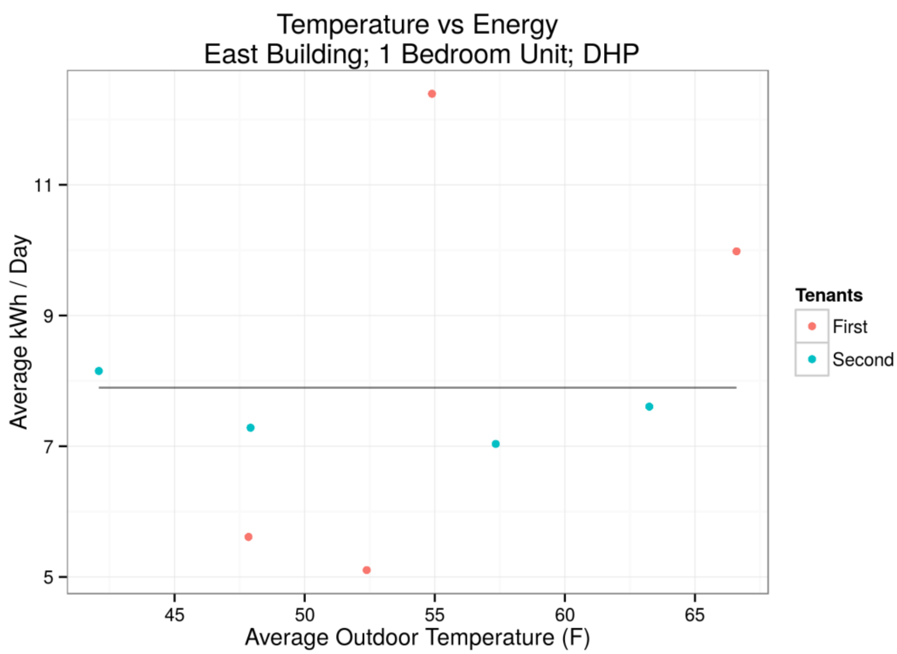

Figure 6, Example of a unit with un-parseable temperature dependence

At their worst (for our analytic purposes), unit bills look as in Figure 6: two sets of occupants, no credible breakdown of heating, cooling, and base load. The regression technique of the rterm package simply shrugged when asked to identify temperature dependence and returned only the mean usage. Asking what the DHP did to reduce energy use at this apartment is a fruitless question: we have no idea, because outdoor temperature was not a systematic driver of energy usage. We also see how hamstrung the exercise is by bi-monthly data. During the project, it became abundantly clear that daily total energy use would provide significantly more insight: imagine with daily data making use of 540 data points rather than 8.

Not all units display such hopeless lack of signal, however. Figure 7 shows an apartment with a strong energy use correlation with cold outdoor temperatures. This particular unit on the sixth floor saw two sets of tenants, but both operated the apartment in a similar enough fashion to generate a fairly clear picture of base load and heating energy.

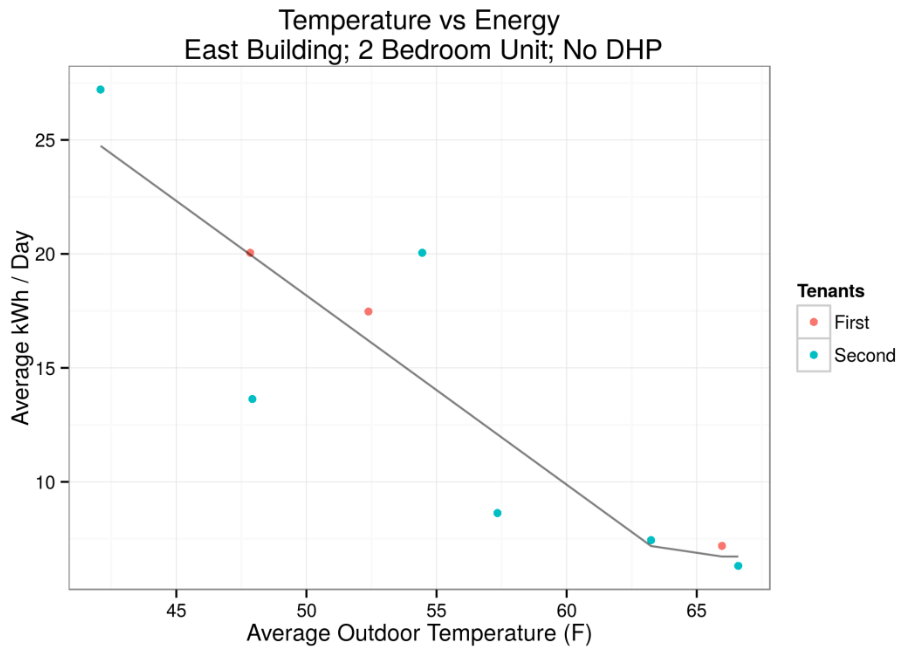

Figure 7, Example of a unit with temperature dependence that can be parsed with regression techniques

With such a smorgasbord of sense and nonsense at the level of individual units, it is clear that we must find some way to aggregate across similar apartments to make any useful statements about space conditioning loads. Note that we would ideally focus on individual units, though, out of a need to control for systematic differences between apartments. We don't want to make implicit comparisons between say 4th floor two bedroom apartments on the north face of the east building to 6th floor one bedroom apartments on the south face of the west building. Those sorts of unfettered comparisons give the descriptive results of the previous section, which, while interesting to observe, cannot be considered rigorous estimates of energy savings.

Figure 8 shows aggregate temperature dependence by apartment size and DHP status. The synthetic data points on the plots were created by averaging across all relevant apartments the average kWh/day, measured across the entire interval, applied to individual days, then aggregating to synthetic bi-monthly observations to match the time span of the underlying data. The figure deftly demonstrates the difficulty of parsing heating and cooling with bi-monthly data. With a heating load that looks similar to the cooling load, the bi-monthly relationship between temperature and energy use looks flat. It is not well defined how to parse a constant energy use profile into heating and cooling. Hearteningly, the non-DHP apartments show noticeably larger energy use corresponding to cold outdoor temperatures, as we would hope. At a qualitative level the regression relationship below helps explain the descriptive statistics above of Table 5: the efficiency of the DHP drops the cold weather energy use, but the addition of cooling raises the warm weather energy use, leaving little noticeable difference in overall consumption.

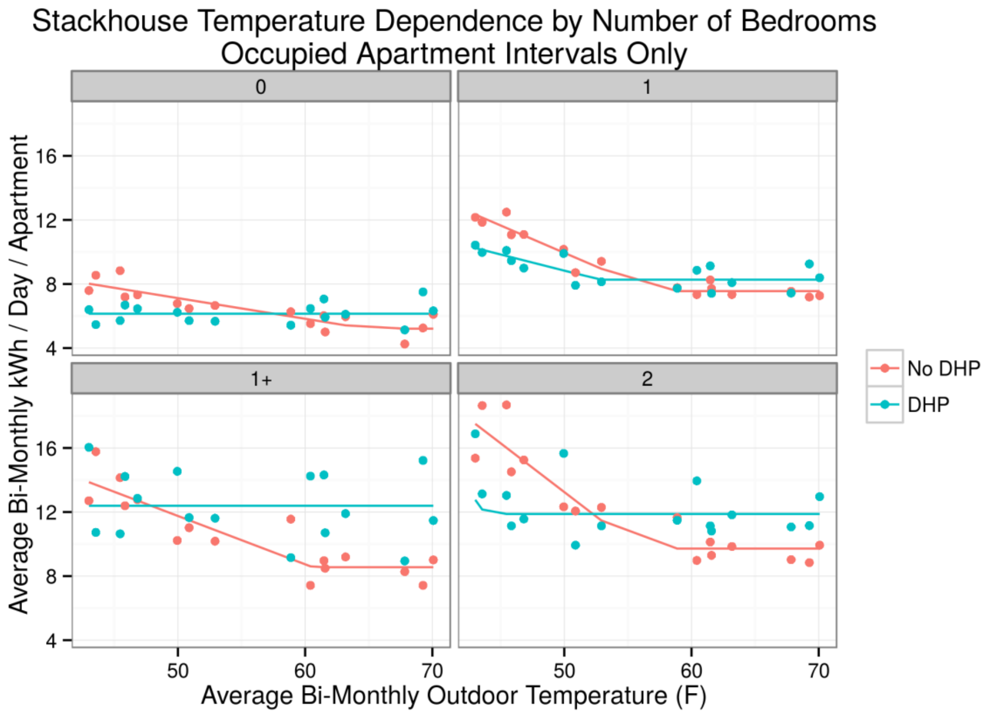

Figure 8, Aggregate temperature dependence by apartment size and DHP status

Perhaps the most concrete possible statement we can make about space conditioning loads from this study relates to the heating signal of the apartments that did not receive DHPs. The DHP apartment energy usage from bi-monthly data is essentially impossible to separate into base load, heating, and cooling, but as seen in Figure 8 the apartments without DHPs show an orderly relationship with cool outdoor temperatures. Extending those curve fits to a Typical Meteorological Year (TMY) gives the inference of Table 6.

Table 6, Results of change point regression on aggregate bills by apartment size for no-DHP units

# Bedrooms	Number of Units	Base Load (kWh/Day)	Change Point (F)	Heating Slope (kWh/Day/F)	R^2	TMY Heating (kWh/Year)	Total (kWh/Year)
0	54	5.3	61	0.157	0.78	554	2490
1	51	7.5	56.4	0.367	0.95	862	3584
1+	21	8.3	60.6	0.321	0.78	1097	4114
2	20	9.6	55.4	0.642	0.86	1359	4852
2+	3	3.0	80	0.368	0.45	3732	4814
3	1	11.3	50	1.752	0.53	1915	6040

Regardless of any concerns about study design, limitations of bi-monthly data, high tenant turnover, etc… Table 6 shows the most concrete finding from this exercise. The loads are low. The heating energy is low. In studio apartments with no DHP, we estimate an average TMY total energy of 2500 kWh/year, with 500 or so of those kWh going towards heating energy. This may sound initially preposterous, but recall the characteristics and context. Most of these studio apartments have no more than 200 square feet of exterior surface area, *total.* We think these apartments tend to be occupied by young, working professionals who simply don't spend a lot of time at home. Similarly for the other apartment sizes, we estimate the average TMY heating load for 1 bedroom apartments at 850 kWh/year, 1+ at 1100 kWh/year, and 2 at 1400 kWh/year. The estimation for 2+ and 3 bedroom units were included in the table for completeness, but are not nearly as trustworthy given the much smaller number of matching apartments. Again, these are estimated heating loads for units *without ductless heat pumps.* This is the total possible heating load to chip away at for energy savings.

5 Savings Estimate

With that in mind, what can we say about the energy savings of the DHPs in this building? The descriptive statistics of the previous section, and even the regressions on aggregate data of apartment type, do little to properly estimate saving as they do not control for systematic differences between apartments receiving and not receiving DHPs. The similarity in overall energy use between DHP and non-DHP units may substantially result from those differences, with larger, more expensive apartments receiving DHPs. The challenge with a study of this type is to control for differences between apartments, to make a fair comparison between DHP and non-DHP energy use.

Luckily, a latent experimental design emerged, with vertical "stacks" of identical floor plans. The exact same apartment floor plan in some cases lies directly above one another in a vertical column, where the third and fourth floor apartments did not receive DHPs and the fifth through seventh floor apartments did receive DHPs. Table 7 describes the high level characteristics of the stacks defined in this manner.

Table 7, Characteristics of apartment "stacks"

Characteristics of Vertical, Experimental "Stacks" of Apartments	
Number	19 Total Groups of Apartments
Building	14 West Building; 5 East Building
Floor Plan	4 Studio; 11 1bdrm; 1 1+bdrm; 2 2bdrm; 1 3bdrm
Aspect	1 NW; 7 S; 2 SE; 3 SW; 6 W

Each stack of identical apartments in this fashion, with the same floor plan existing one on top of the other from floors three through seven, can be thought of as a discrete, experimental unit. The third and fourth floor apartments act as controls since they did not receive a DHP, and the fifth and sixth floor apartments act as cases since they did receive a DHP. We exclude the seventh floor apartment due to its differing heat loss characteristics from external surface area to the roof. This design allows us to control for heat loss characteristics, solar exposure, and some degree of occupancy characteristics in each individual experimental unit. It bears mention that the DHPs were specified for apartments on the basis of a cooling load: south and west facing, upper level apartments received DHPs to meet the cooling load brought on by increased solar exposure and low heat loss rate apartments.

Table 8 shows regression results of using the "rterm" package to fit change point linear models of energy use to outdoor temperature to each of the four units in each of 19 experimental stacks. Specifically, the table shows the results of identifying cold weather and/or warm weather correlations. As mentioned above, it is extremely difficult to parse for heating and cooling bi-monthly data on low load, high turnover apartments. As we see in Table 8, in many instances there was no coherent temperature based correlation with energy use, especially in the apartments with DHPs. The introduction of cooling in the summer counteracted the efficient wintertime heating to frequently leave an unchanging relationship between energy use and outdoor temperature, at least at bi-monthly resolution. Over half of the 38 DHP apartments lying in the experimental stacks showed no distinguishing temperature correlation. A much higher proportion of the non-DHP units showed strong temperature correlation, although two units without DHPs showed increased usage at warm temperatures but not cold. These were verified and confirmed.[4]

[4] Sometimes data just doesn't make sense but you have to roll with it anyway.

Table 8, Regression results for experimental "stacks" design, parsing unit bills for temperature dependence

Temperature Dependence	No DHP	DHP	Total
Heating Only	24	7	31
Cooling Only	2	8	10
Both	0	2	2
Neither/Unparseable	12	21	33
Total	38	38	76

In the case of unparseable temperature dependence we performed no temperature adjustment. The TMY estimate in that case was simply the same as the average observed usage. In other cases, where the regression procedure identified heating, cooling, or both, we applied the resulting fit to the Seattle TMY3 weather file. The results of those TMY predictions are displayed in Figure 9, where each line represents an experimental stack spanning floors three through six.

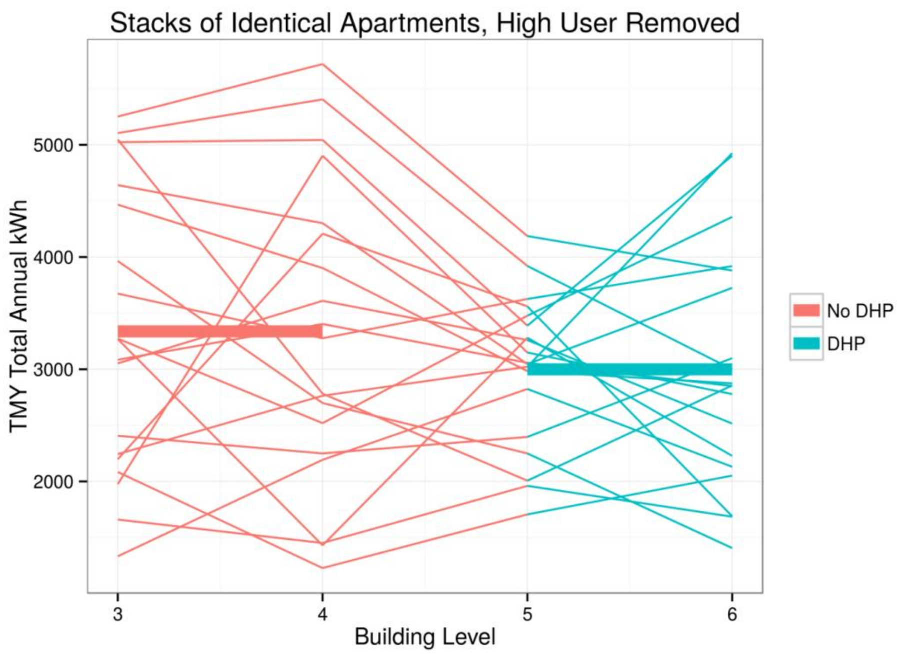

Figure 9, Energy savings analysis using vertical stacks of identical apartments

On average, within a given stack, the annualized TMY energy drops off mildly for the higher floors, but the relationship is messy and not entirely consistent. The third and fourth floor units average approximately 3300 kWh per TMY, while the fifth and sixth floor units average closer to 3000 kWh per TMY, with lots of variation by stack. Energy savings per apartment estimated in this manner work out to 350 kWh per year, TMY adjusted. We have relatively low confidence in this number, though, other than noting that it is of the proper order of magnitude given the temperature dependence found in the non-DHP apartments, outlined above. For example, if the total heating load for a one bedroom apartment is 900 kWh and the DHP meets that load with a COP of 3, then the new usage would be 300 kWh, a savings of 600 kWh. However, if the introduction of cooling created an additional 250 kWh of summertime energy then this would result in 350 kWh of energy savings, the quantity estimated from the apartment stacks experimental design.

So even though we know that 350 kWh lies within range, Figure 10 shows just how muddled the picture of savings estimates by experimental stack truly is. While the average savings estimate around 350 kWh/year lies well within the bounds we would expect (somewhere between zero and the entire heating load), the scatter proves expansive. Among stacks of one bedroom apartments, individual savings estimates range between -1500 and 1750 kWh per TMY. A hypothesis test of significance for the mean savings exceeding zero is not statistically significant. (Note that this is not a totally valid hypothesis test because the "data" are not actually data but rather the result of an upstream, obtuse statistical process. Still it is interesting to note that the large scatter by experimental unit encourages skepticism about latching onto the calculated mean value.)

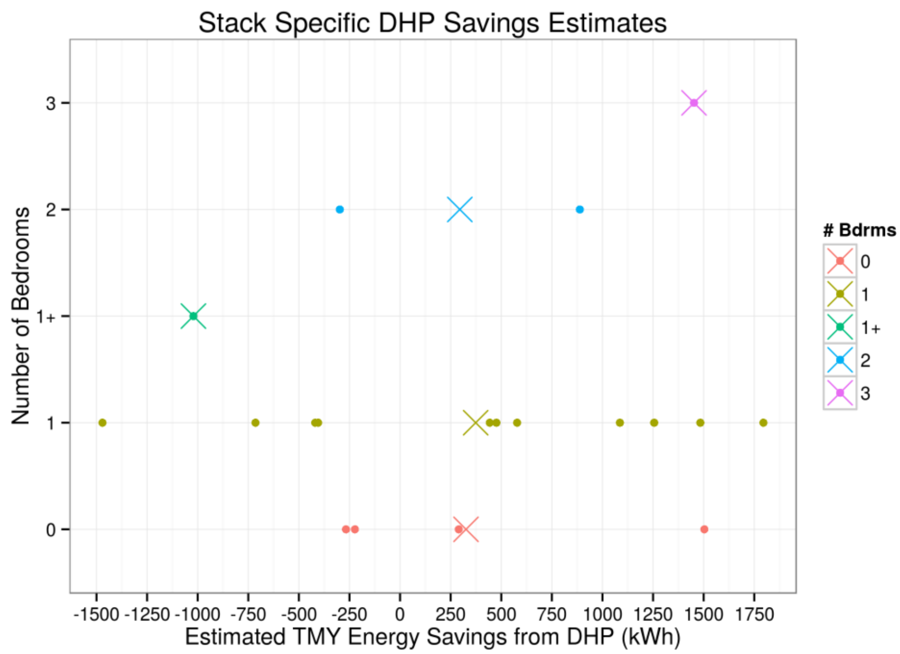

Figure 10, Distribution of Savings Estimate by Stack

While interesting and necessary given that we're already processing and analyzing unit bills, the "stack-based" attempt at estimating savings doesn't add much information beyond what we already know: the heating load is small to begin with, and the DHPs add some amount of cooling. If the average heating load is somewhere around a thousand kWh, then the DHP savings will be somewhere in the hundreds of kWh.

Figure 11 illustrates the generalized finding in another way. To create the graph, we aggregated all apartments in to one of two categories: DHP and non-DHP and then conducted a temperature-energy regression analysis on the groups. Aggregating the individual units in to larger groups does much to reduce the variability. The graph plots the Energy Use Intensity (EUI – Btu/hr/ft^2) against outside temperature bins. Working with bi-monthly bills, these are necessarily the two month energy and outdoor temperature average. As previously discussed, much information is lost in two month averages so caution is needed not to over-interpret the graphic. Nevertheless, the figure shows that at colder outdoor temperatures, the DHP apartments use less energy. Conversely, they use more energy at warmer temperatures. The figure shows a slight uptick in energy use for the no-DHP apartments at warm temperatures. We speculate that this could be from the presence of portable AC units that occupants optionally choose to buy and run. What is made clear in the graph is DHPs use less energy in the heating season and are also used to provide cooling. Compared to units with no mechanical cooling, the overall energy savings is reduced somewhat by DHPs providing new cooling.

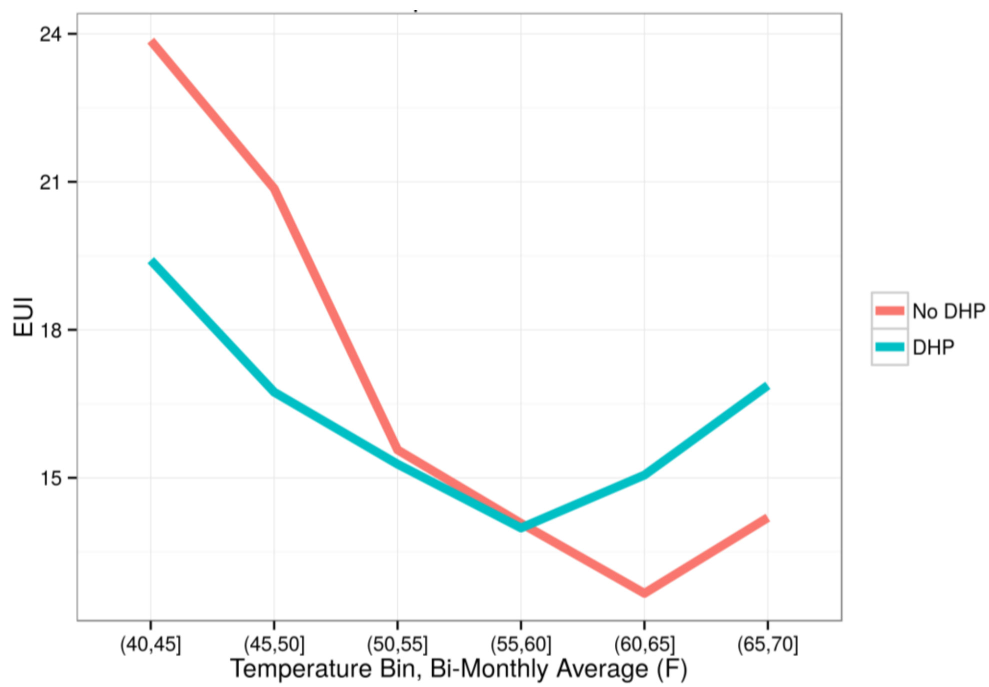

Figure 11, Aggregated Temperature-Energy Dependence for Apartments Floors 3-7

6 Conclusions

This analysis showed that the apartments in this building used very little total energy and even less heating energy. The low heating load simply leaves little energy for a heat pump to reduce. While the heat pump efficiency of a DHP does cut into the heating load, the introduction of cooling energy offsets some of the saved energy. Given the inference from the “stacks”, and the detailed parsing of temperature dependence in non-DHP apartments, the energy savings per apartment likely lies in the several hundreds of kWh per year. Our best estimate of savings shows 350 kWh/year (weather normalized) per apartment. This includes energy saved in heating plus the significant benefit to the occupant of mechanical cooling.

In terms of shell and heat loss characteristics, Stack House is essentially a new, albeit slightly-above energy code, multifamily structure. Our best estimate of heating load for a one bedroom apartment in such a structure is around 1000 kWh/year for the Seattle climate, 500 kWh for a studio and 1500 kWh for a two bedroom. We can expect new buildings to be built with similar heat-loss characteristics and have similar heating loads. Such a low load does not leave open many opportunities for cost effective energy savings by way of introducing heat pump efficiency, especially when the emergence of cooling offsets some of the savings.

In 2011, Ecotope conducted field research for BPA on two low-rise multifamily buildings of the stacked-flat variety with exterior entry (Larson 2012). They were located in Richland, WA (Heating Zone 1, Cooling Zone 3) and Eugene, OR (Heating Zone 1, Cooling Zone 1). The units were a mix of 1 and 2 stories in height. Overall, this configuration represents a fairly significant heat loss rate compared to mid-rise multifamily buildings. That drives up the overall heating load which places the heating requirements above average for multifamily buildings. Both sites had electric resistance baseboard heating and the Richland site had packaged terminal air conditioners for cooling. Nevertheless, the study found an average heating savings of only 800 kWh/yr per unit. The baseline heating loads of 2,200-3,000 kWh/yr were substantially higher than the Stack House apartments but still not nearly as large as with single family structures to provide a rich field for harvesting savings.

In the current market, some buildings are offering portable air conditioners, which operate at lower efficiencies than DHPs, to their occupants. Other occupants buy them of their own accord. If this is the new “normal” for apartment living, then the energy savings for the DHP install would increase on the order of 100s of kWh/yr.

Before generalizing any of these findings, more buildings should be studied to place this result fully in context. As described, this is a new building, with relatively high rents in an urban location. Other mid-rise buildings, both old and new, in urban and suburban locations will likely have different usage profiles. However, total heating loads for mid-rise multifamily buildings are likely to remain low, limiting the total amount of heating energy that can be saved.

This analysis also showed that daily total energy use is needed to get a more accurate estimate of heating and cooling energy by apartment. The analysis was conducted on bi-monthly bills. Using daily totals would increase the number of data points by a factor of sixty resulting in more informed temperature-energy regression fits. Further, the daily totals would more clearly illuminate cooling energy use because the cooling season is often less than sixty days (certainly never sixty contiguous days). Daily total energy would most-readily come from automated meter reading infrastructure but could also be obtained by direct, on-site metering.

Interestingly, builders in Seattle continue to select ductless heat pumps in their multifamily buildings regardless of energy use or incentives. The implication is that as a sales and marketing tool, or simply out of concern for occupant comfort in the increasingly warm Seattle summers, DHPs may prove desirable and effective in new multifamily buildings. From the perspective where the DHP gets installed for comfort cooling, the incremental cost for heating energy savings is zero or simply undefined. Further exploration of the non-energy benefits of DHPs and the reasons developers install them would be useful in helping to explain these decisions. Additionally, it would shed light on how utilities may run incentive programs in this strange space: where DHPs are getting installed for non-energy reasons yet offer up some energy savings.

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