Regression Modeling to Analyze Apartment Space Heating Demand and the Influence of Electrical Use Diversity

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ABSTRACT

In assessing a cold-climate apartment building with suspected defects, it was realized that the sub-metered space heating data allowed analysis of energy use at a much finer scale than is typically possible. Regression analysis of all the energy consumption (space heating *and* electrical use) in the building was employed to better understand the building's performance, and to isolate the location of a heating distribution defect, which was finally identified.

In the process, we developed a new analysis method, useful information and a number of testable theories that more generally inform the process by which energy experts assess and evaluate energy use in apartment buildings. The data indicate the importance of accounting for tenant electrical use in building analysis. Data on the diversity of electrical use is included to demonstrate the magnitude of the challenge involved.

The data further indicate that standard codes require space heating systems dramatically larger than actually needed. This suggests possibilities for improving the energy efficiency of multifamily buildings, while reducing their construction cost.

Is This Building Defective?

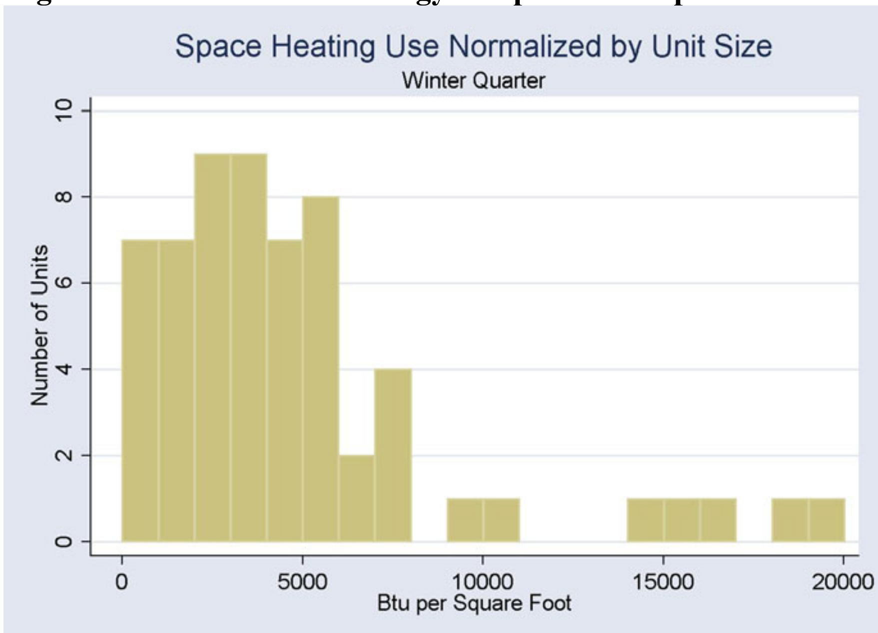
The original study was undertaken essentially to retro-commission the space heating system of a 60-unit apartment building completed and first occupied in late 2003 in southern Wisconsin. The building, developed as affordable housing, has a solar domestic hot water system to capture renewable energy. Two systems were of particular interest in this study; the radiant heating distribution system that delivers space heat to residents, and the sub-metering system that measures space heating energy use and bills tenants accordingly.

In the initial (2003-04) heating season, the sub-metering system appeared not to be functioning properly. At least five of the 60 apartments were receiving heating bills that seemed to be so high as to be in error. (See Figure 1 below.) The many interacting variables affecting heating energy use in apartments suggested many alternative explanations for the high bills. Additionally, this building is unusual enough that typical judgments regarding typical or reasonable energy use were not trustworthy.

Our office was asked to undertake some means of analysis to investigate the suspected problem. A statistical analysis of the bills clarified the reality of these suspected high heating bills. We came to conclude that one unit was indeed defective. We found that the other four suspect units had space heating bills that were reasonable, given their large size and (especially) their unusually low electricity usage.

The analysis method we developed allowed detailed investigation of energy use at the individual unit level. In a sense, the submetering system and electric meters provided detailed information on the actual energy behavior of 60 zones throughout the building. This data and methodology, not previously used by building researchers, provided us some very interesting tools to better understand the performance of large residential buildings.

Figure 1. Distribution of Energy Use per Ft^2 of Apartment Area



Energy Sub-Metering as an Energy Efficiency Strategy

The submetering system was presumed to be the problematic element in the original analysis. It is, if functioning properly, an important energy efficiency tool for multifamily buildings. When space heating is transformed from what economists would call a "public good" commodity into a priced good, consumers can be expected to reduce the amount of excess or "wasted" space heating they use. A pricing signal, in the form of a heat bill, provides (somewhat attenuated) feedback about lifestyle decisions and practices that can significantly affect space heating energy consumption.

The literature regarding housing and resource consumption verifies the theory. Analyses of changes in water consumption and electrical use when master-metered apartment buildings are converted to individual meters generally show significant consumption reductions, solely from resident's decisions and lifestyle changes. Although there are only a few studies, they all show a decrease in energy consumption when tenants are billed for previously unmetered resources, generally on the order of 15 to 20 percent (DiCiccio et. al. 1995, pg. 60-62; Munley 1990) Building operators have adopted similar logic. As energy prices have become more volatile, developers of new multifamily buildings in the Midwest have a clearer bias than ever toward individually-metered heating.

Submetering systems are an attempt by energy-conscious designers to get the best of both worlds. With a central boiler system, tenants get all of the cost advantages of commercial fuel rates and the possibility that one large central heating system will receive better maintenance and monitoring than a large number of individual units. From the perspective of source energy and operating costs, central fossil fuel fired heating systems are generally preferable to individual unit electric resistance heating, although from first costs of installation make electric resistance attractive to multifamily developers.

The central heating system in the building analyzed here has condensing, modulating boilers and an integrated domestic water heating system. These innovations are intended to assure that billing tenants for their energy use to capture lifestyle energy savings leaves tenants with relatively small, predictable heating bills. The fact that the boilers feed a radiant distribution system has further advantages. Condensing boilers extract heat from their combustion gases more efficiently when the boiler fluid is cooler and the heat exchanger has a greater Δ-t across its wall. When the entire floor area of the apartment serves as a radiating surface, it allows effective space heating to occur with lower circulating temperatures (maximum of 120^{o}F., as compared to a minimum of 120^{o}F. in perimeter radiation systems). As a result, the system plumbing in the building supplying the radiant slabs has a smaller Δ-t and wastes less energy through inadvertent heating of non-residential space. Finally, typical hydronic baseboard convectors can be severely compromised when the airflow across them is blocked by couches, dressers, or other large furniture. This problem is eliminated when the entire floor is the radiator.

The sub-metering system for the heating in this building is contained in the manifold between the building-wide heating circulation plumbing and the radiant tubing cast into the unit floors. It consists of three components in series: a sensor that registers an "on" condition when a zone valve is open, a second sensor that registers "on" when the circulating fluid is warmer than 90^{0}F, and an accumulator that records the total "on" time. With this system, all units are presumed to be supplied with heating fluid of essentially identical temperature. Given that the condensing boiler system monitors supply and return water temperatures, and is set up with a very tight swing range, this assumption is generally reasonable. Since it was not possible to do a detailed thermal survey of the system, we could not test this assumption. Using this data, each tenant's bill is calculated as a proportion of the total space heating consumption for the entire building.

One point worthy of note from a policy perspective; this allocation method distributes all general system inefficiencies across all the tenant bills, in proportion to their consumption, whether they result from system breakdowns, deferred maintenance, or a poorly controlled system. It also distributes (in a collective manner, like an insurance pool) the fuel cost risk to the tenants, rather than leaving that risk to be absorbed in the property overhead expenses.

Building Description and Data

The building is more or less typical of new multifamily construction in Wisconsin. The nominally three-story, 60-unit L-shaped building has central double loaded corridors, with 54,600 ft^2 of living space and 15,000 Ft^2 consisting of the double-loaded corridors, a laundry room on each floor, a small office, a small meeting room and a large community room with a small kitchen. The building has a large number of subsidized units, but was designed to support very mixed income levels, so units range in size from 560 to 1,550 ft^2 in size. Eight of the top-floor units have a second story loft, so portions of the building could be said to be four stories tall. The building was designed to support handicapped tenants, so there are approximately 15 enclosed parking spaces, nine adjoining first floor units. The garage is not intentionally heated.

An infill development on a former brownfield, the building is of slab-on-grade frame construction with a brick façade. Two local utility programs supported the design and construction, so insulation levels are somewhat greater than typical; overall R-19 walls, and a flat roof with a high-emissivity (ENERGY STAR®-compliant) membrane over an EPS foam deck with average R-50 insulation. The energy-efficient lo-E vinyl (u = 0.33) double-hung windows might seem to be unusually well-chosen, but we have observed ENERGY STAR®-rated windows specified in a wide variety of new multifamily construction in the state in the last few years. No particular effort was made during construction to reduce/control infiltration. The slab edge has nominal R-7 EPS exterior insulation. All common-area lighting is ENERGY STAR®-rated.

The individual units all have ENERGY STAR®-rated appliances and fluorescent lighting. Every unit has a small balcony or patio, with an ENERGY STAR®-rated door. For acoustic control, R-19 fiberglass batts were installed in common ceilings, and R-11 batts in all demising walls. The radiant tubing runs were engineered to provide essentially identical heat distribution to each unit, and are cast into a litecrete slab floated on top of the wood-panel subfloor. Tubes in the first floor slab were laid on grade, with the entire floor slab poured over them. Considerable research went into the selection of floor coverings on the radiant floor, and the low-pile carpet over jute padding has been reported to deliver good performance. Given the thermal lag time of the radiant slab heating, digital conventional (rather than set-back) thermostats are installed.

The data used in this study comes in three parts: space heating use, building characteristics, and electrical use. The heat consumption data used is the monthly bill output from the sub-metering system. Measurements taken from blueprints were used to calculate all the areas that separate heated from unheated space and have a significant Δ-t. The rest of the data set was developed from simple measurements done in each apartment of the building. In a thermal survey of the building (February 2004, 35^{O}F. outside temperature), staff accessed 59 of the 60 units in the building, and took a number of measurements. Most critical, readings were taken from each unit thermostat.

Although bill data was available for six months by the time this study was completed, only data from the three coldest months were used for analysis. This elimination of the "shoulder seasons" was used to minimize the variation induced by occupancy and lifestyle issues. The data for the three coldest months is when the building's space heating demand is most "shell driven;" that is, when heat demands are most completely affected by the performance of the building itself. Essentially, the time when the outdoor temperatures are coldest is when the "signal to noise" ratio in the heating data is strongest.

Electricity use is an important variable. Most electricity end uses in household appliances are, at very best, a few percent efficient in producing the light, images, sound, air movement, or other end product desired. That is, most uses of electricity actually generate space heating, with an efficiency of heat production of 90 percent or better. Residents that use large amounts of electricity (for lighting, cooking, appliances, etc.) are actually substituting that energy for space heating consumption, at a rate of approximately 3,413 Btu per kilowatt/hour of electricity consumed. Thus, electricity use should be inversely correlated with space heating demand. A complete meter reading for all 60 units was performed in April 2004, summing all in-unit electrical use since the building opened in October.

For comparison purposes, data from a Wisconsin study of single-family homes done in 1998 (Pigg & Nevius 1999) was extremely useful.

Regression Analysis Methodology

The primary analysis for this building was not to predict the actual usage in each unit, rather we were seeking to explain the *variation* in usage form unit to unit. Typically a "logical" model, one that follows classical U_a energy modeling assumptions, for example, as shown on pages 62-64 in Krigger, would essentially "assign" all heat loss to (some unknown level of) air migration and to conduction through all surfaces exposed to unheated space. Due to its size and the fact that it was occupied, infiltration was not practically measurable in this building[1]. There is no good reason to assume a systematic variation in infiltration, so we were forced to ignore it in all models. This "logical model" based on typical conductive energy losses would yield a regression somewhat like this:

$$\mathit{btuftqtr} = (-55030.17) + (-2.61019)\mathit{area} + (1.425885)\mathit{exposedwallft2} + (-4201.82)\,\mathit{loft} + (-1838.187)\mathit{floor} + (-.7004213)\mathit{totalwindowarea} + (-5417.988)\mathit{garagedoor} + (19.73575)\mathit{garagewall} + (5.840399)\mathit{exposedceilingft2} + (894.0573)\mathit{tstatset} + \mu$$

Table 1. "Logical" Regression Model

. regress btuftqtr area exposedwallft2 loft floor totalwindowarea garagedoor garagewall exposedceilingft2 tstatset						
Source	**SS**	**Df**	**MS**	Number of obs = 59		
Model	478358831	9	53150981.3	F(9, 49) = 3.83		
Residual	680105281	49	13879699.6	Prob > F = 0.0010	R-squared = 0.4129	
Total	1.1585e+09	58	19973519.2	Root MSE = 3725.5	Adj R-squared = 0.3051	
Btuftqtr	**Coefficient**	**Std. Err.**	**t-statistic**	**P>|t|**	**[95% Conf. Interval]**	
Area	-2.61019	5.0037	-0.52	0.604	-12.6655	7.445123
exposedwal~2	1.425885	8.059317	0.18	0.860	-14.76992	17.62169
Loft	-4201.82	1921.125	-2.19	0.034	-8062.466	-341.1751
Floor	-1838.187	2572.943	-0.71	0.478	-7008.71	3332.336
totalwindo~a	-0.7004213	43.82876	-0.02	0.987	-88.77761	87.37677
garagedoor	-5417.988	3617.406	-1.50	0.141	-12687.44	1851.46
garagewall	19.73575	17.24053	1.14	0.258	-14.91038	54.38189
Exposedceilingarea	5.840399	3.100376	1.88	0.066	-0.3900404	12.07084
Tstatset	894.0573	181.9923	4.91	0.000	528.3301	1259.784
Cons	-55030.17	15016.95	-3.66	0.001	-85207.86	-24852.48

This regression is problematic in a number of dimensions. While the adjusted R^2 shows it has some predictive power (30%, a surprising amount for such a complex "behavior") it is not very efficient (statistically) in describing space heating demand. Many of the variables that would generally be presumed by energy analysts to be of great importance (exposedwallarea, floor, and totalwindowarea) are of minor predictive power. The "P>|t|" values for these variables of 0.86, 0.99, and 0.48, respectively, indicate that while these variables may appear to have some importance, that appearance is largely due to random chance. Only two of these variables have a t-statistic greater than "2" or "-2", the normal threshold for a statistical reliability on the order of 95% significance.

The primary issue is one of truly understanding what this model should accomplish. A classical energy model is used to analyze and predict overall energy use or energy consumption. In that case, areas of the building with large Δ-t values (especially windows and walls) should be very relevant. However, we were seeking to develop a model that could be used to assess *variations* in energy use from unit to unit, rather than raw consumption. As one example, in this building, window area does vary from unit to unit, but is generally proportionate to the amount of exterior wall. Hence, various regression specifications indicated that window area has little influence on the variation in energy use from unit to unit.

In order to assess the variation of usage from unit to unit, we embarked on an entirely new approach to the issue. It was clear that this analysis needed to focus on factors that varied from unit to

[1] While our office is now involved in considerable investigation of protocols and analysis for infiltration testing for large buildings, that work had not begun when this building was analyzed. The testing procedures presently used in occupied multifamily buildings are complex, and very disruptive to tenants.

unit in concert with the space heating demand. This suggested that behaviors adding energy (electrical use) to the space would be of great relevance, as would those building shell components that varied significantly from unit to unit. These results yielded a number of surprises. At present, it seems that some variables initially presumed to be important actually have little statistically discernable effect on variations in heat demand. It is clear from the model specifications tested that, while many variables like window area may be important for predicting total heat demand, they are less valuable for predicting variation in heat demand.

After over 300 permutations, it did prove possible to specify a variation model with significant predictive value. The final model specification has an R^2 of 0.63, and an Adjusted R^2 of 0.56[2]. With a model specification of this strength, straightforward regression modeling and residual diagnostics proved to be a very realistic strategy to conclude that the heat sub-metering system did indeed have one defect.

The Variation Analysis Model used is as follows:

$$btuftqtr = (-60382.94) + (-73.4058)area + (.0464547)Areasquared + (63.12688)totextwallarea + (-.0602875)Extwallareasquared + (16.60054)totgarwallarea + (3.500949)exposedceilingft2 + (1121.034)tstatset + (-2.192285)kWh + (-4331.088)\, loft + \mu$$

Table 2. Variation Analysis Model

. regress btuftqtr area Areasquared totextwallarea Extwallareasquared totgarwallarea exposedceilingft2 tstatset kWh loft						
Source	**SS**	**Df**	**MS**	Number of obs = 59		
Model	729659924	9	81073324.8	F(9, 49) = 9.26		
Residual	428804189	49	8751105.9	Prob > F = 0.0000	R-squared = 0.6299	
Total	1.1585e+09	58	19973519.2	Root MSE = 2958.2	Adj R-squared = 0.5619	
Btuftqtr	**Coefficient**	**Std. Err.**	**t-statistic**	**P>|t|**	**[95% Conf. Interval]**	
Area	-73.4058	18.53647	-3.96	0.000	-110.6562	-36.15538
Areasquared	0.0464547	0.010455	4.44	0.000	0.0254446	0.0674649
Extwallarea	63.12688	15.84378	3.98	0.000	31.28761	94.96614
Extwallareasquared	-0.0602875	0.01359	-4.44	0.000	-0.0875977	-0.0329774
Garwallarea	16.60054	4.671445	3.55	0.001	7.212918	25.98816
Exposedceilingarea	3.500949	1.058379	3.31	0.002	1.374056	5.627842
Tstatset	1121.034	149.9201	7.48	0.000	819.7583	1422.31
kWh	-2.192285	0.5092718	-4.30	0.000	-3.215705	-1.168865
Loft	-4331.088	1521.854	-2.85	0.006	-7389.369	-1272.807
Cons	-60382.94	11810.61	-5.11	0.000	-84117.24	-36648.63

This model has substantial and useful predictive power, and many of the variables fit in a logical manner. For example, the unit thermostat setting ought to be and is significant, with warmer units (higher Δ-t through the building shell) demanding greater space heating. The exterior wall area is an important predictor of space heat consumption. And, as expected, electric use is inversely related to space heating consumption.

However, this model still has some unknown flaws. The residuals appear not to be entirely random. The standardized residuals are skewed, suggesting some small but systematic bias (t = -0.1075702). That is, the model specification as used generates predictions that are slightly but consistently high, leaving residuals that are slightly and consistently less than zero.

[2] In a strict statistical sense, there is some indication that robust standard errors might be more accurate, but that masks the influence of a specification with multiple variables. Since the coefficients themselves were of secondary interest, the standard regression is reported here.

This suggests that there is some variable that could be found and added to the model that would improve its explanatory power.

More importantly, the distribution is *not* normal; in particular, the standard deviation is substantially smaller than for a standard normal distribution. As it happens, this non-normality mirrors that of the electric use recorded during this time period. This was taken as a suggestion that the specification process itself might lead to important clues (or at least theories) about how energy use varies in multifamily buildings, and how the building behaves when it is heated.

Data Analysis and Building Operations

The calculated t-statistic for each unit gives an indicator of just how abnormal a particular unit's energy usage is, compared to its predicted usage. An ordered list of the t-statistics for the five largest residuals is as follows:

Table 3. Largest T-Statstics from Variation Model

Unit	Residual t-statistic	Original Heat Bill per 3-Month Period
101	+ 3.385	3rd Highest of 60
222	+ 2.384	2nd Highest of 60
314	+ 2.342	Highest
106	- 2.226	30th of 60
324	-2.031	11th highest of 60
325	- 1.484	43rd of 60

Given the clear evidence that the high unit (#101) is substantial abnormal, further investigation and analysis was conducted. The culprit was finally found to be a leaking radiant tube in the floor under the unit. Curiously enough, the tenant did not report a comfort problem in this room; it took an infrared camera scan to find the failed radiant zone. Metering make-up water to the system revealed that this leak was losing 5 gallons of heated water per week into the soil under the slab. While it is possible that the water from the leaking zone did deliver some portion of its heat into the room above, it appears that there was minimal transfer. The infrared scan did not show a "halo" of heat in the slab around the leak, only that the radiant tube in question (clearly visible in the scan even through the carpet and pad) simply "went dark" at the point of the leak.

The Regressions Talk Back: Modeling to Understand Energy Behavior

The process of identifying a useful regression specification itself provided a great deal of information useful to an energy analyst, above and beyond its usefulness in analyzing energy consumption variation. As noted above, various models all indicate that the window area has such limited variation relative to wall area that it has little correlation with unit to unit variation in heat consumption. The window area is not, of itself, statistically significant. At least for these very energy-efficient windows, it is far more realistic from a modeling standpoint to treat the windows as a part of the total exterior wall area. This reinforces the assumption that apartment building design tends to distribute window area approximately evenly between all units. However, it is not clear that this phenomenon will be found in buildings with more typical (less efficient) windows, or in designs with non-uniformly distributed windows relative to wall area.

The specification identified is greatly improved with the addition of the two quadratic variables. (The addition of the square of a variable models a marginal effect of the variable in question. That is, since "totextwallarea" and "extwallareasquared" have opposite signs, as the exterior wall area becomes larger, the affect of each added unit of wall becomes smaller.) The Adjusted R^2 (which tends to modify the correlation upward as fewer variables are used) drops from 0.56 to 0.39 when the "square of exterior wall area" and "square of unit floor area" are dropped. Further, when the quadratic values are removed, the predictive power of the original values, "floor area" and exterior wall area" also decrease significantly.

Table 4. Changes in Statistical Values After Dropping Quadratic Variables

	t - statistic		p > |t|	
Variable	**With quadratics**	**No quadratics**	**With quadratics**	**No quadratics**
Area	-3.96	1.35	0.000	0.183
Areasquared	4.44	(dropped)	0.000	(dropped)
Extwallarea	3.98	-0.30	0.000	0.767
Extwallareasquared	-4.44	(dropped)	0.000	(dropped)
Garwallarea	3.55	2.26	0.001	0.028
Exposedceilingarea	3.31	3.08	0.002	0.003
Tstatset	7.48	5.85	0.000	0.000
kWh	-4.30	-2.88	0.000	0.006
Loft	-2.85	-2.67	0.006	0.010
Constant	-5.11	-5.61	0.000	0.000

This marginal diminishing effect is puzzling. Since all the units are the same depth from outside to hall wall, the exterior wall area is directly proportional to the floor area of the unit. However, the change in predictive value of the model is so significant that it is hard to accept that this might be a statistical artifact; it would seem to capture some significant aspect of the physical behavior of the building.

One theory is that this may be capturing an air infiltration effect. In single family homes, infiltration analysts have generally observed[3] that builders and remodelers have to work far harder to achieve low infiltration levels in small homes than in larger ones. The blower door experimentation performed to date on apartment buildings in Wisconsin has reinforced this observation. A working assumption has developed that, since air volume is proportional to the square of the building envelope area, the given leakage area in the building envelope should have less effect as the volume of the building gets larger. To date, there is little if any empirical data to test this hypothesis. It would be extremely difficult to do so in real-world buildings. Perhaps analysis of this sort in apartment buildings may provide a test platform for the theory.

Also, this building seems in one crucial dimension to operate exactly the opposite of most cold-climate apartment buildings. Almost any apartment resident that has lived in several different buildings has observed that most heated apartment buildings are warmer on their upper floors. (Again, objective and rigorous data has not been developed.) This observation, if confirmed, would conform to known patterns of air flow and heat transfer upwards through buildings that have limited internal air infiltration control. However, in this building, the heat demand seems to be larger *only* on top floor. A simple regression of "Btuftqtr" against "floor" had a negligible R^2, and a t-statistic of 0.14. Adding it to the most effective model specified above, "floor" is of little predictive value, with a t-statistic of –0.67. And, since it is also

[3] This is a general assertion based on the collective experience of several dozen analysts who collectively perform blower door tests on several thousand homes per year.

collinear with the “exposedceiling” and “garagewall” variables, it significantly reduces the predictive value of both those variables.

To further investigate this observation, a “top floor” dummy variable was created and tested as a possible addition to this model. It proved to be of some usefulness, with a t-value of approximately 1.5 depending on the exact model specified. However, the addition of this marginally useful variable also demonstrated some significant collinearity problems. Its inclusion rendered a significant reduction in the statistical significance of the “exposedceiling” and “loft” variables, with only a very small gain in the overall R^2 value. This variable was dropped from the final specification. These observations about different regression specifications might suggest that uncontrolled vertical air infiltration is reduced somewhat in a building with slabs of lightcrete (carrying the radiant heat tubes) on each floor.

The physics of radiant heat slabs may suggest an alternate explanation. It is possible that heat demand being larger on the top floor is related to the very different manner that in-floor radiant heat distribution delivers heat to a space compared to higher-temperature systems. Radiant heat systems create a large plane that radiates heat in both directions, perpendicular to its surface. In a single-level home, there is only one direction of interest, that of heat radiated upward into the living space.

However, in a multi-level building, radiant slabs in the middle of the building will radiate heat both upward and downward. The slab delivering space heat to a unit on the second floor will also deliver some of its heat into the floor cavity below, apparently allowing the lower unit to gain some free heat. While there is fiberglass insulation installed between in the first/second and second/third floor assemblies, its inclusion was primarily for sound attenuation, and its thermal effectiveness in a partially-filled cavity is open to question. It would appear that the unit on the top floor not only does not get the advantage of this “free” heat, but in fact demands more heat than the unit below, to satisfy its own heating demand plus the “parasitic” heat loss to the unit below.

This theory also offers a possible explanation of why a “floor” variable, indicating what floor a unit was on, which energy analysts would generally believe to be important, had little predictive value and was dropped from this model. This theory is reinforced by the fact that the “loft” variable, a dummy variable applied only to those top-floor units with lofts, had strong predictive value in virtually every regression specification tested. This was puzzling, since the added exposed wall area and the added floor area of the lofts was already included in those variables. The behavior of the “loft” variable in the regression specification would make sense in this context, since the radiant slab in the loft floor delivers its heat either into the loft or into the same unit’s lower level. That is, the loft’s considerable radiation area is not subject to the same “parasitic” heat loss as the heating system in top floor units without lofts.

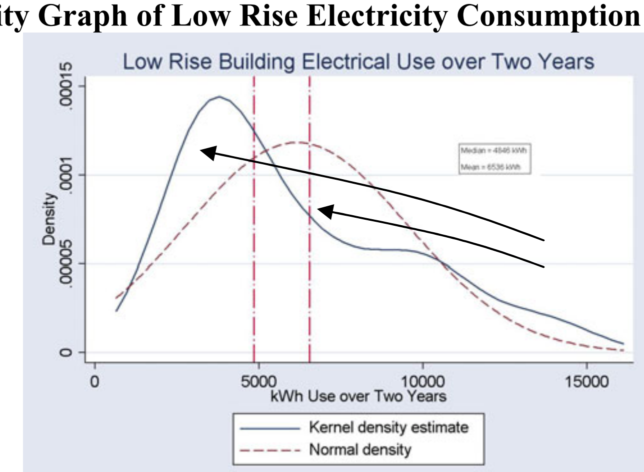
Electricity Use in Apartment Buildings

One fact that leapt out of this analysis was the very poor correlation between the heat loads calculated by the design engineer and the actual space heating energy used during a winter. That is, comparing the heat demand against the design heat loss calculation gives a very weak R^2 value of 0.0219, and the t-statistic of only 1.14. The calculated heat loss in the design does not correlate to any statistically sound degree with the actual heat demanded by residents during this winter. A standard heat loss calculation is designed to reflect building heat needs at southern Wisconsin’s design temperature of -7^0F. At the higher Δ-t that all exterior surfaces would experience at that outside temperature, it is possible that the heat loss calculations would be more in line with instantaneous heat demand. However, I believe that this discrepancy also arises because standard heat loss calculations assume that the heating system is the only heat source to a unit.

Electricity use is an important factor in assessing household energy use, and this analysis shows that in this case it is especially significant. In fact, on the median, the amount of space heating energy delivered to residents via “waste heat” from electricity *exceeds* the heat provided from the space heating system. In the five months of data available (covering 5500 heating degree days), the submeter heating system delivered 1.12 BTU/ft^2/HDD to a unit of median size and median electrical usage. This is presumably a lower bound of the Heating Energy Index as it is usually calculated, as it does not include any standby or distribution losses. While not specifically measured on a monthly basis, the heat content of the supplied electricity during the same period is estimated to be approximately 1.3 BTU/ft^2/HDD.This is essentially “free” heat, given that the resident is already receiving the desired services of the appliance or lights using the electricity. By contrast, the average Wisconsin single family home receives less than 12 percent of its space heating from in-unit electrical use (Pigg & Nevius 2000). This study showed that the average single family home in Wisconsin uses 1,026 therms of natural gas for space heating and 9,900 kWh of electricity. If the electrical use during the five months of the heating season is 4,125 kWh, then electricity use that is 95 percent efficient as space heating energy supplies 11.5 percent of all space heat. One asks immediately if this building could be adequately heated with a far smaller (and less expensive) space heating system. After all, many building efficiency advocates agree that most codes and standards are extremely conservative in their system sizing requirements, and contractors almost always upsize equipment even further. It would appear that even a system sized specifically to meet the design heat load is significantly larger than necessary.

This finding is important to the present analysis in that, as has been observed in most residential settings, residential electrical use varies over a wide range. The initial theory was that electrical use might be distributed normally. Actual use in this building over two years shows wide diversity, but a distinct bimodal pattern. Use ranges from 1,984 to 14,766 kWh (with one wild, eliminated, outlier at 28,500 kWh!) Use is strongly biased to the low end, with an obvious “left wall” influence. The median value is 4,846 kWh and the mean is 6,536 (+/- 4,418) kWh.

Figure 2. Density Graph of Low Rise Electricity Consumption Over Two Years

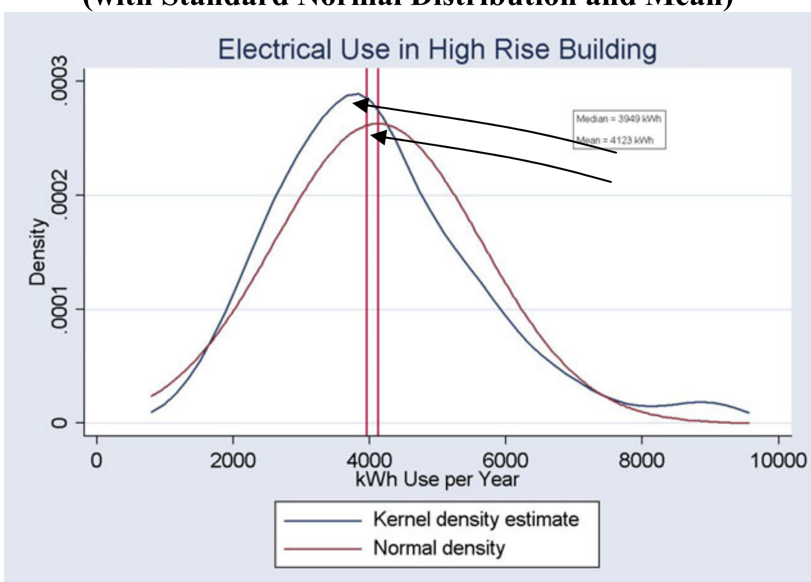


Values for Data Curve; Skewness = 2.34186, Kurtosis = 11.41309

It is clear, however, that this pattern is not universal. It recently became possible to perform similar electric use monitoring in a substantially larger building, a largely market-rate, 12-story high rise apartment (112 apartments, four commercial units). In this case, (See Figure 4 below) the electrical use is similarly diverse, but seems to be more balanced. Some characteristics stay the same; a wide range and some bias toward smaller values are still apparent. Interestingly enough, the left-wall effect has disappeared, the standard deviation is much smaller, and the low-use bias is much less apparent. Still, electrical use in this building spans almost an order of magnitude. The range is 1,302 to 9,065 kWh, the median value is 3,949 kWh, and the mean is 4,123 kWh (s.e. 1,516).

It is not clear whether the differences between these two buildings are real, or a statistical artifact related to the larger sample size. However, the difference is striking, and it seems likely that these two data sets have captured real differences, driven by the building type, characteristics of the resident population, or some other reason. It is not readily apparent that residents in a high-rise building should have dramatically different use patterns. The paucity of data of this sort makes it impossible to resolve this question at present. It is clear that this sort of survey, on even a moderate-sized group of buildings, could greatly expand our general understanding of larger residential buildings.

Figure 3. Density Graph of Electricity Consumption in a High Rise Building over One Year (with Standard Normal Distribution and Mean)



Values for Data Curve; Skewness = 0.924366, Kurtosis = 4.1414

Further exploration of electrical energy use in multifamily buildings is clearly warranted; this information could have substantial effects on the design of new, energy-efficient buildings.

In sum, analysis of the variation in sub-metered space conditioning data in an OLS regression framework offers a new battery of tools to building scientists. A submetering system provides fine-grained data about space heating demand in real-world buildings. When combined with data about electrical use, variation analysis makes it possible to investigate a battery of theories about how large residential buildings really operate. When explored and refined further, such analysis could provide a wealth of information about the physics of large buildings.

Of course, this first attempt at such an analysis seems mostly to generate an entirely new body of questions about residents' energy uses and preferences. More wide-spread use of this body of techniques has great potential, waiting to be exploited.

References

DiCicco, Diamond, Nolden, et. al. 1995. "Improving Energy Efficiency In Apartment Buildings." Washington, D.C.: American Council for an Energy-Efficiency Economy.

Foote, Jennifer, and Don Fugler. 2006. *CMHC Research Highlights Technical Series Report #10-106* (2001). Accessed from website http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/01-106-e.pdf, current as of March 1.

Krigger, John. 2000. "Residential Energy, 3rd Edition." Helena, Mont.: Saturn Resource Management.

Munley, Vincent, Larry W. Taylor, and John Formby. 1990. "Electricity Demand in Multifamily, Renter-Occupied Residences." *Southern Economic Journal*, (July): 178.

Nieman, Scott William. 2001. "Essays in Public Economics: Reductions of Pollution Through Enforcement of Emissions Limits and Reduction of Household Energy Use." Ph D. Thesis. Madison, Wis.: University of Wisconsin, Madison.

Pigg, Scott, and Monica Nevius. 2000. "Research Report 199-1: Energy and Housing in Wisconsin: A Study of Single-Family Owner-Occupied Homes." Madison, Wis.: Energy Center of Wisconsin.

Pigg, Scott, and Andrew Price. 2005. "ECW Report 232-1: Energy and Rental Housing: A Wisconsin Characterization Study." Madison, Wis.; Energy Center of Wisconsin.