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This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Abstract

Although much residential housing in urban areas is found in multi-unit buildings, especially in the older cities of the northeastern United States, the technical and behavioral aspects of energy use in such structures are virtually unknown. Structures of two or more units comprise 20 million households in the United States and account for 20% of residential energy use. A significant potential for energy conservation exists in multi-unit buildings, but if energy savings are to be realized from them, information must be obtained about their energy use characteristics.

In June 1982, the Energy Performance of Buildings group of the Applied Science Division at Lawrence Berkeley Laboratory initiated a study in a 328-unit, 15-story high-rise apartment building in Oakland, California, to investigate energy use patterns in such a structure. We found a 20 to 1 range in baseload electricity consumption and a 40 to 1 range for space heating in a sample of 207 units. Units with an eastern orientation used less electricity for space heating than did those facing other directions. Our analysis suggests that some occupants may be using their gas ranges for space heating, although our results are not conclusive. A second major cause of the variations may be differences in occupants' temperature preferences.

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Some Technical and Behavioral Aspects of Energy Use in a High-Rise Apartment Building

Introduction

Although much residential housing in urban areas, especially in the older cities of the northeastern United States, is found in multi-unit buildings, the technical and behavioral aspects of energy use in such structures are virtually unknown. Structures of two or more units comprise 20 million households in the United States and account for 20% of residential energy use (1). A significant potential for energy conservation exists in multi-unit buildings, but if energy savings are to be realized from them, information must be obtained about their energy use characteristics (2).

In June 1982, the Energy Performance of Buildings group of the Applied Science Division at Lawrence Berkeley Laboratory (LBL) initiated a study in a high-rise apartment building in Oakland, California, to investigate energy use patterns in such a structure. The building, named City Center Plaza, was selected because of several attractive characteristics: 1) in 1980, the management installed electric submeters on all units; 2) the quantity of data available from the building was potentially quite large; 3) in each apartment, electricity is used only for space heating and a few appliances; and 4) the building is near LBL.

We initiated this project to understand how energy is used in a large residential building located in a relatively mild climate. We settled on three primary goals for our research. First, we wished to determine which, if any, of several technical and behavioral factors affect gross electricity consumption and space heating in the building. Second, we hoped to discover the relative significance of each factor in variability of electricity use. Finally, we wanted to understand how energy was being used in the building so we could recommend conservation measures to the management.

During this project, we inspected graphs of raw billing information from groups of similar units (having the same floor plans but different floor levels, orientation, etc.). We analyzed the data using linear regressions to study variations from the group average and also tried to separate baseload from space-heating electricity use. We then tested the data for those technical and behavioral effects for which we could devise tests and assumed that any remaining variations were caused by unknown technical or behavioral factors. The difficulties involved in analyzing energy data from many units in a single building are not trivial. However, the nature and significance of these unknown factors cannot be determined without instrumentation, measurements, and occupant surveys, all of which were beyond the modest scope of this project. The reader should be aware that our analysis must be considered preliminary and that there are aspects of energy use that we did not or could not fully consider.

The Setting

Oakland is located on the eastern shore of San Francisco Bay, about 10 miles from the San Francisco peninsula and 15 miles from open ocean.

The Bay Area experiences a cool, rainy season extending approximately from November to May and a warm, dry season from June to October, but local weather is highly variable because of microclimates induced by the ocean and the region's geography. Because of the summer fog, heating during the summer months is not uncommon. During the winter, temperatures rarely drop below $45^{\circ}F$, but the high winter humidity makes space heating desirable, although not essential. As a result, Oakland's 2800 heating degree days are spread over the entire year, although most occur during the winter months (November through March).

City Center Plaza is a 15-story, 328-unit building located near downtown Oakland (Figure 1). It is one of the tallest buildings in the immediate area and is unobstructed and unshielded on all sides except the northeast. The construction is conventional steel frame with three-inch-thick prestressed concrete slab floors and partition walls. The ground floor (approximately 28,000 square feet) is used for office and commercial space. Floors 2 through 15 (approximately 397,000 square feet) are residential. There are four basic apartment plans in City Center Plaza, designated A, B, C, and D. Each type is further divided into subtypes, such as C1, D2, and so on. Information about the apartments can be found in Table 1.

All units in City Center Plaza are privately owned. Two-thirds of the apartments are owner-occupied; the rest are sublet. The annual turnover in occupancy, concentrated in the rental units, is about 33%. The average number of occupants in an apartment is 1.8 and their average age is about 44 years. The average length of occupancy for all units is 3.3 years. The racial makeup of the building is approximately 59% Asian and Asian-American, 19% Black, and 31% Mexican-American and Caucasian. Based on average rental prices, occupants can be categorized as middle to upper-middle income (3).

The Apartment Energy Systems and Loads

We have identified three major paths of energy loss from the City Center Plaza apartments. The first is through the concrete floors and walls, which protrude from the building like fins and act as heat radiators. The second major path is through the windows and exterior walls, and the third is through the ventilation and exhaust systems.

The apartments are heated by wall-mounted electric resistance heaters rated at two to three kilowatts (kW) for a total of 7 to 11 kW per unit. Each heater is separately wired and thermostated, with a continuous "low" to "high" adjustment that can be set to a fixed, although unknown, temperature. All apartments in the building were originally equipped with the same model of refrigerator and dishwasher. Some of the larger units have compact electric clothes washers and dryers. Only a few built-in lighting fixtures are present in each unit. Each unit has a gas range; domestic hot water is provided by a central gas-fired boiler. An important fact is that all natural gas for the entire building is supplied through a single common meter. City Center Plaza has a central air supply system for the hallways and multiple exhaust shafts that keep the apartments under negative air pressure. Makeup air enters each unit through leaks in the windows and cracks around the entrance door to the corridor. Most of the exhaust flow takes place through the kitchen exhaust vent. Much of the exterior wall of each apartment is taken up by glass. There are floor-to-ceiling windows in the living room and large windows in the bedrooms. We estimate the heat-loss coefficient of a typical apartment to be about 680 Btu/hr-^{o}F. With a temperature differential of 20 to 40^{o}F between indoors and the outside, the winter heating load for a typical unit therefore ranges from 3.7 to 7.4 kW.

<u>Utility Data Analysis</u>

Only electricity use is submetered at City Center Plaza. Because the system does not meet the operating standards of Pacific Gas and Electric Company (the local utility), the building management has maintained and read the meters since their installation in 1980.

Our first step in analyzing the data was to generate month-by-month electricity consumption profiles for all units remaining in our sample after eliminating obvious outliers and correcting meter reading errors. Following this, we applied linear regression techniques to the data. We assumed that: 1) all apartments with the same letter designation were identical; 2) all apartments experienced identical exterior climatic conditions; and 3) average energy use for a set of units of the same type represented the "normal" response of that type of unit to the exterior climate. We calculated average monthly electricity use for categories of apartments, used these averages as an independent variable, and regressed individual unit consumption against these averages. Using this approach, the slope and intercept provide indicators of an individual unit's consumption compared to the average and the R^2 calculated for each apartment is a measure of how well that apartment's actual consumption profile is represented by the average of all apartments of the same type. A total of 207 units remained in the sample after the elimination of outliers, defined in this case as units whose R^2 (as defined below) was less than 0.3. In the absence of direct, long-term measurements of interior temperatures in the apartments, this appears to be the best means of normalizing observed consumption data (4,5). We also calculated a consumption ratio representing the actual annual consumption of a particular unit divided by the average annual consumption for that type of unit; this quantity was utilized in several of our test procedures.

Analysis of the City Center Plaza utility data proceeded through several stages, in a sequence determined largely by our assumptions concerning energy use in the building. Although aware of the importance of occupant effects (6), we initially established the hypothesis that variations in energy use could be accounted for, at least in part, by technical factors. We graphically plotted electricity use data normalized by group and floor area and asked:

1. What were the consumption patterns and levels of different apartment types?

After regressing the data against group averages, we separated baseload from space-heating electricity use. Based on the results of this analysis, we developed a list of technical factors that might account for the variation observed in space-heating electricity use. We then asked whether variations could be attributed to:

2. heat flow between adjacent units (heat-stealing)?
3. differential operation of the ventilation and exhaust systems?
4. apartment orientation?

We next investigated whether the variations might be related to testable behavioral factors. There are a number of occupant factors that might cause large variations in electricity use, such as: i) age of occupants in each unit; ii) number of occupants in each unit; iii) changes in occupancy; iv) ownership status; v) who pays the electric bill; vi) socioeconomic group, race, nationality; vii) use of drapes or other devices for cooling; viii) living patterns (e.g., whether the occupants are at home during the day); ix) temperature preference; x) relationship between appliance use and space heating; xi) use of the gas range for heating.

We concluded that, in the absence of detailed survey data and appropriate measurements, only factors (x) and (xi) might be testable using our data. Hence, concerning behavioral factors, we asked:

5. is there a correlation between baseload and space-heating electricity consumption?

6. could the use of gas ranges for space heating account for some of the observed variation?

The monthly utility data were used to plot month-by-month graphs of electricity consumption for July 1981 to June 1982. Each plot depicts 4 to 6 units of the same type on the same floor; approximately 60 plots were generated. Because only architecturally identical units are depicted on each graph, we expected to see similarities and differences in patterns of electricity use between identical apartments. Many units showed a flat consumption pattern during the summer months corresponding to appliance use, and a peak in the winter due to space heating. However, summer use often varied by as much as a factor of four between identical units on the same floor, while variations in winter consumption tended to be even greater (Figure 2). These large variations made it difficult to perceive systematic differences in electricity use that could be caused by simple differences in apartment design. Consequently, we hypothesized other causes of the variations, such as orientation, heat-stealing, etc.

We next separated baseload from space-heating electricity use. We assumed that no significant space heating took place during the summer and that electricity consumption during the months of July, August, and September represented baseload. We calculated a daily baseload for each unit and subtracted the result from the total daily electricity use for each apartment for each of the five months of the heating season (November to March). We assumed the difference to represent electricity used daily for space heating. Table 2 compares the results of our calculation with an end-use analysis of baseload in the apartments and information based on a limited literature search (7). The agreement is relatively good.

We found a variation in the ratio of actual-to-average baseload for all apartments of about 20; this is plotted as a histogram in Figure 3. The variation in the actual-to-average space-heating consumption ratio for all apartments was about 40 (see Figure 3).

Effect of Technical Factors

Our next step was to investigate the effects of testable technical factors discussed earlier. In order to test for heat stealing between apartments, we plotted the actual-to-average consumption ratios of gross electricity use of adjacent apartments, looking for high users located next to low ones, with one ratio on the ordinate of the graph and the ratio of the neighboring unit on the abcissa. Pairs of apartments showing heat transfer should cluster toward the upper left (high-y, low-x) and the lower right (low-y, high-x) of the graph. We found no such trend (Figure 4), however, heat-stealing may be taking place between only a few units or at a very low level, and our sample size may be too small to show it.

Although we made few measurements of air-flow rates through the building's supply and exhaust systems--too few to provide any conclusive information--we hypothesized that these systems might play a role in the variations in electricity consumption as a result of differences in air flows through different exhaust stacks. There are about 50 exhaust shafts in City Center Plaza, each serving approximately 10 apartments (some of the units are served by more than one shaft). In order to determine whether the exhaust system had any effect on electricity use in the apartments, we calculated average space-heating consumption for units located on the same exhaust shaft. A major effect by the exhaust system on space heating would be indicated by statistically significant differences in average consumption from column to column. Although we found substantial variations in the averages for shafts serving columns of identical apartments, the associated standard deviations were large enough so that the t-test indicated these differences not to be statistically significant at the 10% level (Table 3).

To test for the effect of apartment orientation, we calculated daily electricity use per square foot of floor area for each of the 207 units and regrouped them on the basis of orientation--north, southeast (south-facing units in the east wing of the building), east, west, southwest (south-facing units in the west wing). We then calculated the average consumption for each orientation. We found that east-facing units consumed about 35% less electricity in gross terms than the average for all units, an effect significant at the 99% confidence level as measured by a t-test (Table 4). This difference might be explained either by solar gain during the morning hours when the heating requirement is the greatest or by infiltration patterns that favor east-facing units. Lacking detailed, long-term wind and solar records from the immediate vicinity of City Center Plaza and extensive tracer gas measurements within the building, we are unable to identify positively the causes of this orientation effect.

Effect of Behavioral Factors

We next analyzed the data for two testable behavioral factors. We hypothesized that people who used appliances more than the average (or who possessed more appliances than the norm) might also heat more (or less) than average. To test either of these hypotheses, we compared baseload to space-heating electricity consumption, looking for a positive or negative correlation between the two. We found no observable correlation and concluded that either no relationship exists between the two or that the two opposite effects coexist but cancel each other (Figure 5).

Based on comments by the manager to this effect, we suspected that some of City Center Plaza's occupants were using their gas ranges for partial space heating. Because gas is master-metered, the occupants do not pay directly for this form of energy use. Figure 6 shows the pattern of natural gas consumption in the building during the course of a year. We were assured by the building management that natural gas was used within the building <u>only</u> for cooking and heating of domestic hot water.

Because ranges are not individually metered, we can only speculate whether heating with gas is a plausible explanation of the large observed variation in electricity consumption. If we assume (for the sake of argument) that units consuming less than a specified quantity of electricity compensate with gas heating, we find that this difference, summed over this set of units, is sufficient to account for the winter peak (amounting to 130 therms in January 1983). We do not, of course, know the actual distribution of gas consumption but we can speculate on its shape. We may assume that natural gas use is negatively correlated with electricity consumption and that there exists some level of electricity consumption above which surreptitious use of gas no longer occurs. This yields two equations in two unknowns:

$$G = a - bE \quad \text{and} \quad Gmin = a - (b \times Emax) = 0$$

where: G is gas consumed in a unit in excess of the average consumption for cooking and water heating (in kWh/day);
a is the base quantity of excess gas consumed;
b is the correlation coefficient between gas and electricity use;
E is the observed electricity consumption for a unit for space heating (in kWh/day);
Gmin is the minimum possible level of gas use (zero); and
Emax is the level of electricity consumption above which no space heating with gas is taking place.

We can solve this set of equations for values of a and b (since we know G, E, and Emax), and calculate new distributions of energy use within the sample. We solved these equations setting Emax equal to 1, 2, and 3 standard deviations above the average electricity consumption for the group. The effect of this exercise is to narrow the distribution of energy use and to decrease the standard deviation of total energy use (gas plus electric) by 30 to 50%. Low total energy users are pushed toward the middle of the distribution while high users remain unaffected (Figure 7). In other words, if natural gas is being used for space heating as suggested here, the 40 to 1 observed variation in space heating energy use might be reduced by half.

This exercise is merely speculative since we do not know the actual distribution of natural gas consumption in the building. Most of it may be taking place in a small number of units at the lower end of the distribution. The actual situation in City Center Plaza can be determined only through surveys of the occupants or instrumentation of gas ranges (both of which might affect this behavioral factor), and without such information we cannot say much more of a quantitative nature in explanation of the large observed variation in space-heating energy consumption.

Observations and Conclusions

An important result of our research is the wide variation in electricity consumption between nominally identical apartments: a factor of 20 for baseload and as much as 40 for space heating. Part of this spread may be attributable to apartment orientation and the use of gas ranges for space heating, but these are insufficient to explain a large fraction of the variation. (Other studies, it should be noted, have not found such a range of variation; ref. 8). It is conceivable that more sensitive statistical procedures, such as multivariate regressions with carefully selected variables, and the weeding-out of certain units, could reveal correlations between technical factors that have been masked by noise or the lumping together of too many variables. But, a single technical feature would be unlikely to account for more than a fraction of the observed variation. An accumulation of such factors might increase the explained variation by a factor of 2 to 3 but not, we believe, to the level seen in our analysis.

Behavioral factors are a more probable cause of most of the variation. For example, a simple calculation shows that most of the variation could be caused by differences in interior temperature preferences. Occupants who allow the temperature of their apartments to drift in response to outdoor temperatures are likely to require almost no space heating. Other occupants may prefer to keep their apartments at 75°F. In Oakland, a unit kept at a temperature of 55°F during the winter will experience only about 500 degree days, while one at 75°F may experience several thousand degree days. Hence, space-heating energy use may differ by a factor of 5, 10, or even more. This is contrary to the situation in more severe climates, where space heating is determined to a large extent by a building's physical features . That is, if the average winter temperature is 25°F, a house heated to either 55 or 75°F will differ in space-heating energy use only by a factor of two. We cannot, of course, ignore the importance of other factors of which we may be unaware, such as the use of gas ranges for space heating, however, assessment of such factors must be left to future research.

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Tables

Table 1: City Center Plaza Apartment Data.

Unit type	No. of units per floor	No. of units in bldg.	Floor area (ft^2)	No. of bed-rooms	No. of bath-rooms	Window area (ft^2)	Window/floor area
A1	6	12	1054	2	2	277	0.26
A	26	52	1145	2	2	264	0.23
A3	3	6	1109	2	2 & utility	262	0.23
A4	2	4	1090	2	2 & utility	229	0.21
Aexec	2	4	1335	2	2 & utility	272	0.20
Avg.		78	1133			264	0.20
B	6	60	1232	2	1	258	0.21
C	6	60	784	1	1	209	0.27
C1	2	20	753	1	1	209	0.28
C2	6	60	764	1	1	217	0.28
Cexec	2	20	992	1	1	197	0.20
Avg.		160	799			210	0.26
D	2	20	590	1	1	109	0.18
D1	1	10	590	1	1	125	0.21
D2	-	2	605	1	1	133	0.22
Avg.		32	592			116	0.20

Table 2: Baseload and Space-Heating Electricity Consumption in City Center Plaza.

	N	Baseload usage (kWh/day)	Space Heating usage (kWh/day)
All units	207	7.74 ± 4.18	12.11 ± 9.71
Group A	47	9.00 ± 4.40	16.67 ± 10.80
Group B	38	8.19 ± 4.56	12.78 ± 10.40
Group C	104	7.18 ± 3.75	10.67 ± 8.62
Group D	18	6.76 ± 4.64	7.07 ± 6.48
Results of literature and end-use surveys of City Center Plaza units:			
Burnett (ref. 7):		6.5 - 9.3 kWh/day	—
Lipschutz et al. (ref 7):		7.0 - 9.5 kWh/day	—
End-use survey:		6.3 - 9.9 kWh/day	—

Table 3: Comparison of Electricity Consumption for Sets of Identical Apartments on Different Exhaust Shafts.

Shaft no.	Unit type	N=	Space heating (kWh/day)	Result of t-test	Significance
01	C2	8	17.7±17.8		
02	C2	9	15.5±16.5		
16	C2	9	9.8± 9.9	1.14	< 0.90
17	C2	9	14.6±13.8		
24	C2	9	19.1±22.4		
25	C2	10	14.2± 8.8	1.02	< 0.90
03	B	10	17.8±17.5		
04	B	10	19.6±25.3		
05	B	8	20.3±18.8		
06	B	8	16.8±16.8		
22	B	10	21.3±15.1	1.55	~0.93
23	B	8	11.7±11.2		

Shaft no.	Unit type	N=	Space heating (kWh/day)	Result of t-test	Significance
07	C1	9	22.0±19.4	0.88	< 0.90
11	C1	10	15.7± 9.8		
12	C	10	10.9±11.6		
13	C	9	10.2±10.0		
14	C	8	7.8±10.7	0.98	< 0.90
15	C	8	9.4±10.4		
20	C	10	15.4±14.7		
21	C	9	13.0±11.2		
18	D	8	9.8± 8.4	1.15	< 0.90
19	D	10	5.5± 7.2		

Table 4: Results of Analysis of Electricity Consumption on the Basis of Orientation.

Orientation	N	Ratio of actual to average elec. use	Results of T-test	Statistical significance
North	79	1.03 ± 0.50	0.73	< 0.90
Southeast	24	1.13 ± 0.61		
East	40	0.77 ± 0.29	2.68	> 0.99
West	35	1.04 ± 0.53		
Southwest	33	1.05 ± 0.45		

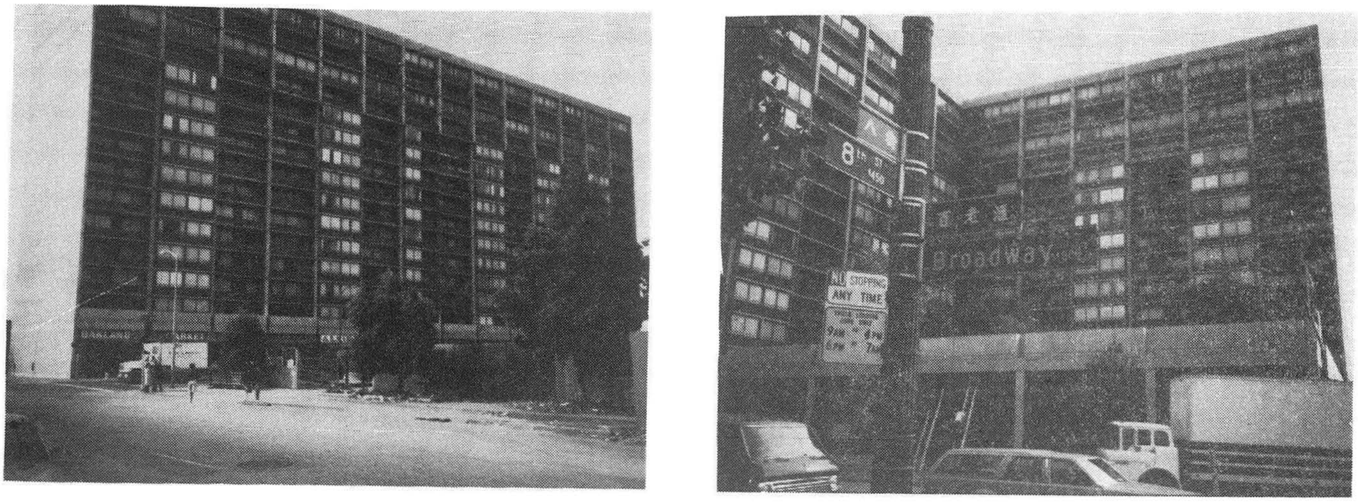

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Figure 1: Two views of City Center Plaza: north (left) and southeast (right).

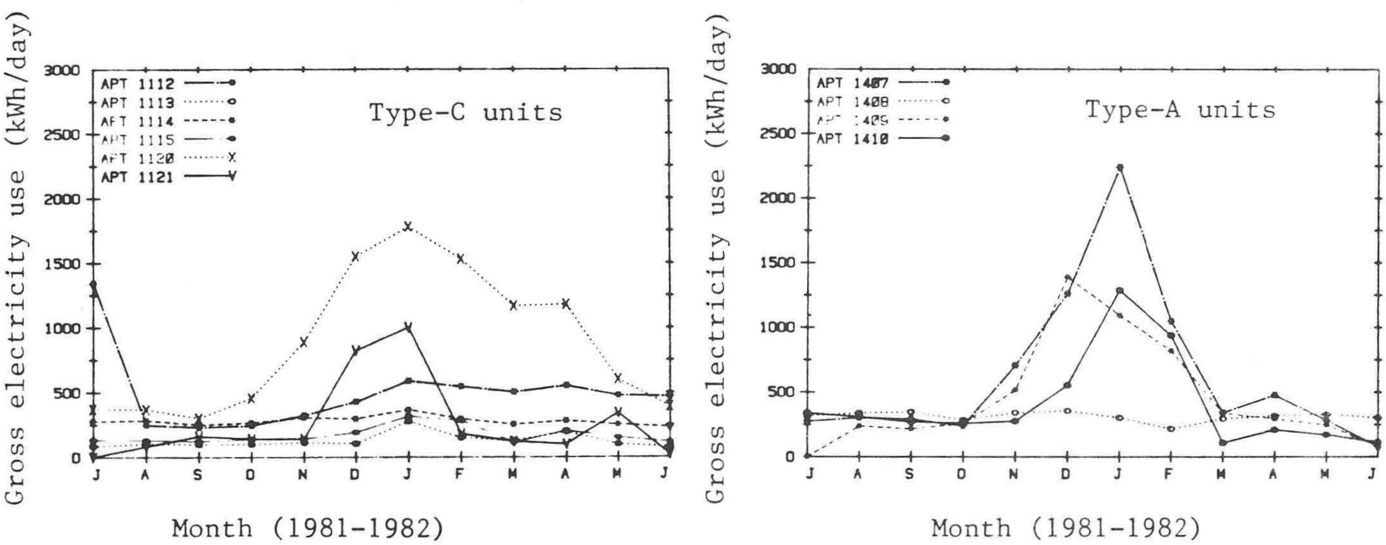

Figure 2: Electricity consumption profiles for two groups of apartments; all units in a single plot are identical. Note the large variations among units for the summer and winter months.

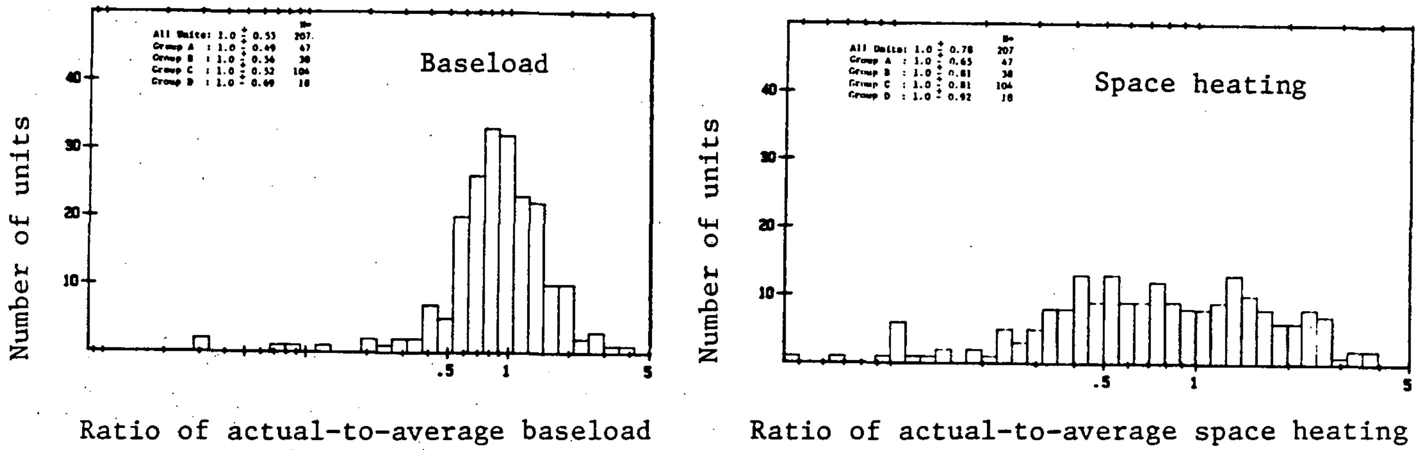

Figure 3: Distribution of actual-to-average baseload and space-heating electricity use for 207 units in sample. (Note scale difference.)

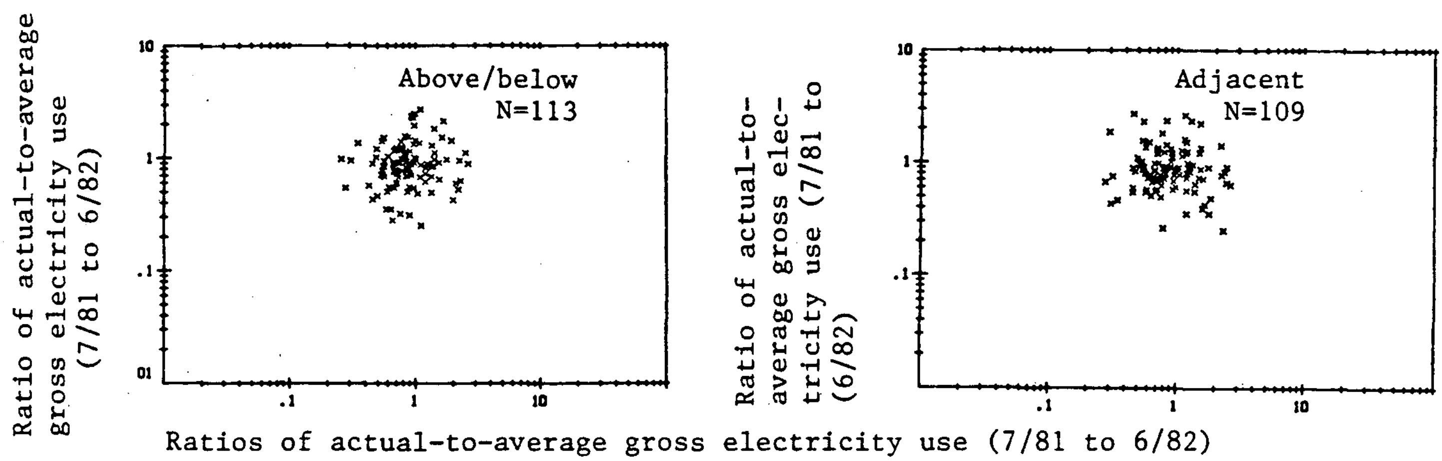

Figure 4: Actual-to-average gross electricity use ratios of pairs of units located upstairs/downstairs (left) and adjacent to each other (right). No off-center concentrations of points are observable.

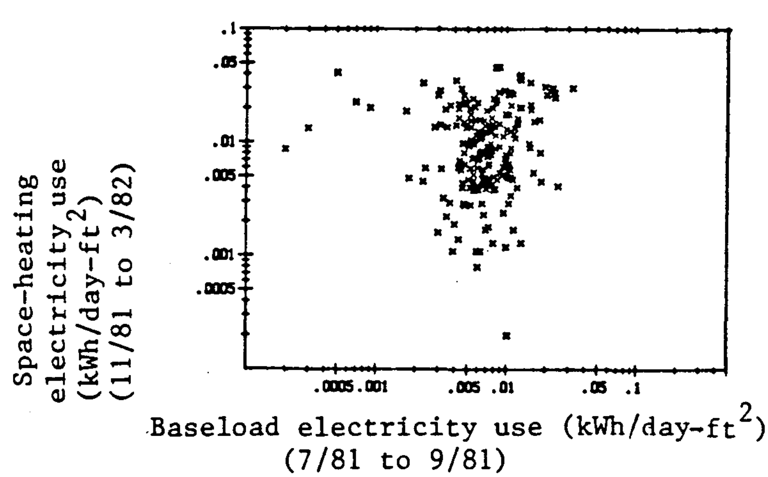

Figure 5: Comparison of baseload to space-heating electricity use for the 207 units in the sample. The plot shows neither a positive nor a negative correlation between the two quantities.

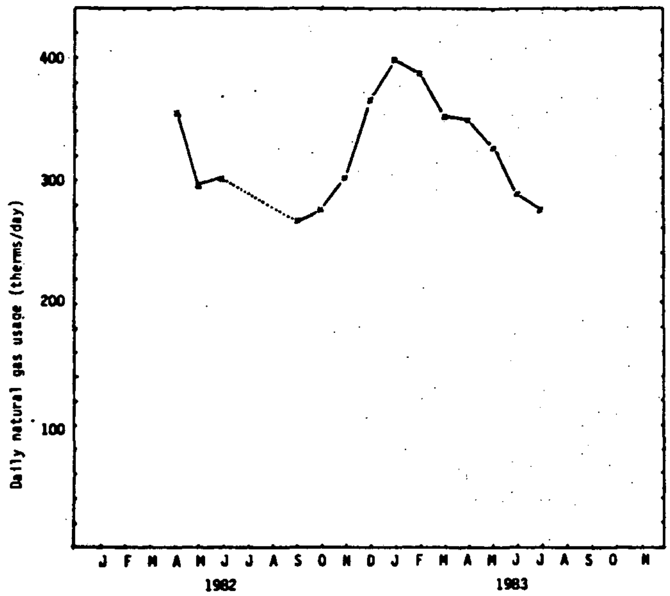

Figure 6: Daily natural gas usage at City Center Plaza, 1982-1983. Note the conspicuous winter peak.

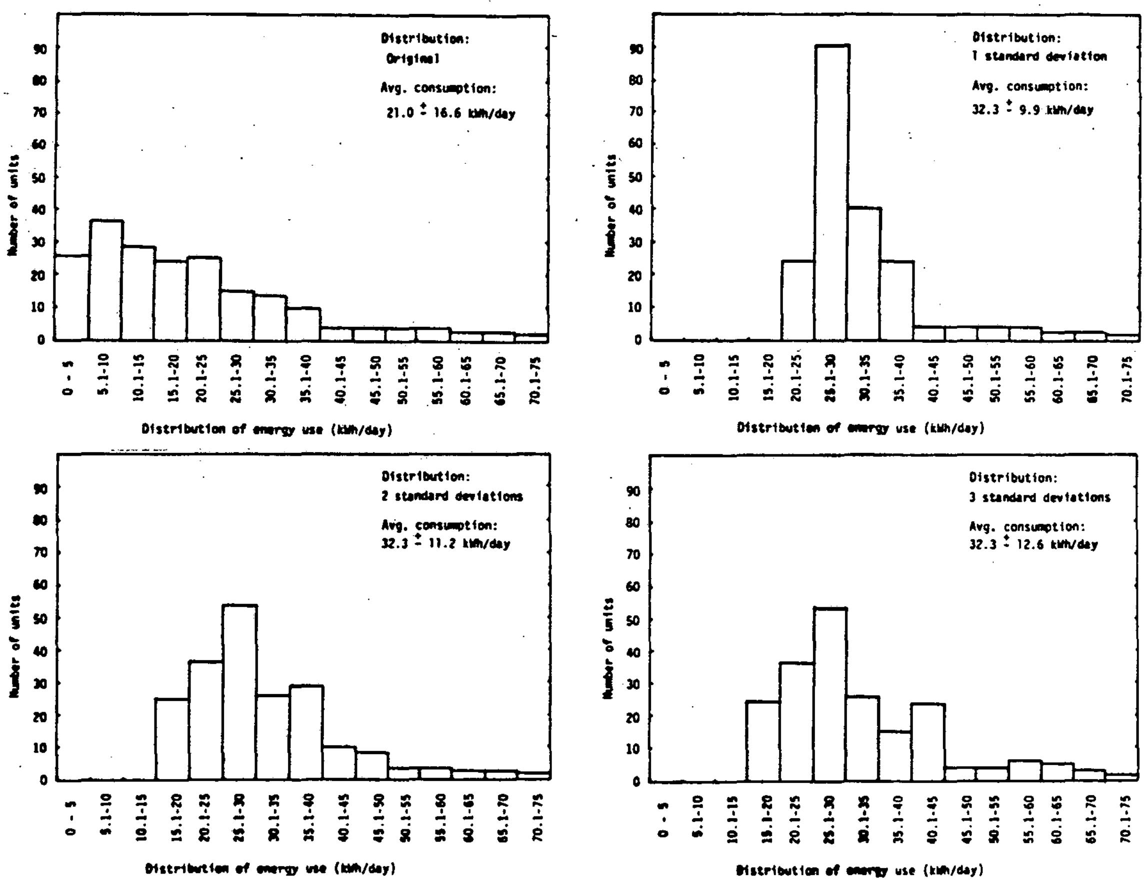

Figure 7: Histograms of distribution of space-heating energy use under the assumption that gas is being used for space heating. The original distribution is for electricity only. The other three distributions represent total (gas + electric) energy use.

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