Measured DSM Energy Savings in New Multifamily Buildings

Pamela Brandis, Bonneville Power Administration
Marc Schuldt and Jeffrey Romberger, SBW Consulting, Inc.

The Bonneville Power Administration (Bonneville) in cooperation with Tacoma Public Utilities (TPU) has sponsored the Multifamily Metering Project. In this project, Bonneville is evaluating the impacts of the Model Conservation Standards (MCS) on the energy consumption characteristics of a sample of new multifamily buildings in the Pacific Northwest. To support the evaluation, continuous hourly measurements of apartment level end-use consumption and other important energy performance parameters are being made on all housing units in a ten building sample. The sample contains five matched pairs of test and reference (comparison) buildings.

This paper provides an overview of the comprehensive Analysis Plan that was developed to guide the evaluation of the energy impacts of the conservation measures included in the MCS. The evaluation procedures are based on an integrated approach that calibrates an hourly simulation model with measured performance data under conditions with and without the MCS features.

This paper also provides graphical and tabular summaries of the measured performance data for the matched building pairs. End-use consumption for all buildings is summarized by month throughout a one year data collection period. The paper concludes with a graphical summary of annual end use consumption by time-of-day for one matched building pair.

Introduction

The Bonneville Power Administration (Bonneville) is conducting an evaluation of the impacts of the Model Conservation Standards (MCS) on the energy consumption characteristics of new multifamily buildings in the Pacific Northwest. To support this evaluation, Bonneville, in cooperation with Tacoma Public Utilities, has sponsored the Multifamily Metering Project. In this project, continuous hourly measurements of apartment level end-use consumption and other important energy performance parameters are being made on each of 84 housing units in a ten building sample. The sample contains five matched pairs of test and reference (comparison) buildings.

During the initial stages of the study, a comprehensive Analysis Plan (Schuldt, 1989a) was developed to guide the evaluation of the energy impacts of the conservation measures (i.e., the efficiency features of the MCS). The Plan includes a set of generic procedures that address all aspects of the evaluation from experimental design, through data collection and analysis, to the evaluation of energy savings realized by the individual conservation measures in each building pair. This paper provides an overview of the Analysis Plan as it was applied to the Multifamily Metering Study. Emphasis is placed on the unique aspects of the Plan that include the calibration of the DOE-2 hourly simulation model with measured performance data under conditions with and without the MCS features.

This paper also provides graphical and tabular summaries of the measured performance data for the matched building pairs. End-use consumption for all buildings is summarized by month throughout a one year data collection period. The paper concludes with a graphical summary of annual end use consumption by time-of-day for one matched building pair.

Methodology

The Analysis Plan consists of six major elements. Each of these elements are discussed below as they were applied in the Multifamily Metering Study to estimate the energy savings that were realized from the Model Conservation Standards.

Study Design

The first step in any study of actual energy savings is the development of the study objectives and identification of research questions to be addressed in meeting the study objectives. Next, an experimental design is selected to establish the overall context in which the research is organized and directed.

For the Multifamily Metering Study, three specific objectives were established as the basis for the evaluation. They included:

(1) Estimation of the total energy savings achieved by the MCS package in each building pair,

(2) Estimation of the energy savings achieved by the individual MCS features in each building pair and their cost-effectiveness, and

(3) Determination of the persistence of the MCS energy savings across multiple years.

To achieve these objectives the test-reference experimental design was employed to assess the impacts of the conservation measures. The test-reference design is the most commonly used approach for new buildings. It requires the use of at least two buildings; a test building that contains the conservation measures and a reference (or comparison) building that does not. This configuration is necessary because "before conservation" data can not be collected on a new building.

Ideally, the two buildings would be identical in all respects except the conservation measures. In practice this will seldom be possible; although an attempt should be made to make them as identical as possible in terms of physical properties, tenant mix and microclimate. Data from this type of design must be integrated with a simulation to adjust energy savings for these factors.

Selection of Building Sample and Conservation Measures

The sample selected for the Multifamily Metering Study consisted of five matched pairs of test and reference buildings (ten buildings total). An attempt was made to select building pairs that were as identical as possible in terms of the number of housing units, tenant mix, microclimate and other physical properties. The matched pairs included two sets of 12-unit buildings, and one set each of 8-unit, 6-unit and 4-unit buildings. A total of 84 apartments were contained in the ten building sample.

The conservation measures implemented in each building pair were defined as the difference in test and reference building features relevant to the MCS code provisions. The specific MCS features varied somewhat across the building pairs because the component performance path (instead of the prescriptive path) of MCS compliance was selected by the developers for all five test buildings. The component performance path provides more flexibility to the developer in selecting a combination of building envelope features that collectively meet the thermal integrity requirements of the code. Errors in the MCS compliance calculations performed by the developers also accounted for variations in the MCS features across the building points.

The MCS features assigned to each building pair were also influenced significantly by the thermal performance characteristics of the reference buildings. All of the reference buildings were constructed in compliance with the minimum requirements of the prevailing state energy code (i.e., the code that would have been used in the absence of the MCS). However, in most cases the reference buildings implemented energy efficiency beyond the minimum code requirements, resulting in greater energy efficiency than expected. Table 1 provides a listing of MCS features that were present in each building pair. These features impact only the space heating end use in each building pair.

Data Collection

The selected study design employs analysis techniques that require the use of a simulation that is calibrated with measured performance data. If the simulation can consistently and accurately predict space heat consumption under conditions that are directly measured, confidence is built in its ability to accurately predict consumption under conditions that are not measured. This will allow the simulation to be successfully used to estimate space heat consumption under any reasonable combination of weather, tenant and building physical characteristics.

The calibration process requires that data be collected to satisfy as many of the input requirements of the simulation as possible. The necessary input data are collected from several sources, including an energy audit, a tenant characteristics survey, professional judgment and continuous monitoring with a data acquisition system. A listing of the minimum data requirements that were specified for the Multifamily Metering Study to satisfy the study objectives is provided in Table 2. The entries in Table 2 are categorized by the most accurate data source, i.e., to minimize the use of professional judgment and maximize the use of continuous measurements. The table shows that the minimum requirement for continuous measurements includes lighting/appliance consumption, domestic hot water consumption, interior air temperature and outside air temperature. The measurement strategy that was actually implemented in the study exceeded these minimum requirements with a continuous (rather than

Table 1. List of Conservation Measures Implemented in the Five Building Pairs

Building Pair	Feature	Value: Non-MCS	Value: MCS
4-unit	AAHX	No	Yes
	Wall Insulation	R13	R19
	Window Glazing	Double without thermal break	Triple with thermal break
	Sliding Glass Doors	No thermal break	Thermal break
	Entry Door Insulation	R1.4	R10
6-unit	AAHX	No	Yes
	Window Glazing	Double without thermal break	Triple with thermal break
	Sliding Glass Doors	No thermal break	Thermal break
8-unit	AAHX	No	Yes
12-unit	AAHX	No	Yes
(1)	Wall Insulation	R13	R19
	Glass Area (Percent of Gross Wall)	13.4	11.0
12-unit	AAHX	No	Yes
(2)	Window Glazing	Double without argon gas	Double with argon gas

AAHX = Air-to-air heat exchanger.

one-time) measurement of AAHX supply and exhaust temperatures.

In addition to the DOE-2 simulation input data requirements listed in Table 2, the simulation calibration process must also be supported by the continuous measurement of space heat consumption for each housing unit. Measured space heat consumption is the standard against which the adequacy of simulated (predicted) space heat consumption is judged. The simulation is considered to be calibrated when predicted space heat matches measured space heat within an established accuracy level. An independent measurement of total housing unit consumption was also necessary to support data verification.

Data collection procedures followed in the Multifamily Metering Study are summarized below:

(1) Select Study Period - The length of the data collection period was selected to provide a sufficient amount of data for the intended analysis.

(2) Select Data Acquisition System (DAS) - A selection of sensor type and data acquisition system was made based upon the requirements for continuous monitoring and the characteristics of the sample buildings.

(3) Develop Measurement Plan - The selected sensor configuration and measurement strategy in each building was documented in a measurement plan.

(4) Logger and Sensor Installation - The data logger and sensors were implemented to satisfy the measurement plan requirements and the hardware was maintained throughout the data collection period.

Table 2. Minimum Data Requirements

Judgment
Contribution of loads to internal heat gain
Shading coefficient of windows

One-Time Measurements and Observations
Energy Audit
Building geometry
Envelope characteristics
Type and performance characteristics of heating system
External Shading
(T) Flow rate of AAHX in test building
(T) Temperature difference across the AAHX
(T) AAHX fan power (KW)[(a)]

Tenant Survey (each unit)
Number and occupancy schedule of tenants

Short-Term Measurements
Air exchange rate (PFT technique)

Continuous Measurements (each unit)
Lighting/appliance consumption
Domestic hot water consumption
Interior air temperature (near thermostat)
Outside air temperature (building level)
(T) AAHX fan on/off time[(a)]

(a) AAHX fan on/off time and fan power were combined into a fan consumption schedule for input to the simulation.
(T) Test building only.

(5) Data Verification - Each installation was subjected to a series of ongoing data quality cheeks throughout the data collection period.

Data Preparation

The verified data set was manipulated in several ways to prepare it for analysis. The first and most important of these manipulations was the treatment of missing entries in the hourly data set. A complete data set was required for an accurate calibration of the simulation. The specific procedures used to fill in missing data varied with both the type and length of the occurrence.

A second required manipulation of the data set involved the preparation of hourly weather files for input to the simulation. The weather files used in simulation calibration were customized to the selected calibration periods and the hourly ambient outside air temperature measurements collected with the data acquisition system. The weather files are prepared by integrating the measured weather parameters with the hourly weather tape for the nearest NOAA weather station.

Another manipulation of the hourly data set involved the aggregation of the filled data set to the building level. A separate aggregation of the individual housing units to the building level was made for each measured end use and building total electric consumption. Building level infiltration rates and interior temperature profiles were also established by averaging the measurements made for the individual housing units. Thermostat setpoint profiles required by the simulation were derived from these interior temperature profiles.

Simulation Calibration

The calibration process consists of three major steps. First, the building characteristics data, tenant data and continuous measurements (except space heat) listed in Table 2 were integrated into the simulation. Second, the simulation was run to calculate predicted space heat consumption under measured site weather conditions and these results were compared to measured space heat consumption. In the final step adjustments were made to the simulation inputs until a satisfactory match of predicted (by the simulation) and measured space heat was achieved. Separate calibrations are made over a one year period for the test and reference cases in each building pair.

The simulation was fully calibrated when the comparison of predicted and measured space heat consumption met two acceptability criteria. First, simulated space heat consumption was within 5 percent of measured space heat consumption on a monthly basis. Second, the average, daily, 24-hour space heating profile generated by the simulation for each month approximated the corresponding monthly measured space heating profile.

Simulation Adjustments

Ideally, conditions in the test and comparison buildings would be identical except for the impacts of the implemented conservation measures. However, in reality, significant changes occur in the building physical and operational characteristics that are unrelated to the conservation measures. Care must be taken to specifically account for these changes in the analysis of energy savings. Factors that were explicitly considered is the Multifamily Metering Study include:

(1) Weather Conditions - During the calibration process a weather adjustment was used to assess microclimate differences that existed between the test and reference buildings. If the calibration periods for the building pairs were not coincident, a weather adjustment was also necessary. An additional weather adjustment was used to compute energy savings under average or typical weather conditions.

(2) Physical Properties - Differences in physical properties of buildings are particularly important to the test-reference design, where the use of two separate buildings is required. Differences in physical properties that were encountered included size of the housing units, amenities provided in each unit, construction type and geometry.

(3) Tenant Behavior - The need for a tenant behavior correction within each matched pair was required in the test-reference design because tenant populations in two separate buildings were evaluated. The correction accounted for variations in appliance mix, consumption patterns and differences in vacancy rates. Tenant behavior was characterized by three variables that are directly controlled by the tenants; thermostat setpoints, hot water consumption and lighting/appliance consumption. Infiltration rate and AAHX fan consumption were also considered when they determined to be highly occupant dependent.

The impacts of these factors were evaluated by resimulating space heat consumption under typical weather conditions for the following four variations in tenant behavior and physical properties. The first variation considered constant reference building tenant behavior and physical properties. The second variation considered constant test building tenant behavior and physical properties. The third variation considered constant test building tenant behavior and constant reference building physical properties. The last variation considered constant reference building tenant behavior and constant test building physical properties.

Each case produced two revised values for energy savings in each building pair. This range of adjusted savings across the cases was viewed as the final result of the adjustment process for the conservation package. This result is indicative of the fact that conservation measures in multifamily buildings often do not produce a fixed amount of energy savings. Actual energy savings fluctuate somewhat with the tenant population, physical properties and weather conditions.

Results

The data acquisition systems were installed in the sample during building construction. Installation began in the spring of 1990 and was completed in May 1991. Formal hourly data collection began in August 1990 and will

Table 3. Measured Monthly End-Use Consumption, March 1991 to February 1992

	Measured Consumption (Kwh/sq.ft.)											
	Building #1 (4-unit non-MCS)				Building #2 (4-unit MCS)				Building #3 (6-unit non-MCS)			
Month	Space Heat	Hot Water	Lts. & Appl.	Total	Space Heat	Hot Water	Lts. & Appl.	Total	Space Heat	Hot Water	Lts. & Appl.	Total
Jan 92	0.54	0.35	0.33	1.22	0.50	0.39	0.41	1.29	0.57	0.38	0.45	1.39
Feb 92	0.39	0.34	0.36	1.08	0.35	0.39	0.39	1.13	0.46	0.32	0.33	1.11
Mar 91	0.16	0.08	0.08	0.32	0.55	0.26	0.31	1.12	0.51	0.51	0.54	1.57
Apr 91	0.09	0.07	0.08	0.25	0.37	0.32	0.35	1.05	0.33	0.47	0.49	1.28
May 91	0.04	0.07	0.10	0.21	0.13	0.31	0.34	0.79	0.12	0.34	0.38	0.84
Jun 91	0.01	0.07	0.09	0.16	0.04	0.26	0.28	0.58	0.05	0.22	0.27	0.54
Jul 91	0.00	0.05	0.06	0.12	0.00	0.22	0.26	0.48	0.01	0.18	0.24	0.43
Aug 91	0.00	0.18	0.22	0.40	0.00	0.23	0.32	0.56	0.01	0.21	0.28	0.49
Sep 91	0.00	0.27	0.30	0.57	0.00	0.25	0.32	0.58	0.01	0.32	0.43	0.77
Oct 91	0.16	0.30	0.30	0.76	0.10	0.32	0.36	0.78	0.19	0.36	0.45	1.00
Nov 91	0.31	0.38	0.36	1.05	0.31	0.33	0.38	1.02	0.35	0.34	0.45	1.15
Dec 91	0.48	0.36	0.33	1.17	0.42	0.35	0.40	1.18	0.51	0.35	0.50	1.37
Annual	2.18	2.52	2.61	7.32	2.77	3.66	4.13	10.56	3.12	4.00	4.82	11.94
Percent	30%	34%	36%	100%	26%	35%	39%	100%	26%	33%	40%	100%

Table 4. Measured Monthly End-Use Consumption, March 1991 to February 1992

	Measured Consumption (Kwh/sq.ft.)											
	Building #4 (6-unit MCS)				Building #5 (8-unit non-MCS)				Building #6 (8-unit MCS)			
Month	Space Heat	Hot Water	Lts. & Appl.	Total	Space Heat	Hot Water	Lts. & Appl.	Total	Space Heat	Hot Water	Lts. & Appl.	Total
Jan 92	0.40	0.33	0.43	1.16	0.52	0.25	0.33	1.10	0.69	0.32	0.42	1.43
Feb 92	0.26	0.30	0.42	0.98	0.45	0.19	0.23	0.87	0.53	0.24	0.35	1.13
Mar 91	0.31	0.27	0.36	0.95	0.65	0.29	0.30	1.24	0.71	0.43	0.49	1.63
Apr 91	0.19	0.27	0.37	0.83	0.37	0.25	0.28	0.90	0.48	0.31	0.36	1.15
May 91	0.07	0.26	0.35	0.69	0.18	0.26	0.32	0.76	0.23	0.39	0.40	1.02
Jun 91	0.03	0.29	0.42	0.74	0.10	0.37	0.39	0.85	0.11	0.37	0.39	0.87
Jul 91	0.00	0.26	0.40	0.66	0.01	0.36	0.39	0.77	0.07	0.34	0.42	0.82
Aug 91	0.00	0.26	0.41	0.67	0.01	0.30	0.38	0.69	0.01	0.25	0.31	0.56
Sep 91	0.01	0.25	0.39	0.64	0.04	0.34	0.43	0.81	0.07	0.38	0.45	0.90
Oct 91	0.13	0.24	0.36	0.72	0.28	0.40	0.53	1.21	0.41	0.40	0.50	1.32
Nov 91	0.29	0.32	0.44	1.05	0.44	0.36	0.51	1.31	0.58	0.38	0.48	1.43
Dec 91	0.36	0.36	0.48	1.21	0.59	0.39	0.49	1.47	0.71	0.34	0.49	1.55
Annual	2.05	3.42	4.83	10.30	3.64	3.78	4.57	11.99	4.60	4.15	5.05	13.79
Percent	20%	33%	47%	100%	30%	31%	38%	100%	33%	30%	37%	100%

Table 5. Measured Monthly End-Use Consumption, March 1991 to February 1992

	Measured Consumption (Kwh/sq.ft.)											
	Building #8 (12-unit MCS)				Building #9 (12-unit non-MCS)				Building #10 (12-unit MCS)			
Month	Space Heat	Hot Water	Lts. & Appl.	Total	Space Heat	Hot Water	Lts. & Appl.	Total	Space Heat	Hot Water	Lts. & Appl.	Total
Jan 92	0.71	0.44	0.51	1.66	0.68	0.31	0.38	1.37	0.58	0.37	0.47	1.42
Feb 92	0.48	0.37	0.45	1.30	0.52	0.27	0.34	1.13	0.45	0.32	0.42	1.19
Mar 91	0.62	0.40	0.49	1.52	0.47	0.30	0.35	1.11	0.45	0.28	0.38	1.11
Apr 91	0.36	0.38	0.43	1.17	0.34	0.31	0.35	0.99	0.32	0.26	0.37	0.95
May 91	0.18	0.33	0.44	0.96	0.19	0.29	0.34	0.83	0.18	0.30	0.41	0.89
Jun 91	0.08	0.26	0.36	0.71	0.12	0.32	0.36	0.80	0.05	0.28	0.37	0.70
Jul 91	0.01	0.24	0.37	0.63	0.01	0.30	0.36	0.67	0.01	0.29	0.40	0.71
Aug 91	0.01	0.22	0.37	0.60	0.01	0.31	0.36	0.69	0.02	0.22	0.34	0.57
Sep 91	0.02	0.26	0.40	0.68	0.04	0.34	0.36	0.75	0.09	0.29	0.39	0.76
Oct 91	0.26	0.33	0.45	1.05	0.28	0.30	0.32	0.90	0.28	0.33	0.40	1.01
Nov 91	0.47	0.30	0.41	1.18	0.46	0.35	0.37	1.18	0.43	0.36	0.39	1.18
Dec 91	0.64	0.41	0.47	1.53	0.60	0.32	0.35	1.27	0.56	0.41	0.49	1.46
Annual	3.86	3.95	5.17	12.98	3.73	3.71	4.23	11.67	3.41	3.71	4.82	11.93
Percent	30%	30%	40%	100%	32%	32%	36%	100%	29%	31%	40%	100%

continue into 1993. Tables 3, 4, 5 provide a compilation of the monthly end use consumption values that were measured in nine of the ten sample buildings for the time period of March 1991 to February 1992. One of the buildings (Building #7) was not included in the table because it was the last building in the sample to be constructed and one year of verified hourly data was not yet available. The energy consumption values in Tables 3, 4, 5 were normalized to the gross floor area of the respective buildings to allow comparisons to be made within each building pair and across the five building pairs in the sample.

The tables reveal a significant range in end use consumption among the nine sample buildings. Lighting/appliances is the largest end use in all buildings, accounting for 36 to 47 percent of total annual consumption. This corresponds to a 2 to 1 variation in normalized annual consumption, from 2.6 to 5.2 kwh/sq.ft. This range is caused by the combined effects of a large variation in average annual vacancy rates (4 to 49 percent) and differences in the consumption patterns of the tenant populations.

These tables also show that space heat is the smallest end use in all but two of the buildings (buildings #6 and #9). Space heat represents 20 to 33 percent of total annual consumption. This corresponds to a large variation in normalized annual consumption, from 2.0 to 4.6 kwh/sq.ft.

Figure 1 provides a graphical display of the measured data for the same time period. In this figure the floor area normalized annual end use consumption values are presented as stacked bar charts that are grouped by building pairs. A comparison of total consumption between the building pairs indicates that the MCS buildings consumed less total energy than their non-MCS counterparts in three of the four cases where the comparison could be made. Measured total consumption is equivalent to the utility billing records. A similar comparison of measured space heat consumption between the building pairs indicates that the MCS buildings consumed less energy for this end use in two of the four cases.

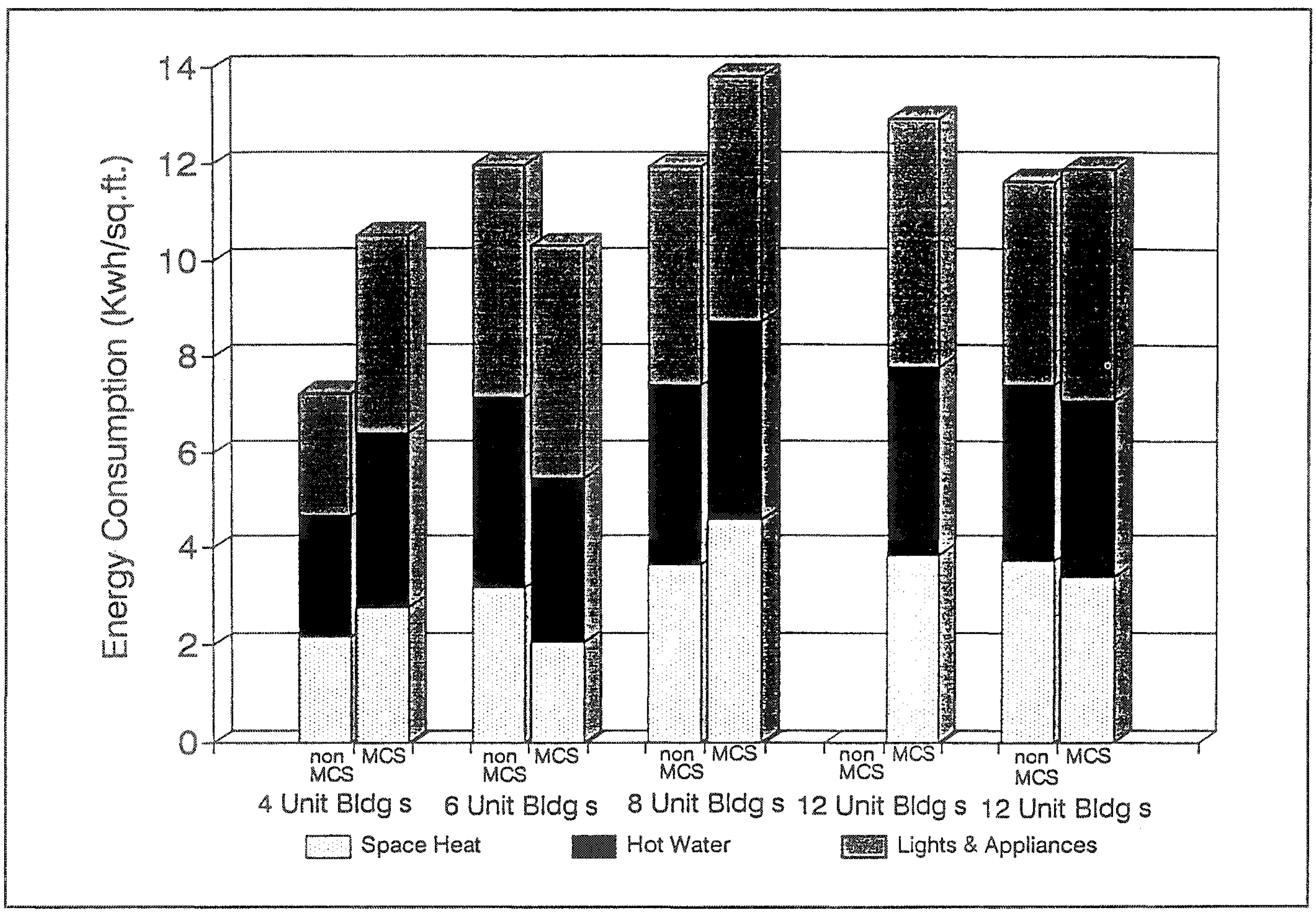

Figure 1. Measured Monthly End-Use Consumption, March 1991 to February 1992

Although their comparisons reflect accurate measurements and are informative, conclusions can not be drawn from these data regarding the performance of the MCS package. The subtraction of space heat consumption between the test and reference buildings does not produce an accurate estimate of energy savings from the MCS until a calibrated simulation is used to adjust space heating for differences in weather conditions, tenant behavior and the physical properties of the building pairs. The study team is currently developing a calibrated simulation for each building in the sample.

End-Use Consumption Profiles

To illustrate the value of the hourly consumption data, 24-hour end-use consumption profiles were prepared for the two buildings in the 6-unit matched pair. The profiles are provided in Figures 2 and 3 for the non-MCS and MCS buildings, respectively. Separate profiles were prepared for each measured end use for the time period of March 1991 to February 1992. The profiles reveal different consumption patterns in these two matched pair buildings. Figure 3 shows that peak consumption for the MCS building occurs during two periods of the day. The morning peak occurs at 7 to 8 a.m. and the evening peak occurs at 7 to 8 p.m. In both cases the peak is caused by high hot water and lighting/appliances usage prior to and after the working day. These profiles are consistent with expected tenant behavior and the consumption profiles measured in previous studies (Schuldt, 1989b).

A very different trend is noted for these end uses in the non-MCS building. Figure 2 shows that consumption for both the hot water and lighting/appliance end uses increases throughout the day, with peak consumption occurring at 9 to 10 p.m. This atypical pattern is caused by the combined effects of a high vacancy rate and an unusual tenant population during this time period. However, the space heat consumption profile for this building is similar to the MCS building. In both cases space heat consumption remains fairly constant throughout the day, without a notable reduction in consumption from night setback in the nighttime hours.

Acknowledgments

The authors of this paper acknowledge the valuable contribution of Tacoma Public Utilities and Pacific Science and Technology staffs, in the collection of building energy performance data for this study. Without their assistance and cooperation, the analysis discussed in this paper would not have been possible.

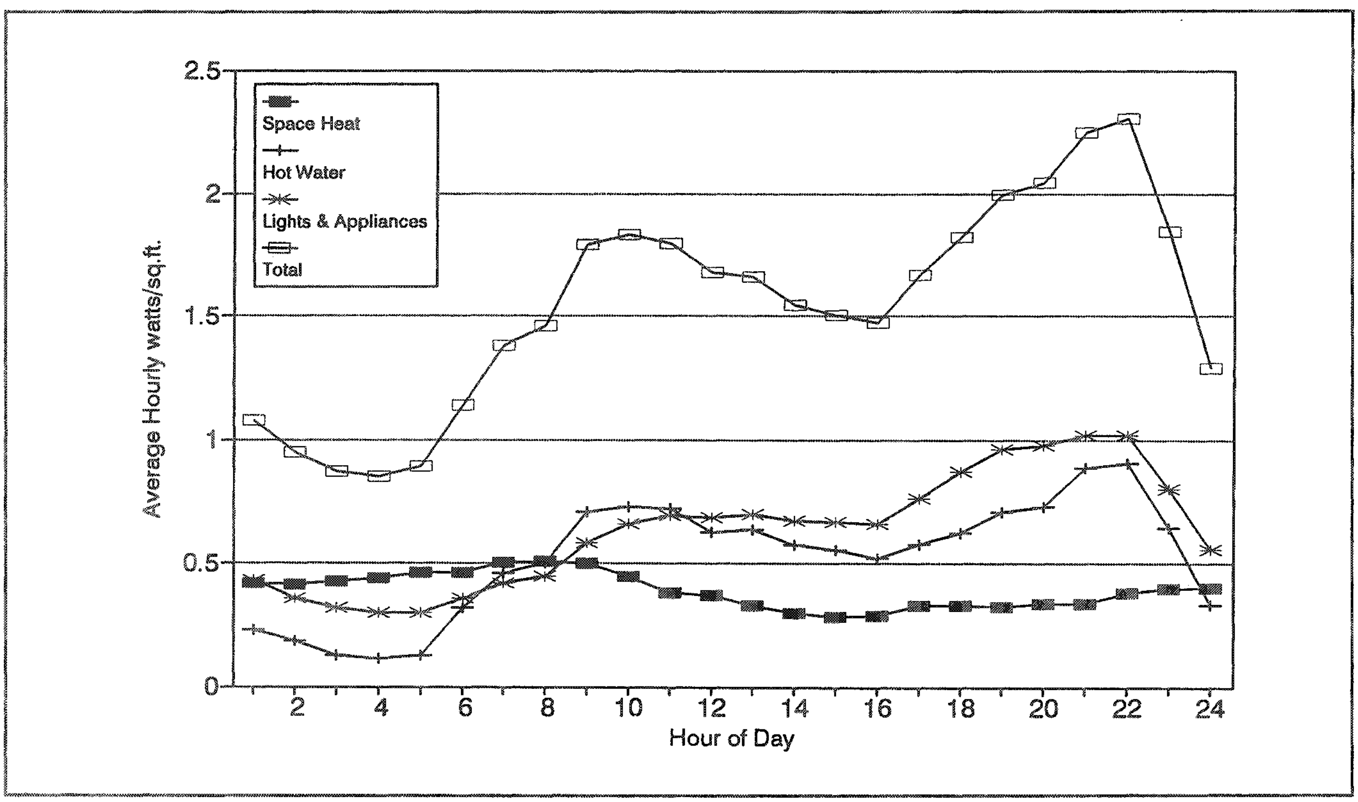

Figure 2. Annual End-Use Consumption Profiles, 6-Unit Non-MCS Building, March 1991 to February 1992

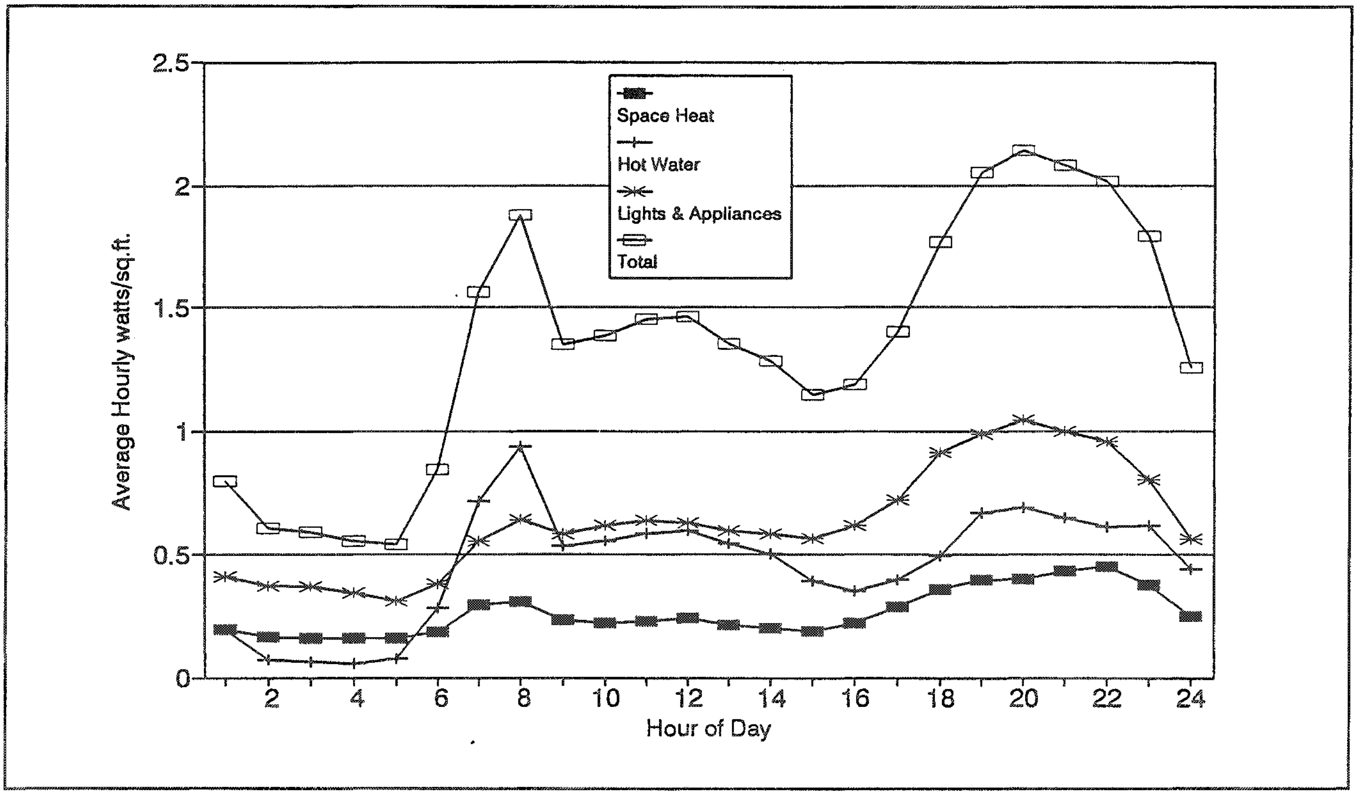

Figure 3. Annual End-Use Consumption Profiles, 6-Unit MCS Building, March 1991 to February 1992

References

Schuldt, M. A. 1989a. *Engineering Estimates of Space Heat Consumption in Multifamily Buildings Final Report.* United Industries Corporation, Bellevue, Washington.

Schuldt, M. A. 1989b. *Energy Conservation Analysis in 3 Monitored Buildings - Final Report.* United Industries Corporation, Bellevue, Washington.