# Commercial Load Shape Disaggregation Studies

**Ingrid Rohmund, Stuart McMenamin and Paul Bogenrieder**
**Regional Economic Research, Inc.**

Three approaches are commonly used for estimating commercial building load shapes. The first is a pure engineering approach using building simulation models. This approach is widely used, but it suffers from the fact that engineering assumptions often diverge substantially from actual behavior. The second is direct end-use metering. Because of the expense, direct metering samples are small, making it difficult to draw general conclusions. The third is end-use disaggregation. This approach combines engineering estimates with whole-building hourly loads, using a calibration or statistical adjustment algorithm.

This paper focuses on the end-use disaggregation approach and reports the results of two studies. In the first study, completed for a southern utility, end-use load shapes were estimated for each of 450 buildings in a statistical sample. The second study, performed for a mid-Atlantic utility, covered a sample of government and private office buildings.

In both cases, on-site audits are performed for a sample of buildings. Next, a detailed hourly engineering analysis is completed for each building in the sample, using weather data for the survey year. Finally, these results are reconciled with whole-building hourly loads, using a statistical-adjustment algorithm. The result is a set of statistically-adjusted end-use loads for each building in the sample. It is concluded that this approach is an economical and technically defensible method for developing commercial end-use load shapes.

## Introduction

Commercial end-use load shapes are typically developed using three approaches: (1) engineering estimates using building simulation models, (2) direct end-use metering, and (3) end-use disaggregation. The purpose of this paper is to describe an end-use disaggregation approach. This approach combines engineering estimates and hourly whole-building loads with a statistical-adjustment algorithm, offering an economical method for developing commercial end-use load shapes.

The technique is applied on a case-by-case basis to individual customer data in a statistical sample. This sample can be expanded to give population estimates for various segments in the commercial sector, as shown in Figure 1. The library of data for individual customers and for specific market segments provides inputs for a variety of analysis tools and spreadsheets.

This approach has been used successfully in two applications: (1) for all commercial building types at a southern utility, and (2) for office buildings at a mid-Atlantic utility.

## Research Approach

The end-use disaggregation approach relies on the analysis framework presented in Figure 2, which is summarized as follows:

- Sample Selection. A sample of buildings with load-profile recorders is selected. As part of this process, data on hourly electricity consumption are assembled and analyzed for each site.

- On-Site Surveys. Survey teams visit the sample buildings to gather information about equipment inventories and operating schedules.

- Survey Analysis. Using the data gathered in the survey, along with hourly weather and whole-building data, end-use load shapes are constructed and statistically adjusted.

- Database Preparation. The adjusted shapes for each case are combined in a single database. At this point, data can be combined into end-use load shapes by building type, rate class or other customer segment.

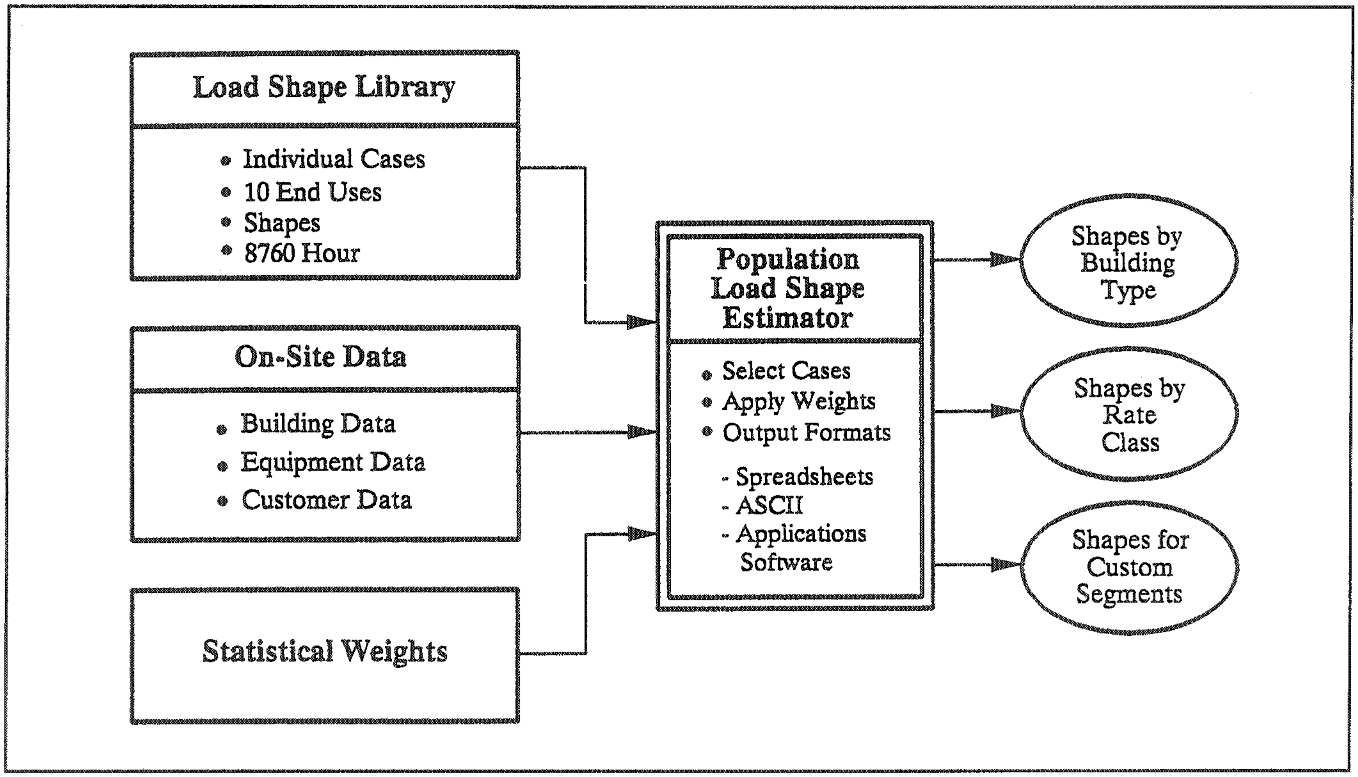


*Figure 1. End-Use Load Shape System*

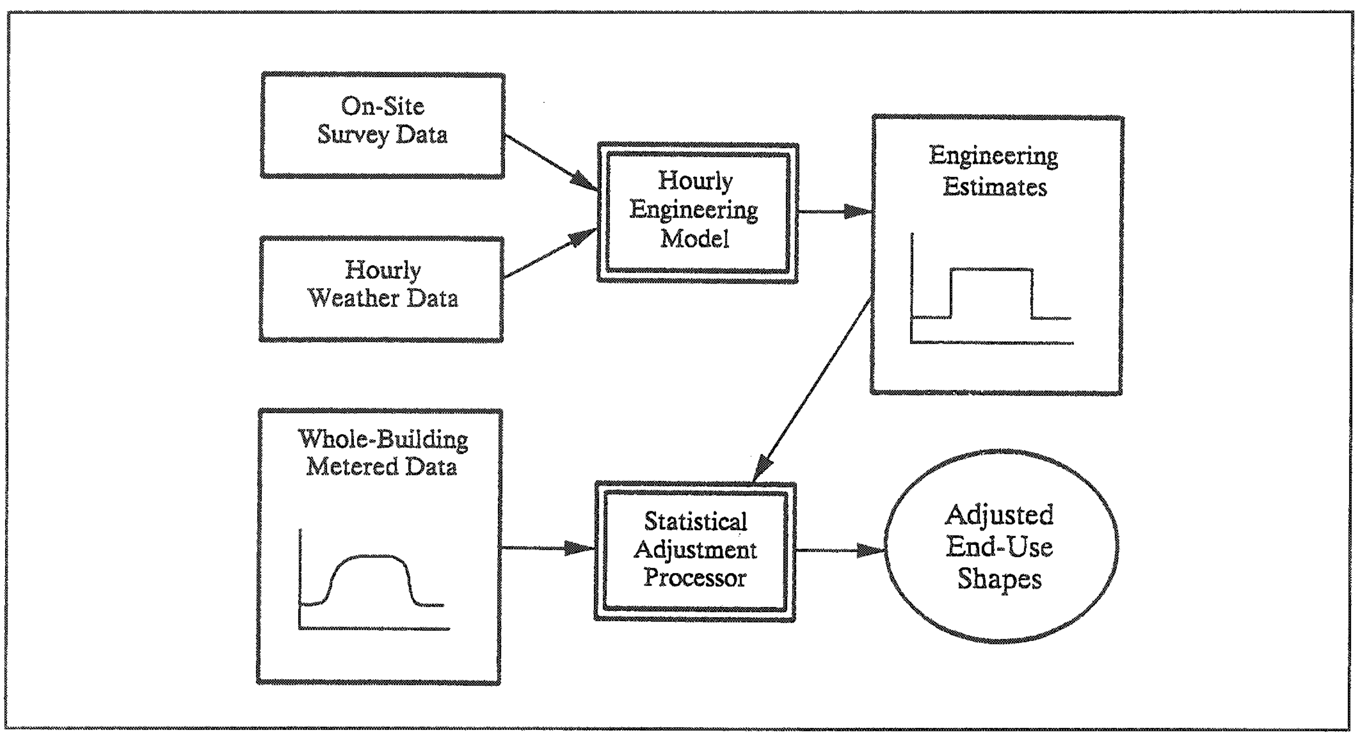


*Figure 2. Analysis Framework for Individual Cases*

In the remainder of this paper, the analysis process is described, and the resulting end-use load shapes are presented.

## Data Collection

The two data collection steps are sample design and on-site data collection. These are described below.

***Sample Design.*** For the southern utility, load shape development took place after a large-scale on-site survey project was completed. End-use load shapes were developed for about 450 sample cases that were also load-research customers or time-of-use customers.

In the office-building studies, sample design was performed using the following steps:

- Definition of the Sample Frame. The sample frame includes all office buildings in the service territory, limited further to include only those customers with hourly load recorders.

- Stratification of the Frame. The qualifying accounts are divided into smaller groups on the basis of three criteria: (1) geographic location, (2) ownership, and (3) size as measured by annual energy sales.

- Sample Selection. A list of customers is selected at random from qualifying accounts in each of the strata.

- Scheduling of Survey Sites. Finally, the on-site visit is scheduled. This involves locating a contact person for the site, obtaining the cooperation of that person, and coordinating their availability with that of the survey personnel.

***On-Site Surveys.*** In each of the three studies, on-site surveys were performed. These involve interviews with maintenance personnel and visual inspection of the facility by a trained surveyor, with a mechanical engineering background. For each site, the surveyor assembles information about inventories of energy-using equipment, energy consumption, and operating schedules for the building.

To a certain extent, equipment inventory data and operating schedules reflect the judgment and experience of the engineer conducting the survey. A medium-resolution survey does not allow sufficient time for an exact accounting of capacities and operating schedules for each piece of equipment. As part of these data collection efforts, the whole-building data are plotted for typical summer and winter days. These plots are provided to the auditor, along with monthly billing data, to assist in the construction of equipment inventories and operating schedules.

The information gathered by the surveyor is compiled on a single survey form, which includes the following:

- Floor space utilization
- Operating schedules
- Building characteristics
- Indoor lighting equipment
- Outdoor lighting equipment
- HVAC system information
- Water heating equipment
- Hot water use
- Cooking equipment
- Refrigeration equipment
- Office equipment
- Miscellaneous electric equipment.

These data from the survey form are entered into a SAS database for analysis.

Statistical expansion of this type of data set provides estimates of floor space, fuel shares, equipment inventories, and energy intensities. These data also provide a strong foundation for estimating annual, monthly, and hourly end-use loads.

## Developing Engineering Estimates

Engineering estimates of hourly loads are based on the inventory of energy-using equipment, the physical characteristics of the building, operating schedules, occupancy patterns and hourly weather. Construction of these estimates is the first step in the end-use load-shape development process. A description of how engineering loads are constructed for each end use is provided below.

***Heating, Ventilation and Air Conditioning.*** Heating, ventilation and air conditioning (HVAC) loads are estimated using a full hourly building simulation model. (The term ventilation is used loosely to refer to energy consumption related to air handling.) This model calculates HVAC loads based on weather, building characteristics, occupancy, HVAC equipment type, and internal loads from other equipment as shown in Figure 3.

The first step in calculation of HVAC loads is the development of building zones. For each zone, the amount of surface area, window area, internal wall area and roof area are computed. Also, the thermal properties of the surfaces must be provided. In these studies a simplified zoning algorithm is used. It defines five building zones, that include four perimeter zones and a core zone. Floor space is allocated to zones automatically, based on the building dimensions and number of floors. End-use equipment is allocated to zones based on the equipment type and the amount of unconditioned space.

Once the building zones are defined, heat transfer is computed on an hourly basis. Heat enters and leaves zones as a result of several factors that include conduction, solar radiation, internal gains, and infiltration. Using the heat flows and thermostat settings, the model estimates heating, cooling and ventilation requirements placed on the mechanical systems. These requirements are translated into estimates of energy consumption using equipment efficiency estimates, which are based on equipment type and size and building age.

*Non-HVAC Loads*. Non-HVAC loads include indoor and outdoor lighting, office equipment, cooking, refrigeration, water heating and miscellaneous electric loads. Engineering estimates of end-use profiles are discussed below.

**Inside Lighting**. As part of the survey, a complete inventory of lighting equipment inside the building is collected. The surveyor also records observations about the fraction of lighting equipment that is on at the time of the on-site visit, which occurs during normal business hours. Also, based on examination of lighting controls and discussions with building occupants, estimates are developed for the profile of lighting use during normal operating hours and the fraction of lights that are on outside of normal operating hours.

Indoor lighting loads are estimated as the product of the total connected inside lighting load and the schedule that gives the percent of indoor lights on in any hour.

**Outdoor Lighting**. Outdoor lighting loads are estimated in a similar manner. Hourly loads are calculated as a percentage of total outdoor lighting capacity. Outdoor lighting capacity is defined in terms of lighting equipment inventory data. With few exceptions, the profiles that are applied to these connected loads give energy use at 100 percent of capacity during nighttime hours and zero percent of capacity during daylight hours.

**Office Equipment**. Office equipment energy consumption is also modeled as a function of equipment inventories and operating schedules. To estimate total capacity, information about the number and size of each type of office equipment is collected as part of the survey process. Using this information, total office equipment capacities are calculated.

Typical connected load values give the hourly load for an equipment unit in typical use. These load values are determined as the product of rated capacity and diversity or cycling factors. For example, the nameplate capacity of a PC may have a value of 300 Watts, but the average load when operating is about 115 Watts. The latter value is used here.

The typical load values are multiplied by an operating profiles multiplier in each hour. This multiplier gives an estimate of the fraction of office equipment that is operating in each hour of the day.

**Cooking**. Cooking load profiles are constructed by applying the total rated capacity of the electric cooking equipment at the site to a usage profile for cooking equipment. The usage profile provides an estimate of the fraction of equipment on in any hour and also adjusts for the normal cycling factor of cooking equipment when it is in use.

Again, the estimate of cooking capacity is constructed from the detailed equipment inventory data, which includes the number of units by type and capacity rating.

**Refrigeration**. Refrigeration covers a wide range of equipment from small domestic units to large commercial refrigeration systems. Although refrigeration equipment is always "on," end-use metered data suggest that energy consumption varies systematically according to the time of day and operating conditions. In particular, refrigeration loads vary as follows.

- Refrigeration loads tend to be higher in the mid-day hours. For small units, this reflects the pattern of usage. For larger units, this reflects both the pattern of usage and changes in condensing conditions for remote compressors. In either case, actual refrigerator loads exhibit hour-to-hour variation.
- Refrigerator loads also have a seasonal component. This has two aspects. First, changes in temperature

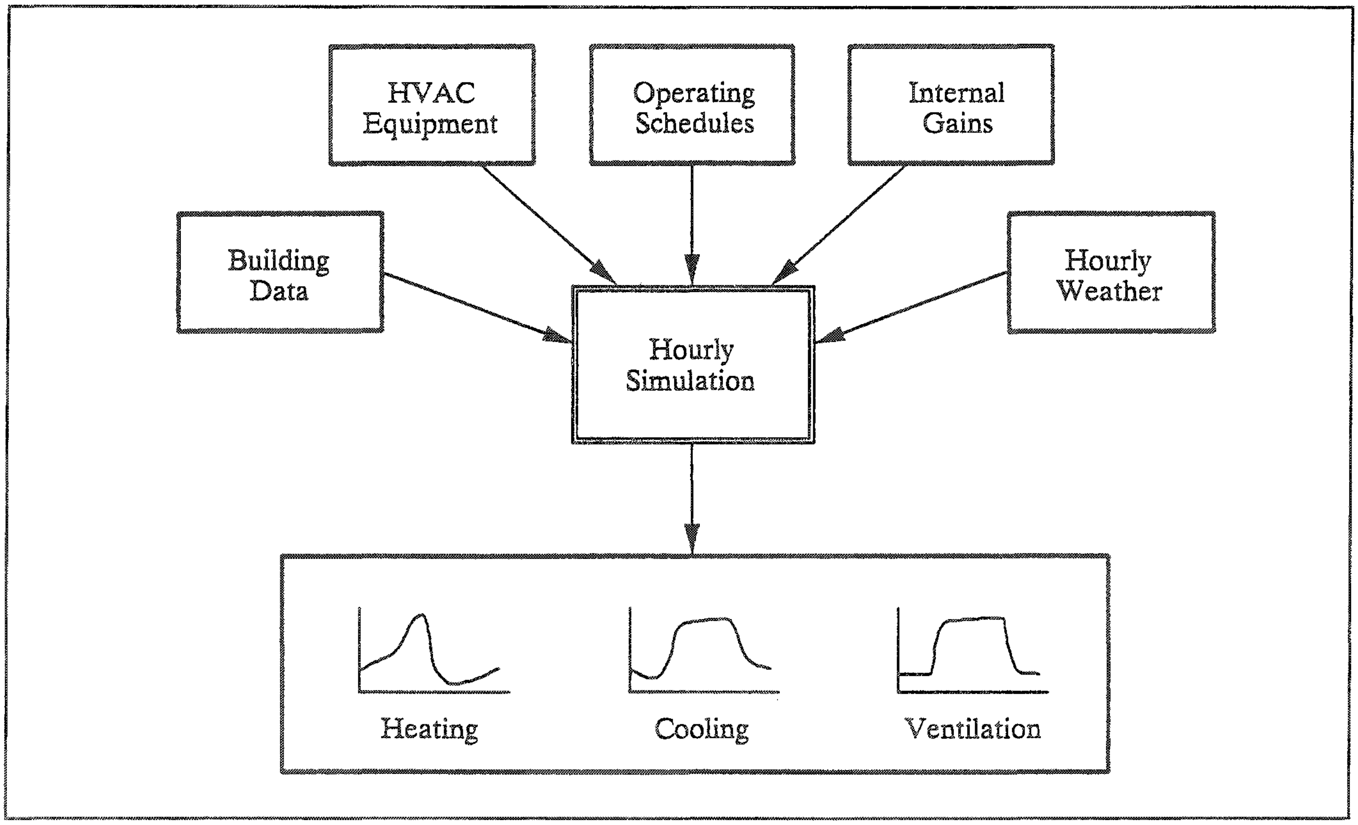


*Figure 3. Estimation of HVAC Loads*

where the unit is located impact energy consumption. Second, for remote compressors, lower outdoor temperatures imply lower energy consumption due to more favorable condensing conditions.

In these studies, refrigeration load profiles are based on observed shapes from end-use metering studies, and the hourly variation is related to occupancy profiles. The occupancy profile is converted to a refrigeration load profile by assuming that the peak energy consumption of the refrigerator is 20% higher than the smallest hourly energy consumption.

**Water Heating.** Water heating is the most complicated of the non-HVAC uses to model. Water heating loads are modeled as a combination of hot water uses and system losses. Uses are assumed to include personal hygiene, laundry, and sanitation related to food service. These are modeled as follows:

- Hot water consumption for personal hygiene is based on occupancy. The water usage profile is based on the occupancy profile.
- Consumption for laundry as based on the number of pounds of laundry washed per day, which is collected on the survey form. Water usage for laundry is distributed evenly over the operating hours of the building.
- Hot water consumption for food service is related to the number of meals served. Hot water use for food service follows the usage profile for cooking equipment with a one-hour delay to reflect the timing of clean-up efforts.

Energy consumption for water heating depends on hot water use, as well as the inlet temperature and the delivery temperature. Energy consumption further depends on system losses, which include tank losses and distribution system losses.

The water heating load profile is the sum of the energy consumption due to hot water uses and the energy consumption due to standby losses.

**Miscellaneous Electric Equipment.** Miscellaneous electric equipment, such as elevators and water pumps, is counted by equipment type and rated capacity. Load profiles are constructed by applying hourly percentages created by the surveyors to the rated capacity.

## Statistical Adjustment

The purpose of the statistical-adjustment step is to refine the engineering profiles developed for each building so that they more closely conform to the actual energy consumption and load profiles. The adjustment process has the following general steps.

1. Develop and review case summaries,
2. Process whole-building hourly loads and engineering estimates,
3. Adjust end-use profiles, and
4. Create a load shape database, and
5. Compress the data into 16-day and 48-day formats.

*Develop Case Summaries.* The survey database provides detailed equipment inventories and operating schedules for each building in the sample. This information is abstracted and condensed into a case summary. This makes it easy to evaluate the adjusted end-use shapes against the equipment inventory data and the operating patterns in the building.

*Process Whole-Building Profiles and Engineering Estimates.* For each customer in the sample, load research data provide hourly whole-building load shapes. In this step, these loads are plotted for visual inspection. Missing data and uncharacteristic data points are identified, marked and excluded from further analysis. These hourly plots reveal daily, weekly and seasonal electricity consumption patterns that provide important information about the presence of certain types of equipment, as well as their utilization.

In addition to the actual whole-building loads, the hourly engineering estimates are summed across end uses for each building. This gives an engineering estimate of the whole-building load. These two sets of hourly profiles are compared in plots such as shown in Figure 4.

For purposes of comparison, both sets of hourly data are condensed into a summer/winter, weekday/weekend format. The sum of the end-use estimates, together with the actual whole-building profiles, is presented in Figure 5. This figure provides a comparison that illustrates the objective of the statistical adjustment process: the engineering estimates must be adjusted to agree more closely with actual whole-building totals.

*Adjustment of End-Use Profiles.* The purpose of this step is to use information available from the whole-building load shapes, the survey database, and the engineering shapes to develop a set of end-use profiles that agrees closely with the whole-building control totals. The adjustment procedure is implemented at the 8,760-hour level. It is described below as a three-step process. These steps are

1. Modify estimated HVAC loads for each building to account for weather sensitivity in the whole-building loads,
2. Statistically adjust non-weather sensitive loads for each building, and
3. Adjust weekend end-use loads for each building.

Modify Preliminary Heating, Cooling and Ventilation Estimates. The purpose of this step is to adjust the engineering estimates of HVAC loads to more closely match actual conditions by

- Modifying the operating hours of the HVAC equipment, and
- Adjusting the magnitude of the estimates when the whole-building loads indicate smaller or larger loads than the engineering analysis.

To do this, alternative estimates of weekday cooling, heating and ventilation loads are developed. The estimates are based on regression analysis of whole-building loads and outside temperature. A separate equation is estimated for each hour to account for differences in the use of HVAC equipment over the course of a day. The equation takes one of three forms:

- Parabolic, which provides a good description of consumption patterns for customers with electric space heating. For these customers, consumption increases as the ambient temperature rises above or falls below some threshold temperature.
- Linear with a positive slope, which provides a good description of consumption patterns for customers without electric space heating.
- Linear with no slope, for buildings whose loads are uncorrelated with outside temperature.

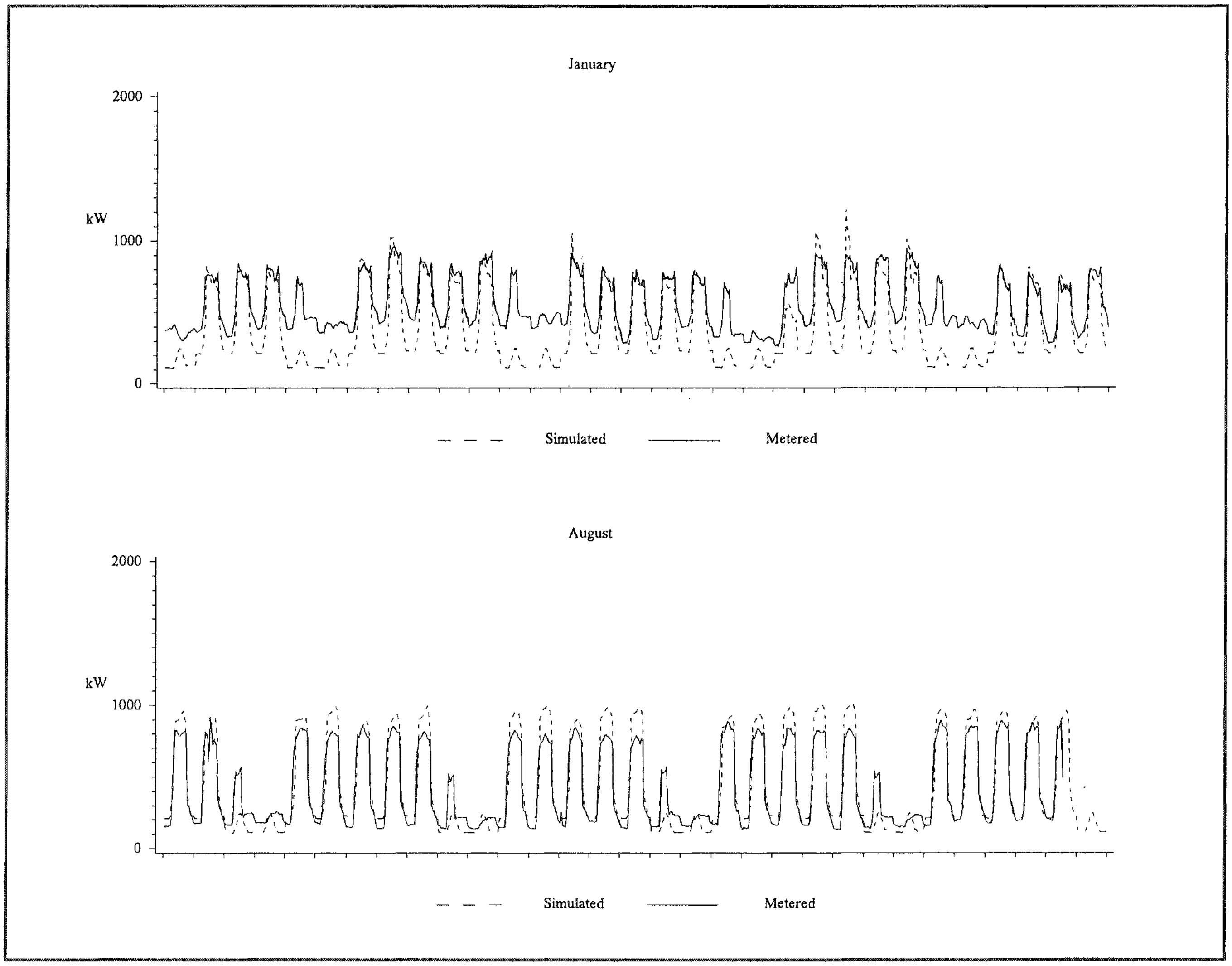


*Figure 4. Comparison of Load Research Control Totals and Preliminary Engineering Estimates*

For weekdays and for weekends, the regression results are plotted separately for each hour of the day. Figure 6 shows a plot of building load versus temperature for selected weekday hours. The vertical axis measures hourly energy use in Watts per square foot, while the horizontal axis measures temperature.

The regression results are then used to develop weather-sensitive and non-weather sensitive load profiles for each day of the year for each building. This approach was suggested by recent work by Akbari, et al. (1988). These plots reveal large weather-sensitive loads on hot summer days. In addition, cold winter days have large weather-sensitive loads during morning hours, a pattern characteristic of heating loads.

*Cooling Load Adjustment.* The process of adjusting cooling loads involves four steps.

- Separating the simulated loads into temperature-sensitive and non-temperature sensitive components.
- Calibrating the temperature-sensitive portion of the simulated cooling load to the weather-sensitive portion of the whole-building load.
- Statistically adjusting the non-temperature sensitive portion of the simulated cooling load.
- Reassembling the total cooling load from its constituent parts.

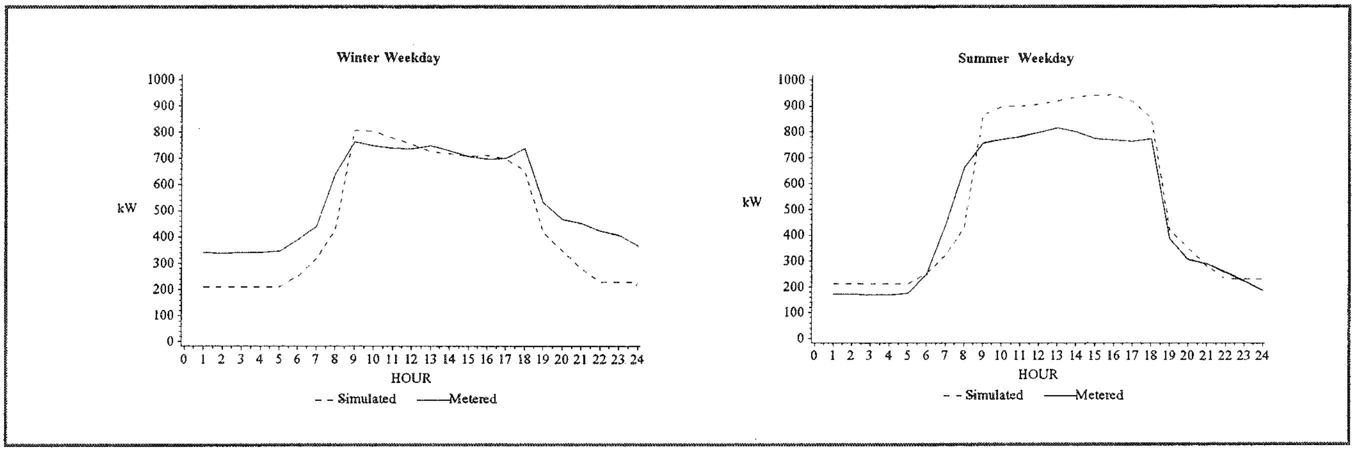


*Figure 5. Weekday Comparison of Load Research Control Totals and Preliminary Engineering Estimates*

Simulated cooling loads frequently have a component that is independent of temperature. In many buildings, internal heat gains from people, equipment and solar radiation exceed heat losses to outside air even on very cold days. In these cases, a cooling load that is not weather sensitive is present. This is illustrated in Figure 7 which is a collection of hourly plots of the simulated cooling load and outside temperature. The presence of a simulated cooling load on the coldest days indicates a component of cooling unrelated to weather.

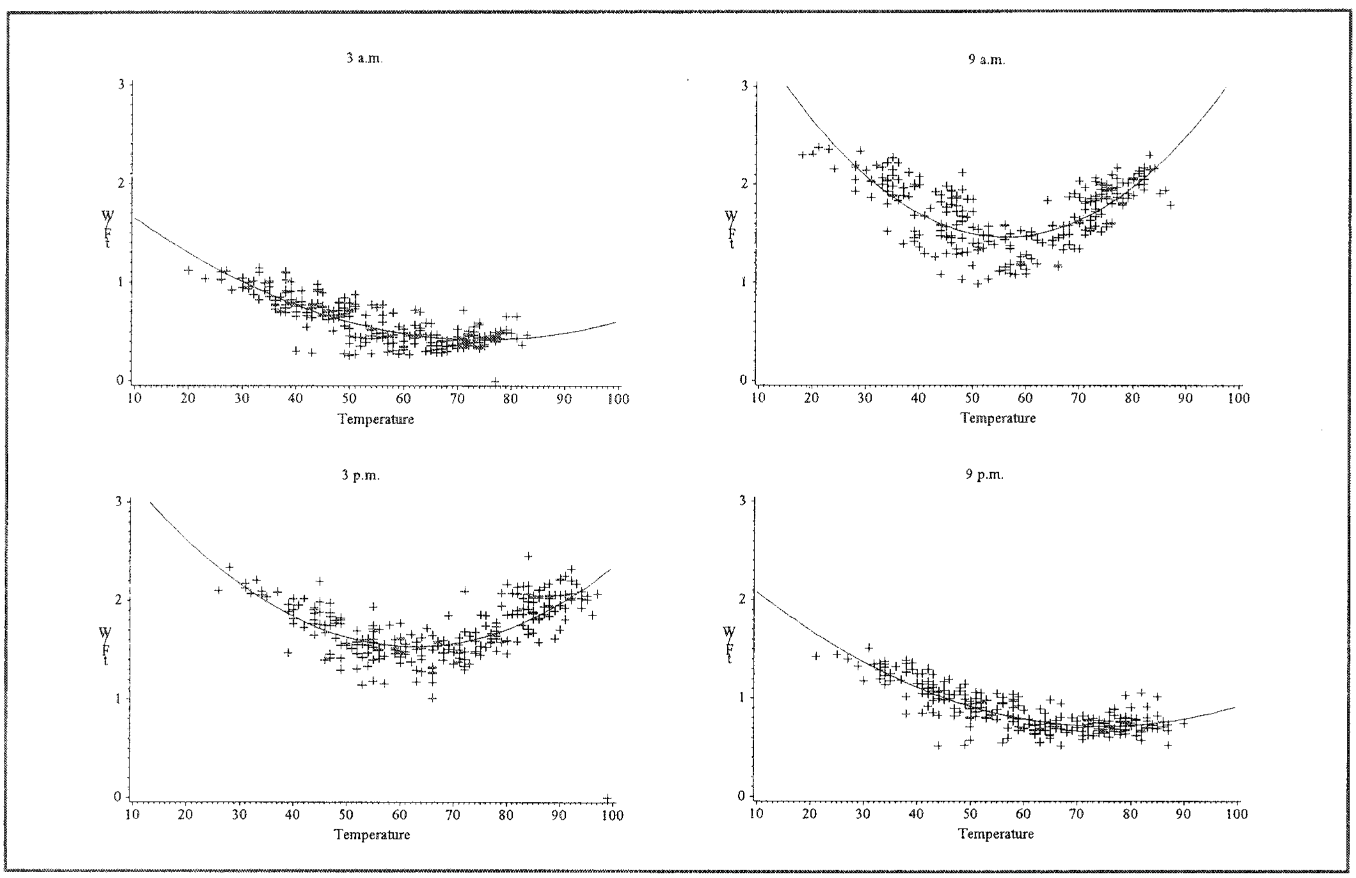


*Figure 6. Hourly Energy Consumption vs. Hourly Dry-Bulb Temperature*

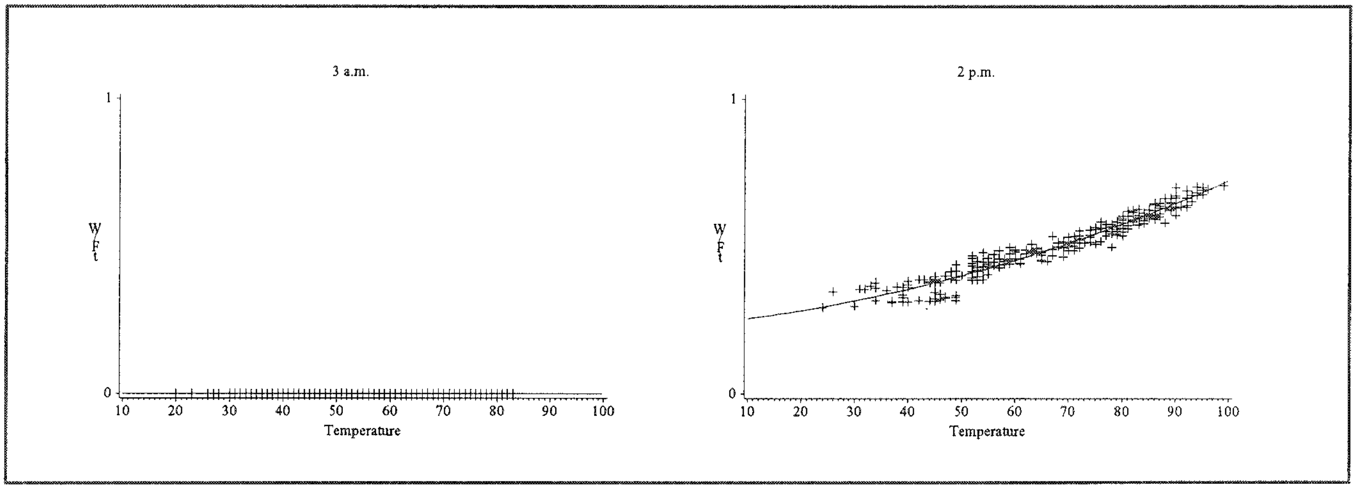


*Figure 7. Hourly Simulated Cooling vs Outside Dry-Bulb Temperature*

There are two reasons to adjust the cooling load to account for the weather sensitivity of the whole-building load. The first involves the timing of HVAC equipment operation and the second involves the magnitude of the HVAC loads. Regarding this first point, the whole-building loads may suggest the presence of cooling loads during hours when the simulation model yields none. This occurs because buildings often operate during hours when the building is officially "closed". During these periods, cooling equipment are frequently operating. The second reason to adjust the cooling load is that engineering simulations sometimes underestimate or overestimate the sensitivity of load to temperature.

In the adjustment process, the weather-sensitive portion of the cooling load is adjusted so that the temperature-load relationship matches that of the whole building. The non-weather sensitive portion of the load is identified and subsequently added to the weather-sensitive portion of the cooling load.

*Heating Load Adjustment.* Adjusted heating loads are constructed using a method similar to that used for adjusting cooling loads. Heating loads can be estimated from whole-building data by taking the difference between the minimum point on the load-temperature curve and the load on days colder than the temperature at which that minimum occurs.

Frequently, simulated heating loads either do not reflect the true operation schedule of the equipment or they underestimate or overestimate the temperature-load relationship. As part of the reconciliation process, the temperature-heating load relationship is adjusted so that it matches the relationship between temperature and the whole-building load during hours when the temperature falls below some heating threshold temperature.

*Ventilation Load Adjustment.* Ventilation load profiles are adjusted only when they are inconsistent with the whole-building load profile. In these cases, a profile that reflects the activity of heating and cooling equipment is constructed and applied to the ventilation load that result from the engineering analysis. Ventilation loads are then statistically adjusted with the non-HVAC end use loads.

**Statistical Adjustment of Weekday Non-Weather Sensitive Loads.** In this step, the non-weather sensitive loads developed in the engineering analysis and in the decomposition of the HVAC loads are adjusted. Regression analysis is used to estimate hourly and seasonal adjustment parameters. These parameters can be estimated for individual end uses or for end-use groups. In the simplest case, a single set of parameters is estimated as shown below:

$$(L_{d,h} - \sum_{e} \hat{L}_{d,h,e} = (b_h + \sum_{s} c_s B_s) \; \begin{matrix} x \\ x \end{matrix}$$

$$\left(\sum_{e} w_{h,e} \hat{L}_{d,h,e}\right) + u_{d,h}$$

where $L_{d,h}$ = Metered whole-building load in day d, hour h,

$\hat{L}_{d,h,e}$ = Simulated load for end use e in day d, hour h,

$B_s$ = Binary variable for season s,

$w_{h,e}$ = Adjustment weight for end use e, hour h,

$b_h$ = Hourly adjustment parameters, and

$c_s$ = Season adjustment parameters.

Unlike hourly calibration algorithms, this statistical-adjustment procedure does not guarantee a perfect fit. Calibration algorithms force a perfect fit, which often causing anomalies in the end-use load shapes. The statistical-adjustment procedure used here provides plausible results that are consistent with equipment inventories and metered whole-building data.

**Review Adjusted Shapes.** An example of the final end-use load shapes is presented in Figure 8. A set of graphs showing the end-use composition of whole-building loads for selected daytypes is presented in Figure 9.

The result of this process is presented in the before and after graphs in Figure 10. The solid line represents the actual whole-building control totals. The dashed line shows the results of the end-use load shape adjustment algorithm.

*Develop Load-Shape Database.* In this step, the adjusted end-use shapes for each case are organized into a load-shape database. There is one data file for each customer.

Each of these cases has an expansion weight. Individual cases in the sample can be expanded to give population estimates for various segments. Examples are end-use load shapes by building type and rate class.

*Compress Data into Presentation Format.* The final end-use databases contains 8,760 observations for ten end uses. For obvious reasons, a compressed data presentation format is necessary. A variety of load-shape formats are used, ranging from "two-day" formats to "48-day" formats. The 16-day format consists of four daytypes for each season of the year. These daytypes are (1) a typical weekday, (2) a typical weekend day, (3) a cold weekday, and (4) a hot weekday.

Each day of the year is assigned to one of these daytypes on the basis of the following criteria:

- Based on a review of weather patterns, seasons are defined.
- The calendar is used to identify weekend days in each season.
- Weather data are analyzed to define hot, typical and cold weekdays. In each season, about 20% of the days with the highest temperature are defined as hot days. About 20% of the days with the lowest average temperature are defined as cold days. The remaining days are defined as typical.

Based on this daytype mapping, a profile for each daytype is constructed by averaging the loads in each hour across days. This is the format depicted in Figures 8 and 9.

## Conclusion

The end-use disaggregation approach described above offers an economical approach for developing reasonable end-use load shapes for individual customers in the commercial sector. This approach works well for the following reasons:

- Analysis is performed on a case-by-case basis, with data review at beginning, middle and end of the analysis process. Reasonable results for individual cases insure reasonable results at aggregate levels.
- Preliminary load shapes are developed for each end use, not just for HVAC. Each end use is modeled using equipment inventory data and operating schedules that are relevant to that end use and that are consistent with observable facts at the site.
- The auditors are provided data on monthly bills and typical-day load shapes for each site. This provides valuable background in determining equipment operation levels and schedules.
- Preliminary end-use profiles are statistically adjusted rather than calibrated. While it does not insure a perfect fit, it does prevent anomalous results for individual end uses on specific days or daytypes.

In future research efforts, this approach will be applied to sites for which end-use metered data are available. These data will be used to refine the engineering equations and to validate the procedure.

## Acknowledgments

This paper is based on the method used and the results from load-shape development efforts at Florida Power & Light, and Potomac Electric Power Company.

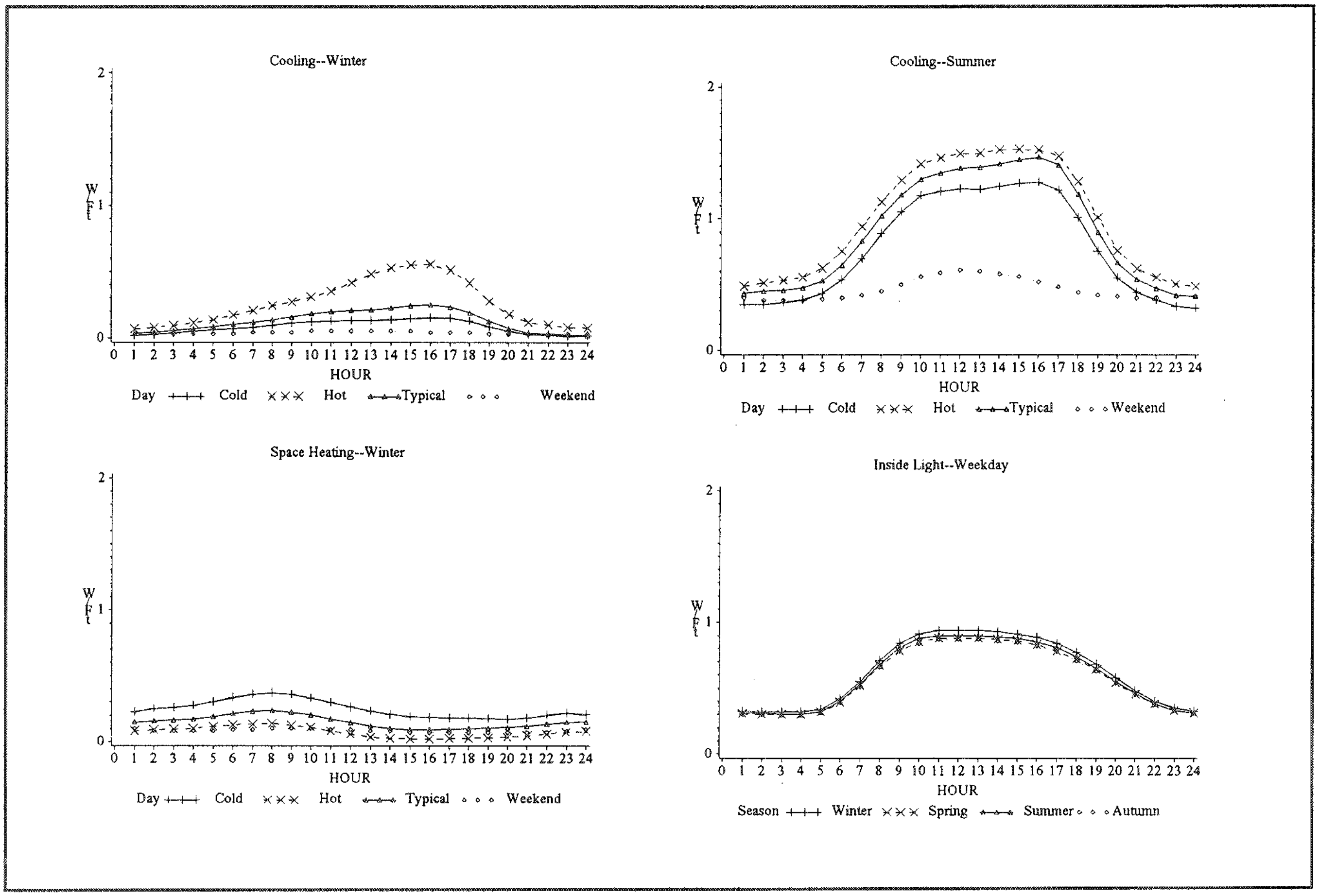


*Figure 8. Adjusted End-Use Shapes for an Office Building*

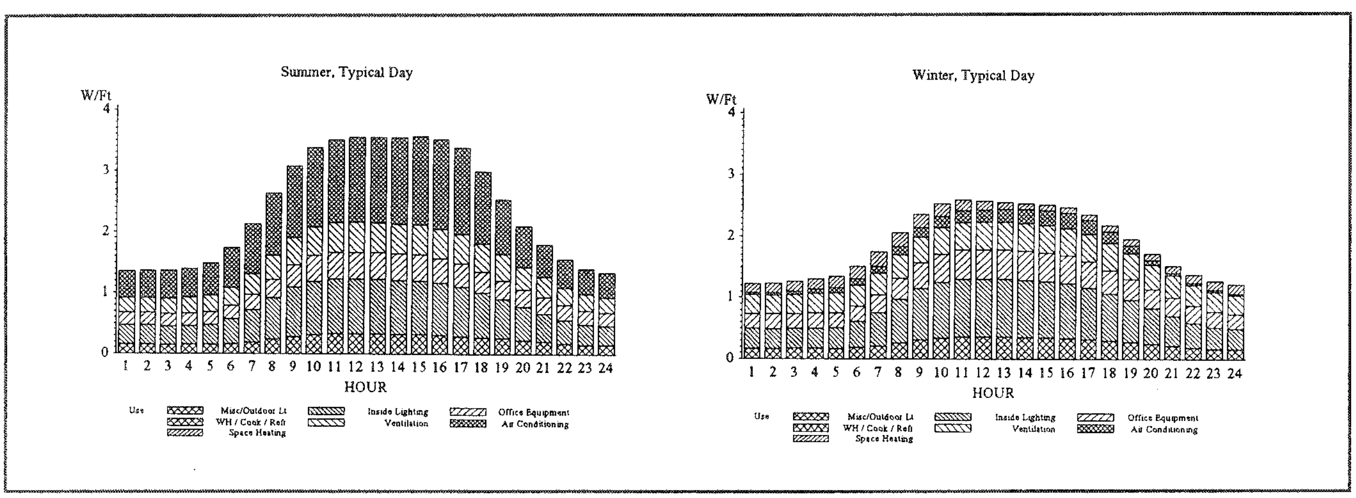


*Figure 9. End-Use Composition of Loads for an Office Building*

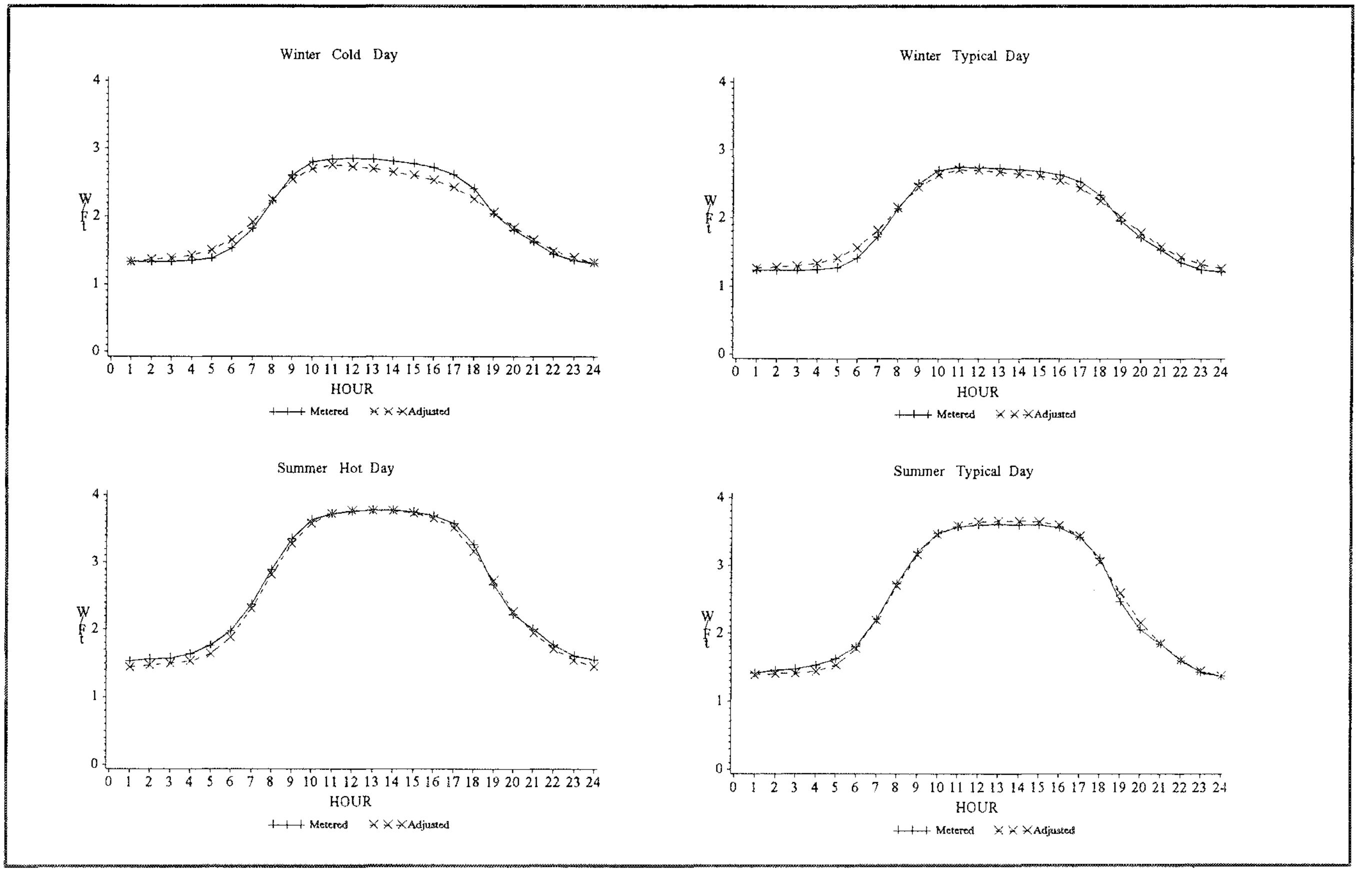


*Figure 10. Comparison of Total Adjusted Loads and Metered Whole-Building Control Totals for an Office Building*

## References

Akbari, H., K.E. Heinemeier, P. LeConiac, and D.L. Flora. 1988. "An Algorithm to Disaggregate Commercial Whole-Building Hourly Electrical Load into End Uses." Performance Measurement and Analysis - Proceedings from the ACEEE 1988 Summer Study on Energy Efficiency in Buildings, Volume 10, pp. 10.14-10.26. American Council for an Energy-Efficient Economy, Washington, D.C.

Akbari, H., J. Eto, I. Turiel, K.E. Heinemeier, B. Lebot, B. Nordman, and L. Rainer, 1989. "Integrated Estimation of Commercial Sector End-Use Load Shapes and Energy Intensities." LBL-27512, Lawrence Berkeley Laboratory, Berkeley, CA.

ADM Associates, Hourly Building Energy Analysis Program, User's Manual, 1990. Sacramento, CA.

ADM Associates, Hourly Building Energy Analysis Program, Reference Manual, 1990. Sacramento, CA.