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Investigation of Metered Data Analysis Methods for Commercial and Related Buildings

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EXECUTIVE SUMMARY

This study presents a review and evaluation of techniques for analyzing metered energy use data to determine baseline energy use and potential energy efficiency improvements in commercial and related buildings. A description of new methods that should be considered in such work is also presented. This work was performed for the Existing Buildings Efficiency Research (EBER) program of the Department of Energy.

The EBER program is particularly interested in advancing methods for measuring and analyzing the performance of energy efficiency improvements. For commercial and related buildings, however, the diversity of potential improvements, the diversity of these buildings in general, and the high rate of change in use cause difficulty in evaluation of energy performance for baseline conditions and for potential improvements. This study examines current analysis approaches and makes recommendations for improvements to those approaches.

Although there may be no concern for how one building compares with another during the time of a study or energy management program, there will be significant benefits if a ``history'' of different buildings is recorded for energy practitioners as a reference on expected energy use or energy use patterns. Presently, this knowledge has gaps and is not easily transferable, because it is usually based on several years of experience concerning expected patterns of energy use for different buildings and on impacts of schedules, uses, geographic location, and system configurations.

Existing data on buildings indicate significant variations in energy intensity (energy use per square foot per year) for buildings of the same type and in amount saved in different facilities. The variation in energy use is a cause of concern because attempting to understand the variations between buildings is a formidable task. More needs to be learned about how to explain observed variations and how to transfer increased buildings knowledge more effectively.

The approach used for this study was to review existing methods employed for analyzing metered energy use in buildings, to meet with other researchers about the types of analysis work they are pursuing, and to study possible development of improvements to existing techniques. A literature review identified over 40 sources (see Bibliography), which covered analysis of all building energy performance that appeared to have import for analysis of data for these buildings. Based on the review of existing methods and discussions with other researchers, ideas for enhancing analysis methods were developed. These ideas are presented in this report, with suggestions for further field study of their use.

A survey of the published literature dealing with the analysis of metered energy use of buildings indicated that several diverse methods are used for analyzing metered energy data. Five general categories were developed to group the metered data analysis methods:

1. Annual total energy and energy intensity comparison

2. Linear regression and component models

3. Multiple linear regression models

4. Building simulation programs

5. Dynamic thermal performance models

Overall, the methods reviewed in the literature indicate that many analysis approaches for metered data of commercial and related buildings are still exploratory. Reasonable results are possible for some buildings using simple measures such as total energy, but the uncertainty of weather variations is still present. Weather adjustments for heating energy use may be possible, but adjustments for cooling are less certain.

The inclusion of specific characteristics of the building and of the activities in the building in a multiple parameter analysis of energy use is an important improvement to analysis methods. Multiple parameter models that analyze effects of occupancy, schedule, special events, and other inputs in addition to weather factors represent an important step forward.

Significant improvements to analysis of metered data for commercial buildings are being tested, and further improvements are needed. These improvements should include continued development of the multiple parameter methods, development of methods for analyzing more detailed (submetered) data (e.g., power signatures), use of macrodynamic methods to generate models with physical significance, and simplification of the methods.

The diversity of methods leads us to conclude that some effort should be made to develop a classification structure to define analysis approaches. Use of this standard structure should be promoted for reporting analyses of commercial building metered data.

In addition to improving the classification and reporting of analysis methods, analysis efforts should be extended to focus on characterizing building types (by appropriate parameters) and the technologies or approaches commonly used to improve efficiency in particular building types. Such an effort is needed to standardize terminology of the types of buildings that are being modified and the nature of the efficiency improvements being made. Improved communication is needed to better explain observed variations between buildings and to more effectively transfer increased knowledge about buildings to more people.

Advanced research on the characterization extension effort should be directed at developing relationships between building characteristics and building power signatures. Development of correlations between these two sets of data offers the opportunity to define better models of building energy patterns by identifying and incorporating important causes of variation in power and energy use.

The recommendations discussed above have implications that extend beyond the framework of energy efficiency improvements, because ultimately the energy performance of buildings must be considered over time. The most important implications are that an improved institutional-type of memory concerning the types of technologies, operations changes, and performance tracking methods that lead to long-term building energy performance improvements could evolve. Therby, a more empirical basis for implementing equitable and usable energy performance standards for existing buildings could be developed.

The first extension is expected to occur as a result of communicating the improved methods to practitioners so there is more commonality in how the energy performance issue is approached. For building energy performance standards, the issue is one of determining how a building is configured and used and how much performance improvement is reasonable at a given time. If any standard is to succeed, the development of a common approach for defining and understanding building performance, the ability to identify key characteristics that affect the levels of service offered by a building, and the ability to suggest potential performance improvement targets and to negotiate with owners, operators, or lessees in approaching these targets are all important. The analysis approaches discussed in this report offer the potential for achieving some of these abilities. The opportunities are there for a research program to examine and implement.

Investigation of Metered Data Analysis Methods for Commercial and Related Buildings

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ABSTRACT

This study presents a review and evaluation of techniques for analyzing metered energy use data to determine baseline energy use and potential energy efficiency improvements in commercial and related buildings. A description of new methods that should be considered in such work is also presented. Development of relationships between energy characteristics and building physical characteristics is seen as an important area for improvement of analysis methods. Knowledge of the causes of variations in energy use and the expected relative impacts of different schedules, functional uses, and energy systems should be upgraded to allow adequate understanding of efficiency changes and better exchanges of efficiency improvement results. Significant advancements in analysis approaches for metered data from commercial buildings are being tested, and further improvements are needed. The improvements should include continued develop¬ment of multiple parameter methods, development of methods for analyzing more detailed data, use of macrodynamic methods to generate models with physical significance, and simplification of the methods. The recommendations of this study are to begin research on advanced analysis methods, to develop a coordinated research program on analysis methods, to develop a classification method to define analysis approaches and promote the use of the method for reporting energy analyses, to extend analyses of energy efficiency improvements to characterize building types, and to classify packages of common efficiency improvement technologies or approaches appropriate to the different building types.

1. INTRODUCTION

This study presents a review and evaluation of techniques for analyzing metered energy use data to determine baseline energy use and potential energy efficiency improvements in commercial and related buildings. A description of new methods that should be considered in such work is also presented. This work was performed for the Existing Buildings Efficiency Research (EBER) program of the Department of Energy (DOE). EBER focuses on assisting public and private sector efforts to improve the energy efficiency of existing buildings. The evaluation of efficiency improvements is a primary interest of the study.

The approaches used for evaluating energy efficiency improvements in buildings depend on several factors, including the:

! Purpose for conducting the analysis

! Level of detail of the metered data available

! Diversity of the buildings and systems covered

The purpose for conducting an analysis affects the methods and approach used. Therefore, it is important to recognize the differences that arise in results and analysis approaches when the purpose changes. Readers of this document should keep in mind that the approaches described here are shaped by the energy efficiency improvement evaluation focus—both for evaluating specific energy efficiency measures or groups of measures and for tracking energy use as part of an energy management program.

1.1 PURPOSE

The EBER program is particularly interested in advancment of methods used for measuring and analyzing the performance of energy efficiency improvements. For commercial and related buildings, however, the diversity of potential improvements, the diversity of these buildings in general, and the high rate of change in use cause difficulty in evaluation of energy performance for baseline conditions and for potential improvements. The evaluation of a single building can often be accomplished if adequate records are maintained, but comparisons between buildings often are not possible. The improvement of ability to compare buildings, as well as to analyze individual buildings, is viewed as an appropriate federal role. Current analysis approaches are examined in this study and recommendations for improvements to those approaches are made.

1.2 BACKGROUND

Although there may be no concern for how the efficiency of one building compares with that of another during the time of a study or energy management program, there will be significant benefits if a ``history'' of different buildings is recorded for energy practitioners as a reference on expected energy use or energy use patterns. Presently, practitioners develop their own sense of what constitutes an energy efficient building based on experience with similar buildings, the types of activities within specific buildings, and any history of achieving reductions in energy use in comparable buildings. Presently, this knowledge has gaps and is not easily transferable, because it is usually based on several years of experience concerning expected patterns of energy use for different buildings and impacts of schedules, uses, geographic location, and system configurations.

Existing data on buildings indicate significant variations in energy intensity (energy use per square foot per year) for buildings of the same type (e.g., hospital, office, school) (Gardiner et al, 1984). In addition, the performance of energy improvements has been documented to the extent of showing that energy savings are being achieved in (over 90% of) buildings that made improvements, but there are significant variations in how much is saved in different facilities (Gardiner et al, 1984). The variation in energy use is a cause of concern because attempting to understand the variations between buildings is a formidable task. Some sentiment exists for stopping ``further broad scale analyses of building energy consumption [for buildings], [because] this activity has probably passed the point of diminishing returns, with no further fundamental lessons to be learned....'' (Wulfinghoff, 1984). However, fundamental improvements are still possible, and more needs to be learned about how to explain observed variations and how to transfer increased knowledge of buildings more effectively.

The ability to compare the energy performance of one building with that of another is important from a national energy efficiency perspective because comparison allows more meaningful evaluation of potential relative improvements. It also may allow different classes of buildings to be analyzed together (e.g., offices and hospitals). The need for comparison is illustrated by the potential problems that can develop when differences between buildings of the same type are not considered. Figure 1 shows data from a study on schools in Mississippi. Energy use intensities (EUIs, $Btu/ft^2/yr$) are reported. The spread in energy performance is pronounced, but no information was provided on whether the schools were high schools, elementary schools, or other type. If some of the schools are operated 9 months while others are operated 12 months out of the year, the overall energy use is impacted. Some schools might have swimming pools that increase energy use. Many potential causes for differences might be found, but the point is that a method for comparison is needed.

Development of relationships between energy characteristics and building physical characteristics is presented as an important area for improving comparison methods for commercial and related buildings. Knowledge of the causes of variations in energy use and the expected relative impacts of different schedules, functional uses, and energy systems should be upgraded to allow adequate understanding of efficiency changes and better exchanges of efficiency improvement results.

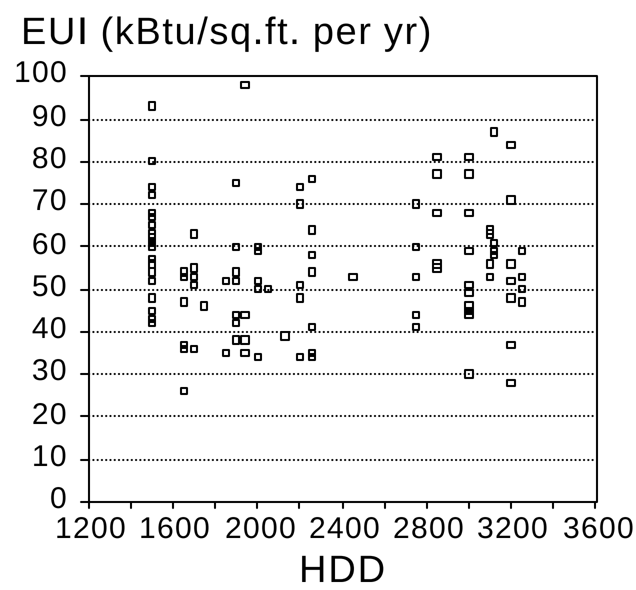

Figure 1– Range of EUIs for schools in Mississippi. Source: Hodge et al, 1986.

Each mark represents the EUI for a school. Please note that the spread is of most interest. No information was available on characteristics that might influence the spread.

1.3 APPROACH

The approach for this study was to review existing methods employed for analyzing metered energy use in buildings, to meet with other researchers about the types of analysis work they are pursuing, and to study possible development of improvements to existing techniques. A literature review identified over 40 sources (see Bibliography), which covered analysis of all building energy performance that appeared to have import for analysis of data for these buildings. Several diverse analysis methods were identified from these sources, and a general categorization scheme was developed for describing the different approaches.

After the literature review was completed, several nationally recognized building research organizations were visited: Princeton University, the Solar Energy Research Institute, Lawrence Berkeley Laboratory, and Pacific Northwest Laboratory. At each of these institutions, the data analysis method categorization scheme was discussed, with ideas for new methods of data analysis and review of what work the other institutions were performing.

Based on the review of existing methods, discussions with other researchers, and original work for this study, recommendations on analysis methods were developed. The literature review, a distillation of the field discussions, the original work on new methods, a discussion of existing methods, and recommendations are presented in this report.

1.4 ORGANIZATION OF THIS REPORT

The review of existing methods for data analysis and discussions with other researchers are presented in Sect. 2. The discussion of existing methods and the original work on new methods for individual buildings is contained in Sect. 3. A discussion of issues related to comparative analyses of buildings—comparisons between buildings—is covered in Sect. 4. The recommendations of this study are presented in Sect. 5, with a discussion of possible extended impacts of improved data analysis methods.

2. REVIEW OF ANALYSIS METHODS

2.1 REVIEW OF METHODS IN PUBLISHED LITERATURE

A survey of the published literature dealing with the analysis of building metered energy use was performed. The emphasis of the survey was on methods that would be useful to consider for analyzing metered energy use data from commercial and related buildings (with institutional buildings considered as part of the commercial sector). Methods used to analyze residential energy use data were also examined for applicability to the buildings of interest for this study. From the sources reviewed, 45 reports of interest to this survey were identified in the literature—40 dealt with commercial/institutional buildings and 5 with residential. There were three principal sources for these reports: the ACEEE 1982, 1984, and 1986 conferences, *ASHRAE Transactions* for the years 1982 to 1986, and the ASHRAE/DOE conferences held in 1979, 1982, and 1984 on the thermal performance of the exterior envelopes of buildings.

Several diverse methods of interest for analyzing metered energy data were found. This diversity reflects the nature of the building stock as well as the varying levels of detail of metered energy use data that analysts had at their disposal. Also affecting the choice of analysis method was the purpose the investigator had for analyzing the metered energy use data. Some of the purposes cited for analyzing metered data were to:

- Support conservation program planning
- Support utility load forecasting
- Pinpoint energy inefficiency in buildings
- Rank energy efficiency improvements
- Determine energy and dollar savings from a retrofit
- Compare energy usage of disparate buildings
- Determine if energy performance meets design goals
- Support energy management of buildings
- Help building designers build more energy efficient buildings
- Validate and/or calibrate computer simulations of building energy performance
- Support implementation of shared savings retrofit programs

Five general categories were developed to define the metered data analysis methods found in the literature. These categories are:

1. Annual total energy and energy intensity comparison
2. Linear regression and component models
3. Multiple regression models
4. Building simulation programs
5. Dynamic thermal performance models

Each of these methods will be discussed below.

2.1.1 Annual Total Energy and Energy Intensity Comparisons

A simple and straightforward way of quantifying and comparing building energy use is by the annual total energy and energy intensity data. Annual total energy is the sum of the energy content of all fuel used by the building in one year. Energy intensity is defined as the total energy used divided by the total floor area. It would also be possible to examine annual energy or energy intensities for individual fuels. Several studies used the value of annual total energy before and after energy efficiency improvements were made to evaluate the savings (Blumstein, 1984; Katrakis and Becker, 1984; Ross and Whalen, 1982; Schultz, 1984). Other studies used energy intensities to compare energy usage in different buildings or in the same building before and after efficiency improvements were made (Cleary and Schuldt, 1986; Gardiner et al, 1984, 1985; Piette, 1986; Wall and Flaherty, 1984). In none of these studies was there an attempt to normalize for weather, occupancy, schedules, or building usage. The implicit assumption is made that these things either remained constant, did not greatly affect the energy usage of the building, or could not be quantified for the analysis that was performed. Depending on the building, these assumptions may or may not be true and add uncertainty to the results. Where multiple climates are involved, the climatic variation is mixed with the other sources of variation.

One author proposes the use of generic, efficiently operated buildings to provide a base energy use (Hodge et al, 1986). Other buildings in similar climates and with similar patterns of use and thermal characteristics could then be compared to the base case (norm). Deviations of total energy usage from the expected norm can then be examined. The data in Fig. 1 are from this paper, and the assumption in this method is that all school buildings can be considered equal when comparing energy use. The lower end of the data is considered to be the ``efficient'' norm, but without specific information on building schedules and the types of facilities involved, some serious discrepancies could arise regarding expected performance relative to this norm. As an example, building size is a known cause of variation, with buildings smaller than 10,000 sq ft using more energy per square foot than buildings in larger size classes (EIA, 1986). A more appropriate approach appears to be to collect data on an initial sample of buildings, check variations and potential causes of the variations, and then collect more data to increase understanding of the variations.

The strength of the total energy and energy intensity comparisons is their ease of use and widespread familiarity. However, knowledge is lacking regarding causes of variation and the relative impacts of factors such as schedules, functional uses, and systems types on the individual building consumption. This general approach to data analysis is of interest for quick comparison of one building's energy use from one year to another or quick comparisons of many buildings, but it does not provide information as to what is causing the variation from year to year or building to building (Fig. 1).

2.1.2 Simple Linear Regression and Component Models

Simple linear regression has been used with reasonable success to model residential heating fuel use (Chang and Grot, 1984; Fels, 1986; Anderlind et al, 1986). For a treatise on some of the complexities of this approach, a Princeton report provides useful background (Goldberg, 1982). Fuel use is modeled as a base consumption component plus a consumption component that is linearly proportional to either ambient temperature (above a reference or balance point temperature) or heating degree days (HDD, proportional to temperature difference). Several authors have examined the application of these models to commercial/institutional buildings (Cowan and Jarvis, 1984; Duerr and Cornwall, 1986; Eto, 1985; Fels, 1986; Palmiter and Hanford, 1986; Rabl et al, 1986; Stiles et al, 1984). Commercial and related buildings, in general, have higher internal heat generation than residential buildings, and the outdoor temperature often has less effect on building energy use than building schedules and use patterns (Reiter, 1986). It is not surprising that mixed success at applying linear HDD models to these buildings was reported in the literature. For buildings that have high correlations between energy use and ambient temperature, energy use can be modeled with these techniques. Some of this effect may be related to a heating dominated climate, such as found in the northern tier of the United States.

School buildings, including university buildings, can usually be modeled with this method. Some other buildings analyzed showed either non-linear or no correlation between energy use and ambient temperature. Clearly, normalizing energy usage of these buildings will have to consider more than the weather.

``Component analysis'' is directed toward understanding patterns (signatures) of energy use available in monthly data and toward determining breakdowns (e.g., heating, cooling, other) of energy use by type of building systems (Cowan and Jarvis, 1984). Time dependence of energy use is often factored in this analysis approach to gain a better understanding of how loads change with the seasons and also to understand loads that are not sensitive to temperature. While linear regression can be used to develop the breakdown of components, other methods can also be used. The presence of multiple fuel types in use in a building can aid in developing component breakdowns; the shape of curves for different fuels can indicate the degree of temperature dependence. Analysis of consumption for different components is typically an important part of understanding building energy performance. Simple linear regression methods for determining component breakdowns have been used for commercial buildings, but more needs to be learned. Overall, the concepts used in component models must be considered when analyzing commercial energy use.

The strength of simple linear regression and component methods is in their simplicity. The methods are based on knowledge accumulated from experience with thousands of buildings over many years. Adequate data usually can be readily obtained to characterize energy use for buildings that have significant heating energy use compared to total energy use. However, in buildings where heating is not the dominant energy use, some analysis difficulties can be expected. Since other energy uses in buildings may dominate or mask heating and/or cooling energy use, some extensions to this method will be needed for analyzing metered energy use for these buildings.

2.1.3 Multiple Regression Models

Some investigators have used multiple regression techniques to account for other factors (besides ambient temperature) that influence building energy use. In one study, the energy use of 50 commercial (institutional) buildings in Michigan was analyzed statistically to identify major contributors to energy consumption variation. An energy predicting model was produced which could account for 93% of energy consumption variations using ten factors (Boonyatikarn, 1982). Another study correlated monthly energy use on a military base with several factors, including HDD, production levels, and labor force levels (Leslie et al, 1986). A third study used multiple regression to model energy use in restaurants (Mazzucchi, 1986). The regression analyses examined the relationship of specific end uses to temperatures and customer count. In another study, energy use measurements in a recreation center were compared to daily energy use predicted by a multiple regression model (based on previous energy use in that building). When measured energy use deviated beyond a certain level from predicted energy use, an expert system diagnosed possible causes of the deviation by comparing conditions in the building to those of previous events (Haberl and Claridge, 1987). In another study a six-parameter regression model (where all parameters are weather-based) for analyzing residential energy use was also proposed (Fowlkes, 1985). It appears that multiple regression may show promise in modeling and comparing the diverse stock of commercial buildings in this country.

An important observation from the studies that were reviewed is that the success of a multiple regression may depend significantly on the usefulness of the variables chosen. For instance, in the Michigan study (Boonyatikarn, 1982) the variables used were novel because of their diversity. Several of the variables used in that study were dummy variables that had values of '1' or '0' to explain whether particular systems or fuels were used in the building. Other variables included the product of the volumetric flow of exhaust air and the percentage of time the exhaust fans were used, the volumetric flow of supply air divided by the power required for the fans, and the average levels of shading (on a scale of 1–5) on the sides of the building in the winter and summer. These variables were selected to model the types of buildings included in that study, and they included some that normally might not be considered. The indications are that multiple regression may provide some significant insights on building energy use.

The strength of the multiple regression modeling approach is the potential it offers to achieve reasonable confidence for predicting energy use for groups of buildings. One area of concern is the determination of which variables should be used to develop the energy use prediction model and how can intercorrelations between independent variables be removed. Another concern is the relative complexity of setting up the model vs the improved usefulness of the results.

2.1.4 Building Simulation Programs

Building simulation programs (referred to as microdynamic modeling by Burch, 1986) are another common way that metered data were analyzed. In some cases the energy usage of a building was modeled in the building design phase. After the building was completed, actual energy usage was compared with the simulated use to evaluate energy performance (Frey et al, 1983; Richtmyer et al, 1979). In another case, a below-ground building was modeled using a detailed simulation program. Actual energy usage was then used to ``calibrate'' the model, and the calibrated model was used to predict energy usage of the building if built above ground (Christian, 1982). Another application of a detailed simulation model was to evaluate the conservation potential in commercial buildings (Cleary, 1986) and the impacts of a lighting retrofit in an all-electric retail store (Cleary and Schuldt, 1986).

This microdynamic modeling approach offers one of the strongest methods for determining building performance, although typically it is costly to calibrate a model of a building this way. The strengths of this approach are that it allows checking of certain complex interactions between systems. One drawback is that the simulation programs typically cannot model systems that do not function properly. For example, with a malfunctioning control system, simulation becomes difficult . Often, detailed knowledge of the building construction and operation, which can be hard to obtain, is needed to achieve good simulation results.

Since the completion of the literature review, additional work on building simulation models has occurred. One important approach that has evolved is use of dynamic thermal performance models (Sect. 2.1.5) to calibrate the simulation model (Hsieh, 1988), which allows operation of the building to be inferred from energy use data instead of from more detailed observations.

2.1.5 Dynamic Thermal Performance Models

Dynamic thermal performance (referred to as macrodynamic by Burch, 1986) models originally were thought to circumvent the need for detailed audit-type information about a building to model its energy usage, but recent developments indicate that more information than originally thought necessary may be needed for this approach to work well. The transient thermal performance is determined from short-term monitoring of the building, and the model is developed from the transient response data.

Most of the work with dynamic thermal performance models has been done on residential buildings because they are simpler. Two studies describe the determination of ``equivalent thermal parameters" of a house (Sonderegger, 1977; Wilson et al, 1985). This approach to dynamic thermal performance models may not be suitable for commercial/institutional buildings. Another approach, originally developed to simulate thermal performance of passive solar houses (Shurcliff, 1985; Subbarao, 1985; Subbarao et al, 1985), has been used to model thermal performance in an office building (Norford et al, 1985). The results from the office building work show promise for improving future models of commercial building energy use.

The use of macrodynamic models for commercial and related buildings is being explored at this time. Use of these models is complicated by the fact that no simplified method of applying them is readily available (the major effort has been to apply them to residential buildings). Because these models have had limited use for commercial buildings, their strengths and weaknesses for these buildings are still uncertain. Current work is directed toward simplifying their use by practitioners, refining the modeling approach, and developing means of obtaining the required building information directly from metered data. The work in this area has expanded since the literature review was completed, and the newer (and proposed) literature has additional valuable information (Hsieh, 1988; Rabl, 1988; Subbarao, 1988; Subbarao et al, 1988; Reddy, 1989; Burch, 1990).

2.1.6 Discussion

Overall, the methods reviewed in the literature indicate that many analysis approaches for metered data of commercial and related buildings are still exploratory. Reasonable results are possible for some buildings using simple measures such as total energy, but the uncertainty of weather variations is still present. Weather adjustments for heating energy use may be possible, but adjustments for cooling are less certain. Other energy uses in buildings, such as lighting, may dominate heating and cooling uses for some types of buildings.

One important consideration regarding analyses of energy performance or efficiency improvement in these buildings is whether the building will be studied in isolation or in comparison. As stated in the Introduction, one of the interests of this study is the ability to compare a buildings' performance with that of other similar buildings. While some methods may provide reasonable answers for individual buildings, the potential for analyzing differences between buildings must also be considered for improving knowledge transfer among energy practitioners regarding relative energy performance expectations and efficiency improvements.

The inclusion of specific characteristics of the building and of the activities in the building in a multiple regression analysis of energy use is important for consideration in potential future improvements to analysis methods. Macrodynamic modeling also appears to have longer-term benefits. The initial results from these approaches indicate that there is potential to achieve more meaningful results in analyses of building energy use. However, these approaches have seen limited application, and generalizing their use will require an extensive effort if it is to cover all or many buildings. Research on these advanced methods appears needed.

Analysis methods were found to examine energy use from the standpoint of timedependence, thermal models, and impacts of building characteristics, and the methods for obtaining time-dependent results were the most limited. In Sect. 3 we propose a ``power signatures'' concept which offers a new approach for producing time-dependent results for commercial buildings. The ``power signatures'' concept provides a means for linking and comparing results from different time steps, such as annual, monthly, and hourly.

2.2 SURVEY OF ONGOING RESEARCH IN THE UNITED STATES

As stated previously, discussions were held with researchers at several institutions. The results of those discussions are presented in this section.

Princeton University Center for Energy and Environmental Studiesœ. The work in this field of most interest at Princeton is the ongoing monitoring and analysis of two large office buildings in New Jersey. Component analysis is achieved using detailed monitored data on individual systems. The impetus for this work came because breakthroughs resulted from monitoring research in residential buildings, commercial monitoring was the next logical step, and funding for this work became available. Significant operational problems have been identified in the buildings that probably would not have been noticed without the monitoring. Since the metered data are complex, data should be presented in compact form. A format has been developed at Princeton for daily records with important parameters plotted close to each other in separate graphs on a single page. This format allows some interactions to be detected through visual inspection. Since there are few buildings with monitored data at the level of detail available for these two buildings, it is not possible to make significant cross comparisons with other buildings. In the future such analysis may be possible. Princeton and the Solar Energy Research Institute (SERI) have collaborated on macrodynamic modeling using the data from these buildings.

Solar Energy Research Instituteœ. SERI has been the primary research organization developing the macrodynamic methods. They are also comparing building simulation (microdynamic) model results with macrodynamic model results to support further development of both types of models. In collaboration with Lawrence Berkeley Laboratory (LBL) and Pacific Northwest Laboratory (PNL) they are testing the macrodynamic approach in additional commercial buildings.

Lawrence Berkeley Laboratoryœ. LBL has looked at analysis of metered data extensively as a result of their Building Energy Use Compilation and Analysis (BECA) data base work and other efforts for the State of California and California utilities. LBL proposed a concept for defining buildings in terms of *levels of service* provided. A similar concept is presented in the Introduction concerning the problems of comparing the energy use of school buildings without some information about how the buildings are used and what facilities they have (use and configuration). The levels of service become characteristics that help define the building, and these characteristics might be used in multiple regression studies of energy use in buildings. Levels of service are not specifically defined but may include such things as the hours of operation (schedule), special facilities (such as a pool), internal temperatures maintained, and other characteristics.

Another item of interest at LBL was a study that examined the detailed electricity consumption for several buildings and that looked for identifying characteristics in the shape of the curves over the year, a week, or a day (Akbari et al, 1987). Other special features were also examined. This approach allows the energy use of a building to be considered part of the characteristics of that building and will be described in Sect. 4.

Pacific Northwest Laboratoryœ. PNL has several efforts under way regarding building monitoring, and their efforts were aimed at collecting and checking the data needed. At PNL, they are interested in methods for simplifying the data that need to be collected, especially by shortening the duration of collection and by minimizing the number of monitoring points that are necessary. The work was not at a point where they could make suggestions concerning recommended analysis procedures. PNL has been a driving force in emphasizing the need for collecting building characteristics data to understand the energy use in different buildings, and their influence has shaped subsequent monitoring efforts.

PNL is interested in the dynamic thermal performance models that SERI is working toward improving and regards this as an important area for further research by DOE. The suggestion was made that some type of workshop would be useful to present the basic theory behind the modeling and some of the concepts for developing models for commercial and related buildings.

3. ANALYSIS OF METERED DATA FOR BUILDINGS

Many purposes underlie analyses performed on commercial building energy use, and the focus of this report relates to developing a data base on building energy use (to be used as a guide for comparison of efficiency levels with that of other buildings), diagnosing sources of energy waste in a building, providing an estimate of benefits from energy efficiency measures, and providing a tool for continuous energy management. Emphasis must be placed on continued energy management to retain increases in efficiency. Part of the basic approach should be the tracking of long-term trends in energy use.

Analysis of metered data does not substitute for more detailed studies of the specific energy systems and the operating and maintenance practices for buildings that are being studied. Instead, analysis should be considered an important tool for guiding and organizing more detailed studies or for evaluating the improvements resulting from such a study (or audit). Detailed studies or audits and analysis methods should complement each other. With these ideas in mind, analysis concepts and approaches will be discussed below.

3.1 SUPPORTING DATA

In addition to the information provided by the metered data from a building, other available information which describes the type of building that is being analyzed can be useful. The basic description of a building allows others not familiar with the building to gain some insight regarding what factors may affect building performance. As mentioned in the Introduction, benefits are expected to be derived from a history of different buildings and from the development of transferable knowledge about what constitutes an energy efficient building.

Considering the need for other data that may be important for understanding building energy use, factors that should be considered for further research were identified. These factors are not necessarily comprehensive, nor will they contribute equally. (Readers may also wish to consult *A Protocol for Monitoring Energy Improvements in Commercial and Related Buildings*, MacDonald et al, 1989). Future work is needed to determine the relative importance of these listed factors.

- Building type, orientation, and location
- Occupancy and temperature schedules
- Building operation and maintenance
- Fuels, capacities, and fuel use
- HVAC systems
- Other equipment
- Building alterations
- Building size
- Control systems
- Building envelope
- Functional use
- Lighting systems
- Weather data

The provision of descriptive information for these types of factors should allow a better understanding of buildings and significantly improve the treatment and analysis of energy data. Further research is needed to define the benefits of such an approach.

3.2 NORMALIZATIONS

Comparison of energy use between buildings typically requires some type of normalization to improve understanding. Normalization involves a transformation of data values to provide a common scale. One of the first normalizations of interest for commercial buildings involves division by some floor area value to develop an EUI (Btu/ft^2/yr). Other indexes, such as Btu/meal-served, are also of interest for specific building types. EUIs can be calculated for the total of all fuels together and for individual fuels, where individual fuels sometimes provide a better breakdown of heating and cooling. The appropriate area to use for a building can be a problem if significant parts of the building are unconditioned or if large parking ramps or lots are included in the overall energy consumption of the building. In general, significant differences between conditioned area, gross area, and gross area without parking facilities included should be described in reporting results of an analysis.

Weather dependence is another important characteristic to check in a comparison of energy consumption in a building (Eto, 1985; Rabl et al, 1986). Corrections for weather have differing degrees of success, depending on building response, the time step of the data, relative magnitude of energy uses not sensitive to weather, and other factors. Some weather normalization can be provided by dividing energy use by HDD or cooling degree days (CDD), but this type of calculation should only be applied to the ambient temperature dependent portion of building loads. Analysis of cooling energy dependence on weather can be difficult with only monthly data (not many data points). As indicated previously in this report, determination of temperature dependent loads can be a problem for commercial buildings.

Consideration should be given to seasonal confounding factors, such as changes in occupancy or number of customers, that influence consumption in either the heating or cooling season. As a warning, ``... corrections should be approached with caution, because it may be impossible to accurately quantify the effects of such changing factors'' (Wulfinghoff, 1984). It is important to develop a sense of the factors that might influence energy consumption and methods for understanding these influences. Analysts should be aware of potential problems that confounding factors may present when any analysis is performed and should consider whether extended analyses of possible relationships are needed.

This report suggests the use of power signatures to present the time dependent behavior of energy use in commercial buildings with normalizations for building size (floor area) and time step in data collection. Further discussion of power signatures is presented below.

3.3 MONTHLY ENERGY DATA

A significant amount of information is contained in monthly data (billing-type data for each fuel). However, this information can be obscured by reporting a single normalized value for the whole year (as with EUI) or by showing only ambient temperature dependence of energy use, which hides the time dependence of energy use. Analysis of energy data for commercial buildings should indicate time dependent behavior of energy use as well as ambient temperature dependence. As indicated in Sect. 2, analyses of time dependence of energy use have been more limited.

Power signatures represent a structure for observing energy characteristics. (For more background on the ``signature'' concept see MacDonald, 1988.) Use of power signatures allows energy or power characteristics of building energy use to be identified better. These energy or power characteristics can be compared with those of other buildings and perhaps be related to physical characteristics of buildings for further comparisons. Note that the *average* power for a discrete time period (such as an hour) is equal to the energy consumption for that time period divided by the time period (kW = kWh/h). With some care, energy and power characteristics may be mentioned together. To improve the understanding of relationships between energy characteristics and physical characteristics, more energy characteristics need to be identified.

Figure 2 shows an annual power signature profile of monthly energy use data for a building with two fuels, natural gas for heating and electricity for all other uses. The EUI for the building in Fig. 2 for all fuels combined during the annual period shown is 135,000 Btu/ft^2/yr (40 kWh/ft^2/yr or 4.5 W/ft^2). The difference in the information available in the profile of monthly data vs the single value for the whole year is immediately obvious. Because this building has two fuel sources, the differences are even more pronounced. The complex nature of the electric and gas data combined can be seen. The cooling impacts are masked due to combined heating and cooling from April to June. This masking means total fuel consumption signatures must be approached with caution, but analysis of the total signature together with those for individual fuel sources may allow recognition of patterns for specific climates. These patterns can be used to analyze buildings that have only one fuel source to understand combined heating and cooling. An electric baseload of about 2.2 W/ft^2 is apparent, and the natural gas baseload is close to zero. The significant peak for total fuel use in this building is high relative to other buildings examined (Fig. 3) and is caused by a high heating energy consumption. Indications were that potential system problems in the building caused the high heating load. Later investigation showed that comfort conditions were maintained during unoccupied hours and a zoning problem caused one of the heating systems to run continuously during moderately cold weather.

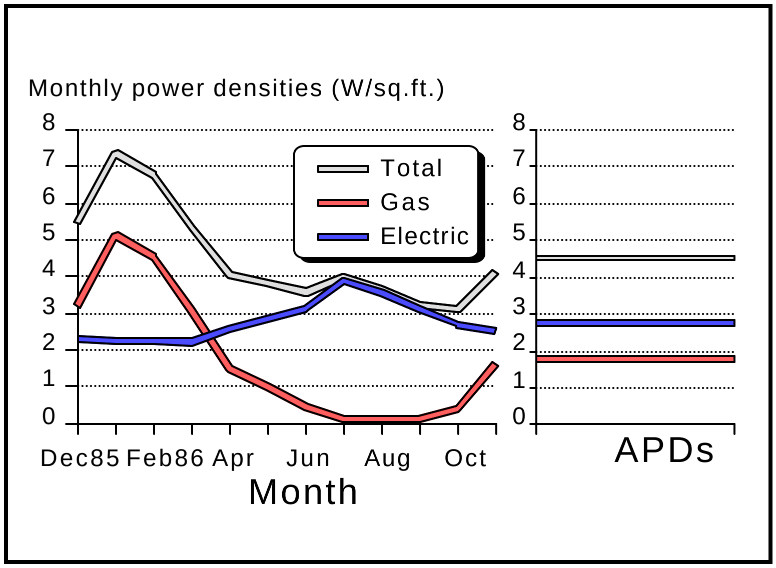

Figure 2— Monthly and annual (APDs) power densities for gas, electricity, and total fuel for a banking services building in Knoxville, Tenn.

The monthly power densities (MPD) (W/ft^2), as shown in Fig. 2, can be calculated as follows:

MPD (W/ft^2) = monthly kWh $\times$ 1000 $\div$ No. of days $\div$ 24 $\div$ ft^2

or

MPD (W/ft^2) = monthly Btu $\times$ No. of days $\div$ 24 $\div$ ft^2 $\div$ 3.412 .

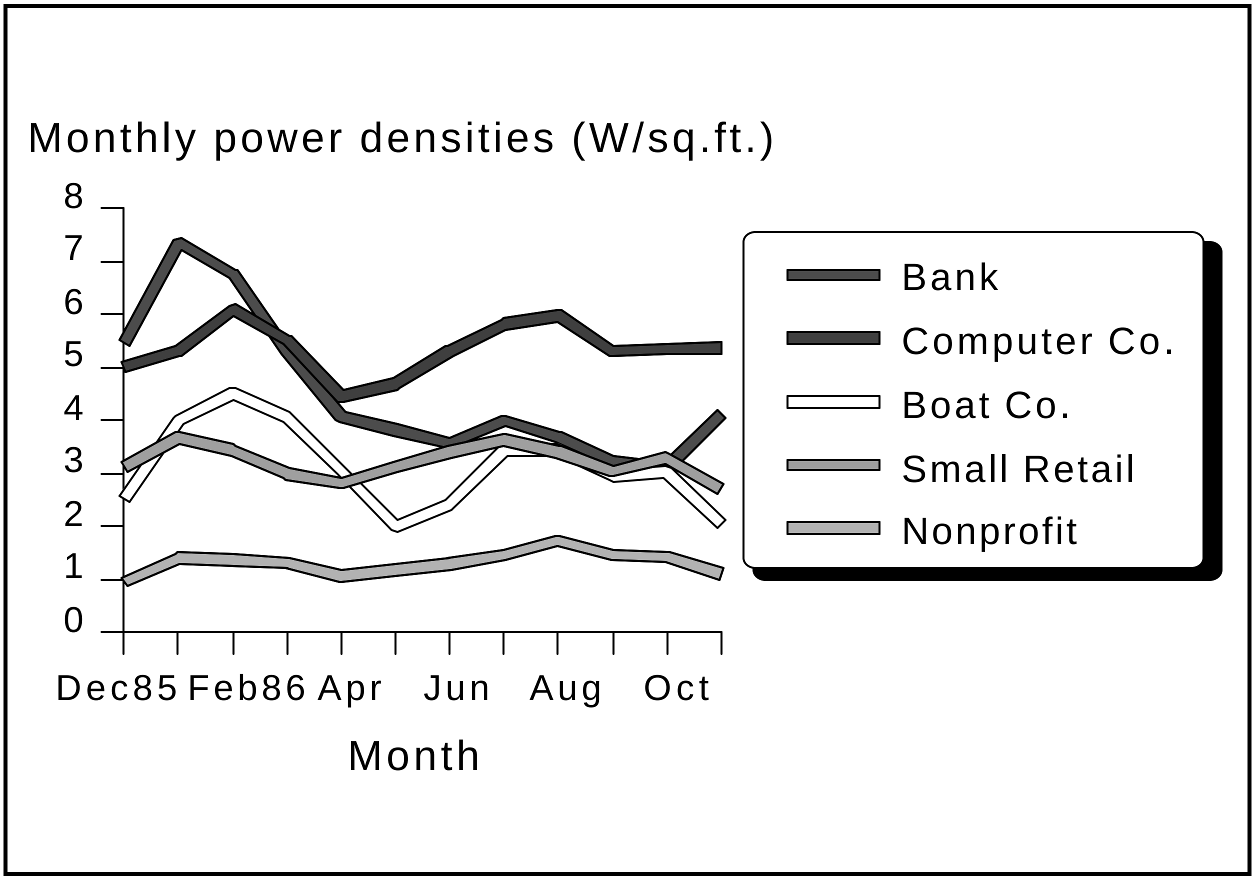

Figure 3— Monthly power densities for five small commercial buildings in Knoxville, Tenn. All buildings received a brief survey. The bank has zoning problems and comfort conditions are maintained during unoccupied periods. The computer co. has heavy computer use that keeps power high. The boat co. appears to have more 'typical' use. The tenants in the small retail building are conscientious about manual setback / setup. The nonprofit building is well insulated, is partially unoccupied during part of the week, and has ground-source heat pumps.

The MPD should be reported for all individual fuels, where available, and for total fuel consumption. The MPD profile provides a power signature of monthly data over the year for the bank building of Fig. 2, and power signatures are given for each fuel and for total consumption. Where fuels that are not metered monthly are used (such as oil), every effort should be made to institute some type of monthly metering to obtain this information. In addition, the annual power density (APD) should be reported for each fuel and the total of all fuels. The APDs for the building in Fig. 2 for the year shown are electric, gas, and total at 2.8, 1.8, and 4.5 W/ft^2, respectively.

The MPD provides the same information on a monthly basis (12 points instead of 1), and the APD, which is an annual average, can be compared with the MPD for each month to determine relative variations in intensity. An EUI presented in terms of Btu/ft^2/yr can be converted to an APD by the simple calculation:

$$\text{APD (W/ft}^2\text{)} = \text{EUI (Btu/ft}^2\text{/yr)} \div 8760 \div 3.412 = \text{EUI} \div 29{,}889 \; .$$

Examination of Fig. 2 indicates that the building appears to have an average electrical use during periods with ambient temperature dependent consumption of about 3 W/ft^2. Combined with the apparent base consumption of 2.2 W/ft^2, a cooling use of about 3.0 ! 2.2 = 0.8 W/ft^2 can be calculated, since we are reasonably confident that this building does not have a fixed cooling consumption base load that occurs year round. This calculation shows that electric uses other than cooling are important in this building. The data for the building in Fig. 2 allow a more detailed analysis than simply providing the APDs and the MPDs. A better understanding of how to use this additional information is needed in future studies.

3.4 ADDITIONAL ENERGY DATA

Additional energy data can be useful in analyzing how energy is used in a building and in tracking the changes in energy performance. Some examples of the next useful level of detail are daily energy use vs each day of the month and hourly energy use for different types of days. These examples can be combined if one of the ``day types'' is the average of (hourly) energy use for several weekdays (workdays or occupied days) over a two-week or one-month period and another day type is the average of weekend (workdays, nonworking, or mixed) days. Depending on the building and how it is used, data from several day types may be obtained. If energy use is different for each day type, care is needed in comparing data of one building with that of another having an unequal amount of data for each day type.

More detailed energy data (e.g., hourly or 15-min time interval data) can be collected, and the discussion in this section focuses on use of hourly data for total electricity use. Additional detail can be obtained by monitoring individual systems or end uses such as heating, cooling, lighting, fans, and other. The Princeton work on the two large office buildings is an example of this more detailed approach.

Figure 4 is a data plot of the hourly electricity consumption (these are *not* power densities) for the building in Fig. 2 for the period June 17–23, 1987. The weekend (June 20–21) energy use is different than on weekdays, which shows the importance of considering different day types. The relative magnitude of the average consumption for different hours of the day and days of the week during the middle of the cooling season is also shown in this figure.

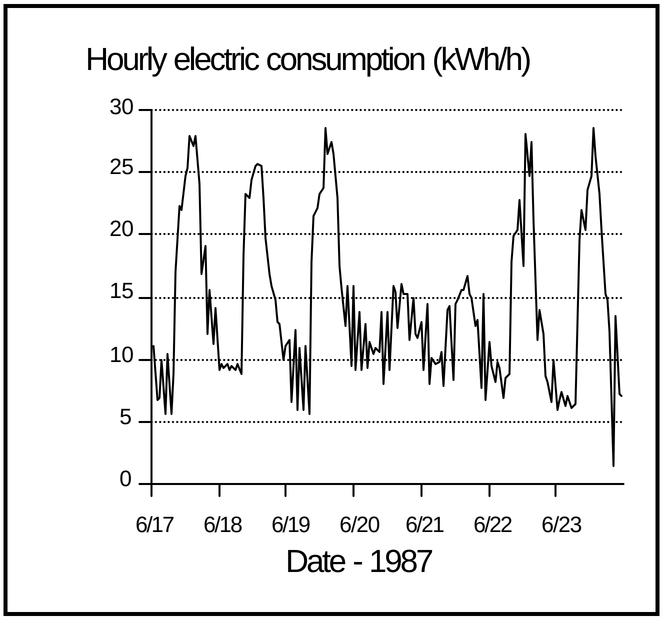

Figure 4—Hourly electric consumption for the banking services building in Knoxville, Tenn.

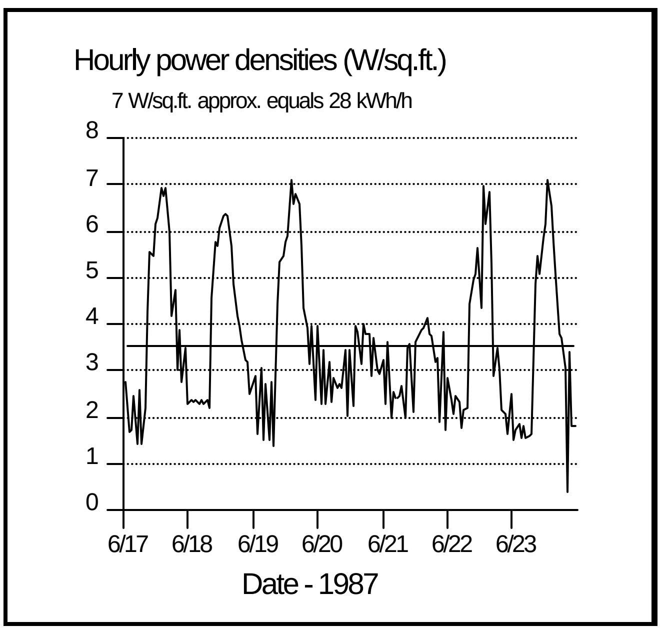

Figure 5—Hourly power densities for the banking services building in Knoxville, Tenn.

Figure 5 shows the same data converted to hourly power densities (HPDs). The solid line indicates the average HPD over the period, and the average HPD may be compared with MPDs for this or a different year. Comparing the average HPD for electricity with the MPD values for electricity for June and July in Fig. 2 indicates that the average HPD is in the same range as the electricity MPD values from the previous year. The HPD plot shows excursions of about 4 W/ft^2 above the average and 2 W/ft^2 below the average. These characteristics potentially can be used to identify the way this building uses power.

Some of the same information given in Fig. 5 is shown in Fig. 6, but the HPDs for each hour are averaged (over the time period shown in Fig. 5) *for weekdays only*. The average HPD for these data is shown by the straight line. This type of plot shows a ``typical" curve of HPDs for this building for a hot summer condition. The potential use of this type of information is expected to be enhanced if this building can be studied for a long period and if more buildings can be studied to determine differences. A history of data for different buildings is needed for the information to become more useful. Figure 7 presents a plot similar to Fig. 6 except that it is *for weekends only* (the weekend data were taken from June 20–21 and 27–28, 1987).

The plots shown in Figs. 2, 5, 6, and 7 all contain different energy or power characteristics that are part of power signature data. Figures 5, 6,

and 7 provide the signature for electricity use, and additional data are needed to define the gas use
signature and the total energy signature. Analysis of the signatures may identify features that can be related to other building characteristics data and included in a data base of the relationships. Such data bases probably should be developed on a regional basis. Some initial work was done to examine load shapes of commercial buildings in the Pacific Northwest (Reiter, 1986), and this study is directed at extending the ideas described in that work.

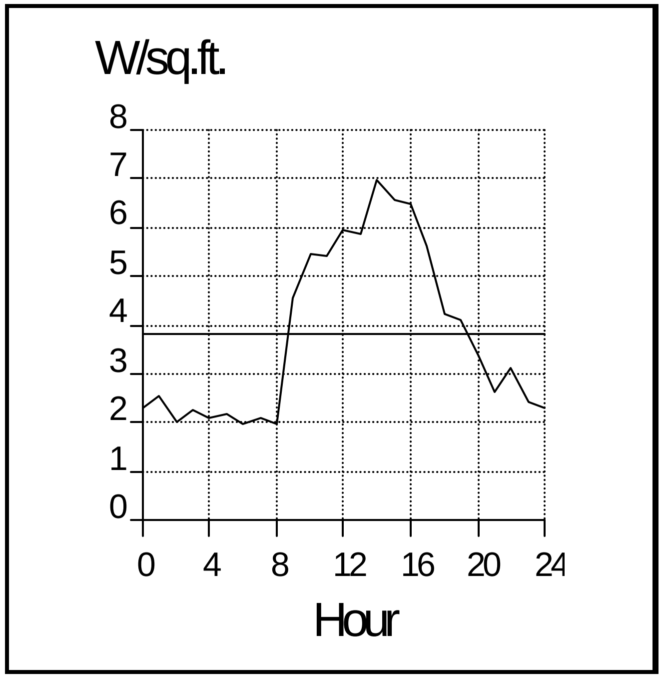

Figure 6—Average hourly power densities for *weekdays* for the week of June 17–23, 1987, for the banking services building in Knoxville, Tenn.

3.5 MULTIPLE REGRESSIONS

Multiple regression methods can be used to analyze the effects of both weather-related and other factors on building energy use. Analysis of the additional factors is important for many types of commercial buildings. Multiple regressions can be used both to model individual buildings and to study characteristics that lead to differences in energy consumption between buildings. These methods are important for advancement of analysis approaches for commercial buildings.

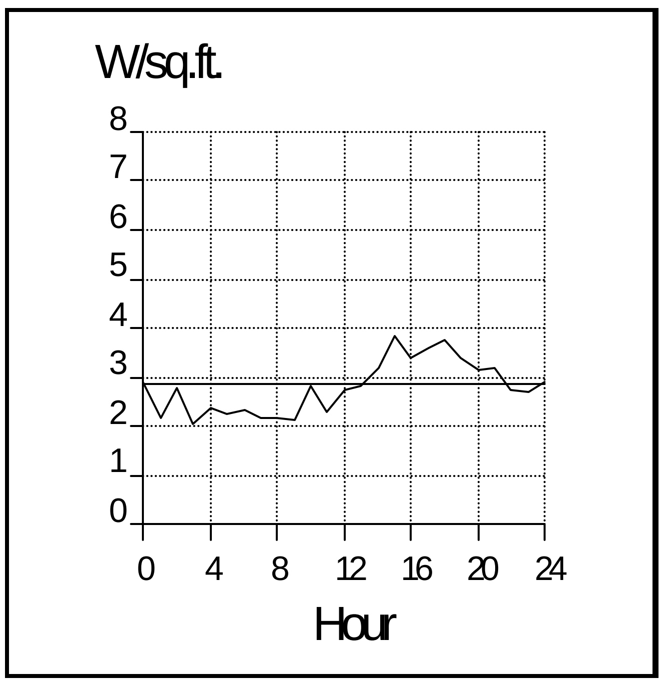

Figure 7—Average hourly power densities for the *weekends* of June 20–21 and June 27–28, 1987, for the banking services building in Knoxville, Tenn.

The use of multiple regression techniques to understand metered energy data has been demonstrated in the development of an ``expert system" prototype. This prototype helped maintain reduced energy use in a recreation center at the University of Colorado (Haberl and Claridge, 1987). Energy use was analyzed by multiple regression techniques to establish energy use predictors. With this approach, results are fed to the expert system and causes for variances from expected norms are determined.

Energy consumption in the recreation building was found to be influenced by ten parameters, including environmental, operational, and system parameters. Intercorrelations were studied to determine the independence of the parameters. Two of these variables were found to have a strong correlation and were combined by multiplication, which reduced the set to nine parameters. Further analysis was conducted using the nine parameters to select seven consumption predictors of energy use. (There must be a corresponding metered value obtained from a physical meter(s) to compare with each predictor.) Criteria were developed to indicate abnormal consumptions, with variations for different predictors. Abnormal was a relative term and could be changed to satisfy the needs for the analysis of the different variances in the predicted vs actual consumptions for each predictor. Daily meter readings were compared with predicted daily consumption for each ``meter," and reasons for abnormal consumptions were then determined by daily site visits and conversations with building personnel so they could be recorded in the expert system knowledge base. Results indicate that savings from use of the system are about 15% of annual use.

The research on this prototype expert system for buildings indicates the potential for development of analysis methods based on multiple regressions. The building chosen for this prototype development had many energy consumption meters, and the installation of improved energy metering in buildings may be a prerequisite for application of these techniques. However, these techniques can be applied effectively in larger buildings today. Less complicated analyses may be possible for smaller buildings and should be studied.

3.6 DISCUSSION

Analysis of metered data for individual buildings should be directed at understanding the general indicators of energy use, recording the building's characteristics that are likely to influence energy use, and developing more detailed breakdowns from monthly fuel data and more detailed results from daily or hourly data where possible. Long-term evaluation of performance trends should also be studied.

Because building energy use may need to be compared with that of other buildings, the development of relationships between building characteristics and building power signatures should be part of research on analysis methods. The development of correlations between these two sets of data appears to offer the opportunity for dealing with the diversity of buildings and uses, while developing an improved understanding of how energy is used in commercial and related buildings.

Energy analyses of buildings are expected to benefit from advanced techniques presented in this report. Multiple regression and power signatures are specifically discussed in Sect. 3, and macrodynamic methods must also be considered as they become more usable. Refinements to component analysis using more detailed end use (submetered) data and simplifications to weather correction methods are also possible improvements. Advanced methods are being tested in limited research, and present results indicate that fundamental advances in analysis methods are possible.

Power signatures are presented as potential improvements for examining time-dependent behavior of building energy use, and the importance of relating building characteristics to variations in energy use between buildings has been highlighted. Improvements in other areas would also be valuable, and coordination of research to direct improvements in all areas would have synergistic benefits.

Some implications of these findings are that:

- More emphasis will have to be placed on obtaining and analyzing the characteristics of buildings
- The monthly power signature data should be considered part of the characteristics
- A classification method to define analysis approaches (five categories proposed in Sect. 2.1) would improve presentations of analysis results
- Although important research is presently being conducted on analysis methods, more work is needed for commercial and related buildings to make the advancements required to handle the diversity of buildings and energy use
- Analyses of individual buildings should consider the need for future comparison of building performance with that of other buildings
- Workshops to present these results to key engineering and building operations organizations are needed to transfer this information

4. COMPARISON OF BUILDINGS

As indicated previously, the benefits from comparing building performance based on information about how a building is configured, used, and operated are expected to be substantial. A three-level approach is described as an initial attempt to suggest how buildings should be compared.

Level 1. Use of physical characteristics to develop an understanding of the types of services offered in different buildings. This is a critical first step for understanding factors affecting energy use.

Level 2. Develop MPDs and APDs (W/ft^2) to determine power signature data for buildings. The profiles should include the total power for all fuels, with profiles for individual fuels. The power signature and the other building characteristics should be studied to determine what relationships exist and what are the key determinants of variations in power signature. Other analyses of monthly and annual data (e.g., ambient temperature dependence regressions, calculation of monthly load factors) are also conducted at this level.

Level 3. Where possible, hourly profiles of energy use should be developed (even for short periods of 1–2 weeks) to better define each building. Impacts of occupied and unoccupied day types on building power profiles must be considered. HPDs (W/ft^2) would allow comparisons between buildings of different size, and awareness of total power (kW) would allow a perspective on the importance of each building for the fuel supplier or utility. These power profiles, together with the level 2 analysis results, comprise the overall power signature for a building. This signature is studied to search for relationships with other characteristics of the building. These relationships are then used to make comparisons with other buildings.

The level 1 data should always be available when comparing different buildings and when comparing their energy use or performance. Further study is needed to develop more reasonable categorizations and to determine which categories are most appropriate for comparison. Without this type of information the diversity of buildings, systems, and uses is likely to make comparisons difficult. As an example, if building energy efficiency improvement awards are based solely on an analysis of energy use, it is conceivable that a building could win an award by having tenants move out and shutting down part of the building. Without characteristics data an informed judgment cannot be made.

The level 2 information is usually available with a combination of billing data and reasonable information on the floor area for the building. Use of the gross area of a building makes comparison of MPDs less meaningful if significant areas of the building are unconditioned or if energy used by large parking ramps or outdoor lot lighting is included in the overall energy consumption of the building. In general, significant differences between gross area, conditioned area, and gross area without parking facilities included should be considered when developing building characteristics data. Mixed use buildings can also cause problems in evaluations of buildings, especially when only a portion of the building has a high power/energy requirement. A consistent method should be formulated for dealing with these characteristics data and the level 2 type data.

The level 3 information has potential for defining buildings more specifically by use of power signatures or other methods. However, this level requires significantly more effort, and research is needed to make application of level 3 approaches more straightforward.

An example of the type of information provided from just the total consumption level 2 data (individual fuel comparisons would also be possible) is provided in Fig. 3. Differences between the buildings are striking—the MPDs provide useful information that could be a significant start toward developing building categories based on power signatures. As more is learned about how to compare building energy performance using the types of data described, it may become possible to define building categories based on power signatures. The possibilities are interesting and challenging.

While many possibilities exist for comparisons with more detailed metered energy data, a potential very useful possibility is the study of specific characteristics of the power signatures themselves. An example of such an effort is presented in Table 1 (taken from Akbari et al, 1987). The analysis that was done to develop Table 1 was based on examination of hourly, whole-building, electric energy use data (kWh) for the year 1984. Examination of the profiles for these data led to the observations of power profile characteristics described in Table 1. Characteristics related to schedules, relative peaks and valleys in the power profile, differences between day types, and building operation practices are tabulated. These characteristics provide a means for categorizing buildings and for making comparisons with other buildings.

With further study it may be possible to develop capabilities to correlate MPDs and HPDs with building characteristics to provide specific ``fingerprints'' of how the building uses energy and how its efficiency can be improved. This type of analysis appears to lend itself to computerization, which might allow large numbers of buildings to be analyzed more effectively using simple audit data and building metered data.

Table 1——Power Profile Characteristics by Building Use Type

	Building type[a]				
ANALYSIS BASIS	Sch (4)[b]	Hos (2)	Off (2)	Ret (2)	RWH (1)
ANALYSIS OF DAILY MINIMA					
Nearly constant minima over the year	x	–	?	x	–
Seasonal variation of minima	–	x	?	–	–
Step changes in minimum	x	?	?	–	–
Variable changes in minimum	–	?	–	x	x
Well defined ``weekday" minimum	?	?	x	x	–
Well defined ``weekend" minimum	x	?	x	x	–
Weekend minimum distinct from weekday minimum	?	–	–	–	x
Minimum power at night	x	x	x	x	–
ANALYSIS OF DAILY MAXIMA					
Seasonal variation of maxima	x	x	?	x	x
Low power requirements in summer	x	–	–	–	–
Sat. maximum greater than Sun. maximum	x	x	x	?	x
Weekend less than weekday maximum	x	x	x	–	x
Saturday maximum $75% of weekday maximum	–	x	?	x	x
ANALYSIS OF BOTH DAILY MINIMA AND MAXIMA					
High minimum compared to maximum (50%)	–	x	?	–	x
Weekend distinct from weekday	x	?	x	–	x
Monday through Friday indistinguishable	x	x	?	x	x
Daily range much greater than minimum	x	–	?	x	–
Weekend power level same as minimum	x	–	–	–	–
ANALYSIS OF HOLIDAYS					
Holidays and weekends similar	x	x	x	–	x
All holidays observed (matching a list)	x	–	–	–	–
Some holidays observed (matching a 2nd list)	–	–	x	–	–
Few holidays observed (matching a 3rd list)	–	x	–	x	x
Seasonal breaks (e.g., Spring) discernible	x	–	–	–	–
ANALYSIS OF DAILY PROFILES					
Large period to period variation	–	–	–	–	x
Mealtime drop significant	x	–	–	–	–
Mealtime drop observed	x	x	x	x	–
Subordinate evening maxima	x	x	–	–	–
Small variation in weekly profile	x	?	x	x	x

[a]Sch = schools, Hos = hospitals, Off = offices, Ret = retail, RWH = refrigerated warehouses.
"x" indicates the characteristic is found, "–" indicates not found,
"?" indicates found sometimes.
[b]Sample size.
Source: H. Akbari et al, 1987.

5. RECOMMENDATIONS

From this study for the EBER program, we have begun to show the diversity of methods used to analyze metered data for commercial buildings. Some of the methods could lead to improved knowledge of how energy is used and how efficiency can be improved in commercial buildings. Perhaps most notable is the concept of multiple regression (multiple parameter) models of building energy use that also analyze effects of occupancy, schedule, special events, and other inputs in addition to weather factors. Significant improvements to analysis of metered data for commercial buildings are being tested, and further improvements are needed. These improvements should include continued development of the multiple parameter methods, development of methods for analyzing more detailed (submetered) data (e.g., power signatures), use of macrodynamic methods to generate models with physical significance, and simplification of the methods.

The diversity of methods also raises a cautionary issue. Results from simple analyses, such as comparisons of total annual energy use should be considered useful only as general indicators of efficiency improvements. Results from more detailed studies that provide knowledge of the causes for change and of anomalies that affect the results presented are more useful for understanding how to improve commercial building efficiency. To better define the extent and usefulness of each analysis, some effort should be made to develop a structure for classifying analysis approaches. Use of this classification structure should be promoted for reporting analyses of commercial building metered data.

In addition to improving the classification and reporting of analysis methods, analysis efforts should be extended to focus on characterizing building types (by appropriate parameters) and on the technologies or approaches commonly used to improve efficiency in particular building types. This characterization effort is needed to improve communication of the types of buildings that are being modified and of the nature of the efficiency improvements being made. Improved communication is needed to better explain observed variations between buildings and to more effectively transfer increased knowledge of buildings.

Advanced research on the characterization extension effort should be directed at developing relationships between building characteristics and building power signatures. Development of correlations between these two sets of data will improve models of building energy use by incorporating important causes of variation in power and energy use.

The BECA-CR data base (Gardiner et al, 1984, 1985; Wall and Flaherty, 1984; Ross and Whalen, 1982) maintained at LBL provides much useful information on the general performance of energy efficiency improvements in commercial buildings. The work to develop the data requirements for BECA-CR is of value to anyone attempting to define the data needed to understand energy use in commercial buildings, including performance of efficiency improvements. Conversely, BECA-CR results could be improved with advanced analysis approaches, including relating building characteristics to energy use.

The requirements for the BECA-CR data base have recently changed to allow inclusion of submetered (more detailed) data that do not cover a whole year. Submetered data generally are collected over a shorter period of time (from one day to one or more months). Submetered refers to additional energy metering that provides more detailed information about total consumption for individual fuels or consumption information about specific end uses of energy, such as lighting. Improvements to analysis methods could benefit BECA-CR as more detailed data are acquired.

The recommendations from this study are to:

- Support additional research on advanced analysis methods directed at commercial buildings such as multiple parameter models that include building characteristics, methods for analyzing more detailed data (e.g., power signatures), macrodynamic models, and simplifications of these methods to promote wider use
- Develop a coordinated research program on analysis methods (for DOE this means combining efforts from buildings, solar, and state and local programs)
- Develop a classification structure to define analysis approaches and promote use of the structure for reporting energy analyses
- Extend analyses of energy efficiency improvements to characterize building types and classify groups (packages) of common efficiency improvement technologies or approaches appropriate to the different building types

The recommendations above have implications that extend beyond the framework of energy efficiency improvements, because ultimately the energy performance of buildings over time must be considered. The most important implications are that:

6. An improved institutional-type of memory concerning the types of technologies, operations changes, and performance tracking methods that lead to long-term building energy performance improvements could evolve, and

7. A more empirical basis for implementing equitable and usable energy performance standards for existing buildings could be developed.

The first extension is expected to occur as a result of communicating the improved methods to practitioners so there is more commonality in how the energy performance issue is approached. This approach is expected to lead to improvements in the overall understanding of energy use and in the level of skills available for analyzing energy use. The possibilities are interesting, and the potential benefits could be large.

For building energy performance standards, the issue is one of determining how a building is configured and used and how much performance improvement is reasonable at a given time. If any standard is to succeed, the development of a common approach for defining and understanding building performance, the ability to identify key characteristics that affect the levels of service offered by a building, and the ability to suggest potential performance improvement targets and to negotiate with owners, operators, or lessees to try to approach these targets are all important. The analysis approaches discussed in this report offer the potential for achieving some of these abilities.

Overall, the emerging and previous work on metered data analysis for commercial and related buildings indicate possibilities for future improvements. The development of meaningful data on building energy performance and of better methods for understanding those data could have important benefits for managing energy in buildings in the future. The opportunities are there for a research program to examine and implement.

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ANNOTATED BIBLIOGRAPHY

of Reviewed Literature

Covering Analysis of

Building Metered Energy Use

Notation categories: (N/A is not applicable)

Source: indicates publication containing the reference

Metering Analysis: "Energy Performance" indicates that the energy behavior of the building was studied
"Retrofit" indicates that the performance of energy improvements were evaluated
"Discussion" indicates that methods and approaches are presented

Building Type: indicates the general types of buildings or class of buildings covered

Measurements: presents a short description of the data parameters of interest for the study presented

Modeling: provides a brief description of energy modeling methods

Metering Duration/Interval: indicates the length of metered data collection period (e.g., 1 year, 2 years) and collection interval (e.g., monthly, hourly)

A brief description of the study is also provided.

Hashem Akbari et al, 1987
End Use Load Profile Analysis of Selected Commercial Buildings
Sourceœ: Lawrence Berkeley Laboratory Report, LBL-23498.
Metering Analysis: Energy Performance
Building Type: Commercial
Measurements: Total electric at 15-min interval, aggregated to hourly
Modeling: Yes, statistical estimates of disaggregated end uses
Metering Duration/Interval: One year/hourly
Developed models of energy consumption for some building types for predicting impact on utility.

Gunnar Anderlind et al, 1986
Effects of Energy Conservation Measures: Results from a Swedish Before-After Study
Source: Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 9, pp. 7-10.
Metering Analysis: Retrofit
Building Type: Residential, single, and multi-family
Measurements: House space and water heating energy, indoor and outdoor temperature, wind, solar
Modeling: Yes, linear regression
Metering Duration/Interval: Two to three heating seasons/monthly
Used a whole year energy model. Normalized for weather.

Carl Blumstein, 1984
Energy Conservation on the Campus
Source: What Works: Documenting Energy Conservation in Buildings, Washington: American Council for an Energy-Efficient Economy, 276.
Metering Analysis: Retrofit
Building Type: Institution, university classroom/research
Measurements: Electricity, estimated steam
Modeling: No, compared pre- and post- energy use without normalizing
Metering Duration/Interval: 4 years pre-retrofit, 1 year post- /monthly
Looks at results of some energy conservation measures instituted on the Berkeley campus. Determines savings based on metered use. Discusses institutional barriers to energy conservation at universities.

S. Boonyatikarn, 1982
Impact of Building Envelopes on Energy Consumption and Energy Design Guidelines
Source: Proceedings of the ASHRAE/DOE Conference, Thermal Performance of the Exterior Envelope of Buildings II, pp. 469-480.
Metering Analysis: Energy Performance
Building Type: Institutional, in Michigan
Measurements: Total fuel use
Modeling: Yes, multiple regression with 10 variables
Metering Duration/Interval: At least one year/monthly
Energy use of 50 buildings in Michigan was analyzed statistically to identify major contributors to energy consumption variation. An energy predicting model was derived. Ten factors accounted for 93% of variations.

Jay D. Burch, 1984
Approaches to Analyzing the Thermal Performance of Commercial Buildings
Source: Proceeding of the Passive and Hybrid Solar Energy Update, pp. 141-150.
Metering Analysis: Discussion
Building Type: Commercial
Measurements: None
Modeling: N/A
Metering Duration/Interval: N/A
Discusses four ways to thermally model a building: 1) Mechanism level, 2) Component level, 3) Macrodynamic level, 4) Time-integrated level.

Y. M. Chang and R. A. Grot, 1984
Determination of Energy Reduction in Retrofitted Homes
Source: ASHRAE Transactions, Vol. 90, Pt 2B.
Metering Analysis: Retrofit
Building Type: Residential, single family
Measurements: Fuel bills
Modeling: Yes, linear regression
Metering Duration/Interval: 2 years pre-, 1 year post-retrofit(?)
Analysis of low-income weatherization in 12 cities. 119 homes in study.

Jeff E. Christian, 1982
Thermal Envelope Field Measurements in an Energy-

Efficient Office/Dormitory
Source: Proceedings of the ASHRAE/DOE Conference, Thermal Performance of the Exterior Envelope Of Buildings II, pp. 297-316.
Metering Analysis: Energy Performance
Building Type: Commercial, small office, and dormitory
Measurements: End use electrical, fan on time, most weather data, heat pump output, detailed temperatures
Modeling: Yes, does energy balance, DOE-2 Simulation
Metering Duration/Interval: 1-1/2 months/hourly
Heavily instrumented new building with many energy conserving features. Study was to assess performance of these features. Used DOE-2 to compare this building to base case building.

C. M. Cleary, 1986
Preliminary Analysis of Conservation Potential in Office Buildings
Source: ASHRAE Transactions, Vol. 92, Pt. 2.
Metering Analysis: Retrofit
Building Type: Commercial, varied office and retail
Measurements: End use electrical, 32 channels per building
Modeling: Yes, used DOE-2 to evaluate conservation potential
Metering Duration/Interval: One year/hourly
Seattle City Light has project to evaluate load and conservation potential in commercial buildings. They created a base case building and simulated with DOE-2. End use did not match energy use in monitored buildings. Examined energy use per square foot.

Colleen Cleary and Marc Schuldt, 1986
Measured End-Use Savings vs. Predicted Savings of a Commercial Lighting Conservation Retrofit
Source: Proceedings from the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 9, pp. 45-57.
Metering Analysis: Retrofit
Building Type: Commercial, small, retail store
Measurements: Electrical end use for heating, cooling, ventilation, lighting, refrigeration, hot water
Modeling: No, compared pre- and post-retrofit electrical use
Metering Duration/Interval: 1 year pre-, 1 year post-/hourly
Seattle City Light is conducting research effort to analyze energy consumption of commercial buildings. Want to find potential for conservation. End use electrical use monitored hourly. Found reduced cooling and light energy.

J. D. Cowan and I. A. Jarvis, 1984
Component Analysis of Utility Bills: A Tool for the Energy Auditor
Source: ASHRAE Transactions, Vol. 90, Pt. 1B, pp. 411-423.
Metering Analysis: Discussion
Building Type: Commercial and institutional
Measurements: Fuel use, monthly
Modeling: Yes, find base energy use, then linear relation for other uses such as heating
Metering Duration/Interval: At least one year/monthly
Author admits that heating/cooling energy in all buildings is not linear but says useful to plot as such as a preliminary to energy auditing. Can see if energy use is dominated by base load, heating, or cooling.

R. R. Crawford and J. E. Woods, 1985
A Method for Deriving a Dynamic System Model from Actual Building Performance Data
Source: ASHRAE Transactions, Vol. 91, Pt. 2B, pp. 1859-1873.
Metering Analysis: Energy Performance
Building Type: Residential, single family
Measurements: Indoor temperature, globe temperature, electric heat, ambient temperature, solar
Modeling: Yes, indoor dry bulb and globe temperatures modeled
Metering Duration/Interval: 30 days/15 minute
Model is similar to BEVA (see Subbarao, 1985, below) but does not use frequency domain equations.

Mark Duerr and Bonnie Cornwall, 1986
Issues Concerning the Use of Weather Correction Methods by Schools and Local Governments to Determine Energy Saved
Source: Proceedings from the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 9, pp. 88-100.
Metering Analysis: Discussion
Building Type: Institutional, schools
Measurements: None

Modeling: Yes, examine several methods for analyzing fuel use data
Metering Duration/Interval: none
The authors look at three methods of comparing fuel use of one year to another: (1) No weather adjustment, (2) The ``ratio'' method using heating degree days, (3) Regression analysis. Depending upon climate, fuel data, and user, recommend each type.

J. H. Eto, 1985
A Comparison of Weather Normalization Techniques for Commercial Building Energy Use
Source: Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelope of Buildings III, pp. 109-121
Metering Analysis: Discussion
Building Type: Office, large and medium
Measurements: none
Modeling: Assesses degree-day weather normalization techniques
Metering Duration/Interval: N/A
This study compared degree-day weather normalization techniques to building performance simulated by DOE-2 in two prototype buildings. Found that all four methods examined did well, mainly because energy use was not as sensitive to weather as expected.

Margaret F. Fels, 1986
PRISM: An Introduction
Source: Energy and Buildings, Vol. 9, Nos. 1 & 2.
Metering Analysis: Retrofit
Building Type: Residential
Measurements: Monthly utility bills
Modeling: Yes, linear regression.
Metering Duration/Interval: At least 1 yr pre- and post-retrofit/monthly
Method finds the NAC for the pre- and post-retrofit periods. Has a method for finding base load of house. Normalize for weather. Usually use weather station data.

Charless W. Fowlkes, 1985
Snapshot: A Short-Term Building Energy Monitoring Methodology
Source: Fowlkes Engineering, 31 Gardner Park Dr., Bozeman, MT 59715.
Metering Analysis: Energy Performance
Building Type: Residential, single family
Measurements: Ambient and House Temperature, hot water and total electric, solar flux, ventilation fan
Modeling: Yes, using 6-variable regression
Metering Duration/Interval: 1 day/hourly averages
Data for 6 to 10 channels are collected for a period of 1 to 3 days. Data analyzed on-site to produce ``Energy Rating Factors.'' Results are compared to longer-term results.

Donald J. Frey et al, 1983
Monitored Heating Season Performance of the Mount Airy Public Library Building
Source: Proceedings of the 8th Passive Solar Conference, Sante Fe, N.M., pp. 391-396.
Metering Analysis: Energy Performance
Building Type: Institutional
Measurements: 22 channels, 5 indoor temperatures, solar, ambient temperature, 5 heat pump electrical-including resistance, hot water
Modeling: Yes, compared energy use to predicted use, used ECAL program to model some parameters
Metering Duration/Interval: 6 months/weekly averages
Did not normalize for weather or solar in making comparisons. Modeled auxiliary heat needed, and then added estimated solar gain to model (building was designed for passive solar). Found substantial differences between measured and predicted loads.

Betsy L. Gardiner et al, 1984
Measured Results of Energy Conservation Retrofits in Non-Residential Buildings: An Update of the BECA-CR Data
Source: Proceedings from the ACEEE 1984 Summer Study on Energy Efficiency in Buildings, Vol. D, pp 30-48.
Metering Analysis: Retrofit
Building Type: Commercial and institutional
Measurements: At least monthly whole building fuel use
Modeling: No, compare energy intensities (energy per unit area)
Metering Duration/Interval: At least one year pre- and one year post-retrofit/at least monthly
Basically same report as previous paper. Authors point out that weather normalizing techniques developed for residences may be useful for small commercial. Their sample has more large commercial

than is representative of building stock.

Betsy L. Gardiner et al, 1985
Measured Results of Energy-Conservation Retrofits in Nonresidential Buildings: Interpreting Metered Data
Source: ASHRAE Transactions, Vol. 91, Pt. 2B, pp 1488-1498.
Metering Analysis: Retrofit
Building Type: Commercial and institutional
Measurements: At least monthly whole building fuel use
Modeling: No, compare energy intensities (energy per unit area)
Metering Duration/Interval: At least one year pre- and one year post-retrofit/at least monthly
This is work done on the BECA-CR data base. 94% of 300 buildings saved energy after retrofit. Based on total energy use in building. No normalizations. They note complications in evaluating retrofits.

J. S. Haberl and D. E. Claridge, 1987
An Expert System for Building Energy Consumption Analysis: Prototype Results
Source: ASHRAE Transactions, Vol. 93, Pt. 1
Metering Analysis: Energy Performance
Building Type: Institutional, university recreational center
Measurements: Fuel use by type, outdoor temperature, hours occupied, many other observations
Modeling: Yes, predict fuel use by multiple regression of significant parameters
Metering Duration/Interval: Multi-year or continuous/daily
The authors have developed a computer program that can predict energy use for this particular building based on previous energy usage. The program is used daily to reveal abnormal energy usage. Building energy management tool.

B. K. Hodge et al, 1986
A Simplified Energy Audit Technique for Generic Buildings
Source: ASHRAE Transactions, Vol. 92, Pt. 2.
Metering Analysis: Discussion
Building Type: Institutional, but for all classes of generic buildings
Measurements: Fuel use by end use (lighting, heating, cooling, food service)
Modeling: No, they use computer model to calculate ``target'' energy use
Metering Duration/Interval: 12 months/annual
Authors propose to classify buildings as to generic type in one climate, and then establish energy use intensity (energy per unit area) for an efficient, well-managed building of this type. Compare actual energy to this ``target'' case to find areas of inefficiency.

John Katrakis and Daniel Becker, 1984
Energy Savings in Buildings of Neighborhood-Based Non-Profit Organizations
Source: Proceedings from the ACEEE 1984 Summer Study on Energy Efficiency in Buildings,
Vol. D, pp. 74-84.
Metering Analysis: Retrofit
Building Type: commercial, small, includes recreational assembly
Measurements: Energy use by fuel, from utility bills
Modeling: No, compared energy use
Metering Duration/Interval: Not stated, probably one winter
This paper discusses attempts to measure performance of retrofits. No normalizing is done. Somehow they determine base energy usage. Most retrofits were to reduce heat load. Examine discrepancies between expected savings and actual.

Patrick Le Coniac et al, 1986
Energy Management Systems as a Source of Building Energy Performance Data
Source: Proceedings from the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 9, pp. 170-185.
Metering Analysis: Energy Performance
Building Type: Industrial/commercial, office building, and manufacturing.
Measurements: 4 zone temperatures, whole building electrical use and demand
Modeling: Yes, correlate energy use with ambient temperature
Metering Duration/Interval: 180 days/hourly
Use existing energy management system (EMS) to gather energy use and temperatures of building. Shows strong correlation between daily peak demand and peak outdoor temp. Able to separate load due to cooling. Can use EMS to find energy use patterns and end use electrical.

N. P. Leslie et al, 1986
Regression Based Process Energy Analysis System
Source: ASHRAE Transactions, Vol. 92, Pt. 1.
Metering Analysis: Energy Performance
Building Type: Military base
Measurements: Production levels, heating degree days, cooling degree days, energy use by fuel, labor force
Modeling: Yes, multiple regression
Metering Duration/Interval: 7 years/monthly
Used whole base data to correlate fuel use with several parameters. Heating degree days were best predictor of energy use; labor force next. Actual regression equations confidential. Had residual changes in energy use as a function of time.

Sukhbir Mahajan et al, 1986
Energy Analysis of a Retrofitted School Building with a Solar Air Heater
Source: Proceedings from the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 3, pp. 115-129.
Metering Analysis: Retrofit
Building Type: Institutional, elementary school
Measurements: Weather data, indoor temperature, fuel use, heat to space, solar flux
Modeling: Yes, did steady state heat balance on building to find solar fraction
Metering Duration/Interval: Two 12-day periods/hourly
School had solar collectors installed with other retrofits. Study was to find how well collectors were doing. Solar fraction determined by doing a heat balance on building. Internal gains were assumed, and heat loss was determined at night.

R. P. Mazzucchi, 1986
The Project on Restaurant Energy Performance End-Use Monitoring and Analysis
Source: ASHRAE Transactions, Vol. 92, Pt. 2.
Metering Analysis: Energy Performance
Building Type: Commercial, small, restaurants
Measurements: Many meters measuring multiple end uses<197>electricity, gas, hot water<197>and weather
Modeling: Yes, multiple regression with weather, customer count, other
Metering Duration/Interval: One year/15-minute.
On average, 1/3 of energy is used for food preparation, 1/3 for HVAC, and 1/3 for sanitation, refrigeration, lighting.

Fuller Moore, 1983
Monitored Performance of Patoka Nature Center: A Direct Gain Building with Beadwall Night Insulation in South Indiana
Source: Proceedings of the 8th National Passive Solar Conference, Sante Fe, N.M., pp. 387-390.
Metering Analysis: Energy Performance
Building Type: Institutional, nature center
Measurements: End use energy, heating equipment, lighting
Modeling: No, did some energy balances to determine solar gain
Metering Duration/Interval: One year/hourly
Found that solar contributed 48% of heat load. Made numerous assumptions to find energy saved by using bead-wall. Basically reports total energy use in heating season.

L. K. Norford et al, 1985
Measurement of Thermal Characteristics of Office Buildings
Source: Proceedings of the ASHRAE/ DOE/BTECC Conference, Thermal Performance of the Exterior Envelopes of Buildings III,
pp. 272-288
Metering Analysis: Energy Performance
Building Type: Commercial, medium office building
Measurements: weather with solar, 5 indoor temperatures, heat pump flow and temperatures, electric use, infiltration
Modeling: Yes, use equivalent thermal parameters and Fourier method
Metering Duration/Interval: Several months/hourly
Assuming steady state in winter leads to consistent UA values. In summer the use of air dampers during day changes UA value. Actually is a transient analysis using work of Sonderegger and Subbarao. The thermal network is too simple; BEVA (see Subbarao, 1985, below) gives good results.

Larry S. Palmiter and J. W. Hanford, 1986
Relationship between Electrical Loads and Ambient Temperature in Two Monitored Commercial Buildings
Source: ASHRAE Transactions, Vol. 92, Pt. 2.
Metering Analysis: Discussion
Building Type: Commercial, small office building and

grocery (ELCAP)
 Measurements: end use electric, indoor and ambient temperature
 Modeling: Yes, examines load vs ambient temperature
 Metering Duration/Interval: 1 year/hourly
Finds a non-linear relation between HVAC energy use and ambient temperature, due to nonlinear equipment performance, manual control, simultaneous heating and cooling on the same day, and multiple uses of building. Relationship is not well determined.

Erik W. Pearson and Larry Palmiter, 1986
Issues in Load Shape Representation
 Source: Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 9, pp. 220-238.
 Metering Analysis: Energy Performance
 Building Type: Residential and commercial, office building
 Measurements: Total electrical load
 Modeling: Yes, mathematical representations of monitored data are derived to explore their ability to represent complicated data.
 Metering Duration/Interval: 1 year, hourly
Mathematical approach to developing functions to represent electrical load shapes is presented. Two approaches are tried, but they are complicated and appear to be more than is needed. They recommend research on a stochastic component to be added to the mean.

Mary Ann Piette, 1986
A Comparison of Measured End-Use Consumption for 12 Energy-Efficient, New Commercial Buildings
 Source: Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 3, pp. 176-192.
 Metering Analysis: Energy Performance
 Building Type: Commercial
 Measurements: End-use energy<197>lighting, cooling, heating, fans, pumps, miscellaneous
 Modeling: No, mostly uses energy intensity to compare buildings
 Metering Duration/Interval: Varied/monthly
Authors run into difficulty when trying to compare buildings in different climates. Do not use a method for normalizing. Also different types of commercial buildings have radically different energy use, so cannot compare directly.

Ari Rabl et al, 1986
Steady State Models for Analysis of Commercial Building Energy Data
 Source: Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 9, pp. 239-261.
 Metering Analysis: Energy Performance
 Building Type: Commercial and institutional, 5 office, 5 university
 Measurements: Ambient temperature, total energy use
 Modeling: Yes, use regression to find base load, balance point, and heating and cooling slope
 Metering Duration/Interval: One year in most cases/monthly
Reviews methods of building energy analysis. Discusses problems with applying PRISM to commercial buildings. Will only work when there is good correlation between energy use and ambient temperature. Use of ventilation air distorts results.

P. D. Reiter, 1986
Early Results from Commercial ELCAP Buildings: Schedules as a Primary Determinant of Load Shapes in the Commercial Sector
 Source: ASHRAE Transactions, Vol. 92, Pt. 2.
 Metering Analysis: Discussion
 Building Type: Commercial, warehouse and retail (ELCAP)
 Measurements: detailed end use electric
 Modeling: No, analyzed load shapes
 Metering Duration/Interval: About 6 months/hourly
Author looks at hourly load profiles of 2 commercial buildings and shows how they are primarily driven by schedules. When doing a comparison, it may be more important to normalize for schedules than for weather.

T. E. Richtmyer et al, 1979
Thermal Performance of the Norris Cotton Federal Building in Manchester, New Hampshire
 Source: Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings, pp. 781-793.
 Metering Analysis: Energy Performance
 Building Type: Commercial, office building
 Measurements: Fuel use by type, electric, gas, oil

Modeling: Partial, used NBSLD predictions to compare to actual use
Metering Duration/Interval: 3 years/monthly(?)
Paper pointed out problems and solutions with the energy conserving features of this building. When energy use was higher than had been predicted, problems were found in the building shell and operation of HVAC equipment.

Howard Ross and Sue Whalen, 1982
Building Energy Use Compilation And Analysis (BECA) Part C: Conservation Progress in Retrofitted Commercial Buildings
Source: Proceedings of the ACEEE 1982 Summer Study on Energy Efficiency in Buildings, Panel 3, pp. 1-28.
Metering Analysis: Retrofits
Building Type: Commercial and institutional
Measurements: Yearly total fuel use by type
Modeling: No, compared annual fuel use directly
Metering Duration/Interval: 1 year pre-, 1 year post-retrofit/annual
No weather normalizing was done. Most of the 223 buildings had floor area over 50,000 sq ft. Found energy and cost savings, and then found payback period of retrofits.

Donald K. Schultz, 1984
End Use Consumption Patterns and Energy Conservation Savings in Commercial Buildings
Source: Proceedings of the ACEEE 1984 Summer Study on Energy Efficiency in Buildings, Vol. D, pp. 103-131.
Metering Analysis: Retrofit
Building Type: Commercial
Measurements: Total fuel use by type, estimated end use from audit
Modeling: None, auditor estimates fuel savings from fuel bills
Metering Duration/Interval: 1 to 2 years pre- and post-retrofit/annual
Author points out difficulty in assessing retrofit savings. Somehow auditors take into consideration changes that might affect the pre- to post-retrofit comparisons of energy use. Study covered several thousand commercial buildings.

William A. Shurcliff, 1985
Frequency Method of Analyzing a Building's Dynamic Thermal Performance
Source: (book, 2/2/85 draft version, published by author, Cambridge, Mass.)
Metering Analysis: Energy Performance
Building Type: Solar buildings
Measurements: none
Modeling: Yes, dynamic response
Metering Duration/Interval: N/A
This book is an easy-to-read guide to using the frequency method to predict temperature responses in a massive solar building. Similar to BEVA (see Subbarao, 1985, below), but author does not explain how to use metered data to calculate response factors of building.

Robert C. Sonderegger, 1977
Modeling Residential Heat Load from Experimental Data: The Equivalent Thermal Parameters of a House
Source: Proceedings of the International Conference on Energy Use Management, Vol. II, Tucson, Arizona, pp. 183-194.
Metering Analysis: Energy Performance
Building Type: Residential, townhouse
Measurements: Indoor and outdoor temperature, solar flux, furnace heat rate
Modeling: Yes, using four-variable regression
Metering Duration/Interval: 7 days/hourly(?)
Defines and calculates ``equivalent thermal parameters'' (ETPs) of a house using metered data. ETPs are: house heat loss per degree (F), equivalent solar window area, rate of constant heat transfer to ground and adjacent houses, and furnace efficiency.

L. G. Spielvogel, 1984
One Approach to Energy Use Evaluation
Source: ASHRAE Transactions, Vol. 90, Pt. 1B, pp. 424-435.
Metering Analysis: Discussion
Building Type: Commercial
Measurements: End use energy, when available
Modeling: No, only determine energy end uses from available information
Metering Duration/Interval: N/A
Author shows the benefits of knowing end use of energy when contemplating conservation measures. Energy use patterns are often not at all what is expected.

Lynn F. Stiles et al, 1984
An Analysis of Energy Savings in the Academic Buildings at Stockton State College
Source: Proceedings of the ACEEE 1984 Summer Study on Energy Efficiency in Buildings, Vol. D, pp. 132-147.
Metering Analysis: Retrofit
Building Type: Institutional, college buildings
Measurements: Total building gas and electric use
Modeling: Yes, linear regression with heating degree days
Metering Duration/Interval: 5 years pre-, 90 days post-retrofit
Analyzed energy savings using linear regression. Heating and cooling play large role in energy use in these buildings.

Kris Subbarao, 1985
Building Parameters and Their Estimation from Performance Monitoring
Source: ASHRAE Transactions, Vol. 91, Pt. 2B, pp. 1886-1992.
Metering Analysis: Energy Performance
Building Type: Residential
Measurements: Ambient and indoor temperature, solar flux, heater power
Modeling: Yes, BEVA (see below)
Metering Duration/Interval: 7 days/half-hourly(?)
This paper describes aspects of the BEVA model. It gives no clear indication on how to proceed with modeling a building after data are collected.

Kris Subbarao et al, 1985
Short-Term Measurements for the Determination of Envelope Retrofit Performance
Source: ASHRAE Transactions, Vol. 91, Pt. 2B, pp. 1516-1524.
Metering Analysis: Retrofit
Building Type: Residential
Measurements: Ambient and indoor temperature, heater power, solar flux
Modeling: Yes, BEVA; find transfer functions that describe house
Metering Duration/Interval: 7 days/half-hour
BEVA is a method to determine building thermal performance from short-term measuring. May need to ``intervene'' to get needed data (i.e., may need to heat building to higher than normal temperatures). Method is not straightforward.

Leonard W. Wall and John Flaherty, 1984
A Summary Review of Building Energy Use Compilation and Analysis (BECA) Part C: Conservation in Retrofitted Commercial Buildings
Source: What Works: Documenting Energy Conservation in Buildings, Washington: American Council for an Energy-Efficient Economy, 257.
Metering Analysis: Retrofit
Building Type: Commercial
Measurements: Total energy use by type
Modeling: No, compared energy intensities
Metering Duration/Interval: At least one year pre- and post-retrofit /annual
Most of the buildings were large, so weather normalization may not be important. However, weather normalization should be an issue for the many schools in the data base.

N. W. Wilson et al, 1985
Equivalent Thermal Parameters for an Occupied Gas-Heated House
Source: ASHRAE Transactions, Vol. 91, Pt. 2B, pp. 1875-1884.
Metering Analysis: Energy Performance
Building Type: Residential, single family
Measurements: All weather, indoor room temperatures, furnace run time, duct temperatures
Modeling: Yes, looked at dynamic, steady state from daily data and steady state from monthly data
Metering Duration/Interval: One year/hourly
For the dynamic model, needed at least a month of data to get statistically meaningful results. Found that accuracy of predictions of model for other periods was affected by differences in weather. Dynamic model did not necessarily do better than the steady-state models.

Donald R. Wulfinghoff, 1984
Common Sense about Building Energy Consumption Analysis
Source: ASHRAE Transactions, Vol. 90, Pt. 1B, pp. 437-447.
Metering Analysis: Discussion
Building Type: Commercial
Measurements: None
Modeling: No
Metering Duration/Interval:
A discussion of what can be inferred from energy use data. Submetering is sometimes the only way to know

end use fuel use. Energy waste in a building should be determined by examining entire building<197>not just by a study of consumption.

Edward Wyatt and Olivier de la Moriniere, 1986
Measured Performance of Cool Storage in Buildings: Summary of Initial Analysis
Source: Proceedings of the ACEEE 1986 Summer Study on Energy Efficiency in Buildings, Vol. 3, pp. 248-250.
Metering Analysis: Discussion
Building Type: Commercial
Measurements: Uncertain
Modeling: No
Metering Duration/Interval:
Part of the BECA-LM data base work. Submetering needed to identify effects of load management on buildings total energy use. Cool storage benefits may not be seen for 3-4 years.