Power Signatures as Characteristics of Commercial and Related Buildings

MICHAEL MACDONALD
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

This paper proposes the use of "power signatures" as an important concept for building energy analysis. Power signatures are considered to contain "energy or power characteristics" of a building. Developing relationships between energy characteristics and building physical characteristics is seen as an important area for improvement of analytical tools 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 improved. A categorization of analysis methods is presented to define the parameters of interest for several currently used methods. Power signatures indicate building energy behavior with respect to time, so the parameters of interest are average power level and time of occurrence. Because a rate quantity (power) is used, comparisons between different time steps are practical. If practitioners could begin using power signature concepts to present energy use data on buildings, improved communication of results appears possible. Potential future study could be continued in several areas to improve the use of power signatures and energy analysis overall.

INTRODUCTION

The term energy signature has been used in the past in a number of ways. Perhaps the best known use relates to the energy behavior of a building with respect to outdoor temperature or indoor-outdoor temperature difference.[1] However, energy signature may sometimes be used to indicate building energy behavior with respect to time, and a device called the "energy signature monitor" was developed to collect and store time-dependent temperature or energy parameters of interest.[2] Distinctions between time temperature domains are needed when discussing "signatures," as both approaches provide useful but different information.

This author has proposed the term "power signatures" as an analysis concept that is directed at examining time dependence of building energy behavior.[3] This tool is proposed for use in comparing energy use in commercial and related buildings (including institutional, large multifamily, and some industrial facilities). The use of power signatures was proposed as part of a 3-level approach to analyzing characteristics data for commercial buildings.[3] Improving the ability to perform analytical comparisons between buildings (including energy audit analyses) is a driving factor in developing the concept and approach.

In the proposed 3-level approach, the first level of data covers obtaining physical characteristics of buildings to understand what systems, schedules, or uses might impact energy use. The second level covers analysis of energy data. The development of monthly power density values (W/ft^2) is recommended for this level to determine annual power signature profiles and analyze possible relationships between the physical characteristics and the power density characteristics exhibited in the annual power profile. Study of these relationships is needed to improve knowledge of the causes of variations in energy use, including the expected relative impacts of different schedules, functional uses, and energy systems.

The third level of the proposed approach involves extending the analysis to more detailed data, such as hourly data or more detailed breakdowns of end uses. Examination of relationships between more detailed data, such as hourly, and less detailed data, such as monthly, is also needed. Daily data, or other time steps, are also of interest. Improved knowledge is needed about how to extract more information from less detailed data and how much detailed data should be collected to improve understanding of the less detailed data. Conceivably, rules governing data hierarchies could be developed.

Significant effort has been directed towards developing a classification structure for building characteristics (first level) in the Pacific Northwest. This classification structure was developed to provide consistency and coordination in collection of end-use energy data for a large-scale monitoring program directed at utility load research. The classification structure uses a hierarchical taxonomy, where building types, end-use loads, and key building characteristics are organized to accommodate analysis at many levels.[4] Readers interested in collecting energy data for commercial buildings should consider this classification scheme as a starting point for organizing data on physical characteristics to assist in making comparisons between buildings.

Analysis of the collected data is the second level of the 3-level approach, and the most commonly available energy data will be monthly utility billing data. Monthly billing data can be used to study results for a particular building, and the data can be converted to an energy use intensity (EUI, typically Btu/sq.ft./yr). However, the monthly data are often not directly comparable between buildings, and the EUI condenses all the information contained in the data to one value for the whole year. Monthly power densities are an improvement over annual EUIs, in that the useful information contained in the monthly data is retained to supplement any annual values.

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The time series of monthly power densities is part of a "power signature" that provides important information about how a building is operated and the energy use in the building. Power signature is a generic term covering normalized power profiles of buildings for any given time step. The power level is the average power for the time step of interest, and because power is a rate instead of an integrated quantity, power densities for hourly data can be compared to power densities for monthly data. This ability to compare different time steps appears to be important for improving the potential analysis that can be performed when studying variations among commercial buildings and their energy use (there are potential benefits for residential buildings also).

BACKGROUND

Although there may be no concern for how a 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 to refer to when considering the energy use in a building. Presently, practitioners develop their own sense of what constitutes an energy efficient building based on their experience with similar buildings, the types of activities within specific buildings, and any history of achieving reductions in energy use in comparable buildings. However, this knowledge is not easily transferable, because it is usually based on several years of experience about patterns of energy use that can be expected for different buildings and impacts of schedules, uses, geographic location, and system configurations. In the past, the use of common "indexes" such as EUIs has often provided the basic information needed to determine and compare general performance. Other methods use increased levels of analysis to compare performance. A categorization scheme for methods to analyze metered data in commercial and related buildings is presented below to describe the differing approaches and the parameters of interest.

NORMALIZATIONS

Comparison of energy use between buildings typically requires some type of normalization to improve understanding. Power signatures represent an attempt to normalize analysis results relative to building size (floor area) and time step used for data collection. 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. Weather correction is another important consideration. The weather dependence of a building is an important initial characteristic to check[5]. Corrections for weather can be accomplished with 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. Analysis of cooling energy dependence on weather can be difficult with monthly data (not many data points). There may also be seasonal confounding factors, such as changes in occupancy or number of customers, that influence consumption in either the heating and 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."[6] This means that 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 consider whether extended analyses of possible relationships are needed.

ANALYSIS CATEGORIES

Five general categories for grouping data analysis methods for buildings are:

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

Annual total energy and energy intensity comparison. The EUI falls in this category, and this is the general index approach used for many analyses. Annual total energy is the sum of the energy content of all fuel used by the building in one year. Energy intensity (such as the EUI) is the total energy divided by the floor area. Several studies have used the annual total energy before and after a retrofit to evaluate savings.[7-10] Other studies used energy intensities to compare energy usage in different buildings or in the same building before and after a retrofit.[11-15] The use of generic, efficiently operated buildings to provide a base energy use for comparison with other buildings has been proposed.[16] In this comparison approach, 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 that expected in the generic buildings could then be examined. Some caution is needed when buildings span a range of sizes, because small (< 10,000 ft^2) commercial buildings are known to use more energy per square foot than larger buildings.[17] The strength of the total energy and energy intensity comparisons is their ease of use and widespread familiarity. What is lacking is knowledge regarding causes of variation and the relative impacts of differing schedules, uses, and systems on individual buildings. This general approach to data analysis is useful for quick comparisons of many buildings but does not provide information as to what is causing the scatter (Figure 1).

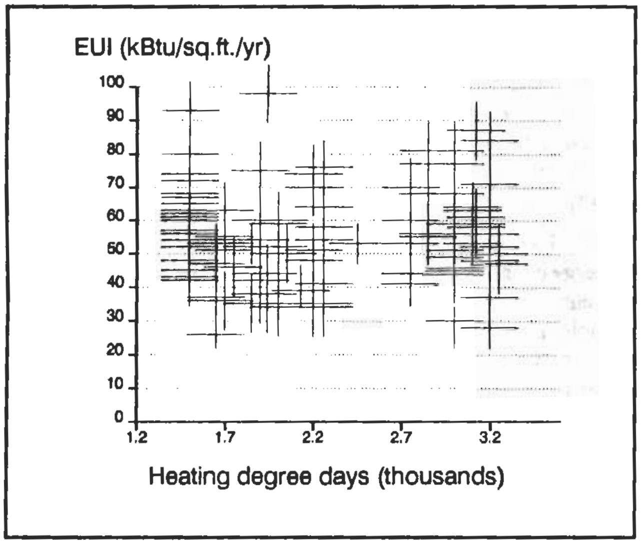

Fig. 1 – Range of EUIs for schools in Mississippi.[16]
Each mark represents the EUI for a school, and the spread is of most interest. No information was available on characteristics that might influence the spread.

Linear simple regression and component models. Linear simple regression has been the subject of significant analysis. Fuel use is typically modeled as a base consumption component plus a consumption component that is linearly proportional to either outdoor temperature or heating degree days (HDD) (temperature difference). The typical approach to this analysis provides temperature dependent information, although time dependent results can also be derived. Several authors have examined applying these models to commercial/institutional buildings.[18-22; 5] Commercial 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.[23] It is therefore not surprising that mixed success at applying linear heating degree day models to these buildings has been reported in the literature. For the 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 being in a heating dominated climate, such as found in the northern tier of the U.S.

"Component analysis" is directed towards understanding patterns ("signatures") of energy use available in monthly data and determining breakdowns of energy use by type of building systems.[18] Time dependence of energy use is often used in this analysis approach to understand loads that are not sensitive to temperature. The components typically examined in linear regression models are mentioned above. Cooling energy use is also often of interest for commercial buildings. While linear regression can be used to develop the breakdown of components, other methods can also be used. The presence of multiple fuels in a building can aid in developing component breakdowns, and the analysis of consumption for different components is typically an important part of understanding building energy performance. Overall, component models represent an important method for analysis. Linear simple regression methods for determining component breakdowns have been used for commercial buildings, but more needs to be learned. The information available in power signatures is similar to what can be learned from component analysis, and extending the capabilities of component analysis is central to better comparisons of building energy performance.

Multiple linear regression models. These models are in the early development stage, and they can be used to account for factors other than outdoor temperature that influence building energy use. As with simple regression models, time dependent results can be generated. Also, effects of factors related to time, such as schedules, can be included. In one study, the energy use of 50 commercial buildings in Michigan was analyzed statistically to identify major contributors to annual energy consumption variation. An energy-predicting model was produced which could account for 93% of energy consumption variations using ten factors.[24] Another study correlated monthly (time dependent) energy use on a military base with several factors, including HDD, production levels, and labor force levels.[25] A third study used multiple regression to model energy use in restaurants.[26] In the restaurant study both temperature and time dependent metered data were presented. The regression analyses examined the relationship of specific end uses to temperatures and customer count. Models of total monthly energy use were developed based on outdoor monthly average temperature (monthly time dependence). 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 (daily dependence on temperature and other parameters, which provides a model with a time step of one day that indicates time dependence). When measured energy use deviated beyond a certain level from predicted energy use, an expert system was used to diagnose possible causes of the deviation by comparing conditions in the building to previous events.[27] Multiple regression methods appear to have promise in modeling and comparing the diverse stock of commercial buildings in this country.

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 what variables should be used to develop the energy use prediction model. Another concern is the relative complexity of setting up the model vs the improved usefulness of the results.

Building simulation programs. This category will be covered only briefly. Modeling buildings with simulation programs is sometimes used to analyze metered data for commercial buildings.[11] Detailed data on building configuration and use must typically be collected to develop a model. Time and temperature dependence of energy use can usually be readily examined with a simulation model. Sometimes projected energy use of a building is modeled as the building is being designed, and actual energy use is compared to simulated use to compare energy performance. In other instances, energy use may be modeled and actual energy use used to "calibrate" the model. A calibrated model can potentially be used to compare predicted and actual savings from retrofits.

Dynamic thermal performance models. This category will also be covered only briefly. Development of these techniques has been primarily for determining heat flows associated with the building structure and not heat flows of the building systems.[28] These models do not *require* detailed information about the building, and they provide an empirical description of the real energy performance of a building. As with simulation models, both time and temperature dependence of energy use are typically readily determined. Transient thermal performance is often determined from short-term monitoring. These techniques offer significant promise for the future.

DISCUSSION

Many purposes underlie analyses performed on commercial buildings energy use, and the particular focus of this paper relates to purposes such as: developing a data base on building energy use to be used as a guide for comparison of efficiency levels with other buildings, diagnosing sources of energy waste in a building, providing an estimate of benefits from energy efficiency measures, and providing a tool for continued energy management. With this in mind, the use of power signatures in such analyses is presented below.

While the different analysis techniques presented above all have strengths and weaknesses, the particular interest in using power signatures is to provide a method that can examine annual, monthly, hourly, and more detailed time step dependence of energy on a common scale – power – to determine information about different uses of energy in a building. Power profiles indicate magnitudes of weather dependence with time or year, which can help in determining what other types of analysis might be useful. Power signatures are meant to supplement other analysis methods, but they may be the most useful initial method for studying a building. Temperature dependence of energy use is important and should be analyzed at some point in most cases, but time dependence appears to be more important to check initially. This does not mean a "signature" of Watts per square foot could not be generated for temperature dependence, but I propose the time domain as the first signature to examine.

As mentioned above, component analysis is typically aimed at providing equivalent information, and power signatures extend component analysis to allow comparisons of different time steps. For both component analysis and power signatures (or other methods), development of an understanding of the relationships between physical characteristics and the energy behaviors of buildings is needed.

Energy analysis provides information about energy use in buildings, and this information can be thought of as "energy characteristics" or "power characteristics." 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). Thus, 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. An important example in this area is developed in a report from Lawrence Berkeley Laboratory,[29] that discusses potential energy characteristics exhibited in profiles of hourly energy use over an extended period for several buildings in California. Important information is also contained in profiles of monthly data, and the purpose for presenting the concept of power signatures is to provide a proposed method to begin making comparisons between monthly–hourly energy characteristics and building physical characteristics.

EXAMPLES

Figure 2 shows the monthly power densities (MPDs) for a banking services building located in Knoxville, Tenn.

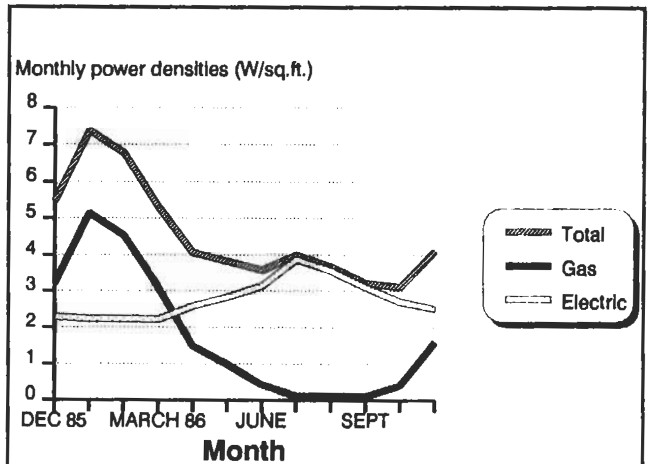

Fig. 2 – Monthly power densities for electricity, gas, and total fuel for a banking services building in Knoxville, Tenn.

The MPD for a month can be calculated as:

$$\text{MPD (W/ft}^2) = \text{monthly kWh} \times 1000 \div \text{\# of days} \div 24 \div \text{ft}^2$$

or

$$\text{MPD (W/ft}^2) = \text{monthly Btu} \div \text{\# of days} \div 24 \div \text{ft}^2 \div 3.412$$

The monthly signatures for total energy and individual fuels are provided in this figure. In some cases, an analysis may be interested in an individual fuel, the total of all fuels, or total energy and individual fuels together. For this building the interaction between heating and cooling in the total is interesting, because 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 both together may allow recognition of patterns for specific climates that can be used to recognize similar masking in other buildings. The significant peak in heating indicates an important temperature dependence for heating. The peak power of about 7 W/ft^2 is high relative to other buildings examined (Figure 3), is caused by heating load, and indicated that there were potential energy system problems in this building. Later investigation showed that HVAC systems maintained comfort conditions during unoccupied hours and that a zoning problem caused one of the systems to run continuously during moderately cold weather.

As practitioners develop histories of power signatures for buildings, recognition of relative performance patterns and amplitudes of power profiles associated with specific characteristics (e.g., problems) will improve. (This includes developing a sense of when potential problems with areas—such as including a storage area with little consumption or having a high energy using area in the building—have occurred with the calculations.)

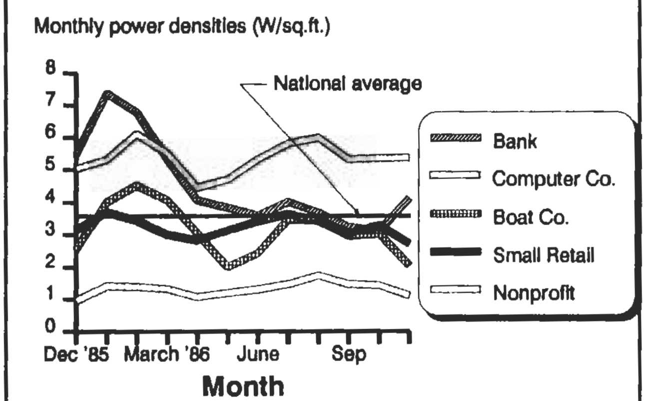

Fig. 3—Monthly power densities for total fuel for 5 small buildings in Knoxville, Tenn.

Figure 3 provides power density profiles for total fuel use in 5 small (10,000 ft^2 or less) buildings in Knoxville, Tenn. The line shown for the national average is the mathematical average of the aggregate values for all commercial buildings in the 1979 and 1983[17] Department of Energy (DOE) surveys of commercial buildings. Note that annual data plot as a constant line on the monthly profile.

Comparisons between buildings and the ranges of power densities for buildings are striking. The bank has the highest overall power peak (in the winter), but the computer company is consistently higher overall (due to high base loads for computer equipment operation). The boat company profile is based on conditioned area, which is only half the total area of the business. The other half is a storage area, which contributes some energy use for lighting, and possibly for occasional use of portable heaters. The small retail store shows reduced temperature dependence, and the occupants were conscientious about manual temperature setback and setup. The nonprofit building was well insulated, had water-source heat pumps, and was not fully occupied all week. The profile for this last building shows minimal temperature dependence and low overall consumption. The information presented here provides an intriguing starting point for developing a data base of relationships between power characteristics and physical characteristics of buildings.

For a comparison with a large building, Figure 4 shows preliminary data obtained for the headquarters building of DOE in Washington, D.C. This is a large building of over 1 million square feet. The profiles show a building with strong peaks for heating and cooling, which indicates significant temperature dependence of both loads. There is a decrease for 1986/87 heating relative to 1984/85 and 1985/86 loads, and this is thought to be caused by a conservation program initiated in late 1986. The peaks are presently thought to be due to high ventilation loads caused by clogged return air paths in the HVAC systems.[30] No cooling consumption data are available for 1985 or 1986. The cooling data for 1987 indicate one of the potential problems in comparing data for different buildings. The cooling consumption is measured for chilled water supplied to the building, which neglects the effect of the coefficient of performance (COP) of the chiller providing the chilled water. With a typical overall COP of 3, the overall 1987 summer peak for all energy might be

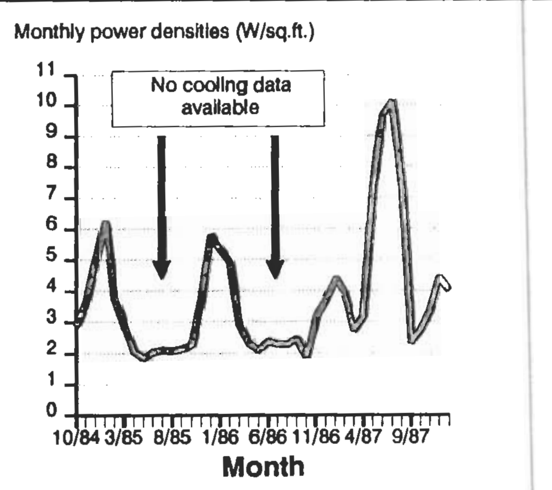

Fig. 4—Monthly power densities for total fuel for the Forrestal Building in Washington, DC.

reduced by about 50%. A higher overall COP would reduce the value further. However, the strong cooling peak remains and indicates that cooling systems are important to examine for potential improvements in this building.

As mentioned above, there may be interest in examining the profile for an individual fuel. The gas profile in Figure 2 shows the heating requirements for the bank building. The average load during the heating season is about 2.5, and the heating load averaged over the whole year is just under 2 W/ft^2. The ratio of peak to average load is about 2 for the heating season average and about 3 for the whole year average for this building in this climate.

The electric profile shows all other uses. A base electric power density of 2-2.5 can be seen for months that have no apparent temperature dependent load (cooling), and the average of the temperature dependent load is about 3 W/ft^2. This implies that the average cooling requirements for the cooling season are just under 1 W/ft^2 ($3 - 2.2 = 0.8$). The cooling load averaged over the whole year is about 0.5 W/ft^2. The ratio of peak to average load is similar to heating at about 2 for the cooling season average and about 3 for the whole year average in this climate.

Figure 5 shows hourly power densities (HPDs) for the bank building of Figure 2 during a week in June 1987 (6/17–6/23). The solid line shows the mean for the data presented. The hourly densities indicate the power peaks that occur for this building when lighting and air conditioning are energized during workdays. The weekend period is 6/20–6/21. The high levels during nights and weekends indicate that energy systems are not turned off during these periods. The ratio of peak to average power is slightly less than 2 for this period.

The plot from Figure 2 is placed beside the hourly densities in Figure 5, and it is interesting to note that the mean of the hourly densities is comparable to an interpolated value from a similar period the previous year (see dashed line). Examination of relationships between monthly and hourly power densities may be useful for developing an understanding of how to obtain more information from less detailed data and how much detailed data may be needed to supplement less detailed data. For example, hourly data can provide indications of end-use breakdowns of energy from analyzing the power profiles together with information on equipment sizes. Hourly data also provide information on power peaks and building schedules that may otherwise be difficult to verify.

As a final example of possible uses of power signatures, Figure 6 shows how average electric power densities can be compared to other power quantities that might be measured by a utility. The building in Figure 6 is a drug store in North Carolina. The electric data are presented in three categories: average electric power density for each month (average), metered demand density for each month (demand), and billed (or billable – which means the demand billed is a function of previous demand values also) demand density for each month (ratchet). The terms 'average,' 'demand,' and 'ratchet' are used in the figure to indicate these data categories. The data for this building indicate high consumption and power. This building has not been visited, but provides an example of the data categories that may be of interest for some analyses. Load factor [kWh/(kW x 24 x days)] may also be of interest, and it is equal to the 'average' monthly power density divided by the 'demand' power density. By coincidence for this building, the load factor is almost identical to the 'average' curve divided by 10. The exception is in the winter, January–March, 1987, when the load factor is about 0.3 instead of 0.2.

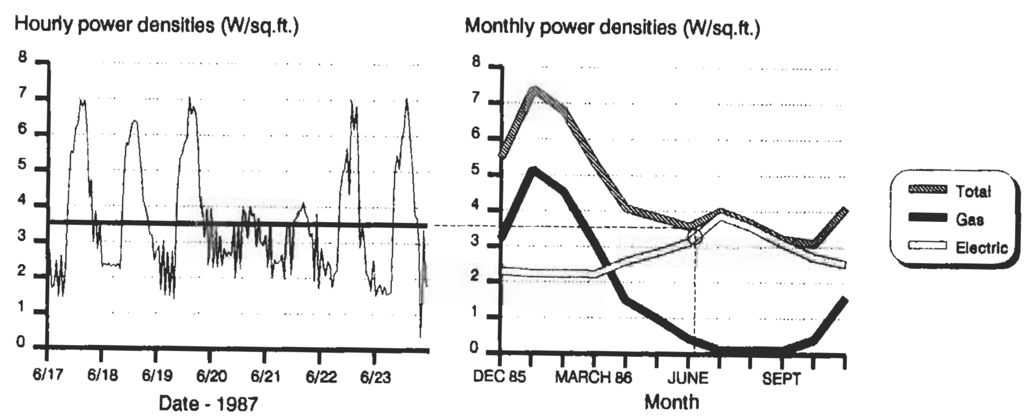

Fig. 5 – Hourly power densities for electricity for one week in June 1987 compared with electric monthly power densities for 1986 for the banking services building in Knoxville, Tenn. The hourly data provide a 'window' to view inside the monthly aggregation. Other time steps (e.g., daily) could also be included in the potential 'chain' of windows.

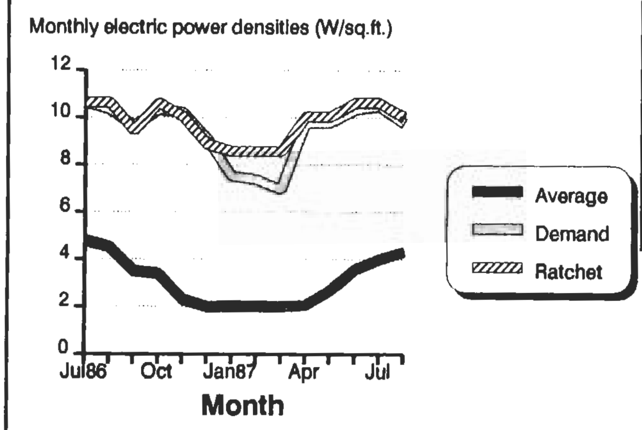

Fig. 6—Monthly power densities for electricity for a drug store in North Carolina.

The higher power levels for this building may indicate that no setback/setup is used, and the lighting levels may also be high. The building is small (about 1,700 ft^2), and the high levels may be partly due to size. The possibility that the air conditioner is oversized was considered, but total demand values indicate that the air conditioner is about 3.5 tons—which is not unreasonable for this store. As relationships between the physical characteristics and energy characteristics are better understood, and potential energy problems are related to energy or power characteristics, diagnostics may be significantly improved and the productivity associated with improving energy efficiency increased. In addition, if an understanding of patterns that indicate the potential for demand reductions can be developed, power reduction benefits may be possible for equipment replacements (e.g., reduced lighting, higher efficiency lighting, and air conditioner replacement).

CONCLUSIONS

The use of power signatures as energy characteristics of buildings offers potential for improving diagnostics of energy problems and comparisons of relative energy and power use between buildings. Improved understanding of the relationships between physical characteristics and energy or power characteristics is needed to advance energy analysis capabilities. If practitioners could begin using power signatures to present energy use data on buildings, improved communication of results appears possible. Potential future study could be continued in several areas to improve the use of power signatures and energy analysis overall. In particular, examination of the uses of more detailed data to supplement monthly data appears to offer significant promise, and a challenge is presented in developing better understanding of relationships between patterns of data at different time steps.

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