EVALUATING AND MONITORING ENERGY CONSERVATION IN MULTIBUILDING CLUSTERS WITH STATISTICAL MODELS

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ABSTRACT

A standardized method for modeling energy consumption in mixed clusters of residential and commercial buildings is described. The basic approach is to delineate energy consumption along three dimensions: time, day-length, and temperature. The temperature-sensitive portion of energy consumption is captured by the Princeton Scorekeeping Method (PRISM). The time- and daylength-sensitive portions of energy consumption are captured by other variables. The models were designed to aid in determining the scope and performance of alternative financing activities on a U.S. Army base.

INTRODUCTION

This paper presents a relatively simple statistical process for modeling energy consumption in mixed clusters of residential and commercial buildings. Concrete examples are presented using models developed for U.S. Army facilities at Fort Sheridan. The models were developed under a Federal Energy Management Program (FEMP) project jointly sponsored by the U.S. Army and the U.S. Depart-ment of Energy.

These simple statistical models can be used to delineate important sources of energy savings, simulate the impacts of potential conservation measures, uncover potential baselining problem areas, and monitor and verify engineering-based predictions. The process used to derive the models is designed to be transferred easily to other locations or situations. This generality will lead to the development of generic decision process algorithms that could be incorporated into computerized artificial intelligence packages.

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METHOD

The basic approach of the modeling method is to delineate energy consumption along three dimensions: time, daylength, and temperature. In addition to an intercept term, the models use the following independent variables: a trend term; the length of the billing period, hrs; a daylength variable, hrs; and heating or cooling degree days, °F-day, as appropriate.

Time-sensitive variables. The time-sensitive portions of energy consumption are captured by the trend term and the length of the billing period. The purpose of the trend term is to determine whether energy consumption has unidirectionally increased or decreased over the period being modeled. Unidirectional increases or decreases may be correlated with some factor that is either not known or not readily included in the model. For example, changes in population, the use of energy-consuming machinery, the amount of floor space, or the implementation of energy conservation measures can cause long-term increases or decreases in energy consumption. The time trend variable can be constructed as a simple sequence of whole numbers beginning with the number one.

Knowing about such trends is particularly important to the establishment of energy consumption baselines in shared energy savings contracts. Assume, for example, that the energy savings of a given conservation project is calculated as the amount of energy consumed per year after the project was implemented minus the amount of energy consumed per year before the project was implemented. Assume also that long-run energy consumption has and continues to increase. Because of this long-term trend, the calculated savings are likely to be smaller than the savings actually attributable to the conservation measure. The contractor, therefore, is likely to obtain less of a return than is due him. If, on the other hand, long-run energy consumption has and continues to decrease, the contractor is likely to obtain more than is due him.

The length of the billing period is used to delineate the portion of the load that tends to be a strict function of time. Often this variable is eliminated by a normalization process in which some or all of the other variables are divided by the number of days in the billing period. We currently retain the length of the billing period as a separate variable because we expect to evaluate the impacts of more detailed partitions of time in future models. In some instances, for example, it may be appropriate to determine whether the amount of work time, i.e., the number of weekdays, is correlated with energy consumption differently than the amount of nonwork time, i.e., the number of weekends and holidays, in a billing period.

Daylength-sensitive variable. Energy consumption sensitive to daylength is captured by a variable that tracks the cyclical increase and decrease of nighttime hours during the course of a year. These daylength changes occur at both the beginning and the ending of the day --sunrise and sunset--when humans are generally at home and relatively active. Daylength changes probably have the greatest impact on energy used for lighting. Other impacts, however, may be traced to behavioral changes that might occur as indoor activities are substituted for outdoor activities and vice versa. For example, the use of equipment such as radios, televisions, stereos, and tape decks might change cyclically over the year. The internal gains that might accompany such behaviors could affect heating or cooling systems as well.

The variable used to track daylength changes in this modeling method is derived as

$$CNH = TNH - (NHS * N) \qquad (1)$$

where CNH is the change in nighttime hours, i.e, the hours between sunset and sunrise, cumulated over the billing period; TNH is the total number of nighttime hours in the billing period; NHS is the number of nighttime hours for the shortest night of the year; and N is the number of days in the billing period. This variable can be estimated knowing only the beginning and ending dates of the billing periods and the latitude of the facility.

Temperature-sensitive variables. The temperature-sensitive portions of energy consumption are tracked by heating or cooling degree days. Heating degree days are usually highly correlated with space heating and other loads sensitive to cooler temperatures, and cooling degree days are often reasonably correlated with cooling loads such as air conditioning and refrigeration.

The procedure for deriving the degree day variables is embodied in the Princeton Scorekeeping Method (PRISM) (1). At PRISM's core is a weather normalization procedure in which the base temperature used to derive heating or cooling degree days is treated as a variable rather than as a known constant such as 65 °F. The basic process is to find the base temperature(s) for which the R-squared statistic is maximized.

Note that no attempt is made to separate temperature-induced impacts on space heating or air conditioning from temperature-induced impacts on other temperature-sensitive loads such as refrigeration or water heating (2). Actually refrigeration and water heating loads are likely to be sensitive primarily to the amount of time in a billing period and only partially sensitive to temperature. The modeling process outlined here would split the two components of these and similar loads.

Data availability. To summarize, the basic independent variables used in the modeling process include a time trend, the lengths of the billing periods, changes in the billing periods' nightlength relative to a summer minimum, and heating or cooling degree days with various base temperatures as appropriate. The dependent variable would be the amount of energy used per billing period.

The data required to derive these variables are readily available for most federal facilities. Monthly bills, for example, generally contain the amount of energy used and the date measured, as well as the cost of the energy. The latitude of a facility can easily be obtained from maps. Daily weather data, if not collected immediately onsite, are usually collected close enough to the site to be highly correlated with site-based weather observations.

Other variables could be constructed from data on variables such as the number of military personnel, the number of dependents, the number of civilian employees, the amount of output, and the amount of floor space, and added to the models. These data, however, are less generally available on a per billing period basis than the data required to derive the core variables. In this paper we focus primarily on the general variables, and although less general variables are sometimes alluded to, none has yet been incorporated into the sample models.

SAMPLE MODELS

The modeling method outlined above was developed while investigating energy consumption at Fort Sheridan. Fort Sheridan is the headquarters of the Fourth U.S. Army, U.S. Army Reserve, and numerous other U.S. Army activities. The base personnel include an administrative staff, officers, enlisted personnel, military dependents, and a significant number of civilians. The average population during fiscal year 1987 totaled 6,379.

Fort Sheridan is located approximately 20 miles north of Chicago, Illinois, on the shore of Lake Michigan. Fort Sheridan was established as an Army base in 1890. Between 1890 and 1895, 64 buildings were built. These buildings range in size from 3,000 to 27,000 square feet. They are generally two story brick buildings with pitched roofs. Another 38 buildings were constructed between 1890 and 1938. From 1939 to 1945 an extensive building program was implemented. The resulting 91 units are generally two-story frame buildings that range from 1,000 to 22,000 square feet. After the 1940s, two-story frame multiple-family housing units were constructed. These are generally 1,000 to 7,000 square feet.

As of September 30, 1987, there were approximately 2,656,749 total square feet of building space at Fort Sheridan. Approximately 472,266 square feet are being heated with steam produced at a gas-fired central heating plant. Approximately 1,368,372 square feet are being heated with individual gas-fired units. The remaining 816,111 square feet are heated primarily with fuel oil. Approximately 822,092 square feet are air conditioned.

Three separate models were developed to analyze energy consumption at Fort Sheridan--one for electricity and two for gas. The number of models is limited by the number of meters from which energy consumption data are available. The models are for: total on-base electricity consumption, mwh; central heating plant gas consumption, therms; and other gas consumption, therms.

The models are the result of ordinary least-squares regressions calculated in a LOTUS spreadsheet. The data upon which the models are based extend from the beginning of fiscal year 1985 through fiscal year 1987. The models are presented in Table 1. Figures 1 through 3 show how the values of energy consumption predicted by the models compare with the actual amount of energy consumed over the 3-year period.

Electricity consumption model. The parameter estimates for all of the independent variables (except the intercept) in the electricity consumption model are statistically significant at the 5% or greater level. This indicates that the use of electricity increases when the total number of hours increases, the number of nighttime hours increases, the number of heating degree days increases, and the number of cooling degree days increases. The model also indicates that the use of electricity has generally increased during the past 3-years.

A number of interpretations are possible. First, the amount of electricity used generally, e.g., for lights, motors, computers, is greater during long billing periods than during short billing periods.

Second, more electricity appears to be used when nights are relatively long than when nights are relatively short, probably by lighting equipment, and possibly by indoor recreational equipment such as televisions and stereos.

Third, greater use of electric space heaters, electric blankets, or electric automobile water heaters, may be causing an increase in electricity use during cold weather.

Fourth, greater use of air conditioners and electric fans, or larger refrigerator loads may be causing an increase in electricity use during hot weather.

Fifth, some factor or group of factors is related to electricity increases over the entire 3-year period. Possibilities include on-base population or work force increases, greater use of personal computers and other workplace tools, or additions to the amount of floor

Independent Variables and Miscellaneous Statistics	Parameter Estimates[1] for Models with the Following Dependent Variables: Electricity (mwh)	Gas at Central Heating Plant (therms)	Other Gas (therms)
Independent Variables			
Intercept	332.64 (278.23)	20488.66 (40040.39)	-9363.75 (25920.18)
Time Trend	11.54 (1.29)	-1371.59 (549.89)	-112.45 (356.84)
Total Hours in Billing Period	1.31 (0.41)	30.18 (54.66)	83.19 (35.65)
Nighttime Hours in Billing Period	1.33 (0.44)	-212.23 (170.95)	-192.11 (101.44)
Heating Degree Days[2]	0.15 (0.06)	165.64 (19.93)	191.18 (14.55)
Cooling Degree Days[3]	1.07 (0.13)		
Miscellaneous Statistics			
Number of Observations	36	34	35
Degrees of Freedom	30	31	31
Standard Error of Y Est	75.54	29670.33	19255.47
R-Squared	0.8934	0.8975	0.9468

1 Standard errors in parentheses.
2 Heating degree day bases were derived using the PRISM method and are as follows: for electricity - base 63; for gas at the central heating plant - base 75; for other gas - base 60.
3 The cooling degree day base is 57 and was derived using the PRISM method.

Table 1. Models of energy consumption at Fort Sheridan.

space in general or to the amount of floor space heated or cooled.

Gas consumption models. Two gas consumption models are presented--one for gas used at the central heating plant and another for other gas. Gas is not used for cooling at Fort Sheridan, so the cooling degree day variable was not included as an independent variable in either model. Gas consumed at the central heating plant is used primarily to generate steam for space heating, and, as one would expect, gas consumption at the central heating plant is primarily correlated with the number of heating degree days. The only other statistically significant variable (at the 5% or greater level) is the time trend, which indicates that gas use has generally declined over the period.

A number of reasons might account for this decline. Some buildings heated by the central heating plant at the beginning of the modeling period might now be heated by individual gas units. Or various conservation measures may have been implemented. Or increased electricity consumption in the buildings may have generated enough internal gains to reduce the need for gas-fired space heating.

The length of the billing period is not statistically significant at the 5% level and, therefore, probably has no direct impact on gas consumption at the central heating plant. The length of the billing period does, however, have an indirect impact on gas consumption through the heating degree days variable.

Other gas is used primarily for space heating, water heating, and cooking. This usage is reflected in the statistical significance of the parameter estimates in the other gas model. Other gas, like central heating plant gas, for example, is positively correlated with the number of heating degree days. The space heating component of gas consumption as well as the temperature-sensitive portions of gas water heating and cooking are probably being picked up by this variable. Other gas, unlike central heating plant gas, is also

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correlated with the length of the billing period. This correlation probably reflects the fact that a certain amount of cooking or water heating is done each day, no matter what the temperature is.

None of the other independent variables in the other gas model is statistically significant at the 5% level. There does not, for example, appear to be a hint of any long-term trend. The nightlength variable, on the other hand, is very close to statistical significance and, even more interestingly, indicates a negative correlation between long nights and gas consumption. This correlation might be the result of internal gains associated with greater indoor activity during the winter season.

MODEL USES

These simple statistical models are useful energy management tools. They can be used to delineate important sources of energy savings, simulate the impacts of potential conservation measures, uncover potential baselining problem areas, and monitor and verify engineering-based predictions. In this section, however, we focus primarily on how the models can be used to delineate important sources of energy savings.

Figures 4 through 6 show how the models can be used to decompose energy consumption into separate "end uses" over the modeling period. Such decomposition graphs are useful in indicating what types of loads might be targeted for conservation measures.

For example, Figure 4, depicting the decomposition of electricity, indicates that electric heating and cooling loads make up relatively small portions of the total load. Most of the electric load is relatively "fixed" or "base" load, and probably reflects fairly consistent day-to-day lighting and receptacle loads. This indicates that an evaluation of electricity conservation measures might be directed at reducing these loads.

The increasing trend in electricity usage has some implications for establishing a baseline of electricity consumption at Fort Sheridan. Additional variables might be introduced into the model, if monthly data on the factors underlying the trend could be obtained.

In the current model the trend is assumed to be associated with the base load. Thus, before additional data are collected, it would be wise

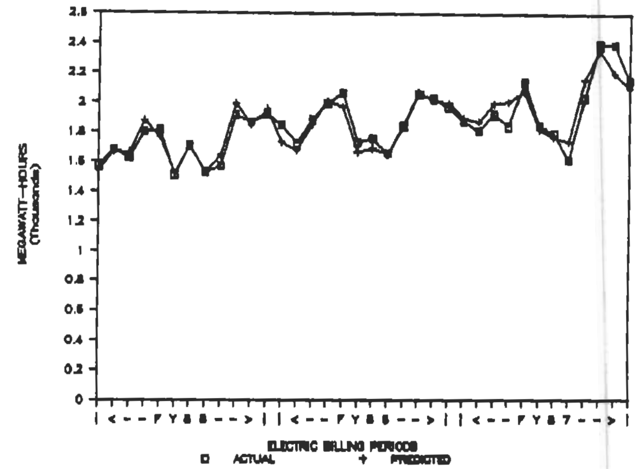

Fig. 1 Electricity consumption

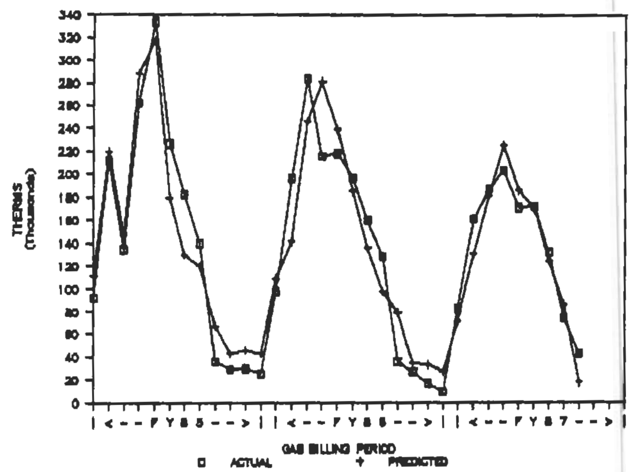

Fig. 2 Gas consumption at the central heating plant

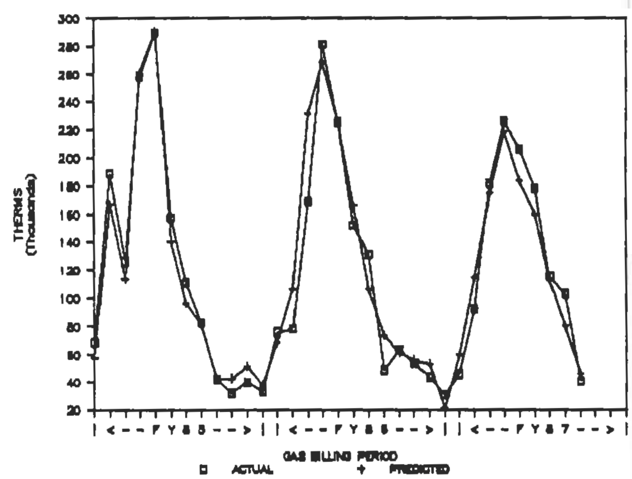

Fig. 3 Other gas consumption

to see if the trend might be directly attributable to an increase in the amount of floor space electrically heated or air conditioned. This hypothesis would be supported if it could be shown that the parameter estimate on the heating or cooling degree day variable had incrementally increased during the period. In any event, the parameter estimate on the trend term serves as a flag for further potential modeling efforts.

Figures 5 and 6 show how the gas models can be used to decompose gas consumption into end-use loads. These graphs indicate that space heating is a relatively large load and, therefore, might yield substantial energy savings.

Information about the relative or absolute sizes of end-use loads is not enough, however, to make a final decision about the best energy conservation investments. Measures of how efficiently energy is being used for various purposes is needed to improve potential conservation investment decisions. Fortunately, such measures can be obtained from the models if the end-use loads can be normalized as discussed below.

Dividing the amount of energy used for space heating or cooling by the appropriate number of square feet yields measures of operating efficiency that are more comparable. Even more comparable measures of efficiency can be obtained by normalizing for climate and intensity of use as well.

For example, the gas models developed for Fort Sheridan indicate that the central heating plant uses about 35 Btu/ft^2-degree day, while the individual gas heaters use only about 14 Btu/ft^2-degree day. Obviously, some savings are possible.

Measures from similar models of energy consumption at other Army facilities also could be generated and compared. The delineation of such sources would be the first step in determining which energy conservation projects are likely to yield the greatest returns at U.S. Army facilities.

CONCLUSIONS

A standardized method of modeling energy consumption has been presented in this paper. The method delineates energy consumption along three dimensions--time, daylength, and temperature. The results of the modeling method can be used to delineate important sources of energy savings, simulate the impacts of potential conservation measures, unco-

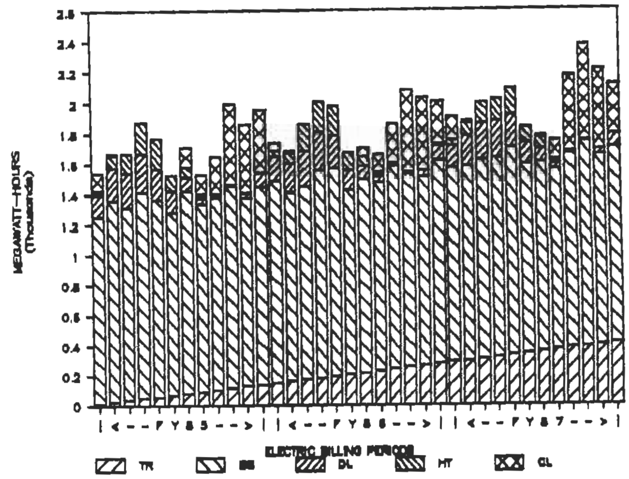

Fig. 4 Decomposition of electricity consumption

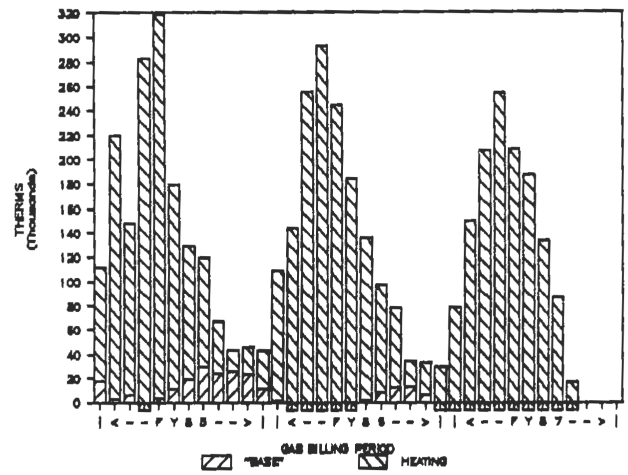

Fig. 5 Decomposition of central heating plant gas consumption

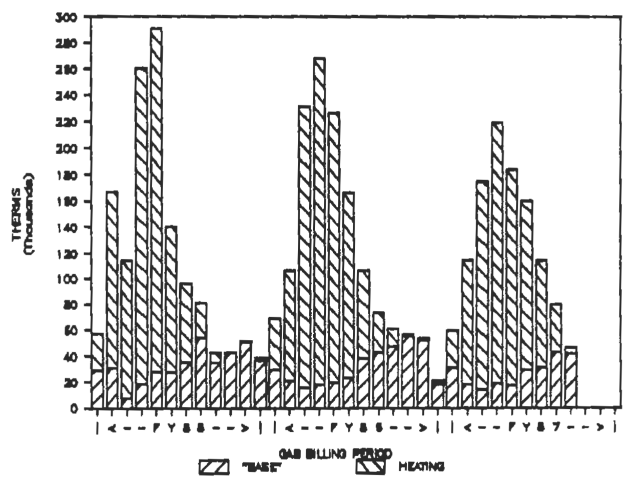

Fig. 6 Decomposition of other gas consumption

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ver potential baselining problem areas, and monitor and verify engineering-based predictions. Additional research in various energy consumption environments will be required, however, before the modeling method can be properly evaluated.

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