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R. G. Pratt

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Pacific Northwest Laboratory
Richland, Washington 99352

AUDIT PREDICTIONS OF COMMERCIAL LIGHTING AND PLUG LOADS

Robert G. Pratt*

INTRODUCTION

In this paper, data for the Commercial Audit Program (CAP) buildings instrumented to collect end-use metered data as part of the End-Use Load and Consumer Assessment Program (ELCAP) illustrate the uncertainty and range of error that can result from the energy audit process in commercial buildings. In theory, lighting loads should be easy to predict, based on the site inspection of installed lighting and the business operating hours reported by the building owner/manager. The implications of these results go far beyond these end-use loads themselves when it is recognized that the audit process involves subtraction of estimated lighting and plug loads from monthly billing data. This is then followed by efforts to match the predicted heating, ventilation, and air-conditioning (HVAC) loads predicted to the remainder. Thus errors in estimating lighting and plug loads are likely to propagate through the audit process, impacting all end-use loads.

The objective of the CAP metering is to provide data to the Bonneville Power Administration (Bonneville) for assessing the quality and predictive power of commercial building energy audits conducted under the CAP. Detailed monitoring of energy consumption is being conducted in 31 commercial buildings selected from over 3,000 buildings that received audits under Bonneville's Commercial Audit Program (1). Each of the buildings metered received a level 2 or level 3 audit conducted in accordance with carefully designed procedures (2). Level 2 audits (for buildings consuming 4,000 to 83,000 kWh/month) may use bin method-based thermal analysis tools, while level 3 audits (for buildings consuming more than 83,000 kWh/month) are required to use detailed hourly simulation-based thermal analysis tools.

Energy audits may be conducted at low or no cost to point out cost-effective conservation measures that could be adopted by the building owners. Alternatively,

* Robert Pratt is a Senior Research Scientist with Pacific Northwest Laboratory in Richland, Washington.

evaluating of the level of conservation measures that should be installed at utility expense. The energy and peak load savings resulting from audit programs are influenced by both the rate of adoption and the installed effectiveness of conservation measures recommended by audits. The accuracy of savings predicted by the audits has long been in question, and affects both the rate of adoption (via "word-of-mouth" and media communication of customer satisfaction) as well as the actual benefits to the utility for installed measures. Hence, assessing the accuracy of the audits is an essential element in the implementation and evaluation of effective audit programs designed to utilize the conservation resource. This paper presents an end-use view of audit accuracy for lighting and plug loads. Other analysis of the data from the overall building point of view has been conducted elsewhere (3).

METHODOLOGY

The results reported here are based on a brief exploratory analysis designed to make a simple comparison of actual metered interior lighting and equipment (plug) end-use loads with audit predictions. These comparisons are made on an annual basis, since the original estimates were provided by the auditors to Bonneville on that level of aggregation. Unlike the evaluation report that focuses on individual buildings as case studies, this analysis takes a cross-sectional view of two end-uses across a number of buildings.

The only manipulation of basic ELCAP end-use data involved in the analysis is for four sites (the large office B, restaurant A, the first restaurant B, and retail A) in which a mixed general (lights and plugs) end-use load was present. This occurs due to the ELCAP protocol of metering loads at the circuit level, where some circuits have a dual end-use. The mixed loads for these sites were approximately disaggregated by making the simple assumption that the ratio of the mixed general load to the pure lighting load is the portion of the mixed general load that is purely plugs. Only in the two restaurants was this uncertainty larger than 35% of the pure lighting load.

To place the results in some perspective, a brief discussion outlining the audit process follows. Audits are used to establish baseline consumption estimates at the end-use level. These end-use load estimates then form the basis for estimating energy and peak load savings that ensue from installation of energy conservation or demand-side management technologies. It is crucial to understand that energy audit analysis tools do not predict end-use loads, but in fact predict heating, ventiation, and air conditioning (HVAC) loads as a function of assumed lighting and equipment loads, weather, thermostat strategy, and building thermal characteristics. The attempt to match the total load predictions to monthly billing data typically is the only process in which the assumptions about the lighting and equipment load levels and schedules are (indirectly) tested. Because as much as 60% to 70% of the total load may result in lights and equipment in commercial buildings, the predictive accuracy of audits can vary widely depending upon the skill level of the modeler, the accuracy of the building characteristics data used, and the HVAC load simulation model itself.

There are typically four types of information available to the auditor:

- a physical description of the building's envelope, HVAC system, and lighting and other connected equipment loads
- data from interviews with the owner/manager and occupants regarding schedules of occupancy, thermostat settings, and ventilation
- utility billing data indicating monthly total consumption and possible peak load
- temperature data for the recent year and the long-term average weather for the nearest National Weather Service station.

Additionally, the auditor may make some one time measurements of air and/or water flow rates and temperatures, and may also contact the HVAC equipment manufacturer for performance specifications of the HVAC equipment.

The basic tool the auditor uses in this process is an energy analysis of the HVAC system loads. This analysis typically takes the form of computerized hourly simulations of the heat flows in the building, or may use simpler bin methods that group hours with similar outdoor temperatures and time of day. The simulations typically account for hourly weather; transient conductive heat flows through the various building envelope surfaces; transmission of solar energy through the windows and other opaque surfaces; assumed schedules of internal heat gains from lights, equipment, and occupants; assumed schedules and rates of ventilation and infiltration; and the capacity and conversion efficiency characteristics of the HVAC equipment. While bin methods do not account for these processes with the same high level of detail or on a time-series basis, bin method modeling accounts for most of these effects.

There are inherent difficulties in using billing data for calibrating building simulations for energy audits. The input data describing the building systems and their use are adjusted until a reasonable fit to the monthly totals and peak demand is achieved. A typical situation is shown in Figure -1. Indicated is a base load consisting of lights and equipment, that the auditor estimates based on the available survey data. These loads are the product of the number of hours of operation of each lighting circuit or piece of equipment, times the actual power consumption of the device when operating (which may differ significantly from its nameplate rating). These loads may vary by time of year, but are typically assumed to be steady.

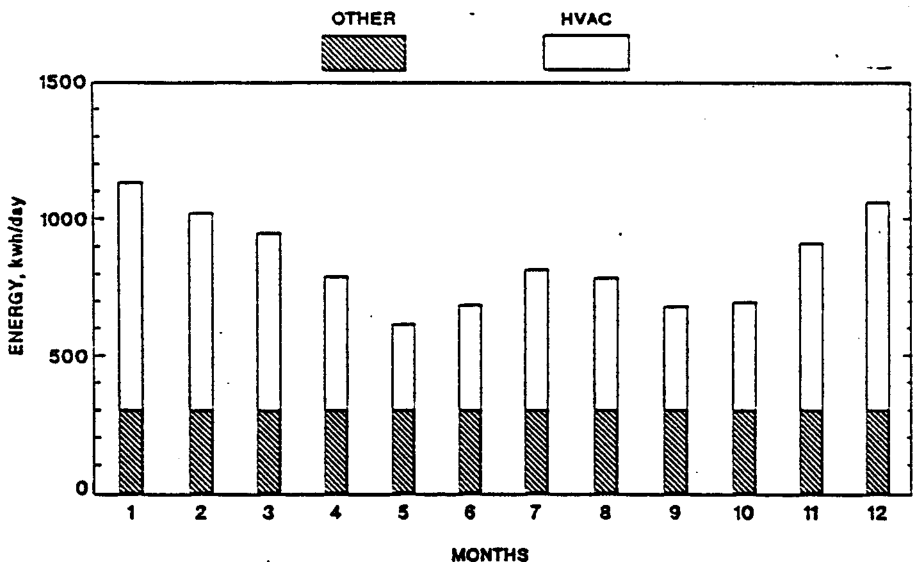

FIGURE -1. Winter Peaking Building Monthly Loads

The auditor then develops a monthly engineering estimate of the HVAC loads for the building, by entering a detailed description of the thermal characteristics of the envelope and HVAC system into a simulation model. The model accepts a weather data file (usually a typical weather year, as the actual weather for the period analyzed is not readily available in a form suitable for most engineering tools) and a thermostat schedule developed on the basis of discussions with the building operator. The heat given off by the lights and equipment displaces heating loads or increases cooling loads, and so these are also critical data entered into the simulation.

The monthly HVAC load predicted by the model is then added to the assumed lighting and equipment loads to produce a monthly building total energy estimate, which is then compared with the billing data. It is particularly useful to make these comparisons across months, as the monthly pattern of HVAC loads provides clues as to the actual thermal response of the building. In Figure -1, the monthly pattern indicates that the building is dominated by its heating requirements, as can be discerned by its higher winter loads and its minimum loads in May and September. Figure -2 shows a cooling dominated building, in which the increased summer loads and minimum consumption in March and November are indicative of a lower balance temperature (the temperature at which heating and cooling are zero or minimized) than the building in Figure -1.

The auditor examines the predicted pattern of total building consumption, and then iteratively adjusts parameters of the building description or the assumed schedules until a reasonable fit is obtained. Agreement within 10% is generally considered an outstanding fit to monthly billing data. If the pattern of predicted loads indicates that the balance temperature of the building is wrong, adjustments are made (hopefully within reasonable bounds) to the levels of internal gains or the thermal integrity of the building envelope. If the loads are generally too high or low, this suggests that the internal gains assumptions may be in error. Changes in the absolute and relative heating and cooling system efficiency curves can also produce similar effects. This is a trial-and-error process in which there is insufficient information in the billing data to make a precise determination of which input parameters that should be adjusted to achieve a proper fit.

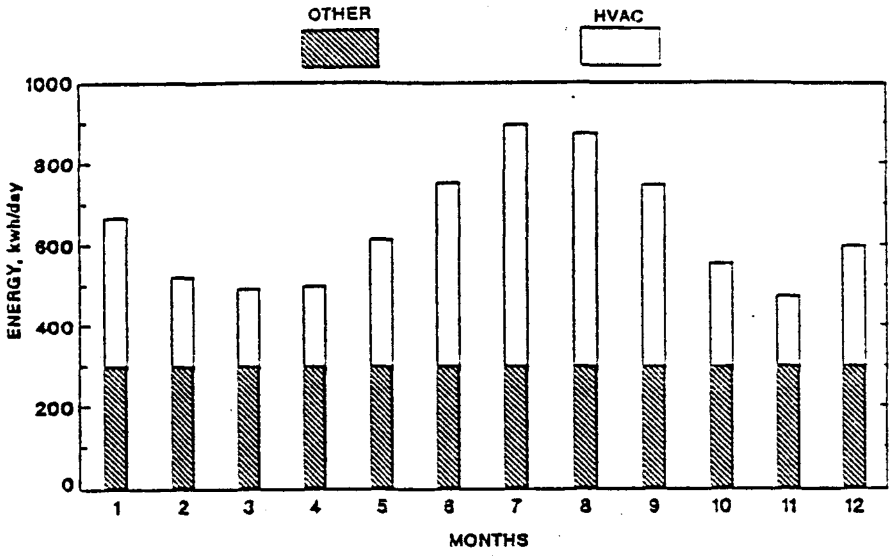

FIGURE -2. Summer Peaking Building Monthly Loads

The key point is that the energy analysis does not have a unique "solution",but is complete once reasonable agreement is obtained. In this audit calibration process, heat gains from lights and equipment are indistinguishable from one another, and the division of the other (non-HVAC) end-use into lighting and plug loads is usually derived by subtracting the assumed lighting loads from the total of the non-HVAC end-uses. Energy savings predictions are then made by changing the engineering model to reflect the characteristics of the conservation measure and simulating the resulting energy consumption.

It is entirely possible for this "solution" to provide a reasonably accurate description of the total consumption for the wrong reasons. Where these reasons result in incorrectly attributing consumption to one end-use at the expense of another, predictions of savings from conservation measures involving those end-uses are usually proportional to the error in the estimated baseline consumption. An example is the savings from a lighting retrofit in which 15% more efficient fixtures are installed. If an average of 80% of the lights are on during the day whereas the model assumption was 90%, then the predicted savings will be high by 11%. Note that the lighting technology performs as expected, saving 15% of the power when the lights are on, but the usage simply was not as predicted.

RESULTS

Lighting Loads

The actual metered lighting loads and loads predicted by the audits are compared in Table -1 and Figures -3 and -4 for 12 sites. The audits were conducted by several different audit firms for four different building types and a range of building sizes, as shown. The consumption and savings data are normalized by floor area to facilitate comparison of the lighting loads across buildings of different sizes. The data is not weighted by floor area, since the sites are not a random sample of either the region or the CAP audit sites, and better represent the diversity due to the audit process. As can be seen in Figure -4, the audit predictions are more accurate for the restaurant and retail buildings, compared to the grocery and office buildings.

The audit error is the percentage difference of the audit prediction from the actual measured load. As illustrated by Figure -4 for this set of metered CAP sites, the error ranges from 142% overprediction to 33% underprediction. The mean and median error indicated in Table -1 for the 12 sites are 16% and 7% overprediction, respectively. In the case of the small office building, this is known to be in part caused by a partial vacancy during the period of metering. If this building is excluded the mean error is reduced to 4% overprediction, and the mean absolute error is reduced to ±30%. In the case of this building an external cause for error in the consumption estimate is present, nevertheless the shifting of commercial occupancy is noted to continually affect the loads in ELCAP buildings and most likely will affect programmatic energy savings in a similar way.

Although this sample of buildings is too small to provide a statistical basis for conclusions, the variance in predicted versus actual loads is clearly large. The standard deviation of the audit errors is 57%, and the mean absolute error is ±39%. Thus the data analyzed to date suggests that there is a range of uncertainty on the benefit side of the cost/benefit calculations for lighting loads that is on the order of ±50% for individual buildings.

TABLE -1. End-Use Metered Data Versus Audit Estimated Lighting Loads

Audit Firm	Building Type	Floor Area (ft2)	Consumption ($kWh/yr-ft^2$) Metered	Audit	Audit Error (%)
A	Grocery	3,538	3.7	8.4	128
B	Grocery	25,500	23.3	17.8	-24
A	Restaurant	8,193	5.3	6.0	13
B	Restaurant	4,859	10.5	9.2	-12
B	Restaurant	2,964	13.8	16.0	16
B	Office	50,500	10.4	5.7	-45
F	Office	6,336	3.4	8.2	142
A	Retail	11,720	9.4	10.8	15
B	Retail	69,283	9.9	11.2	13
F	Retail	5,140	5.0	4.8	-6
J	Retail	15,600	9.1	6.1	-33
N	Retail	115,300	13.0	10.5	-19
Mean Error					16
Median Error					7
Standard Deviation					57
Mean Absolute Error					39

Plug Loads

The comparison of audit estimated baseline plug loads with the metered loads for the set of CAP metered buildings is shown in Table -2 and Figures -5 and -6. Plug loads are defined here as receptacle loads exclusive of major process loads such as refrigeration or mainframe computers. Because plug loads are diverse, major energy conservation measures are difficult to implement and as a consequence are infrequently recommended. Nevertheless, it is widely hypothesized that plug loads are underestimated and increasing fairly rapidly because personal computers and other office automation equipment have penetrated into the work place. Also, as pointed out in the discussion of the audit process, plug loads are typically the unaccounted remainder from the process of resolving the assumed lighting and the predicted HVAC loads with the building total, and so may also be indicative of one form of error in the overall audit process.

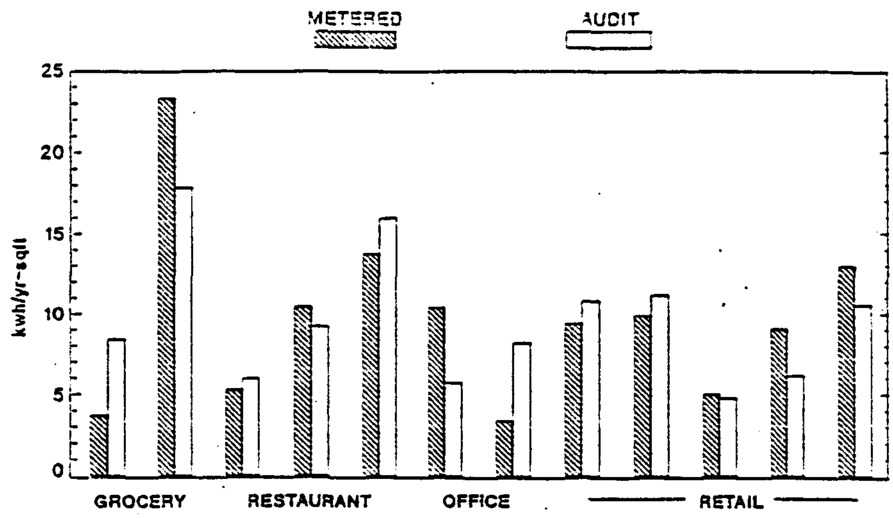

FIGURE -3. Metered Versus Audit Estimated Lighting Loads

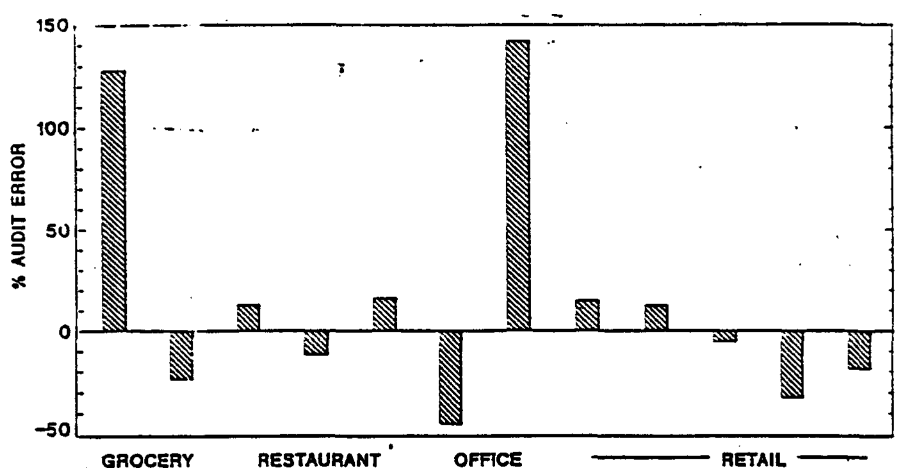

FIGURE -4. Percent Audit Lighting Load Error

As shown in Figure -5, plug loads are almost universally underpredicted by large amounts for the set of analyzed CAP buildings. The audit error in Figure -6 - ranged from 94% under-prediction, to 19% retail and grocery buildings as for the office building. The sample is too small to be conclusive, but the results indicate that plug loads may be in error from misestimation of the equipment usage, capacity, and/or the audit process itself, rather than a consequence of underestimating penetrations of automated data processing equipment.

TABLE -2. End-Use Metered Data Versus Audit Estimated Plug Loads

Audit Firm	Building Type	Floor Area (ft2)	Consumption (kWh/yr-ft2) Metered	Consumption (kWh/yr-ft2) Audit	Audit Error (%)
A	Grocery	3,538	17.0	3.9	-77
B	Grocery	25,500	4.0	0.8	-79
A	Restaurant	8,193	10.7	12.8	19
B	Restaurant	4,859	12.0	10.2	-15
B	Restaurant	2,964	7.2	0.8	-89
B	Office	50,500	5.5	1.0	-83
F	Office	6,336	6.5	3.6	-44
A	Retail	11,720	1.7	0.5	-73
B	Retail	69,283	1.3	0.1	-94
F	Retail	5,140	0.6	0.4	-25
J	Retail	15,600	5.8	1.4	-76
N	Retail	115,300	2.6	1.4	-47
	Mean Error				-57
	Median Error				-75
	Standard Deviation				33
	Mean Absolute Error				60

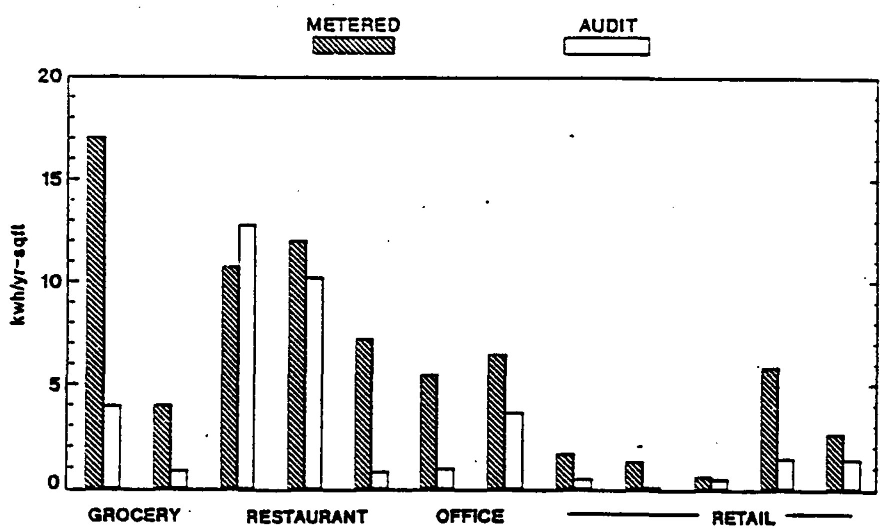

FIGURE -5. Metered Versus Audit Estimated Plug Loads

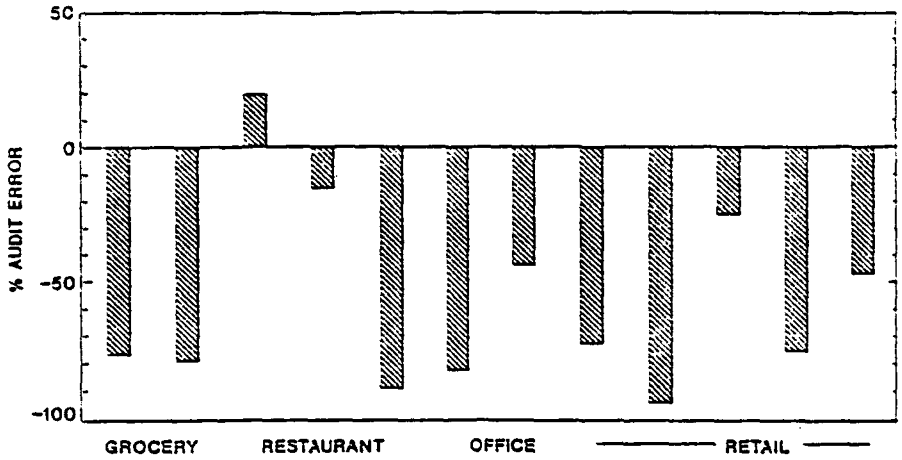

FIGURE -6. Percent Audit Plug Load Error

Combined Lighting and Plug Loads

Given the nature of the audit process, the total of the lighting and plug loads might be expected to be more accurately estimated than the individual end-uses. Table -3 and Figures -7 and -8 indicate that this observation may be valid. The average of the audit estimates for the combined end-use are 17% under-predicted compared to the actual loads (the median is also -17%). This is a reversal in sign, but is similar in magnitude to the observed 16% overprediction error for the lighting loads. This represents a significant improvement in the mean error for the plug loads.

The variance of the estimates from the actual loads is also reduced, with the standard deviation dropping to 24% and the mean absolute error dropping to 24%. In both cases this is a significant improvement over the individual end-use estimates. The analysis of the combined end-uses did not greatly increase the audit error for any building, and significantly improved it for several sites. Although only a small sample of buildings is analyzed here, the data suggest that some of the error in prediction of the individual lighting end-use may be off set by compensating errors in the plug load end-use.

TABLE -3. End-Use Metered Data Versus Audit Estimated Lighting/Plug Loads

Audit Firm	Building Type	Floor Area (ft^2)	Consumption ($kWh/yr-ft^2$) Metered	Audit	Audit Error (%)
A	Grocery	3,538	20.7	12.4	-40
B	Grocery	25,500	27.3	18.6	-32
A	Restaurant	8,193	16.0	18.8	17
B	Restaurant	4,859	22.5	19.4	-14
B	Restaurant	2,964	21.0	16.7	-20
B	Office	50,500	15.9	6.7	-58
F	Office	6,336	9.8	11.8	20
A	Retail	11,720	11.1	11.3	2
B	Retail	69,283	11.2	11.2	0
F	Retail	5,140	5.6	5.2	-8
J	Retail	15,600	15.0	7.6	-49
N	Retail	115,300	15.6	11.9	-23
	Mean Error				-17
	Median Error				-17
	Standard Deviation				24
	Mean Absolute Error				24

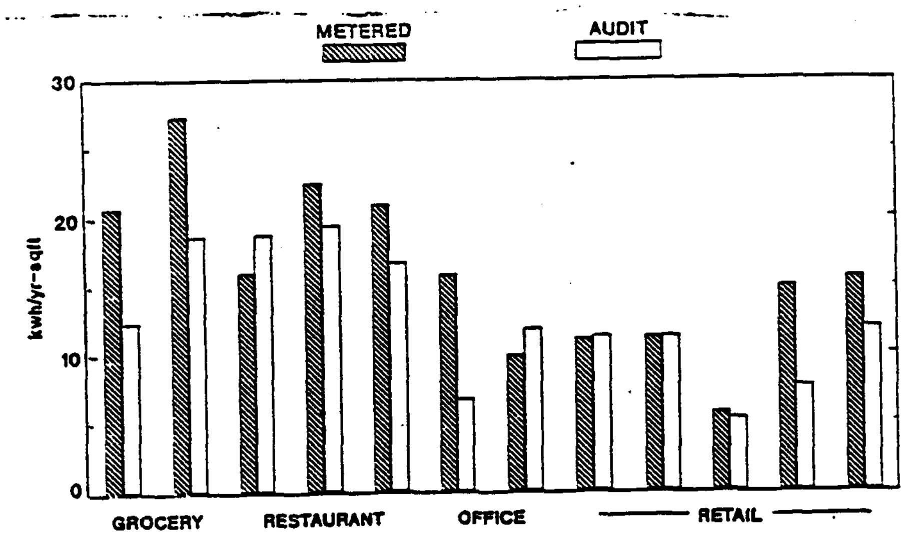

FIGURE -7. Metered Versus Audit Estimated Lighting/Plug Loads

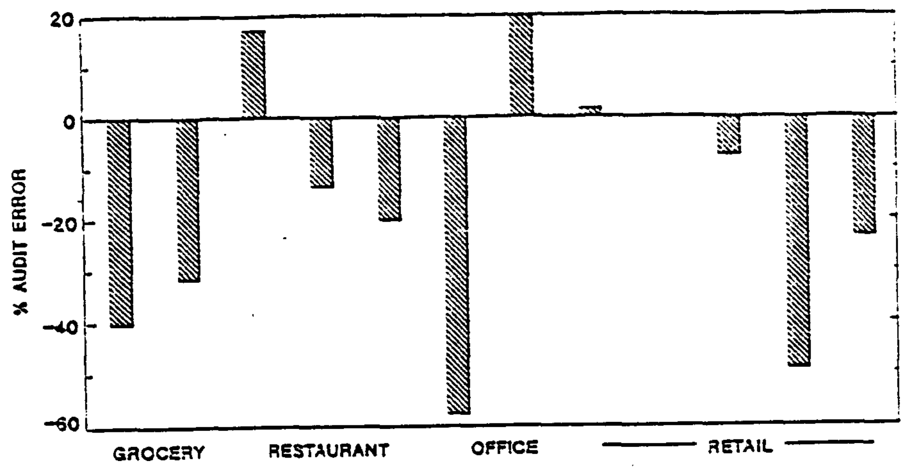

FIGURE -8. Percent Audit Lighting/Plug Load Error

Of the four sites in which pure end-use loads had to be approximated from mixed general loads, only retail building A showed significant improvement. This indicates that the arbitrary nature of the disaggregation approximation for these sites did not appreciably alter the results of the analysis.

APPLICATIONS

The magnitude and range of errors in audit baseline estimates of lighting and plug loads (standard deviations of ±57% and ±33%, respectively) indicates that significant uncertainty exists for CAP audit based conservation predictions involving these end-uses for individual buildings. The error in predicting direct benefits might increase further when the interactive effects on heating and cooling loads are included. The risk for investment in conservation from the viewpoint of an individual building owner is thus seen to be significantly greater and in part of a different nature than is normally recognized. Verification that the audit process has uncertainty of this magnitude will lead to reexamination of payback criteria for audit recommendations and conservation programs. This has important implications for conservation program planners and regional forecasters in that the burden of risk and level of financial incentives provided in connection with commercial audit-based programs must be evaluated as part of the program design.

For the relatively small sample of buildings as a whole, the mean error in the baseline estimates are +16% for the lighting loads and -57% for the plug loads. This indicates the possibility that systematic over-prediction or under-prediction errors of these magnitudes for audit based conservation potential involving these end-uses are possible. While the analysis needs to be completed for more of the metered CAP sites and extended to the full set of end-use loads to strengthen these conclusions, serious questions are raised as to the validity of savings estimates based on large commercial audit programs. This has important implications for resource and program planners intending to utilize the conservation resource.

The detailed examination of the audit process itself made possible by the presence of the end-use data will undoubtedly lead to improvements in the audit procedures and the establishment of guidelines that reduce this level of uncertainty to a more manageable level. These early results have already resulted in an experimental design involving systematic reaudits of these buildings, using increasing amounts of ELCAP end-use data to evaluate the potential benefits of acquiring various levels of measurements as part of an improved audit protocol. Similarly, the indication that lighting loads may be overpredicted at the expense of plug loads as a consequence of the audit process itself may lead to guidelines improving these estimates. These results could be applied by program designers and auditors themselves to improve the audit programs and the audit process.

The data also suggest plug loads may be consistently underestimated across building types, and that the errors are not concentrated solely in office buildings. If supported by analysis of more buildings, this result would indicate that audit plug load errors are not related to the penetration of personal computing equipment in the office environment, but more likely are a consequence of poor estimates of equipment usage patterns generally. Thus the hypothesis that plug loads are growing rapidly in the commercial sector is neither supported nor refuted, but is not indicated as a source of error when the equipment in a building is observed first hand by the energy analyst. This result may have importance for commercial sector load forecasters and modelers involved in the development of conservation supply curves.

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