Short-Term Measurements to Support Impact Evaluation of Commercial Lighting Programs

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Impact evaluations of commercial DSM programs often benefit from field measurements to enhance and/or verify engineering estimates of program savings. A primary focus of field measurements in commercial sector programs has been on long-term end-use electricity measurements. These measurement programs are typically very expensive, resulting in reduced sample sizes in order to keep costs within budget constraints. A recent trend has been to replace traditional, long-term end-use metering projects with short-term monitoring projects. This trend has been accelerated by the emergence of small, portable, battery-powered data logging equipment suitable for short-term monitoring. Many of the battery-powered devices measure lighting fixture on/off status, fixture operating hours, or circuit current. These “surrogate” measurements are generally easier to make, but are less accurate than true electric power measurements.

This paper discusses the application of short-term monitoring to two commercial lighting projects. Fixture sampling strategies, measurement and sampling errors, and comparisons between surrogate measurements and true electric power measurements are discussed.

Field Measurements to Support Lighting Measure Evaluation

Long-Term Electricity Measurements

A common approach to estimating lighting energy savings through monitoring involves pre/post measurement of lighting power consumption. A data logger, capable of measuring true electric power, is installed on the lighting circuits of a building. The data logger takes time series measurements of lighting energy consumption for a period of time before and after the installation of improved lighting systems. The monitoring period can range from a few months to several years. Lighting energy savings are calculated from the difference between the pre-retrofit consumption and the post-retrofit consumption. Direct calculation of lighting energy savings from pre/post measurements is often confounded by changes in building occupancy and lighting schedules, which may or may not be attributable to the lighting retrofit.

The data loggers are generally mounted on the wall near the electrical panel box(es) containing the lighting circuits. Since the measurement of true electric power requires connections to the building electrical system, electricians are generally required to install the data logging equipment. Because of the large amounts of data gathered in a long-term project, a phone line is usually installed and the data logger contents are downloaded via modem to a remote computer for archiving and further processing. Once the project is completed and the data logging equipment is removed, drywall repairs and painting may be necessary to return the building to its original condition. Long-term pre/post electricity measurement studies generally provide very accurate impact estimates, but at a high cost.

Short-Term Electricity Measurements

A variation of the long-term electricity metering approach is the short-term electricity metering approach. A data logger capable of measuring true electric power is installed in the facility. Before the lighting system is improved, the data logger is operated for a short period of time, ranging from two to four weeks. After lighting system retrofit, the data logger is used to monitor the lighting system for a short period after the retrofit, again for a period of two to four weeks. Lighting energy savings are calculated from the difference between the pre-retrofit consumption and the post-retrofit consumption. These short term savings estimates are extrapolated to the annual energy savings.

As with the long-term electricity metering approach, electricians are generally required to install the data logging equipment. Drywall repairs and painting may be necessary to return the building to its original condition after the monitoring is completed. However, the amount of data gathered is often small enough to fit within the internal memory of the data logger, thus eliminating the need for a phone line. Short-term electricity measurements provide an accurate estimate of energy savings *for the monitoring period.* The introduction of errors when short-term data are extrapolated to estimate annual savings are an important issue, that is not covered in this paper.

Short-Term Surrogate Measurement Techniques

To reduce the costs associated with true power measurements, surrogate measurement techniques were developed. In this case, specialized data loggers are used to monitor some easily observed parameter such as fixture on/off status, fixture light output, or lighting circuit current. This information, combined with measurements of lighting fixture power, is used to estimate energy consumption and savings resulting from lighting measures. The surrogate measurement techniques have been developed to reduce costs over traditional electricity metering methods. Cost savings from surrogate measurements can result from lower hardware costs, lower installation costs, and reduced data analysis costs. Surrogate measurement techniques fall into three general categories: lighting circuit current, fixture on/off status, and fixture light output .

Lighting Circuit Current Monitoring. This technique is similar to the short term power measurement technique, except that current, rather than true power measurements are taken. Split-core current transducers are used to non-intrusively monitor lighting circuit current. A series of one-time measurements of lighting circuit true power vs. current is made to “calibrate” the current measurements to true electric power. The data loggers used to monitor circuit current are small enough to hide inside the circuit panel box, thus eliminating the need for external wiring and logger mounting, along with subsequent removal and patchwork. Depending on local building codes, an electrician may not be needed to install the equipment, since direct connections to the electrical system are not made.

Fixture On/Off Status Monitoring. Status monitoring devices (also called “lighting loggers”) fall into two general categories: accumulated run time and time series devices. Fixture on/off status is used to estimate lighting operating hours, which is one factor in the overall estimate of lighting energy savings. Lighting status loggers can be deployed to monitor the status of the specific fixtures affected by the DSM program. Electric circuits in buildings provide power to many different types of fixtures and equipment. In some cases, lighting and equipment end-uses are supplied by the same circuit. Monitoring fixtures and equipment not affected by the program adds noise to the measurement.

Certain types of time series lighting loggers record information on light fixture output, rather than a simple on/off status measurement. These loggers can be used to infer additional information, such as relative power consumption for variable output systems (Reichmuth 1992), (Krepchin 1993), (Gregerson 1994).

Because the status measurement techniques do not measure electric power directly, an engineering model is necessary to convert the data collected to an estimate of electric power consumption. The basic form of the an engineering equation to estimate lighting energy consumption is:

$$kWh = \left(\sum_{i=1}^{m} \frac{Watts_i \times OH_i}{1000} \right) \tag{1}$$

where:

kWh = energy consumption
i = index for each data logger deployed
m = total number of data loggers
$Watts_i$ = connected load associated with logger i
OH_i = operating hours associated with logger i

Equation 1 requires an estimate of the connected load and the annual operating hours of the lighting system, and assumes that the lighting power is constant when the fixtures are on. Connected load is estimated from manufacturers’ data or field measurements. Lighting loggers are installed to monitor operating hours for a sample of fixtures throughout the building. After a period of monitoring, the data loggers are retrieved and downloaded, and lighting energy consumption is calculated from Equation 1. If the objective of the analysis is to produce hourly lighting load shapes rather than lighting energy consumption, data loggers that make time series measurements of lighting status are required.

Example 1: Fixture Status Measurements Compared with True Power Measurements in a Small Office Building

An estimate of lighting energy consumption in a 3800 SF office suite using fixture status measurements was compared to true electric power measurements on the same set of fixtures over the same monitoring period. The procedure used was as follows:

1. Identify control points (switches). Fixture status monitoring involves the observation of the operation of a set of fixtures connected to an individual control point or light switch. In this example, a total of 26 control points were identified in the space.
2. Identify fixtures controlled by each switch. Once the control points were identified, the number of fixtures controlled by each control point was determined.
3. Record non-functioning fixtures. Non-functioning or de-lamped fixtures were noted to calculate the correct connected load for each control point.
4. Estimate connected load for each fixture. Manufacturers' data were used to estimate the connected load for each fixture. The fixtures were a mix of recessed fluorescent, incandescent track lighting, and recessed incandescent PAR fixtures. Manufacturers' data for the recessed fluorescent fixtures were confirmed with spot-watt measurements.
5. Rank control points according to connected load. The individual control points were ranked according to the total connected load controlled. The connected loads ranged from 46 W to 1056 W.
6. Stratify sample based on connected load. The control point sample was stratified as shown in Figure 1.
7. Randomly select fixtures from each stratum. Control points were selected at random from each stratum as indicated in Figure 1.
8. Deploy data loggers for short-term monitoring of fixture status. Nine data loggers were deployed on functioning fixtures connected to each of the control points sampled.
9. Download data and compute energy consumption, Each data logger was downloaded and time-series measurements of fixture on/off status were multiplied by the connected load represented by each sample point. These data were summed to obtain a full-building load shape and compared to the true electric power measurements, as shown in Figure 2.

The estimates of average workday energy consumption from surrogate measurements varied from the true power measurements by about 4 percent. The estimates of average workday peak demand varied from the true power measurements by about 30 percent. A total of 9 status loggers were used to monitor 26 control points.

The space consisted largely of private perimeter offices. Each office had a glazed interior wall facing the building interior, allowing daylight to penetrate into the core spaces. Although daylighting controls were not installed, much of the lighting was switched off by the occupants during the day. The space connected load was about 7.5 kW, while the average occupied load was on the order of 2.2 kW, or about 30% of the connected load. This somewhat atypical occupant behavior resulted in a substantial variability in the lighting operating hours within the

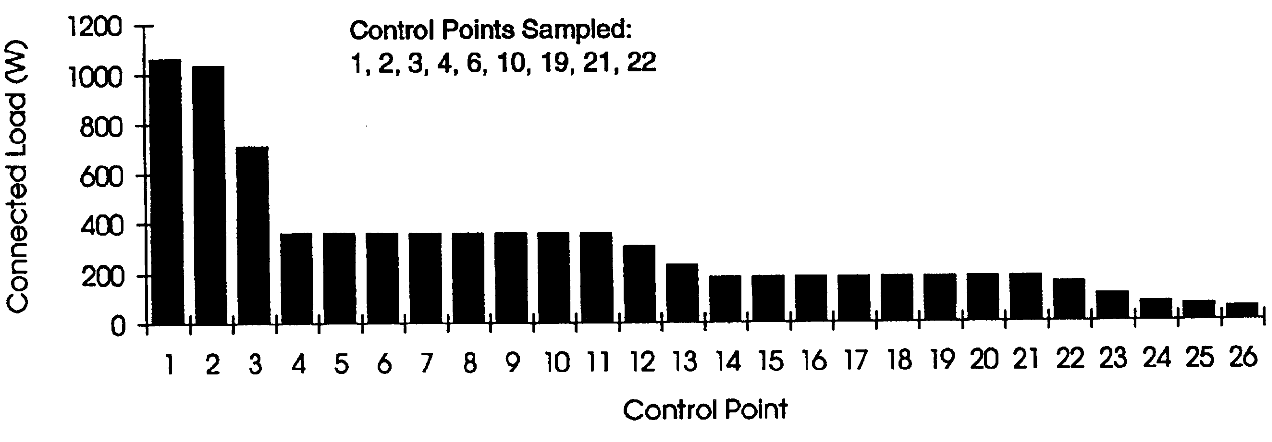

Figure 1. Control Point Stratified Sample Design

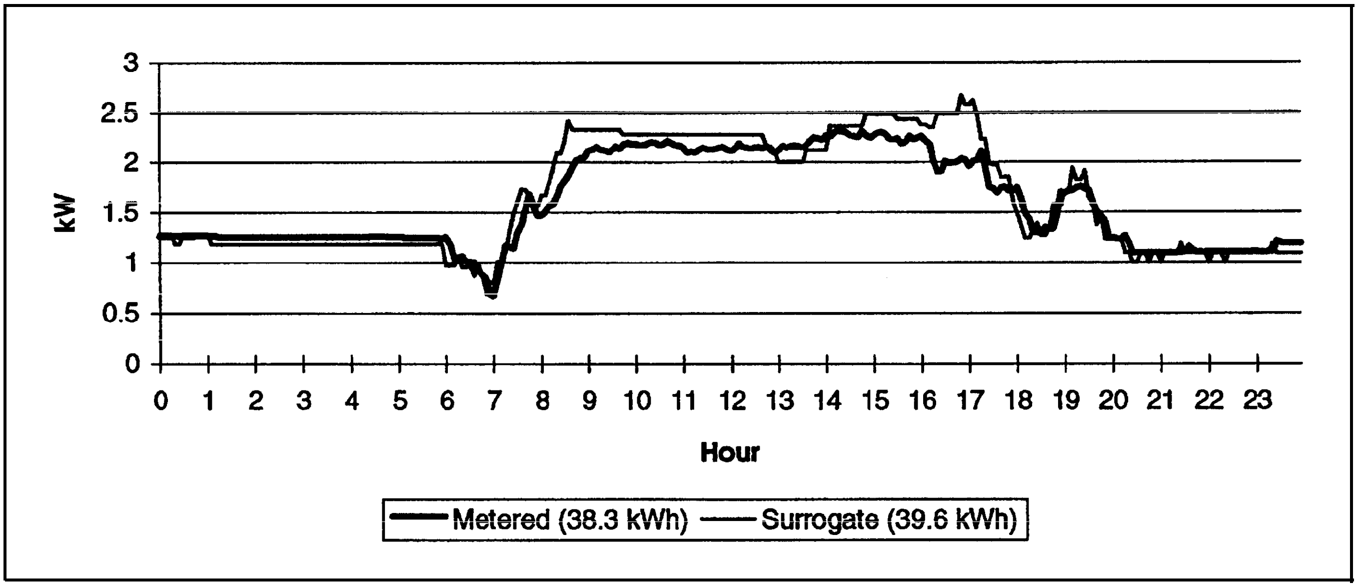

Figure 2. Comparison of Status Monitoring and True Power Monitoring for Average Workday

sample. Even with this large variability, the use of a stratified sampling technique produced estimates of total energy consumption within 4% of the metered data. However, the error in the peak demand prediction was much greater than the error in the energy consumption prediction.

Example 2 Fixture Status Measurements Compared with Current Measurements in a Large Office Building

In another test, lighting power consumption estimates from fixture status measurements were compared to lighting power consumption estimates from current measurements in a 10,600 SF area of a large office complex.

Current Measurements. The procedures followed for the current measurements were as follows:

1. Identify lighting circuits. Lighting circuits for the area affected were identified from the building electrical plans. A total of eight 277-V circuits were identified.

2. Measure true electric power at various circuit current levels. Circuit current levels were varied by switching various fixtures on and off. A hand-held true power meter was used to measure power at various current levels. An example of the power vs. current data is shown in Figure 3.

3. Deploy data loggers for short-term monitoring of circuit current. A split-core current transducer was installed on each lighting circuit. The data loggers were battery powered and contained sufficient internal memory to log for the period of the test without the need for remote access and downloading. A total of eight circuits were monitored, requiring two four-channel data loggers. The data loggers were installed inside the lighting panel. Since no direct connections to the panel were made, an electrician was not required for this particular installation.

4. Download data from test. The data loggers were retrieved by building personnel and mailed back for downloading.

5. Calculate lighting energy consumption, Time series records of circuit current were combined with the power vs. current measurements made at the panel. Data for each circuit were summed to calculate the lighting energy consumption.

Fixture Status Measurements. The same space was instrumented with lighting status loggers. The procedure used in this test was similar to the procedure used in the previous example, except that the control points were stratified by space type rather than connected load. The space types identified and the connected load associated with each space type are shown in Figure 4.

Lighting status loggers were randomly assigned to control points within each space type, without regard for the connected load associated with each control point. A total of 13 status loggers were used to monitor 65 control points in the space. The average workday load shapes obtained from the current measurement and status monitoring tests are shown in Figure 5. The difference in the average workday energy consumption predicted by the two techniques was 30 percent. Average workday peak demand varied by about 20 percent.

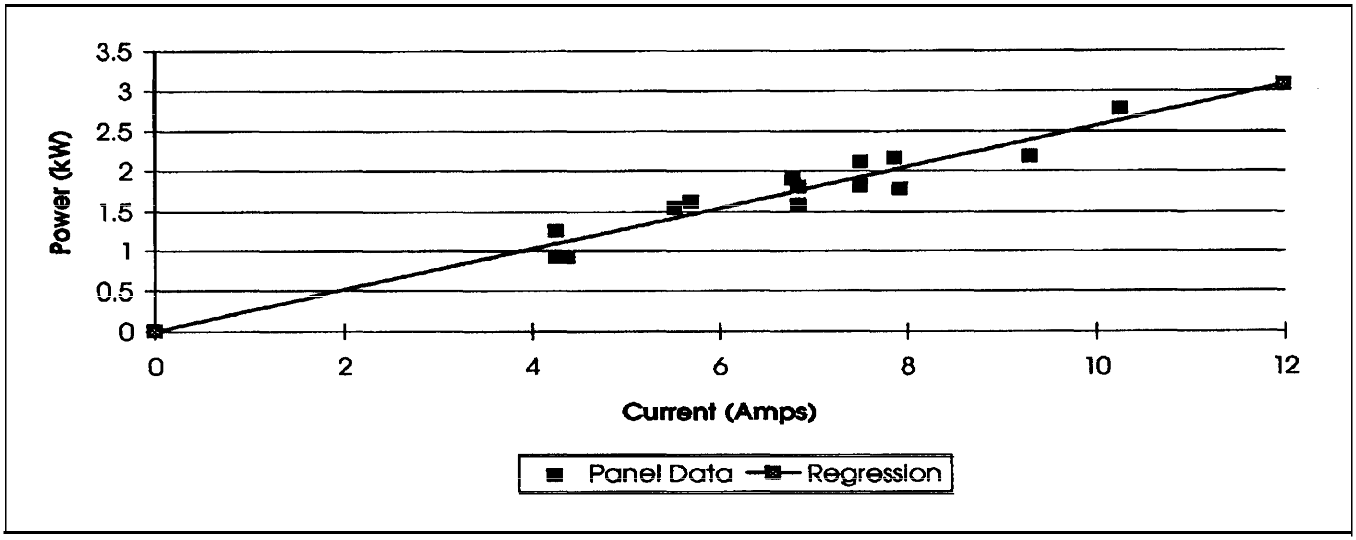

Figure 3. Measured Relationship of Power Versus Current

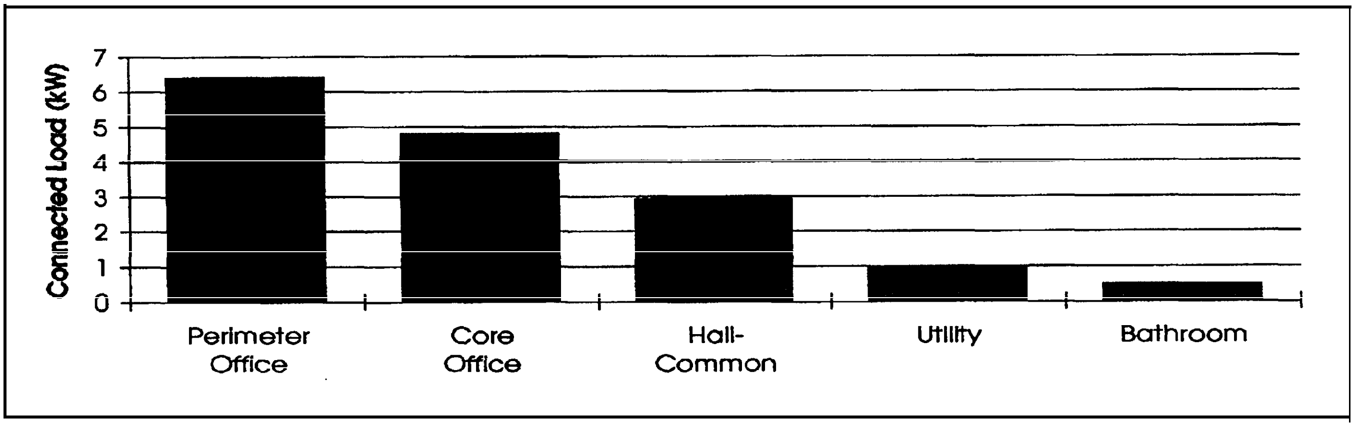

Figure 4. Connected Load by Space Type

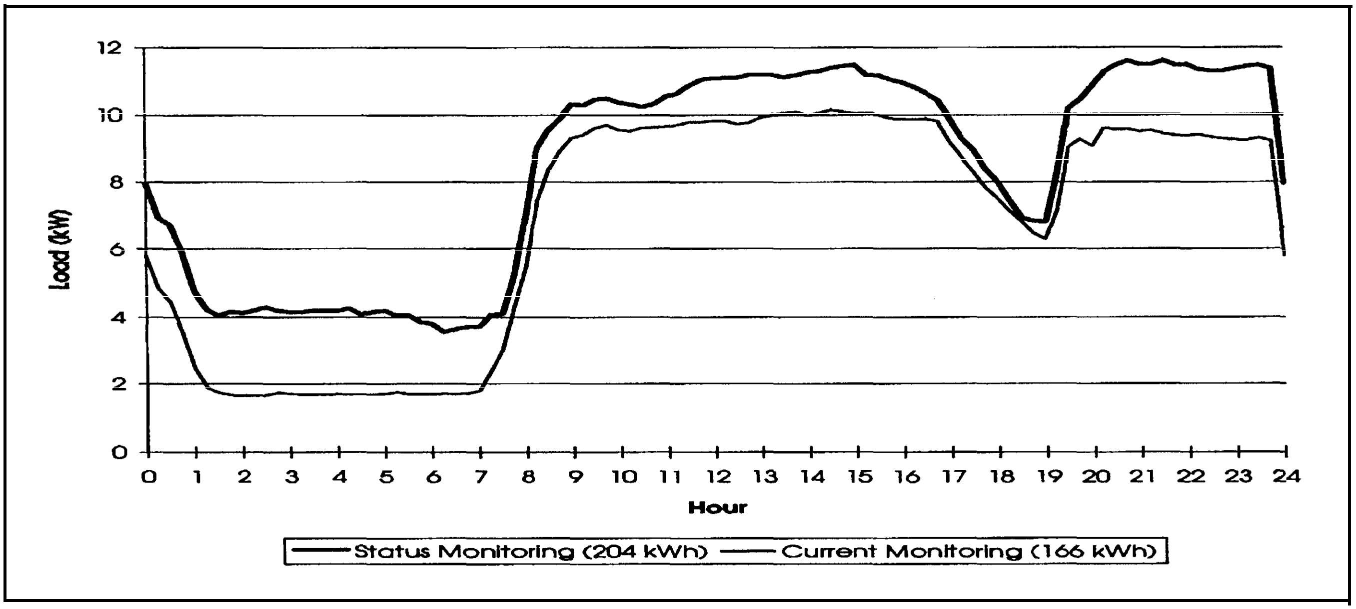

Figure 5. Comparison of Status Monitoring and Current Monitoring for Average Workday

Discussion

Sampling. Lighting fixture status monitoring involves the observation of a group of fixtures connected to a single control point, usually a wall switch. Since it is clearly not practical to monitor the status of each lighting control switch in the building, it will be necessary to select a sample of fixtures for status monitoring. A random sample of control points affected by the program can be drawn and loggers assigned to a fixture in each control point group. Improvements in accuracy and reduced sample size can be obtained with a stratified sample. Control points in the building can be stratified based on space type, connected load, and/or expected run time. A random sample is drawn from each stratum, and the results are weighted according to the relative load represented by each stratum.

Sample sizes are selected based on the precision and confidence level required in the estimate, and the expected variability in the lighting operating hours within the sampled population. The sample size required to achieve a particular relative error in the run-time estimate is given in Equation 2.

$$n = \frac{Z^2}{RE^2} \times CV^2 \qquad (2)$$

where:

n = sample size required to achieve a specified relative error
Z = Z value at a specified confidence level
RE = relative error
CV = the coefficient of variation, defined as the sample standard deviation divided by the mean.

Equation 2 is valid for samples of 30 or more, If a smaller sample is drawn, the t statistic should be substituted for the Z value. If the sample size given by Equation 2 is greater than 20% of the total number of control points, Equation 3 should be used.

$$n = \frac{N \times CV^2 \times Z^2}{N \times RE^2 + CV^2 \times Z^2} \qquad (3)$$

where:

N = total number of control points

The sample size requirements calculated by Equation 2 are shown graphically in Figure 6. In order to calculate the sample size, it is necessary to determine the relative error, confidence level, and CV. The relative error and confidence are parameters set by the requirements of the study. The CV is not known beforehand, and must be estimated.

Statistics calculated from the two test buildings are reported in Tables 1 and 2. These data lend some insight into the sampling issues associated with lighting status monitoring. In both buildings, the perimeter offices were all private offices with individual lighting controls. The occupants in Building 1 relied primarily on natural lighting, thus using the electric lighting system relatively infrequently. The occupants of Building 2 were often out of the office due to travel requirements. In the first building, fairly good agreement was reached using the stratified sampling design, even though a large measure of variation was observed in the use of the perimeter offices. In the second building, the CV observed in circulation and core spaces was about 0.2, and in perimeter office spaces, the CV was about 0.5. The sample sizes used were inadequate to achieve a 10% relative error in the estimate of operating hours at 90% confidence, thus partially explaining the disagreement in the two monitoring techniques.

Connected Load. Status measurements require an estimate of the power consumed by each fixture when in operation. Manufacturers' estimates of fixture power are frequently used to estimate this value. However, measurements of actual fixture power have been shown to deviate widely from manufacturers' data (Davis 1992), (Landsberg and Johnson 1991). The variability of the in-situ performance of lighting fixtures can account for discrepancies in the estimated savings on the order of 20% (Davis 1992). Power consumption for a particular lamp/ballast combination can vary from manufacturers' specifications according to fixture design (open vs. closed fixture), fixture mounting (recessed vs. suspended fixture), and return air path (lamp compartment return vs. ceiling return). The Electric Power Research Institute (EPRI 1992) has published tables of correction factors that can be applied to manufacturers' data to improve connected load estimates according to installation characteristics.

Field measurements of in-situ lighting power (commonly called "spot-watt" measurements) can improve the estimates of fixture operating load. In both of the buildings tested, manufacturers' connected load data were confirmed with spot-watt measurements.

Sensor Sensitivity y and Variable-Output Fixtures. Fixture on/off status monitors must be able to discriminate between light levels from an operating fixture and light levels from background sources such as daylight or adjacent fixtures. Most on/off status monitors provide a field adjustment to account for sensor mounting, fixture luminous output and background illuminance. These

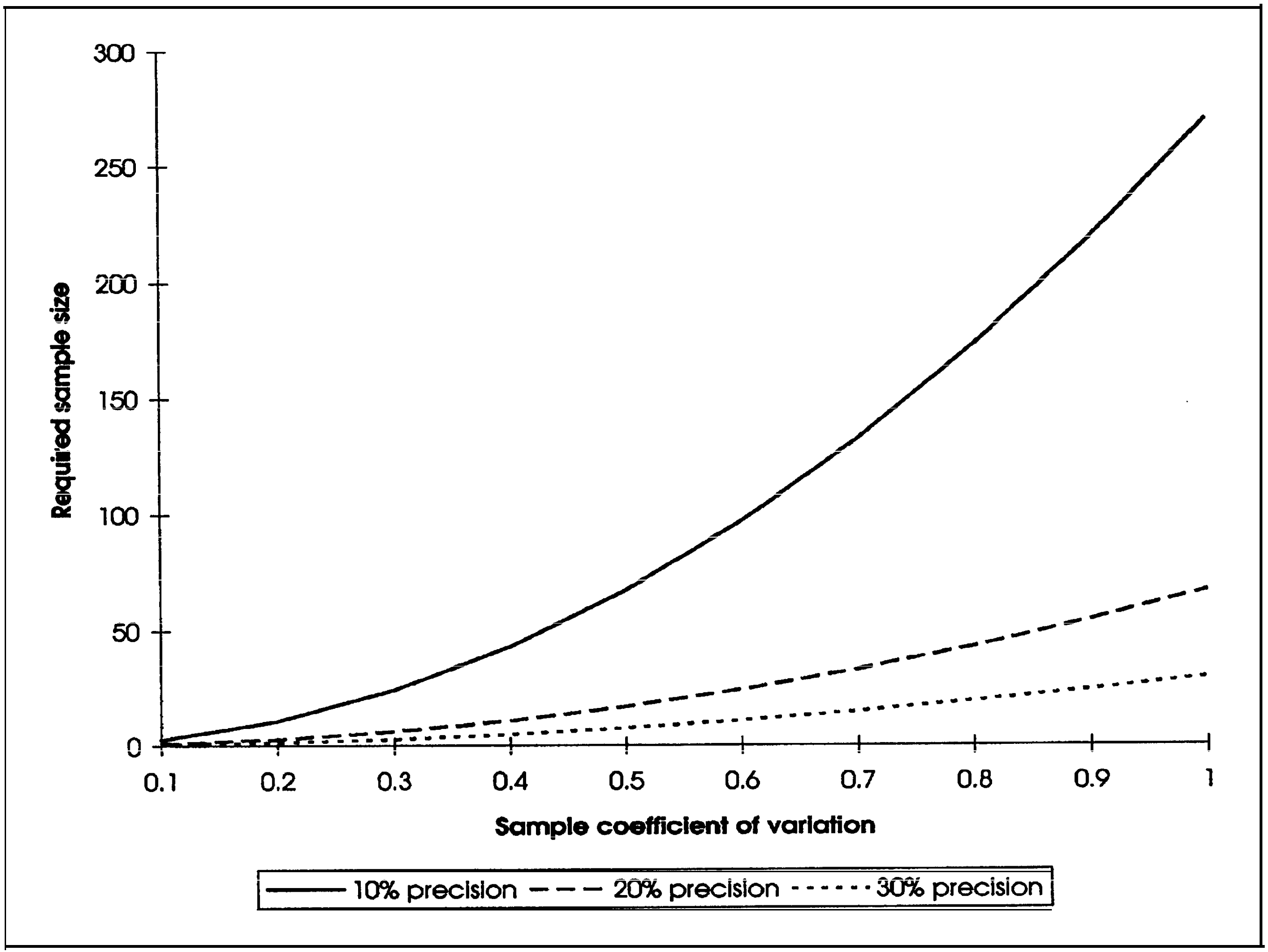

Figure 6. Sample Size Requirements at 90% Confidence

Table 1. Summary of Lighting Status Measurements for Example 1

Stratum	Space Type	Connected Load (kW)	Total Control Points	Number Sampled	Sample Mean Oper. Hr	Std Dev	CV
1	Workroom	1.06	1	1	23.2	0	0
2	Interior open office	0.88	1	1	215.8	0	0
3	Interior open office	0.70	1	1	133.5	0	0
4	Perimeter office	2.94	9	3	34.2	46.8	1.4
5	Perimeter office	1.54	9	2	23.6	19.3	0.8
6	Conference room	0.43	5	1	47.6	N/A	N/A

Table 2. Summary of Lighting Status Measurements for Example 2

Space Type	Connected Load (kW)	Total Control Points	Number Sampled	Sample Mean Oper. Hr	Std Dev	CV
Perimeter Office	6.37	24	6	89.4	43.9	0.49
Interior Private Office	4.78	19	5	142.4	41.6	0.29
Hall/Commons	2.89	13	2	292.5	62.2	0.21
Bathrooms	0.47	6	0	336 (est)	N/A	N/A
Utility	0.94	3	0	0 (est)	N/A	N/A

monitors are adjusted to record on/off status around a single field-selected threshold, and are not capable of identifying different on states of variable output fixtures, such as dimming fixtures and fixtures with multi-level switching. Data gathered from devices that measure light output can be filtered to eliminate background illuminance and identify discrete "on" states of multilevel fixtures.

Data loggers that measure fixture output were used in the status monitoring tests reported here. Data gathered by the loggers were filtered to discriminate between background illuminance and fixture operation. In Building 2, multi-level switching was used. The fixture light output data were filtered to associate discrete levels of fixture light output with the operation of the multi-level switching system.

Accuracy. The overall accuracy in the lighting energy consumption estimate is a function of the accuracy of each step in the overall energy calculation. An error propagation analysis (ASHRAE 1991) can be used to calculate the overall error in the calculation from the errors in the individual sensors and/or data elements. For true electric power measurements, errors in the current transducers and the power measurement electronics contribute to the overall error in the energy consumption measurement. For the current monitoring technique, uncertainty in the power vs. current relationship and errors in the current transducers contribute to the overall error in the energy consumption measurement. With lighting status loggers, errors in the estimate of connected load and sampling error associated with the run-time estimate contribute to the overall error in the energy consumption measurement. Estimates of the total measurement error for true power measurements, current measurements, and fixture status sampling are summarized in Table 3.

Conclusions

Short-term monitoring can be a useful tool for improving the engineering estimates of savings for commercial lighting programs. Accurate estimates of lighting energy consumption using status loggers require an adequate sample of control points. Stratified sampling strategies, based on control point connected load, can increase the accuracy of the run-time estimates for lighting status loggers. The overall accuracy of the current logging technique is driven by the accuracy of the current to kW measurements, which is driven by the accuracy of the hand-held power meter and the mix of lighting fixtures on each circuit. The current monitoring technique may be more cost-effective than lighting status monitoring, since it eliminates the need for detailed lighting surveys, control point identification, fixture mapping to control points and control point sampling.

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Endnotes

1. F.S. = full scale.
2. Current transducer accuracy values are for split-core devices. Improved accuracy can be obtained from solid nickel-core transducers.

Table 3. Errors Propagation Analysis for True Power, Lighting Current, and Fixture Status Monitoring

Measurement Strategy	Error Source	Relative Error	Error Source	Relative Error	Total Error
True Power	Power Measurement Electronics	±0.5% typ	Current Transducer	±2% F.S.[1,2]	±3.4% typ
Current	kW vs Current Conversion	±4% typ	Current Transducer	±2% F.S.	±11% typ
Fixture sampling, stratified by space type	W_{conn}	±5% typ	Sampling error on operating hours	±20% typ	±21% typ

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