Short-Term Monitoring of Commercial Lighting Systems—Extrapolation from the Measurement Period to Annual Consumption

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Short-term monitoring of lighting system performance has gained wide acceptance as an effective technique to reduce costs of evaluating DSM programs and verifying savings for energy services contracts. Short-term monitoring protocols are based on the assumption that commercial buildings have fairly regular lighting schedules, and that two weeks of monitoring is sufficient to characterize the annual performance of the lighting system. In practice, variability in building occupancy and availability of natural daylight places some uncertainty on the annual savings calculated from short-term measurements.

The paper reports on a study undertaken to quantify extrapolation error associated with short-term monitoring of lighting systems. Long-term lighting end-use data were obtained for six commercial office buildings located in the Northeast. From the end-use data, annual lighting energy consumption was calculated. Estimated annual energy consumption was then calculated for all possible two-, three-, and four-week monitoring periods over the year. Extrapolation error was calculated by comparing the estimated annual consumption from each short-term monitoring period to the actual annual consumption.

The paper reports on the average and maximum extrapolation error for each building, and the change in extrapolation error resulting from the use of two, three, and four week monitoring periods. Conclusions are drawn relative to the costs and accuracy tradeoffs of short-term monitoring protocols for the buildings studied, and practical suggestions on conducting short-term monitoring of lighting systems are offered. The applicability of the results to a wider population is discussed.

INTRODUCTION

Short-term monitoring of lighting system performance has gained wide acceptance as an effective technique to reduce costs of evaluating DSM programs and verifying savings for energy services contracts. Short-term monitoring protocols are based on the assumption that commercial buildings have fairly regular lighting schedules, and that two weeks of monitoring is sufficient to characterize the annual performance of the lighting system. In practice, variability in building occupancy and availability of natural daylight places some uncertainty on the annual savings calculated from short-term measurements.

Short-term lighting studies are usually done with portable, battery powered data loggers. These devices offer the ability to make non-intrusive surrogate or ''proxy'' measurements of lighting energy consumption and/or operating hours at low cost. The data loggers are used to monitor some easily observed parameter such as fixture on/off status (''light-loggers''), fixture light output, or lighting circuit current. This information, combined with spot measurements of lighting fixture power, is used to estimate energy consumption and savings resulting from lighting measures. Cost savings from surrogate measurements can result from lower hardware costs, lower installation costs, and reduced data analysis costs in comparison with hard-wired data acquisition and recording equipment.

Since it is impractical to observe the on/off status of all fixtures in a building, monitoring projects involving light-loggers generally observe the status of a sample of fixtures in the space. Similarly, a sample of lighting circuits may be selected for current monitoring. These techniques introduce sampling error into the analysis. In some cases, the sampling error can represent a significant source of uncertainty. A previous paper (Jacobs, et al., 1994) discussed sampling error and related issues associated with surrogate measurement techniques. The subject of errors associated with short-term measurement extrapolation is the subject of this paper.

The issue of seasonal variability in lighting energy consumption has been previously discussed by Taylor and Pratt (1989). Aggregated monthly lighting consumption data were summarized for a sample of buildings in several commercial

Table 1. Summary of Building Characteristics

ID Number	Program Type	Building Type	Building Size (SF)	Total Interior Lighting Connected Load (kW)	Lighting Load Monitored	Data Capture Rate
1	Retrofit	Office	200,000	185	100%	98%
2	Retrofit	Office	120,000	240	100%	99%
3	Retrofit	Office/Industrial	186,000	243	100%	86%
4	Retrofit	Industrial	50,500	32	100%	98%
5	New Construction	Office	20,150	16.2	100%	100%
6	New Construction	Office	250,000	300	33%	100%

building sectors. These data show very little seasonal variability in the aggregate monthly lighting consumption.

Short-term monitoring of commercial building lighting consumption was addressed by Misuriello et al. (1994). In this paper, comparison of short-term lighting hours of operation calculated from two-week pre-retrofit monitoring were compared to post-retrofit data. The paper concluded that pre- and post-retrofit operating hours were quite similar, and that short-term monitoring studies using post-retrofit monitoring provided acceptable results.

In the previous research cited, the issue of variability in individual buildings over two to four week monitoring periods, and the extrapolation of short-term results to annual consumption was not specifically addressed. The issue is important to consider when developing measurement and verification plans for energy services contracts, and allocating resources to building monitoring for program evaluation purposes. Once the extrapolation error is estimated, then an appropriate tradeoff can be made between study uncertainty (or savings at risk) and monitoring costs. The issue of variability across buildings can be considered along with the uncertainty in the individual building measurements to assess the tradeoff between the per building monitoring costs and the total number of buildings studied.

A study of expected extrapolation error resulting from short-term monitoring of lighting systems was undertaken in the context of an EPRI Tailored Collaboration aimed at developing short-term monitoring techniques for evaluating commercial building lighting and HVAC systems. In order to specifically address this issue, high-quality, long-term lighting end-use metered data from a member utility were obtained for six commercial buildings. The study focused on interior lighting systems only. The building sample, although fairly small, was selected to be representative of the commercial building stock of the member utility.

METHODOLOGY

Long-term end-use metered data were assembled for each building in the study. True electric power measurements were collected by a Synergistics DM-50 data logger. The data records were averaged over a 15 minute period. A continuous annual time-series data file was assembled for each building. In all but one building, 100 percent of the lighting circuits in the building were monitored. A description of each building is summarized in Table 1.

The time-series data records were processed into average daily values for each day of the year. Data capture rates for the project were generally quite good, as shown in Table 1. Days with missing data were filled in with daily averages according to daytype. Annual consumption was calculated from the sum of the daily values.

Once the actual annual lighting energy consumption was tabulated, the data were segmented into continuous two, three, and four week periods. Thus, a series of short-term lighting tests were simulated from the annual time-series data. The average daily consumption for weekdays and weekends was calculated for each of the simulated short term periods, and the annual energy consumption was extrapolated from the daily values for each period. The extrapolated

Table 2. Summary of Short-Term Estimated Consumption to Actual Annual Consumption

Building	Period	Actual Consumption (kWh)	RMSE (kWh)	RMSE (%)	MBE (%)	Maximum Error (%)
1	2-wk	426,869	25,117	5.88%	0.06%	21.32%
1	3-wk	426,869	20,305	4.76%	−0.03%	13.76%
1	4-wk	426,869	17,402	4.08%	−0.05%	10.03%
2	2-wk	1,048,132	65,371	6.24%	0.09%	17.22%
2	3-wk	1,048,132	56,490	5.39%	−0.07%	11.45%
2	4-wk	1,048,132	52,574	5.02%	−0.12%	10.06%
3	2-wk	1,662,028	274,762	16.53%	−0.15%	44.67%
3	3-wk	1,662,028	236,153	14.21%	−0.34%	43.55%
3	4-wk	1,662,028	191,666	11.53%	−0.25%	24.19%
4	2-wk	168,915	4,190	2.48%	0.00%	9.73%
4	3-wk	168,915	3,637	2.15%	−0.06%	6.64%
4	4-wk	168,915	3,226	1.91%	−0.11%	4.88%
5	2-wk	95,962	7,990	8.33%	1.14%	21.38%
5	3-wk	95,962	6,843	7.13%	1.14%	18.20%
5	4-wk	95,962	5,947	6.20%	1.19%	14.83%
6	2-wk	315,744	21,502	6.81%	0.07%	18.54%
6	3-wk	315,744	19,411	6.15%	−0.23%	14.00%
6	4-wk	315,744	18,558	5.88%	−0.44%	13.06%

annual consumption was compared to the actual measured annual consumption, thus providing a comparison between the value calculated from a simulated short-term test to the actual value. This exercise was repeated over all possible two, three, and four-week periods throughout the year. An example of the annual consumption extrapolated from the short-term measurements, and the actual annual consumption is shown in Figures 1 through 3.

Summary statistics were developed for each building. The maximum error represents the largest deviation (plus or minus) from any of the simulated test periods relative to the actual annual consumption. The RMS error (RMSE) was calculated according to Katipamula, et al., (1995):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{n} |E_{c,j} - \hat{E}_c|^2}{n}} \tag{1}$$

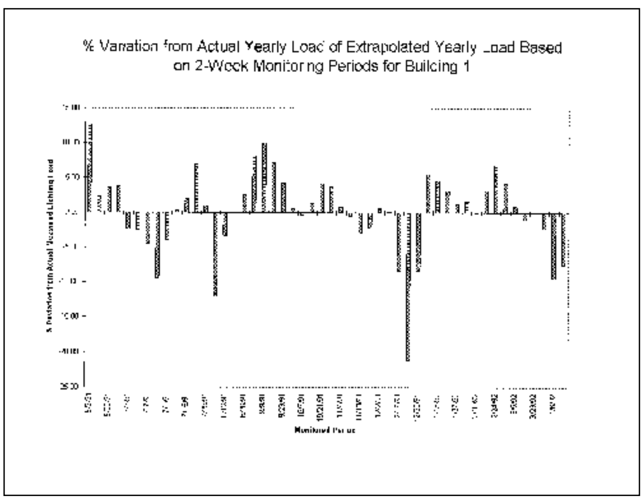
where:

$E_{c,j}$ = extrapolated annual consumption for period j
$\hat{E}_c$ = actual annual consumption
n = total number of simulated monitoring periods

Table 3. *Reduction in Extrapolation Error with Increased Monitoring Duration*

Building ID	RMSE reduction relative to 2-wk period: 3-wk	RMSE reduction relative to 2-wk period: 4-wk	Max. Error reduction relative to 2-wk period: 3-wk	Max. Error reduction relative to 2-wk period: 4-wk
1	19%	31%	35%	53%
2	14%	20%	33%	42%
3	14%	30%	3%	46%
4	13%	23%	32%	50%
5	14%	26%	15%	31%
6	10%	14%	24%	30%
avg.	14%	24%	24%	42%

Figure 1. *Extrapolation Error from Two Week Monitoring of Building 1*



The mean bias error (MBE) was calculated from:

$$\mathrm{MBE} = \frac{\sum_{j=1}^{n} (E_{c,j} - \hat{E}_c)}{n\bar{E}_c} \qquad (2)$$

where:

$\bar{E}$ = average predicted annual consumption

Figure 2. *Extrapolation Error from Three Week Monitoring of Building 1*

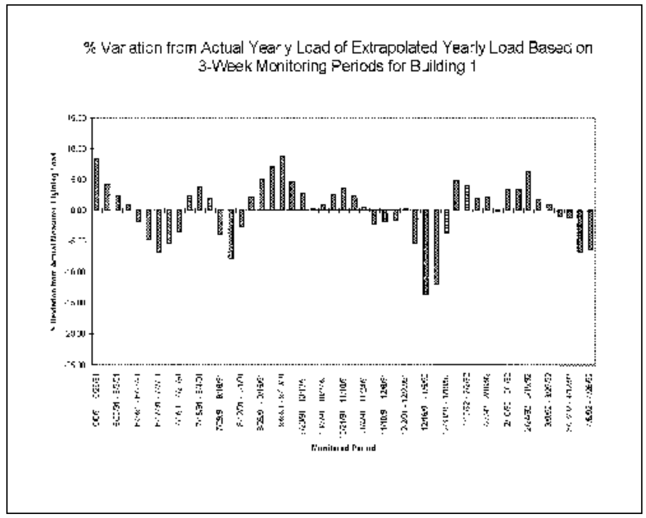
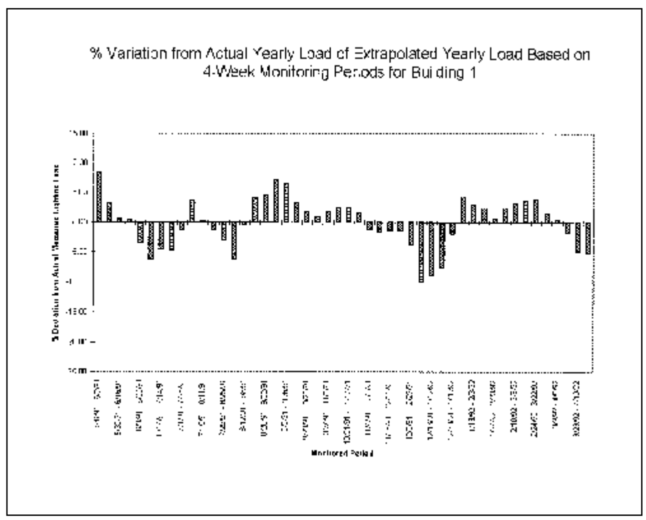


Figure 3. *Extrapolation Error from Four Week Monitoring of Building 1*



RESULTS

A summary of the statistics calculated for each building is shown in Table 2. The RMSE and maximum error are also shown graphically in Figures 4 and 5. The mean bias error for all cases is quite low, suggesting that the extrapolation of savings calculations do not contain systematic errors, such as an incorrect assumption on the annual number of weekend days and holidays. The maximum error ranges from about 5 percent for building 4 to about 45 percent for building 3, while the RMSE ranges from about 2 percent for building 4 to about 17 percent for building 3.

Figure 4. *RMS Error*

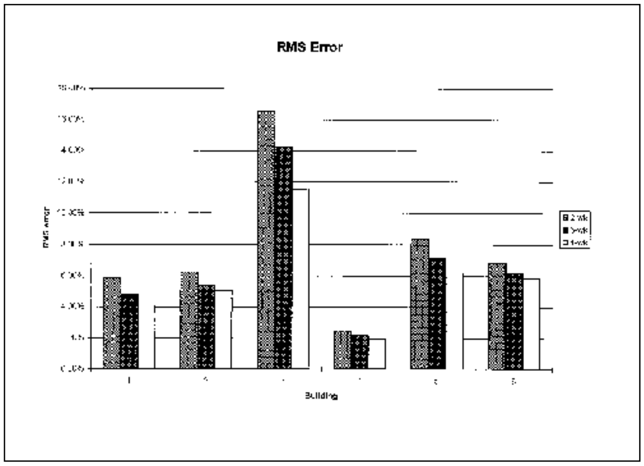


Figure 5. *Maximum Error*

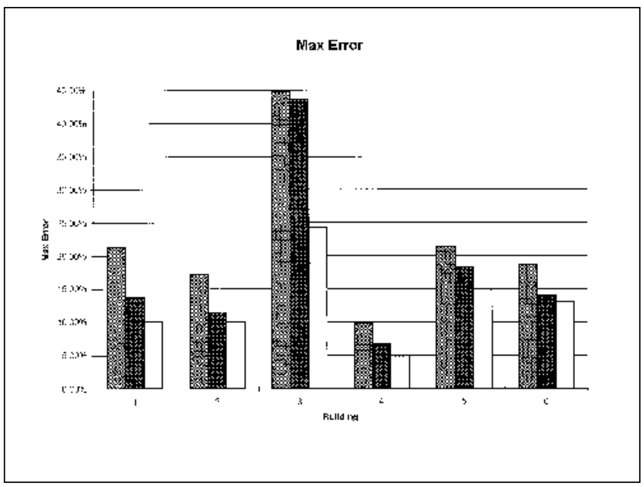


Figure 6. *Reduction in RMS Error with Increasing Monitoring Duration*

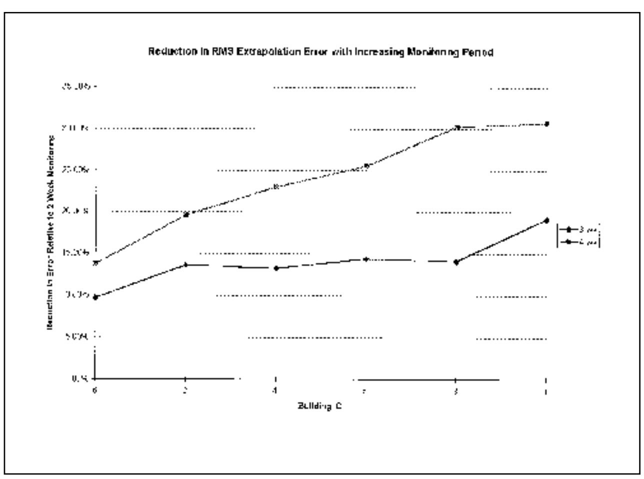
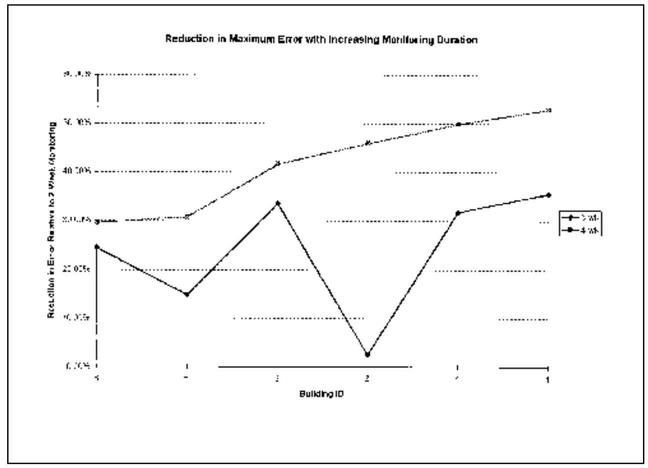


Figure 7. *Reduction in Maximum Error with Increasing Monitoring Duration*



The incremental benefit of increasing the monitoring period beyond two weeks was also investigated. The reduction in error resulting from increasing the monitoring duration from 2 weeks to 3 weeks, and 2 weeks to 4 weeks is shown in Table 3. The average reduction in RMSE is about 14 percent and 24 percent respectively. The average reduction in maximum error is about 24 and 42 percent respectively.

Additional analysis was done to look at the period-to-period variability in the projected energy consumption. The data were cleaned to remove overlapping periods and periods containing the week between Christmas and New Years. The mean, standard deviation, and coefficient of variation (CV) was calculated for annual consumption, the average workday consumption, and the average weekend/holiday consumption, as shown in Table 4. The CV for annual consumption ranged from about 2 percent for building 4 to about 13 percent for building 3. The CV for the weekday consumption was approximately equal to the annual CV, since the majority of lighting usage occurs during workdays. The CV for weekend days was much higher than workdays, indicating much greater variability in weekend than workday lighting use.

CONCLUSIONS

Overall, the extrapolation errors associated with short-term monitoring are quite reasonable. With the exception of one building, the RMSE is generally in the range of 2 to 8 percent, and the maximum error is in the range of 5 to 20 percent. These errors are generally lower than the sampling errors associated with making measurements on a subset of the total lighting fixtures or circuits in a building. For example, sampling error is on the order of 20 to 30 percent for a typical project using fixture status monitoring (Jacobs, et al., 1994).

Table 4. *Variability Across Individual Short-Term Monitoring Periods*

		Annual				Avg. Workday			Avg. Weekend		
Building	Period	actual kWh	mean pred	Stdev	CV	mean pred	Stdev	CV	mean pred	Stdev	CV
1	2-wk	426,869	427,288	23,311	5.46%	1,566	85	5.45%	266	96	36.15%
1	3-wk	426,869	430,914	17,591	4.08%	1,578	76	4.83%	271	101	37.26%
1	4-wk	426,869	426,961	18,233	4.27%	1,567	61	3.87%	261	81	30.94%
2	2-wk	1,048,132	1,050,362	73,134	6.96%	4,092	258	6.31%	2122	449	21.18%
2	3-wk	1,048,132	1,039,049	51,283	4.94%	4,035	159	3.93%	2127	317	14.89%
2	4-wk	1,048,132	1,041,184	42,220	4.05%	4,058	138	3.39%	2098	296	14.10%
3	2-wk	1,662,028	1,681,951	226,265	13.45%	5,376	730	13.58%	2850	695	24.38%
3	3-wk	1,662,028	1,678,979	230,910	13.75%	5,378	780	14.51%	2821	692	24.55%
3	4-wk	1,662,028	1,686,413	152,618	9.05%	5,378	472	8.78%	2887	614	21.28%
4	2-wk	168,915	169,053	3,862	2.28%	517	11	2.22%	512	23	4.45%
4	3-wk	168,915	169,353	4,148	2.45%	518	10	1.99%	513	20	3.90%
4	4-wk	168,915	168,838	3,896	2.31%	517	10	2.00%	510	17	3.41%
5	2-wk	95,962	97,579	7,978	8.18%	309	24	7.89%	181	59	32.46%
5	3-wk	95,962	97,584	5,607	5.75%	309	21	6.72%	180	53	29.18%
5	4-wk	95,962	97,711	6,206	6.35%	310	19	6.16%	180	54	30.00%
6	2-wk	315,744	316,148	21,918	6.93%	983	39	3.92%	603	115	18.99%
6	3-wk	315,744	316,321	21,520	6.80%	985	41	4.21%	600	106	17.69%
6	4-wk	315,744	313,837	18,521	5.90%	979	32	3.31%	591	97	16.34%

The maximum extrapolation error can be reduced by avoiding certain periods of the year, such as the Christmas holidays. By examining Figure 1, it is evident that the maximum error will decrease from 21% to 13% if the Christmas holidays are eliminated from the analysis.

Increasing the monitoring period beyond two weeks can reduce the RMSE on the order of 10 to 30 percent, and reduce the maximum error on the order of 30 to 50 percent. The majority of the costs involved in performing a short-term lighting study are contained in developing the monitoring plan, installation and retrieval of data loggers, and data analysis. Thus, increasing the study duration (assuming a single deployment of the data loggers) may not have a significant impact on costs, and can help to ‘‘smooth out’’ anomalous short-term behavior. However, practical considerations, such as availability of monitoring equipment and project elapsed time constraints may be overriding concerns.

The CV calculated for annual energy consumption within an individual building is much less than those typically calculated across buildings in the commercial sector. This suggests that short-term measurements taken on a greater number of buildings will minimize overall error in estimating the characteristics of the population.

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