More is Better? Analyzing the Relation between Metering Duration and Accuracy of Results for Residential Lighting Evaluations

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ABSTRACT

Lighting retrofits and replacements are a significant part of almost every residential energy efficiency program, and are also some of the most commonly evaluated project types. The deemed savings for nearly all residential lighting projects are determined using a prescriptive approach, wherein tabulated data of annual operating hours is used to determine projected savings. This tabulated data often comes from Technical Reference Manuals (TRMs) or Program Savings Documentations (PSDs) from other jurisdictions. However, lighting use data can also be found with a study performed within the service territory.

When a study is performed to determine the “typical” lighting use for residential customers, lighting loggers are often used to monitor a sample of lights for a set period of time. However, there is no industry-standard for how long the sample of lights should be monitored. This paper determines, quantitatively, how the precision of residential lighting hours of use measurements changes with logging duration. Field data was analyzed from eight residences collected over a period of six months. Additionally, the cost associated with improvements in precision is discussed to inform stakeholders of the relative extra cost required for a corresponding improvement in the level of precision.

The results of this analysis provide a comprehensive overview of the relation between logging duration and the relative precision of projected annual lighting hours of use for residential customers. The data suggests that after approximately four months of metering, the incremental improvements in results may not be worth the extra time and expense to leave metering equipment in place any longer.

Introduction

Residential lighting evaluations are often based on engineering algorithms, in which hours of use is a key parameter. Hours of use, in turn, are typically based on either deemed estimates of hours of use or on on-site hours of use monitoring. Often times, tabulated information about residential lighting use in other service territories is used, in which case there are several assumptions and estimations that have to be made; “typical” lighting use varies throughout the country because of variations in peoples’ lifestyles, the average age of the population in a given area, employment rates, cultural differences, geography, and various other factors. Adjustments must be made to account for factors such as these, or it must be assumed that these factors will not cause a significant difference in the lighting use patterns when comparing service territories and adapting lighting use data across service territories. It must also be assumed that the participants in a given lighting energy efficiency program or study represent a “typical” group of customers, and not customers who are prone to using their lights more or less than the average customer.

For every lighting study that is completed, many approximations and assumptions have to be made using engineering judgment such that the values to be reported can be determined within acceptable margins of error. In a house with five bedrooms, can the lighting use in a random sample of two bedrooms be used to accurately estimate the lighting use of the other three bedrooms? Is the lighting use in the basement of a house during the summer the same as it will be during the winter? Questions of this nature must be answered and taken into account to the greatest possible extent when completing a lighting study. However, inaccuracies will always exist because, in most cases, only a representative sample of lights are metered, lights are metered for a finite, often short amount of time, and there are always variations in lighting use due to variations in human behavior or activity.

A significant portion of lighting studies and evaluations involves monitoring lights to gather information about how much the pertinent lights are being used. The collected data are often used to determine the expected operation of the lights, which in turn is used to determine the expected energy and demand savings for a given project or program. This is consistent with the methodology used for several other residential lighting studies that have been completed in various service territories.[1,2] The duration of lighting monitoring varies significantly across program evaluations and studies, from as little as one week to greater than three months. The monitoring duration for any given program evaluation or study is often set based on the monitoring duration of past evaluations and studies, engineering judgment, and the idea that a longer monitoring duration will yield more accurate results. But is this assumption even reasonable? Does the data suggest that a longer metering duration improves accuracy significantly? Is there a monitoring "sweet spot" that maximizes data accuracy and cost effectiveness?

The monitoring duration for any program evaluation or study has a significant effect on the timeliness with which the evaluation or study can be completed and the overall cost. Before any evaluation or study is started, a decision must be made as to what metering duration should be used so that the resulting hours of use estimates will be within an acceptable margin of error, the metering and evaluation can be completed within an acceptable timeframe, and the cost of the evaluation will be kept within a specific budget.

Michaels Energy has performed residential lighting studies and lighting project evaluations for several major utilities throughout North America. Studies have involved hundreds of residential participants and the installation of thousands of light meters. The process of performing a residential lighting study or evaluation often times involves installing specialized equipment to monitor the operation of pertinent fixtures. These data are used to calculate the expected operating hours for the lights. Aggregating this data together can provide extremely useful insights into how the duration of the logging period impacts the precision of the lighting hours of use measurement. Additionally, it provides useful information regarding the cost of the increased precision associated with longer monitoring periods.

This paper uses metered data from lighting in eight separate residences to explore the relation between metering duration and the statistical precision of the resulting lighting operation data. The relative accuracy and relative error associated with a range of metering durations will be presented, and will be done for two separate analysis methods – one in which the metered lighting use is weighted based on the wattage of the metered fixtures, and one in which each logger is given equal weighting.

Data Collection Procedure and Evaluation Process

The process that is undergone at each site for most lighting studies or project evaluations includes the same core components – customer interview, lighting survey, metering equipment installation and documentation, and follow-up visits that include metering equipment retrievals and follow-up customer interviews. During such site visits customers are asked about the use of the lights pertinent to the site visit, any known sources of seasonal variations in lighting use (such as kids being

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1 United States Department of Energy Residential Lighting End-Use Consumption Study
http://www.calmac.org/publications/FinalUpstreamLightingEvaluationReport_Vol1_CALMAC_3.pdf

2 Northeast Residential Lighting HOU Study
https://app.box.com/s/o1f3bhbunib2av2wiblu/1/1995940511/17399081887/1

on summer vacation or if any trips are taken), and if any timers, occupancy sensors, computer systems, daylight sensors, or other mechanisms are used to control any lights. Notes are taken about lighting circuit configurations and controls, the types and wattages of the lights pertinent to the site visit, and the locations of the lights. During follow-up visits the installed metering equipment is collected and the customer is asked follow-up questions about the lighting use during the metering period and possible sources of inconsistencies or anomalies in the metered lighting use.

The type and quantity of the light metering devices that are installed during each site visit are dependent on the quantity of lights pertinent to the site visit, the circuit configurations of the lighting, how the lights are controlled, the locations and accessibility of the lights, and the information provided by the customer during the customer interview. The installation of metering equipment is done in a random manner, though there are sometimes factors that affect which lights are metered, such as accessibility. In many cases only a sample of lights are metered, and sufficient information is collected during the site visit such that the information gathered with the metering equipment can be used to accurately characterize the operation of the lights that were not metered. In some cases, metering equipment can be installed to measure lights on every pertinent circuit.

Two types of light metering equipment are frequently used by Michaels Energy when evaluating lighting operation – HOBO UX-90 light on/off data loggers and HOBO U12-012 lumen level loggers. HOBO UX-90 data loggers record the times at which lights turn on and off, and are primarily installed when the logger can be placed near the lights and/or to monitor lights for which there are minimal chances of any daylight interference. HOBO U12-012 data loggers record luminous intensity at a user-specified time interval, and are often used to monitor lights for which daylight interference may be a concern. Finding and isolating daylighting interference in light level data is much easier than data of on/off status.

Data Set

The logger files used in this paper are from 52 individual HOBO UX-90 light on/off loggers that were installed in eight houses. All of the loggers were installed during the summer and were in place for approximately seven months. Loggers were installed to monitor a variety of interior and exterior lights including table lamps, lights in ceiling fans, floor lamps, chandeliers, and several other fixture types. After the installed light loggers were collected, the recorded data was downloaded and saved as a spreadsheet file. Figure 1 provides a graphical representation of sample of data from one logger, showing the status of a light (on/off) as either a 1 or a 0, and how the on/off state of the light changes over time.

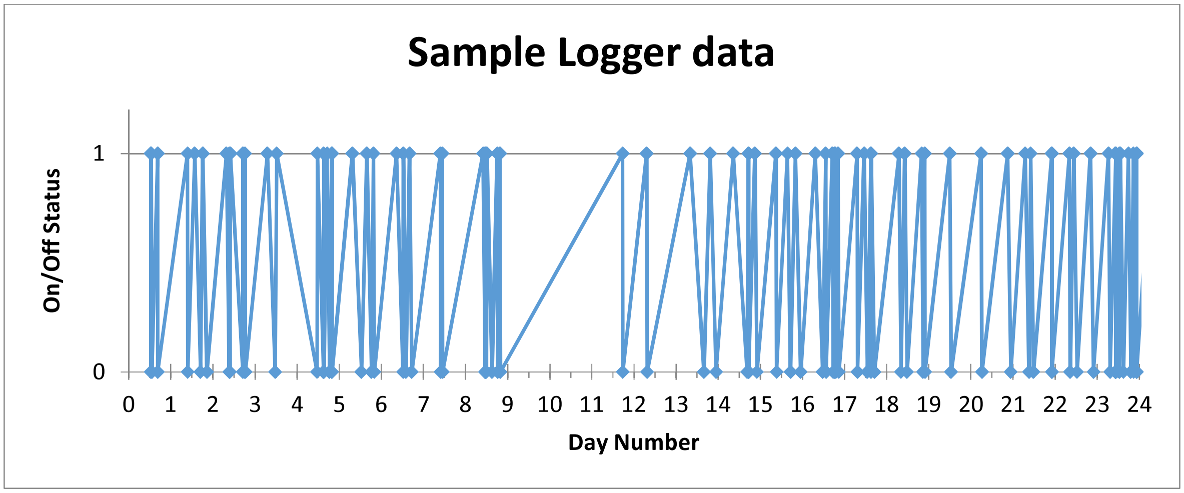

Figure 1. Sample Logger Data

The data collected with the installed loggers was closely examined to ensure that there was no daylight interference, no data that would indicate the light quit working properly or the logger was disturbed (was moved, covered, or fell from its installed location) during the metering period, and there were no errors in the logger data. Daylight can sometimes cause a light meter to detect that the lights are "on" (when they are actually off), which can cause inflated lighting use data. Quite often, daylight interference can be seen in the collected data because of gradual increases and decreases in lighting levels or the lights being shown as "on" during periods when people are not expected to be using the lights. When daylight interference was realized, that compromised the lighting use data (lighting operation cannot clearly be distinguished and isolated); therefore, the data from that logger was not used in the analysis. For the eight residences from which the loggers were analyzed for this paper, a total of 59 loggers were installed, seven of which were removed from the sample due to evidence of daylight interference or the logger not working properly during part or all of the metering duration.

Daylighting can cause the lights in perimeter rooms to sometimes be used less than in internal rooms. Changes in lighting use can sometimes be correlated to sunrise and sunset times or the amount of darkness. Because the loggers were installed for an extended period of time, in some instances it was possible to identify seasonal variations in lighting use, which were taken into account in the determination of annual use using regressions. All of the data collected for this paper starts in the summer (June) and ends in the winter (January). Lighting use tends to correlate to hours of daylight; therefore, if no usage regressions were included in the analysis, the data would likely show a gradual increase in lighting use over the term of the metering (as hours of daylight decreased). The diurnal usage regressions[3] normalize the data, so that the data from any part of the metering period is relevant to all times of the year. Figure 2 shows how the weekly lighting use found with one logger relates to the average amount of darkness per day. For this logger, there is a linear relation between the amount of darkness and the amount that the metered light is used.

3 Lighting hours of use related to daily hours of darkness, as defined by sunset and sunrise times

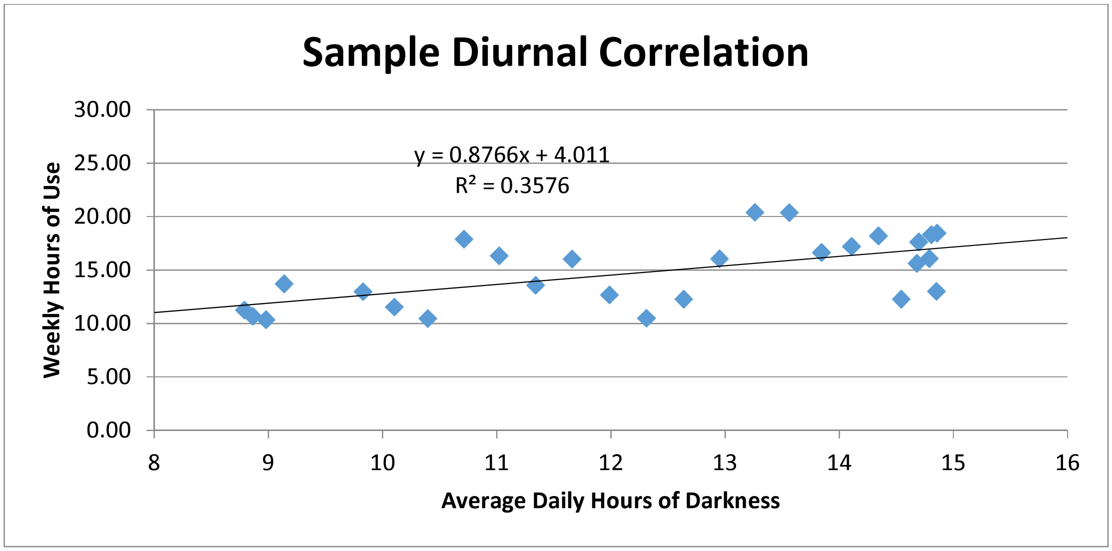

Figure 2. Sample Diurnal Correlation

The data for each logger was analyzed to check for diurnal correlations. For loggers where diurnal correlations were found, the calculated regression was used to calculate an adjustment factor that was applied to the data so that the expected annual hours of use for the metered light could be more accurately determined. For each of the loggers analyzed, periods of atypical lighting use (vacations, burned out bulbs, etc.), identified through the customer interview, were removed.

Each day of the year contains a specific amount of darkness, which was found using the sunrise and sunset times reported by the United States Naval Observatory for the location of the site most near where the data loggers were installed. The expected lighting use for each day of the year can be calculated using the regression found as shown in Figure 2. For a given time period, the expected amount of lighting use can be calculated, and comparing this value to the total expected lighting use for an entire year, the percent of the expected annual lighting operation occurring during the time period can be determined. The diurnal regression was used to determine the operating hours for the average daily hours of darkness for the year, which in turn was used to determine the expected annual lighting operation.

The average operation of the metered light was then found for each full week of the metering duration. The lighting use from each week of metered data is what was used in the statistical calculations described in the following sections.

Data Analysis Methodology

For the analysis presented in this paper, all of the metered data spans more than six months. After vacation periods and other sources of anomalies in the data were removed, the data were used to determine the average weekly lighting operation for each week of the metered period. Using these calculated values of average weekly lighting use, diurnal correlations were used (when appropriate) to determine the projected annual hours of use of the lights for metering periods ranging from one week to 27 weeks.

To determine how the projected annual hours of use for lights varies with metering duration, the incremental average was used to determine the average weekly lighting use for metering durations spanning from one to 27 weeks. To better illustrate this, Figure 3 shows how a sample of data points were determined for any given logger. The first data point utilizes the average projected hours of use of only the first week of metered data; the second data point is an average of the projected hours of use for the first two weeks of data, etc. The result of this analysis is a set of 27 points for each logger, each point representing the projected annual hours of use for the metered light had a different metering duration been used.

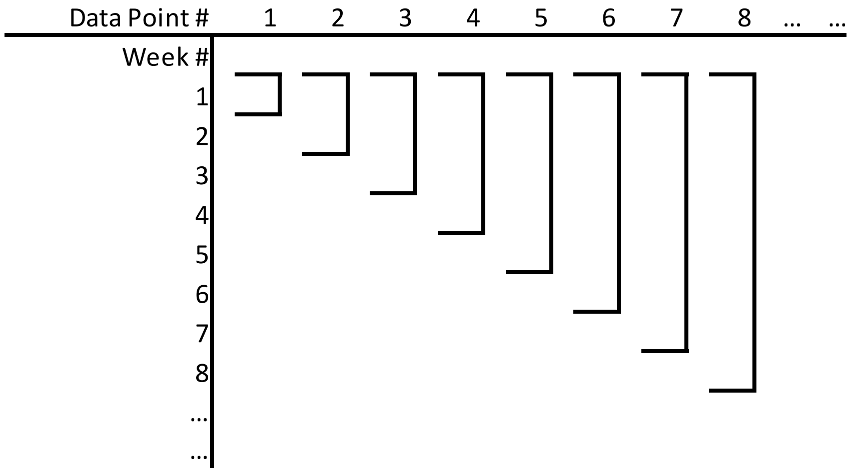

Figure 3. Data Sampling Method

Each logger that was installed for the residential lighting study was placed to measure a single fixture or circuit. In order to aggregate the results from each logger on a common scale, the projected annual hours of use based on each metering duration for a logger was compared to the projected annual hours of use for the full metering duration for that same logger. The result of this analysis is a measure of the relative accuracy for each metering duration (ranging from one to 27 weeks); the logger data is presented as a percentage of the projected hours of use for the logger that was found using the full duration of metered data. With this analysis, it is assumed that the metered data from the full metering duration will produce the most accurate projected hours of use for any particular logger, and thus is the best point of comparison for the projected hours of use that are determined from shorter metering periods.

To aggregate all of the points calculated as described above, two separate approaches were used: a weighted approach wherein the data is weighted based on the wattage of the metered circuit; and an unweighted approach, wherein data from each logger is given equal weighting. The average, standard deviation, and relative error[4] of the relative accuracies were determined for each metering duration.

It was found that there is a non-normal distribution to the relative accuracies for some metering durations, primarily due to outlying points caused by lights that are used very infrequently. Because of this, a Box-Cox Transformation[5] was used to improve the normality of the data. For each metering duration ranging from one to 27 weeks, the average relative accuracy and the standard deviation of the relative accuracies was determined. Figure 4 shows how the relative accuracy of the projected hours of use varies with metering duration, and also shows the average relative accuracy plus and minus one standard deviation. As the metering duration increases from one week to 27 weeks, the graph converges to 100% because the projected annual hours of use from each metering duration is being compared to the full duration (27 weeks) projected results; as the metering duration goes to 27 weeks, the average goes to 1.00 and the standard deviation goes to zero because the last metering duration that is analyzed is the same as the full-duration projected use.

4 Relative error is standard deviation divided by average

5 Box-Cox Transformation is a transform using power functions that is used to give data a more normal distribution. More information about the use and application of Box-Cox Transformations can be found in *Practical Assessment, Research & Evaluation*, Volume 15, Number 12, October 2010 http://pareonline.net/getvn.asp?v=15&n=12

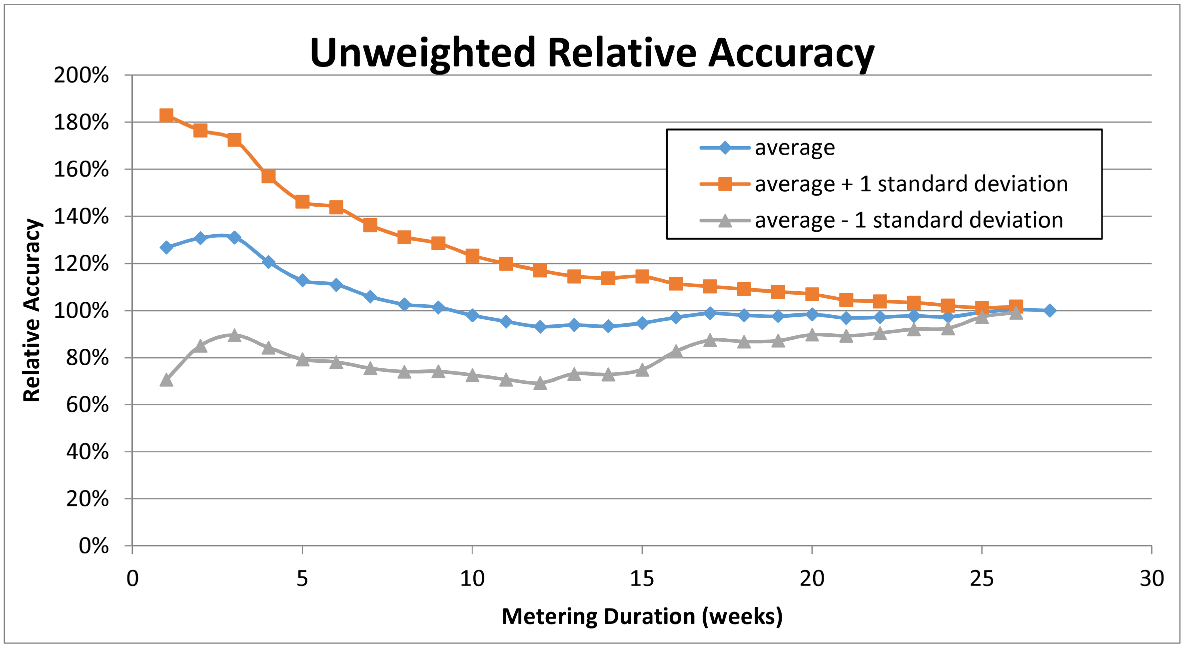

Figure 4. Unweighted Analysis

To determine the weighted average relative accuracy and weighted standard deviations of the relative accuracies for each metering duration ranging from one to 27 weeks, the same analysis method was used as for the unweighted results. However, in the weighted case the relative accuracies were weighted based on the wattage of the lighting circuit that was metered by each individual logger. The resulting graph, shown in Figure 5, depicts the weighted average relative accuracy and the weighted average relative accuracy plus and minus one weighted standard deviation.

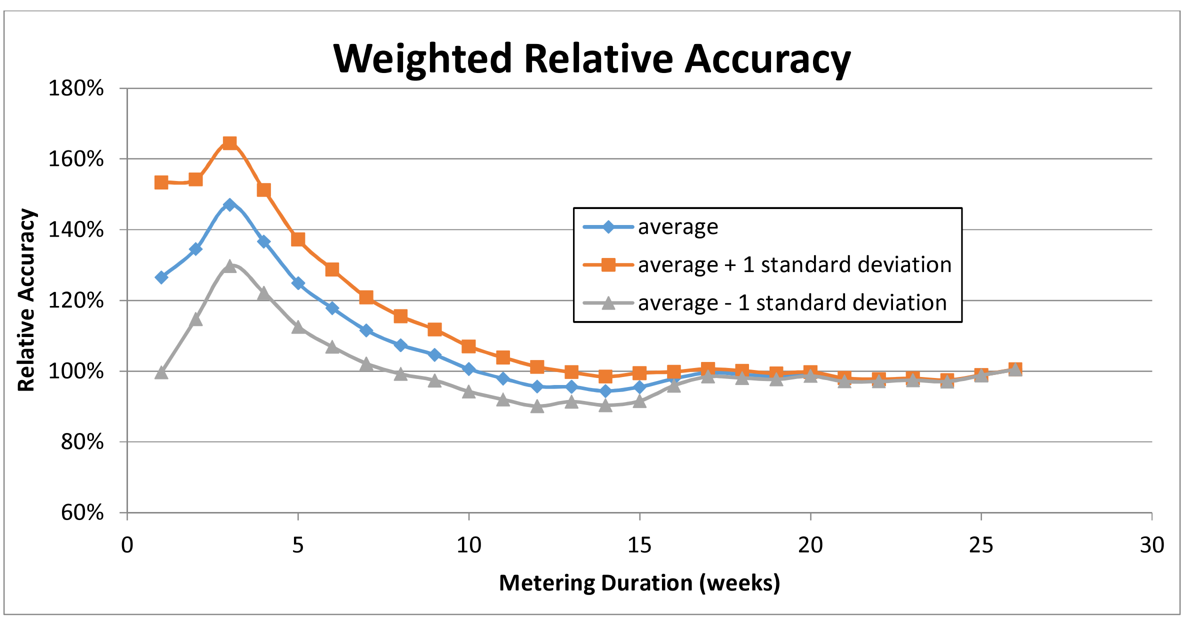

Figure 5. Weighted Analysis

Relative Error Analysis

For both the weighted and unweighted analyses described above, the relative error for each metering duration was determined. The relative error was defined as the size of the standard deviation (weighted or unweighted) relative to the average relative error (weighed or unweighted) for a given dataset. The relative errors for both the weighted and unweighted analyses are shown in Figure 6.

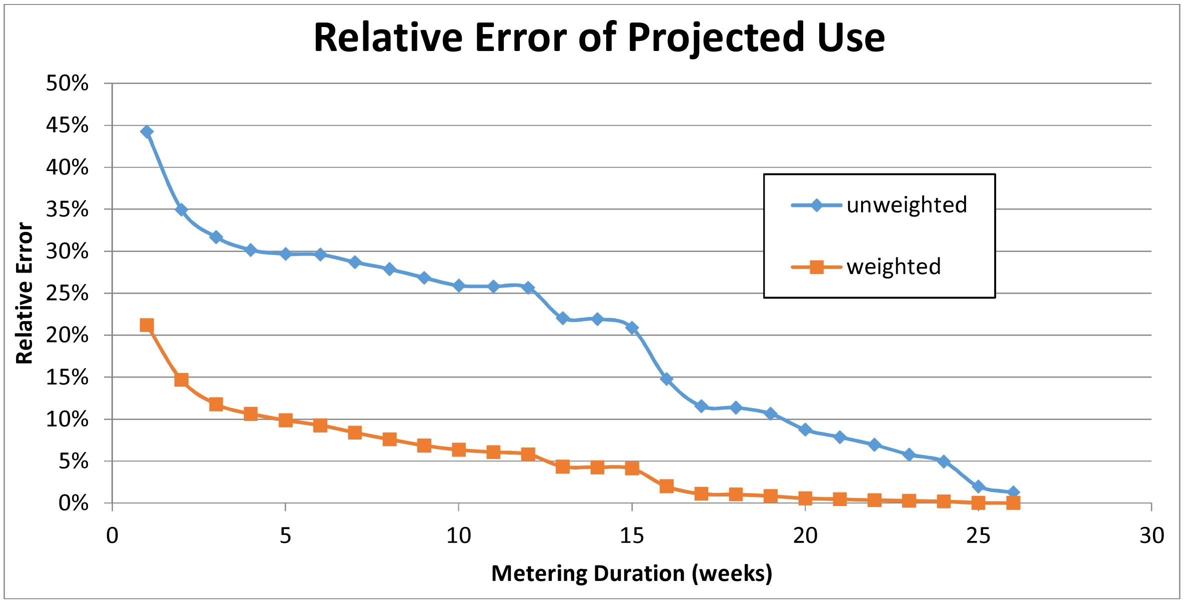

Figure 6. Relative Error of Projected Use

As can be seen in Figure 6, the relative error for the weighted analysis becomes extremely small as metering duration is increased. After 16 weeks the relative error is less than 2%, and the incremental improvements in relative error continue to decrease. Because of this, it can be suggested that for a weighted analysis, after 16 weeks of metering the improvements in the results resulting from longer metering are not worth the additional time that the metering equipment would be left in the field.

Comparing Metering Duration to Accuracy of Results and Analysis Costs

For this paper, 52 loggers were analyzed, whereas lighting evaluations or studies will quite often involve several hundred or thousand loggers. Having a much larger sample of logger data in any given study or evaluation will likely result in smaller standard deviations and relative errors than what is presented in this paper. Standard deviation and relative error are not only dependent on the number of points in a data set, but are also dependent on the scatter of the data, so there is no guarantee that a larger set of data will in fact result in lower standard deviations or relative errors. The values presented previously are only meant to show trends in how the accuracy of results changes with metering duration. Because the data used are from residences, the fluctuations and scatter in the data are likely very different than what would be found in commercial or industrial buildings, or in data from the operation of a different type of equipment, such has HVAC.

Accuracy of Results from Various Metering Durations

Several observations were made from the analyses that were rather surprising. One observation was that the weighting of the relative accuracies has a significant effect on the standard deviations. It was originally thought that each light circuit throughout a house is used consistently from week to week, thus weighting the data would not have a significant effect on the results. However, the relative error and the standard deviations calculated with weighted data suggest that circuits that control higher wattages of lights (such as circuits in living rooms and kitchens) have much more consistent operation than circuits of lower wattages.

Another observation that was made from the analysis presented above is how the improvement in relative error quickly becomes approximately linear. In the unweighted and weighted determinations of relative error, the incremental improvement averaged 6% and 4% per week, respectively, during the first three weeks. For the unweighted analysis the incremental improvements in relative error for the remaining 24 weeks are consistently around 1.6%, and for the weighted analysis are consistently around 0.6% until week 16, after which the improvement falls to about 0.2% per week. As can be seen in Figure 6, the improvements in relative error are not perfectly consistent, but this is simply because of inconsistencies in the use of the metered lights.

One additional observation that was made was how much the average relative accuracy changes. For both the weighted and unweighted analyses, the average relative accuracy starts out above 100%, increases for a few weeks, and eventually decreases to below 100% before coming back up to 100% at the full metering duration. This can likely be attributed to the fact that not all of the seasonal variations in lighting use were captured in the diurnal analysis. The diurnal adjustments made, as described earlier, only account for changes in lighting use that correlate to changes in the amount of daylight.

Cost Analysis

A factor that plays a significant role in deciding how many sites to sample and how long that metering equipment should be installed for, is cost. For any given study or evaluation, whether it be lighting, HVAC systems, or another equipment type, and whether it is done in residential, commercial, or industrial facilities, there is a fixed cost associated with each site visit. This includes recruiting the customer, scheduling the site visit, traveling to and from the site, the actual time spent at the site doing logger installations, surveying customer interviews, analyzing logger data, and writing reports after the loggers have been collected. There is also a variable cost associated with each site that is largely dependent on how long any metering equipment is left in place, as clients are billed an equipment rental fee for the duration that metering equipment is deployed. The use of loggers for a lighting study or evaluation might carry a rental fee of around $50 per week per participant, which can become a significant portion of the budget for a project if it is decided that metering equipment should be left in place for several months.

Typically, the shortest period of time that metering equipment is left in place at any given facility is three weeks, and quite often equipment is left in place for between one and two months. Using the relative error that was calculated for each increment in metering duration in the weighted analysis, the costs associated with improvements in relative error were determined. Using the three week metering duration as a point of comparison, it was found that in order to achieve a relative error that is 10% less than what is achieved with three weeks of metering, less than one additional week of metering is needed, which might carry an additional metering fee of $42 per participant. This same calculation was done for 10% increments all the way up to 90%. The results are displayed in Table 1.

Table 1. Relative Error Improvement Cost

Improvement in Relative Error	Weeks of Metering Required	Cost Increase Per Participant
0%	3	-
10%	3.8	$42
20%	4.8	$90
30%	7.1	$205
40%	9.7	$335
50%	11.5	$425
60%	12.9	$495
70%	14.3	$565
80%	15.9	$645
90%	18.1	$755

Table 1 shows that compared to metering for just three weeks, if the relative error is to be decreased by 50%, nearly three months of metering is required, and if the relative error is to be decreased by 90%, over four months of metering is needed. The relative error for any set of metered data is dependent on the scatter in the data, the size of the sample, and various other factors. Though the values presented in Table 1 are not going to exactly reflect changes in relative error with respect to metering duration for other studies or evaluations, they should provide a good indication as to how increasing metering durations may affect the precision and cost of a study or evaluation.

In the Relative Error Analysis it was noted that after 16 weeks of metering, leaving metering equipment in place longer may not be worthwhile. Assuming $50 per week per participant for equipment costs, metering for 16 weeks instead of 27 weeks (the duration of metered data used in this paper) would save $550 per participant. In a study with hundreds or even thousands of participants, the savings resulting from this could be significant, and the study could be completed in a more timely manner.

Conclusions

This paper analyzed data from 52 loggers that were installed in eight residences to monitor a random sample of lighting fixtures in all types of interior and exterior spaces. The data collected spanned greater than six months, and was examined to check for seasonal variations in lighting use and periods of atypical lighting use. When applicable, seasonal effects in lighting use were taken into account in the determination of projected annual lighting use, and periods of atypical lighting use were identified and removed on a case-by-case basis using information collected from the customers and engineering judgment. Using the projected lighting hours of use from the full duration of metering as a baseline for each logger, the relative accuracy of the projected hours of use for metering durations spanning from one to 27 weeks were found. The relative accuracies found for each logger for each metering duration were aggregated together to examine trends in how the relative accuracy of the projected lighting use changes as metering duration increases. The data was aggregated using two different methods – an unweighted approach, wherein each logger had an equal contribution to the calculated results, and a weighted approach, wherein the results from each logger were weighted based on the wattage of the circuit that was monitored by each logger.

The analysis of the residential lighting study metered data showed that the precision of the projected hours of use continues to improve as metering duration increases, and there is no point at which it is clear that additional metering would no longer be beneficial to the results of the study. This was found to be true for both the weighted and unweighted analysis methods. The improvements in precision resulting from incremental increases in metering duration gradually decrease over time, but never became zero or negative in the analysis of 27 weeks of metered data done for this paper. Additionally, it was found that the results from the weighted analyses were more favorable than from the unweighted analysis, as it yielded smaller standard deviations and the average relative accuracy of the results did not fluctuate as much.

It is the intent of any data collection effort to produce results with an acceptable level of accuracy and precision. The accuracy and precision of any set of data is dependent on the size of the sample and the scatter in the data, it can be expected that the accuracy and precision of the data from any logger will continue to improve as metering duration increases, as there is no point at which there is no benefit resulting from increased metering durations. For the logger data used in this paper, it was found that the relative error quickly decreases during the first few weeks, and continues to decrease at a relatively consistent rate as metering duration is increased.

In the weighted analysis, the standard deviation of the relative accuracy is extremely small after 16 weeks, so it could be argued that this is the point at which longer metering would no longer be worth the additional time and expense. In the unweighted analysis, a good cut-off point is not as easy to identify, but around the same metering duration (16 weeks) it can be seen that the incremental improvements in the results are in fact very small.

Future Work

The data analyzed for this report is from a set of eight residential customers that are all located in one service territory. Future work on this topic may include analyzing metered data from residences located in other regions of the country, and analyzing metered data from lighting in commercial and industrial facilities. It is expected that the lighting use in commercial and industrial facilities is much more consistent than in residences, so perhaps with these facilities there is a point at which there is no improvement in projected hours of use. Additionally, it could be determined if extremely low relative error can be achieved by metering the lights in commercial or industrial facilities for just a few weeks rather than several months.

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