Self-Reporting in Lighting Controls Systems: An Evaluation in the FLEXLAB

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Introduction

Since their introduction decades ago, lighting controls have presented a dilemma with regards to energy savings. These systems offer the potential for substantial energy savings, but it is extremely difficult to quantify exactly how much savings a particular lighting controls technology or strategy may yield. Even after a lighting controls system is installed, it can still be difficult to quantify savings as it can be extremely dependent on occupancy patterns, user preferences, seasonal variations, and/or weather patterns, which themselves can be extremely variable. The net result is that investments in energy efficiency lighting are often directed to more predictable – but perhaps less cost effective – technologies, such as higher efficacy light sources or lamps and ballast retrofits. Essentially decision makers often take the guaranteed and verifiable 20% savings over the potentially more difficult to verify 30%-50% savings.

Increasingly sophisticated and "connected" lighting controls systems are starting to address this dilemma. A new generation of lighting controls is emerging that can estimate energy use and savings down to the individual luminaire level and estimate how much energy the system is saving from each control strategy (e.g., daylight harvesting, occupancy sensing, etc.). This access to informative data has been missing until recently and may have value in a variety of ways:

- Building managers can see exactly how much energy their systems are using and explore strategies for achieving deeper savings.
- Lighting controls manufacturers can better market their systems by showing potential customers verified savings reports for applications from similar customers.
- Energy-efficiency program designers may be more interested in promoting advanced lighting controls systems investments when the risks associated with variable and/or unverified savings are mitigated.
- Regulators with an interest in reducing overall building energy use (rather than simply reducing lighting power density) can use this data for compliance verification for next generation "outcome-based" codes.

> Increasingly sophisticated and "connected" lighting controls systems are starting to address the dilemma of how to estimate energy use and savings down to the individual luminaire level and estimate how much energy the system is saving from each control strategy (e.g., daylight harvesting, occupancy sensing, etc.) to establish the foundation to move towards verifiable "outcome-based" code compliance.

However, all of these outcomes rely on the data accuracy being collected by the lighting control system itself. Meanwhile, there are no existing standards or test procedures that describe how lighting controls systems should measure, estimate, record or report energy use or attribute energy savings. And, there are numerous factors that may lead to inaccuracies in collecting these data, including:

- Poorly calibrated power meters
- Inaccurate fixture look-up tables containing lamp-ballast performance data
- Inaccurate savings attribution algorithms
- Insufficiently programmed 'change-of-state' levels and time steps

For the first time, this project directly addresses this issue by measuring lighting system performance over a broad range of conditions and controls settings, and then comparing reported luminaire-level energy use to measured energy use. While the test described in this report presents the reported-versus-measured results for a specific lighting controls system, the methodologies developed can be applied more broadly to lighting controls systems generally. Ultimately these methods may lead to test procedures and codes for lighting controls systems that ensure accurate and uniform energy use reporting.

Research Objectives

In February and March 2015, LBNL researchers conducted an experiment in partnership with Lutron Electronics to evaluate lighting energy self-reporting in their latest generation lighting controls system. This report describes this experiment, the key findings and recommended next steps.

The main research objective was to determine how accurately lighting control systems self-report energy usage and savings once a given lighting control system is installed and commissioned with respect to the lighting loads it manages. To meet this objective, the research team developed a test protocol to evaluate measured versus reported lighting energy use over a variety of settings and environmental conditions. This test protocol was initially used to evaluate the Lutron Quantum system operation, and it can be further refined to evaluate other lighting controls systems more generally.

A secondary research objective was to evaluate how changes in energy savings corresponded to changes in lighting quality metrics. Specifically, the research team looked at which controls setting and environmental conditions generated energy savings and improved glare metrics and which conditions generated savings at the expense of lighting quality. This second research objective was added during testing, as we were able to extend and expand our testing period beyond what we had planned (as discussed later in this report).

Experimental Design

Simply stated, this experiment took a lighting system and evaluated its performance when it was subject to a wide variety of environmental conditions and lighting control settings. This section discusses the experiment in four sections:

1. Test conditions
2. Parameters measured
3. Control strategies evaluated
4. An overview of all the tests performed

The test conditions sections discusses the lighting systems installed in the test cell, the physical configuration of the test cell, and environmental conditions experienced during testing. The parameters measured section discusses the variables that were monitored in evaluating system performance, including luminaire power readings and light levels. The controls strategies section discussed the controls settings utilized during testing (e.g. daylight harvesting, occupancy sensing, scheduling, etc.). The experimental overview section walks through the specific tests that were conducting during the 7-week testing period.

The energy usage profiles programmed into the system for controlled lighting loads (full load wattage and dimming profiles) greatly affect energy reporting accuracy during operation. In short, good lighting energy reporting is contingent upon the initial system setup and the input of correct wattage and ballast/driver power-dimming curves.

An iterative process where energy reports from the controls system are compared with measured energy would allow for adjustments to wattage and dimming inputs to improve energy reporting accuracy. For this study some adjustments to the lighting controls inputs were made after initial energy monitoring, but continued iterative improvements to the controls system assumptions were not a part of this study.

In practice (in the "real world"), without robust measurement and verification in the field, it may not be obvious whether energy reports from a lighting controls system are accurate, so the accuracy of the original programmed energy usage assumptions of the controlled loads is critical.

Test Conditions

The U.S. Department of Energy's FLEXLAB™ (**F**acility for **L**ow **E**nergy e**X**periments in **B**uildings) at Berkeley Lab provides researchers an unparalleled facility to study energy efficiency of building systems (Figure 1). Eight test cells (including two high-bay test cells and two rotating test cells) each have the ability to test HVAC, lighting, fenestration, façade, control systems and plug loads under real-world conditions. FLEXLAB users (building owners, developers and/or contractors) are able to test individual or integrated systems before construction.

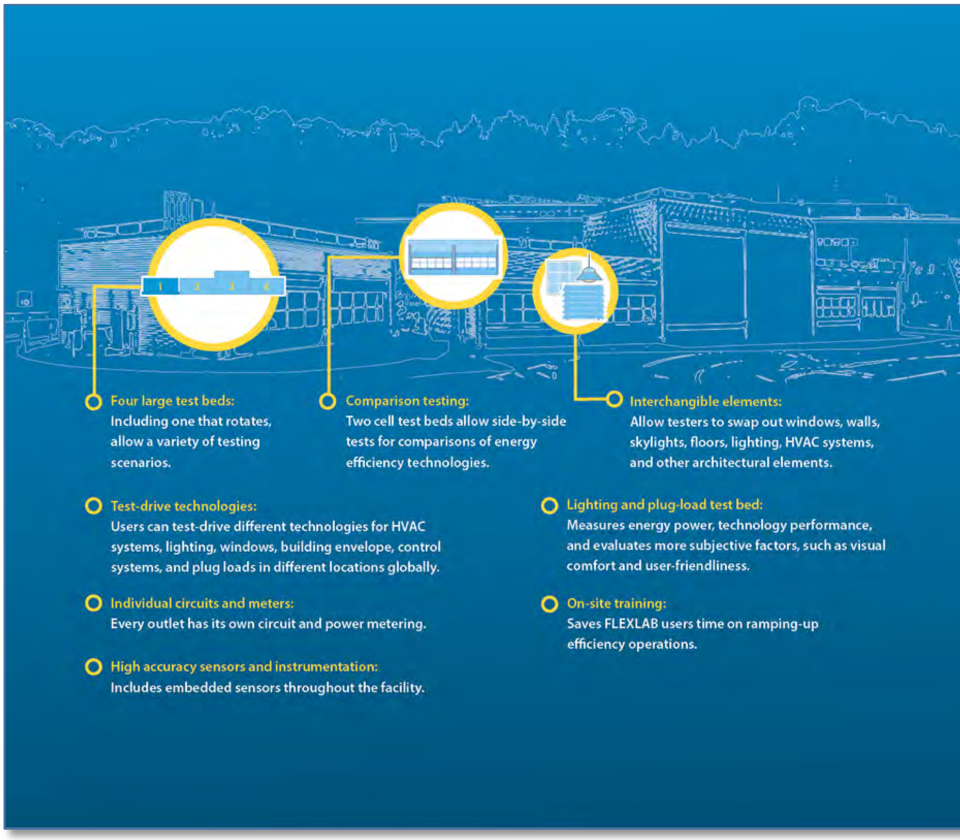

Figure 1: Diagram (above) & photo of DOE's FLEXLAB facility at LBNL. This experiment utilized one of the two rotational test cells in this photo's foreground.

This experiment utilized one of FLEXLAB's rotational test cells. This cell is 20 feet wide by 30 feet deep with a ceiling height of 13 feet. The test cell façade used a GL-1 glazing with a visible light transmission (VLT) of 42% and had a window-to-wall ratio of 0.31. The façade was oriented due south for much of the experiment, but was rotated to other orientations during testing, as will be detailed below. Six 2x2 recessed luminaires were installed in the test cell: (1) three dimmable fluorescent luminaires on the left side of the room (when looking towards the window wall), and (2) three dimmable LED luminaires on the right side of the room. Each row of luminaires had 8 foot spacing between them with a spacing of 10 feet between the two rows. The luminaires were controlled by a beta version 3rd Generation Lutron Quantum lighting control system. A control photosensor for the Lutron Quantum system was placed midway between the fluorescent and LED luminaire rows and was approximately 10 feet from the window wall. Figure 2 shows the test cell test cell layout.

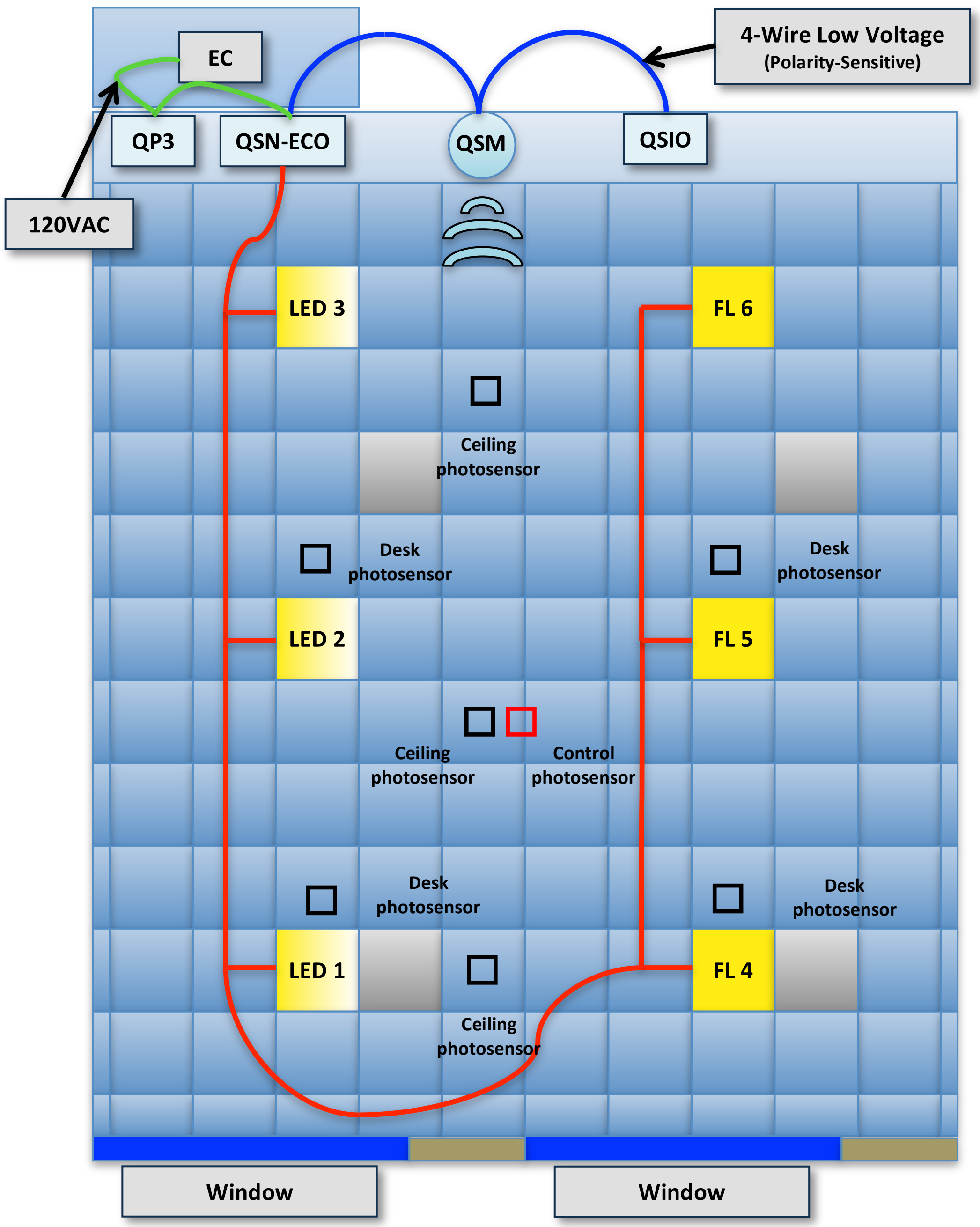

Figure 2: Schematic (previous page) and photo (above) of luminaires, lighting controls & photosensors layout during experiment.

Parameters monitored

Luminaire power

During all experiments, the power to each luminaire was monitored both by the FLEXLAB data acquisition system, and by Lutron Quantum system's self-reporting systems. The FLEXLAB data acquisition system measures and records power every minute. The Lutron system did not measure power to the luminaires but rather estimated power based on what controls signals were being sent to the dimmable luminaires, using programmed look-up tables or algorithms to correlate controls signals and luminaire power level. The Lutron system did not record power data continuously but rather when the system experienced a state change (e.g. when a luminaire turned on or off, or change power level).

The Lutron system required the luminaires' maximum wattages controlled by the system to be inputted in the software up-front during system set-up. These values are used as a variable in the systems self-reporting algorithms. For this method of energy reporting (reported energy usage based on fixture wattage assignments and dimming profiles that are inputted during commissioning), the lighting energy reporting accuracy is contingent upon the initial system setup and user input of correct wattage and ballast/driver power-dimming curve.

As provided by the luminaire manufacturer, the fluorescent luminaires were understood to have a rated wattage at full output of 34.0 W, while the LED system had a full output rated wattage of 36.9 W. Lutron technicians commissioned the Lutron system to use the 34.0 W value for the fluorescent lamp and initially inputted 33.0 W for the LED fixture power at full output.

After several weeks of testing, we noted that FLEXLAB measured values for the LED system at full output were actually closer to 26 W. On February 27th, the maximum wattage for the LED luminaires was updated to 26 W in the Lutron system. This adjustment affected the values reported by the Lutron system, so we did not combine data from before and after this calibration correction in our analysis. In this report, we identify whether the results presented are from the period before or after this correction.

In our post-analysis, it is also clear that the actual wattage at full output for the fluorescent fixtures was higher than the 34.0 W assumption reported by the luminaire manufacturer, though that value was unadjusted in the controls system programming during the study period, which is reflected in the results. The origin of the error in fluorescent wattage entered into the self-reporting setup is unclear, but continued iterative improvements to controls system assumptions, with fixture power levels and dimming curves updated to more accurate could improve self-reporting outcomes. This type of process was not a part of the project plan or execution but could be a useful next step in lighting controls self-reporting research.

Illuminance levels

Illuminance levels (lux) inside the space were monitored by the FLEXLAB data acquisition system at seven locations, as seen in Figure 2. Four illuminance sensors were placed to collect horizontal illuminance at the task plane (30 inches above the floor). Two of these sensors were on the left side monitoring the fluorescent luminaires; one sensor was directly underneath the luminaire closest to the window and directly underneath the middle fluorescent luminaire. The two sensors on the right side were placed in analogous locations to monitor the LED luminaires. Three illuminance sensors were installed along the midline of the ceiling facing downward to measure horizontal illuminance on the ceiling plane. One was placed approximately 6 feet from the window, one was place right next to the control photosensor (10 feet from window), and one was placed 16 feet from the window.

HDR / luminance cameras

Two digital SLR cameras were installed in the test cell – one was place in the back of the room aimed towards the window wall; the other was located in the middle of the left side wall aimed perpendicular to the window wall. These cameras were outfitted with controls and processors to automatically take multiple exposures every 5 minutes, which were processed into high-dynamic range (HDR) photographs used to evaluate luminance (candela/m^2) and glare (DGP – daylight glare probability) over time in the test cell.

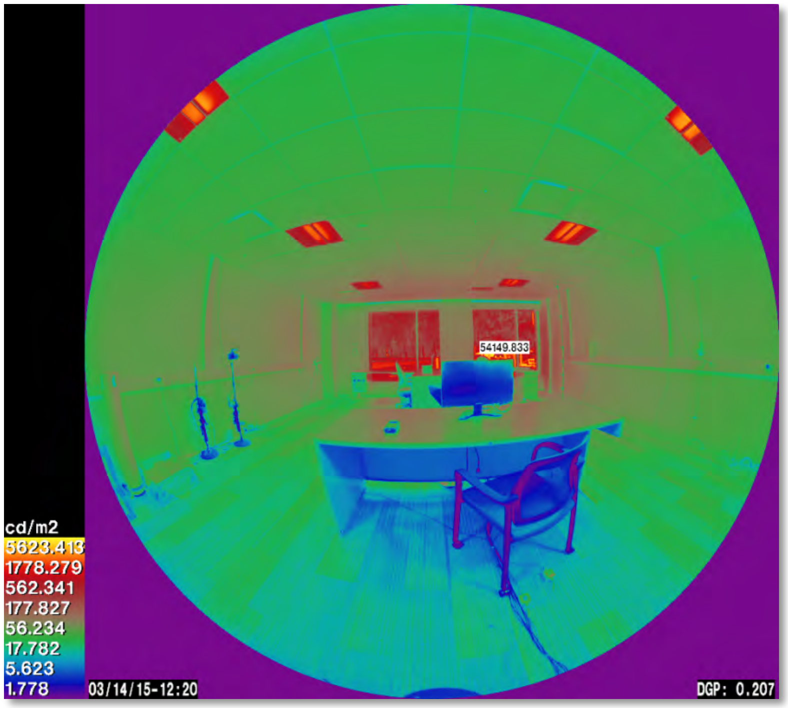

Figure 3: Example of luminance plot during testing from HDR/luminance camera

Controls Scenarios

Step-Dimming

The Lutron Quantum system includes a scheduling feature, which was utilized at several points during testing to run the system at specific conditions. One scenario that was repeated several times during testing was to operate all luminaires at full output for 1 hour and then reduce the light level control setting to each luminaire in 10% steps with a 1-hour operating period at each step. Figure 4 and Figure 5 show an example of measured and reported luminaire wattages during one of these 10-hour test periods. This allowed for a clean comparison of measured versus reported energy use throughout each luminaire's dimming range. This procedure also allowed for the observations of transitional effects before and after luminaires power input became stabilized.

In the figures presented in this section, the bottom graph presents an area graph representing the difference between reported and measured power as a function of time. In **Figure 4**, the reported versus measured difference initially is negative (indicated measured power is greater than reported power) but becomes positive (indicated measured power is greater than reported power) later in the test at lower dimming settings. We note that the area in these plots represent the errors in energy use estimations, areas greater than zero indicate an overestimate of energy use, while areas less than zero indicate an underestimate of energy use, as these plots show power (W) versus time (hrs.). Consequently, longer durations with small power measurement errors (as seen during the majority of the test period in Figure 4) represent larger energy use reporting errors than very short periods with large power measurement errors (as seen at the very end of the test period).

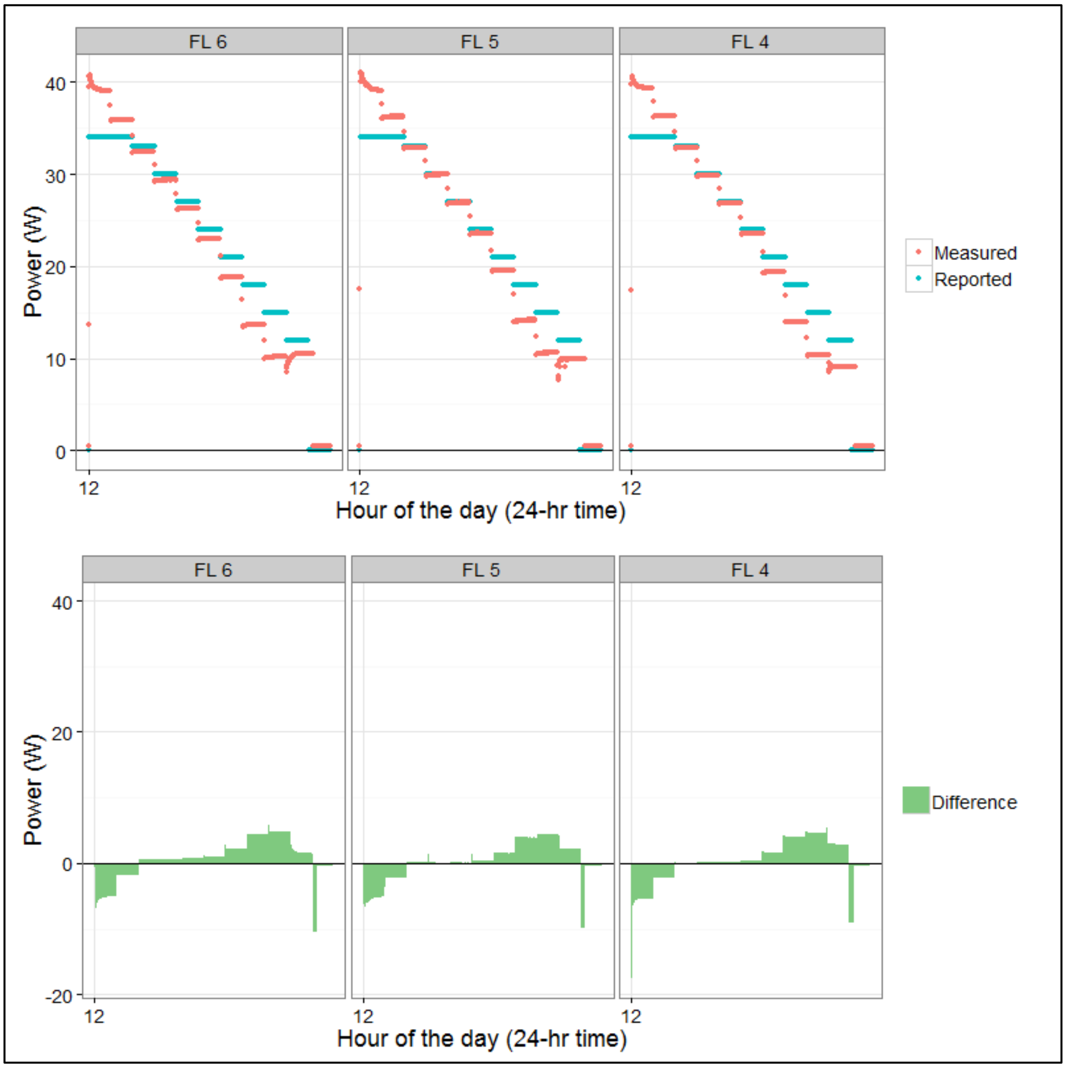

Figure 4: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for fluorescent luminaires during sample step dimming period

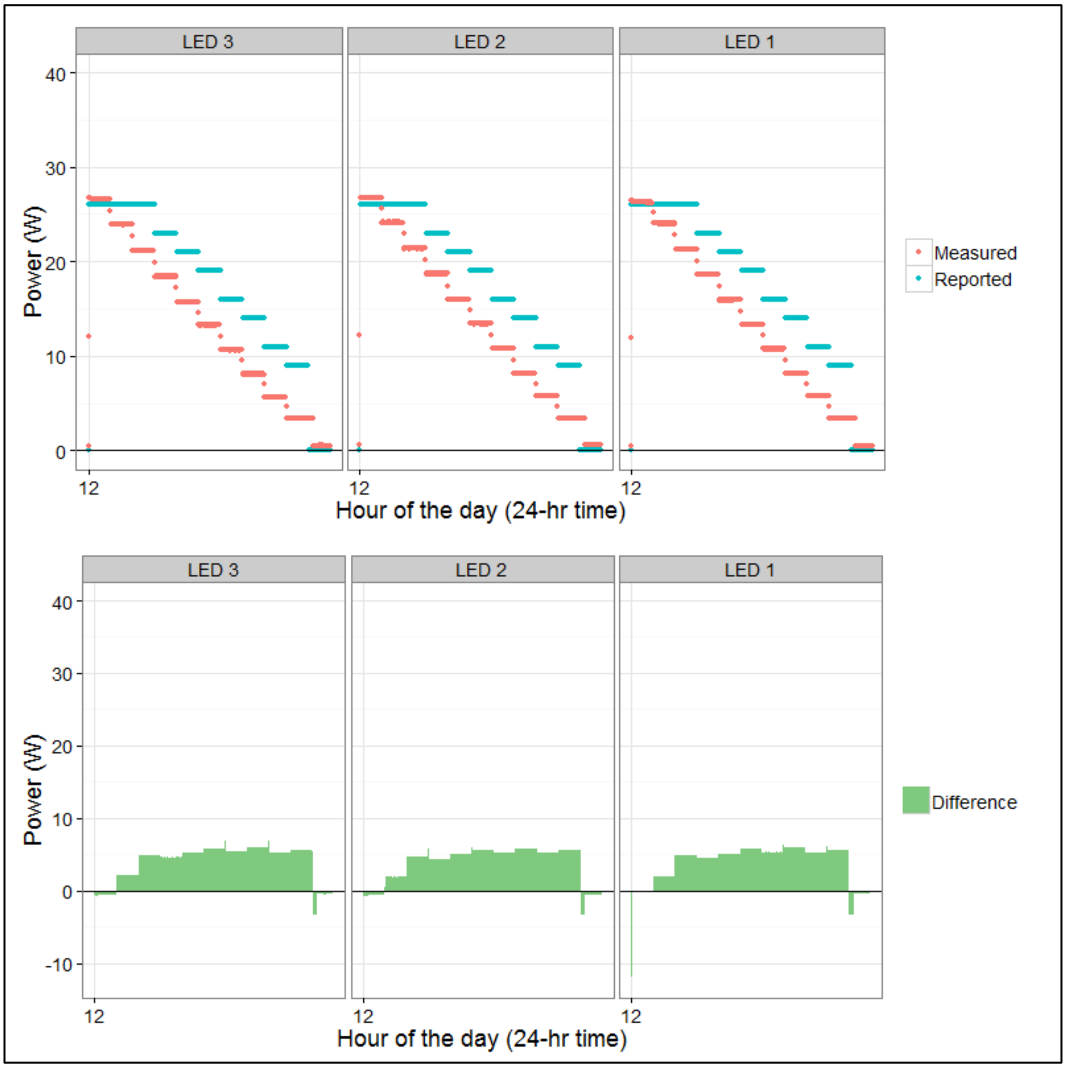

Figure 5: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for LED luminaires during sample step dimming period

Daylight Harvesting

The Lutron Quantum system performed closed loop daylight harvesting under a wide variety of conditions. These included variations in daylight conditions (sunny, partly cloudy, cloudy) and variations in building orientation. The daylighting configuration was set to Lutron's default setting, with different gain values for the luminaire rows closer to the windows, in the middle of the cell, and furthest from the windows. Logically, based on the degree to which daylight penetrates a space with windows (more daylight closer to windows, and less deeper in the space) settings were such that luminaires closest to the window dimmed most aggressively when daylight was present and luminaires furthest from the windows dimmed most conservatively. Typically, periods of maximum daylight penetration in the space resulted in the luminaires nearest to the window turning off; those in the middle of the room, dimming significantly; and those furthest from the window, dimming slightly. **Figure 6** and **Figure 7** show FLEXLAB-measured and Lutron-system reported luminaire power for each luminaire during one typical day during daylight harvesting operation, and the difference between measured and reported power. Note that luminaires closest to the windows (FL4 and LED1) dim more aggressively that those furthest from the window (FL6 and LED3).

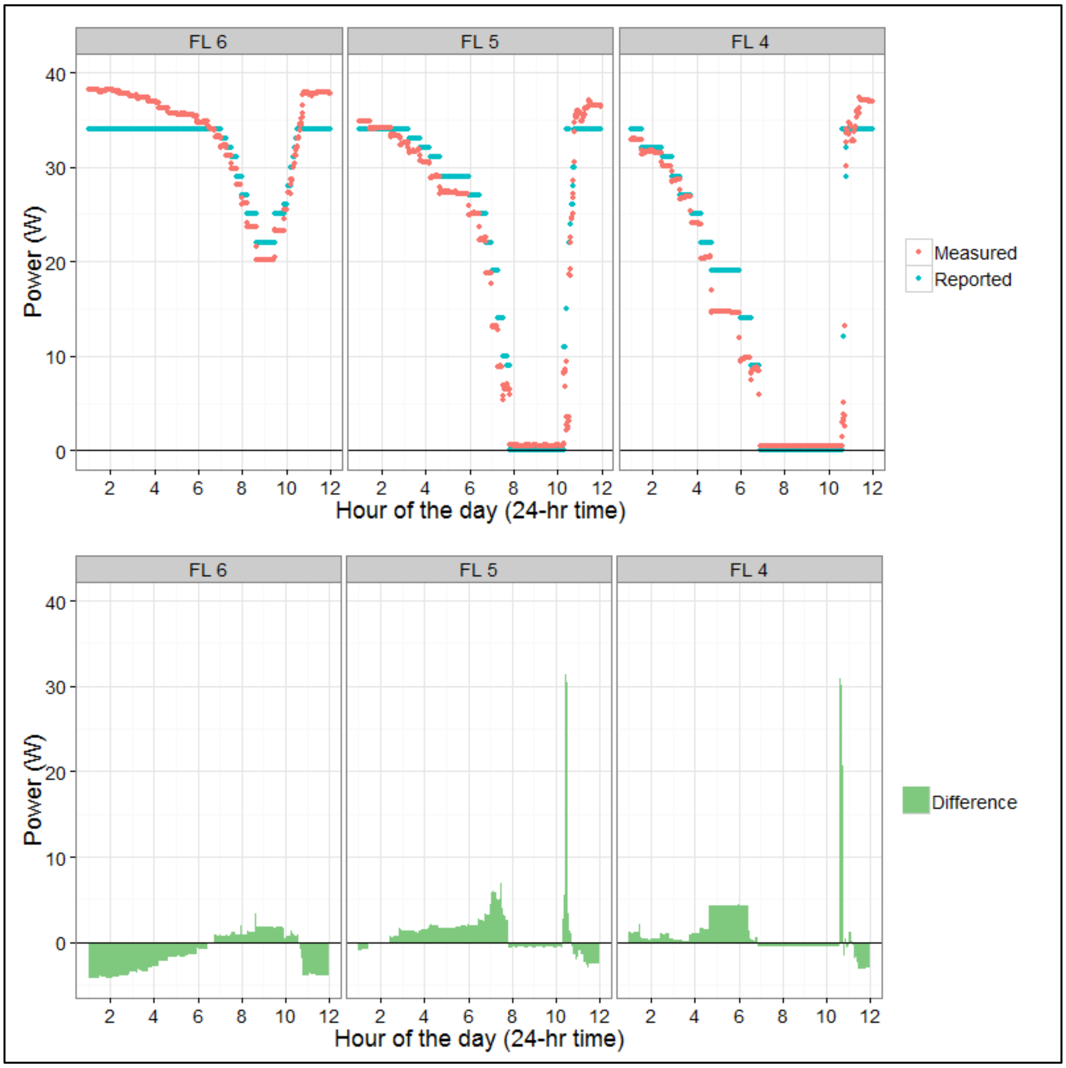

Figure 6: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for fluorescent luminaires during sample daylight harvesting period

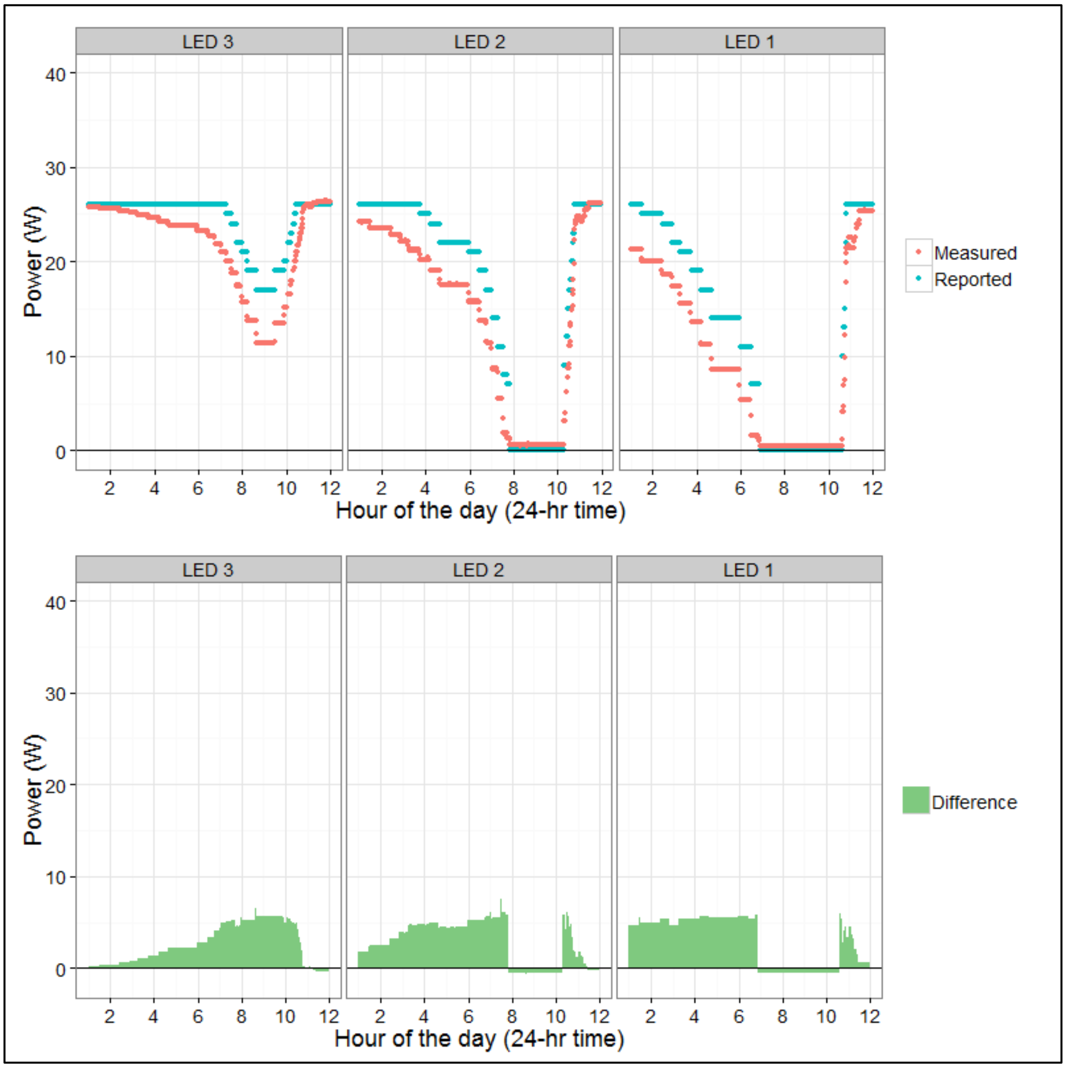

Figure 7: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for LED luminaires during sample daylight harvesting period

Occupancy Sensor

Because the FLEXLAB test cell was an unoccupied experimental space, we were unable to evaluate occupancy sensor effect directly. Nonetheless, we were able to evaluate the effect of occupancy sensors by utilizing a novel simulation procedure. This procedure involved received occupancy pattern data from similar spaces occupied by our Chinese partners at the China Academy of Building Research (CABR), as gathered by their Lutron Quantum system. These data were fed into the Quantum controller at FLEXLAB. This resulted in periods where luminaires in FLEXLAB turned on and off based on real occupancy patterns observed days earlier in the CABR building in Beijing. Several days of data were collected where occupancy sensing was the only control strategy evaluated. For periods where we desired to measure the occupancy control (on/off) strategy independently, the on/off occupancy control was run nightly, when no daylighting was present. **Figure 8** and **Figure 9** show an example of a typical occupancy-sensing period during testing for fluorescent and LED luminaires, respectively.

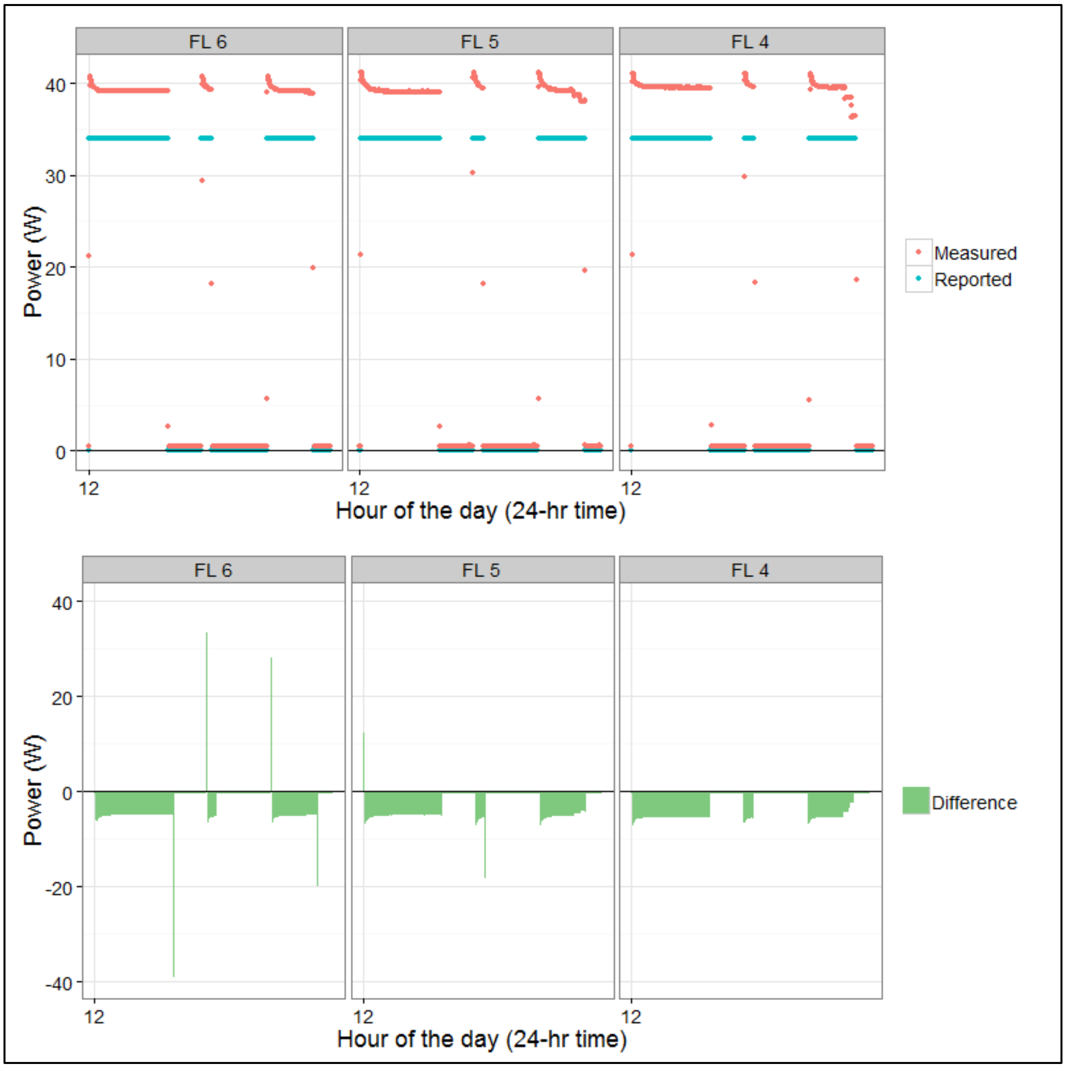

Figure 8: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for fluorescent luminaires during sample occupancy only period

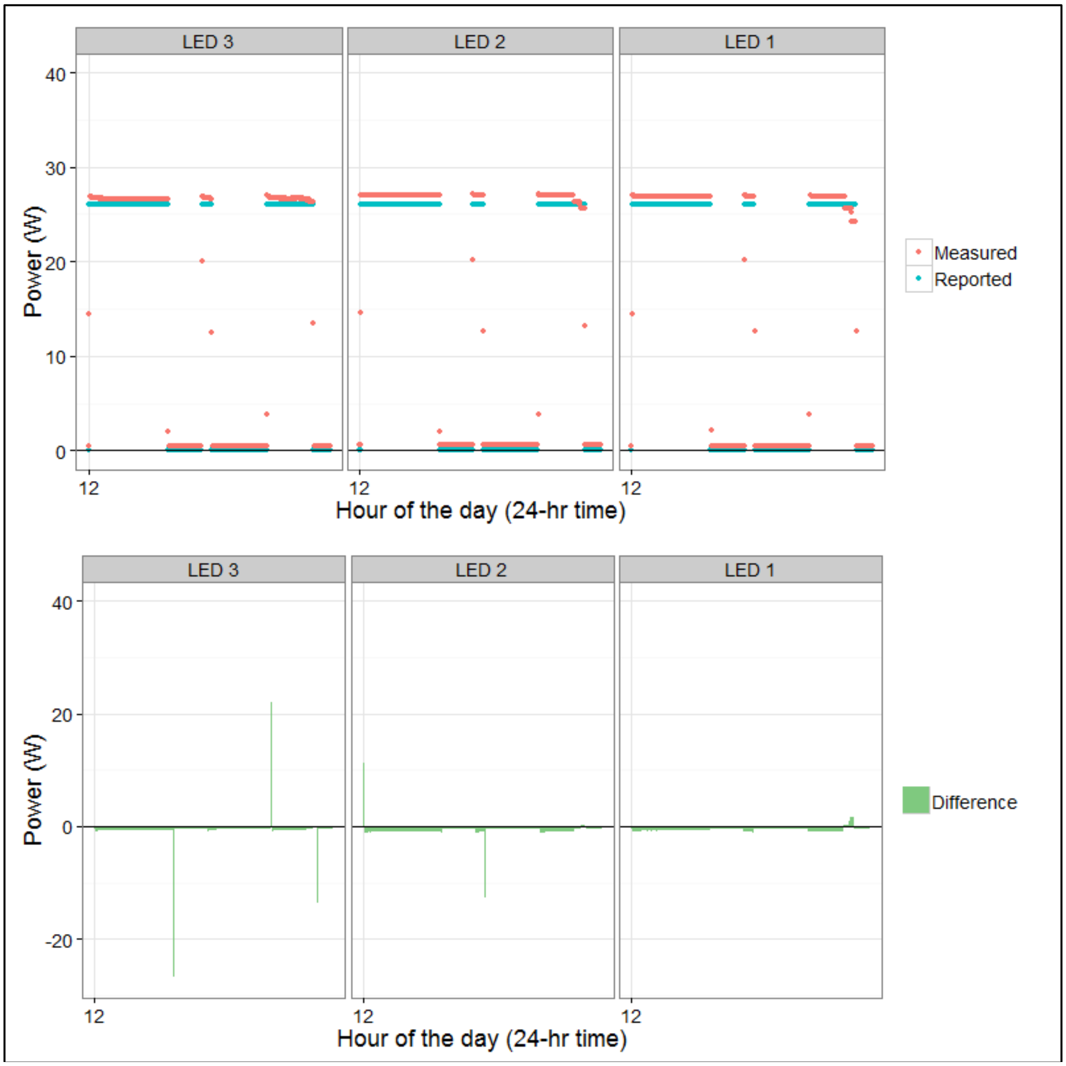

Figure 9: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for LED luminaires during sample occupancy only period

Occupancy + Daylighting

Several testing periods occurred in which the occupancy sensing and daylight harvesting strategies were engaged simultaneously. For these periods, the CABR occupancy data was time-shifted to match daylighting periods occurring at FLEXLAB in Berkeley. This allowed us to realistically simulate typical building operations, such as during lunch break periods when low occupancy and high daylighting levels are coincident. **Figure** 10 and **Figure 11** show FLEXLAB measured and Lutron system reported luminaire power for fluorescent and LED luminaires, respectively, during one typical day during daylight harvesting + occupancy sensing operation and the difference between measured and reported power. Note that these results are similar to the daylight harvesting results shown in **Figure 6** and **Figure 7** but now there are periods where all luminaires are powered off during unoccupied times.

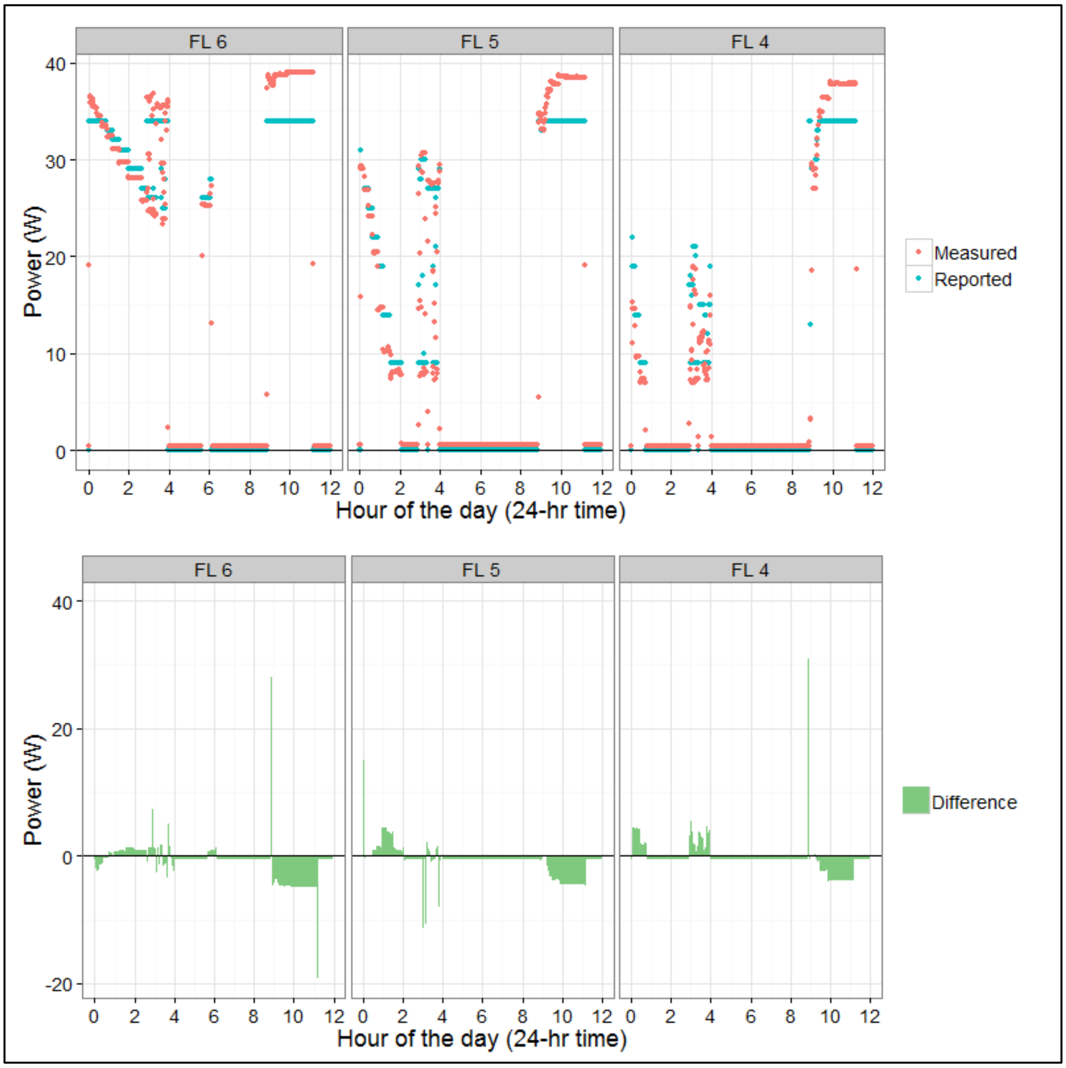

Figure 10: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for fluorescent luminaires during sample daylight harvesting + occupancy sensing period

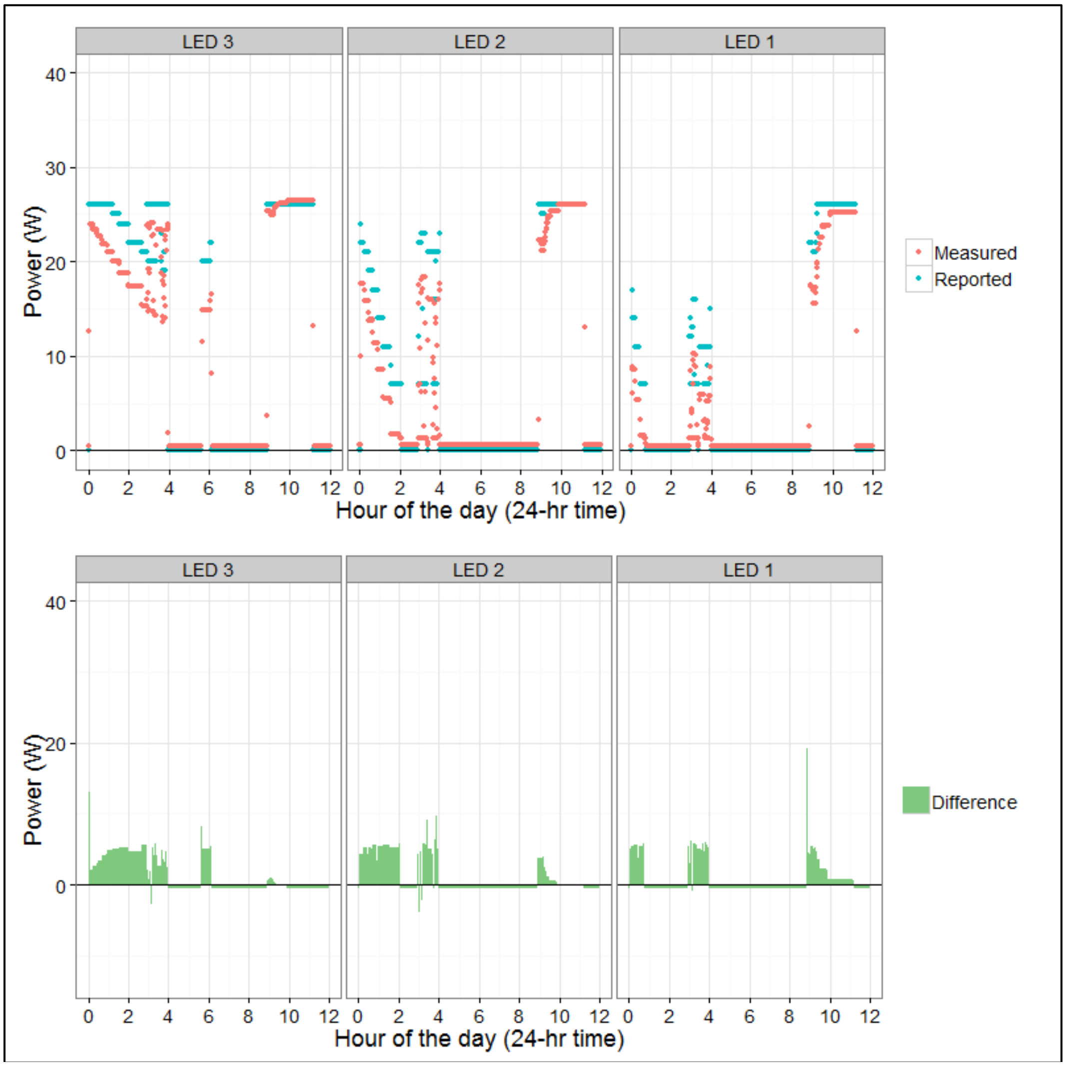

Figure 11: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for LED luminaires during sample daylight harvesting + occupancy sensing period

Experiment and Analysis Overview

As discussed previously, we operated the lighting systems in the FLEXLAB under a wide variety of conditions and made a wide variety of measurements over the 7-week testing period. **Figure 12** provides a graphical FLEXLAB experiment overview during this testing period - the top schematic summarizes testing between February 12, 2015, and March 8, 2015, while the bottom schematic summarizes testing between March 8, 2015, and April 1, 2015. The following section provides a detailed overview of the experiment by walking through this graphic.

- The ***testing dates*** are shown across the middle of this graphic. The controls strategies implemented are shown above the dates while information on the measurements taken and experimental conditions are shown under the graphic.

- The ***control strategies*** are shown above the testing dates. A separate line is shown for night and day periods for the controls strategies as we typically employed different strategies during the night and during the day.
- The ***FLEXLAB data*** line indicates the periods during which FLEXLAB was collecting data. We note that February 19-21 and February 28- March 3 show periods where testing was temporarily suspended with no data collected and the lighting system off during both day and night periods.
- The ***Lutron data*** line indicates periods in which the Lutron system was collecting data. We note that the Lutron system did not record data from February 15-18th. Also, as previously noted, between the test start up on February 12 and February 27th, the Lutron system assumed that the maximum wattage of the LED luminaires was 33W, and after this date, the system maximum wattage assumption was corrected to 26 W.
- The ***Glare/HRD*** line indicates when data from the glare HDR cameras were collected. These cameras were installed on February 26th, and remained in place for the experiment's duration.
- The ***Rotational Direction*** line indicates the window façade orientation during testing. The façade was south facing for the majority of testing with periods of north and west facing during the 2nd part of the test. On March 19-20, FLEXLAB was dynamically adjusted to track solar movement – the test cell rotated hourly so that the façade directly faced the sun.
- The ***Weather*** line provides a general overview of the weather conditions during the test day. Full sunlight is indicated as yellow and partly cloudy and cloudy are indicated as grey.
- The ***Events*** line indicated when notable events occurred during testing. These include FLEXLAB or Lutron data outages, illuminance meter (Licor) movements, fixture outages, and furniture movements in the test cell.

The initial plan was for FLEXLAB testing to be conducted for 1 week and to focus solely on evaluating the lighting control system energy use reporting accuracy. However, as displayed in **Figure 12,** we were able to extend testing well beyond the planned period, in part, because there was an unexpected FLEXLAB experimental schedule slot available after our planned slot. This allowed us to greatly expand the number of tests that we conducted and consequently, the amount of data collected. Specifically, this allowed us to:

- Capture data during a wider range of weather conditions
- Evaluate a wider range of controls settings
- Evaluate operations at multiple building orientations
- Evaluate performance with different furniture arrangements
- Install additional sensors to collect additional illuminance and luminance data.

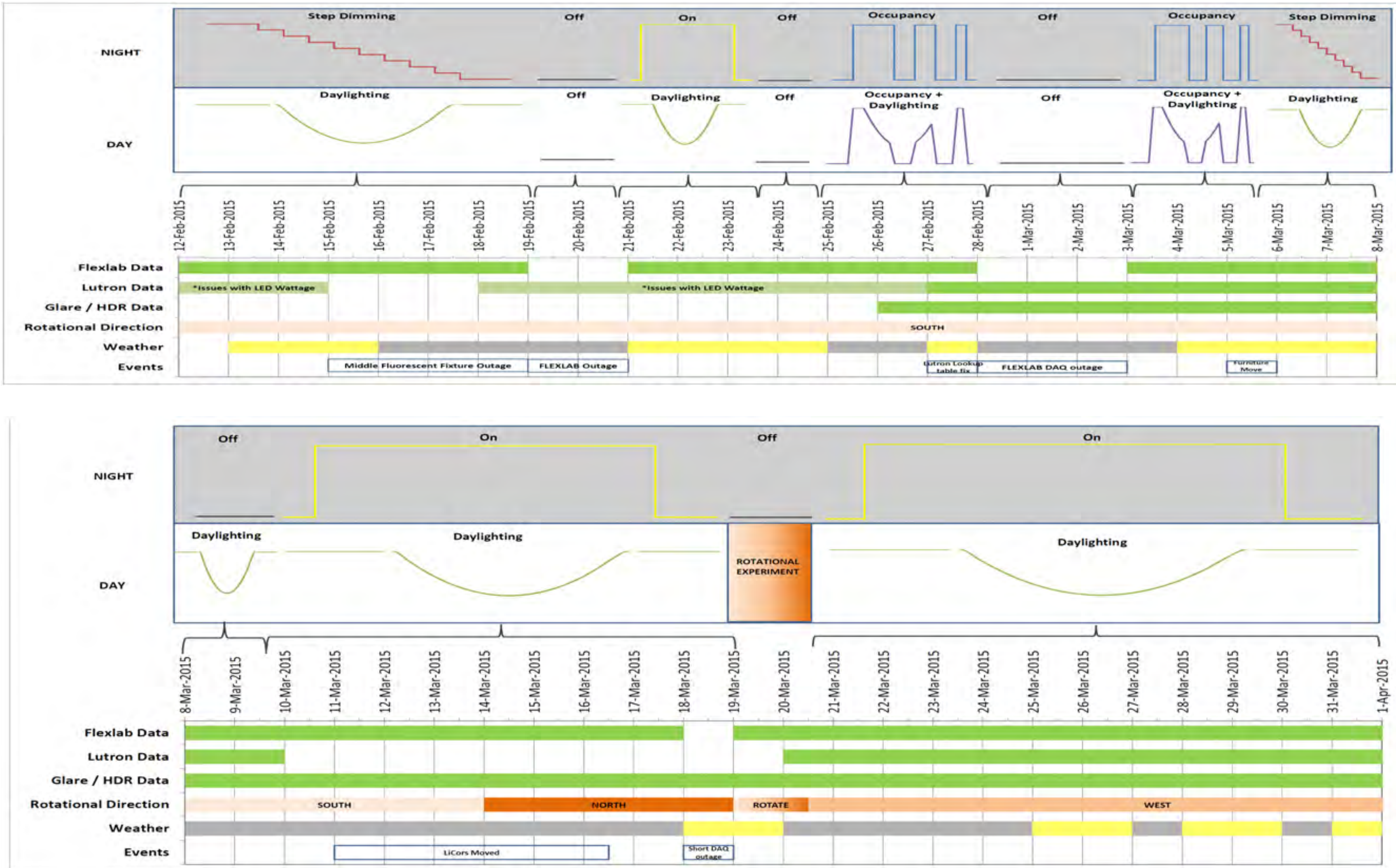

Figure 12: Schematic overview of FLEXLAB experiment. Top schematic summarized testing between February 12, 2015, & March 8, 2015, while bottom schematic summarizes testing between March 8, 2015, & April 1, 2015.

Results

This report's primary analysis evaluates the lighting controls system energy use reporting across a wide range of controls setting and environmental conditions. A limited discussion of the photometric data gathered (e.g. luminance cameras, glare analysis) and the dynamic rotational experiment is also presented, but a full analysis of these results is excluded as these experiments were not part of the original experimental plan but rather, were data that were gathered opportunistically. It is our hope that we will be able to fully analyze these additional data at a future date when funding becomes available.

Baseline Power Measurements

For this analysis, we first filtered the lighting power data so that we only considered periods where both the Lutron controller's and FLEXLAB's data collection systems were working concurrently. To estimate the control strategies under investigation's power reduction (or equivalently the energy savings) we needed to establish a baseline for comparison and used the full power data collected at night during the period March 21-30, 2015. The baseline power is the average power for each luminaire over this time period. All subsequent control strategies are compared to this baseline, see Table 1 below for baseline power reported by the Lutron system and measured by FLEXLAB for all luminaires.

Table 1: Baseline reported (Lutron) & measured (FLEXLAB) power averaged for 10 days running at full power for 12 hours a day, & percentage difference between measured & reported values, for all luminaires

Luminaire	Mean Reported Watts	Mean Measured Watts	Difference between reported & measured
FL 6	34.0	39.1	-13%
FL 5	34.0	37.7	-10%
FL 4	34.0	38.4	-11%
LED 3	26.0	26.5	-2%
LED 2	26.0	26.4	-2%
LED 1	26.0	25.7	1%

For the fluorescent luminaires, reported values were lower than measured values by 11-13%. This implies that the fluorescent luminaire full output wattage value programmed into the Lutron system during commissioning had an offset error. As stated previously the origin of this error is unclear.

For the LED luminaires, the reported values were found to range from 2% lower to 1% higher than the measured values. The reported and measured values were closer to one another (on average) for the LED luminaires largely because the measured values after initial operation were used to calibrate the reported values based on the calibration adjustment made on February 27th.

Step Dimming

During the step-dimming phase, all luminaires were set to full power, run for one hour, dimmed 10% and run for another hour, and so on until they were turned off. In this context, percentage dimmed refers to the Lutron control setting; it is unclear from the controls system and user interface if this is meant to represent light levels or power levels.

Step dimming testing was conducted over two time periods: February 12-19, 2015, and March 6-8, 2015. The initial test period was before the LED luminaires maximum wattage was updated and the second testing period was after this update. Because of this, the LED luminaire data set has been broken down into two parts, before the lookup table correction and after. This does not affect the fluorescent luminaires, so the data for the two fluorescent dimming sections are treated together.

The dimming curves for the fluorescent luminaires are shown in **Figure 13**. These plots were generated by averaging reported and measured power at each dimming level for each testing period for each luminaire and plotting against the control setting. For example, FL6 was operated for 1 hour at 60% on 11 different days and was found to have an average measured power over those 11 testing periods of 25 W and an average reported power of 27 W. For all fluorescent luminaires, reported values were lower than measured values at full output on average by more than 4 W while reported values during dimming were on average nearly 2 W more than measured values.

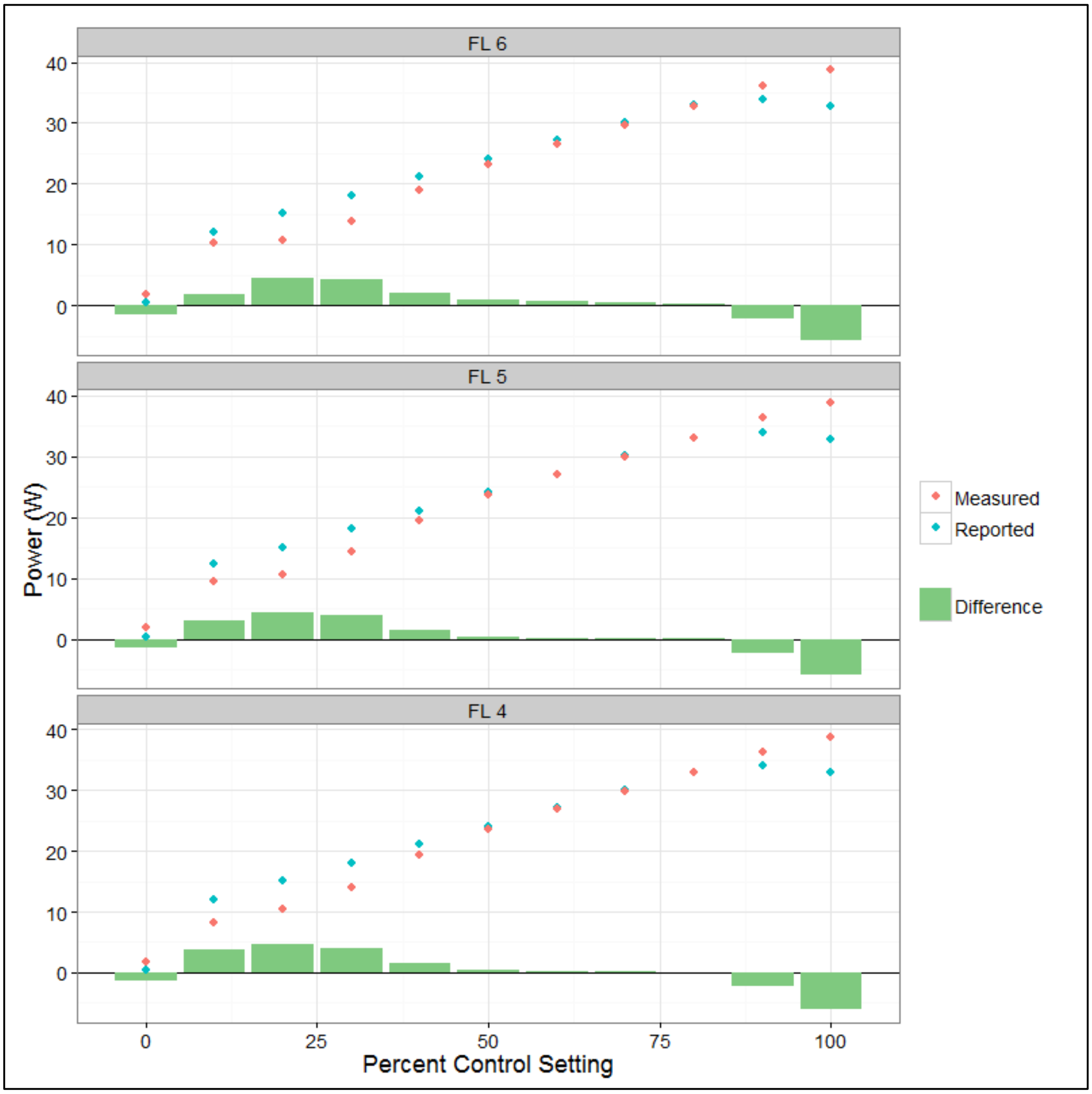

Figure 13: Fluorescent luminaire measured & reported mean power levels, & difference between reported & measured values, during step dimming

Figure 14 shows the measured and reported dimming curves for the LED luminaires before the calibration adjustment was made. Reported values are substantially larger than measured values – on average more than 9 W higher. We note that if the maximum luminaire wattage from the LED luminaires specification sheet (36.9 W) were used rather than 33 W in programming the Lutron system, these differences would likely be even larger.

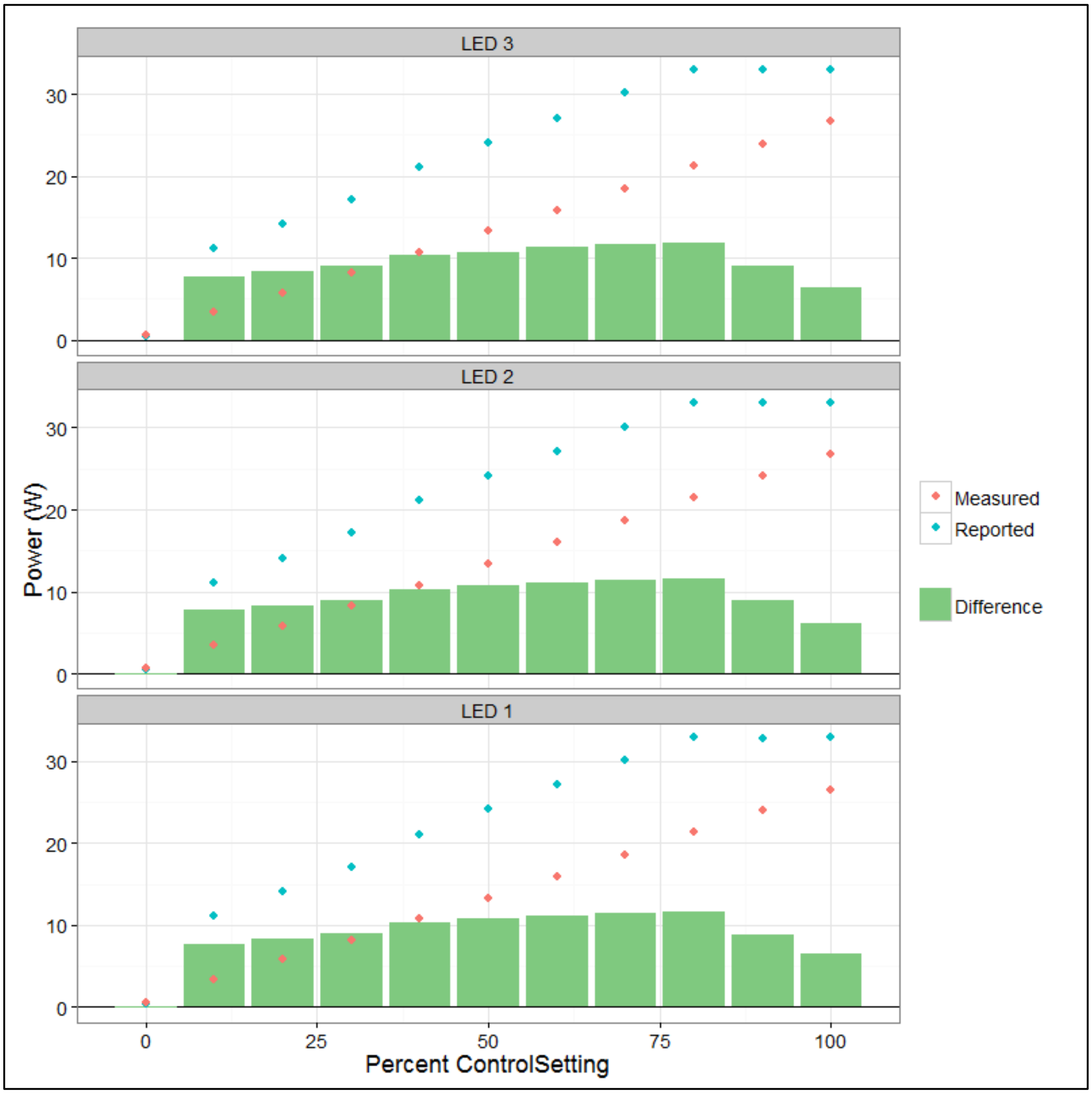

Figure 14: LED luminaire measured & reported mean power levels, & difference between reported & measured values, during step dimming before the calibration adjustment was made

Reported values in **Figure 15**, are still found to be larger than measured values, now higher by nearly 5 W, on average. Reported and measured power at full output is nearly equal for all luminaires, as would be expected since the power calibration was made to bring these values into alignment. Significant differences at the dimming levels suggest that the lookup tables in the Lutron system do not closely match the dimming behavior of the specific LED system used.

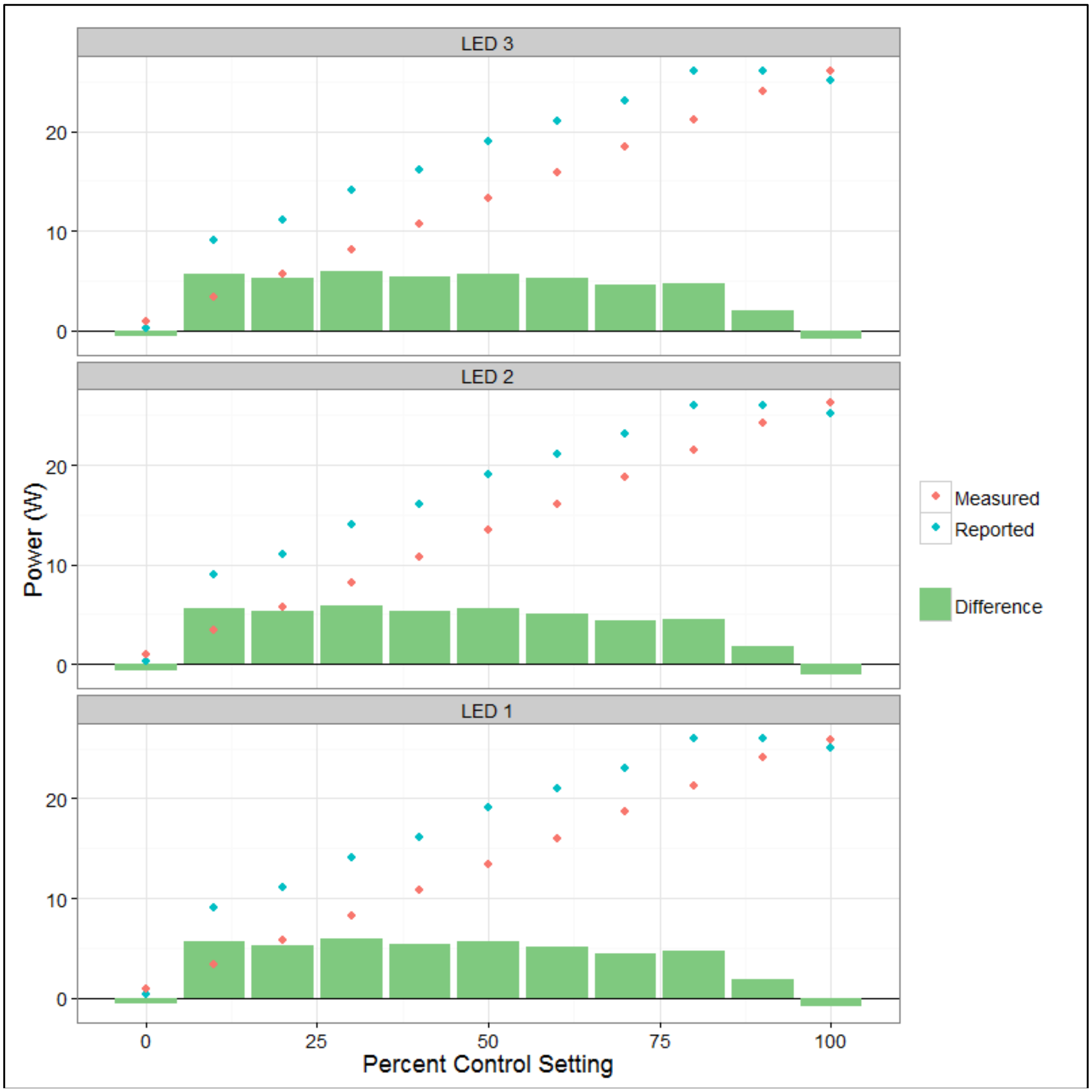

Figure 15: LED luminaire measured & reported mean power levels, and the difference between reported & measured values after reported power correction

Daylight Harvesting

Daylight harvesting was the operational controls strategy during the daylight hours from March 21-30, 2015. During this test period, the window façade was west facing.

Table 2, below, lists the daily average power when the fixtures were scheduled on during this daylight harvest period, and percentage difference between the measured and reported values. This data shows that the distance from the window strongly affects the power reduction; FL 4 and LED 1 were located closest to the window – side of the cell and FL 6 and LED 3 furthest from the window - side. As with the step-dimming test, this daylight-harvesting test also found that reported values overestimate the power drawn.

Table 2: Daylight harvesting reported & measured mean power & percentage difference between measured & reported values for all luminaires

Luminaire	Mean Reported Watts	Mean Measured Watts	Difference between reported & measured
FL 6	32.6	33.6	-3%
FL 5	24.4	23.5	4%
FL 4	20.5	17.9	15%
LED 3	24.9	21.9	14%
LED 2	19.4	15.6	24%
LED 1	15.5	11.1	39%

Occupancy Sensing

In this analysis, a set occupancy schedule was used to turn lights on and off according to occupancy data gathered the CABR building in Beijing. Lighting power data resulting from on/off operation based on the occupancy data were collected in the FLEXLAB from March 3-5, 2015 during night hours so that power and light levels could be observed without the influence of daylight or daylight harvesting. Table 3 shows the reported and measured average power values during the occupancy control strategy.

These results follow the same trends found in the baseline measurements summarized in Table 1. This makes sense as the mean luminaire power during occupancy sensing should essentially be a time-weighted average of time spent at full output (as summarized in the baseline measurements), and time spent with the luminaires off. When luminaires were off, the measured power was 0.4 W, on average, while the reported power was 0.0 W. Presumably the 0.4 W measured values can be attributed to standby power that the luminaire controls draw to remain network-connected.

Table 3: Occupancy sensing reported & measured mean power & percentage difference between measured & reported values for all luminaires

Luminaire	Mean Reported Watts	Mean Measured Watts	Difference between reported & measured
FL 6	17.3	20.2	-14%
FL 5	17.2	20.3	-15%
FL 4	17.2	20.4	-15%
LED 3	13.2	13.8	-4%
LED 2	13.2	14.0	-6%
LED 1	13.2	13.8	-5%

Occupancy Sensing plus Daylight Harvesting

This strategy combines daylight harvesting and occupancy sensing to turn luminaires on during occupied periods, dimming power down in response to ambient light levels, and turn luminaires off when the space is unoccupied. Under this strategy, the occupancy schedule is the same as the occupancy sensing-only schedule with the addition of daylight harvesting. Data were collected March 3-5, 2015 during daytime hours with the window façade facing south. This strategy provides the greatest power reduction (and therefore energy savings) of all the control strategies. Table 4 below lists the reported and measured average power values during this test period and the difference between the reported values and measured values.

Again, deviations between measured and reported values are largely explainable by combinations of the errors identified in **Tables 1-3**. For the fluorescent luminaires, we note that some of these errors have a cancelling effect (e.g. reported values overestimate during daylight harvesting and underestimate during occupancy sensing).

Table 4: Occupancy sensing plus daylight harvesting, reported & measured mean power & percentage difference between measured & reported values for all luminaires

Luminaire	Mean Reported Watts	Mean Measured Watts	Difference between reported and measured
FL 6	18.0	18.6	-3%
FL 5	8.9	9.4	-5%
FL 4	6.0	6.3	-5%
LED 3	13.8	12.0	16%
LED 2	6.8	5.9	16%
LED 1	4.6	4.0	14%

Energy Savings from Different Controls Strategies

Table 5 and Table 6 below summarize the average power for all luminaires as measured by the FLEXLAB system and reported by the Lutron system, respectively. As might be expected, energy savings increases as more controlled strategies are added and luminaires closest to the windows see more average energy reductions than those furthest from the windows. While it is informative to see the relative impact of various controls strategy, we note that these results were strongly tied to the specific input conditions used during testing. For example, if our occupancy sensing simulation included longer periods of vacancy, the occupancy sensing results could be expected to see greater power reductions. Similarly, if we had tested on more fully sunny dates, did more testing facing due south, and/or tested in summer instead of spring, the daylight harvesting results could be expected to show greater power reductions. It also should be noted that the data occupancy plus daylight harvesting results discussed here are with a south facing window façade while the daylight harvesting only results are with a west facing façade.

Table 5: Average power as reported by FLEXLAB, under all control strategies for all luminaires

Luminaire	Baseline (W)	Daylight Harvesting (W)	Savings	Occupancy Only (W)	Savings	Occupancy plus Daylight Harvesting (W)	Savings
FL 6	39.1	33.6	14%	20.2	48%	18.6	52%
FL 5	37.7	23.5	38%	20.3	46%	9.4	75%
FL 4	38.4	17.9	53%	20.4	47%	6.3	84%
All FL	**115.2**	**74.9**	**35%**	**60.8**	**47%**	**34.3**	**70%**
LED 3	26.5	21.9	17%	13.8	48%	12.0	55%
LED 2	26.4	15.6	41%	14.0	47%	5.9	78%
LED 1	25.7	11.1	57%	13.8	46%	4.0	84%
ALL LED	**78.7**	**48.7**	**38%**	**41.6**	**47%**	**21.9**	**72%**

Table 6: Average power as reported by Lutron system, under all control strategies for all luminaires

Luminaire	Baseline (W)	Daylight Harvesting (W)	Savings	Occupancy Only (W)	Savings	Occupancy plus Daylight Harvesting (W)	Savings
FL 6	34	32.6	4%	17.3	49%	18.0	47%
FL 5	34	24.4	28%	17.2	49%	8.9	74%
FL 4	34	20.5	40%	17.2	49%	6.0	82%
All FL	**102**	**77.5**	**24%**	**51.7**	**49%**	**32.9**	**68%**
LED 3	26	24.9	4%	13.2	49%	13.8	47%
LED 2	26	19.4	25%	13.2	49%	6.8	74%
LED 1	26	15.5	40%	13.2	49%	4.6	82%
ALL LED	**78**	**59.8**	**23%**	**39.6**	**49%**	**25.2**	**68%**

Glare Analysis

Between February 26 and April 1, 2015, SLR cameras automatically captured images inside the test cell at 5-minute intervals. These images were converted to HDR images that are useful for luminance mapping and also for generating graphs of Daylight Glare Probability

(DGP) vs time for each day. **Figure 16** shows an example of a luminance plot (left) that was generated from an HDR image (right). **Figure 17** shows an example of glare, as defined by DGP, as a function of time for a day. DGPs values above 0.45 are generally considered intolerable while values under 0.3 are considered barely perceptible.

As mentioned previously, a detailed analysis of glare is not offered in this report. We plan to evaluate glare in the final report of this project by evaluating DGP during different controls setting and environmental conditions. We plan to compare this analysis to the similar analysis of energy use discussed in this report and highlight scenarios in which low glare and large energy savings are concurrent as well as scenarios in which low glare and energy savings seem to be in conflict.

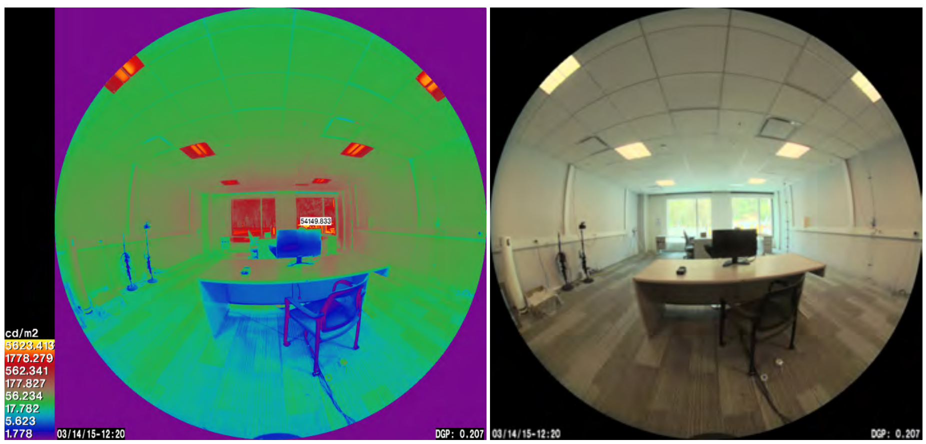

Figure 16: Luminance plot (left) based on HDR image capture (right)

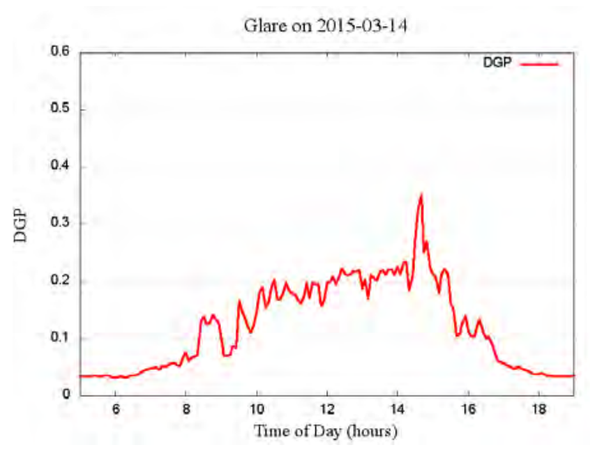

Figure 17: Daylight Glare Probability (DGP) for an example day

Rotational Experiment

On March 19th, an experiment was conducted in which power, light level, and glare measurements were taken in the FLEXLAB test cell as it was regularly rotated to track the sun. Initial measurements were taken at solar noon when that sun was at its highest point for the day (51.8 degrees at 1:18 PM). The test cell was then rotated hourly with four additional measurement points collected with the window façade rotated to directly face the sun. These measurement points could be used to simulate solar noon on March 19th at other latitudes or conditions in Berkeley at other times of the year. Data from this experiment were not fully analyzed, but we expect to evaluate these in the final report for this project. **Figure 18** shows the latitudes for which solar noon were simulated during testing. **Figure 19** shows photographs from the FLEXLAB test cell during the rotational test. As time progressed, these photos show sunlight reaching deeper into the test cell but still always entering the space perpendicular to the windows. The rotation of the test cell can also be noted by the changes in window view.

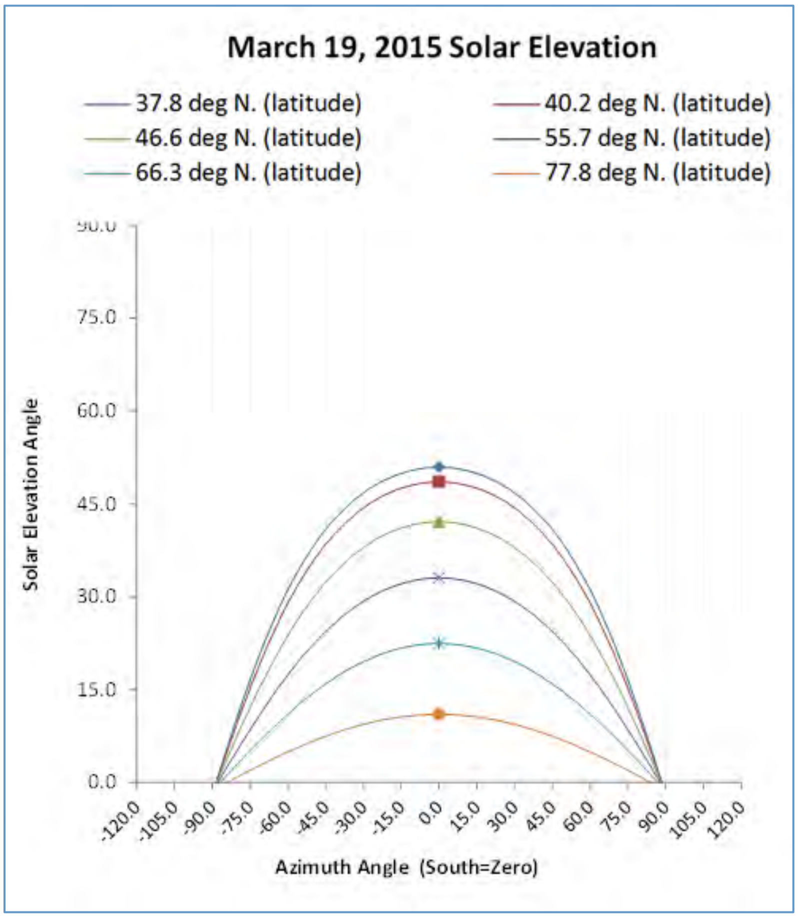

Figure 18: Solar Elevation as a function of latitude

Figure 19: Photographs from inside test cell during rotational testing

Conclusions and Recommendations

Our FLEXLAB testing found that there are some scenarios in which the energy use reported by a lighting controls system can vary significantly from actual energy use. Differences of over 10W per luminaire (over 100% variance) were observed in some scenarios. Inaccuracies such as these may limit the potential to use the energy logging capabilities of lighting control systems for accurate data logging, energy-efficiency incentive program savings estimation, and energy code compliance verification. In some cases, the lighting controls system overestimated actual power use while at other times it underestimated power use.

This study highlights that lighting energy reporting accuracy is contingent upon the initial system setup and input of correct wattage and ballast/driver power-dimming curves. With inputs in the controls system during commissioning that more closely match actual fixture power draw at full power and through the dimming range; it is possible that the evaluated approach to controls system self-reported energy usage could be greatly improved.

We did not observe timing errors or event-based errors during testing (i.e., the Lutron system and the FLEXLAB system were generally in agreement as to the timing at which luminaires were turned on, off, or dimmed). The errors observed all related to the magnitude of the luminaire power during operation. These variances most likely stemmed from inaccuracies in the dimming curves used in the Lutron system look-up tables as provided by the luminaire manufacturers (with the exception of default tables). If inaccurate dimming curves are used, errors are likely to be observed in power reporting regardless of the control strategies utilized.

The step dimming tests shown in **Figure 14** and **Figure 15**, most clearly illustrate the issues related to improper dimming curves and the impacts these have on reported wattages. While these results point to potential limitations using self-reported energy use data from lighting controls systems, we note that these results are based on just one lighting control system (Lutron's Quantum system) and two specific luminaire types (a 2x2 dimmable fluorescent luminaire and a 2x2 dimmable LED luminaire). Ideally, we would like to replicate this result in a wider range of lighting controls systems and luminaires (e.g., 5 different controllers and 10 different luminaires) to better document the range of reporting accuracies likely in real-world application.

While LBNL performed the test described in this report on a single lighting system, the testing protocol developed may have wider applicability. We can envision a test procedure for evaluating this broader set of lighting systems that would be similar to the step-dimming test we performed in the FLEXLAB. This test could be done as a power-only "bench top" test that simply compares the measured luminaire power to the lighting control system reported power through a range of different dimming settings. The purpose of this test would be to document errors in energy use, whether they were power-level related (e.g. power reported as 10W but measured as 12W) or time-period related (e.g., power reported to drop after 1 hour but measured to drop after 1 hour, 5 minutes). This test could be used both for lighting control systems that directly measure luminaire power as well as those that report power based on control settings and power look-up tables.

The results from the additional test described above would provide information about lighting controls system-reporting accuracy in general (e.g., are the results found in this report typical of lighting controls system self-reporting or atypical?). This test procedure development may serve as a valuable device for evaluating lighting control system reporting performance, perhaps ultimately resulting in a methodology for certifying self-reporting system accuracy. Codes, standards and/or utility programs could rely on these test procedures to encourage the use of lighting controls systems that are appropriately accurate at self-reporting. This enhanced methodology has significant cost savings and value across industry stakeholder groups in verifying accurately lighting system performance.

One of the key lessons arising from this research that is typically represented as a market gap, is that a significant number of construction projects involving lighting controls system installations lack either the budget, scope description, time frame or singularly accountable professional to adequately obtain and commission accurate luminaire lamp/ballast or LED/driver performance look up tables into a specific manufacturer's control system. Additionally, its important to recognize that frequently, a single project involves integrating a large number of different luminaires from different manufacturers, suppliers, distributors, and wholesale representatives, and that projects lack fully-funded commissioning agents and a single information channel sourcing accurate look up tables. This is not necessarily the failing of the resident lighting controls system reporting, but rather an artifact of the information interjected in it in an inherently 'flawed' construction process. With that said, our research does indicate a modicum of reporting errors associated with varying light source/driver/luminaire combinations. The seriousness of these errors is highly dependent on the extent of employed control strategies and obviously the veracity of the luminaire performance tables. As indicated previously, more research in this area would establish a firmer foundation for the full market impact related to this issue.

As mentioned earlier in this report, we collected but did not analyze a significant amount of illuminance and luminance data as well as on the rotational test. We plan to evaluate these data in the coming months, pending budget availability, in order to investigate correlations between energy savings and lighting quality metrics.

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