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Measurement and Verification of Energy Savings and Performance from Advanced Lighting Controls

February 2016

EE Richman

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Abstract

This document provides a framework for measurement and verification (M&V) of energy savings, performance, and user satisfaction from lighting retrofit projects involving occupancy-sensor-based, daylighting, and/or other types of automatic lighting. It was developed to provide site owners, contractors, and other involved organizations with the essential elements of a robust M&V plan for retrofit projects and to assist in developing specific project M&V plans. It provides an overview of how to conduct energy measurements and develop cost-effectiveness analyses to evaluate energy savings and compare different lighting control systems where applicable.

Acronyms and Abbreviations

fc	footcandle(s)
CIE	International Commission on Illumination
FEMP	Federal Energy Management Program
kWh	kilowatt-hour(s)
LED	light-emitting diode
M&V	measurement and verification
O&M	operations and maintenance
UFC	Unified Facilities Criteria

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1.0 Background and Application Summary

This document provides a framework for M&V of energy savings, performance, and user satisfaction from lighting retrofit projects involving occupancy-sensor-based, daylighting, and/or other types of automatic lighting control. It is designed to assist in developing specific project M&V plans and support cost-effective retrofits (partial and complete replacements) of lighting system controls, and is intended to serve the following purposes:

- Provide a foundation for M&V plans for occupancy sensor and other automatic lighting control retrofits following a “best practice” approach that considers engineering accuracy as well as practicality. This document may need to be customized for individual applications.
- Provide site owners, contractors, designers, and other involved organizations with the essential elements of a robust M&V plan for lighting projects.

The plan and details in this document have wide applicability across all building types and can be a useful tool in supporting the federal requirements for the use of lighting controls in federal agency facilities. In applications where the Unified Facilities Criteria (UFC) (U.S. Army Corps of Engineers 2016) and the General Services Administration PBS-P100 (P100) guide (U.S. General Services Administration 2014) allow and encourage the use of occupancy sensors and other lighting controls, this document provides methods for evaluating and verifying the effectiveness of the controls and the potential energy savings. Note that the UFC and P100 documents place some restrictions on where occupancy sensors can be used and how wireless communication protocols for controls can be applied. Other documents available through the Federal Energy Management Program (FEMP) provide guidance on the practical application of occupancy sensors in various space types and facilities. Consult these documents for lighting control applications and guidance.

This M&V approach is specifically tailored for retrofit projects involving automatic lighting control such as occupancy sensors or more involved advanced lighting controls. The M&V approach outlined herein contains many parameters. The prescribed methodologies were developed considering technical accuracy and practicality. Capturing control savings typically requires additional monitoring and calculation compared to simple lighting technology changes (i.e., fluorescent to light-emitting diode [LED] lamp retrofits). This M&V plan can apply to projects where there is interest in comparing savings among different control systems. The installation, setup, and calibration of occupancy sensors, daylight sensors, and other lighting controls often involves manufacturer-specific steps and procedures that can significantly affect the control’s function and therefore the energy savings. This setup and calibration for effective function is beyond the scope of this document. Consult the product manufacturer’s setup and calibration guidance to ensure that controls are optimized.

2.0 Measurement and Verification Activity Details

This section details each primary element of a useful and effective M&V plan. Specific guidance on applying the plan in varying field conditions is included to accommodate common differences in project applications.

2.1 Basic Considerations

For measurements to provide a useful comparison of different lighting control technologies, several conditions must be considered:

- Operating hours: Operating hours should be identified during an initial survey of the facility and are assumed to be the same before and after the retrofit. Savings (or increased energy use) associated with changes in facility operating hours should not be considered when evaluating the potential for energy savings from an installed or modified control system, and should be considered separately.
- Existing lighting controls: If lighting controls other than the new control or control modification being implemented already exist in the areas to be measured and are not being replaced, it is important that these existing controls function the same before and after the retrofit if possible. This ensures that the energy effect of just the new control can be measured by having existing control be the same before and after. If it is not possible or practical to maintain existing controls, it is desirable to deactivate these controls for a reasonable period (2 weeks preferred) prior to installing the new control to provide a comparable baseline of pre-existing conditions for comparison.
- Light levels: Typical occupied lighting levels (illuminance on task surfaces) are often necessarily or unavoidably changed from pre-retrofit to post-retrofit conditions. Implementing changes in light levels with the installation of a new lighting system (with or without controls) will affect the occupied energy use and therefore potentially skew results of any comparison involving energy savings. Therefore, it is important to capture occupied lighting levels before and after the retrofit to be able to adjust savings for a fair comparison or at least recognize that this change is an important element of the project energy savings or increase.
- Site selection: The specific characteristic of an evaluation site or area can have a large effect of the measured potential savings. If daylighting is part of the control system, the evaluation site(s) with daylighting characteristics should be as similar to the expected applications as possible. If more than one control system is being evaluated, the evaluation areas selected should be similar to one another. This would include areas facing the same orientation to the sun, having similar/identical window layouts, and having similar clear or obstructed views related to solar angles. If occupancy sensing is part of the control system, evaluation site(s) should have an occupancy that is as close as possible to what would be typically expected in anticipated applications. Because occupancy in work spaces is extremely variable depending on worker type and activity, it is important to have as large a set of occupants as possible in each evaluation area. This helps support measured energy use data that is as close to statistically valid as possible. If more than one control system is being evaluated, the evaluation areas selected should be similar to one another.
- Heating and cooling system effects: Potential effects on the energy use of heating and cooling systems from changes in lighting energy use are beyond the scope of this plan. Heating and cooling energy use can be affected by interior lighting changes, but in most cases (other than in extreme

climates) the heating and cooling interactions at least partially offset each other or are relatively minor.

2.2 Site Selection and Setup

An effective comparison of lighting controls requires an environment and conditions that eliminate unnecessary variables that could invalidate the results. All installations and real-world conditions are unique; however, equivalent conditions are needed for a reasonable comparison. Each setup condition described below should be evaluated in terms of potential effects on collecting useful data.

2.2.1 Stable Operational Baseline

When assessing any lighting control system, it is desirable that the basic lighting system be in stable operating condition both before and after the retrofit of controls. This ensures that the effect of only the new control is captured in any measured energy savings. However, lighting retrofits commonly involve multiple changes, including lamp technology (i.e., fluorescent to LED) and light level adjustments (i.e., increase or reduction to meet recommendations or occupant needs). These changes will affect energy use and therefore affect any fair comparison of control options or true energy savings from an installed control. Thus, it is highly desirable and important for the analysis to either eliminate or otherwise accommodate for these other variables.

The energy use of lighting technology changes and light level changes can be roughly accounted for. This energy use that is separate from control savings can be adjusted for by measuring the power draw of both the pre- and post-retrofit lighting systems at full power (typical operation when any automatic controls are not activated). The difference in power can then be applied to any energy savings data to remove the effect of the technology or light level change to provide energy savings from the control application only.

The effect of controls on the new technology may result in differences in its steady state power draw, but these would be expected to be minor and would likely not affect any comparison analysis. The controls may also affect the longevity of the lighting, which is addressed separately in the operations and maintenance section.

2.2.2 Stable Conditions for Measurement

The test site chosen should provide stable conditions before and after the retrofit installation. Physical site changes that could affect results include electrical circuit reconfigurations or interior renovations that would disrupt normal facility operations. The conditions most likely to affect the data collected include a change in occupants, holiday schedules, and changes in occupant tasks or schedules. If changes such as these are likely in the test area(s), their effect on collected measurements should be carefully considered or an alternate site chosen.

2.2.3 Equipment Burn-in and Warm-up

For newly installed retrofit or replacement lighting equipment, the energy consumption and light output may change until the product has been operated for a reasonable amount of time (also known as seasoning). This has been a concern for some fluorescent systems, but is typically not of much concern for other technologies including LED.

Some lighting technologies such as compact fluorescent light and linear fluorescent can take time to warm up to stable operating conditions when first turned on at the start of a business day. This can be particularly true in colder conditions. Therefore, for both baseline and post-installation measurements of energy and light levels, the system should be allowed to warm up to typical operating conditions. Appropriate warm-up periods will vary depending on the technology, but 1 hour should cover all interior and exterior situations.

2.2.4 Measurement Access

The test site should provide easy access to the circuits serving the test lighting system. The illuminated area should be available for light level measurements during periods when potential obstructions (e.g., vehicles, occupants, customers, and temporary materials or equipment) and daylight can be avoided. It is important to avoid daylight conditions in order to specifically evaluate the electric lighting system only.

2.3 Instrumentation Recommendations

The measurement of real world application of lighting controls is necessarily going to include potentially wide uncertainty. This is simply because of the natural variability in the architecture of spaces (daylight availability) and the activity of occupants (occupant sensor activation) which directly drives advanced control energy use and savings. Therefore, unlike other laboratory and field measurement activities, the measurement of building energy use in real world situations does not require extremely small measurement tolerances to be effective. However, consistent measurement and reasonable accuracy are still important.

Measurement equipment can have listed uncertainties that can help in understanding the variability of the energy use that is recorded and lower uncertainties are naturally preferred. At the same time, energy use can vary significantly because of the human factor (occupancy sensors) and solar availability (building architecture and location). These variabilities are likely much larger than any equipment uncertainties. Therefore, while equipment accuracy is important, it is not a critical parameter beyond a tight tolerance within a few percent. However, this M&V plan does recommend minimum accuracy requirements for measurement instruments that are reasonably achievable with standard available equipment. Table 1 provides instrument specifications appropriate for the types of measurement applications covered in this M&V plan. Specific brands or manufacturers are provided as examples only and do not represent an all-inclusive list. Testing documentation should include the actual specifications and measurement accuracies of any equipment used. If the accuracy is significantly less than the values listed in Table 1, the measurements may not be suitable because they would introduce additional error to the energy calculations.

Table 1. Recommended Instrumentation Specifications.

Equipment Type	Purpose	Measurement Uncertainty and Range	Meter Characteristics	Brand Name[a] Examples
Energy Logger/CT system	Measure real time energy use via circuit or panel	Uncertainty: ±1 % of reading		Wattnode Onset-Hobo Extech
Light on/off data logger	Measure run time of lighting fixtures	Uncertainty: ±1 minute per week; Light threshold adjustment range: 1 to 100 fc (10 to 1,000 lux)		Onset Computer Hobo Loggers Dent Instruments SmartLogger Omega OM-53
Power meter (for one-time measure-ments)	Establish true power of baseline and new lighting controls/systems	Uncertainty: ±3% Decimal precision	Power factor calculation and/or adjustment. High sampling rate of 240hz or better preferred	Fluke Extech Hobo
Illuminance meter	Establish functional performance of baseline and new lighting equipment	Uncertainty: ±3% Range: ≤0.1 fc (1.0 lux) to ≥10,000 fc (100,000 lux)	<3% deviation from cosine function for reported single value or ≤10% at incidence angle of 60° for multiple angle reported values. Spectral response within 10% of the CIE spectral luminous efficiency function	Minolta Photo Research Cooke Extech Amprobe Solar Light

(a) Brand names listed are examples only. Associated products **may not** meet all of the requirements in this table. Verification of the individual equipment is required.

2.4 Energy Measurement Method

The measurement of energy typically involves the installation of equipment inside live electrical panels and the attachment of equipment to live circuits. This work necessarily requires a level of safety practice and diligence that is practiced by electricians and individuals who are trained to install energy monitoring equipment. Specific safety procedures and protocols to accomplish this are out of the scope of this document. This document focuses on the protocols and suggested metering and measurement formats needed to capture energy use data for lighting control system evaluation. Specific electrical installation techniques and safety methods should be addressed by the equipment installer.

Measuring the energy use of a lighting project may be of interest for different reasons. Two primary reasons for measurement are: 1) to determine savings for a specific project to validate project cost-effectiveness, identify savings towards a programmatic goal, and/or for use in project cost reimbursement contracts and 2) for use in estimating potential energy use/savings over a wide set of applications. Energy measurement of lighting controls for either of these reasons presents similar challenges.

Measuring the energy use of a variable load produced by a lighting system with advanced occupancy sensor and daylighting controls is more involved than measuring the difference in energy from a simple technology retrofit (i.e., fluorescent to LED). This is directly because of the variability in hours and/or levels of operation with these systems from unscheduled occupancy control and daylight dimming control. Some installations that involve only simple automatic on-off control from basic occupancy sensors may be measured with one time power measurements and runtime lighting loggers. However, this will not work in most advanced control systems with individual fixture-embedded control and/or daylight dimming or step control. Therefore, the most realistic method for capturing actual energy use with advanced control systems including occupancy sensing is true energy metering over time.

The measurement of energy to meet the two primary reasons noted previously can effectively be accomplished by: 1) measuring the entire power circuit system that serves the entire project area (total circuit measurement method) or 2) measuring a sample of representative space types, fixtures, or individual circuits within the project area (sampling measurement method).

The total circuit measurement method is generally preferred when only the total savings for a specific project is needed. This method typically captures the energy consumption of the complete project without relying on estimates from a few example spaces to generate a project total. The sampling method is generally preferred if the collected data is to be used to estimate savings for a variety of potential projects. This method can provide specific data on space type energy use that is more useful for estimation across a variety of building types. Both of these methods are described in more detail below.

Regardless of the measurement method chosen, some basic measurement principles should be followed as part of a successful metering approach:

- Site setup documentation: Photographs and sketches of the test site conditions, energy measurement setup, and measurement points within panels or circuits are recommended to provide a record of the conditions to be applied for repeated sets of measurements. These will help identify obstructions and other conditions that may affect future measurements.
- Representative operations/areas: Measurement of a complete lighting system with controls for an entire facility can be the simplest method for capturing energy use and savings. However, this may be difficult because of possible mixed loads on lighting circuits, and estimation may need to be applied (see the description of the total circuit method in 2.4.1). For M&V projects where the data may be used to estimate savings for other buildings or locations, the mix of space types in the building being evaluated may not be representative of these other buildings. It is therefore often more practical to measure representative spaces within a facility when possible. It is important to measure as many spaces as possible that represent the majority of typical operations to provide a useful average for the space type that is as close as possible to a statistically valid savings value.
- Measurement periods: Facility operations vary with time, seasons, holidays, and other business activity. Therefore, it is important to capture a long enough operating period to reasonably represent standard operation. An entire year of measured data could be ideal but this is typically impractical and shorter periods must be considered. To account for typical business operational variance, this is typically at least 2 weeks of normal non-holiday operation. More time is preferred if business operations vary over a typical 2-week period (e.g., changing tasks or hours of operation). Holidays and vacation periods are then accounted for separately based on business schedules. It is also desirable to measure continuously for the entire period and not just on business days or during operating hours because off-hour operation of the control is also an important part of the total system. In addition to business operational variation, seasonal changes related to daylighting can also significantly affect energy use when daylighting control is part of the lighting system. In these cases, a separate set of issues with the measurement period arises with those lighting controls that involve daylight sensing control capabilities. See the section below for guidance on dealing with seasonal daylighting energy savings. For capturing energy use after installation of lighting system controls, the same 2-week or more time periods are recommended.

- Multiple control layers: If the control system has multiple control layers (i.e., occupancy sensing plus daylighting), then where possible, it is useful to capture periods of 2-weeks or more with each control layer separately operating. With some advanced control systems, this may not be easily accomplished but it should be part of the metering plan in order to separately capture daylight control savings with the system.
- Daylighting assessment: When daylighting control savings can be separately measured, there are multiple issues that will affect the accuracy of the resulting estimate of savings. Daylight availability varies greatly with the architecture of the facility (window shape and location, overhangs, blinds). Daylight availability also varies over the entire year and with the building's geographic location. Longer energy measurement periods can help capture the seasonal variability of daylight throughout the year, but typically this will be considered impractical. Analysis and computer modeling of various architectures in buildings of interest can help develop ratios that can be applied to one building's measured data for application in other buildings. However, this is also likely not practical for the typical retrofit project. For energy savings estimates that can be used to prioritize projects, simpler methods and realistic project approaches may be appropriate and necessary.
  - Daylight control savings over an entire year for a building can be estimated by using a simple ratio of solar radiation that directly drives daylighting energy savings. The appropriate ratio in this case is the total solar radiation for the year ($Wh/yr/m^2$) divided by the solar radiation during the measurement period of 2 weeks or more ($Wh/measurement\ period/m^2$). This ratio multiplied by the energy use measured during the measurement time period calculates an estimated energy use for the year as follows:

    $$\text{Estimated yearly } EU = (ASR/MPSR)*(MPEU)$$

    where *EU* is energy use, *ASR* is the total annual solar radiation for the site location, *MPSR* is total solar radiation during the measurement period for the site location, and *MPEU* is the energy use measured during the measurement period.
  - The difference between energy use for measurement periods with and without the daylight controls activated will provide an estimate of the energy savings available from the use of the daylight controls. A useful database of hourly solar availability data can be found as part of the National Solar Radiation database (National Renewable Energy Laboratory 2012) in the form of Typical Meteorological Year (TMY3) data[1].
  - Daylight control savings estimates from one building can be applied to another building if the architecture (window configuration and orientation) is the same for both buildings. In this case the ratio used is

    TSR proposed building location/*TSR measured building location*

    where *TSR* is total solar radiation.

    This ratio when multiplied by the estimated yearly energy use for the measured building provides similar yearly estimates for the energy use in the proposed building. This can provide a rough but realistic estimate of the potential savings over an entire year at different locations with similar architecture.

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[1] TMY data is available by location and time of year at: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

- If the architecture of multiple buildings is different, applying simple daylight savings radiation ratios to estimate possible energy savings in other buildings is not realistic. The realistic approach in most projects like this is to have a determination made of the applicability of daylighting controls in each location. This would necessarily involve a lighting design professional but is the only realistic method of ensuring that daylighting controls are only installed where they may be effective.

2.4.1 Total Circuit Measurement Method

The total circuit measurement method involves identifying the circuit(s) that serve the baseline and post-installation lighting systems. Typically, these are the same circuit(s) and can provide a direct representative measurement of actual energy for the project. This is most appropriate when the goal of the evaluation is estimating the total savings in a specific building or application only and it is not intended to be applied to other projects.

In some cases because of mixed loads on circuits, the total lighting load for a building may not be easily measured. Estimating total project lighting energy use from energy metering for a majority of the project area can still be appropriate. In these cases the total energy use for a building can be estimated using ratios of the metered square footage and the total square footage. For this estimate to be valid, it is desirable to capture as much of the project energy use as possible. A value of at least 75% is recommended. Less than 75% may still be valid if it can be considered representative of the entire area. Specifically, for less than 100% of the project area, the circuits measured should: 1) provide power to a mix of spaces that are the same as the mix of spaces in the entire project and 2) the circuits should be as clean as possible and not include non-lighting loads or loads from neighboring areas that are not part of the project.

2.4.2 Sampling Measurement Method

The sampling measurement method involves measuring the energy use of a representative sample of the spaces in a project and using this data to extrapolate to the energy use of the entire project or the potential energy use in future projects. It is advantageous to measure the energy savings of lighting controls by space type because control activation and therefore energy use is directly dependent on the architecture of the space, the function of the space, and its occupant activity. This method provides the possibility of the most valid data that can be applied to a variety of project energy savings estimates or evaluations. However, if the specific site being measured has limited types of spaces or few examples of these spaces, then the resulting data may not accurately represent an entire site or other sites. Therefore, it is important to capture the energy use of as many samples of each space type or large areas encompassing each specific space type as possible. This will provide the most realistic estimate of energy use and savings when applied to other sites and projects.

2.5 Energy Measurement Application Details

Regardless of which method of measurement is chosen, similar principles apply when choosing measuring equipment and setting up the systems to capture valid data.

The basic activity in measuring energy is capturing the true power over time of individual lighting circuits. This is typically accomplished by real time measurement of the current flow in a circuit and the circuit voltage and applying the measured power factor. These data represent the energy flow over time in kilowatt-hours (kWh). Most energy measurement equipment designed for field measurement incorporates the current, voltage, and power factor calculation in the same system and therefore can directly report energy (kWh). It is possible to capture current/power factor and voltage separately with different instruments and then combine them for an energy estimate. However, this is not recommended because typically it involves one time measurement of voltage and power factor that usually always varies with time and introduces unneeded accuracy variation to the measurement. Setup and verification of operation are critical to collecting useful data. The following attributes and activities for effective metering should be considered:

- <u>Equipment choice:</u> Energy metering equipment is available from several manufacturers. The typical system includes one or more power meters that capture circuit or equipment energy use with a combination of current transformers and voltage measurement nodes. These meters are tied to a data logger that collects and can then transfer the data to a computer for analysis.
  - Many of the options are similar in operation but can offer a variety of data capture and data transfer options. Early energy metering systems provide only readout or hard-wire download capability. Newer equipment offers wireless data access and download through various options including hardwired USB or similar cabling, wireless cell signal transfer, Wi-Fi connection transfer, or Ethernet connection transfer.
  - The accuracy of the metering equipment can be important but it needs to be considered in relation to the other variables associated with the data collection effort. As noted previously, the energy savings achieved from lighting controls is directly dependent on real world facility and occupant characteristics and behavior that naturally have significant variation. Therefore, for the typical limited field assessment with limited sample sizes, the reading accuracy of the equipment needs to be reasonable but not laboratory grade. Table 1 provides some recommended accuracies and other characteristics for equipment.
- <u>Identify/trace circuits:</u> Whether using the total circuit or sampling measurement method, it is important to identify those circuits that serve the lighting for the desired spaces or project. **Note that it is very important to verify with site representatives that it is acceptable to cycle circuits to ensure no adverse effects on facility operations.**
  - In newly constructed facilities, circuit identification within electrical panels can be very accurate and up to date and with limited verification can likely be taken as accurate. However, lighting retrofit projects will likely involve older facilities where the labeling of panels may be incomplete or incorrect. This is typically an artifact of less detailed requirements for panel documentation in the past and electrical changes that were not completely documented. This situation can create problems when collecting data that can be associated with specific spaces. Therefore, it is important to trace circuits in order to correctly identify what is on each one. For lighting loads, this is best accomplished as a group activity where spotters located throughout the facility can verify lights on/off as circuit breakers are cycled. This is also best done after business hours to cause the least disruption to occupants.
  - If the lighting is all powered by 277 volt systems, it is likely that the lighting circuits are “clean” and do not include any non-lighting loads but tracing may still be needed to verify the spaces that

each circuit serves. In older facilities with 120 volt lighting systems, it is very likely that other non-lighting loads may be on lighting circuits. These need to be verified and assessed. If the load is small, it may be considered insignificant to the overall energy assessment. If the load is not consistent (i.e. rarely used), it may also be ignored. However, if the load is significant, then that circuit may need to be bypassed. In this case, this may mean the loss of one sample of a space type if using the sampling method. If using the total circuit method, this will be one part of the non-measured load that is estimated from the measured load.

  – An effective method for capturing before and after retrofit energy use with limited onsite presence is to install the metering equipment such that it can continue to operate during and after the new lighting system is installed. Coordination with the contractor who will be installing the new lighting system is important. This can help ensure that the energy metering equipment will not affect the lighting system installation and that the control system installation will not disrupt the energy metering setup. In most cases the lighting control system installation will not affect any of the circuiting within the panels and the same circuits will serve the same areas before and after the installation. In other cases with major retrofits, some circuit changes may disrupt the capture of clean before and after energy data. In these cases coordination with the system installer may lessen the impact.

- <u>Equipment placement:</u> Where possible, metering equipment should be installed within electrical panels or in locations away from other activities near the panels. This is often not an issue when panels are in electrical closets or rooms away from daily activities. For panels located in visible or traffic areas, other arrangements may be necessary and may affect the choice of equipment. Equipment should not be visible to occupants for safety, security of data, and aesthetic reasons.
- <u>Energy data verification:</u> It is critical to data collection efforts to ensure periodically that data is being correctly captured. It is good practice at the time the metering equipment is installed to perform one-time circuit measurements to compare with the energy loads seen for each circuit by the energy metering equipment. After the system has been verified as operating correctly, periodic checks using either physical data download or remote wireless connection (cell, Ethernet, Wi-Fi) should be made to ensure good data streams. The recommendation is for checks at least weekly to avoid costly loss of data.
- <u>Equipment removal:</u> After the required data is collected, metering equipment should be removed and the electrical system left in the same condition as found.

2.6 Basic Light Level Measurement Protocols

Light level (i.e., illumination) measurements are not technically a part of measuring the effectiveness of wireless occupancy sensor controls. However, most lighting energy projects must be cognizant of the light levels being provided by any new lighting technology installation to ensure its effectiveness for occupants. Therefore, guidance is provided here on taking effective measurements of light levels in the space for comparison with other technologies and/or standards.

In general, it is important to measure only the light being provided by the technologies being tested. Any neighboring area lighting or daylight should be excluded from the measurements. The following guidelines will help to ensure accurate and representative light level data. Follow these guidelines for all measurements (exterior and interior) as applicable:

- Where possible, use the same calibrated illuminance measurement meter. If the same meter is not available, use the same make and model of calibrated meter to minimize underlying differences in accuracy and internal meter spectrum correction characteristics.
- When taking measurements, verify that occupants and objects/materials are not blocking light to the meter head. The use of a remote meter head cabled to the meter body is recommended to prevent the operator from blocking the meter's "view" of the lighting system being measured. Measurement points that are shaded, even partially, by immovable obstructions should be noted for potential elimination.
- Identify the appropriate task plane at which to take the measurements. For most outdoor areas and indoor corridors, gathering spaces, and warehousing or manufacturing spaces, this plane will be the ground or floor surface (where walking is the primary task). For most other indoor areas, the task plane (work plane) will be a typical office desk height (30 inches above the floor).
- Identify the measurement locations by marking and/or mapping. It is important to measure the same locations for the baseline and post-installation lighting systems, or the same representative types of locations if fixtures are relocated for the retrofit. Therefore, it is necessary to provide some permanent record of measurement point locations.
  - For interior areas, mapping (e.g., using a sketch or marked-up plans with dimensions) is usually the best option because marking on measurement surfaces will often not be allowed or the marking will not be retained between measurements. Be sure to reference the measurement points to some permanent features of the space because desks and other furniture may be moved between the baseline and post-installation measurements.
  - For exterior areas such as parking lots, it may be possible to mark locations with dots or numbers using striping or other paint (durable but non-permanent), subject to site representative approval. Otherwise, a map of the measurement grid referenced to permanent site features can be developed such that the same measurement locations can be identified later. It is advisable to map the measurement points even if marking is possible in case the exterior area is resurfaced or otherwise cleaned of all markings.
- Photographs of the test site conditions, light meter setup, and measurement layout are recommended to provide a record of the conditions to be applied for repeated sets of measurements. These will help identify obstructions and other conditions that may affect readings. Note that using photos for color comparisons of baseline and retrofit installations may not provide accurate results because camera model settings including white (color) balance and exposure may vary. If photos are to be used for comparison, the camera color accuracy should be assessed and appropriate caveats noted.
- Record time and ambient temperature at start and finish of measurements. Temperature may not seem important for light level measurements, but it can affect some lighting technology output—specifically LED if the temperatures are extreme. For most indoor office type environments, temperatures will not be critical.

Additional detailed guidance on precautions, methods, and appropriate techniques for taking effective light level measurements is provided in Appendix A.

2.7 Occupant and Installer and Operator Experience Assessment

Occupant satisfaction and feedback from installers and building system operators are not technically a part of measuring the energy effectiveness of controls. However, they can be an important part of the success of a lighting control system project and the decisions to replicate the system at additional sites. It is important for occupants to be satisfied that a new system is at least as good as the previous one for their work environment. The input from system installers can be important for determining which systems are easy to install and which may present difficulties during initial installations and/or with future maintenance. Operator experience is also important in evaluating the long-term usability of a system and the potential for future operating issues. Methods of assessing these inputs include individual interviews and distributed surveys. Survey instruments are historically easiest to implement and can also provide the most secure anonymity of responses.

Survey data (as well as interview input) is naturally very subjective and therefore requires care to ensure that the data is representative enough for future decisions. In the world of statistics, survey data has multiple variables that determine the data's statistical significance. In general, very large sample sizes are needed for human response data to achieve statistical significance. Generally, a threshold of 30 respondents is considered useful for making value judgments from the responses. At sample sizes of 30 or more, comparisons between systems or before and after conditions can be effective. For purposes of assessing work environments, it is often difficult to achieve this sample size within the same work area which can lessen the ability of the data to be used for detailed comparisons of systems or system attributes. However, for smaller sample sizes, the results cannot be as effective but can serve to assess significant issues with a system and be used to assess general satisfaction.

2.8 Operations and Maintenance and Other Cost Savings

Operations and maintenance (O&M) cost savings are often a large part of cost-effectiveness economics. They can generally vary significantly from project to project or because of specific technology characteristics and should be carefully considered separately from energy savings. For lighting control applications such as wireless (and wired) occupancy sensors, the controlled operation of the lighting can affect energy savings and O&M due to maintenance required for the additional control equipment and expected reductions in replacement schedules for the lighting sources (lamps). These costs and savings can involve many variables, including the following:

- <u>Expected "life" of the lighting source technology:</u> This is typically the main driver for O&M savings and is commonly based on industry accepted values for how long various lighting technologies will continue to provide light to a space. For standard incandescent, fluorescent, and high-intensity discharge technologies, the on-off control typically associated with occupancy sensors is known to shorten the life of these types of lamps and therefore needs to be accounted for in O&M calculations. For LED technology, on-off control is not known to have an effect on expected or rated life.
- <u>Lamp replacement policy:</u> Replacement upon failure is a common approach to lamp maintenance that gets the most from the lamp but likely involves additional labor to replace individual lamps on failure. Group lamp replacement takes advantage of maintenance staff time to replace multiple lamps effectively but needs to be carefully planned to make best use of lamp life. The most effective option may be a combination where a set frequency of lamp failures prompts an efficient group relamping.

- Calibration and maintenance/repair requirements: Some control parts or systems may require periodic recalibration or repair to maintain their effectiveness.
- Lighting system cleaning policy: The cleaning of lighting systems such as luminaire lenses and lamps may be useful in industrial and other higher dirt accumulation areas to maintain light levels and reduce occupant concerns.
- Labor rates or similar contracted lighting maintenance/cleaning cost structures: Depending on the facility or site type, cleaning and repair may be done in-house within existing schedules or separately contracted. In-house services may or may not save costs depending on how the funding for these services is arranged.

Often, any developed O&M savings (or losses) can be part of an overall evaluation of project viability. In other cases, these savings are not considered for programmatic or conservative analysis reasons. Because of the wide variety of characteristics, applications, and policy approaches associated with the variables involved, a full treatment of costing these potential savings is not provided in this document. Spreadsheet and other format systems and methodologies for calculation of these savings may be available from lighting manufacturers and distributers or other sources online.

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Appendix A

Additional Guidance for Accurate and Repeatable Illuminance Measurement

Appendix A

Additional Guidance for Accurate and Repeatable Illuminance Measurement

Accurate and repeatable illuminance measurements can be influenced by many factors, including characteristics of the measurement instrumentation as well as the setup and execution of the actual measurements. This appendix provides detailed guidance on two major areas that require special consideration: 1) measurement accuracy at low light levels and 2) test site obstructions.

A.1 Measurement Accuracy at Low Light Levels

Low light levels create particular accuracy and comparability problems for measurements taken using standard field light measurement equipment. This is partly because of the typical variability among sensors and measurement electronics, which may produce different readings of the same lighting source. Ambient temperatures can also affect illuminance readings by up to 1% per 10°C and typically 3% over the equipment operating illuminance range. These effects can occur during any measurement, but are most noticeable with low light levels, where small actual differences can represent a large percentage difference.

To reduce the effects of meter accuracy and differences in sensors, the following practices should be considered:

- Use a meter with the highest overall accuracy possible that meets the specifications in Table 1 in the main document.
- Set the meter to the lowest available measurement range if not auto-adjusted.
- Use the same meter—or at least the same make and model of meter—for pre- and post-measurements, as well as measurements between sites, to ensure comparability of readings.
- Where possible, avoid extreme temperatures (toward the limits of the meter's stated operating temperature range). If extreme temperatures cannot be avoided, ensure that similar temperatures exist for pre- and post-measurements.

The test setup for the measurements (including handling of the meter) will also affect readings—particularly at low light levels. Careful test setup and measurement procedures can reduce potential variances from the handling and placement of the meter. When multiple measurements are taken and averages calculated for comparisons, minor variations in placement of the meter should have minimal effect. However, in critical areas such as perimeters and special areas where fewer measurements are taken and/or perimeter conditions are being verified, the measurement placement will be important.

To reduce the effects of test setup and meter handling, follow these guidelines:

- Ensure that critical measurement locations are marked and easily identifiable (e.g., using an "X" or small dot) such that the center point of the identifying mark can be accessed for each measurement.

- Ensure that the sensor head is placed parallel to the horizontal or vertical task plane (typically the paved surface or ground for horizontal exterior measurement). Many exterior surfaces are not perfectly flat, and placing the sensor in a slightly different location can tilt the sensor and produce a potentially large difference in reading. For rough surfaces, it is recommended that the sensor head be placed on a platform (e.g., a 12-inch × 12-inch or larger square of plywood) to eliminate the effect of small surface differences on the small meter head. When using a platform, it is suggested that the sensor head be attached at the edge of the platform so that it can be more easily centered over the measurement location mark.
- For vertical measurements, a tripod is recommended to provide consistent height and angle of orientation. With particularly rough locations, a leveling bubble may be needed to ensure that the apparatus is level to the ground and that the meter head is vertical. Placing the tripod on a platform (e.g., a 3-foot × 3-foot square of plywood) may also reduce this error.
- Ensure that all measurements are made with no obstructions blocking the direct light from surrounding luminaires. Also ensure that objects such as cars and persons are not close enough to the measurement point to reflect light onto the sensor head. For this same reason, dark clothing is recommended when taking exterior nighttime measurements. However, a reflective vest may be necessary for safety.
- For exterior areas, ensure that measurements are not affected by sources of ambient light that are not part of the typical operating conditions, which could include any of the following:
  - Daylight; take measurements well after sunset. Even a modest amount of daylight on the horizon can affect the measurements.
  - Temporary construction lighting.
  - Vehicle lights.
  - Lighting for neighboring structures. For neighboring lighting controlled by occupancy sensors, conduct all measurements while this lighting is off. For neighboring lighting on timer controls, take all measurements either with or without this lighting.

A.2 Test Site Obstructions

Basic considerations for avoiding obstruction of the light to be measured are covered in the measurement section of this document (Section 2.6). However, additional issues that may not be obvious or clear are discussed here. Obstructions include both objects that block the light being measured and objects that reflect unwanted light. When preparing to take light measurements at a site, it is important to identify permanent obstructions that should not be adjusted or moved. However, temporary obstructions should be moved to create a repeatable site configuration for light measurements. When future measurements are taken, temporary obstructions should again be moved to replicate the original site configuration.

In some cases, semi-permanent or permanent obstructions are added between sets of measurements. In these cases, the obstructions should be evaluated to determine actual effect on readings and action taken where possible. Examples are detailed here:

- Temporary piles of material, plants, and desk objects: If objects are near the test point, temporarily move them prior to taking the measurement. To minimize these issues, test points should be located away from partitions and other nearby surfaces where materials might accumulate.
- Overhead signage and banners: Hanging interior signs and exterior pole banners are often added to locations as general improvements or for holiday events. If these will block the light for a reading, they should be removed if practical; otherwise, their presence should be noted.

Obstructions can also cause unwanted reflection of lighting that will affect the readings. In many cases, objects both reflect and obstruct light. As described above, these objects should be moved if possible. Some temporary or newly installed objects (between sets of readings) may not obstruct light but may reflect it into the sensor's field of view. These might include

- vehicles,
- pedestrians,
- material stockpiles,
- temporary furniture, or
- added wall treatments such as whiteboards.

When these are encountered and are considered detrimental to light measurements, removal is preferred. Vehicles, pedestrians, and furniture are easily removed; however, more permanent items such as whiteboards may not be. In such cases, note the item's location relative to the test point. Photographs of the initial site conditions are useful for identifying changes for subsequent sets of measurements.

A.3 Specific Exterior Light Level Measurement Activity

In addition to the guidelines in Section 2.6, follow these guidelines for exterior area measurements.

A.3.1 Set Up Measurement Grids

- Identify a horizontal grid of measurement points on the site surface that contains the expected minimum and maximum of each different exterior area for both baseline and post-installation conditions (see sample layouts in A.5).
- Locate measurement points on gridlines covering the test measurement area. Ensure that the spacing between measurement points is uniform in both directions and is less than one-half the pole height or less than 15 feet, whichever is smaller. For installations with lights spaced less than 15 feet apart, locate measurement points no farther apart than one-half the pole height, with at least three points between poles in both directions.
- Record the location of all measurement grids and point layouts with dimensions from surrounding poles or other structures. Provide this information, including a sketch or rendering of the grid layouts, to the site owner such that the measurement points can be reused for future verification measurements.

- For open areas such as main parking, make the measurement grid large enough to completely encompass at least four poles that represent typical layout and spacing of poles (or the complete installation if fewer than four poles). See Figure A.1, for an example.
- For site perimeter open areas or areas adjacent to a building edge or façade (e.g., front drive aisle, rear drive, pallet/loading), establish the test area measurement grid in a typical perimeter or building edge area. The depth of the test area should extend from the paved site boundary or building edge inward to the nearest line of light poles that are at least 15 feet from the boundary or building edge. The width of the test area must cover at least two of the poles in the line that is at least 15 feet from the boundary or building edge. See Figure A.2.
- For areas that include separate or main entry drives, establish the measurement grid across the entire drive or other area and extending the typical distance between two adjacent light poles. See Figure A.3.
- For each separate horizontal grid, also identify a vertical plane representative of the lighting in the area (typically the gridline directly between two light poles). On this vertical plane, set a grid (line) of points at 5 feet above the site surface at each of the corresponding horizontal measurement points. See Figure A.4.
- **Note that in some exterior applications, the layout of the lighted area and location of luminaires will not be conducive to uniform grids of measurements.** In these cases, follow the intent of the grid layout as closely as possible. In cases where all luminaires are not arranged in a uniform grid pattern, identify a row of luminaires, preferably parallel to the site boundary or drive, to use as the basis for setting a measurement grid. Use a reasonably typical spacing of luminaires at the site to identify the grid spacing. Use this spacing, starting with the initially identified row, to develop a grid of measurements without regard to existing luminaire locations that do not match the grid. Extend the grid to ensure that enough clear, unobstructed points will be available to provide adequate characterization when the obstructed point data is eliminated.

A.3.2 Measure and Record Illuminance

- At each measurement point on each grid, measure and record the horizontal illuminance on the ground or finished surface. Also measure and record the vertical illuminance at 5 feet above the site surface at the points identified in the vertical plane. See Figure A.4.
- Schedule and take all measurements so as to minimize the effects of other light sources and weather conditions on the results.
  - When possible, schedule measurements for both baseline and post-installation when the moon phase is at half or less to eliminate moon glow as a variable in the measurements. Record a background measurement of ambient lighting (e.g., moonlight, sky glow) in an area shielded from all site lighting and subtract it from other measurements if it is determined to be significant.
  - Ensure that rain, fog, or winds that might introduce particulates into the air, or other conditions that might obscure the light between the fixtures and the meter, are not present for the measurements.

A.4 Specific Interior Light Level Measurement Activity

In addition to the guidelines in Section 2.6, follow these guidelines for interior area measurements.

A.4.1 Set Up Measurement Grids

- Identify a set of measurement points that sufficiently represents the overall lighting of the space for both baseline and post-installation conditions. See Figure A.5.
- For each different set of lighting conditions (i.e., different space types or lighting layouts), locate at least 12 measurement points at easily identifiable points. It is commonly very difficult to identify a rigid grid of measurements because of the many variations in layout and obstructions at desk height (work plane) in office environments. Therefore, select a sampling of measurement points both below and between fixtures, in both 90° directions and diagonally. Include at least two measurements of each location type and in the most uniform grid pattern possible.
- For circulation-type spaces such as corridors and gathering spaces, establish a measurement grid on the task surface (floor) that includes representative points both directly beneath and between fixtures.
- For office and other task areas, identify a set of measurements points on desktops and other work surfaces that best represents lighting conditions in the space. It may not be possible to develop a uniform spacing grid, but points chosen should represent the various lighting conditions across the space.
- For each separate horizontal grid, identify a vertical plane representative of the lighting in the area (typically the gridline directly between two light fixtures). On this vertical plane, set a grid (line) of points at 5 feet above the site surface at each of the corresponding horizontal measurement points. See Figure A.4.

A.4.2 Measure and Record Illuminance

- Schedule and take all measurements so as to minimize the effects of other light sources and location conditions on the results.
- Schedule measurements for both baseline and post-installation when there is no daylight in the space. This typically requires taking measurements after sunset. Adjacent electric lighting need not be blocked or turned off as long as it is noted and remains the same for both the baseline and the post-installation measurements.
- Ensure that potential temporary obstructions such as occupants, temporary materials, and furniture are removed for both the baseline and the post-installation measurements.

A.5 Sample Measurement Point Layouts

The following figures provide sample layouts for selecting horizontal measurement points for typical areas where lighting measurements are taken.

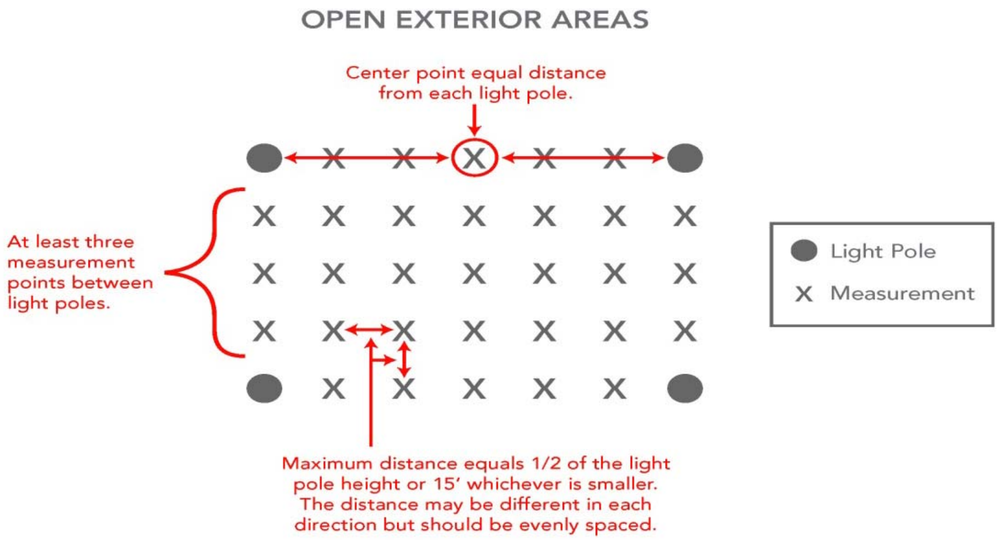

Figure A.1. Open Exterior Areas such as Parking Lots or Storage Yards

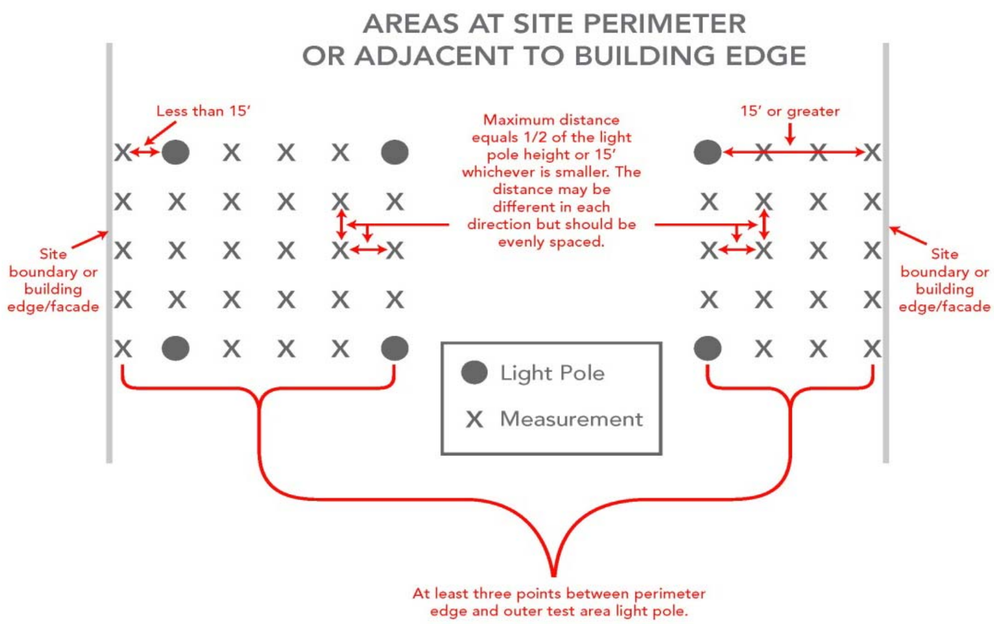

Figure A.2. Site Perimeter or Adjacent to Building Areas

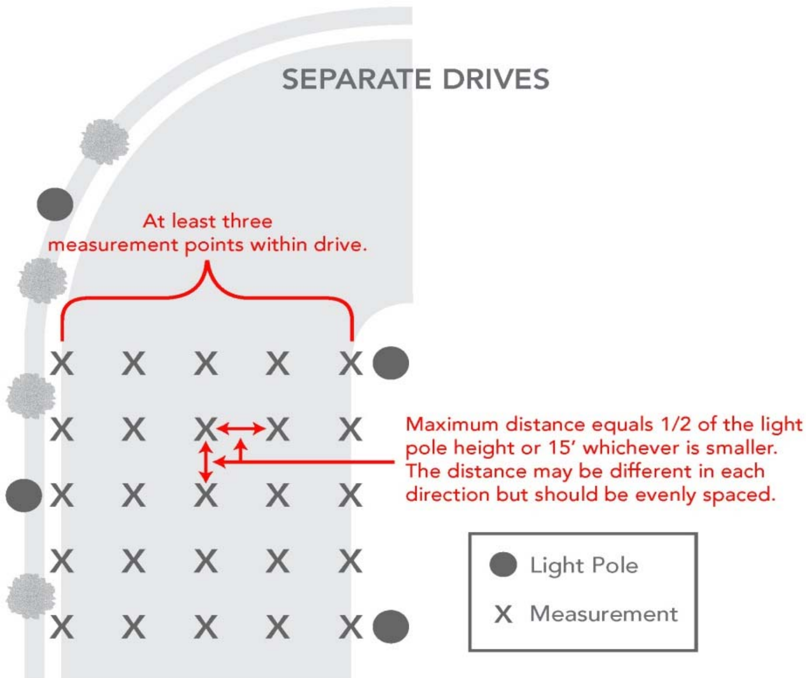

Figure A.3. Separate or Main Entry Drives

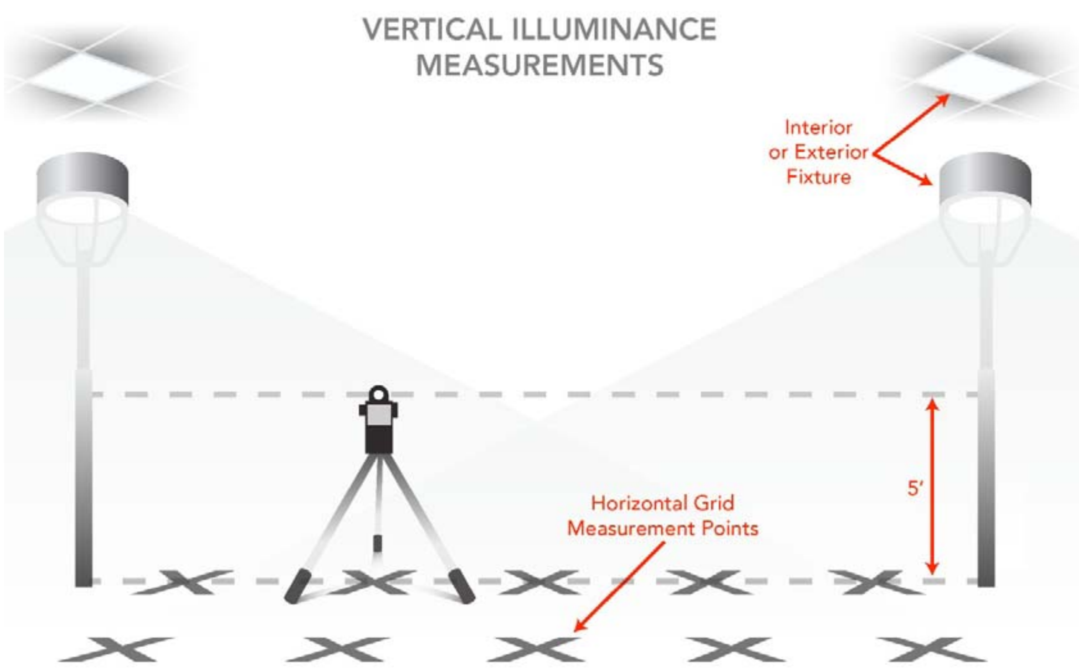

Figure A.4. Typical Vertical Measurements. Exterior application shown. Use a similar approach for interior applications with points along a horizontal gridline between fixtures and taken directly above the horizontal grid point at 5 feet above the floor.

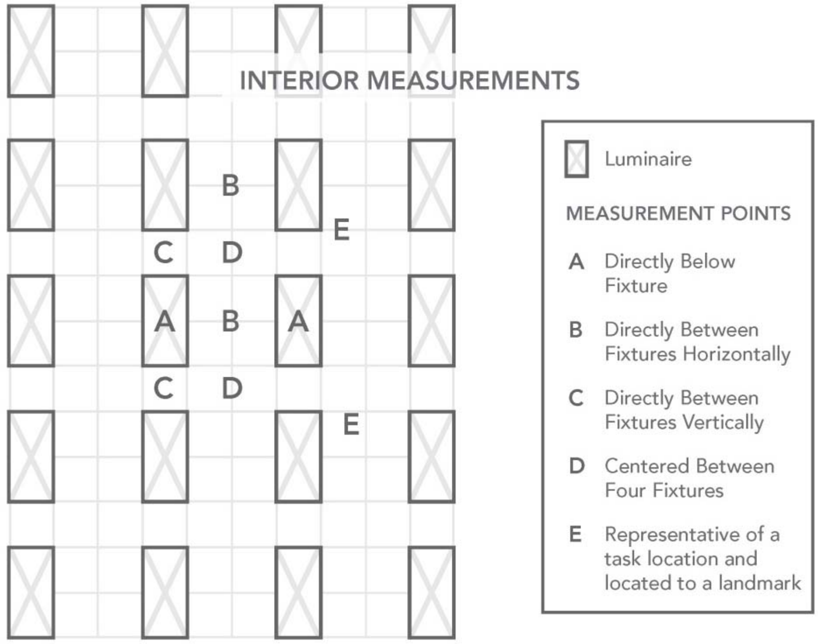

Figure A.5. Typical Interior Measurements

Appendix B

Sample Survey Instruments

Appendix B

Sample Survey Instruments

Occupant Lighting Conditions Survey

This survey is being distributed by facility staff to help understand how effective the lighting in your workspace is in meeting your needs. Results from the survey will help facility staff evaluate this type of lighting and identify any useful future changes. Participation is voluntary and no identifying information will be shared or published.

1. Please identify your type of workspace.
___Private office
___Cubicles with partitions
___Open office with no partitions
___Other – please describe ____

2. Do you sit in an area or office that has windows?
___Yes. ___No.

3. Can you see out of a window from your workspace?
___Yes. ___No.

4. Age category?
___30 or under ___31-50 ___Over 50

5. Gender?
___Male
___Female

6. What percentage (roughly) of your time is spent in your workspace doing the following?
___View materials on paper
___View materials on screens
___Typing
___Filing
___Face-to-face meetings
___Other

7. How is the BRIGHTNESS of just the overhead electric light in the MORNING?
___Too bright ___Neutral ___Too dim

8. How is the BRIGHTNESS of just the overhead electric light in the AFTERNOON ?
___Too bright ___Neutral ___Too dim

9. How satisfied are you with the electric lighting system's brightness response to changing occupancy (when occupants arrive, leave, and sit at their workstations)?
___Very satisfied
___Neutral
___Very dissatisfied
___N/A

10. How satisfied are you with the overhead electric lighting system's brightness adjustment (dimming) in response to daylight?
___Very satisfied
___Neutral
___Very dissatisfied
___ N/A

11. Overall, how satisfied are you with lighting conditions in your workspace?
___Very satisfied
___Neutral
___Very dissatisfied
___ N/A

12. Please describe any issues related to your workspace **lighting** that are important to you.
____
____

13. Please describe any other issues related to your workspace in general that are important to you.
____
____

Facilities/Building Manager Lighting System Operation Input

Your responses to these questions will help the lighting system manufacturer and others understand how well the system works and what's involved for its effective operation in a building. Participation is voluntary and no identifying information will be shared or published.

Controllability

1. How easy is it to make sure the system is operating as desired?
___Easy
___Ok
___A bit tricky
___ N/A

2. What tasks did you need to perform most often (if any) to keep the system functioning effectively?
____

3. How does this system's ease of control compare to the past system?
___Easier
___About the same
___Not as easy
___ N/A

Observability

4. How easy is it to understand how the control system was functioning by looking at the interface?
___Easy
___Ok
___A bit tricky
___ N/A

5. What steps did you take to understand how the system was functioning?
____

6. How does this system's interface usability compare to the past system?
___Better
___About the same
___Not as good
___ N/A

Reliability

7. How many system failures or malfunctions did you experience during the test? ______

Please describe them. ____

8. How does this system's reliability compare to the past system?
___Better
___About the same
___Not as good
___ N/A

Maintainability

9. How easy was it to isolate system problems?
___Easy
___Ok
___A bit tricky

10. How easy was it to restore system function after a failure?
___Easy
___Ok
___A bit tricky
___ N/A

11. How does this system's ease of maintenance compare to the past system?
___better
___About the same
___Not as good
___ N/A

12. Please describe any outside help needed to maintain the system.
____

Lighting Conditions

13. Were the lighting conditions produced by the system adequate for this building?

___Yes. ___No (please describe) _________________________________

14. How do the lighting conditions produced by this system compare to the past system?
___Better
___About the same
___Not as good
___ N/A

Occupants

15. Were the lighting conditions produced by the system adequate for building occupants?

___Yes. ___No (please describe) ____________________________________

Please describe any comments you received from occupants about the lighting system.
____

Contractors'/Installers' Input

Your responses to these questions will be used to help facilities staff and other's understand any installation issues or preferences for this lighting system. Participation is voluntary and no identifying information will be shared or published. Answering the questions should take less than 5 minutes of your time.

Background

1. Which lighting system did you install? ______________________________________

2. At which location did you install the product? _______________________________

3. On what date did the install start? ____

4. On what date did the install end? ____

5. On what date was the system activated for use by occupants? ________________

Installation Instructions

6. Were the installation instructions easy to understand?
___Easy
___Ok
___A bit tricky
___ N/A

7. Did the installation instructions address all installation steps?
___Yes
___No
___Almost (Please Describe) ____
___ N/A

8. Were the installation instruction needed to complete the install?
___Yes ___No

Installation

9. Were there any safety issues related to installing this particular system?
___No
___Yes (Please Describe) ____
___ N/A

10. Were there any complications related to installing this particular system?
___No
___Yes (Please Describe) ____
___ N/A

11. Was the system as easy to install as a standard fluorescent system with basic controls?
___Yes
___No (Please Describe) ____
___Almost (Please Describe) ____
___ N/A

Maintainability

12. Is there anything about the system that you believe may create future maintenance issues?
___No
___Yes (Please Describe) ____
___ N/A

13. Does the system seem to be as easy to maintain as a standard fluorescent system with basic controls?
___Yes
___No (Please Describe) ____
___Almost (Please Describe) ____
___ N/A

Other

14. Please describe any other issues related to the installation of the system that are important to you.
____
____

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