LIGHTING RESEARCH PROGRAM

Project 3.3 Classroom Photocell and Control System

FINAL REPORT

CONSULTANT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for Project 3.3 Classroom Photocell and Control System under the Lighting Research Program, Contract #500-01-041. This project contributes to the PIER Lighting Research Program.

The key deliverables for each project, in the form of guidelines and technical reports, are attachments to this report and are listed and described at the start of the attachment section. Due to market dynamics and the normal passage of time between the completion of research and the publication of research results, products anticipated for market delivery in this report may not necessarily reflect the actual array of products as delivered, or planned for delivery, by manufacturers. Therefore, the reader is advised to contact the lighting product manufacturers directly to ascertain the current status of products.

For more information on the PIER Program, please visit the Commission's web site at www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at (916) 654-5200.

Abstract

This project demonstrated a prototype of an advanced daylighting control system for classrooms. This system integrated dimming control with On/Off switching and teacher control. The design of the system was based upon research into existing daylighting controls, research into common classroom designs, computer daylighting simulations, laboratory testing and field testing. One of the primary points of emphasis in the system design was to greatly simplify the setup and calibration of the lighting control system

The system demonstrated in this project provides significant enhancements over commercially available daylighting control products. The project team believes that it is a commercially viable product that with further development work could be commercialized.

The energy and non-energy benefits have been evaluated and this system would benefit the State of California and school owners.

Executive Summary

Introduction

This project demonstrated a prototype of an advanced daylighting control system for classrooms. This system integrated dimming control with On/Off switching and teacher control. The design of the system was based upon research into existing daylighting controls, research into common classroom designs, computer daylighting simulations, laboratory testing and field testing. One of the primary points of emphasis in the system design was to greatly simplify the setup and calibration of the lighting control system.

Project Objectives

The specific technical objectives for this project were as follows:

- Review the state-of-the-art photosensor technologies, including the LRC's photosensor system, if possible, and characterize the performance of models from The Watt Stopper.
- Identify the necessary photosensor performance characteristics for spatial and spectral sensitivity, electronic control algorithm, commissioning, and compatibility with other control devices (manual switches, occupancy sensors, dimming ballasts) using computer simulations and knowledge from leading researchers.
- Build pre-production product prototypes.
- Evaluate the prototypes in laboratory and field installations.
- Share the project results with the public-at-large.
- Apply knowledge gained to the development of a new family of daylighting controls.

Project Outcomes

The project substantively met all the project objectives as given above. The following are the primary outcomes of this project:

1. The project team identified the key photosensor performance parameters for typical classroom applications.
2. The project team developed a performance specification for the proposed photosensor and desktop device.
3. The project team gained valuable input from the lighting community regarding the proposed photosensor control system performance specification.
4. The project team constructed and tested a new control system that demonstrated the concept of an advanced daylighting control system.

Conclusions

The system demonstrated in this project provides significant enhancements over commercially available daylighting control products. The project team believes that it is a commercially viable product that with further development work could be commercialized.

The energy and non-energy benefits have been evaluated and this system would benefit the State of California and school owners.

Recommendations

As this system represents a fundamentally new concept, the project team believes this system would benefit from installation in one or more demonstration projects to demonstrate the system performance, energy savings, and customer satisfaction.

Benefits to California

The California Energy Commission estimates that the energy use for lighting in schools consumes a total of 1,200 giga-Watt hours of electricity in California per year. It is believed that approximately 70% of this usage is for classrooms. It is further assumed that 50% of the classrooms are adequately daylit to allow a lighting reduction during daylit hours. It is further assumed that in the controlled classrooms that this control system will on average save 35% of the energy used for lighting. (The energy savings for schools designed to optimize the use of daylight will be considerably higher.) These assumptions produce total estimated annual savings in California schools of 147 giga-Watt hours. This represents annual savings of more than 11 million dollars.

Introduction

Background and Overview

It has long been recognized that fluorescent lighting could be dimmed or shutoff in classrooms when daylight provides adequate illumination. The energy savings are typically significant. However, this strategy has failed to gain widespread adoption because of the challenges in achieving the desired results.

The goal of this project was to develop and demonstrate a daylighting control system that solved many of the problems inherent in commercially available lighting controls. The project was targeted to work in classrooms. Classrooms are a great market for daylighting controls because the positive effects of daylight in enhancing the teaching environment has been demonstrated. Additionally, classrooms provide a collection of common configurations that included a variety of daylighting configurations (side-lighting only, top-lighting only, side- and top-lighting) and electric lighting configurations (recessed and pendant lighting)

The project team brought together 3 entities that have focused on daylighting controls. The Watt Stopper is a lighting controls manufacturer. Penn State University and Lawrence Berkeley National Laboratory both have ongoing research efforts in daylighting control.

The Watt Stopper has been manufacturing and selling daylighting controls for more than 25 years. In the early 1990s, TWS developed and began selling its first dimming photosensor soon after dimming fluorescent ballasts became available. Since that time, TWS has manufactured and sold 4 generations of photosensors. These products have incorporated more sophisticated control algorithms, improved filtering, and measurement of illumination and microcontroller technology.

Richard Mistrick has headed an ongoing research effort at Penn State to model photosensor-based lighting control systems in lighting analysis software. This research involves modeling all aspects of the lighting control system in detail, including the following:

- The photosensor’s spatial response to incident light.
- The difference in spectral response between electric light and daylight.
- The control algorithm and variable calibration settings built into the photosensor system by the manufacturer.
- The ballast response to a control signal provided by the photosensor system.

The computer model addresses the light distribution in a room created by daylight, in addition to both the controlled and uncontrolled portions of the electric lighting system. The software determines the impact of these three sources on both the photosensor signal

and work plane illuminance, and computes the equilibrium point for a photosensor system at a particular calibration condition.

Previous work has shown that photosensor field of view affects a sensors ability to closely track and appropriately respond to the daylight in a space. The less light that a sensor receives directly from a daylight source, such as a window, the better the system will likely perform in tracking the daylight levels within the space. This research also showed that a closed-loop proportional control algorithm generally provided good overall system control, and determined the best conditions for system calibration to avoid undershooting the target illuminance level.

LBNL has had extensive experience with researching the performance of photosensors, and were the pioneers for revealing the importance of control algorithms for optimizing photosensor performance. Beginning in 1984, LBNL has studied the suitability of existing photocell control systems to achieving good daylighting control. Research showed that the photocell systems at that time used a simple control algorithm that did not work well for typical daylighting applications. The paper (see Reference Section) showed that the conventional control algorithm (constant setpoint) caused total light levels to undershoot the desired level under most typical applications. The paper went on to present the mathematical basis for a new control algorithm (closed-loop proportional control) that could be easily incorporated into a photocell to greatly improve the performance and reliability of the daylighting system.

Project Objectives

The specific technical objectives for this project were as follows:

- Review the state-of-the-art photosensor technologies, including the LRC's photosensor system, if possible, and characterize the performance of models from The Watt Stopper.
- Identify the necessary photosensor performance characteristics for spatial and spectral sensitivity, electronic control algorithm, commissioning, and compatibility with other control devices (manual switches, occupancy sensors, dimming ballasts) using computer simulations and knowledge from leading researchers.
- Build pre-production product prototypes.
- Evaluate the prototypes in laboratory and field installations.
- Share the project results with the public-at-large.
- Apply knowledge gained to the development of a new family of daylighting controls.

Project Tasks

Key tasks for this project were as follows:

1. Review the State-of-the-Art Photosensor Technologies, Including the LRC's Photosensor System, and Characterize Performance of Current Version of TWS Photosensor

2. Confirm Common Classroom Electric Lighting and Daylighting Configurations for California
3. Create 3-D Computer Models of the Common Configurations to use in the Computer Simulations
4. Conduct Parametric Computer Simulations
5. Write Performance Specifications
6. Conduct Roundtable Meeting to Obtain Feedback on Specifications
7. Build New Alpha Prototypes or Modify The Watt Stopper Existing Designs
8. Evaluate Alpha Prototype Performance in Laboratory Setting
9. Refine Prototype Design
10. Test Beta Prototypes in Small-Scale Field Test

Changes and Modifications

The following are the primary changes and modifications made to the work plan during the course of the project:

Task 8 was restructured to focus on lab testing of the spatial response of the photocell. In addition to the spatial testing, this task initially included spectral testing and control response testing. Using previously received spectral response data expedited the project work. The control response testing was not conducted because the prototype was not ready for performance testing at that time.

Task 10 was originally described as being a field test in an actual school. This test was modified because the project team could not find a school in the Bay or Sacramento area that had 0-10 VDC dimming ballasts installed in its classrooms. The project team contacted numerous daylighting experts, all of the ballast manufacturers known to manufacture this type of ballast, lighting fixture manufacturers, a representative from the Collaborative for High Performance Schools, and the Commission in an effort to locate a school. The project team was unable to find a suitable school. Instead, the project team conducted the test in Southern California at a relocatable classroom owned by Southern California Edison.

This facility proved to be excellent for testing but it changed the test in several ways. First, it restricted TWS and LBNL's easy access to the test facility because each site visit required a plane flight. Second, the test period was shortened in part due to the additional scheduling requirements of the remote facility as well as the prototypes' readiness for testing. Second, there were no actual teachers using this facility so the project team was unable to collect teacher's opinions as to their preferences. The project team, ultimately, performed a short test that is described in Task 10.

The above changes supported the successful, positive outcome of the project.

Project Outcomes

The project substantively met all the project objectives as given above. The following are the primary outcomes of this project:

1. The project team identified the key photosensor performance parameters for typical classroom applications.
2. The project team developed a performance specification for the proposed photosensor and desktop device.
3. The project team gained valuable input from the lighting community regarding the proposed photosensor control system performance specification.
4. The project team constructed and tested a new control system that demonstrated the concept of an advanced daylighting control system.

The outcomes and results by task are discussed in detail in the following section. Project reports referenced are available for review at the following web site: www.archenergy.com/lrp/demandresp_lighting/project_3_3_reports.htm.

Project Results by Task

Task 1. Review Photosensor Technologies and Characterize Performance of Current Version

The work on Task 1 resulted in the creation of two reports. The first report reviewed the State of the Art in Photosensor Technologies. The second report described the results of the laboratory testing of the current version of the TWS photosensor.

Report on the State of the Art Photosensor Technologies

The project team surveyed the currently available daylighting controls and collated information from five sources. The first was a survey of available products being sold in the U.S. and in Europe today. The survey of products was based on a search of marketing materials available on the Internet and the limited personal experience of team members with some of the products. Second, the project team reviewed published research studies because these studies provide the only actual performance evaluations. The third source of information was the product development work conducted by Andrew Bierman at the Lighting Research Center along with Sensor Switch. Their work has resulted in a prototype product that incorporates many of the findings of Mr. Bierman's previous research in this field. Mr. Bierman has shared a sample of their design and a report, which includes his team's test results. The fourth source of information was the team's knowledge of emerging technologies that may impact the future of these systems.

In surveying the available products, the project team found more than 15 companies actively marketing the capability of providing daylight responsive dimming in the United States. However, the project team found little information regarding the performance and the applicability of the products. The project team found only limited detailed technical performance data for any of these products. The primary information provided was the photocell's cone of view. An example of such technical data is found in a study of photosensors by Bierman et al (see Reference Section) that identified the three major technical components of these devices as 1) the spatial sensitivity of the photocell, 2) the spectral sensitivity of the photocell and 3) the type of control algorithm used to calculate a signal to the controlled lamps. This lack of technical information is in contrast to what is typical of other control products such as occupancy sensors where coverage patterns are routinely provided so that competing products can be compared. The project team also found few case studies available from the manufacturers.

Several research studies (Rubinstein et al., 1989, Rubinstein, 1984) showed that the variability of daylight throughout the day and year resulted in situations where the existing generation of controls were not maintaining adequate lighting levels or were otherwise behaving unexpectedly (See Reference Section). The project team found research studies, as well as anecdotal evidence, that suggest that systems had been disconnected or disabled because of poor product performance or inappropriate application of the product. From this information, it is easy to formulate the opinion that

no one existing product provides the perfect solution. The perfect solution would be to provide the following on a consistent basis at a cost-effective price under a variety of different applications:

1. Provide adequate work plane illuminance and avoid over dimming.
2. Avoid drawing the occupant's attention to the dimming action by dimming too fast or making noticeable changes in the light level.
3. Provide only as little electric light as required.
4. Require minimal effort in commissioning the system.

The project team found daylight dimming systems to be constructed of four essential elements:

a. A photocell to sense the light level.
b. A control circuit or engine that changes an output based on the photocell input.
c. A control output that drives the ballasts.
d. Calibration adjustments, usually implemented as dials, that are used to establish the actual relationship between input and output signals.

The project team found that daylight dimming systems are available in three different configurations. Of these configurations, the one explored in the work of this project was the self-contained unit.

The self-contained units contain all four elements in one unit, usually ceiling-mounted. Generally, these units are dedicated to providing daylight dimming and do not attempt to provide other lighting control functions that the more complex units often include. All of the units in this category appear to use analog electronics with no microprocessor-based products available. Typically, these units are powered by the 10 VDC signal supplied by the ballast. Within this type of unit, there is a standardization of features, generally providing control for only one zone. These products are commissioned by adjusting one or more dials, jumpers or dipswitches. It is estimated that at least eight major manufacturers are currently selling a product of this type.

The project team created an outline of the product design that evolved into the product specification. This information is presented in detail under Task 5.

Photosensor Characterization Report

The results of laboratory measurements performed on The Watt Stopper's LS-201 photosensor at the Lawrence Berkeley National Laboratory in January 2003 were presented. The purpose of these measurements was to characterize two key parameters, the spatial response and spectral response functions, of the LS-201 photosensor. The purpose of this work was to offer suggestions for improvement in the prototype product to be developed under this project.

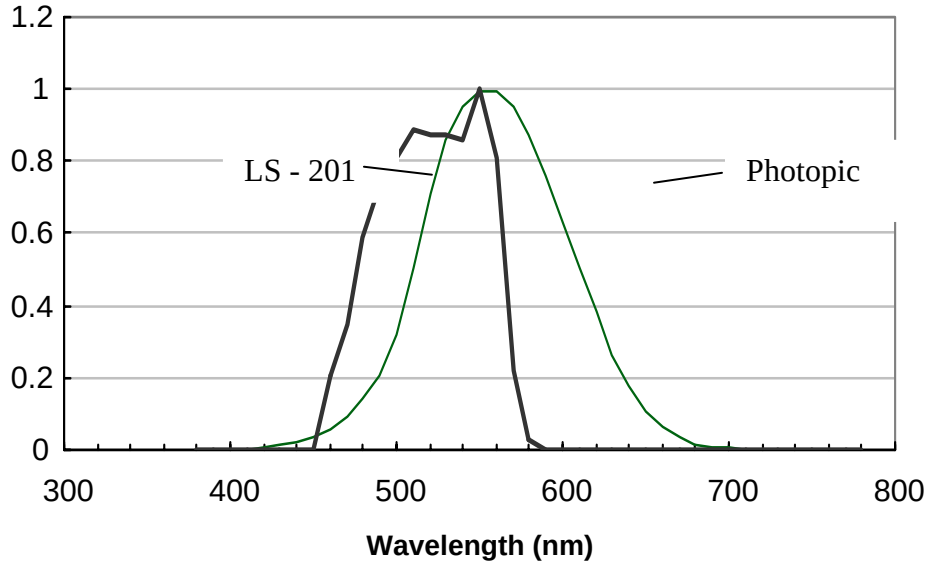
The spectral response function of the LS-201 photosensor was found likely to be acceptable in many daylighting applications, including classrooms. Although its response curve was slightly narrower than the photopic curve, and the "peak" shifted slightly to the blue, it is better color-corrected than many of the photosensors currently on the market. One particularly favorable attribute is its insensitivity to infrared radiation. Most photosensors available today for lighting control applications are based on silicon photodiodes that, if uncorrected, are more sensitive to the infrared portion of the electromagnetic spectrum than to visible light. Previous work has shown that photosensor sensitivity to IR can cause significant errors in control systems.

Because of the different physical principle underlying the operation of the LS-201, the sensor is entirely blind to IR. Essentially, photons with wavelengths greater than about 560 nm (for this LED) have insufficient energy to excite any charge carriers within the LED. Conversely, photons with shorter wavelengths than the peak response of the LED can excite charge carriers within the LED and this action tends to shift the "peak" of the spectral response function about 40 nm towards the blue. As a result, the sensor serves (fortuitously) as a decent *scotopic* meter. Since a daylight control system built around the LS-201 would be more sensitive to the scotopic function than the photopic, the energy savings benefits of the scotopic research could be directly realized with an automatic control system assembled from hardware available today.

The spatial response function of the LS-201 as it currently stands is probably adequate for many applications. However, its narrow field of view (FOV), effectively a cone of 15 degree half-angle, may be overly sensitive to changes in the luminances in the FOV resulting in unexpected behavior of the lighting system under extreme conditions. Since the FOV for the sensor with the lens removed is significantly wider (a cone of 35 degree half-angle), it is the action of the lens itself that is causing the narrowing of the FOV. It is suggested to replace the Fresnel lens with a slightly diffuse flat lens. This would judiciously broaden the FOV without compromising external appearance. A photosensor with a FOV of 35 degrees would not be sensitive to direct window light (which previous work indicates should be avoided) unless it were mounted very close to the window wall.

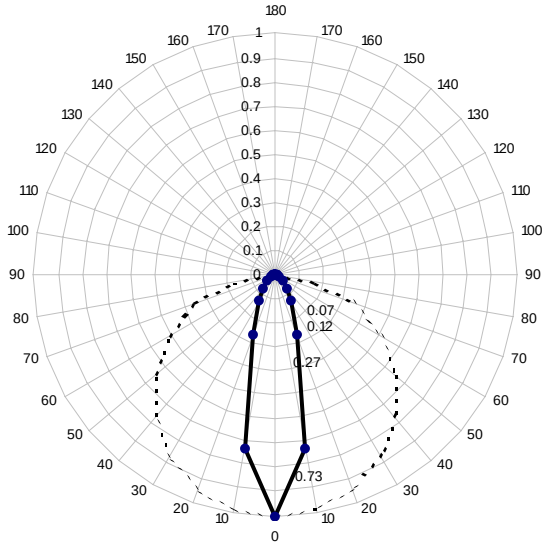
Overall, the LS-201 photosensor is the first commercially available control photosensor that LBNL has seen that basically "gets it right." It implements the most appropriate control algorithm for daylighting ("sliding setpoint") as well as provides critical adjustments of gain, offset, and minimum trim. One cautionary note is that the simulations have not been run to ascertain that the correct range of commissioning adjustments have been realized in this product for daylit classroom applications. Furthermore, although all the correct commissioning adjustments are physically present, the sensor is a daunting array of trim pots and jumpers that can only be adjusted in the field by a person on a ladder. As it stands, the product could probably not pass the five-minute commissioning test. However, it has been used successfully in recent building projects. *As long as sufficient time is allowed in the building contract for commissioning by a qualified commissioning agent*, the LS-201 may be an appropriate solution for many commercial daylighting applications.

Results of the spectral response and spatial response are shown below.



Spectral Response of Photocell Compared to Photopic Curve
Relative Response (normalized at 555 nm)

Figure 1 Spectral Response of Photocell



Polar Plot of Spatial Responsivity Function of the LS – 201 Sensor #1
(Cosine corrected curve shown for comparison)

Figure 2 Spatial Response

Task 2. Confirm Common Classroom Configurations for California

The goal of this task was to develop an understanding of the common electric and daylighting configurations for new classrooms in California. Meeting this goal helps to achieve the project objectives by assuring that the Classroom Photosensor is designed to work for the majority of classroom electric and daylighting designs.

Telephone interviews with designers and decision makers were the primary method used for gathering information on common classroom design strategies. Interviews were conducted in an open-ended conversational manner, with the interviewer using the questionnaire to guide the discussion and obtain information about the key architectural and lighting design elements. The top school designers and consultants in California were targeted for the interviews. Telephone interviews were conducted with the architects, consulting engineers, school districts, and electric utility personnel. A total of 24 professionals were interviewed in January of 2003.

The report summarized information collected on the typical configurations of classrooms being built in new K-12 schools in California. It concentrates on the design decisions, which influence the use of daylighting in a classroom including classroom size and ceiling height, window configuration, glazing type, window treatments, skylights and reflectance conditions. Also collected was information on common electric lighting configurations. This work was done in preparation for creating 3-D models and running computer simulations of five common classroom configurations.

The common classroom footprint is between 900 and 1000 ft^2, with 30’ X 30’ and 32’ X 30’ aspect ratios being the most popular. Ceiling configuration is driven by the desired daylighting design strategy, with preferences for daylight penetration from high angles, using vertical glazing strategies. Preference is given to bringing natural light in from two parallel directions rather than one. Light shelves are an exception rather than the rule for most new school designs. This is driven by budgetary and maintenance considerations. Clerestories and shed roofs with bi-directional daylighting distributions are relatively common in some of the high performance school designs. Skylights are also applied in a number of school districts in single story schools, but are frequently not selected because of leakage concerns. Although the low-E glazing types are highly desirable and frequently applied, uncoated and clear glazings are also applied in some designs.

A relatively small number of school designs appear to qualify as high performance schools with regard to daylight utilization. The presence of the CHPS (Collaborative for High Performance Schools) Program may help to increase the relative number of these schools in the future, but at the present time the numbers appear somewhat limited. The use of photosensor controls appears to be quite limited at this time. In many of the schools in which daylight is being addressed, photosensor controls are often value-engineered out of the design near the end of the project.

Tasks 3 & 4. 3-D Computer Models and Parametric Computer Simulations

The goal of these tasks were first to develop 3-D models of the configurations selected for study in Task 2 and then conduct parametric computer analyses of the selected electric and daylight configurations. The research was conducted by Dr. Richard Mistrick and his team at Penn State University. Meeting this goal helped to achieve the project objectives by providing the spatial sensitivity performance criteria for the photosensor.

The aim in selecting these classrooms was to obtain a group of realistic daylight delivery systems that apply a variety of daylight delivery methods, daylight aperture conditions, and luminance distributions in a classroom space. These classrooms provide the following range of conditions:

- Classroom 1: Toplighting.
- Classroom 2: Sidelighting with a long skylight well wall-wash system.
- Classroom 3: Light shelf (interior and exterior).
- Classroom 4: Sidelighting with a sloped ceiling and a north-facing clerestory on the wall opposite the window.
- Classroom 5: Sidelighting (i.e., a window).
- Classroom 6: Sidelighting on both north and south-exposure with skylights for lighting the interior of this modular classroom.

This study has involved an analysis of the following impacts on photosensor performance:

1. Photosensor spatial sensitivity
2. Photosensor location
3. Impact of direct versus indirect lighting
4. Impact of changes in reflectance on the work plane.
5. Location of the critical point, which is the point used for the calibration of system performance.
6. Dimmed lighting zone configuration (number of rows of luminaires applied to dimmed zone).

The study addressed a number of important issues related to photosensor system performance. Performance parameters such as photosensor spatial distribution and location within a space were studied by comparing the relative agreement between the photosensor's signal and the work plane illuminance at a critical point within the space. As in previous studies, the photosensor's view of the window was an important parameter. Photosensors that are influenced less by direct light coming from the window due to a narrower spatial sensitivity or due to a mounting position farther from the window or daylight aperture generally show better agreement with the daylight illuminance at the targeted point.

In addition, the impact of changes in localized work plane reflectance on photosensor performance was studied. Sensors with a wider view of the space are impacted less by these changes, which would be expected. A compromise between a wide signal to minimize work plane reflectance variations and a limited width to minimize the impacts from indirect lighting is a spatial distribution with a 55-degree half angle. This sensor still provides some latitude with regard to placement between two rows of indirect luminaires.

This analysis only considered one dimmed lighting zone, but estimated the energy consumed over a typical year if one, two, and three rows respectively were assigned to this dimmed zone. Energy consumption in the unilateral case was in the range of 60% of that provided by no dimming whereas it was approximately 35-55% under the bilateral conditions when the entire room was dimmed. The lightshelf condition that was studied provided much lower daylight illumiance levels and energy savings than the other lighting system that were considered.

The analyses that were performed for this study focused primarily on the ability of the photosensor to accurately track the level of daylight in a space. Lighting quality issues on special task areas such as chalkboards were not addressed, but these must be considered in the layout of a lighting design in a classroom space.

A number of different photosensors configurations were tested. The Watt Stopper's (TWS) Model LS201 sensor, which was measured by LBNL, was studied along with a number of different prototype distributions. As seen in the curves presented in the figure for the sensors studied, the TWS LS201 sensor has a relatively narrow spatial distribution. The prototype sensors that were tested included a pure cosine sensor, which is a standard illuminance meter, and used to represent a sensor with a very wide field of view. For other fields of view, a series of cosine sensors with cutoff half angles of 45, 55 and 65 degrees were considered. All sensors were axially symmetric to avoid problems with incorrect mounting that might occur with non-axially symmetric sensors. These sensors were considered to study the effects of wider and different fields of view on photosensor performance. Since a restricted view of the window and indirect lighting equipment is desirable, some form of cutoff distribution is generally necessary. This combination provided a range of photosensors to study, including very narrow (TWS), very wide (cosine) and a number of distributions between these extremes (the 45, 55 and 65-degree half angle sensors). A cosine response was considered for the cutoff sensors to model a photosensor that is wide and has an ideal cutoff condition.

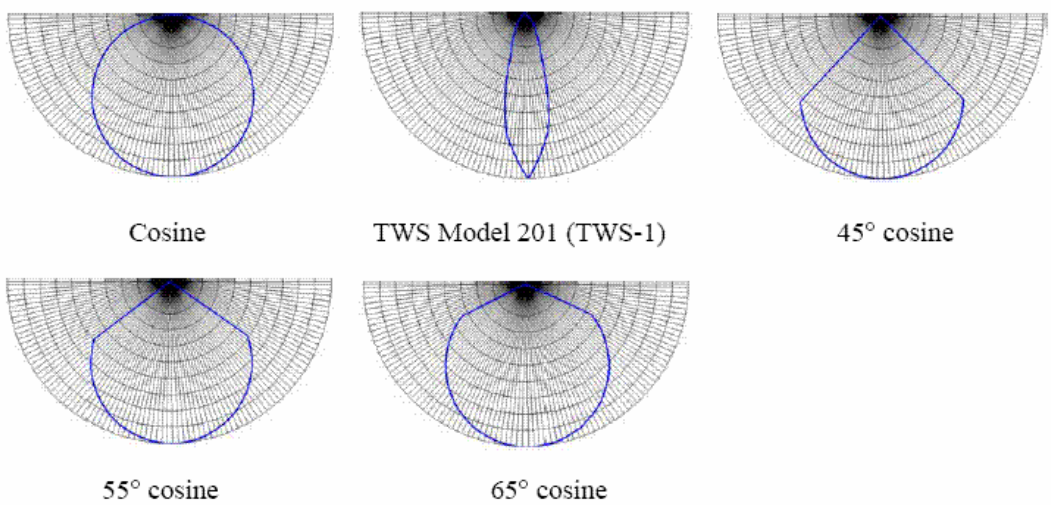


Figure 12. Photosensor spatial sensitivity distributions considered in this project. The degree range shown on three of the cosine photosensors is the half-angle to the cutoff point (beyond which the photosensor sensitivity is assumed to be zero).

Figure 3 Spatial Responses Tested

The following conclusions have been derived from the data gathered in this study:

1. Photosensors that receive a significant amount of light from the windows do not have as high a correlation between the photosensor signal and the work plane illuminance as does a photosensor whose signal from a daylight aperture is small. This holds for narrow sensors and for wide sensors that are located away from a window.
2. A photosensor location that reduced the photosensor's view of the window is desirable. However, placing the photosensor too deep into a room will result in a low daylight signal and therefore a steep daylight signal to work plane illuminance correlation line, which would make the system more difficult to calibrate. The daylight signal may also drop below the electric light signal, which could create control problems.
3. Points that permit direct sunlight to enter a space appear to deviate from most of the other points on a work plane illuminance to photosensor signal graph in most situations. For these conditions, the higher photosensor signal would generally result in the system providing a dimming setting that is too low.
4. The dimmed electric lighting system can produce a signal with a lower slope than the slope for the daylight correlation line when a photosensor receives too much light from an indirect lighting system.
5. A cutoff angle of 55 degree appears to work reasonably well at minimizing the signal received from an indirect lighting system, but should not be mounted within 3 feet of a luminaire than is suspended 2 feet from the ceiling.

6. A wider photosensor spatial distribution is impacted less by changes in room surfaces reflectances. In addition, mounting the sensor away from any surfaces, such as a desktop, can help to reduce the impact of desktop reflectance.
7. The critical point for a classroom that consists of three rows of luminaires (direct or indirect), and where the outside two rows of luminaires make up the dimmed zone controlled by the photosensor, is generally located within one to two feet of the center row of luminaires, and for simplicity, can be located directly beneath that second luminaire row. Also, locating this point closer to the side wall than the center of room, on the side of the room that receives less daylight for the daylight condition provided at the time of calibration should be the most appropriate location.
8. A dimmed lighting zone can generally consist of the first two rows of luminaires from the window in an unobstructed classroom space when the daylight condition involves only sidelighting. Energy savings for the space are likely to be in the range of 30-45% with a sidelighting condition that provides generous levels of daylight, even with the application of horizontal blinds.
9. Dimming of a single row of luminaires (along a window wall) will allow that row of luminaires to be placed at the minimum light output setting a large fraction of the year in a space with ample daylight.
10. In spaces with toplighting or bilateral daylighting, it may be possible to dim all of the luminaires in the space. Whether or not this is possible depends on the uniformity of the daylight under a range of sky conditions.

To summarize the above results, a wide sensor, such as a cosine sensor is likely to provide less than optimum results due to its tendency to respond to light from both windows and indirect luminaires. A wide sensor with sharp cutoff, such as one with about a 55-degree half angle, appears to perform quite well, with respect to limiting the direct response from windows and from an indirect lighting system, while also receiving flux from a broad area to minimize the effects due to changes in reflectance across the work plane.

It is important to note that certain characteristics that can be added to the photosensor system's control algorithm can reduce some of the negative impacts that are experienced in ceiling-mounted photosensor systems. For example, the system may subtract out the system that results from the dimmed portion of the electric lighting system based on the dimming system signal that it is providing. This estimate of the signal can also potentially be updated to account for changes in reflectance and light loss factors that occur over time.

Task 5. Performance Specifications

The goal of this task was to develop a draft performance specification for the Classroom Photosensor Control System incorporating things learned in this project.

This specification attempts to solve two primary areas of concern with daylighting control systems. The first priority is to provide accurate control of the electric lights in

response to changes in the available daylight. The goal is to maintain the target setpoint while avoiding over dimming or under dimming and any attention causing action. The second priority is to make the setup and adjustment of the control system fast and repeatable. The specification addresses other requirements of a daylight responsive control system including providing a means for occupant adjustment as well as working with common lighting configurations.

The daylighting responsive control system concept presented consists of 4 control devices. It uses low voltage wiring to simplify the installation of these devices and wireless communication to simplify the setup and calibration of the control system. The first component is a power pack. The power pack provides two key functions. The first function is to provide a source of low voltage power to provide power to the photosensor. The second function is to provide a means of switching the line voltage power supplying the controlled electric lights in the classroom. The power pack is typically mounted above the ceiling and contains both a power supply and a relay. The second component is a photosensor. The photosensor is designed to be ceiling mounted. The photosensor reads the light level in the classroom and commands the lights to provide the appropriate light output. The third component is a desktop tool that is used at startup to automate the setup and adjustment of the device. The fourth component is an occupant adjustment control. In this specification, this device would be a wall switch that would allow the occupants to turn the lights on and off or to raise or lower the target light level. In addition, it is assumed that in many applications, particularly classrooms, this daylighting responsive control system will be used in combination with one or more occupancy sensors.

Power Pack

The power pack is the single point of connection to the line voltage wiring. All of the control devices interface to the line voltage wiring at this point. All of the control wires emanating from the power pack shall be low voltage.

The intent is to use an existing commercially available power pack manufactured by The Watt Stopper, the BZ-100E-P and to leverage the resources available for this project by adapting an existing product.

The selected power pack can be connected to either 120 or 277 VAC. It does not need to be specified for a specific voltage thus requiring one less specifying and purchasing decision.

This power pack also provides additional signal inputs not typically found in a power pack that simplify the wiring connections in this application. A typical power pack has only one control input, typically connected to an occupancy sensor. The occupancy sensor signals the power pack on this input to turn lights on and off. The selected power pack has two additional signal inputs that have a higher priority than the occupancy sensor input. One of the inputs is Force On. When this input is signaled, the power pack switches the lights on even if the occupancy sensor indicates the room is not occupied. The other signal input is a Force Off. When this input is signaled, the lights are switched

off even if the occupancy sensor indicates that the room is occupied. The control function in this application of these two high priority inputs will be described in the operation section of this document.

Photosensor

The photosensor shall be designed for mounting either on the ceiling or integrated into a pendant lighting fixture. The photosensor shall use a microcontroller to provide the operating intelligence for the control system. The photosensor is designed to provide control for one zone of closed loop control daylight responsive dimming control.

All setup and adjustment required following installation shall be done remotely from the photosensor. All adjustment parameters shall be stored in non-volatile memory such that these parameters shall not be lost if power is removed from the photosensor.

The photosensor shall be powered by the low voltage power supplied by the power pack.

A photodiode shall be used to provide a light level measurement that can be correlated to the desktop illuminance. The photodiode shall be optically filtered to measure light to closely match the human photopic response. This corrected response shall solve the problem of over reporting the illuminance provided by daylight.

The photodiode shall be housed in an enclosure that reduces the photodiodes light receptivity to a 110 degree cone of view (55 degree half angle). While freely admitting light within this cone, it shall block nearly all of the light from angles beyond this cone of view. This sharp cutoff of the light shall be useful in blocking light received from windows and pendant fixtures. This sharp cutoff shall provide flexibility in installing in proximity to windows or pendant fixtures. The cone of view is wide to reduce the response to changes in reflectivity caused when objects or individuals enter the viewed area. By viewing a larger area, the impact of an individual object shall be reduced. Also, this larger cone of view shall be beneficial for applications where the photosensor's distance from the task surface is reduced. For example, when the photosensor is integrated into a pendant fixture, its mounting height is reduced and its distance from the task surface is reduced thus reducing the solid surface viewed by the photosensor.

The full scale of the light level measurements shall be scaled as found appropriate for the application. The range is initially defined as a light level reading corresponding to a ceiling illuminance range of .1 to 400 footcandles. Within this range, the resolution of the light measurements shall be greatest at the lower light levels and decrease as the light level increases. The range of light level measurements is extended well beyond the normally anticipated control range to facilitate setup and adjustment over a range of daylit conditions. Also for the same reason, the resolution over this range is also far greater due to the precision required for two reasons. The first is for calibration when changes in illumination from electric light may have to be measured at a time when a great deal of daylight is present. The other reason is for the photosensor to work with indirect lighting utilizing pendant fixtures. These fixtures direct their light primarily up to

the ceiling to reflect and distribute light to the illuminated area. The result for the photosensor is that the ceiling illumination is greatly increased. With this elevated range, it is still critical to be able to resolve changes in task illuminance from daylight even though the magnitude of the signal change may be small in relation to the overall light level signal.

Occupant Adjustment – On/Raise

This input shall be connected to a wall switch used for occupant control and adjustment. The wall switch shall be connected to the photosensor by 3 low voltage wires, one for the On/Raise, one for the Off/Lower and a common wire.

A contact closure of ½ second or less shall be interpreted as a request to turn on the lights. After ½ second of closure, the signal shall be read as a desired amount of light increase. The lights shall continue to rise for the duration of the contact closure.

Occupant Adjustment – Off/Lower

This input shall be connected to a wall switch used for occupant control and adjustment. A contact closure of ½ second or less shall be interpreted as a request to turn off the lights. After ½ second of closure, the signal shall be read as a desired amount of light decrease. The lights shall continue to dim for the duration of the contact closure.

Dimming Control Signal

The dimming control signal shall operate by providing a variable resistance to modulate the control voltage sourced by the ballasts. The range for the control signal shall be from 0 – 10 VDC with a maximum supply of 16 VDC.

The maximum range of current shall be from .2 to 20 mA. This range of current corresponds to the requirements anticipated from controlling 1 standard dimming ballast up to a maximum of 30 ballasts equivalent to an Advance Transformer Mark VII.

The voltage level of the control signal shall able to be stepped by increments of .1 VDC or less, providing a minimum of 100 steps of control over the ballast range.

Force On Signal

The photosensor shall have a control relay rated to switch a 24VDC signal. This control relay shall be used to signal the power pack to switch the controlled lights on. This signal shall be transmitted over low voltage wires to the power pack.

Force Off Signal

The photosensor shall have a control relay rated to switch a 24VDC signal. This control relay shall be used to signal the power pack to switch the controlled lights off. This signal shall be transmitted over low voltage wires to the power pack.

Wireless Communication

The photosensor shall communicate over wireless communication with the desktop tool. Communication shall be bi-directional. The maximum required communication distance shall be 25 feet. Only line of sight communication is required.

Future versions will likely require address specific communication to allow individually addressing a photosensor in an area with multiple photosensors.

Communication Port

For programming and testing this device shall have a serial port.

Future versions would likely replace the serial port with another type of communication port to be used for manufacturing purposes only.

Desktop Tool

The desktop tool is a portable tool intended for setup and calibration by the installer. It is intended that only one desktop tool would be required for a building with potentially hundreds of photosensors. The desktop tool may also act as an information source for a commissioning agent aiding in their creation of a commissioning report.

The desktop tool shall direct the setup process as well as contain the processing power required for the calibration calculations. The desktop tool is intended to sit on the task surface and measure task level illuminance. Placing it on the task surface puts it at a height that can be documented as well as allowing the setup agent to step away and not block the light seen by the photocell. While portable, it is not intended to be a handheld device.

The primary goal of the desktop tool is to simplify the setup and calibration process. It directs an automated process to determine the photosensor signal to task illuminance ratios for both the controlled electric lights and for daylight. By automating this sequence and resulting calculations, it is intended that the setup and adjustment for the photosensor be completed in one short duration action.

The desktop tool shall differentiate the calibration process from the setup process with the intent that both could be completed at one time under most daylit conditions. The calibration process shall equate the photosensor signal to the task illuminance by sharing illuminance information from the task level with the photosensor.

The adjustment process shall include the entering of target illumination setpoints and other operating characteristics. The desktop tool shall be designed to facilitate repetitive commissioning by organizing these adjustment parameters into “profiles” which may be selected and reloaded in a single step.

It is envisioned that future versions shall operate on a battery to provide greater portability. However, prototype versions shall be powered by an external power supply.

A photodiode shall be used to provide a light level measurement that corresponds to the desktop illuminance. The photodiode shall closely match the spectral response of the photosensor's photodiode.

The photodiode shall be covered by a plastic enclosure and a light transmitting diffuser, combining to provide a cosine corrected response.

The full scale of the light level measurements shall be scaled as found appropriate for the application. The range is initially defined as a light level reading corresponding to a ceiling illuminance range of .2 to 400 footcandles. Within this range, the resolution of the light measurements shall be greatest at the lower light levels and decrease as the light level increases.

The desktop tool shall have a display screen used to display task illuminance readings as well as allow user adjustment to the photosensor setup parameters. Display shall have a minimum of 2 rows with a minimum of 24 characters.

There shall be 4 buttons for a user to select menu options or to raise or lower the light level. The function of the buttons shall change with the context, but shall raise target setpoint, lower target setpoint, next, and enter.

The desktop tool shall communicate over wireless communication with the photosensor. Communication shall be bi-directional. The maximum communication distance shall be 25 feet. Only line of sight communication is required.

For programming, this device shall have a serial port.

Occupant Control

The occupant control shall be provided by a wall switch. The wall switch shall have 2 momentary buttons. One button shall provide on or raise control, depending on the current state of the lights and the duration of the press. The other shall provide off or down control.

Existing available wall switches shall be identified and utilized for this prototype. Methods for adding modular connections shall be explored to simplify the wiring.

Description of Operation

Operating Mode

Photosensor light level measurement

Light level measurements shall be averaged to minimize reactions to transient conditions.

The photosensor shall use the light level reading in combination with the dimming signal reading to calculate a more accurate approximation of task illuminance. The electric light contribution is calculated by using the electric light reference table to determine the electric light illuminance and the equivalent light level signal expected from the lights when commanded to the dimming level. Next the daylight illuminance is calculated by finding the remaining light level signal and multiplying this value by the daylighting task illuminance to photosensor ratio.

This integrated logic will also include error checking. For example, if the total light level signal is not equal to or greater than the expected electric light illumination then there is a problem. One possible application of this error checking would be to defeat the common tactic of taping over the photocell to defeat the dimming control. When the light level reading was at or near zero at the same time that the dimming control signal was present, then the dimming control signal could be commanded to minimum.

In addition to greater accuracy, the ability to differentiate daylight and electric light shall allow the photosensor to be mounted on the ceiling in applications with direct/indirect pendant lighting fixtures. Mounting a photosensor in proximity to this type of fixture can present the inverted from normal relationship where the light level signal at the photosensor decreases as the daylight increases and the electric lights dim. With the photosensor able to differentiate light sources, the photosensor can utilize the calculated daylight illuminance for its critical variable.

Monitoring dimming control voltage

The dimming control signal shall be monitored both to provide feedback for normal dimming control and to provide exception reporting. An example of an exception is when another control device such as an occupancy sensor switches off the controlled lights. This exception would be indicated by a control voltage at or near zero because the power to the ballasts has been switched off. Receiving indication of this exception is important for the photosensor operation for several reasons. First, it is important to avoid overshooting the desired light level when the controlled lights are switched back on. The control function can be further enhanced by having the electric lights ramp up when switched back on. The second key reason for monitoring this signal is to lock out the automated calibration process if the controlled lights are not switched on or properly connected to the photosensor.

Dimming Control

The photosensor shall utilize sliding setpoint control with a separate night, or electric light, target setpoint and a separate daylight, or full dimming, target setpoint. The daylight illumination target setpoint is limited to be no less than the electric light target setpoint but may be higher if desired for the application. Having a higher daylight setpoint would allow the overall task illumination to rise before the electric lights are fully dimmed.

The electric light target setpoint shall allow the reduction of the electric lights from their full output. This capability, sometimes referred to as “tuning” shall provide energy

savings. In addition because the system is attempting to maintain illumination levels, the illumination levels shall be maintained automatically over time thus compensating for lumen depreciation.

In addition, it shall be possible to set a minimum dimming control signal. The minimum dimming control signal shall be the minimum signal even when the daylight task illumination is greater than the target setpoint. The minimum illumination level shall be maintained automatically over time thus compensating for lumen depreciation.

The control response shall provide a fast ramp up and slow dim down strategy to minimize the occupant's awareness of the dimming control. This strategy shall error toward providing too much light while reducing the chance that the task illuminance can drop below the target setpoints.

The dimming signal shall be updated under steady state operation no more frequently than once every 30 seconds. During periods of transition, the updates may be more frequent. When the light level is far away from the target setpoint, predictive control shall be used based on the reference lookup table. The dimming control signal that produces the desired illumination shall be identified and then sent to the controlled lights. When the light level is close to the target setpoint, incremental control shall be used. If the light level is below the target, the dimming control signal shall be stepped up until the desired level is reached. Conversely, if the level is too high then the dimming control signal shall be reduced in small steps.

On/Off Control

If selected at setup, the photosensor shall command the lights off when there is sufficient daylight. There shall be an adjustable time delay for this to occur. This control shall utilize the Force Off signal to override a possible indication of occupancy. This signal shall remain present even if occupancy is terminated. When it is determined that the daylight task illuminance has dropped sufficiently, then the lights shall be allowed to turn back on by removing the Force Off signal.

An occupant shall be allowed to switch off the lights by pressing the off button on the wall switch. Pressing off shall turn on the Force Off signal. Pressing on shall turn off the Force Off signal. If the daylight illuminance drops, then the Force Off signal shall be released allowing the lights to turn back on. (Note that with the lights forced off, it shall not be possible to monitor if the lights have been switched off due to the termination of occupancy.)

The lights shall normally automatically turn on when occupancy is resumed except if there is sufficient daylight. However, if the lights have been commanded off because daylight is considered sufficient, they will not automatically switch on when occupancy is resumed. However, pressing the wall switch shall allow the lights to temporarily override the lights on. The Force Off signal shall be turned off. When occupancy is terminated, if Force Off had been overridden off then it shall be turned back on.

During the automated setup and calibration process, the Force Off and Force On commands shall be used to first turn off the lights and then turn them back on and ensure that the controlled electric lights remain on during the calibration process.

To create a reference table for electric light illumination, the photosensor may turn on the lights during an unoccupied nighttime period. To accomplish this test, the Force On command shall be used.

LEDs

An LED shall flash rapidly until the photosensor has been setup. Any time that the photosensor is returned to its factory defaults, the LED shall flash.

An LED shall also flash whenever the desktop tool is communicating with the photosensor.

Occupant adjustment

In addition to being able to switch the lights on and off with a wall switch, an occupant shall also be able to raise or lower their target illuminance setpoint.

By pressing the Raise button for longer than ½ second, the electric lights shall rise at a rate fast enough to observe. The lights shall continue to rise for as long as the button is pressed or until the maximum allowable level has been reached. Similarly, if the Lower button is pressed for longer than ½ second, the electric lights shall lower at a rate fast enough to observe for as long as the button is pressed. While providing feedback to the occupant with an observable change in illuminance, the photosensor is also making an internal calculation of the magnitude of the adjustment. This calculation creates a numerical offset used to raise or lower the target setpoint. This offset shall remain active when the daylight illumination changes. It will be used to calculate a new target setpoint using the new daylight information as well as the user adjustment offset. The magnitude of the allowable user adjustment offset shall be adjustable at startup.

<u>Setup and Calibration</u>

The sequence of events in the setup and calibration mode shall be directed by the desktop tool. The desktop tool shall act as the master and the photosensor shall be the slave. (The one exception to this is if, in the final design, it is determined that the photosensor shall create an electric light reference table during an unoccupied period.)

Setup shall consist of two distinct operations, parameter setup and calibration. Parameter setup shall consist of adjusting the operating characteristics of the photosensor. Calibration shall involve calculating the task illuminance to photosensor ratios unique to each space. Typically, parameter setup is completed first and calibration is second. It is also recommended that any time a target setpoint is changed that the calibration be redone.

Setup and calibration shall be completed in one visit. Setup and calibration is to be allowed when the daylight illuminance on the task exceeds the target illumination setpoint. The automated process is to take 5 minutes or less on average per photosensor.

The following parameters shall be displayed on the user display of the desktop tool. It shall be possible to press a button to scroll through the parameters and select an individual parameter to adjust. Alternatively, the parameter setup process could be bypassed by using either the factory default settings or by reloading a previously saved profile. It is anticipated that on a given project that the profiles, or collection of setup parameters, are reusable for most photosensors.

These parameters may be entered under any lighting conditions. If the parameters are adjusted individually (as opposed to reusing a profile), then the adjusted value is transmitted from the desktop tool to the photosensor when the new parameter has been entered.

The units for the target setpoints directly represent desired footcandles on task. These target levels are independent of room specific conditions such as room finishes, furniture placement, and lighting fixture type. The benefit in this scheme is that the target setpoints are fully portable, being moveable from room to room. During the calibration of each photosensor, the room specific conditions are measured and used to convert the target setpoints into operational setpoints.

Nighttime setpoint

This is the target illuminance setpoint when there is no daylight contribution. The units for this parameter are footcandles at the task level.

Daytime setpoint

This is the target illuminance setpoint when the electric lights are dimmed to their minimum. The units for this parameter are footcandles at the task level.

Minimum electric light setpoint

This is the minimum illuminance setpoint provided by the electric lights to be maintained when the total illuminance equals or exceeds the daytime setpoint.

Daylight off delay

This parameter enables the electric lights to switch off when there is sufficient daylight or disables this function and therefore does not allow the lights to switch off automatically due to an abundance of daylight.

Daylight on delay

This parameter is only used if the daylight off delay is enabled. This is a time test for the electric lights to turn back on. If the daylight level falls sufficiently for the length of time set, then the electric lights shall turn back on.

User adjustment authority - Reduce

This parameter sets the maximum limit that an occupant can reduce their target setpoint.

User adjustment authority – Increase

This parameter sets the maximum limit that an occupant can increase their target setpoint.

Duration of user adjustment

This parameter defines whether the user adjustment resets to the primary setpoint or continues to remain active until an additional adjustment is made. The options for this parameter are “terminate when lights are switched off” or do not terminate.

Set Address

The photosensor address shall be settable from 1 to 255 for purposes of correspondence with building documents and setup reporting. It shall be possible to assign each photosensor one of a possible 255 addresses.

Store settings into a profile

The adjusted setup parameters shall be able to be stored into one of two profiles to facilitate repetitive commissioning.

Reload profile

Either profile 1 or 2 can be selected to reload into the photosensor thus automatically configuring the photosensor.

Calibration

Calibration refers to measuring the room specific characteristics that influence the relationship between the task level in the room and the photosensor on the ceiling. Calibration is an automated process that captures and calculates the task illuminance to photosensor ratios independently for the electric lights and for daylight.

Calibration for every photosensor shall be mandatory.

The calibration process is directed by the desktop tool. For each of the steps, the desktop tool commands the photosensor to take an action such as turning on or off the controlled lights or commanding them to a specific level of dimming. It then requests the photosensor to take a light level reading and transmit it. It then matches the light level reading with a corresponding reading of its own and calculates the ratio between the readings. When complete, the desktop tool then transmits the results of the calculations to the photosensor for use as a “task to photosensor” conversion factors.

During the calibration process, the conversion factors are also used to convert the target setpoints from the units representing task level illuminance into the equivalent photosensor light level values.

An additional aspect of calibration is to measure and record the illumination provided by the controlled lights over the dimming range. This information is used by the photosensor to calculate the expected amount of the illumination contributed by the electric lights. However, the illumination provided cannot be represented by one factor or equation because these ballasts do not dim over the entire 0-10 V range. The solution to this problem is to build a reference or lookup table to record the light output at each dimming level. The principle is that for every control voltage sent to the ballast there is a predictable and repeatable task illumination with a corresponding sensor signal (with an estimated 15 percent of repeatability due to operating temperature and age of the lamp. The actual repeatability will be identified for typical lamps during the testing phase.)

During the calibration process using the desktop tool, the electric lights shall be commanded to at least a minimum number of dimming levels. The photosensor light level and the desktop tool light level for a sampling of dimming levels shall be recorded.

Task 6. Roundtable Meeting

The goal of this task was to conduct a roundtable meeting consisting of the project team and key school specifiers and lighting designers to obtain feedback on the specification and performance criteria. Meeting this goal helped achieve the project objectives by obtaining input from specifiers and end users that helped guide the development of the prototype.

The roundtable meeting was held on May 21, 2003. The roundtable brought together a group of exceptional expertise. The group's insight into the priorities for daylighting control was collected from the group in three ways: response to a written questionnaire, an individual statement of priorities, and an extensive group discussion. Providing better daylighting products as well as better application tools were very important to the group. Overall, the four priorities were:

- simplified installation
- simplified setup and testing
- occupant adjustment capabilities
- tools for providing information to commissioning agent

The group was supportive of the PIER LRP Project 3.3 work as well as being insightful with suggestions. Many people praised the work and reinforced the need for better daylighting controls and tools. Several people commented on how important this work was. No one suggested that the direction was not correct. Furthermore, none of the suggestions contradicted the current specification and direction. Instead, the suggestions added applications and concerns that the project team may not have anticipated as well as a prioritizing of function and features.

At the end of the roundtable, several people suggested that sites that they were working on might be possible beta sites for testing. These volunteers further reinforced the feeling by the project team that the audience supported the project's direction.

In reviewing what was learned or heard from the group, it is important to consider the possibly contradictory information received. For example, there were many concerns about keeping the cost of the controls inexpensive, but there were many more requests for additional features that would increase the product cost. It is also important to evaluate the suggestions against a very tight schedule and budget for this PIER LRP Project. As stated to the group, the goal of this PIER LRP Project is, first and foremost, to provide improved daylighting control.

Suggestions received that were incorporated into the specification:

> Plug and play wiring including color-coding and quick connectors.
>
> Maintain the flexibility to mount photosensor on a ceiling or in a pendant fixture.
>
> Use "setup and testing" instead of "commissioning" to refer to initial adjustment made by the installing contractor.
>
> Add a port to the setup tool to support reporting on photosensor setup and testing. Begin to look at report formatting.
>
> Consider additional possible application requirements such as individually addressing a photosensor in an area with multiple photosensors.
>
> Provide a wall switch for dimming adjustment. Wall switch may include a visual indication of current adjustment.

Task 7. Alpha Prototype

The goal of this task was to build a new alpha prototype, or modify The Watt Stopper existing designs. Meeting this goal helped to achieve the project objectives by developing the Classroom Photosensor Control System.

To satisfy the specification, an entirely new photosensor was designed. A new device was created for the desktop tool. Both devices were prototyped for faster development without concern for manufacturability. A common set of printed circuit boards was used and populated with components as required for each device.

The initial prototypes were designed, built, and programmed starting in August, 2003 with work on the prototype continuing until June of 2004. Initial functional testing was performed in The Watt Stopper test facility. The initial functional testing determined that

the hardware design provided all of the functions required to meet the specifications except for monitoring of the dimming control voltage.

The original intent of monitoring the dimming control voltage was to provide exception reporting. An example of an exception is when another control device such as an occupancy sensor switches off the controlled lights. This exception would be indicated by a control voltage at or near zero because the power to the ballasts has been switched off. Receiving indication of this exception was considered important for the photosensor operation for several reasons. First it could help avoid overshooting the desired light level when the controlled lights are switched back on. The control function can be further enhanced by having the electric lights ramp up when switched back on. The second key reason for monitoring this signal was to lock out the automated calibration process if the controlled lights are not switched on or properly connected to the photosensor.

The project team was unable to implement this function because the photosensor itself generates a voltage signal. Therefore, to read the voltage provided by the ballasts would require disconnecting the signal provided by the photosensor. This would result in a change in the signal to the ballasts. Researchers felt that this function could not be implemented while being undetectable to the occupants.

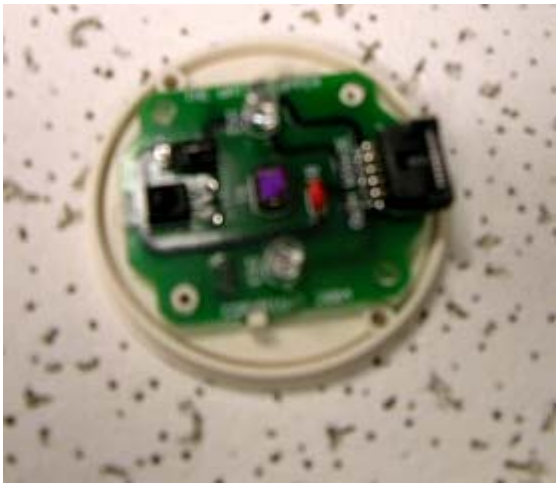


Figure 4 Photosensor Prototype

Figure 5 Desktop Tool Prototype

Task 8. Evaluate Alpha Prototype Performance in Laboratory Setting

The goal of this task was to determine the product performance in a controlled laboratory setting. Product spatial and spectral response and the control algorithm under controlled electric and daylight conditions were evaluated.

It is important to note that this task was modified to concentrate on lab testing of the spatial response of the prototype. The spectral response was not tested because it was felt that test data previously received confirmed conformance to the specifications.

Meeting this goal helped to achieve the project objectives by testing the product in a controlled setting to evaluate performance based on the specifications approved in Task 6.

The laboratory tests were performed by Lawrence Berkeley National Laboratory in February and April, 2004 on the prototype photosensors. The primary purpose of these measurements was to characterize the spatial response function of the prototype photocells.

In task 1, LBNL tested the spatial and spectral measurements of the commercial photosensor product. For this test, The Watt Stopper had redesigned the photosensor in two key ways: first, they have replaced the original LED-based light detector with a color-corrected silicon photodiode. Secondly, they have modified the exterior housing and lens assembly so the photosensor's field of view (FOV) is constrained to about 100 degree full angle with very little sensitivity outside this angular range.

The tests were conducted on two separate occasions. In February 2004, LBNL tested four different types of photocell that The Watt Stopper had prototyped. In April 2004, LBNL tested the final photosensor configurations (four of them).

The spatial measurements showed that the April 2004 photosensors had the spatial response that was closest to the desired properties; that is a cut-off angle of about 55 degrees with reasonably fast cutoff. The four different photosensors had a FOV of 41-48 degrees with cutoff range between 7 and 15 degrees. With additional work, the FOV could be expanded to approach the 55 degree cutoff recommended by Mistrick's simulations.

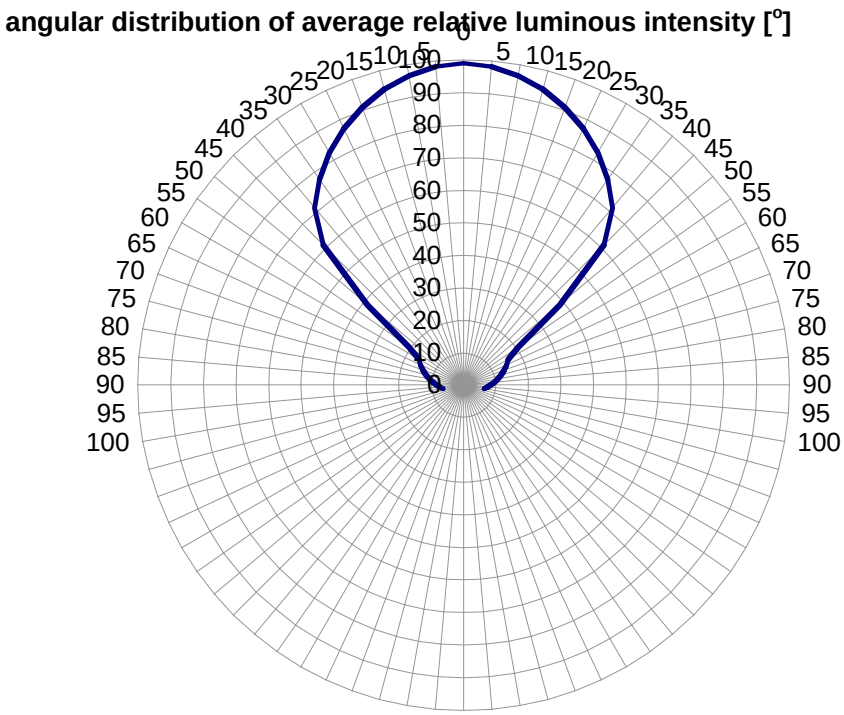


Figure 6 Average Spatial response of new photosensor

Task 9. Refine Prototype Design

The goal of this task was to refine and adjust the prototype design based upon results from the laboratory evaluation. Meeting this goal helped to achieve the project objectives by assuring that the design is robust and complete for the field evaluation.
Work performed under this task concentrated on refining the programming of the prototype. This work continued until the completion of the field testing in August, 2004.

Task 10. Field Test

The goal of this task was to evaluate the prototype performance in a small-scale field test. Meeting this goal helped to achieve the project objectives by evaluating the performance in a real space.

The photosensor prototype was temporarily installed in August of 2004 in a relocatable classroom in Irwindale, California. The classroom was located at Southern California Edison's CTAC facility. The photosensor was installed in the center of the classroom, temporarily mounted to a piece of white foamcore that was suspended from the underside of the center-mounted HVAC duct. The mounting height was approximately 11 feet. This location was centered between the two pendant fixtures. To provide additional hours of data regarding the effectiveness of the daylight responsive dimming, the occupancy sensor was disabled for the duration of the tests. At the completion of the short field test, the photosensor was removed and the existing controls were reinstalled.

Each row of fixtures was fed from its own circuit breaker. There was one existing power pack for each of these two circuits. The two existing power packs were replaced by the new power packs required for this test, which were installed in the ceiling above the utility closet. Additionally, a wall switch with two individual buttons was temporarily installed. The functionality for these buttons was demonstrated; however, the occupant was not able to adjust the target levels for the test.

The desktop tool used in conjunction with the photosensor was functional for the test. The ability of the desktop tool to manually control the lights as well as retrieve data from the photosensor was demonstrated. For instance, the desktop tool can query the photosensor to retrieve the dimming signal currently being sent to the dimming ballasts.

The photosensor calibration routine was demonstrated. This is an automated routine that allows a single step setup of a sliding setpoint device. The calibration routine has the desktop tool work in conjunction with the photosensor to measure the task level illuminance at the same time that the photosensor records its light level reading. The desktop tool then calculates the task to photosensor ratios for both electric light and daylight.

The intent of the system, while not fully implemented for the test, is for the power pack to switch off the lights when there is sufficient daylight for a sufficient period. However, it was observed that the Motorola ballasts do not keep the lamps lit when the control voltage drops below .5 VDC. This control issue with the ballast added additional complexity to the test. This problem indicated the importance of one feature of the photosensor, which was not functional for the test. This feature allows the setting of the minimum voltage signal when dimming. If this feature had been working, then the minimum voltage could have been set to a level higher than .5 VDC.

Researchers from LBNL found that the photosensor was on the right track in keeping within the target illuminance and reduces energy consumption when there is enough daylight in the space. The desktop tool provides promise as a calibration device that results in faster and simpler setup as well as more accurate daylight dimming control.

The available data contains limited information. There is one full day that shows the general behavior of the photosensor identifying control problems. These problems were obvious at the day of the installation, but The Watt Stopper was unable to immediately make the programming changes required. In a return trip to the site, The Watt Stopper made revisions to the control software. After these revisions, less than 4 hours of data was collected. The data suggests that some of these problems were solved. However, it also suggests that there may be fine-tuning needed. To understand the behavior and to better evaluate the photosensor, more experiments and tests should be conducted in a more controlled environment with a set of test cases over a longer period of time. In particular, the effect of performing the calibration from alternate locations must be conducted. Data after each of the calibrations must be collected for a full day. It would be valuable to be able to repeat the calibration routine under various conditions to determine if the variation in daylight distribution allows control of the task illumination within acceptable limits.

Continued Development Work

In September of 2003, this project received an extension and additional funding to continue work on making this product closer to being ready for commercial release. This extension allowed The Watt Stopper researchers to reexamine many of the decisions that the project team made in creating the prototypes. Creating a device that could be commercially viable has required design changes to both the photosensor and the desktop tool. This work is currently underway and expected to be completed in mid March of 2005.

Photosensor

To develop the prototype within the initial project schedule, the project team designed the prototypes for the photosensor and the desktop tool on a common platform. In proving the concept, the project team chose to explore the size, installation, and cost constraints that a commercial product would operate under.

In constructing the two prototype devices, the project team used a common set of PCBs for both the photosensor and the desktop tool. The project team tried to use as many of the same common components as possible. The project team then constructed the two devices by populating the PCBs with the components required for that device. The assembled prototypes of the two devices left sections of the PCB unpopulated. While functional, this was neither space nor cost efficient. In the case of the photosensor, this method resulted in the photosensor being assembled from the two PCBs with the larger PCB being mounted above the ceiling in the tests.

The priorities for commercializing the product are as follows:

1. Design one new PCB that houses all of the components that will fit into the form factor that The Watt Stopper has standardized on for a photosensor. This form factor is an approximately 2.5 inch diameter circle.
2. Review each of the components for cost, size, and performance. For the prototypes, many of the components were selected for easy availability and convenience with less consideration for cost and size. For a commercial unit, cost and size are critical concerns. As an example, in the prototype, both the photosensor and the desktop tool used the same microcontroller. Using the same microcontroller allowed portions of the programming for the two devices to be fully portable. The microcontroller was sized for the processing requirements of the desktop tool. The project team found the capacity required for the photosensor to be much smaller. In creating a commercial unit, the project team has selected a smaller microcontroller.
3. Design of new front plastic to meet the functional requirements and provide an aesthetically pleasing design. The initial work on the project has provided specific guidelines for the photocell cone of view. Additional work is now required to configure the plastic and the PCB for the cone and the other

components to fit. This work must be coordinated with the new layout of the PCB. The specific functional requirements for the plastic are to provide the desired photocell field of view while facilitating trouble free IR communication.

4. Facilitating IR communication is of particular concern because the project team found that the prototypes could only communicate when the desktop tool was almost directly below the photosensor. The two devices should be able to communicate at an angle equal to 45 degrees from vertical. (Mounted at a height of 12, it should work anywhere in a circle with a radius of 12 feet.)
5. Adjustment of the photocell circuit to provide more resolution at lower ranges. In the prototype, the photocell circuitry was identical in the photosensor and the desktop tool. However, the light level readings at the photosensor are lower than at the desktop tool. This operation is sensitive because increasing the low end resolution increases the risk of raising the background noise levels.
6. Redesign of the wall switch input circuitry to use smaller and lower cost components.

Desktop Tool

The priorities for redesigning the desktop tool are quite different. The size and configuration of the PCBs used in the prototype was acceptable. In addition, the photocell sensing range was acceptable. The selected microcontroller was also suitably sized for this application. However, a number of other items required addressing in order to make this product commercially viable:

1. Design and build a plastic enclosure. For the prototype, the project team used only the bare printed circuit boards. The project team did not create a plastic housing for the prototype. The housing would be designed for a certain degree of ruggedness. The enclosure will have a display, 4 buttons, an opening for the photocell and another for the wireless transmission. It will also require access for the battery and USB port.

2. The prototype was operated by a 120 VAC power supply. It was designed with a power cord intended to plug into a wall outlet. The project team chose this solution to avoid the power management issues required for a battery-operated device. However, for a commercial device, portability is crucial. In many instances, the best location used for setup and calibration is in the center of the room, at least 10 feet from an electrical outlet. The project team is now converting the desktop tool to operate on 4 AA batteries.

3. The largest electrical draw in the prototype was the backlight on the display. The project team has deleted the backlight in favor of a new technology display that provides improved legibility. The project team rationalized the deletion of the backlight because the target conditions for using this device are fully lit conditions. In tests, the project team found the display to be readable at illumination levels of 2 footcandles and above.

4. The second largest power consumer was the display itself. The project team will select another display trying to balance the power requirements and the legibility requirements. The project team is also exploring options for reducing the size of the display in order to reduce the power consumption. The display could meet the functional requirements with 2 lines instead of 4.

5. An additional power management issue is that the desktop tool needs to reduce or eliminate its power consumption when not being used. The prototype was powered at all times when it was plugged in. In the redesign, the project team is adding an on/off switch. It will be a push button switch. This switch will be used to turn the tool on or off. In addition, the desktop tool will power itself down after 5 minutes of inactivity.

6. The project team found that date and time stamping of the setup and calibration reports is particularly valuable. Neither of the devices in the prototypes had a real time clock. In the redesign of the desktop tool, the project team is adding a real time clock. This change will require two other changes. First, the clock will need its own battery backup. Second, a menu item will be required to adjust the date and time.

7. The prototype had a serial port for communication to a personal computer. This port is used to download the photosensor calibration and setup reports to a personal computer for printing. The project team chose a serial port because it was faster to implement. However, for a commercial product, the project team believe that it is preferable to have a USB port instead of a serial port because it appears that newer laptop do not always have a serial port. Therefore, the project team has selected the components to provide a USB port for the desktop tool.

8. The project team also found that storing report data in the desktop tool is extremely valuable. During the demonstrations, the project team received suggestions for additional reporting functions that would require more data storage. Therefore, in the redesign the project team has chosen to add additional memory so that additional data may be stored.

9. In the product redesign, the project team is revisiting the menus and sequence of menus on the display. The project team will be deleting some of the less used functions and combining other functions that originally used multiple screens into a single menu screen. The project team will also be adding functions such as setting the date and time.

10. To retrieve the data from the desktop tool into a personal computer, the project team created a simple computer application program. While fully functional, this program was rather primitive. To commercially distribute this software along with the desktop tool will require a redesign of the application program. The redesign will support USB communication. It will also provide additional tools for managing the extracted data and for managing the desktop tool.

The project team anticipates manufacturing a small run of devices when the redesign is complete. The project team will be testing these devices in The Watt Stopper test facilities and at other test sites.

Project Final Update

This is an update reporting on The Watt Stopper's progress in the two months since the final report for this project was written in February, 2005. The Watt Stopper is actively working on this project with the goal of having a commercial version of the control system available in the first quarter of 2006.

Our project team's development work has been working in 7 areas:

1. Photosensor circuit board design
2. Photosensor plastic enclosure design
3. Photosensor programming
4. Desktop tool circuit board design
5. Desktop tool plastic enclosure design
6. Desktop tool programming
7. Computer software application

The results achieved are as follows:

<u>Photosensor</u>

1. We have redesigned the circuit board to fit into the form factor that The Watt Stopper has standardized on for a photosensor. All of the required components and circuitry now reside on one circuit board. The fabrication of the new circuit boards has been completed. Working prototypes are currently being assembled. We expect to have the units ready to begin testing within the next few weeks.
2. A smaller microcontroller with less memory has been used in the new design. The existing photosensor programming has been modified to run on the new microcontroller. The existing program has been successfully tested on a simulator for the new microcontroller.
3. A new plastic enclosure has been designed to meet the functional requirements and provide an aesthetically attractive design suitable for a commercial product. The technical requirements for the plastic are to provide the desired photocell field of view while facilitating trouble free IR communication. We anticipate receiving the prototypes of the new plastic design within the next month.
4. The photocell circuitry has been modified to provide more signal resolution at lower light levels.
5. The wall switch input circuitry has been redesigned to use smaller and lower cost components while still maintaining immunity to noise.
6. Provisions to record the date stamp for the calibration procedure have been made.

Desktop Tool

1. We have created initial design drawings for the plastic enclosure. The design of the desktop tool will match certain of the design elements incorporated into the photosensor. The housing is designed for a certain degree of ruggedness. We anticipate having prototypes of the plastic enclosure for testing built in 10 weeks.

2. A new schematic design for the circuit board has been completed. All required components have been selected. The layout of the circuit board will begin immediately. Additionally, the circuit board layout will be refined as the final design of the plastic enclosure progresses. We anticipate having working prototypes of the new circuit board in 6 weeks.

3. The desktop tool has been redesigned to use a battery as its primary power source. Testing will begin shortly to finalize the choice of battery type to be used in the device. The desktop tool will also have the option of being powered by a DC adapter. The desktop tool will have an input connection suitable for connecting a DC adapter.

4. The backlight for the display has been eliminated to reduce power consumption.

5. A selection of commercially available displays have been tested to replace the display initially used. A display with sharper contrast has been selected. It is also slightly smaller. The new display has 4 lines with 16 characters per line.

6. A push button on/off switch has been added to the desktop tool. This switch will be used to turn the tool on or off. In addition, the desktop tool will switch itself off after 5 minutes of inactivity.

7. A real time clock has been added to the desktop tool to provide date stamping of the calibration procedure. A second battery to backup the real time clock has been added.

8. A USB port has been added to the desktop tool to provide communication with a personal computer.

9. Additional memory has been added for data storage and additional reporting.

10. A buzzer has been added to provide audible indication when the calibration has been completed or of any error condition.

11. An initial design review of the previous menu structure has been completed. The final menu structure will be specified shortly. Programming revisions to the menus will begin following the completion of the operating desktop tool prototypes.

Computer Software Application

The Watt Stopper is creating a software application used to retrieve, view and print the data stored in the desktop tool into a personal computer. The application would be used following the completion of the setup and calibration of an individual photosensor or group of photosensors.

We have completed the initial step of porting the previously created application to a platform suitable for commercial distribution. Initial work required to support USB communication has begun.

We have written a functional specification for the application summarized below. When using the application, it shall be possible to:

1. View retrieved data in individual pages, one page per photosensor address. Provide tabular access to the pages.
2. Inquire which addresses in the connected desktop tool have valid data. For addresses with valid data, display the time and date of the photocell calibration. Provide the ability to print this report.
3. Retrieve data stored in the desktop tool by selecting all data for all addresses or by selecting data only for an individual address
4. Clear data from the desktop tool by selecting data for all addresses or data for an individual address
5. Enter text in the individual pages for the addition of photosensor location information and additional comment information. Store this text data along with data retrieved from desktop tool.
6. Print formatted reports similar to the individually displayed pages
7. Export data files to Excel (for additional reporting capabilities)
8. Save data to files for storage on a personal computer. Provide the ability to name these stored files.
9. Open data files stored on the personal computer and view them in individual pages. The application should provide similar functionality for viewing, commenting and printing the data as when the data is initially retrieved from the desktop tool.
10. Delete all data stored for an individual address in the currently open file. (This function is local to PC.)

The application should provide visual indication when a desktop tool is successfully communicating with the personal computer. Display the serial number of the connected desktop tool.

System Testing

This system still requires considerable testing prior to final determination as to its commercial viability.

The Watt Stopper will begin testing the prototype devices in The Watt Stopper test facilities when the devices are complete enough to test. It is anticipated that the primary functional testing will begin this summer.

Conclusions and Recommendations

Codes and Standards

Code-Change Vulnerability

The product's energy saving and cost advantages do not depend on any current or scheduled code requirements. This product is commercially viable with the existing energy codes that provide credits for daylighting controls.

Code-Change Dependency

While not critical to the products success, the product could benefit from future revisions to the energy codes. The project team believes that daylighting controls provide a major energy savings target for energy code enhancements. Furthermore, the project team believes that the demonstration of daylighting controls installations that perform correctly and save the estimated energy will encourage the energy codes to adopt requirements for daylighting controls.

This market demand for this product would increase significantly if additional daylighting requirements are adopted in the energy codes. One such code change will take effect by the end of this year. In California, this market demand for this type of product is likely to increase from the 2005 revisions to Title 24 that will require automatic daylighting controls in larger daylit areas under skylights. While dimming is only one compliant option and not the lowest cost solution, some building types and applications will favor dimming.

Nationally, two of the other major energy codes, ASHRAE 90.1 and IECC, may choose to review automatic daylighting control provisions in their upcoming revision cycles.

Recommendations

The Watt Stopper is continuing its development work on this project and continuing to explore the commercialization of this system.

As it is a fundamentally new concept, the project team believes this product would benefit from installation in one or more demonstration projects to demonstrate the system performance, energy savings, and customer satisfaction.

Commercialization Potential

The project team believes that this system is a commercially viable product that provides significant energy and non-energy benefits.

The existing market for daylighting products sold for lighting control in commercial buildings in the U.S. is believed to be about $6 million dollars per year. Of this market, it is believed that daylighting products that dim lights account for approximately $2 million dollars of the $6 million total. It is further believed that the bulk of this market is used in new construction with schools being one of the most active segments. It is believed that nationally less than $1 million dollars is currently being spent on daylighting lighting controls in schools.

It is believed that the national spending on education construction averages greater than $25 billion dollars. Therefore, current spending on daylight dimming controls is less than 0.04 % of the school construction spending. This is believed to be a very low market penetration.

With improved products and demonstrations, the project team believes that this market could grow ten-fold in the next 10 years.

Benefits to California

The California Energy Commission estimates that the energy use for lighting in schools consumes a total of 1,200 giga-Watt hours of electricity in California per year. It is believed that approximately 70% of this usage is for classrooms. It is further assumed that 50% of the classrooms are adequately daylit to allow a lighting reduction during daylit hours. It is further assumed that in the controlled classrooms that this control system will on average save 35% of the energy used for lighting. (The energy savings for schools designed to optimize the use of daylight will be considerably higher.) These assumptions produce a total estimated annual savings in California schools of 147 giga-Watt hours. This represents an annual savings of more than 11 million dollars.

Conclusions

The system demonstrated in this project provides significant enhancements over commercially available daylighting control products. The project team believes that it is a commercially viable product that with further development work could be commercialized.

The proposed system has the potential to provide energy and non-energy benefits to the State of California and school owners with an acceptable payback period.

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