Dual-Loop Photosensor Control Systems:
Reliable, Cost-Effective Lighting Control for Skylight Applications

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ABSTRACT

The researchers developed and demonstrated a novel approach termed “dual-loop” for daylight harvesting controls in big-box stores with skylights. A dual-loop photosensor control system combines a closed-loop sensor with an open-loop sensor and an intelligent algorithm which work together to adjust the electric light. The result is a new daylight harvesting system with an accuracy and reliability not available in existing daylight harvesting products. The system includes an automatic calibration feature that configures the set points automatically at initial installation based on the designed electric light levels. The set points are continuously updated nightly to account for changes in the interior geometry and reflectance of the space. The prototype dual-loop system with continuous dimming was tested in a laboratory environment and at a retail store in West Sacramento, CA. The dual-loop system operating the electric lighting in 10% of the floor area was compared to the baseline open-loop system operating the remainder of the store. During the monitoring months of December 2008 to November 2009, the light level provided by the dual-loop system more consistently matched the designed electric light level with an energy savings 50% greater than the baseline open-loop system. These results can not only be applied to the stores with skylights and dimmable ballasts, they can be applied to other spaces including stores with skylights and fixed light output ballasts or stores with HID systems. To make this system available to consumers, the researchers currently are working with a commercial sensor manufacturer to move the innovation from the laboratory to the marketplace.

Background

Photosensor control systems are electronic devices that sense light in a space and adjust electric light accordingly. Despite being commercially available for more than two decades, however, photosensor control systems have struggled to find widespread use and acceptance in interior environments. Although case studies have shown up to 50% in electric lighting energy savings in spaces that use photosensor control systems, negative experiences with unreliable operation and unproven technology have contributed to challenges in achieving greater market penetration (Bierman 2003).

Ideally, the proper specification, installation, and commissioning of a photosensor control system result in energy savings and an appropriate light level for a task. However, problems with over-dimming and under-dimming often diminish reliability and energy savings in systems using photosensor control. One study on the effectiveness of daylighting control systems in side-daylight applications found that more than half of the installed systems were not achieving any energy savings, mostly because they were disabled by occupants. In systems that were operable, only 25% of the expected energy savings were achieved because the systems were under-dimming (Heschong 2005). In another study, occupants in spaces with photosensor control in skylight applications reported dissatisfaction with the initial commissioning of the photosensor system and in many cases overrode the system (McHugh et al. 2004).

One area of interest for photosensor control systems is their increased requirement in skylight applications in California. California's Energy Efficiency Standard for Residential and Nonresidential Buildings Code (Title 24 – 2008) requires the use of a photosensor control system and skylights for certain buildings larger than 8,000 sq. ft[1] (compared to buildings larger than 25,000 sq. ft. in Title 24 – 2005). This change further increases the need for a commercially available photosensor control system that is more reliable, inexpensive, and achieves greater energy savings.

In response to Walmart's need for an improved photosensor system, the California Lighting Technology Center (CLTC) has developed an innovative dual-loop photosensor control system for skylight applications that addresses shortcomings in previous systems. The CLTC also is in the process of developing a dual-loop system for side-daylight applications.

Scope of Research

Photosensor systems on the market today use a photosensor (a device that senses light) and a controller (the hardware and control algorithm that determine the appropriate electric light level) in either an open-loop or closed-loop configuration.

In an open-loop system, the photosensor is oriented so that it senses only daylight and adjusts the electric light accordingly. Figure 1 shows an open-loop photosensor mounted inside a skylight well aimed at the sky. The primary drawback of open-loop control is that it only responds to changes in daylight, but does not always accurately respond to actual light levels in the interior space. An open-loop system is most accurate during midday hours when the sun is directly overhead with clear or overcast skies. An open-loop system has limitations with over- and/or under-dimming during early morning and afternoon hours when the sun is at a low angle in the sky and under partly cloudy skies. These are the conditions when dimming the electric lights to the appropriate level is most critical.

In a closed-loop system, the photosensor is oriented so that it senses both daylight and electric light and adjusts the electric light accordingly. Figure 1 shows a closed-loop photosensor mounted inside a skylight well aimed at the floor. A closed-loop system also can be unreliable at daylight sensing, mainly because the system is unable to distinguish between daylight changes and changes caused by occupant interferences or changes in the reflectance of objects within the space. Time delays may reduce these types of errors, but this prevents the system from responding to actual daylight changes in a timely fashion and reduces energy saving potential. Occupant interferences and interior changes (such as updating retail displays, painting, or carpeting) change the amount of light that is incident on the photosensor from both electric light and daylight. These conditions cause the electric light to either over- or under-dim and the system must be recommissioned, which is an added maintenance cost.

To maximize the benefits and minimize the limitations of open-loop and closed-loop systems, the CLTC developed a dual-loop system (Figure 2) for skylight applications the Building Energy Research Grant (BERG) program from the California Energy Commission. The CLTC worked closely with Walmart to develop a novel, reliable dual-loop system laboratory prototype and place the prototype in the skylight well of a 150,000 sq. ft. Walmart store. The result is a system that can detect a true daylight change, automatically commission the system,

[1] Buildings that require skylights are described in greater detail in Title 24 – 2005 and 2008 and include requirements for the number of stories for a building, the height of the ceiling in the space, and the area of the daylight control.

provide a consistent light level, and save significant energy. A primary component of the system is a control algorithm that monitors the open-loop and closed-loop photosensors and controls the electric light to provide the designed light level. This control algorithm has two key features. First, the control algorithm automatically recommissions the system every night. Recommissioning adjusts the dimming profile so long-term interior disturbances such as a change in object/wall/flooring reflectance do not cause the system to over- or under-dim. Second, the control algorithm distinguishes between a true daylight change and occupant interference (i.e., a person walking under the closed-loop photosensor).

Figure 1: Open-Loop Photosensor System (left) and Closed-Loop Photosensor System (right)

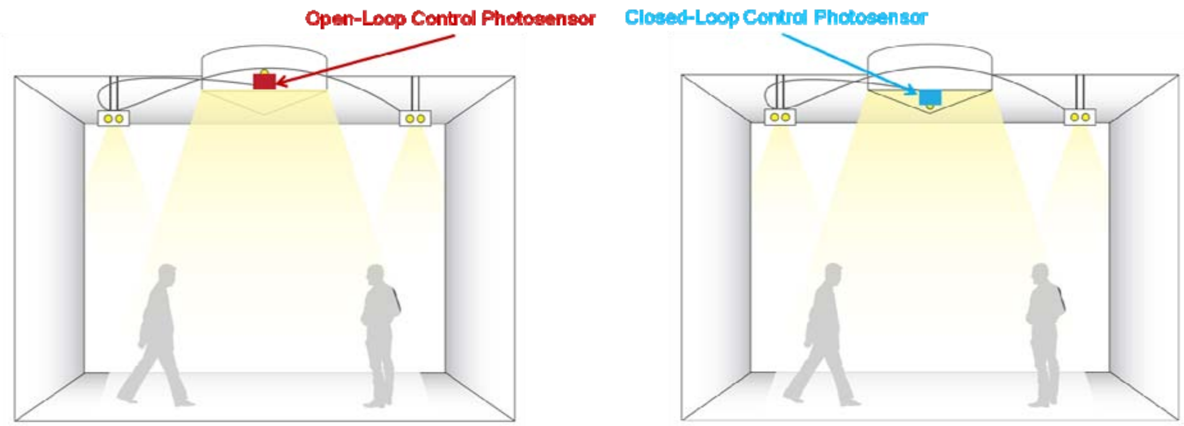
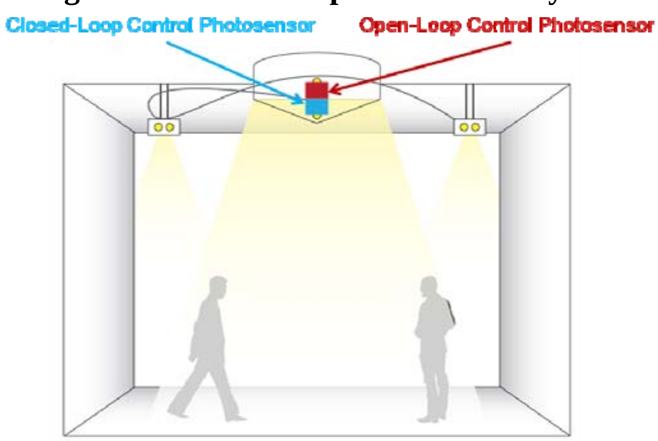


Figure 2: A Dual-Loop Photosensor System



Findings

From November 1, 2008, to October 31, 2009, the dual-loop system and a pre-existing open-loop system were monitored in a Walmart in West Sacramento, CA. Both systems operated 24 hours per day. Energy consumption and the light level at the photosensors were recorded for each system. The following are the results for the two systems over the 12-month period. Key successes of the dual-loop system include the automatic calibration feature, light level consistency, and energy savings.

Automatic Commissioning

While the dual-loop system was in operation, the seasonal displays below the skylight changed. In November and December, seasonal products included red, green and other colors. In January and February, the products changed to white storage boxes. In March and April, the products changed to gardening and outdoor items. As the displays and products changed throughout the year, the reflectance of those products changed. Figure 3 shows the products displayed for select days from December 25, 2008 to January 5, 2009 and the associated closed-loop photosensor signal used in the dual-loop system. Figure 4 shows how the closed-loop photosensor signal changed each day from December 4, 2008 to May 31, 2009. The closed-loop photosensor signal changed significantly during that timeframe. The automatic commissioning feature was able to account for and adjust the dimming performance of the electric light to minimize over- or under-dimming.

Light Level Consistency

To compare how the dual-loop system performed in relation to the open-loop system, two histograms show the light level consistency of each system (Figures 5 and 6). The histograms show how close each system was able to keep the actual light level to the designed light level. The light level consistency limits were set to be within 10% of the designed light level. The frequency of occurrence was summed for the entire year and presented as a percentage of either when the system over-dimmed, was at the designed light level, or under-dimmed. The open-loop system was within 10% of the designed light level 18.1% of the time, while the dual-loop system was within 10% of the designed light level 63.7% of the time. These findings indicate that the dual-loop system was able to control the electric light more accurately and maintain a more consistent light level compared to the open-loop system.

Energy Savings

To compare energy savings between the dual-loop system and the open-loop system, a bar graph shows the energy usage for each system. Figure 7 compares the energy uses between the dual-loop and open-loop systems and expresses monthly energy use as kWh per 4-lamp dimming ballast. The first bar represents a 24-hour store with no photosensor system. The second bar represents a 24-hour store with an open-loop system. The third bar represents a 24-hour store with a dual-loop system. The results show that a store with the open-loop system and the dual-loop system saved 24.4% and 36.6% respectively over a store without a photosensor system. Thus, the dual-loop system saved 50% more energy than the open-loop system.

Figure 3: Products and the Closed-Loop Photosensor Signal

Figure 4: The Closed-Loop Photosensor Signal at Night

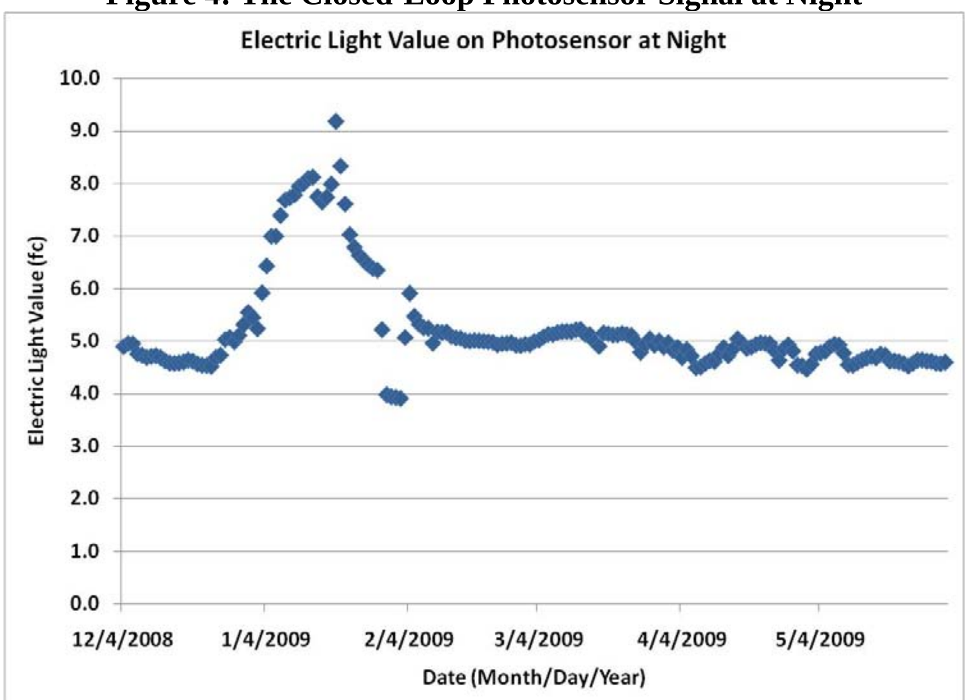


Figure 5: Open-Loop System Light Level Consistency

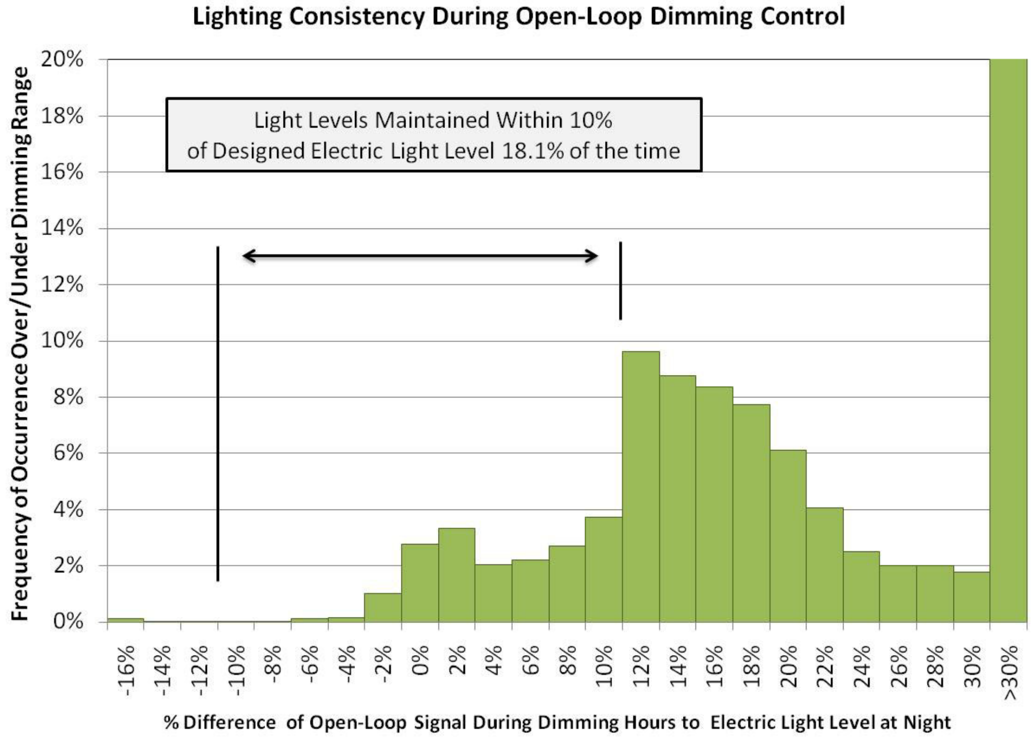


Figure 6: Dual-Loop System Light Level Consistency

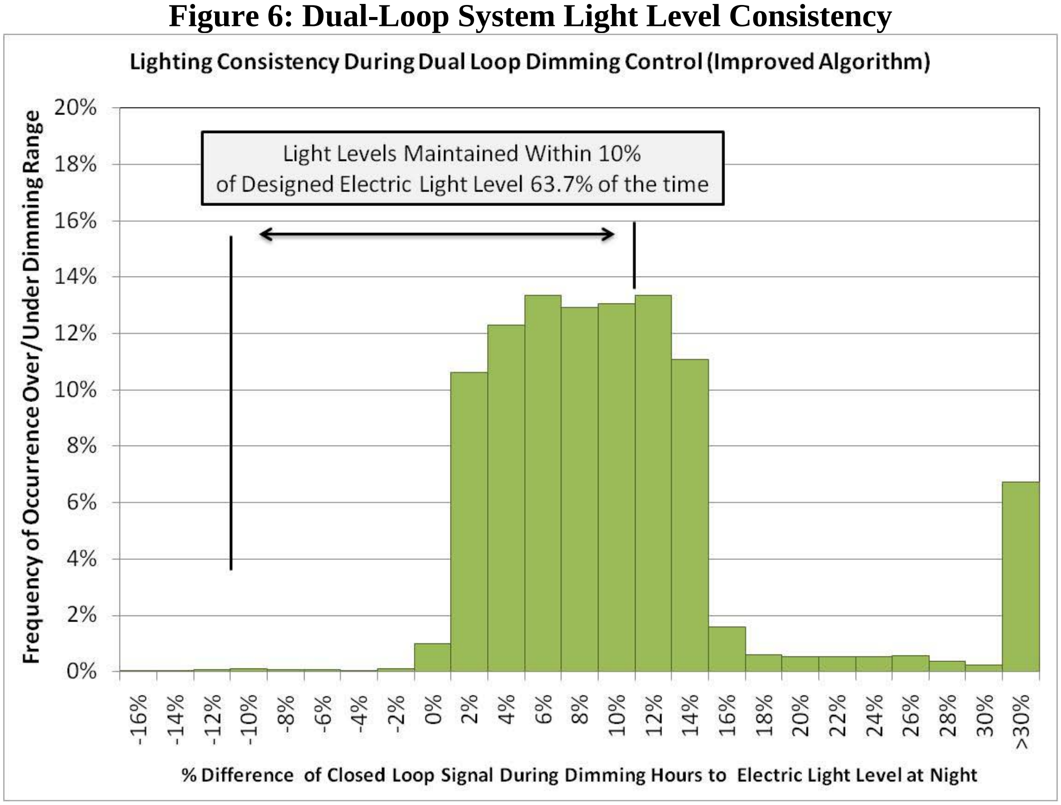
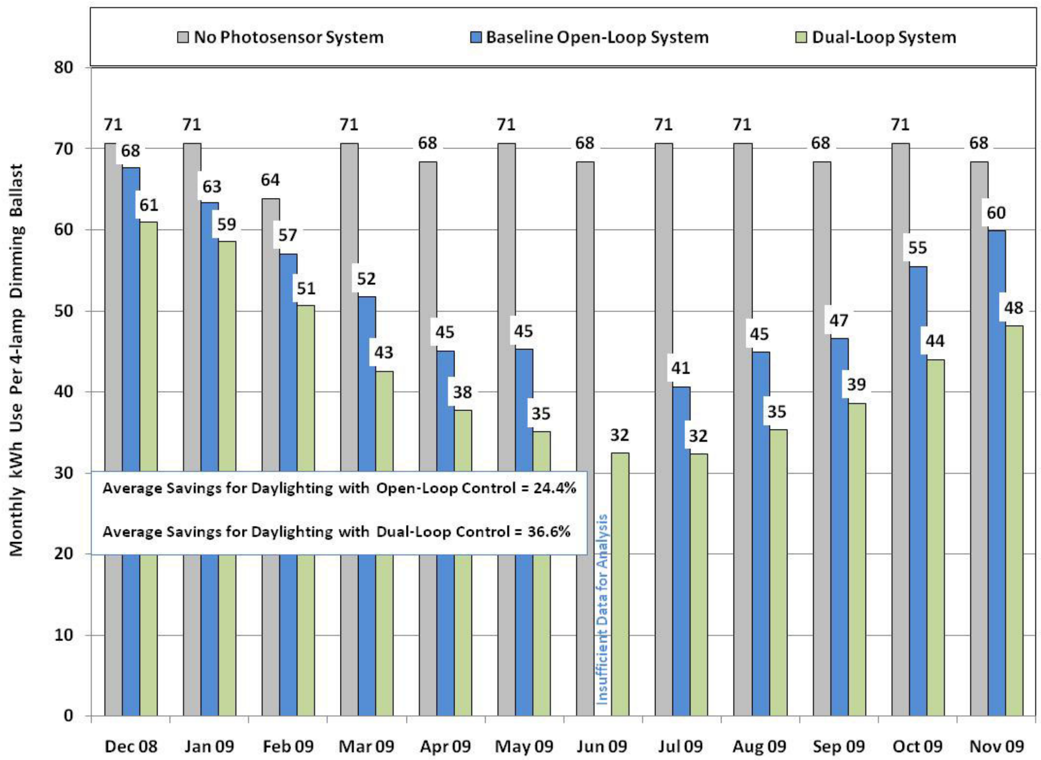


Figure 7: Energy Use for a 24-Hour Store with No Photosensor System, Open-Loop System, and Dual-Loop System



Implications

The dual-loop system for skylight applications addresses and corrects the shortcomings of earlier systems and has been successfully installed and monitored for a year in a retail space. This photosensor system has shown significant energy savings: more than 50% energy savings compared to an open-loop system.

The Walmart store, which was used to demonstrate the dual-loop system, has 1,000 ballasts and an area of 150,000 sq. ft. The potential energy and cost savings for this store are contained in Table 1. The dual-loop system could save 113.5 MWh or $14,500 more than the open-loop system over a 12-month period. Assuming the dual-loop system retrofit costs $1,000 in material and $1,000 in labor, the simple payback would be 1 month, 20 days. There are approximately 3,500 Walmart discount stores and supercenters in the U.S. Assuming 50% of Walmart's existing store base is similar to the store in this study, Walmart could save 198.5 GWh or $25.4 million by switching to the dual-loop system.

The analysis so far has situated its findings in terms of Walmart and this study, but the implications, including payback analysis, can be extrapolated to other types and sizes of spaces. A store with existing skylights and dimmable fluorescent ballasts potentially could save 0.76 kWh/sf/yr or $0.10/sf/yr. A large retail store, warehouse, industrial facility, or commercial space that has skylights and is using a dimming fluorescent lighting system can multiply these numbers by the area to be controlled and determine their energy saving potential, cost savings potential, and payback.

If a building has skylights and a fluorescent lighting system but no dimmable ballasts, it could be retrofitted with dimmable ballasts and a dual-loop system. Using the assumptions used to calculate Table 1, the dual-loop system could save 315.8 MWh or $40,400 more than a system with no photosensor system. Assuming the dual-loop system costs $1,000 in material and $1,000 in labor and each dimmable ballast costs approximately $65 in material and $30 in labor, the simple payback would be 2.4 years and it would save 2.11 kWh/sf/yr or $0.27/sf/yr (Table 2).

The scenarios described above demonstrate the relevance and potential impact of the dual-loop system. Further scenarios where the dual-loop system could have a significant impact include commercial, instructional, warehouse, and industrial facilities. A space retrofitting high-intensity discharge (HID) high-bay fixtures with high-bay fluorescent fixtures could benefit from a dual-loop photosensor system. Switching from HID to T5HO fluorescent can reduce the connected power by as much as 50% (Thorne and Nadel 2003). Specifying a dimmable ballast will allow the system to incorporate a dual-loop photosensor system and save over 30% more energy than a fluorescent system with no photosensor control system. These examples show the potential of the dual-loop photosensor system to change the photosensor control system market.

Table 1: Energy and Cost Savings for a Dual-Loop System over an Open-Loop System

Average Open-Loop Energy/Ballast/Month	**52.5**	kWh
Average Dual-Loop Energy/Ballast/Month	**43.0**	kWh
Dual-Loop over Open-Loop Energy Savings/Ballast/Month	**9.5**	kWh
Average Energy Cost	**0.128**	$/kWh
Average Cost Savings/Ballast/Month	**1.21**	$
Ballasts/Store	**1,000**	
Cost Savings/Store/Month	**1,210**	$
Months in a Year	**12**	
Cost Savings/Year/Store	**14,529**	$
Energy Savings/Year/Store	**113.5**	GWh
Store Floor Area	**150,000**	sf
Cost Savings/Year	**0.10**	**$/sf**
Energy Savings/Year	**0.76**	**kW/sf**

Table 2: Energy and Cost Savings for a Dual-Loop System over a Fluorescent Lighting System with no Photosensor System or Dimmable Ballasts

Average No Photosensor Energy/Ballast/Month	……….**69.4** kWh
Average Dual-Loop Energy/Ballast/Month	……….**43.0** kWh
Dual-Loop over No Photosensor Energy Savings/Ballast/Month	……… **26.3** kWh
Average Energy Cost	………**0.128** $/kWh
Average Cost Savings/Ballast/Month	………..**3.37** $
Ballasts/Store	………**1,000**
Cost Savings/Store/Month	………**3,370** $
Months in a Year	……………**12**
Cost Savings/Year/Store	…….**40,400** $
Energy Savings/Year/Store	………**315.8** GWh
Store Floor Area	…..**150,000** sf
Cost Savings/Year	**……….0.27 $/sf**
Energy Savings/Year	**……….2.11 kW/sf**

Future Research

The California Energy Commission has acknowledged the need for a reliable, economical dual-loop photosensor system by funding two projects. The first is the commercialization of a dual-loop photosensor control for skylight applications and the second is dual-loop photosensor control for side-daylighting applications.

Commercialization of Dual-Loop Daylighting Controls for Skylight Applications

The dual-loop system has been licensed by three manufacturers and should be commercially available by the end of 2010. Working with WattStopper, a commercial lighting control manufacturer and research partner, the CLTC has experimented with a commercial photocell prototype with some success. When the commercial photocell prototype was used in conjunction with the CLTC control algorithm, the system was able to successfully control the electric lighting in a laboratory environment. The next step is to use a commercial photosensor to control the lighting within a Walmart store and for WattStopper to manufacture a commercially available dual-loop system.

Dual-Loop Daylighting Controls for Side-Daylighting Applications

The CLTC also is exploring the use of multiple photosensors in a laboratory space with windows. The existing dual-loop system for skylight applications works successfully in side-daylighting spaces when window treatments are not used; however, research is ongoing to develop a photosensor system that works with side-daylighting applications and window treatments. This research will provide tremendous energy and cost savings in even more applications.

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