# Sidelighting Photocontrols Field Study

*Owen Howlett, Lisa Heschong, Jon McHugh and Abhijeet Pande,*
*Heschong Mahone Group, Inc.*
*Gregg Ander, Jack Melnyk, Southern California Edison*
*Steve Blanc, Pacific Gas and Electric Company*
*David Cohan, Northwest Energy Efficiency Alliance*

**ABSTRACT**

This paper describes the first large-scale US field study of daylight-responsive lighting controls (photocontrols) in buildings that are lit by windows (sidelighting). The aim was to determine whether any characteristics of the building or the photocontrols were associated with more or less successful outcomes, and how much energy is actually being saved by photocontrols in real sidelit spaces.

Daylit commercial buildings have enormous potential to save energy by switching off electric lighting and reducing their cooling loads, especially during peak hours. Yet anecdotal reports call into question whether the photocontrols necessary to produce these savings are fulfilling their technical potential.

We conducted detailed on-site surveys and monitored lighting energy use in 123 daylit spaces in Washington, Oregon and California. The primary metric of performance was the "Realized Savings Ratio," the ratio of monitored lighting energy savings to the savings predicted by a DOE-2 simulation.

We found that while half of the controls were not saving any energy at all, the top quartile of controls were achieving 82% of their expected savings, based on design of the system. The top quartile of systems averaged 1.1 kWh/sf·yr of savings, equivalent to 51% of the lighting load. They also averaged 0.6 W/sf whole building peak demand reduction in the controlled area, equivalent to 65% of the installed lighting power density.

This paper reports on the various characteristics of the buildings and the photocontrols that were significant predictors of success in saving energy. This information can guide program managers and designers in choosing the best targets for achieving daylight energy savings.

## Introduction and Background

Our team had conducted an earlier large scale survey on photocontrol performance in toplit spaces (i.e., those with skylights[1]). This experience helped us develop some of the analysis methods and concepts for this study of sidelit spaces. However, visual quality issues in sidelit spaces are dramatically more complex due to the changing distribution of light from windows and the directionality and steep illuminance gradients in sidelit spaces. Since this was the first large-scale US field study of the performance of photocontrol systems in sidelit buildings, we collected a very wide range of information about the sample buildings to ensure that we captured most of the potentially significant factors associated with successful photocontrol system performance. The goal was to find out:

[1] Heschong Mahone Group. 2003. *Photocontrol System Field Study*. Report submitted to Southern California Edison. Available online: www.h-m-g.com.

- How much energy photocontrols are saving, as installed and operated in real spaces
- How these savings compare to the expected savings as predicted by simulation models
- If sidelit daylighting systems are serving to reduce peak electricity usage
- If there are any characteristics of the buildings, the control systems or their operation that are more likely to lead to success or failure in practice

**Magnitude of Potential Energy Savings**

Lighting energy consumption in commercial buildings is approximately 33% of all commercial energy end-uses in California[2]. Photocontrols have the potential to greatly reduce both energy use and peak demand in commercial buildings. The California utilities' *Savings by Design* program accrued approximately 9% of its energy savings and 10% of its demand savings from photocontrols between 2001 and 2003[3].

In this field study we found that the top performing quartile of photocontrol systems averaged 51% lighting energy savings (1.1 kWh/sf·yr), and a net peak demand reduction of 0.6 W/sf in daylit areas that they controlled. These values provide a reasonable approximation for the "achievable potential" of sidelit control savings, based on current design, installation, and operating conditions in appropriate applications in West Coast buildings.

If these savings could be achieved in one quarter of the applicable area in new construction in California, about 9 GWh of new savings would be added *each year*, along with 5 MW of demand reduction.[4] In the Northwest these numbers are about 2 GWh and 1 MW.

If photocontrols could be retrofitted in 25% of the national commercial building stock (58 billion sf) and maintain the same magnitude of savings, the savings would be 3,190 GWh per year and 1,740 MW, or about the capacity of four medium-sized power plants.

## Methodology

The study required us to find buildings with sidelit photocontrolled spaces; we estimate (from our own findings and from industry sources) that there are only 200-500 such buildings on the West Coast as of 2005. To ensure a balanced sample we created a sampling frame broken down by building occupancy type and by geographical location. We then conducted phone interviews to screen out buildings without photocontrols, and finally sent the survey team to perform a detailed daylighting survey on site, including installing recording current and illuminance loggers. These loggers collected data for two weeks in the spaces; the surveys were conducted between October 2004 and March 2005.

The detailed survey data was used to develop DOE-2 simulations for each space, which were compared with actual energy consumption during the monitoring period. The comparison of actual savings to idealized savings is the realized savings ratio (RSR). The RSR was used to

[2] RLW Analytics. 2000. *RNRC Baseline Report,*

3 RLW Analytics. 2003. *2003 Building Efficiency Assessment Study - An Evaluation of the Savings By Design Program*, Report submitted to Southern California Edison, Study ID SCE0208.02. www.calmac.org.

[4] Assumes 157M sf added per year in California, 25% with daylighting controls, and 20% of commercial floor area daylit (15' from exterior wall) achieving 1.1 kWh/yr·sf energy savings (and 0.6 W/sf demand savings) from top quartile photocontrols. California data from F.W.Dodge database. National forecast from Commercial Buildings Energy Consumption Survey, www.eia.doe.gov/emeu/cbecs/

extrapolate the two week monitored data to an estimate of savings over an entire year. This extrapolated data was then correlated with various characteristics of the building and the control system, to identify which characteristics are associated with higher energy savings.

### Site Identification and Selection

To find sufficient candidate buildings for this field study, extensive professional networks were tapped to identify a total of 373 buildings that would potentially fit the study criteria, i.e., with daylight provided primarily from the side, and photocontrols installed to reduce electric lighting energy use. Of the 373 buildings identified as likely having sidelit photocontrols, we were able to determine the building *type* for 331. Of these, 36% were schools, 35% offices and 29% "other." Our sample frame goal was to conduct on-sites in a similar proportion of 1/3 schools, 1/3 offices, and 1/3 other.

A phone survey was conducted with the building managers of 162 of these buildings to verify their eligibility, to collect preliminary information and to recruit sites for more detailed on-site surveys. Ultimately, 56 of these buildings were visited, and the monitored performance of 123 spaces in 49 of these buildings was included in the analysis. The final distribution of space types is shown in Table 1. The proportion of office *space* type rose higher than 1/3 since many schools and "other" building types included daylit office spaces.

**Table 1: Number of Surveyed Spaces by Occupancy Type and by Region**

| Location | Classroom | Office | Other | Totals |
|---|---|---|---|---|
| Southern California | 2 | 25 | 13 | 40 |
| Northern California | 28 | 20 | 16 | 64 |
| Northwest | 4 | 10 | 5 | 19 |
| Totals | 34 | 55 | 34 | 123 |

### On-Site Survey Methodology

The onsite survey methodology was loosely based on the study of photocontrols in toplit spaces that we carried out for Southern California Edison in 2003[5]. Since sidelighting is more complex than toplighting, this survey was more extensive. The survey consists of three parts:

- A "host interview" with the person who is responsible for the building's lighting system
- An extensive physical and lighting survey of the space
- Installation of data loggers that record illuminance and circuit current for two weeks

**Host interview**. The host was asked about the history of the system, any problems that had been observed and/or remedied, and how the system was adjusted and maintained. The host took the surveyor on a tour of the building to help select 2-3 spaces for the detailed survey. Spaces were

[5] Heschong Mahone Group. 2003. *Photocontrol System Field Study*. Report submitted to Southern California Edison. Available online: www.h-m-g.com.

selected to increase the diversity of the sample whenever possible. Thus, if two classrooms per school were surveyed, one might be north facing while the other was south facing. If a building had a variety of space types with photocontrols, we selected more than one space type. Some spaces were excluded if the host felt our survey would disturb the occupants. Ultimately, we averaged 2.3 daylit spaces studied per building.

**Survey of the space.** Once the study spaces were selected, the surveyor conducted a physical survey, gathering data on the daylighting, the electric lighting, and the geometry and reflectances of the space and any relevant exterior features. This data was sufficient to create a DOE-2 model of the space, and was also grouped into potential explanatory variables, such as window head height and control zone depth. In addition, a series of hand-held illuminance readings were taken, and photographs taken of the space. The surveyor identified the appropriate study space, the size of the photo controlled zone, and the critical task, as shown in Figure 1. Note that we attempted to characterize the different control algorithms and set-points of the systems but found that this was impossible due to the wide variety of system types.

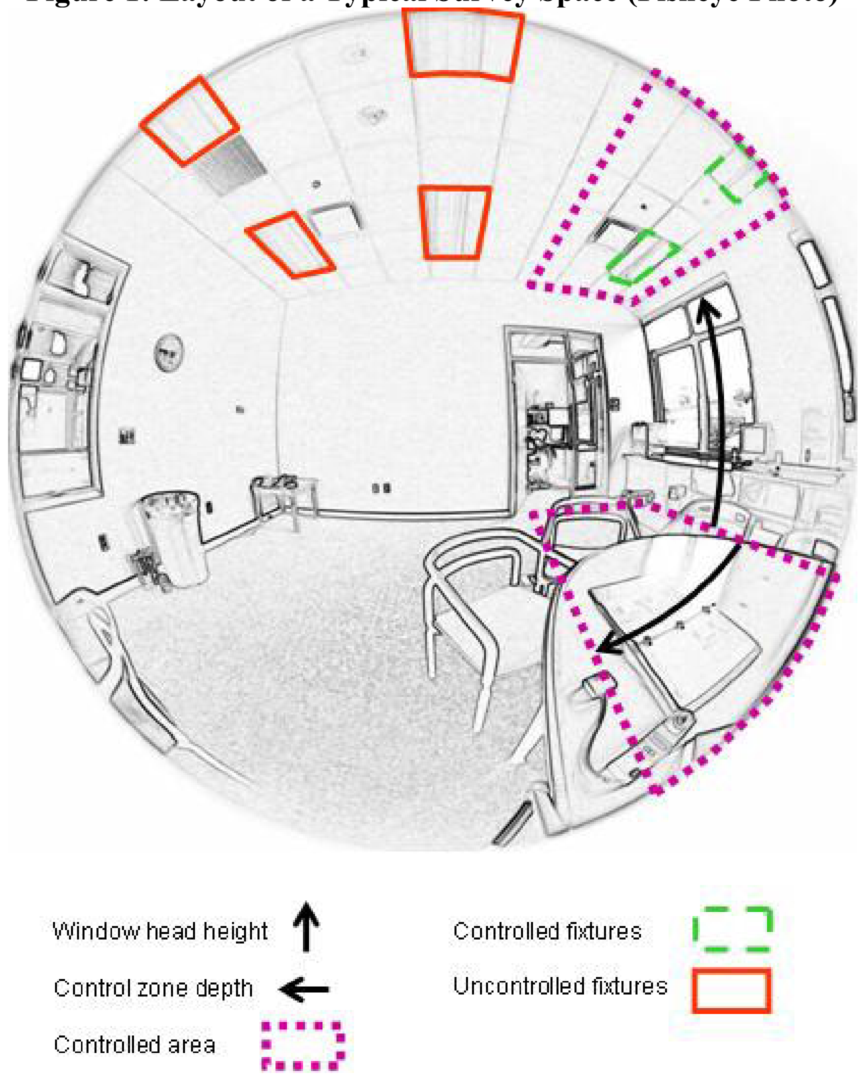
**Data logging**. Data loggers collected current and illuminance data at 5 minute intervals over a two week period. The number of loggers installed varied from three to eight, depending on the complexity of the space. In every space loggers were installed in the following locations:

- **The photocontrolled circuit(s)**. Sufficient loggers were installed to monitor the electrical current (or light output) of every photocontrolled circuit.
- **One or more non-controlled circuits.** Where the space had luminaires that were *not* controlled by the photocontrol system, we monitored these additional circuits as a proxy for the occupancy of the space, to work out energy savings during occupied periods. Note that we did *not* install logging occupancy sensors due to time and budget constraints.
- **The window**. This logger recorded the amount of daylight entering the space (vertical illuminance inside the window pane).

Additional illuminance loggers were installed in the following locations when there was a safe and suitable mounting location and when sufficient loggers were available:

- **The photosensor**. The surveyor placed a logger next to the photosensor (usually on the ceiling) to record the amount of light reaching it. This logger provided more accurate information about how the photocontrol system responded to light, and gave an insight into the functioning of the photocontrol systems, but it was not essential for our analysis.
- **The critical task**. A logger was placed near the critical task. A spot measurement was made with and without the lights on to obtain a ratio of illuminance at the critical task to that at the window logger location for both daylight and electric lighting components of illuminance.

**Figure 1: Layout of a Typical Survey Space (Fisheye Photo)**




The downloaded logger data was processed and checked to ensure that it was free from errors and interference. In 26 out of 123 spaces there was a problem with the logged data, but in all but one case the corrupt data was recovered using redundant data from other loggers. Examples of the logger data recorded in a single space are shown in Figure 2 and Figure 3.

In Figure 2 the photocontrol system is aggressively dimming the electric lights as soon as a modest amount of daylight is available. This type of control is suitable for a brightly daylit space, in this case a small private office. In Figure 3 the lights are only dimmed by about one-third even during the brightest part of the day; this type of control is suitable for more dimly daylit spaces.

**Figure 2. An Example of Logged Data from an Onsite Survey**

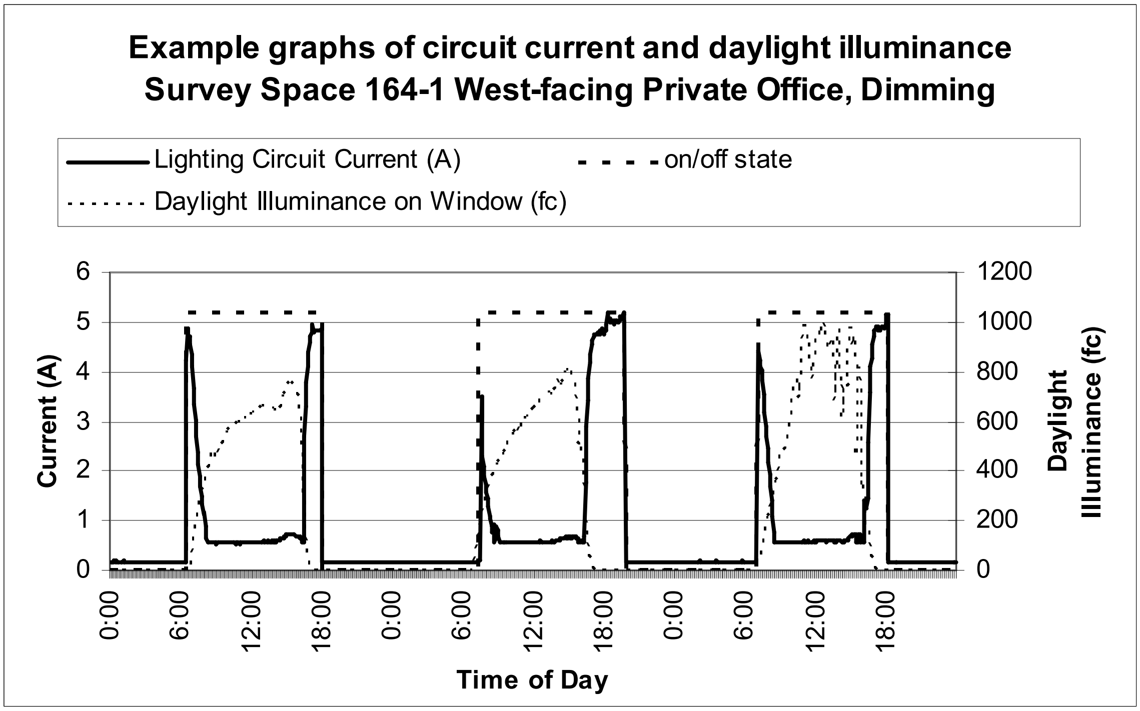
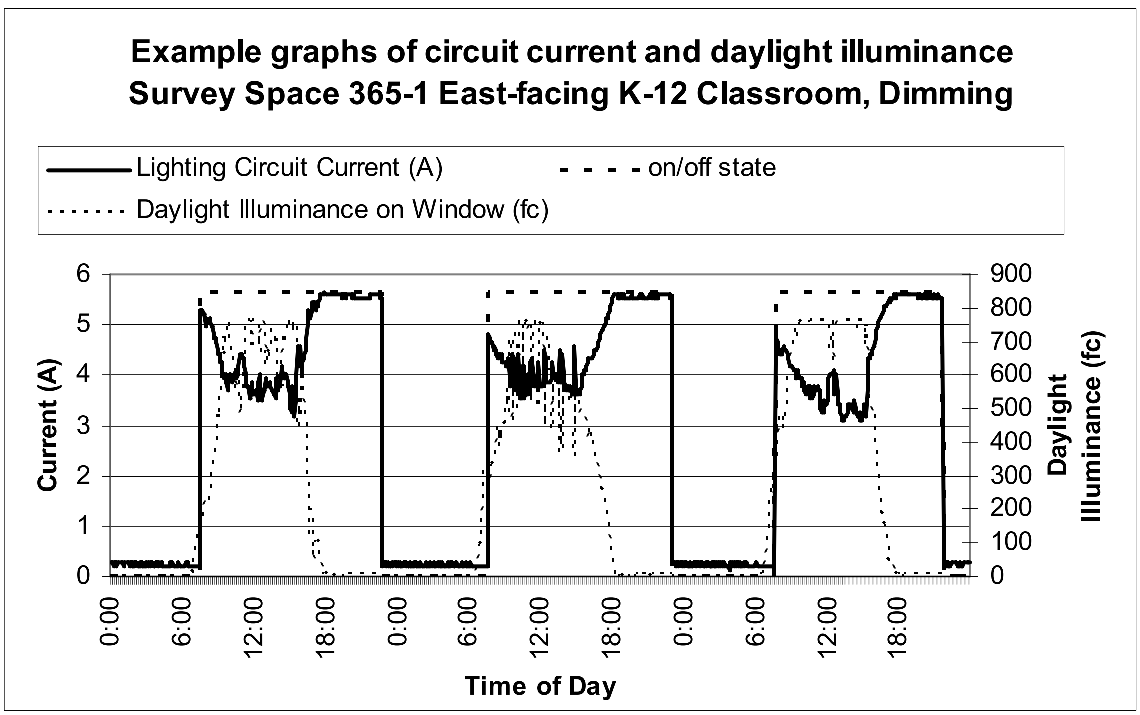



**Figure 3. An Example of Logged Data from an Onsite Survey**



### Building Simulation

Each of the spaces with completed site surveys was modeled using eQUEST, a front end for the DOE-2.2 simulation engine. DOE-2 has some technical limitations such as an inability to model multiple interior light reflections. However, we felt it provided adequate simulation accuracy, and since it's the most commonly used tool to model the annual energy performance of buildings in California, the energy estimates we use in this study are directly comparable with those that would be produced by many designers.

We simulated each of the surveyed spaces four times: with and without photocontrols each for two time periods – one using real weather data collected during the 2-week monitoring period, and the other using Typical Meteorological Year (TMY2) data for an annual simulation. By comparing the measured lighting energy savings with the energy savings simulated during the same period we obtained a measure of how well the photocontrol system is actually working compared to predictions. This ratio of actual savings to predictions from DOE-2 analysis is called the Realized Savings Ratio (RSR). When RSR = 0, the photocontrols are not saving any energy; when RSR = 0.5 it is saving half as much energy as is predicted by DOE-2.

### Statistical Analysis

The analysis of the data looked at two conditions. First we compared all functioning systems (RSR >0) to all non-functioning systems (RSR = 0), to test which characteristics were associated with functionality. Second we looked at which system characteristics were associated with better energy performance (increasing RSR) for the 57 functional systems.

## Results

In this section we discuss the energy and demand savings, failure modes of systems, and the characteristics associated with success and failure. To provide context for these results, here is a brief description of the characteristics of the surveyed spaces:

- 45% of the spaces had windows facing only north and/or south
- The average window head height (including clerestories) was 11.9 feet
- 65% of the control systems were dimming and 35% switching
- The installed lighting power density for the surveyed spaces averaged 1.2 W/sf

### Energy and Demand Savings

There was a considerable range in the achieved savings among the spaces. 64 spaces had non-functional controls and achieved no savings at all; and there were 59 functioning spaces. We classified 28 of the functional spaces as "high functioning" (RSR>0.5) as shown in Table 2.

We found that, on average, the photocontrol systems were saving only one-quarter as much energy as they could, according to the DOE-2 prediction; i.e., the average RSR across all the spaces was 0.26. However, excluding the non-functioning systems, those systems that *were* working were achieving slightly more than half of their predicted energy savings. The "high functioning" systems (approximately the top quartile) achieved on average over 80% of their predicted savings. This demonstrates that significant savings *can* be achieved in many spaces. In Table 2, four outcome variables are quoted:

- RSR as described above
- Annual energy savings in terms of kWh/sf *of photocontrolled area*
- Annual energy savings in terms of "daily full load hours" (FLH). FLH quantifies how many hours of lighting energy the system saved per day, e.g., a ballast dimmed to 50% power for four hours would save two FLH per day.
- Peak demand savings in W/sf *of photocontrolled area.* This corresponds to the average demand saved in the photocontrolled area during the summer peak schedule of the PG&E E-19a energy tariff, during the highest-consumption month (usually July or August). The E-19 summer tariff runs from 12:00-6:00pm from May 1st to October 31st.

The annual values for energy savings and peak demand are calculated by multiplying the RSR by the DOE-2 annual estimates of energy savings. Throughout this study energy savings are quoted as electric lighting energy savings only, i.e., they do not include the effect of electric lighting use on HVAC systems. However, the quoted *demand* savings *do* include HVAC effects.

For comparison, Table 2 also shows the savings achieved by photocontrols in toplit spaces, from a previous field survey[6]. The toplit spaces achieved substantially higher average RSR values than the sidelit spaces mainly because almost all of them were functional. Also, when toplit systems were overridden by occupants, they switched the lamps *off* whereas in sidelit spaces they switched the lamps *on*.

**Table 2: Energy and Demand Savings; For All Spaces, Functioning Spaces, High Function Spaces and Comparisons**

| | **All spaces** | **Functioning (RSR>0)** | **High functioning (RSR>0.5)** | **Comparison: toplighting study (all spaces)** |
|---|---|---|---|---|
| Number of spaces | 123 | 59 | 28 | 33 |
| Average RSR | 0.25 | 0.53 | 0.82 | 0.98 |
| Average energy savings per photocontrolled sf (kWh/sf•year) | 0.4 | 0.7 | 1.1 | 1.2 |
| Average energy savings in daily full load hours (FLH) | 1.0 | 2.2 | 3.4 | Not available |
| Average peak demand savings per photocontrolled sf (W/sf) | 0.2 | 0.4 | 0.6 | Not available |

[6] Heschong Mahone Group. 2003. *Photocontrol System Field Study*. Report submitted to Southern California Edison. Available online: www.h-m-g.com.

## Failure Modes of Photocontrol Systems

Occupant complaints were the most common reported reason for disabling a sidelit photocontrol system, while incomplete or improper installation and commissioning was the second most common cause a system was not working. For 14 failed systems we had no information and/or could not diagnose a failure mechanism.

We did not find any evidence that any photosensors or photocontrols had failed on their own after they had been observed to be working. Indeed, the older systems we studied were saving *more* energy than younger systems. This result suggests that there can be good persistence in savings once a functional system is established. For those systems where we could diagnose a specific failure mechanism, the majority (35/50) had been intentionally disabled: by setting the sensor setpoint too high (17), taping over the sensor (7), disconnecting the wire to the sensor (4), or deactivating the whole system (7).

Other reasons why systems did not function included the system had never worked (5), the system had never been initiated (4), not enough daylight for various reasons (4), incompatibility with the overall building energy management system (1).

## Characteristics Associated with Success or Failure

We searched for statistical links between *characteristics* (i.e., features of the space, the controls or the occupants) and the *outcomes* in terms of functionality and energy savings. These associations are summarized in Table 3. The values shown are the probabilities (p-values) that the effect is due to random variation. The smaller the p-value the more likely it is that a real effect is observed. Values in bold indicate that an increase in that characteristic results in an increase in the outcome variable (energy savings).

We do not report the *magnitude* of the savings associated with each characteristic because we believe the sample is too small and diverse for estimates of magnitude to be stable.

Perhaps the strongest finding is that **more uniform daylighting** and **higher levels of daylight** are both strongly linked with functionality and with higher energy savings. Both these ends can be achieved by having windows on more than one side of the space, by having higher view windows and clerestories, by using windows with a high visible transmittance, by providing high-reflectance finishes on the floor and walls, and by using low (or no) partitions.

Spaces with **off-site management**, i.e. where the building operator would call someone in to repair or adjust the photocontrols, had higher energy savings. Spaces in which **occupants were trained** how to use the photocontrol system were more likely to have functioning systems.

We did not find that the **manufacturer** of a photocontrol system could be used to predict failure or better performance. While two manufacturers dominated our survey, both were equally represented among poorly and well performing systems. **Dimming controls** were more likely to be functioning but saved slightly less energy than **switching controls**.

Spaces with **higher window head heights** had both better functionality and higher savings, and spaces with **deeper controlled zones** had lower savings. Combining these two variables into the “ratio of control zone depth to window head height” produced a variable strongly associated with higher energy savings. This ratio is used in several states and countries as a means of defining the “daylit zone”. The best functioning systems (RSR>0.5) had ratios averaging 1.3 with a standard deviation of 0.4. Thus, 0.9 to 1.7 was the normal ratio for well functioning systems, with a ratio of 2 as the maximum observed, i.e. a control zone depth that was twice the window head height. This suggests that limiting photocontrol zone depth to less than 2 times the window head height is a reasonable guideline.

**Table 3. Significance Levels (p-values) and Direction of Effect for Explanatory Variables (Values in Bold Show a Positive Direction of Effect on the Outcome Variable)**

| Explanatory Variable | Functional (RSR=0 vs. RSR>0) | Energy Performance (for space with RSR>0) | | | |
|---|---|---|---|---|---|
| | | RSR | FLH | EUI | Demand |
| **Control zone** | | | | | |
| Distance of photosensor to window (ft) | | 0.0047 | 0.0010 | 0.0011 | 0.0062 |
| Area of daylit control zone (sf) | **0.0000** | | | | |
| Ratio of ctrl zone depth to window head ht | | | | 0.0700 | 0.0400 |
| Depth of control zone (ft) | | 0.0310 | 0.0040 | 0.0030 | 0.0480 |
| Size of controlled load (Watts) | | | | | |
| **Controls** | | | | | |
| Dimming vs. switching | **0.0118** | 0.0088 | 0.0598 | 0.0835 | 0.0298 |
| Photosensor is looking down | **0.0307** | 0.0309 | 0.0801 | | |
| Multiple circuits vs. single controlled circuit | 0.0000 | | | | |
| **Fenestration Design** | | | | | |
| Ratio of (net Tvis * window area) to ctrl area | | | **0.0021** | **0.0000** | **0.0015** |
| Ratio of window area to control area | | | **0.0056** | **0.0000** | **0.0159** |
| Space has high windows (>8') vs. low only | **0.0325** | | | | |
| Net Tvis of windows w blinds | | | | | |
| Window head height (ft) | **0.0016** | **0.0897** | | | **0.0214** |
| Tvis of glass | | | | | |
| **Luminaires/illuminance** | | | | | |
| Luminaires use direct light distribution | 0.0088 | | | | |
| Illuminance ratio, horizontal min to max | 0.0163 | | | | 0.0776 |
| Illuminance ratio, vertical min to max | | | | | |
| Illuminance ratio, from front to back of room | 0.0008 | | | | |
| Illuminance ratio, horizontal std. dev./average | 0.0002 | | | | |
| **Occupancy** | | | | | |
| Library space v all others | 0.0207 | | **0.0969** | **0.0004** | **0.0046** |
| Classroom space | **0.0005** | | 0.0841 | | |
| "Other" type space | | | **0.0868** | | |
| Office space | 0.0074 | | | | |
| Open office vs. all others | 0.0107 | | | | |
| Owner occupied building | **0.0008** | | | | |
| Private office space vs. all others | | | | | |
| **Operator** | | | | | |
| Building was commissioned | | | 0.0074 | 0.0282 | |
| Building has off-site management | | | | | **0.0549** |
| Occupants were trained about PC system | **0.0009** | | | | |

| Explanatory Variable | Functional (RSR=0 vs. RSR>0) | Energy Performance (for space with RSR>0) | | | |
|---|---|---|---|---|---|
| | | RSR | FLH | EUI | Demand |
| Site host believes system is working (1-7) | **0.0000** | | | | |
| Site host is satisfied w system (1-7) | **0.0012** | | | | |
| **Space and Building Design** | | | | | |
| Number of years of photocontrol operation | | | **0.0004** | **0.0001** | **0.0139** |
| Room size (sf) | **0.0000** | | | **0.0000** | |
| Small bldg (<15,000 sf) vs. all others | | **0.0105** | **0.0284** | | |
| K-12 school building | **0.0012** | | 0.0669 | | |
| Large bldg (>50,000 sf) vs. all others | 0.0002 | | | | |
| Office building | 0.0019 | | | | |
| Space has partitions | 0.0000 | | | | |
| Number of yrs building has been occupied | | | | | |
| Weighted reflectance of surfaces | | | | | |
| Ceiling height in room | | | | | |
| Office building or K-12 school | | | | | |
| **Windows** | | | | | |
| Space has clerestory (vs. no clerestory) | | | 0.0553 | 0.0923 | |
| Daylight comes from only one direction | 0.0150 | | | | |
| Space has north facing windows | **0.0937** | | | | |
| Windows have blinds | | | 0.0133 | 0.0295 | |

Note: some values in this table differ from previously published values, see the addendum to the original report.

### Other Observations

Several of the characteristics which we believe likely to be most associated with successful photocontrols - such as occupant choice of window blind settings, occupant dissatisfaction with the quality of daylight or with the photocontrol interface - have not been extensively researched and cannot yet be easily quantified or predicted. They are not at present included in simulations of photocontrol operation; these include the use of window blinds, and the reasons why occupants become dissatisfied with their photocontrols and decommission them.

Most buildings had either all functional or no functional systems. There were 33 buildings surveyed that had more than one space; in 12 of these all the controls were functional and in 11 none of the controls were functional. Only 10 buildings (30%) had a mixture of functional and non-functional controls. This suggests that whole-building factors are highly influential in determining whether controls are successful.

## Summary of Findings Relevant to Utility Program Designers

**Working systems are saving significant amounts of energy and reducing peak electric demand**. These impacts are on a par with those possible with toplighting (skylighting) per square foot of controlled area, and appear to persist over time. Therefore, photocontrol systems in sidelit spaces offer an important opportunity for energy and demand savings.

**Better energy performance seems to be most attributable to appropriate application and design of the daylighting system *as a whole;*** i.e., the architecture, occupancy type and controls must work well together**.** Helping the design team to understand the success factors of photocontrols early on, and integrate these into the design of the space, is likely to foster success.

**Program efficiency may be increased by focusing on "likely" buildings**. Success is more likely in libraries and schools, spaces without of partitions, low ratios of control zone depth to window height, bilateral daylighting, and whether the building is owner-occupied.

**Occupant dissatisfaction was the most common reason for the failure of photocontrols**. Occupants who became dissatisfied with the system decommissioned it, either directly or via their facilities manager. Systems where occupants were trained were more likely to remain working. Occupants and facilities staff should be familiar with the function of the photocontrols.

**There are several simple design choices that can improve the success of photocontrols**; e.g., using multiple separately-controlled circuits parallel to the window rather than a single circuit for the entire space (reduce the effective zone depth); positioning the photosensor close to the window, designing shallow control zones and avoiding the use of partitions.

## Next Steps

This field study of sidelit buildings is the largest such study to date. The findings presented here are but the first pass at understanding all of the data collected. Further insights are likely from additional evaluation of the data including multivariate regression analysis of all of the variables collected, and further evaluation of the luminance data.

Because so many non-functional systems were found, the next step for the development of photocontrols should logically be to gain more understanding of why systems fail or succeed and why occupants deactivate them. This involves the whole process from product design through building design, installation and commissioning to post-occupancy evaluation.

Though a tremendous amount of data was collected for this study, one very important variable could not be observed – how people control their blinds over time. A field protocol and a low-cost, unobtrusive tool for monitoring the control of blinds over an extended period would be a useful addition to further field studies on sidelit photocontrol performance.

Furthermore, improved metrics that describe the important aspects of the quality and quantity of daylight may help provide more understanding of why some systems succeed or fail, and why occupants are dissatisfied with the daylighting in some spaces.