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Abstract

Photocontrols or "light level controls," which reduce electric lighting in response to sufficient interior daylight illuminance, are the next frontier for saving energy with lighting controls. However, many recent anecdotal reports of photocontrol performance have been negative. Our hypothesis is that many of these negative reports are for photocontrol systems that have been applied to spaces that are sidelit with windows and that the success rate for photocontrols under skylights would be much higher. The rationale for this hypothesis is that skylighting is "easier" than sidelighting – the distribution of light from skylights remains fairly constant regardless of sky conditions or sun position.

This paper describes site surveys of 32 photocontrol systems under skylights, the calculation methods used, and the findings of this study. The primary metric of photocontrol performance developed for this study is the "realized savings ratio," or the ratio of the actual lighting energy savings over a two week period as measured by power monitoring to that predicted by a daylighting simulation using the SkyCalc software and weather station illuminance data over the same period.

The realized saving ratio varied from 25% (little energy savings) to 156% with the mean realized savings ratio of 98%. In all but one case the realized savings ratio was greater than 60%. In many cases, realized savings ratios greater than 100% were self-reported as being due to manual switching. The results of this field study present compelling evidence that photocontrols under skylights reliably save energy.

Introduction

Energy efficient lighting design can be summarized in the following concepts:

1. Provide the appropriate light levels where they are needed. This is the foundation of task/ambient lighting design and is the basis of luminaire selection and placement.
2. Use the highest efficacy (lumens per Watt) source as is appropriate for the task.
3. Provide flexibility to adjust light levels. The need for light varies between people and varies over time or by task performed. Multi-level switching, multiple lighting circuits or dimming provide this flexibility.
4. Turn off electric lighting when it is not needed. Time clocks and timers automatically turn off lighting based on a schedule or a duration of needed light.

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Occupancy sensors directly sense occupancy and turn off lights when areas are unoccupied.

5. Turn off or dim electric lighting in response to increasing levels of daylight in the space. Lights can be automatically controlled in response to daylight through the use of photocontrols or "light level" controls.

This last element of efficient lighting design, photocontrols is the subject of this paper. The subject of photocontrols in interior spaces is quite timely in that they are rarely used, are not very well understood but have the capability of being the next big energy savings opportunity in lighting design.

In well daylit spaces well-designed photocontrol systems can reduce lighting power by 50% - 70% for at least 2,000 hours per year. Where are these daylit spaces? The California Title 24 energy standard describes the "daylit area" as being within 15 feet of perimeter windows or within a cone of light that expands the "footprint of the skylight" by 70% of the ceiling height in all directions. See Figure 1 for a graphical description of the daylit area.

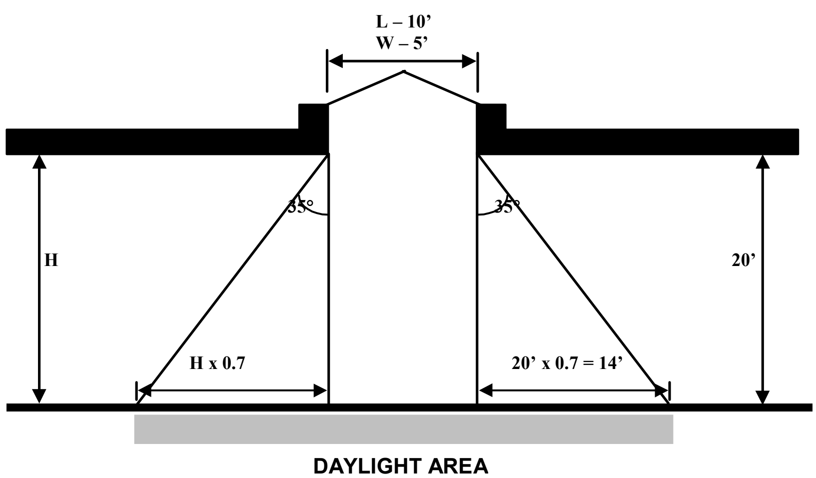

Figure 1: Daylit Area under Skylights in 2005 California Energy Code (PG&E 2002)

From an analysis of the Energy Information Agency's Commercial Building Energy Consumption Survey (CBECS) database, (McHugh et al., 2003) found that approximately 47% of US commercial building space is within 15 feet of the building perimeter, or could be potentially daylit with windows. As shown in Figure 2, this CBECS database contains a breakdown of commercial floor space by number of stories. From this data it is easy to see that 58% of commercial floor space is low-rise and directly under a roof and thus is potentially daylit by skylights.[3] There is an overlap of areas that could be sidelit with windows and toplit by skylights and some of these areas are excessively shaded by other buildings, penthouses, rooftop equipment etc. The

[3] From Figure 2, adding the single story floor area with one half of the two story floor area and one third of the three story floor area results in 42% + 24%/2 + 12%/3 = 58%

primary finding is that around half of all of commercial floor area has the potential to be daylit if buildings are designed for daylighting.

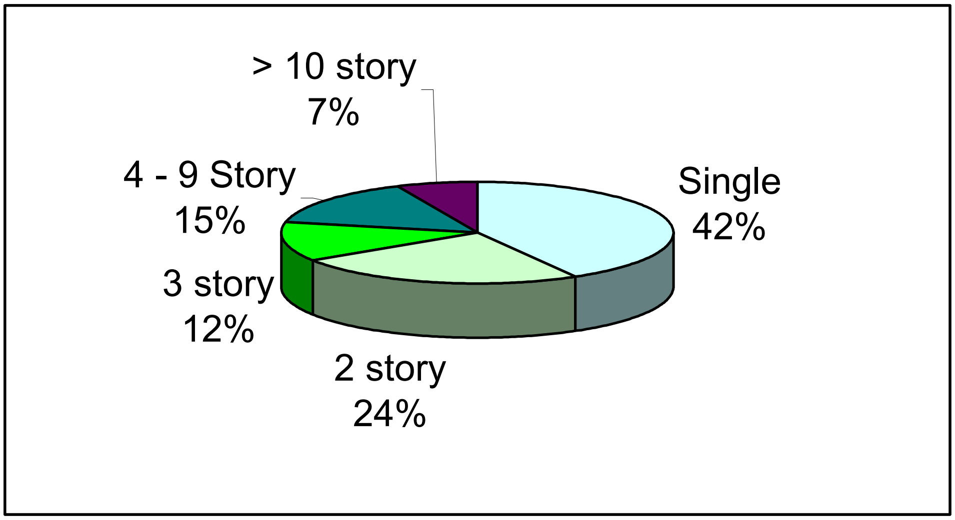

Figure 2: Fraction of Commercial Floorspace by number of stories (EIA 1999)

Some estimates suggest that daylighting can reduce electric lighting consumption by as much as 50% to 70% (Selkowitz & Lee 1998). If we assume that 50% of lighting energy can be saved 2,000 h/yr, or approximately half of the daylight hours, and that it is feasible to daylight only 25% of all potential sidelit areas, the savings are phenomenal. From the US Energy Information Administration publication, "Lighting in Commercial Buildings" (EIA 1992), there are 58 Billion sf of commercial floor space and on average the lighting power density (LPD) is estimated to be 1.4 W/sf.

If we are conservative and assume that only one half of all the areas that could be daylit are can feasibly be daylit (accounting for daylight obstructions, structural or cost issues etc.), the savings from daylighting are huge. The energy savings, ES, from sidelighting with photocontrols applied to half of all the commercial floorspace within 15 feet of a perimeter wall would be approximately:

ES = (Total sf)(fraction feasible)(daylit fraction)(savings fraction)(LPD)(h/yr)

ES Sidelighting = (58 Billion sf)(0.5)(0.47)(0.5)(1.4 W/sf)(2,000 h/yr) = 19,082 GWh/yr

A similar estimate for Skylighting applied to half of all low rise commercial spaces directly under a roof is:

ES Skylighting = (58 Billion sf)(0.5)(0.58)(0.5)(1.4 W/sf)(2,000 h/yr) = 23,548 GWh/yr

There is quite a bit of overlap between areas that could be toplit and sidelit so if both measures were applied the total savings would be less than the sum of these two estimates. The demand savings from sidelighting and toplighting half of the potential areas are around 9,600 MW and 11,800 MW respectively. The potential lighting demand savings from toplighting half of all low rise commercial roofs are comparable to the peak output of 20 medium sized power plants.

However, photocontrols are currently a tiny faction of the lighting controls market. We think that the current photocontrol market is reminiscent of the occupancy sensor market 15 years ago – not very well understood by designers, installers or occupants.

Background

Better understanding of photocontrol performance in skylight buildings is needed now as there is a growing interest in skylighting. Without effective photocontrols, adding skylights to buildings would increase overall building energy consumption whereas with photocontrols energy consumption can be reduced. Reports of increased student test scores and increased retail sales associated with daylighting (HMG 2001, 2003), have school districts and retailers demanding skylights in their new buildings. Another motivating force behind increased skylighting is LEED ratings that provide credit for daylighting and another credit for energy savings when photocontrols are applied.

In the past, photocontrols were recognized as critical for extracting energy savings from skylighting. In the 1989 version of the ASHRAE/IESNA 90.1-1989 standard for energy efficient design of new commercial buildings, a fairly generous skylight area was allowed if photocontrols were installed. However, due to reports of photocontrol failure, newer energy codes such as ComCheck-EZ and the International Energy Conservation Code (IECC) dropped the requirement for photocontrols and drastically reduced the allowable skylight areas. The 1999 revision of the ASHRAE/IESNA 90.1-1999 standard also reduced allowable skylight areas and dropped the requirement for photocontrols.

But as described above, skylighting has the potential to save significant amounts of lighting energy and, in large open spaces, the paybacks from installing skylights with photocontrols are relatively short. The California investor utilities recognize the energy savings potential of skylighting and give incentives to their customers to install skylights and photocontrol systems. The systems that were installed during the 1999 to 2001 program years saved 8.7GWh/yr, or 21% of the energy savings of California's nonresidential new construction energy efficiency programs. (RLW Analytics 2003)

Given that skylighting with photocontrols was very cost-effective in certain applications and was being applied fairly broadly in certain market niches (primarily warehouse, big box retail and groceries) a sea change in thinking about skylighting was under way in the California energy code community. Where skylights were previously seen as a source of heat losses and heat gains, and the role of energy codes was to minimize the impact of skylights, a new consensus began to emerge that skylights with photocontrols was a method of saving energy in commercial buildings and should be required in some circumstances. A detailed technical document described the feasibility, energy savings and cost-effectiveness of such a requirement. (PG&E 2002) Life cycle discounted energy savings over 15 years were 2 to 3 times that of the conservatively high initial cost estimates of skylights and photocontrols. Key in the debate over requiring skylights in the 2005 revision of the California Title 24 building energy efficiency standards was whether photocontrols can reliably save energy.

The Southern California Edison Codes and Standards program funded this study specifically to answer the questions around the reliability of photocontrols under skylights. The intent was to provide systematically collected data to help inform the evaluation of the feasibility of a skylighting requirement in the California Title 24 building energy efficiency standards.

Hypothesis

The primary hypothesis of this research was photocontrols in skylit spaces are more likely to work than is popularly believed. One explanation for this is that these opinions are formed based upon anecdotes rather than a systematic evaluation of successes and failures. When controls work properly no one notices but when they fail the lights are too dim and people remember this instance of failure. The other explanation is that photocontrols are lumped together regardless of the application and no differentiation is made between photocontrols in toplit versus sidelit applications. We expect photocontrols under skylights to work better and to be less frequently disabled than those used with sidelighting for the following reasons

1. Effective sidelighting design is more difficult than skylighting. Sidelighting often has high luminance gradients between the windows and task, and the spatial distribution of daylight can be changing during the day. With skylighting, the source is mostly out view and though the magnitude of daylight changes over the course of the day, diffusing skylights limit the change in spatial distribution of light.
2. Calibrating closed loop photocontrols for sidelit spaces often requires a nighttime and daytime calibration to account for the difference in the ratio of light on the task to that from daylight and the ratio of light on the task to that from electric light. (Rubinstein et al., 1989) Since skylights and electric lighting are in the same general location (above the task) often they have similar ratios of task to photosensor illuminance – this allows for a simpler control and a simpler calibration procedure.
3. Photocontrols are more likely to be disliked and disabled in spaces with static tasks and where the occupant feels they have personal ownership of the space is the case in personal offices. We thought that many toplit spaces, such as retail and warehouses, would be less likely have static tasks and personal ownership than many of the traditionally sidelit spaces of offices and classrooms. Post-occupancy research by the Building Research Establishment (BRE) found that occupants of small offices want control over their lights (Slater 1996).
4. Sidelit spaces often require more control points because the controls must account for occupants in adjacent spaces adjusting blinds to different tilt angles. Usually skylights have no sun control outside of glazing diffusion. Thus a single photocontrol will control a larger number of light fixtures in a skylit space. As a result, each photocontrol system has a greater financial impact– this places more emphasis on correctly calibrating the control. It is less likely that photocontrols, which control a large grouping of lights, can be disabled without someone being aware of the negative financial implications of operating electric lighting unnecessarily.

Though the above discusses the relative reliability of savings from sidelighting versus toplighting, this study is not a comparative one. The purpose of the study is to investigate in a systematic manner the monitored energy savings of photocontrols in toplit buildings and how these measured results compare with calculated predictions of their theoretical performance.

It was also hypothesized that in skylit buildings, open loop controls would be more reliable and thus have higher realized savings ratios than closed loop systems. Open loop controls which sense daylight only are less complex than closed loop controls which sense both daylight and electric light. Open loop controls typically position the photosensor in the light well pointing up towards the skylight. Closed loop controls typically mount the sensor pointing down and receiving reflected light from both the skylights and the electric lighting system. In addition to the correctly adjusting the setpoint for turning lights off, closed loop switching controls must have the deadband between lights on and off, correctly adjusted. Deadband adjustment in open loop systems is relatively simple and can be a small fraction of the setpoint value.

Method

The project involved three distinct phases: site selection, site data collection, savings analysis.

Site Selection

We initially generated a list of 150 buildings in the Southern California (primarily SCE's service territory) from various SCE program databases and photocontrol systems and skylight manufacturers, lighting designers, and architects.

We prepared a telephone survey with approval from SCE aimed at screening each building to ensure their eligibility for participation in the field study. We completed phone interviews for 62 eligible sites in total. The objective of the script was to identify that the building contained a photocontrol system and to obtain permission to conduct the on-site survey. We also confirmed our information about the key photocontrol system characteristics in each building. The scheduling for the on-site survey was completed at the end of each call. Of the 62 eligible sites, we were successful in scheduling on-site surveys on 46 sites.

On site procedures

We collected site level characteristics on all the 46 sites scheduled during the telephone surveys. We developed a standard data collection protocol in order to ensure that we collected the same information on all the sites, with similar levels of detail. Further we developed a set of data entry forms that the surveyors used to note the onsite information.

There were three main components to the survey on each of the sites visited during this project –

Onsite Interview

While the initial telephone interview provided basic information about the building in order to facilitate the onsite survey, the onsite interview focused more on the practicalities of operating and maintaining the photocontrol system. The surveyor interviewed the site contact, and also the space users when possible to get different perspectives on the photocontrol system performance. Where the decision maker was different from the site contact, the surveyor interviewed the decision maker in addition to the site contact and users. The onsite interviews collected historical information such as the age, level of satisfaction, nature of problems, maintenance practices and suggestions about installation, design and maintenance practices for photocontrol systems as expressed by the site contact.

Inspection of the system

After conducting the short interview(s) the surveyor then proceeded to record the physical and control characteristics of the space using standard data entry forms. The data collection included various tasks such as recording -

a. Physical space characteristics
    a. Space dimensions, skylight dimensions and spacing, surface color and textures
    b. Electrical lighting layout, type of light fixtures, ballasts and circuit layout
    c. Task layout
b. Control system characteristics
    a. Photo-sensor location, manufacturer and make, orientation
    b. Photo-controller location, manufacturer and make
    c. Other control equipment location and manufacturer
    d. Control layout
    e. Physical signs of failure, equipment damage, tampering
c. Record data on
    a. Daylight and electric light levels at various task levels and locations in the space
    b. Power consumption of the electrical system in various control conditions (as permitted by site conditions)

Monitoring lighting energy consumption

While sample light level and power levels were measured during the site visit, energy consumption of the lighting system was recorded over a two week period to judge the performance of the photocontrol system over a variety of outdoor illuminance and sky conditions. The surveyors therefore installed portable current dataloggers on the lighting circuits identified during the site visit as being controlled by the photocontrol system.

Of the 46 sites we visited, 3 sites had occupancy sensors not photocontrols, 4 sites were sidelit and were not to be analyzed to limitations of our energy analysis tool (SkyCalc) and 7 sites had logger problems so the data was not collected. Thus the energy savings verification was conducted on 32 of the 46 sites visited.

Energy Savings Analysis Method

The metric used to evaluate how well photocontrols are performing is comparing how much energy they actually did save during the metering period as compared to how much energy one would predict would be saved based on calculations of daylight availability and photocontrol response. This metric we called the Realized Savings Ratio and is given in the equation below.

$$\text{Realized Savings Ratio} = \frac{\text{Measured Energy Savings}}{\text{Predicted Energy Savings}}$$

The predicted energy savings is the theoretical energy savings for a given control in a building having the characteristics of the building analyzed. But the predicted energy savings is the theoretical savings for that control not the optimum savings because a better control may have been used. So if the lighting system we are evaluating is a single step on/off control, the comparison is terms of that control and not in terms of a multi-step control that might save even more energy.

The predicted energy savings are based on the control specific lighting energy savings algorithms as contained in the SkyCalc skylighting design software. These algorithms are described in (Heschong & McHugh 2000). As an example of the predicted energy consumption of lighting using these algorithms, Figure 3 illustrates a two level plus off control and a fluorescent dimming control. It should be noted that dimming controls are specific to the lighting technology controlled. At minimum light output, the fluorescent system consumes approximately 20% of rated power whereas a metal halide system consumes approximately 60% of rated power. This algorithm calculates the lighting power fraction with respect to interior daylight illuminance (foot-candles) for a given design illuminance of the system.

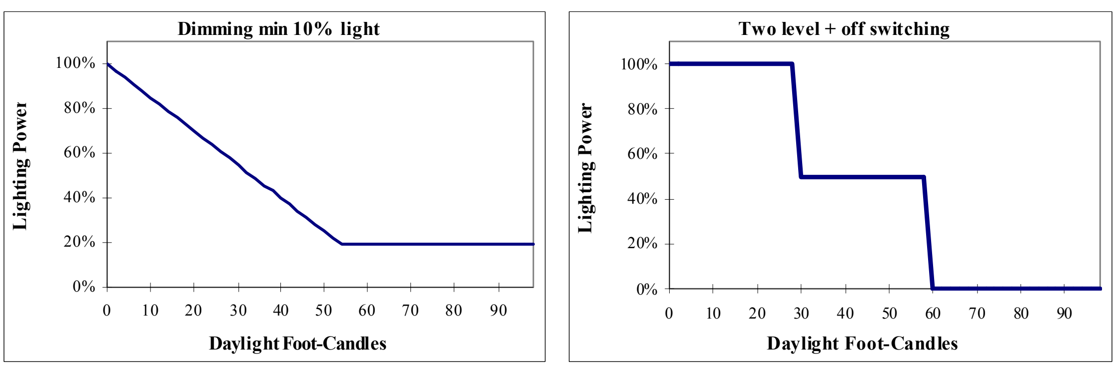

Figure 3: Plot of Fluorescent Dimming and Two-Level Switching Lighting Control Functions

Thus the predicted energy savings fraction is a function of the interior illuminance and the type of control used. To calculate interior illuminance, we made use of the Lumen Method for Skylighting as described in the Daylighting chapter of the IESNA Handbook (2000).

Interior illuminance is the product of the Daylight Factor and the outdoor global horizontal illuminance. As shown below the Daylight factor describes the fraction of light that makes it from outdoors to the work surface inside.

Daylight factor = SFR x Tvis x WE x DF x CU

where,

SFR = skylight area to floor area ratio, essentially the fraction of the roof that is transmitting.

Tvis = overall visible transmittance of skylight glazings and diffusers or lenses in the light well

WE = well efficiency, the fraction of light entering the well that leaves the light well. We use the algorithms developed for SkyCalc that perform a Lumen method calculation for the light well with the ceiling reflectance equal to 99% and the floor reflectance equal to 0% and the wall reflectance equal to the average reflectance of the light well walls.

DF = Dirt factor, this accounts for dirt build-up on the skylight and in the light well. This analysis used a 70% dirt factor as recommended in the IESNA handbook for horizontal glazing in clean areas.

CU = Coefficient of utilization, the fraction of light leaving the light well that makes it to the "work surface" 30 inches above the floor assuming a Lambertian distribution of light.

Calculating Ambient Illuminance from Weather Data

The Southern California Edison electric utility has a network of weather stations collecting hourly temperatures, relative humidity, and global horizontal irradiance (the total heating power of sunlight across all wavelengths). Our project was able to obtain this weather data coincident with the period that lighting energy was monitored. However what we really needed was ambient illuminance.

If one knows the spectral distribution of sunlight then the illuminance can be calculated as well as the luminous efficacy (lumens per Watt) of sunlight. The spectral distribution and thus the luminous efficacy of direct beam sunlight varies by sun angle, turbidity and moisture content. Diffuse light from the sky has a higher luminous efficacy than direct beam sunlight. Thus it was necessary to decompose global horizontal irradiance into direct beam irradiance and diffuse horizontal irradiance. This was accomplished by calculating, K_T, the ratio of global horizontal illuminance to extraterrestrial illuminance and then applying the Erbs (1982) correlation, which yields the ratio of diffuse irradiance to total irradiance. Multiplying this ratio times global horizontal irradiance yields the diffuse irradiance. Subtracting diffuse irradiance from global horizontal irradiance provides horizontal beam irradiance.

Direct beam luminous efficacy and diffuser luminous efficacy can now be applied to the components of sunlight. These luminous efficacies can be calculated by means of the Perez et al. (1990) correlation to irradiance, Zenith angle, air mass and dewpoint temperature. Multiplying the calculated efficacies by their corresponding components of irradiance yields direct beam and diffuse ambient illuminance. Global horizontal illuminance multiplied by the daylight factor calculated earlier gives the interior workplane illuminance. From this calculated interior illuminance predicted energy savings estimates are generated. This estimate forms the basis of the comparison to the measured energy savings and the Realized Savings Ratio.

Results

Results from phone interviews, site interviews and the comparison of monitored data to energy savings estimates were compiled and compared to identify trends in the data. The information below summarizes a larger analysis contained in the Photocontrol Field Study final report. (HMG 2003b)

Phone interviews

Of the 62 sites eligible for the study, a majority of the sites were commercial and industrial warehouses (40%), followed by retail (27%), manufacturing (19%), offices (8%) and school classrooms (5%). Most of the eligible sites were large buildings (100,000 sq. ft +) which corresponds to the nature of the building occupancy. Over half the sites were reported to have all their lights on photocontrols, while the rest had portions of their lights on photocontrols.

On site interviews

The surveyors asked the building operators about their satisfaction levels with the photocontrol system operation with the intent to find out if the building operators felt that the photocontrol systems were performing per their expectations. The expectations of the site operators do not always reflect the design intent, and in many cases the building operators are not aware of the design intent. It should be noted that these observations do not always match up with the actual state of the control system, as observed through short-term monitoring reported later in this paper.

User satisfaction was reported on a subjective scale, and categorized as -

1) *Photocontrols working well* – Site operators were satisfied with the control system operation, and the control system controlled the lights as per the site operators' expectations on 16 of the 46 sites.

2) *Photocontrols working with problems* – The site operators reported satisfaction with the control system, but wished that the system worked a little better on 20 of the 46 sites. The problems ranged from lights being controlled too often causing cycling of lights, to lights being controlled too conservatively, resulting in the system keeping the lights ON when the operators would prefer them to be OFF. Of these 20 sites, 13 sites reported that the problems exist since the time of commissioning, indicating the commissioning process may have not completely succeeded in satisfying user needs. It could also point to possible disconnect between design intent and site operators' expectations.

3) *Photocontrol not working* – The photocontrol systems were reported to be installed but never turned lights OFF or dimmed the lights as programmed on 2 of the 46 sites. One of the two sites was a recent construction and the system had not been fully commissioned yet. At the second site, the system had been commissioned but it never worked as intended despite repeated attempts at troubleshooting.
4) *Photocontrols with supplemental switching* - The building operators often (at least once a day) supplemented the photocontrol systems by manually turning the lights OFF on 4 of the 46 sites visited. The stated reason was incorrect setpoints (too high). Setpoint is the threshold illuminance level set for the photocontrol system to control the lights. Thus users wished for more aggressive savings than possible with the more conservative photocontrol system configuration.
5) *Photocontrols overridden* – The building operators often (at least once a day) overrode the photocontrol systems by manually turning the lights ON at 1 of the 46 sites visited (a warehouse). The system had been commissioned when the high stacks were empty. Once the stacks were stocked, the boxes partially blocked light from skylights directly above the stacks, reducing the total light coming into the space. To get adequate light in the space, the users often bypass the photocontrol circuit by using a manual switch to turn the lights ON.
6) *No photocontrols* – On these sites, no photocontrol system was installed. Instead either an occupancy sensor or time clock was controlling the lights.

Inspection of the system

Of the 46 sites visited, the greatest number of sites (44%) was classified as manufacturing/warehouse, and the second most common (37%) was retail. About 10% of the sites were classified as offices and 10% as classrooms. The manufacturing/warehouse and retail applications account for the 'low hanging fruit' in the existing potential for daylighting controls, as these building types typically have large open spaces that can be easily skylit to provide uniform daylight penetration.

The building vintages ranged from buildings commissioned in 1993 to buildings commissioned in 2002. However, 29 of the 46 buildings were commissioned in the last three years. 7 of the 46 buildings had been retrofitted with photocontrols, and the retrofits had occurred in the last three years. The building vintages for these sites were adjusted to reflect the photocontrol system vintage.

We found two main lighting system types in the survey population – HID (high intensity discharge) and fluorescent luminaires. The HID's were found predominantly in the manufacturing/warehouse spaces while the fluorescents were common in the office and classroom buildings.

We found five different types of controllers in the buildings surveyed: a. fixture integrated photosensors that control a single light fixture (3 sites); b. Outdoor sensors adapted to control indoor light fixtures by facing the sensor to the sky (3 sites – all warehouses); c. Power packs (relay switches) that control light fixtures using input from a photosensor, time clock or occupancy sensor (8 sites); d. Centralized control panels that can control various lighting circuits and zones (13 sites); and e. EMS tied control panels that allow EMS overrides for load management, emergency shutdowns, time sweeps etc. (16 sites). We also surveyed three sites that turned out not to have photocontrols but occupancy sensors.

We analyzed the observed site data to seek patterns of success or failure of the photocontrol systems (as reported by site operators) associated with specific site characteristics. We compared various building and photocontrol characteristics against the six photocontrol operational status definition explained above in the site interview section. We found that the failure rates did not coincide with any particular characteristic of the lighting system (lamp type, circuiting etc), control algorithm (hi/lo, on/off, dimming etc), controller type (fixture mounted etc), control type (open loop vs. closed loop) as well as the age of the system and the amount of daylight in the space.

While the problems were not reported to be associated with any mechanical failure of the equipment, or with any of the building, lighting system and photocontrol system features, the problems were reported to be existing from the time of commissioning of the systems on most sites. Most commonly reported problems hinted that the photocontrol systems were not calibrated properly and therefore did not control the lights as effectively as the site operators expected, and as a result there is a possibility that few users may override them occasionally.

The site operators also showed a general lack of knowledge on how to change the photocontrol system setpoints and other settings, and the documentation on the procedures to do so was minimal at best on most sites. While the site operators had asserted during the telephone screening survey that their buildings had photocontrol systems, we still encountered three sites that did not have any photocontrols installed. Site operators on these three sites confused occupancy sensors with photocontrols.

Predicted and Measured Energy Savings Comparison

For any given system, the realized savings ratio expresses the scope for improvement in system operation, while predicted annual energy savings provide the significance of the photocontrol system savings. The predicted annual energy saving from each system was the product of the SkyCalc estimates of annual energy consumption and the realized savings ratio. The key assumption is that over the course of the year, the system will save the same fraction of the estimated photocontrol energy savings as was saved during the monitoring period. Only 32 sites were both toplit and had monitored power consumption data.

The first task was to verify if the user reported operational conditions matched the actual system performance data. We re-classified all the sites under two categories – systems that were operational without any manual controls (Fully Automated), and systems that had some level of manual control (Manual Assist). Two thirds or 21 sites were fully automated while 11 sites were manual assist. Sites included in the ‘manual assist’ category included:

1) Occasional Manual Control – to provide additional savings than what the photocontrol system alone can provide. Here the photocontrol system is still

controlling the lights, but the users manually control lights occasionally to supplement the photocontrol operation. (5 sites)

2) Consistent Manual Control – to achieve savings that the photocontrol system could not provide. Here the photocontrol system is not disabled, but the users follow a regular schedule for operating the lights through manual control. (4 sites)

3) Overridden System –the photocontrol system is regularly bypassed by the users through a manual switch due to dissatisfaction with its operation. (1 site)

4) Disabled System – this is an extreme case where the photocontrol system is permanently disables by the users due to dissatisfaction with its operation. (1 site)

In all the cases it is possible for the lights to be turned OFF or turned ON through manual action. We observed that only one site from the 11 sites categorized as manual assist was actually physically disabled. It is also important to note that of the 11 manually overridden sites only one site was overridden to be ON. The other 10 sites were using manual switches to turn the lights OFF, thus indicating that the users are supplementing energy savings by making use of their manual controls.

Table 1: Monitored sites with skylights and photocontrols

Building Type	***Fraction of Sample***	***Fully Automated***	***Manually Assisted***
Mfg/Warehouse	*50%*	*10*	*6*
Retail	*38%*	*10*	*2*
Office	*3%*	*1*	*--*
Classroom	*9%*	*--*	*3*

Table 1 illustrates the types of buildings that use skylights. Even though efforts were taken to locate a sample that represented each building type, 88% of the skylit buildings are either warehouse or retail.

This table also illustrates the impact of occupancy type on likelihood of manual intervention. Manufacturing and warehouses have large open areas that are amenable to automatic control. However, these sites usually do not necessarily have an energy manager and there are not aesthetic considerations about lights being controlled manually. Nonetheless, 2/3s of the systems we surveyed reported little manual control of lights. In contrast, retailers often have an energy manager who will try to maximize energy savings from lighting controls while being very conscious of minimizing under-lighting. Thus these systems are very well controlled and only 17% of the sites were manually controlled. These site surveys were conducted in summer/fall 2002, soon after California's energy crisis, and it is not surprising some store managers may use manual controls to show their concern for saving energy. In classrooms, teachers are turning off lights earlier than the photocontrol systems. Since the photocontrol is adjusted centrally, the teachers have no ability to adjust the lighting setpoints of the photocontrol systems and must rely on manual switches to reduce light levels. With a sample size of one we cannot say anything definitive about offices. Thus we can rank occupancies that are most likely to have fully functioning photocontrols from highest to lowest as follows: retail, manufacturing/warehouse, schools.

We then compared the revised system operation status to the user reported system status as shown in Table 2 below. The four manual assist categories are combined together for ease of presentation.

Table 2: Comparing User Satisfaction with Actual System Performance

User Satisfaction (subjective assessment)	***Actual Performance (# Sites)***		***Mean Predicted Savings (kWh/sf.yr)***	***Mean Realized Savings Ratio***
	Fully Automated	***Manual Assist***		
Working Well (13 sites)	13	--	*1.58*	*0.96*
Working (14 sites)	7	7	*0.90*	*1.02*
Not Working (2 sites)	1	1	*0.62*	*0.36*
Supplemented (2 sites)	--	2	*0.83*	*1.28*
Overridden (1 site)	--	1	*1.16*	*0.69*
Total # sites (32)	*21*	*11*		
Mean Measured Savings (kWh/sf.yr)	***1.39***	***0.79***		
Mean Realized Savings Ratio (RSR)	***0.92***	***1.07***		
Std. Dev. of RSR	***0.15***	***0.34***		

All 3 sites that the users had reported to be manually overridden or supplemented were indeed being operated manually, while 7 of the 14 sites with some problems were being manually controlled in addition to photocontrols. All the 13 sites categorized by the users as working well were operational without the need for manual control of lights.

Data in Table 2 also shows the mean predicted annual savings for the sites under various categories. It was seen that the sites categorized by users as working well had the highest predicted savings with a mean savings of 1.58 kWh/sf. The sites that were working with some problems had much lower predicted savings with a mean savings of 0.90 kWh/sf. This implies that buildings with fewer skylights were more likely to require manual intervention. The last row of the table also shows the predicted mean savings for the operational systems and manual overridden systems overall. The operational systems had a much higher predicted savings with mean savings of 1.39 kWh/sf, while the manual assisted systems had mean savings of 0.79 kWh/sf.

While the mean predicted savings describe the size or magnitude of savings, it does not indicate how much the system is performing in reference to its theoretical savings potential. The realized savings ratio provides the comparison of actual savings to theoretical savings. While the manually assisted systems have a lower mean measured savings they have a higher realized savings ratio than the fully automatic systems. Combining the two criterions, it may be surmised that the users are more prone to manually assist systems that have lower predicted savings, and achieve more savings on such sites through more aggressive lighting control strategies. It is however not clear how persistent savings from manual assist will be over time, when public consciousness of the energy crisis declines. Not surprisingly, there is a much larger variance in the performance of systems that are manually assisted than systems with fully automated controls as seen by the standard deviation of the realized savings ratio in Table 2.

Further, we did not find any correlation between the status of the photocontrol system operation to the various system characteristics. Systems were being manually assisted partly due to increased energy awareness from the 2001 energy crisis in California, and partly due to commissioning errors with setpoints.

Contrary to our hypothesis that open loop controls would be more reliable than closed loop controls, this survey did not find any correlation between realized energy saving ratio and control type. Closed loop controls have a realized savings ratio of 1.01 whereas closed loop controls had a realized savings ratio of 1.04. However, one third of the control systems were not identified as either open loop or closed loop as site staff was unable to locate the photosensor and the sensors were not located by surveyors during the brief on-site survey.

Conclusions

Photocontrol systems in toplit spaces were found to save very closely to the amount of energy as predicted. The entire sample of 32 skylit buildings with photocontrols had measured savings that were 98% of theoretical energy savings.

Savings would have been lower if occupants did not supplement savings by turning off lights when sufficient daylight was available but the setpoint of the photocontrol had not been exceeded. This manual switching strategy was often used because site staff often did not know how to adjust the photocontrol system. This implies that user interface and commissioning instructions could be improved. It is also indicative that this technology is still fairly new and not well understood. This finding that staff doesn't adjust the control settings highlights how important initial commissioning is to long term energy performance of the systems.

From a review of manufacturer's literature, we found that there was not much guidance to installers on the step by step methods required to commission photocontrols systems or to lighting designers on placement and selection of controls. To fill this gap Southern California Edison published the Photocontrol System Design Guidelines (HMG 2003c). These guidelines provide a generic format for developing more specific guidelines for their products.

From interviews with site staff, 2/3s of photocontrol systems were working or working well. The high realized energy savings ratio bears out that this is not just a perception but reflects actual energy savings.

Photocontrols with toplighting is a cost-effective and sustainable method of saving energy. Thus it should be incorporated into commercial building energy efficiency policy as it has been in California. Other regions should consider the value of photocontrols with skylighting in their energy efficiency programs and energy codes. The ASHRAE/IESNA 90.1 efficient building design committee is encouraged to revisit skylighting as an energy efficiency measure in new commercial building standards. At the very least the 90.1 committee should require photocontrols whenever the skylight area exceeds some threshold amount. In the 2005 California Title 25 building standards photocontrols or an astronomical timeclock are required whenever the daylit zone under skylights in a room exceeds 2,500 sf.

This study did not address the reliability of photocontrols when used in conjunction with sidelighting. Given the large technical potential savings from this technology, we think photocontrol research for sidelit applications is in dire need of systematic study including site surveys.

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