Pacific Gas and Electric Company

Emerging Technologies Program

Application Assessment Report #0816

Advanced Skylights- Passive: Solatube 750DS

Issued:	**10/ 31/09**
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PG&E Emerging Technologies Advanced Skylights- Passive: Solatube DS750

Project Report for Site II – Solatube 750DS Skylight

HMG Project No: 0515q ET Adv Skylights

Date: October 29, 2009

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ACKNOWLEGMENTS

This report is one of two final project reports for the Pacific Gas and Electric's (PG&E) Emerging Technologies project on Advanced Skylights. The project and the research presented herein was carried out by the Heschong Mahone Group Inc. PG&E project manager was Daryl DeJean, senior program manager was Thor Scordelis.

HMG senior project manager was Mudit Saxena, who was responsible for overall project management, research direction, analysis and report writing; principal in-charge was Lisa Heschong, who provided oversight and input. The HMG team that worked on this project consisted of research associate Joshua Rasin, who was the technical lead on data analysis, and in charge of the data collection and site visits; Derrick Leung, who assisted in site visits and data collection, and Seth Wayland, who performed the statistical analysis.

1. EXECUTIVE SUMMARY

The objective of this study was to determine and quantify the advantage of light-redirecting technology employed in 'advanced' skylights as compared to 'standard' skylights. Here advanced skylights are defined as skylights incorporating technology which enables optical redirection of low-angle sunlight into the building, and high-angle sunlight away from the building. Advanced skylights use either 'active' or 'passive' technology. An advanced skylight with active technology employs use of moving parts such as rotating mirrors inside the skylight dome, while one with passive technology has no moving parts and uses advanced optics on the skylight dome surface. Both types of advanced skylights claim better overall daylighting performance by increasing amount of daylight during hours with low angle sun, and reducing HVAC cooling loads during hours with high angle sun.

To accomplish the objective of this study, we monitored energy use in a building (hereon called study space) with 'advanced skylights'. We compared that to monitored or estimated energy use for the same building with 'standard skylights' and 'no-skylights'. Where it was not possible to monitor actual energy use for 'standard' and 'no-skylight' cases, we used DOE 2 (eQUEST) simulation to estimate the energy use. Our study chiefly focused on lighting energy savings through automatic photocontrols in the study space and HVAC energy savings. An analysis of net energy use in each case was done to quantify the advantage of advanced skylights over standard skylights and no-skylights. We also surveyed occupants of the study spaces to understand occupant satisfaction and determine if there were any problems with visual quality of the daylighting in the space from the advanced skylights.

The study plan was to monitor and compare energy usage in three sites with different advanced skylight technologies. However due to time constrains and limitations of site availability, the pursuit of a third site was dropped. The two sites monitored were

Site 1: An installation of **Ciralight's Suntracker** skylights at a warehouse style retail store in Martinez, CA.

Site 2: An installation of **Solatube's DS750** dome skylight at a bookstore in Santa Cruz, CA.

This report describes the second of the two studied sites. The Solatube 750DS skylight is a passive system that employs advanced optics the surface of the skylight dome to intersect and redirect lower angle sunlight.

1.1 Lighting Energy Savings

We calculated *lighting energy savings* for the standard skylights case (on-site monitoring), advanced skylights case (on-site monitoring), and no-skylights case (DOE 2 estimate), and by solar altitude angles (5 deg bins). Figure 1 shows the percent lighting energy savings compared to no skylights, calculated by solar altitude angle bins. The last column shows the difference in percent lighting energy savings between standard and advanced skylight cases.

Site 2 (Solatube)				
Solar Altitude	STANDARD Skylight - % Ltg Energy Savings	ADVANCED Skylight - % Ltg Energy Savings	ADV vs STD	
0	18.3%	**19.3%**	1.0%	
5	29.0%	**56.7%**	27.7%	
10	29.8%	**48.1%**	18.3%	8.3%
15	34.7%	**43.1%**	8.4%	
20	50.2%	**67.8%**	17.5%	
25	**50.5%**	24.6%	-25.9%	
30	44.6%	**78.6%**	33.9%	
35	**45.7%**	37.6%	-8.2%	
40	48.5%	**76.5%**	28.0%	
45	**61.8%**	48.6%	-13.2%	7.6%
50	**57.0%**	55.0%	-1.9%	
55	61.8%	**78.9%**	17.1%	
60	57.3%	**59.2%**	1.9%	
65	**85.1%**	72.6%	-12.5%	
70	NA	**59.4%**	NA	
75	NA	**68.3%**	NA	
80	NA	**76.2%**	NA	
Angles 0 to 65 (weighted)	**42.0%**	**51.6%**	**9.6%**	

Figure 1: Standard and Advanced Skylights - Percent lighting energy savings for Site 2

We expected to find greater lighting energy savings for the advanced skylight case for hours with low solar altitude angles, when compared to the standard skylight case. This hypothesis was proven correct. The advanced skylight had higher energy savings compared to standard skylights between angles 0 – 20 deg by an average of 8.3%. Above 25 deg solar altitude the monitored performance shows that standard skylights had higher energy savings than advanced for some altitude bins, however, across the angles of 25 – 65 deg, on average, the advanced skylights had greater energy savings compared to standard by 7.6%.

Overall for all angles, weighted over the study period, the advanced skylights performed better than standard skylights with **9.6%** greater lighting energy savings.

These results indicate that the Solatube 750 DS advanced skylight has been optimized for better daylighting performance at lower solar altitudes by redirecting low angle sun into the building. At higher solar altitudes, it is designed to reject most incoming sun to reduce cooling loads. This is resulting in a slight decrease in daylighting performance. However, overall the product seems to be well optimized to deliver better daylighting compared to a standard skylight.

1.2 HVAC Energy Savings Analysis *

** NOTE: While performing the HVAC analysis using eQUEST version 3.63 (a DOE2.2 based simulation program), we noticed that solar heat gain from skylights modeled in eQUEST was being underestimated by the program. This anomalous result was reported to Jeff Hirsch and Associates, the authors of the eQUEST program. However we were unable to get a "software fix" to the program in time for this report. Subsequently we calculated the magnitude of solar heat gain underestimation using a hand calculation method, and artificially increased the SHGC of the skylights in order to report results in this report. While the results after implementing this make-shift "fix" look reasonable, readers should keep in mind that the HVAC (cooling and heating savings) analysis results presented here may not be an accurate representation of the skylights performance. Lighting savings calculated using monitored data, however are not affected by the issue.*

For Site 2, HVAC energy use monitored on site could not be used in this analysis due to several reasons explained in Section 5.2. Hence HVAC energy use was estimated using DOE2 for all three case: advanced skylights, standard skylights, and no-skylights using eQUEST.

Figure 2 and Figure 3 shows results for lighting, heating and cooling for Climate Zone 12 and 3, for a typical 5,000 sf retail store. Overall, the results in Figure 3 show a decrease in cooling energy use for the "advanced skylights" case compared to both "no skylights" and "standard skylights" case. Heating energy use on the other hand increases in the "advanced skylights" case as compared to "standard skylights" and "no skylights" case. These results indicate that over the course of a year, the advanced skylights are reducing need for space cooling, and increasing need for space heating. This result can be attributed to two issues - reduced internal heat gains from photocontrolled electric lights, and the intentional design of the advanced skylight which rejects high angle sun, associated with high heat gains. At the same time, the advanced skylights are also reducing electric lighting need compared to both the "standard skylights" and "no skylights" case.

The advanced skylights save total energy by 10% or 3,514 kWh in climate zone 3, and 7% or 2,651 kWh in climate zone 12. Figure 2 and Figure 3 also give results for peak demand and peak demand reduction. The advanced skylights reduce peak on the 10 hottest days by an average of 1.56 kW in CZ3 and 2.27 kW in CZ12 compared to standard skylights.

Advanced Skylight Type 2 SOLATUBE 750DS
ENERGY USE estimation from DOE2 for a 5,000 sf Retail Store

	CZ 3				CZ 12			
"No Skylights" Case	Lighting Only	Cooling Only	Heating Only	Total	Lighting Only	Cooling Only	Heating Only	Total
Annual Energy Use (kWh)	35,588	12,557	557	48,702	35,588	16,699	2,981	55,268
Peak Demand (kW) [Average during PG&E peak period]	7.50	5.80	-	13.30	7.50	8.91	-	16.41
Peak Demand (kW) [Average for 10 hottest days]	7.50	8.51	-	16.01	7.50	11.45	-	18.95
"Standard Skylights" Case								
Annual Energy Use (kWh)	20,239	13,042	1,212	34,492	18,564	17,351	4,848	40,763
Peak Demand (kW) [Average during PG&E peak period]	4.94	6.45	-	11.39	4.55	9.80	-	14.35
Peak Demand (kW) [Average for 10 hottest days]	5.14	9.31	-	14.45	4.11	13.15	-	17.26
"Advanced Skylights" Case								
Annual Energy Use (kWh)	18,038	11,631	1,310	30,978	17,033	16,034	5,043	38,111
Peak Demand (kW) [Average during PG&E peak period]	4.73	5.83	-	10.56	4.46	8.99	-	13.45
Peak Demand (kW) [Average for 10 hottest days]	4.98	8.51	-	13.49	4.17	11.67	-	15.84

* PG&E Peak period is defined as 12PM to 7PM on weekdays between June 1 and September 30
* Typical retail store assumed to have operating hours from 7AM to 8PM, Lighting power density of 1.5 W/sf and area of 5,000 sf. Lights on photocontrols with 2-level switching, as found in Site 2.
Store has 28, 21"dia skylights (SFR is 1.34%)

Figure 2: Advanced Skylight: Solatube – Energy Use

Advanced Skylight Type 2 SOLATUBE 750DS
ENERGY SAVINGS estimation from DOE2 for a 5,000 sf Retail Store

	CZ 3				CZ 12			
Compared to **"No Skylights"**	From Lighting Only	From Cooling Only	From Heating Only	Total Savings	From Lighting Only	From Cooling Only	From Heating Only	Total Savings
Annual Energy Savings (kWh)	17,550	926	-753	17,723	18,554	664	-2,062	17,156
Percent Energy Savings (%)	*49%*	*7%*	*-135%*	*36%*	*52%*	*4%*	*-69%*	*31%*
Peak Reduction (kW) [Average during PG&E peak period]	2.77	-0.03	-	2.75	3.04	-0.08	-	2.96
Percent Peak Reduction (%)	*37%*	*0%*	-	*21%*	*41%*	*-1%*	-	*18%*
Peak Reduction (kW) [Average for 10 hottest days]	2.52	0.01	-	2.52	3.33	-0.22	-	3.11
Percent Peak Reduction (%)	*34%*	*0%*	-	*16%*	*44%*	*-2%*	-	*16%*
Compared to **"Standard Skylights"**								
Annual Energy Savings (kWh)	2,201	1,411	-98	3,514	1,530	1,316	-195	2,651
Percent Energy Savings (%)	*11%*	*11%*	*-8%*	*10%*	*8%*	*8%*	*-4%*	*7%*
Peak Reduction (kW) [Average during PG&E peak period]	0.21	0.62	-	0.83	0.09	0.81	-	0.91
Percent Peak Reduction (%)	*4%*	*10%*	-	*7%*	*2%*	*8%*	-	*6%*
Peak Reduction (kW) [Average for 10 hottest days]	0.16	0.81	-	0.97	-0.06	1.48	-	1.42
Percent Peak Reduction (%)	*3%*	*9%*	-	*7%*	*-2%*	*11%*	-	*8%*

* PG&E Peak period is defined as 12PM to 7PM on weekdays between June 1 and September 30
* Typical retail store assumed to have operating hours from 7AM to 8PM, Lighting power density of 1.5 W/sf and area of 5,000 sf. Lights on photocontrols with 2-level switching, as found in Site 2.
Store has 28, 21"dia skylights (SFR is 1.34%)

Figure 3: Advanced Skylight: Solatube - Energy and Demand reduction

1.3 Occupant Satisfaction Survey

An occupant survey was distributed to the employees at the retail store, who were asked to rate the overall quality of the daylighting in the store with advanced skylights. The survey found that 100% of the respondents rated the visual attractiveness of the store higher than neutral, with an average score of 5.9 out of 7 and 89% of the respondents rated quality of daylight from the skylights highly. They also indicated a high level of satisfaction with working with SOME of the electric lights turned off. Notable, there was no negative feedback on the issue of glare or too much daylighting from the Solatube advanced skylights. 87.5% of the occupants surveyed were "occasionally" to "never" uncomfortable due to glare from skylights. These results indicate a high level of acceptance with the advanced skylights technology among occupants.

1.4 Simple Payback Analysis

We calculated the simple payback and net present value (NPV) for a 15 year period for the advanced skylight compared to “no skylights” and “standard skylights”.

In the no skylights comparison, we took the full cost of the advanced skylight as reported to us by Solatube, and the energy savings compared to no skylights from Figure 3. The result was a simple payback of about **4 yrs** for both CZ 3 and CZ 12.

In the standard skylights comparison, we took the incremental cost of the advanced skylight compared to the standard Solatube skylight, and the energy savings compared to standard skylights from Figure 3. The result was a simple payback of **3 yrs** for CZ 3 and **4 yrs** for CZ 12.

2. PROJECT BACKGROUND

2.1 Description of Advanced Skylights

Standard skylights are typically either shaped plastic skylights, or flat glass skylights, with a light well and a diffuser, used to bring daylight into buildings. Flat skylights typically provide the most light at high sun angles and the least at low sun angles. Domed skylights perform better than flat, with the ability to refract light and redirect it into the building owing to its dome profile.

Advanced skylights, as defined for this project, include two features that distinguish them from standard skylights:

1. The capability to intersect and redirect sunlight at low solar altitude angle and,
2. The capability to differentially reject more high-angle sun, which is also typically has the highest solar radiation intensity (i.e. heat content).

Admitting low angle sun substantially increases daylit hours for daylight harvesting, and rejecting high angle, high intensity sun reduces solar heat gain at peak cooling periods.

The advanced skylights also have greater advantages for applications with dropped ceilings, where daylight needs to pass through a light well. Since advanced skylights redirect low angle sunlight perpendicular to the ceiling plane, it can get through a light well with the least number of reflections, hence increasing the efficiency of resulting light output.

2.1.1 Types of Advanced Skylights

Depending on the design, advanced skylights can be an ‘active’ or a ‘passive’ system. An active system uses light redirecting elements such as mirrors that rotate on one or more axis to track the position of the sun. A passive system uses advanced optics on the surface of the skylight dome to redirect the sunlight and do not use any moving parts.

We found the following manufactures in the market that sell advanced skylights in each of the two categories:

Active Skylights

1. Solar Tracking Skylights Inc

Natural Lighting Inc.

Sundolier

Ciralight Inc

Passive Skylights

1. Solatube Inc.
2. Monodraught Skylights

2.1.2 Product Description: Solatube 750DS

Figure 4: Solatube 330DS (standard skylight)

Figure 5: Solatube 750DS (advanced skylight)

Solatube’s 750DS is a ‘passive’ system, where reflectors and lenses are designed to capture the maximum amount of light in a fixed position, as opposed to a ‘active’ system where moving parts such as mirrors are involved in redirecting low angle sun. The optics on the ‘passive’ system lens are designed to maximize the available surface area to capture light while reducing glare and high intensity direct sunlight.

Our host site (study space), a book store in Santa Cruz, CA, had 20 Solatube 330DS standard skylights, which were then upgraded to the 750DS advanced skylights for this study.

Within each 330DS standard skylight unit, a ‘reflective collar’ is provided which was installed in this store, facing west. This collar, which was about 4” in height is a feature within the standard skylight that helps capture only low angle afternoon sun. The presence of the opaque collar, has an inherent limitation that it blocks morning sun from the east. The 750DS advanced skylight improves on the 330DS design by using advanced optics (Fresnel lenses) on the dome surface instead of a collar to capture low angle sun from all 360 degrees and a higher dome height that increases the effective daylight capture area from the 330 to 750 square inches. The Fresnel lenses can be seen as etches into the surface of the dome pictured in Figure 5. The captured sunlight travels down the

21 inch diameter Spectralight® Infinity Tubing, which has a specular reflectivity of more than 99.7%, to a diffuser at the end of the tube which helps to reduce hot spots and glare.

Figure 6: Close-up of the Solatube 750DS

Figure 7: Interior shot showing Solatube skylights with diffusers at Site 2

Figure 8 is a graphic from Solatube Inc. that shows the advantage of advanced skylights over standard skylights in three distinct seasons. The gray line represents the amount of light entering the building using standard skylights. The red line represents the light being admitted by the advanced skylights. The green fill shows the advanced skylights outperform standard skylights in the mornings and evenings and most of the winter by allowing more light from low-angle sun to enter the space. The yellow dome represents the light rejected by the advanced skylights once the space is saturated with sufficient light which reduces solar heat gain. This is particularly relevant to the summer months when the sun is high in the sky and the too much light in the middle of the day would induce glare and cause the cooling system to work harder because of the additional heat gain. The Fresnel lenses in the dome of the advanced skylights help refract more of the desired low-angle sun down into the space while rejecting more of the superfluous mid-day sun during summer months that can overwhelm air conditioning systems.

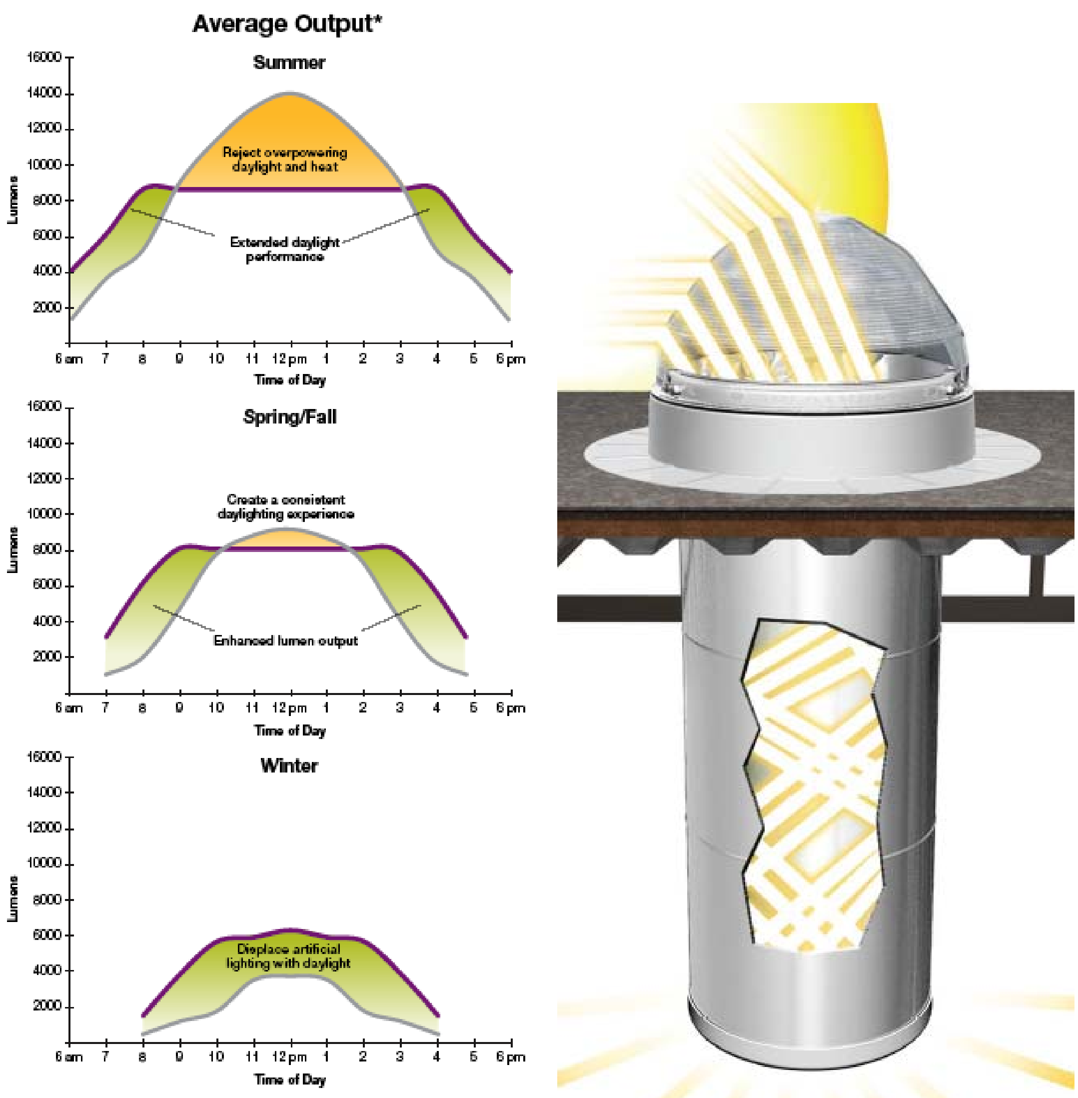

Figure 8: Graph/diagram from Solatube Inc. of 750DS skylights performance.

2.2 Solatube 750DS - Cost Information

Since the Solatube 750 DS is an acrylic dome, which fits on top of an existing Solatube standard skylight (330 DS), the cost of upgrading to the advanced skylight is only the cost of the 750DS dome. Our experience installing the 750 DS dome at the study site for this project showed that the installation is very straight forward and requires little to no expertise. Infact, the store owner for the study site was able to install the advanced skylight domes himself, with no hired help. The upgrade cost of the “750 DS Dome (Acrylic) and Tube Ring Kit” for this project was **$80.38** (per unit).

To install a 750DS domed skylight for a new construction project would include the cost of the dome as well as the cost of the tubular light well, and curb. This cost was reported to us by Solatube as **$384.88** (per unit, not including cost of installation)

2.3 Existing State of Technology

The 750 DS advanced skylights that were installed at the study site are made by Solatube International. The tubular skylight design was introduced in the US marketing the mid-90s by Solatube International. Solatube introduced the Raybender™ 3000 technology, and the 750DS (advanced) skylight in 2007. The tubular skylight design has greater advantage over standard skylights in buildings with plenums and dropped ceilings.

Solatube has a network of distributors and field representatives that create the market outreach and help educate potential users of their products benefits.

The main competitors for the advanced skylights are manufacturers of shaped plastic standard skylights. These skylights are better in performance than flat skylights, as the geometry of the dome or pyramid helps angle some low altitude angle sun in via refraction. These shapes enhance the refractive effect that a dome shape has on low angle sun.

2.4 Size of Existing Market

The existing market for advanced products is the same as that for standard skylights. All building floor area that falls below a roof, and has significant lighting energy usage and lighting power density, that are considered cost effective for standard skylights, can be considered potential market for this technology.

Additionally, spaces with lower ceilings and deep plenums that may be considered ineffective for standard skylights, primarily due to loss of efficacy due to a light well, may also be considered potential market for this technology. Advanced skylights that use mirrors are more effective in sunny climates as direct sun is required to take advantage of the features.

2.5 Reason for this Project

Assessments of benefits from advanced skylights have not been done in actual installations with site monitoring. This project was commissioned by PG&E through the

Emerging Technologies Coordinating Council to understand and quantify the benefit that these advanced skylight technologies provide over standard skylights

3. METHODOLOGY

3.1 Site Selection Criteria

We created detailed site selection criteria which were then distributed to the advanced skylights manufacturers to suggest potential host sites. These were identified as 'preferred characteristics' of participating host sites, with room for adjustment if one or more criteria were not met.

Preferred Hours of Operation

As the advanced skylights are expected to perform best with low altitude sun, we preferred buildings that have operating hours that capture this low angle sun in the early mornings and late evenings. So the preferred hours of operation were from early morning to late afternoon. Businesses that operate 7 days a week and 12 months a year were also preferred, as they offer the potential for greater daylighting savings, and better cost effectiveness.

Preferred Building Occupancy Type

To ensure that the site selected has the characteristics that bring out the unique advantages of the advanced skylights, we suggested our preferred occupancy type as retail stores, because of the generally higher lighting power densities and longer hours of operation in that space type. Furthermore, smaller retail stores ("little box"), especially with suspended ceilings, less than 15ft in height, were preferred as they are a likely target for further program deployment and code development requiring skylights.

Other building types could include gymnasium/exercise center, restaurant, library, office, classroom, lobby, atrium, storage, convention center, automotive service, manufacturing, distribution/sorting area.

Preferred Space Characteristics

The buildings that would best utilize the advantage of advanced skylights over conventional skylights would have a dropped ceiling, and hence a substantial light well. The specific advantage of tubular skylight with advanced optics is the ability to redirect daylight to enter the space at a more-or-less perpendicular angle to the ceiling, with very low loss of light in the light well. This advantage is lost in a space that has no dropped ceiling, as sun coming in at any angle gets into the space without much loss of light in the light wells.

Preferred Building Location

Since the greatest energy savings with these systems was likely to be in the sunniest locations, an interior valley area was indicated as a preferred location. The site was to be location in PG&E service territory.

Preferred Building Area

Since larger (warehouse type) stores that are <8,000 sf, already require skylight in Title-24 (2008 version), we wanted to target buildings that are currently just below this target area which are likely to be considered for mandatory skylights with future codes and standards refinement. Spaces that are between 5,000 and 8,000 sf were indicated as preferred candidates. Buildings smaller that 5,000 sf could also be included, if they fit the other criteria.

3.2 Monitoring and Analysis Methodology

We proposed three evaluation methodologies based on the type of installation existing at the host site. Monitoring periods were decided based on PG&E's recommended timeline for the completion of the project. Monitoring and Analysis plans for each are explained below:

1. SWAP

For a site with standard skylights already installed, we planned to retrofit the existing skylights with advanced skylights.

- 'Base Case' is monitored energy performance with standard skylights installed
- 'Advanced Skylights Case' is monitored energy performance with advanced skylights installed

We planned to monitor HVAC and lighting energy usage and daylight distribution for

a. Older standard skylights – for a minimum of 3 month period

b. New advanced skylights – for a minimum of 3 month period

2. RETROFIT

For a site with no skylights, we planned to have install advanced skylights.

- 'Base Case' is monitored energy performance with no skylights
- 'Advanced Skylight Case' is monitored energy performance with advanced skylights installed

We planned to monitor HVAC and lighting energy usage and daylight distribution for

a. No skylights – for a 1 month period

b. New advanced skylights – for a minimum of 3 month period

3. NEW INSTALLATION

For a site with one of the candidate advanced skylights already installed, we planned to monitor the site as is.

- 'Base Case' is standard skylight estimated using DOE 2 simulation

- 'Advanced Skylight Case' is monitored energy performance with advanced skylights installed

We planned to monitor HVAC and lighting energy usage and daylight distribution for

a. Existing advanced skylight – for a minimum of 3 month period

3.3 Monitoring Equipment

Following is a description of the proposed methodology for installed equipment on site for monitoring of energy use and lighting.

Lighting Energy Use

Current Transformers (CTs) hooked onto Hobo Data Loggers, logging data at 1 hr time steps. The monitoring equipment use was installed on site at the breaker panel. The CTs and Hobo loggers was left in place for the entire monitoring period and uninstalled at the end of the monitoring period

Daylight Distribution:

To study daylight distribution, two methods were used:

a. High Dynamic Range (HDR) Images were taken by a staff researcher on a single day at 1 hr time intervals for period of 12 hrs (max). The staff researcher visited the facility on a clear day, and took HDR images using a digital camera setup.

b. Hobo Data loggers with built-in illuminance loggers logged the illuminace at a 1 hr time interval. The loggers were installed at various locations within the host site. These matchbox size loggers were left in place for the entire monitoring period and uninstalled at the end of the monitoring period.

HVAC Energy Use

Current Transformers (CTs) hooked onto Hobo Data Loggers, logging data at 1 hr time steps. The monitoring equipment use was installed on site at the breaker panel. The CTs and Hobo loggers were left in place for the entire monitoring period and uninstalled at the end of the monitoring period.

3.4 Occupant Survey

A paper survey was distributed to the occupants, at the end of the monitoring period, collected and sent back to HMG by site host. See Appendix A – Survey Instrument, for a copy of the survey.

The survey was given out to employees of the store. The questions in the survey were rated by the occupants on a scale of 1 to 7, with high scores always indicating better performance. The questions gauged the level of acceptance of the advanced skylights by the occupants.

3.5 Monitoring Schedule

Figure 9 provides the timeline for the monitoring period for Site 2. A total of 17 weeks were monitored from September 2nd 2008 to December 31st 2008.

PG&E Advanced Skylight	2008				2009						
	September	October	November	December	January	February	March	April	May	June	July
New Installation:	Eq.In. / Standard Skylights Data Logging							Advanced Skylights Data Logging			Eq.Out
Site Two	I	I		I				I			I
	September 2	October 10		December 31				April 23			July 10
	Data Collection	Download Data and Clear Logger Memory		Data Collection				Data Collection Begins			Data Collection Ends
	Begins	Add. Illum. Readings		Ends				Add. Illum. Readings			Collect Equipment
								Final HDR Images			

Figure 9: Project Timeline

During the monitoring period for the standard skylights, we captured the low fall – winter solar altitude angles for Santa Cruz, CA. The highest solar altitude angle at 12:00pm we captured in the first study period was 60.9 deg and the lowest was 29.6 deg. The highest solar altitude angle at the summer solstice for this location is 76.3 deg.

4. DESCRIPTION OF HOST SITES

4.1 Site 2: Solatube 750DS

The site was chosen after reviewing four recommended sites from Solatube Inc. Solatube provided the project team a list of sites that met with the criteria for this study. From that list, Site 2 was chosen as it fit most of our criteria for the project. The selected site was a book store in Santa Cruz, CA (Title 24 Climate Zone 3).

Site Selection Criteria: Site 2 – Solatube

The site selected as Site 2 – Solatube, met most of the site selection criteria listed under Section 3.1.

- The site was one of our preferred occupancy type, a retail store
- Lighting power density was 0.4 Watts/sf. The store mostly uses pendent cfl's, and track lights with either LED lamps with low wattage or small halogen reflector lamps.
- The site had operating hours that extended into late evening, which meant that low angle setting sun would be captured in our analysis, and was open 7 days a week, 12 months a year.
- The ceiling height was less than 15ft (12.5ft), and building area was less than 8,000sf (3,726sf) which puts it below the current Title 24 requirement of 15ft ceiling height and 8,000sf area
- Building was located in PG&E territory, coastal climate zone (CZ3)

Some of the criteria were not met:

- The site did not have a dropped ceiling

This site was chosen, as most of the important criteria were met, and the one criteria not met was not critical to the analysis.

Description of Store

The store is a bookstore that covers approximately 3,726 square feet. The ceiling height is 12.5ft. There are 20 Solatube 32"dia 330-DS skylights (see Figure 10). The skylight to floor ratio (SFR) is 3.38%.

There are a total of twenty-nine 7ft wide aisles, with 7ft high stacks in which merchandise is displayed. The lighting is open cell fluorescent, 2-lamp T-8 fixtures. The lighting power density is 0.4 Watts/sf.

The store's lighting is on photocontrols. A light sensor is placed inside one of the skylight wells, facing upwards. Based on the amount of light on the light sensor, the photocontrols logic is a two-stepped switching system that turns off lights when enough daylight from skylights is available. From our monitoring we determined that the photocontrols are maintaining about 25 fc on average horizontal illuminance, at the mid point of two skylights, 5 ft from the floor.

The store is open from 10am-9pm all days of the year.

Figure 10 shows the plan and Figure 11 shows the section of the Site 2 store. The section A-A' (shown as the dotted horizontal line A-A in the plan view) measures 48 feet across, while Section B-B measure 77.5 feet long. The building has flat roof, with a ceiling height of 13 feet 6 inches. The blue line in the section represents illuminance measured at 12 pm on a clear sunny day in September 2008 using a hand-held illuminance meter at about 2.5' height.

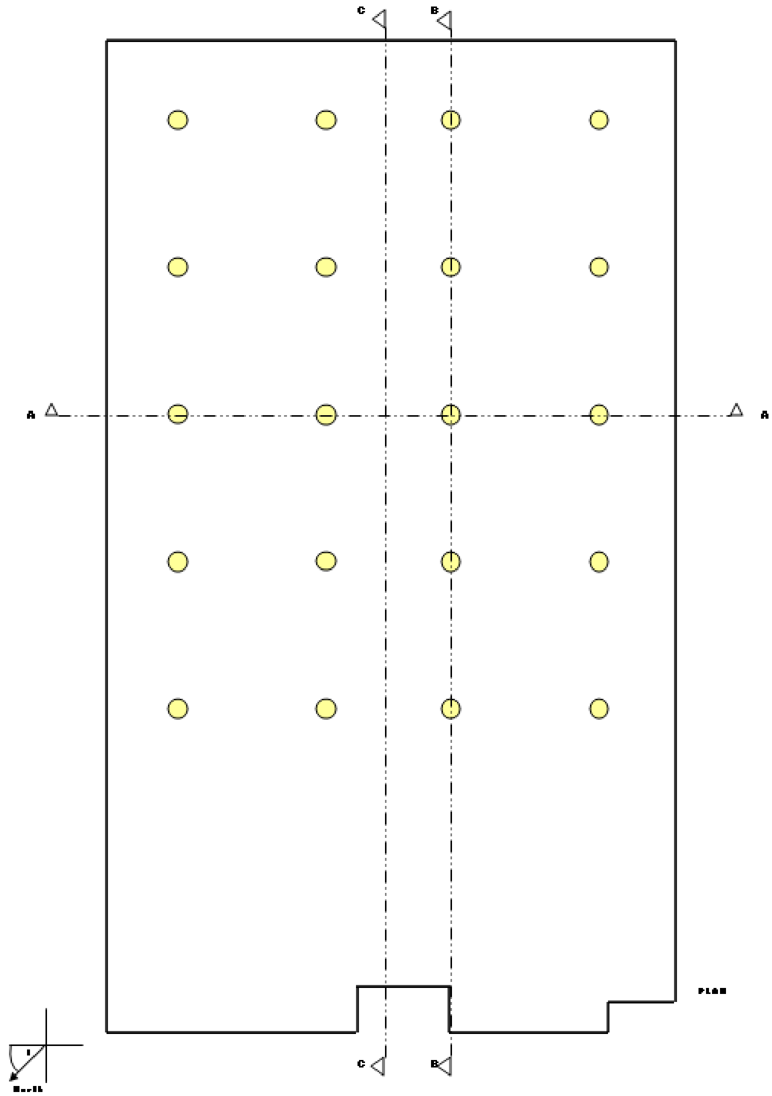

Figure 10: Plan view of Site 2

The average illuminance reading was 113 fc, with highest reaching 238 fc directly under a skylight on the second row from the front door. The lowest readings in-between skylights was 41 fc.

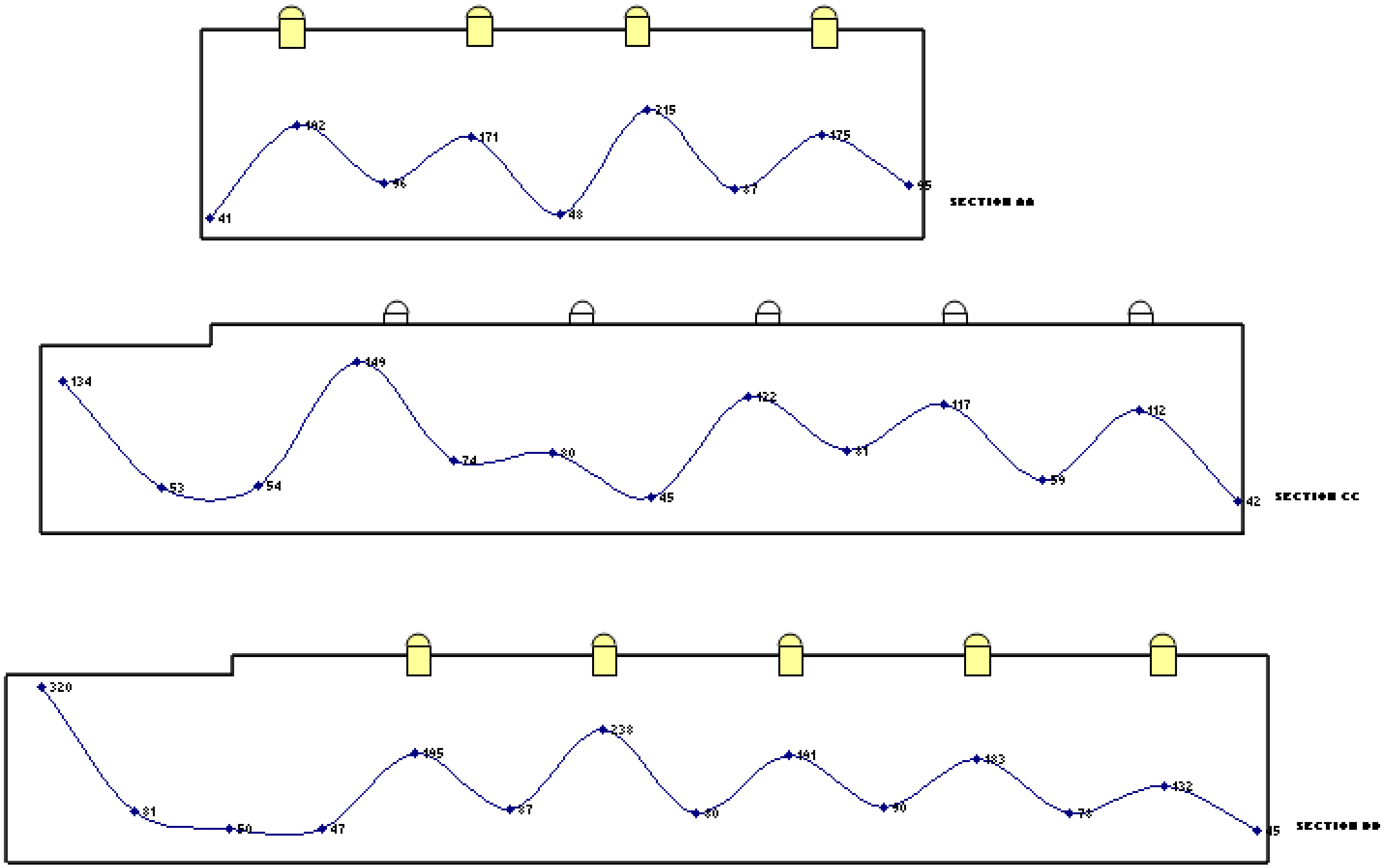

Figure 11: Section view of Site 2

4.2 Monitored Data

Figure 12 shows the output from the three circuits plotted over the course of a typical sunny day (10/25/08). The primary axis (on left) gives the current readout for the three circuits. The figure has a secondary axis (on right) that shows outside solar radiation in Btu/hr-sf (orange dotted line).

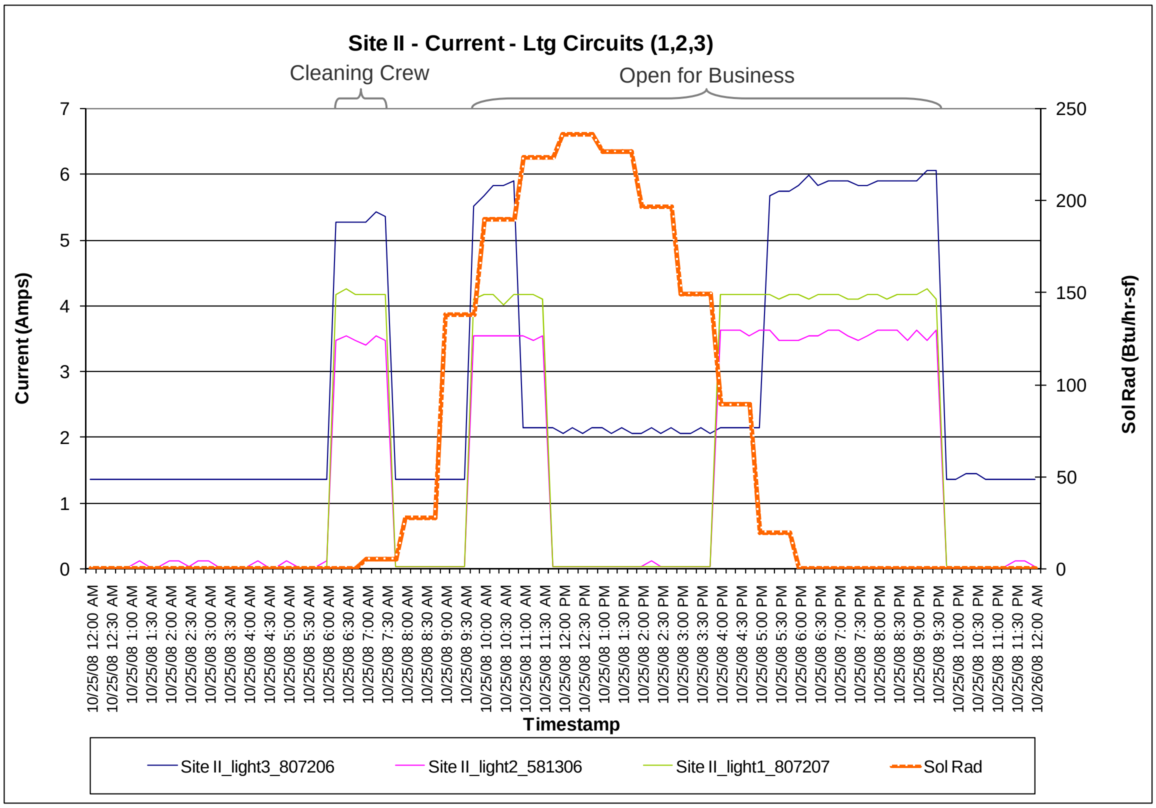

Figure 12: Monitored electric lighting energy usage data from three lighting circuits

The lighting system comprising of pendent CFL's, and track lighting with LED's and Halogen lamps, were arranged in three circuits. All three circuits were photocontrolled. Circuit 1 (Site II_light1_807207) had an automatic on/off control (100% - 0%), circuit 2 (Site II_light2_58136) also had an automatic on/off control (100% - 0%), and circuit 3 (Site II_light3_807206) had an automatic 2-step control (100% - 90% - 35%). Figure 12 shows that, as expected, when enough daylight is present, circuits 1 and 2 turn off completely, while circuit 3, which contains pendent lights above the register, goes to its lowest level ie 35%. The lights above the register always remain on during business hours. During non-business hours, some of the lights above the register remain on.

The initial hump of the lighting circuits from 6am to 8am is a result of the cleaning crew that comes in early every day.

Hobo data recorders were also placed measuring vertical illuminance on the south-west wall (facing north-east) at three levels along to record net indoor lighting illuminance in foot candles from both electric and daylight. These hobos were placed at high level (12ft), mid level (2.5ft) and low level (6 inches) from the ground. The location of the three Hobos are indicated in Figure 12 by letters L. M and H. The graph in Figure 13 shows the illuminance recorded by the Hobo data recorder for the three levels over the course of a day. The figure has a secondary axis that shows outside solar radiation in Btu/hr-sf (orange dotted line)

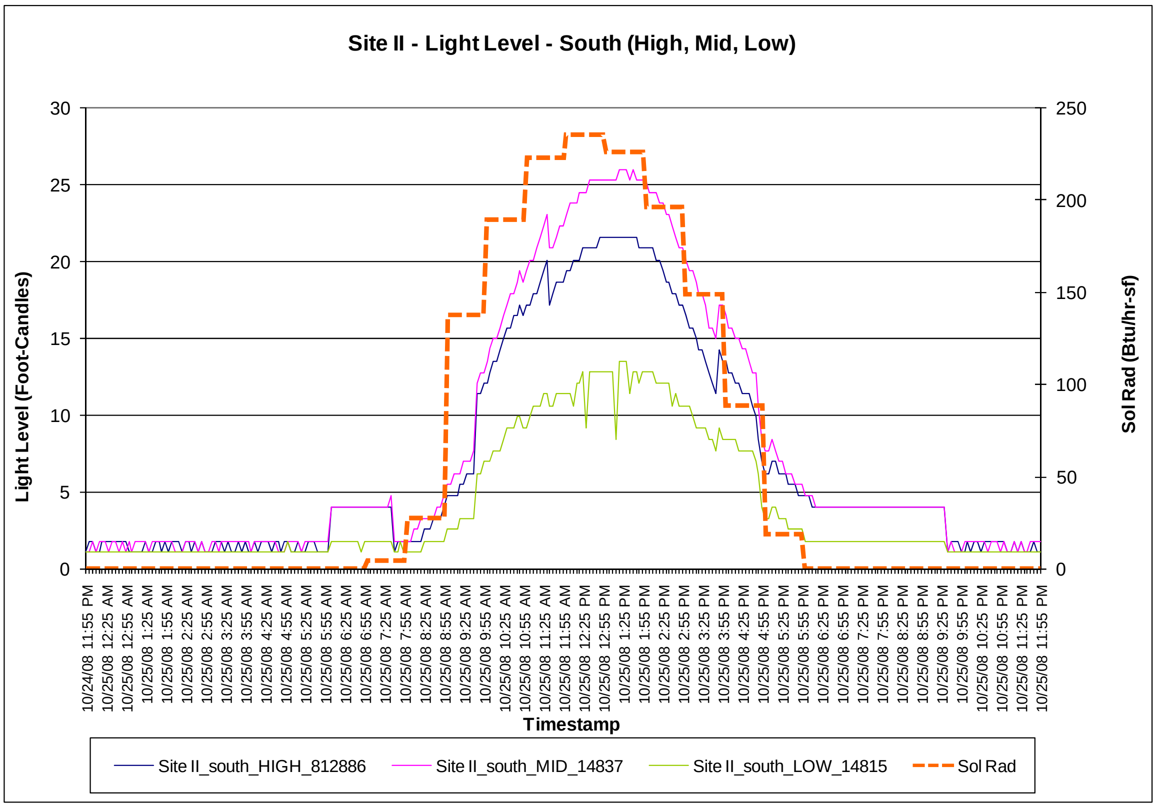

Figure 13: Monitored indoor illuminance from Hobo data recorders place at three levels in on the south-west wall facing north-east

The mid level data is presented in pink, and has the highest illuminance readings of the three hobos. The reason is that the high level hobo was closer to the height of the light diffuser at the bottom of the skylight tube. Therefore more light was thrown from the skylights down to the mid level hobo that to the high level hobo. As seen in Figure 13, the mid level Hobo recorded early morning and late evening readings of 4 fc, which is compose entirely of electric lighting, while in the middle of the day, the illuminance levels commonly reached 30 fc from mostly daylight. The times when automatic photocontrolled lights switched on or off can be seen as ‘spikes’ in the data at about 11:00am and 4:00pm. The spike from 6am to 7:30am can be attributed to the cleaning crew, who come in every morning and turn on the lights manually.

5. DATA ANALYSIS

5.1 Lighting Analysis

The analysis for lighting energy was done using Base Case (or Standard Skylights Case) and Advanced Skylights Case monitored data from the two monitoring periods. The data from both cases was analyzed by solar altitude and radiation, to determine not only which case had better overall lighting performance, but the solar altitude angles and solar radiation conditions where the performance of advanced skylights was better or worse than standard skylights. Finally the data from the monitoring period was also extrapolated for an entire year, using a multi variate regression analysis to determine annual energy savings and peak demand reduction. The data analysis was performed according to the following steps.

5.1.1 Local Weather Station Data

Hourly outdoor weather data is available from the California Irrigation Management Information System, Department of Water Resources, Office of Water Use Efficiency.[1] We used the local data from the Santa Cruz station (~2.5 miles from site location in Santa Cruz) to fill in global horizontal radiation, global horizontal illuminance, dry bulb temperature and dew point temperature for our analysis, for the dates that coincided with the logged data. The data required conversion from Fahrenheit to Celsius and Langleys/day to Watts/m^2 and hundreds of lux. Solar elevation (Altitude Angle) is based on the calculation procedure by NOAA[2].

Occasionally there were days for which CIMIS was missing some or all of the data. In these cases the most recent complete day's values were used to fill in the blanks.

5.1.2 HOBO Logger Data Interpretation

As described earlier, three lighting circuits were monitored at the participant site. The sum of these three lighting circuits was used to determine the percentage of the lights that were on and off at each given hour. In order to provide a snapshot of how the advanced skylights were operating, we created an hourly database that uses the circuit current values on the hour. These values directly indicated the amount of lighting that was on or off at any given hour.

5.1.3 Frequency Bins

The first step in the analysis required the construction of a frequency table showing the number of occurrences at various intersections of solar altitude and radiation. This was

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[1] http://www.cimis.water.ca.gov/cimis/data.jsp

[2] http://www.srrb.noaa.gov/highlights/sunrise/azel.html

accomplished by using excel to roundup the radiation and altitude values into bins of 5 and 10 respectively. The top charts in Figure 18 and Figure 19 show the frequency tables of all the occupied hours that were monitored at Site 2. Solar radiation is measured in Btu/hr-sf and solar altitude is measured in degrees above the horizon. The color coding from light to dark illustrates which intersections have the lowest and highest number of data points.

5.1.4 Analysis of Hourly Monitored Data

For analysis, we made use of R, a free software environment for data manipulation, statistical computing and calculation.[1] We tightened up the analysis by filtering the data to only include occupied hours. This was done via careful examination of the data, and imposing a flexible schedule of opening around 10:00AM and closing at approximately 9:30 PM daily, modified according to actual data and daylight savings time. Also taken into account was the fact that each morning at around 6am the cleaning crew came in, turned on some lights, and then cleaned and left before the employees showed up. The time in between the cleaning crew leaving and the store opening for business fluctuated on a day-to-day basis from 15 minutes to multiple hours.

5.1.5 Annual Data Extrapolation

The monitoring period for Site 2 was limited to Fall 2008 (September 6th to December 31st 2008) for the standard skylights and Spring 2009 (April 23rd to July 10th 2009) for the advanced skylights. Annual lighting schedules for both the standard and advanced cases were extrapolated from the available monitored data based on solar radiation and solar altitude angle data for two California climate zones, namely CZ 3 and CZ 12. The climate zones were chosen to represent the most populous region in PG&E territory (CZ3) and a climate zone with mostly sunny weather (CZ12) where the performance of advanced skylights was expected to be close to optimal for the most part of the year.

The monitored data was used as inputs for a multivariate linear regression model using R. (A Tobit model was also considered, but deemed less practical for this particular model).

Figure 14 compares the “percent of lights turned off” at 15 degree solar altitude angle bins across the different scenarios for the spring monitoring period. Starting on the left, the column “Advanced Monitored” gives the percent of lights off based on monitored data from the advanced skylights. The next column to the right, “Advanced Extrapolated” contains the numbers from the extrapolated data for the advanced skylights during the same time period (April to July). The rightmost column, “Standard Extrapolated” gives the percent of lights off from the extrapolated data for the standard skylights during the same time period.

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[1] http://www.r-project.org/

Percent of lights off at 15 degree altitude bins

Solatube	Spring (Apr-July)		
Altitude Angle	Advanced monitored	Advanced extrapolated	Standard Extrapolated
0-15	35%	28%	0%
15-30	47%	42%	36%
30-45	65%	68%	46%
45-60	63%	81%	62%
60-75	66%	82%	81%

Figure 14: Spring 2009 comparison of monitored and extrapolated savings estimates

The extrapolation of the data was necessary to compare the two scenarios directly, as the standard and advanced monitoring period were during different seasons.. As can be seen in Figure 14, the monitored and extrapolated data for the advanced skylights both demonstrate higher performance compared to the standard skylights extrapolation. At higher solar altitude angles, particularly the 60-75 degree bin, saturation of light leads to the percent of lights off being similar in the two extrapolated scenarios.

5.2 HVAC Analysis

Our monitoring plan included monitoring HVAC energy use at the rooftop unit every 5 minutes using clamps to monitor the current to the HVAC system However, after preliminary analysis of the data, it was determined that a key variable that was not captured in our monitoring was the hourly thermostat setpoint. Without data on setpoint, we were unable to determine when the HVAC was in heating and cooling modes. This was further complicated by the fact that our monitoring periods spanned months when both heating and cooling are required, sometimes on the same day.

Another difficulty in determining total energy from the monitored data use was that the HVAC unit was an electric AC with gas heating and not a heat pump. Hence the monitoring using CT clamps could only gave us electric fan energy use data during heating periods, and not full heating energy use.

Because of these issues, we decided that instead of using monitored data on HVAC energy use, we will create a DOE 2 simulation of the study space, modeled with a standard rooftop HVAC system, and estimate the energy performance with standard and advanced skylights from it. To estimate heat gain from advanced and standard skylights we used angle-dependent SHGC values calculated from lumen performance data obtained from the manufacturer as described in the section below.

5.2.1 Angular dependent SHGC for Advanced Skylight Case

On our request Solatube Inc. provided us with lumen performance data from photometry (developed by Lighting Technology) by altitude angle. Along with that, SHGC values for both the standard 330DS and advanced 350DS skylights measured at 60deg altitude angle were given as 0.40 and 0.30 respectively. Using the angular lumen performance value, angular SHGC values were calculated for both skylight types, shown in Figure 15. This data was used as input to the DOE 2 model in eQUEST.

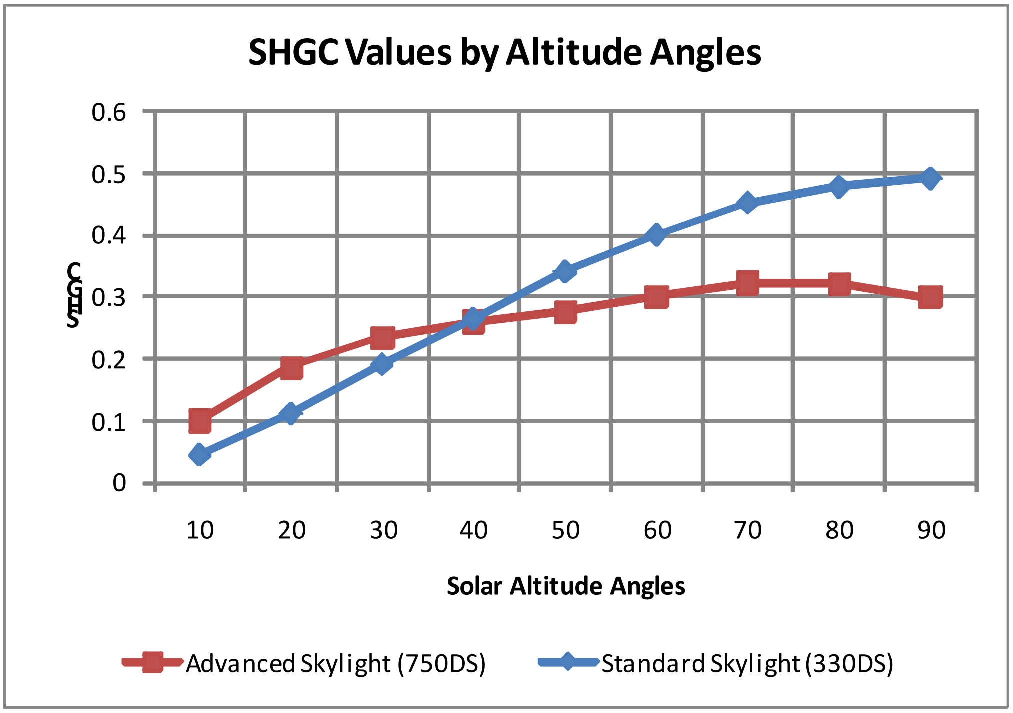

Figure 15: Angular Dependent SHGC Values

As seen in Figure 15, SHGC for the advanced skylight is higher than that of standard skylight for low angle sun. At 40deg altitude angle, the SHGC values are the same and for higher altitude angles, standard skylight has higher SHGC values.

Figure 16 and Figure 17 give the photometric data for the standard (335DS) and advanced (750DS) skylights.

Tube	Size	Domes	Diffusion	Sky	Solar Altitude	Output Lumens
OC	21"	330DS	K12	Clear	10	1556
OC	21"	330DS	K12	Clear	20	3965
OC	21"	330DS	K12	Clear	30	6746
OC	21"	330DS	K12	Clear	40	9404
OC	21"	330DS	K12	Clear	50	12060
OC	21"	330DS	K12	Clear	60	14215
OC	21"	330DS	K12	Clear	70	16028
OC	21"	330DS	K12	Clear	80	16974
OC	21"	330DS	K12	Clear	90	17464

Figure 16: Photometric Lumen Output Data for 330DS Skylight

Tube	Size	Domes	Diffusion	Sky	Solar Altitude	Output Lumens
OC	21"	750DS	K12	Clear	10	2867
OC	21"	750DS	K12	Clear	20	5349
OC	21"	750DS	K12	Clear	30	6749
OC	21"	750DS	K12	Clear	40	7473
OC	21"	750DS	K12	Clear	50	7935
OC	21"	750DS	K12	Clear	60	8617
OC	21"	750DS	K12	Clear	70	9261
OC	21"	750DS	K12	Clear	80	9231
OC	21"	750DS	K12	Clear	90	8603

Figure 17: Photometric Lumen Output Data for 750DS Skylight

6. PROJECT RESULTS

6.1 Daylighting Performance – Electric Lighting Energy Use

Results from monitoring lighting circuit energy use for advanced skylights and standard skylights were analyzed by solar altitude and radiation, to determine not only which case had better overall lighting performance, but the altitude angles and solar radiation conditions where the performance of advanced skylights was superior or inferior to standard skylights. This section describes those results in detail.

6.1.1 Performance Analysis by Solar Altitude Angle and Radiation

Site 2 has a slightly unusual lighting pattern due to the fact that every day around 6am the cleaning crew comes in, turns on all the lights, cleans and then leaves and turns off the lights between 8am and 9:30am. The store then opens for business around 10am. The lights always turn on to a level determined by the photocontrols. To ensure consistent analysis, the data is filtered for occupied hours, and so the time in between the cleaning crew leaving and the bookstore opening for the day is removed. Therefore, the majority of the hours with mid-angle sun are representative of the afternoons.

Performing the hourly lighting analysis at Site 2 required converting 15 minute lighting data to hourly values. The solar radiation values from CIMIS were the average of data collected every minute for the 60 minutes preceding the hour. To represent the correct solar radiation value for our hourly analysis, we calculated the average of the solar radiation value at the current hour and the three preceding 15 minute intervals. The percent of lights off at the hour is derived using the same method, the average of the value at the hour and the values at the three preceding intervals. The values for solar altitude were not averaged; the value at the hourly timestamp was used to create five-degree bins. Hence, in the following tables the values at zero degrees solar altitude represent the average of the previous hour's solar radiation and percent lights off.

The first table in Figure 18 is a frequency table that shows the number of occupied hours for our monitoring period, at each interval of solar altitude, measured in degrees above the horizon, and radiation, measured as Btu/hr-sf. We then performed an analysis to determine the average percentage of lights that are turned off by the photocontrols at each of these intervals. The average percent lights off is shown in the second table in Figure 18.

The frequency table includes two rows on the right hand side that indicate the number of hours for each segment of sun angles (0-15°, 15-30°, 30-45°, and 45-60°) as well as the percentage of total hours for each segment. The frequency table is color coded to indicate the density of hours in each box; more hours are depicted by a darker background. The table depicting average percentage of lights off is shaded darker to indicate higher percentages of lights turned off. For this system, 90% was the maximum level that the lights are switched off by the automatic photocontrols. The figure shows a surprising result that for a given solar radiation bin, as altitude angle increases, the % lights off reduces. This was counter-intuitive for a standard skylight where we would expect % lights off to increase as solar altitude increases. This result is further explained in a subsection below under '*Explanation of Results for Standard Skylights*'.

Figure 19 depicts the same type of information for the advanced skylights case. This data appears to have gaps when compared to the data collected for the standard skylights. However, this is due to the rate at which the sun rises and sets during the monitoring months of April through July. In the morning and the afternoon, the sun moves more than ten degrees in altitude in a single hour. Since the time of day being monitored remains constant, certain altitudes simply are not achieved in an hourly analysis such as this.

Frequency Table

STANDARD SKYLIGHTS — Solar Radiation

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	Total Hours	% of total
0	81	31	32	19	5	7	5	13	10	2																							
5	6	1	1	1	13	16	1	2	2	2	1																						
10	53	5	1	1	2	2	8	12	2	7	2	2	15	8	4																		
15	38	10	7		1		1		2	1	8	9	7	1	1	3																464	35%
20	39	14	6	4	6	1	1	1	2		3	2	7	11	15	9	12	6	2														
25	5	19	6	7	9	10	6	4	1	2	1	1	2	1	4	7	14	20	6														
30	1	8	2	3	3	10	7	4	17	8	10	9	3	8	6	4	14	11	12	17	13											436	32%
35	1	4		5	3	2	2	3	2	1	2	5	15	13	11	4	10	5	5	9	9	12	3										
40		3	3	5	1	1	2			3	1	3	3	1	9	5	3	8	10	2	3	4	6	15	9	3							
45							1				1			1	1	1	2		3	3	9	3	12	13	8	14	4					305	23%
50					1	2	1		3	1		1		1	1	1	2	4	1	1	2	4	5	5	5	9	5	7	6				
55							1		2				1		1	1		1		2			2	1	4	2	5	8	8	5			
60									1			1			1			1					2			2	5	2	1	5	5	138	10%
65																														1			
70																																	
75																																1	0%
80																																	
85																																	
90																																0	0%

Total: 1344

Percent lights OFF Table

STANDARD SKYLIGHTS — Solar Radiation

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310
0	15%	20%	17%	20%	13%	17%	19%	24%	30%	42%																					
5	19%	-2%	14%	16%	29%	36%	36%	15%	33%	36%	40%																				
10	20%	15%	7%	12%	8%	20%	33%	48%	62%	29%	16%	28%	43%	43%	50%																
15	20%	9%	7%		14%		56%		21%	69%	68%	77%	64%	69%	73%	59%															
20	32%	34%	26%	22%	36%	11%	7%	18%	12%		27%	54%	68%	74%	71%	77%	79%	90%	58%												
25	25%	34%	29%	22%	32%	29%	24%	18%	18%	55%	13%	30%	27%	69%	75%	72%	76%	88%	85%												
30	10%	17%	46%	12%	12%	19%	25%	22%	23%	34%	25%	19%	26%	36%	18%	45%	50%	72%	89%	81%	87%										
35	11%	21%		14%	15%	11%	35%	20%	5%	16%	35%	20%	27%	35%	32%	37%	41%	47%	61%	85%	86%	89%	91%								
40		12%	7%	11%	0%	47%	19%			14%	29%	30%	37%	25%	28%	33%	53%	27%	33%	36%	22%	72%	90%	89%	89%	91%					
45							6%				11%			47%	6%	55%	28%		26%	10%	23%	32%	59%	83%	91%	88%	90%				
50					-1%	0%	26%		17%	-1%		26%		35%	6%	4%	19%	36%	36%	26%	34%	29%	44%	61%	81%	88%	84%	89%	88%		
55							-2%		1%				1%		3%	34%		1%		7%			36%	33%	59%	52%	86%	86%	85%	85%	
60									-1%			-1%			1%			1%					25%			26%	61%	83%	65%	82%	89%
65																														85%	
70																															
75																															
80																															
85																															
90																															

Phase 1 (Lights off ~27%)

Phase 2 (lights off ~80%)

Figure 18: Frequency table and average percent lights off during occupied hours at Site 2 (base case).

Frequency Table

ADVANCED SKYLIGHTS

Solar Radiation (columns) / **Solar Altitude** (rows)

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	Total Hours	% of total
0	51	27	25	11	3	4																											
5		1		3	3	3	18	16	21																								
10	2				1						1	3	2																				
15	11	1		2	1	1		1				5	13	16																		246	25%
20	4	4				1				1		2		5	21	1																	
25	30	20	21		1	1	1	2					1		2			3	9	10													
30								1							1	1	1	1	5	21	16											187	19%
35			3	4	2			1	2		1	1	1								1		1	4	3								
40			4					1					1						1	2	3	2	2	8	30	13							
45				1	1		2		1											1								2	1			100	10%
50				4	5		2			1	1	1		1		2								2	4	1	2	12	10				
55					1				1	2		1					1	1	1	2	1		1		3		2	5	22	1			
60		1	1	1		9	7	4		4	3	2	2	1	4	4	3	4	1	6	14	5				1	1	1	1	10	7	190	19%
65				1	1			2			2		1	1	2	1	1				1	1	1	3	4	2	4	1	5	16	19		
70						2	2	2	5	4	2	4	4	2	2	1		1	3	3	3	2	3	4	7	21	5	2	6	3	9		
75										1	2				2	1	1	1	1	3	1	2	1	1	2	4	1	1	13	13	20	242	24%
80												2		1		2					1		1	3		2	3	2	15	7			
85																																	
90																																39	4%

Total: 1004

Percent lights OFF Table

ADVANCED SKYLIGHTS

Solar Radiation (columns) / **Solar Altitude** (rows)

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310
0	13%	12%	31%	34%	32%	22%																									
5		3%		13%	24%	20%	36%	62%	89%																						
10	68%				12%						60%	47%	42%																		
15	47%	2%		2%	3%	2%		1%				34%	42%	60%																	
20	16%	15%				21%				44%		53%		72%	90%	92%															
25	16%	14%	15%		0%	1%	11%	8%					18%		33%			69%	52%	62%											
30								28%							19%	81%	45%	76%	57%	83%	89%										
35			7%	10%	6%			6%	11%		12%	3%	11%								80%		60%	92%	89%						
40			10%					15%					58%						30%	62%	54%	76%	92%	72%	88%	89%					
45				2%	1%		15%		66%											60%								92%	92%		
50				30%	11%		11%			20%	10%	32%		12%		41%								62%	58%	74%	68%	79%	78%		
55					31%				10%	4%		59%					48%	71%	61%	81%	93%		92%		85%		93%	90%	88%	92%	
60		23%	24%	25%		18%	27%	7%		41%	29%	52%	74%	23%	31%	83%	55%	54%	90%	75%	86%	90%				93%	54%	43%	92%	82%	91%
65				0%	1%			7%			11%		46%	27%	18%	61%	82%				44%	88%	68%	50%	74%	92%	87%	80%	82%	86%	88%
70						3%	2%	18%	16%	20%	7%	11%	20%	26%	67%	2%		80%	54%	61%	55%	80%	59%	73%	84%	81%	80%	92%	86%	80%	76%
75										4%	25%				7%	12%	11%	70%	12%	46%	88%	21%	70%	56%	62%	67%	93%	70%	77%	80%	84%
80												24%		35%		47%					58%		69%	60%		85%	74%	84%	87%	90%	
85																															
90																															

Phase 1 (Lights off ~27%)

Phase 2 (lights off ~80%)

Figure 19: Frequency table (hourly) and average percent lights off during occupied hours at Site 2 (advanced skylights).

Full Load Equivalent OFF Hrs

STANDARD SKYLIGHTS

Solar Radiation

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	Total Hours	% of total
0	12.3	6.16	5.52	3.72	0.65	1.17	0.93	3.16	3.03	0.83																							
5	1.12	-0	0.14	0.16	3.78	5.74	0.36	0.3	0.65	0.71	0.4																						
10	10.8	0.74	0.07	0.12	0.16	0.41	2.67	5.81	1.24	2.05	0.33	0.56	6.52	3.42	2.02																		
15	7.55	0.95	0.51		0.14		0.56		0.42	0.69	5.46	6.92	4.51	0.69	0.73	1.78																118.7	26%
20	12.4	4.82	1.58	0.87	2.18	0.11	0.07	0.18	0.23		0.8	1.09	4.73	8.19	10.7	6.94	9.43	5.4	1.17														
25	1.23	6.43	1.71	1.53	2.87	2.89	1.44	0.71	0.18	1.1	0.13	0.3	0.54	0.69	2.99	5.07	10.6	17.6	5.08														
30	0.1	1.38	0.92	0.37	0.36	1.87	1.75	0.9	3.88	2.74	2.52	1.73	0.79	2.89	1.06	1.78	7.05	7.9	10.6	13.9	11.4											209.8	48%
35	0.11	0.83		0.7	0.45	0.22	0.71	0.61	0.1	0.16	0.71	1.02	4.07	4.61	3.51	1.47	4.14	2.33	3.07	7.68	7.75	10.6	2.74										
40		0.36	0.22	0.53	-0	0.47	0.39			0.41	0.29	0.9	1.1	0.25	2.55	1.66	1.58	2.15	3.32	0.72	0.65	2.88	5.4	13.4	7.99	2.73							
45							0.06				0.11			0.47	0.06	0.55	0.57		0.78	0.3	2.03	0.96	7.07	10.8	7.29	12.3	3.6					154.5	51%
50					-0	0.01	0.26		0.51	-0		0.26		0.35	0.06	0.04	0.39	1.43	0.36	0.26	0.67	1.17	2.2	3.07	4.05	7.95	4.22	6.21	5.29				
55							-0		0.01				0.01		0.03	0.34		0.01		0.15			0.72	0.33	2.36	1.04	4.32	6.84	6.77	4.27			
60									-0			-0			0.01			0.01					0.51			0.52	3.03	1.66	0.65	4.08	4.44	80.83	59%
65																														0.85			
70																																	
75																																0.851	85%
80																																	
85																																	
90																																0	0%

Total: 564.6

Full Load Equivalent OFF Hrs

ADVANCED SKYLIGHTS

Solar Radiation

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	Total Hours	% of total
0	6.76	3.23	7.69	3.79	0.95	0.89																											
5		0.03		0.38	0.72	0.61	6.55	9.86	18.7																								
10	1.36				0.12						0.6	1.41	0.84																				
15	5.21	0.02		0.03	0.03	0.02		0.01				1.7	5.42	9.52																		86.48	35%
20	0.66	0.59				0.21				0.44		1.07		3.6	18.9	0.92																	
25	4.77	2.79	3.13		-0	0.01	0.11	0.16					0.18		0.67			2.07	4.72	6.19													
30								0.28							0.19	0.81	0.45	0.76	2.85	17.4	14.2											88.16	47%
35			0.22	0.39	0.12			0.06	0.21		0.12	0.03	0.11								0.8		0.6	3.69	2.67								
40			0.38					0.15					0.58						0.3	1.25	1.63	1.51	1.85	5.73	26.3	11.5							
45				0.02	0.01		0.3		0.66											0.6								1.85	0.92			64.63	65%
50				1.19	0.54		0.23			0.2	0.1	0.32		0.12		0.82								1.23	2.3	0.74	1.36	9.51	7.76				
55					0.31				0.1	0.09		0.59					0.48	0.71	0.61	1.61	0.93		0.92		2.54		1.85	4.52	19.3	0.92			
60		0.23	0.24	0.25		1.62	1.9	0.3		1.62	0.88	1.03	1.48	0.23	1.25	3.33	1.64	2.17	0.9	4.5	12	4.5				0.93	0.54	0.43	0.92	8.24	6.36	119.4	63%
65				0	0.01			0.13			0.21		0.46	0.27	0.36	0.61	0.82				0.44	0.88	0.68	1.5	2.98	1.85	3.47	0.8	4.11	13.7	16.8		
70						0.06	0.03	0.35	0.82	0.81	0.14	0.42	0.8	0.51	1.33	0.02		0.8	1.62	1.82	1.66	1.61	1.77	2.92	5.85	16.9	3.98	1.85	5.14	2.41	6.87		
75										0.04	0.49				0.14	0.12	0.11	0.7	0.12	1.37	0.88	0.42	0.7	0.56	1.25	2.68	0.93	0.7	10	10.5	16.8	159.1	66%
80												0.48		0.35		0.94					0.58		0.69	1.81		1.69	2.23	1.68	13	6.28			
85																																	
90																																29.73	76%

Total: 547.5

Figure 20: Full load equivalent OFF hours for Site 2- Standard Case (top) and Advanced Case (bottom)

Figure 20 shows the energy savings from the skylights. These numbers represent the full-load equivalent number of hours that the lights are off because of the skylights and photocontrols. These tables were created by multiplying the number of observed hours for each combination of solar altitude and radiation with the average percentage of lights that are turned off. For example, there were 10 observed hours at an altitude of 55 degrees and solar radiation of 270 Btu/hr-sf. At this intersection, and average of 71% of the electric light was turned off or dimmed. Thus, we say that 7.1 full-load equivalent hours (of the 10) were saved.

The totals on the right hand side show that the advanced skylights at Site 2 saved 548 full load equivalent hours out of a total of 1004 occupied hours (total from frequency table in Figure 19), which is 54.5% savings compared to no skylights. The standard skylights saved 565 full load equivalent hours from a total of 1344 occupied hours(total from frequency table in Figure 18), which is a 42% savings compared to no skylights. To make the comparison equitable, we will only consider angles from 0 to 65 deg for advanced skylights, as the total monitoring period for standard skylights had no angles above 65 deg. In the 0 to 65deg range, the advanced skylights saved 51.6% compared to no skylights. The advanced skylights hence had 9.6% greater lighting energy savings compared to the standard skylights (for the same range of altitude angle ie 0 to 65deg)

Difference in Monitoring Periods

As the standard skylights case was monitored during fall/winter (Sept – Dec), the vast majority of the hours are low altitude angle ie. below 30deg. The advanced skylights case was monitored during spring/summer (Apr – July), hence there are equal hours with low and high altitude angles. This can be seen in the rightmost column of the frequency tables in Figure 18 and Figure 19.The difference in total hours on the frequency table between standard and advanced is due to the difference in monitoring time periods. The standard skylights were monitored for a total of 116 days while the advanced skylights were monitored for only 77 days due to project time constraints.

The benefit of our analysis methodology is that performance of each skylight type can be evaluated on the basis of their performance by altitude angle. The results, quantified as percent lights off, are hence independent of the difference in monitoring periods.

Explanation of Results for Standard Skylights

There are two possible theories to explain why for a given solar radiation bin, as altitude angle increases, the % lights off reduces in Site 2 Base Case (Standard Skylights).

1. Site 2 is located in Santa Cruz, which is a coastal city. It is fairly common to have foggy mornings and then the fog burns off by the afternoon. As a result of this weather, the same solar altitude will have a higher solar radiation value associated with it in the afternoon than the morning, thus the performance of the skylights is superior in the afternoons as compared to the mornings.
2. The business hours for Site 2 are approximately 10AM to 9PM. For this reason the business owner installed the reflective collar that came with the original

Solatube 330DS inside the Solatube dome facing west to amplify the afternoon sun (See Figure 4).

Both issues identified above work in favor of greater lighting energy savings in the afternoon as compared to the mornings. We split our data into before-noon and after-noon hours to determine if this was indeed the case. Figure 21 shows occupied morning hours that occur before noon. The top chart displays the average percentage of the lighting load that is turned off at each intersection of solar radiation and solar altitude for the standard skylights. The morning hours create a relatively smooth “S” curve. The right most values (along the curve) indicate the clearest, brightest morning hours monitored, with those bins identifying the highest solar radiation values before noon at each solar altitude. This should be compared with the bottom chart, which contains the same information for the afternoon hours. The tables for the afternoons are filled in for the most part on the other side of the “S” curve. There are some values that overlap with the morning and afternoon tables, most of which can be attributed to cloudy days when the solar radiation values did not reach their full potential.

After having separated morning and afternoon hours, it becomes clear that the high altitude hours with low percent lights off in both Figure 18, are mostly ‘morning’ hours, which perform poorly due to the morning fog typical in Santa Cruz. Additionally the position of the reflective collar facing west restricts daylighting from the east. The afternoon hours are showing high percent lights off for high altitude sun, as would be expected from a standard skylight

Percent lights OFF Table

STANDARD SKYLIGHTS: BEFORE-NOON HRS ONLY

Solar Radiation

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310
0	34%																														
5	26%																														
10	20%	14%																													
15	20%	9%	6%																												
20	32%	38%	34%	33%	36%																										
25	28%	38%	29%	23%	34%	32%	30%	25%																							
30	10%	20%	46%	11%	12%	22%	28%	22%	25%	29%	29%	20%	26%	34%	18%																
35		23%		14%	15%	11%	35%	20%	5%	16%	35%	20%	27%	35%	27%	40%	35%	37%													
40		12%	-2%	11%	0%	47%	2%			10%	29%	39%	37%	25%	25%	23%	53%	21%	33%	18%	22%										
45							6%				11%			47%	6%	55%	28%		26%	10%	23%	32%	42%								
50					-1%	0%	26%		17%	-1%				35%	6%	4%	9%	7%	36%	26%	33%	29%	44%	50%	45%						
55							-2%		1%				1%		3%			1%		7%			36%		59%	52%					
60																											61%				
65																															

Percent lights OFF Table

STANDARD SKYLIGHTS: AFTER-NOON HRS ONLY

Solar Radiation

Solar Altitude	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310
0	15%	20%	17%	20%	13%	17%	19%	24%	30%	42%																					
5	12%	-2%	14%	16%	29%	36%	36%	15%	33%	36%	40%																				
10		15%	7%	12%	8%	20%	33%	48%	62%	29%	16%	28%	43%	43%	50%																
15	12%		12%		14%		56%		21%	69%	68%	77%	64%	69%	73%	59%															
20		12%	11%	10%		11%	7%	18%	12%		27%	54%	68%	74%	71%	77%	79%	90%	58%												
25	11%	10%		13%	14%	16%	12%	10%	18%	55%	13%	30%	27%	69%	75%	72%	76%	88%	85%												
30		9%		16%		11%	6%		11%	68%	17%	14%		42%	17%	45%	50%	72%	89%	81%	87%										
35	11%	13%		14%	16%								26%	43%	46%	26%	66%	86%	61%	85%	86%	89%	91%								
40		12%	12%				36%			20%		13%	37%		39%	73%		66%		55%		72%	90%	89%	89%	91%					
45																							76%	83%	91%	88%	90%				
50												26%					29%	45%			35%			79%	90%	88%	84%	89%	88%		
55																34%								33%			86%	86%	85%	85%	
60									-1%			-1%			1%			1%					25%			26%		83%	65%	82%	89%
65																														85%	

Figure 21: ''Before-noon' and 'After-noon' hours average percent of lights off (Standard Skylights)

6.1.2 Performance Analysis by Altitude Angle

To explain the results from our analysis further, Figure 22 graphs the percent lighting energy savings for the advanced skylights case against the standard skylight case by solar altitude and Figure 23 presents the percent lighting energy savings by solar altitude in a table.

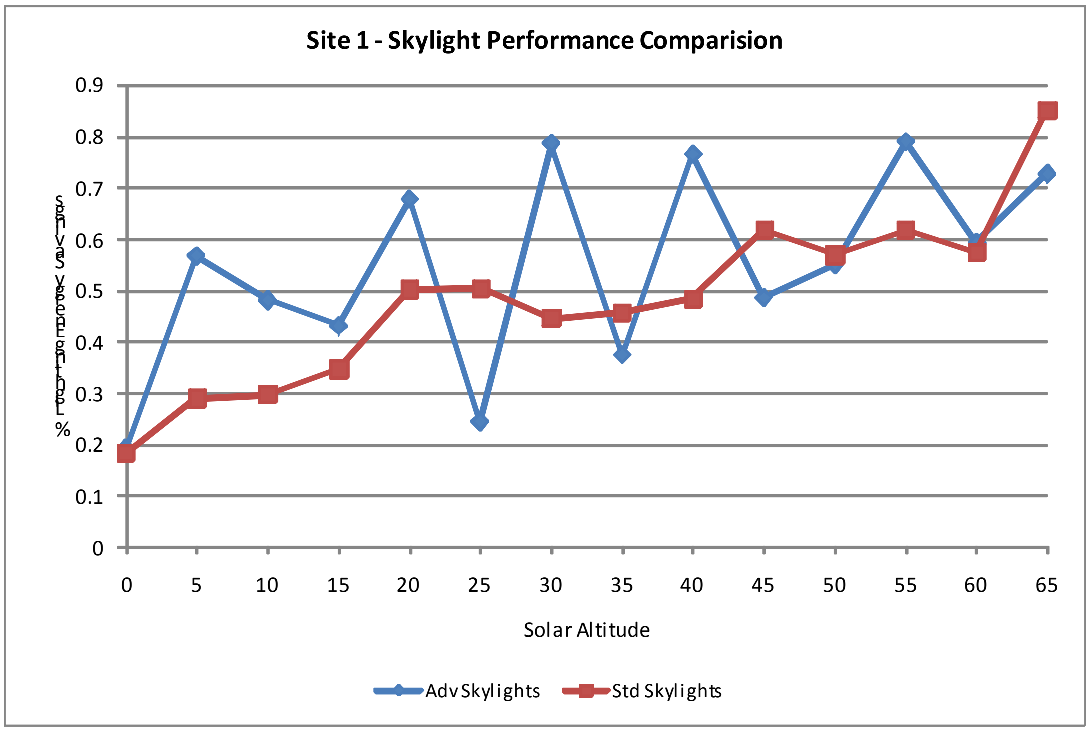

Figure 22: Percent Lighting Energy Savings by Solar Altitude

Both Figure 22 and Figure 23 show that advanced skylights clearly perform better than advanced skylights at altitude angles lower than 20deg. On average in that range, advanced skylights show 39.6% energy savings compared to no skylights, while the standard skylights show 31.3% energy savings compared to no skylights. Advanced skylights hence perform 8.3% better than standard skylights in the range of 0deg – 20deg..

Between 25deg to 60deg, the advanced skylights perform decreases slightly to an average of 58.4% compared to no skylights. The standard skylights in this altitude angle range average 50.8% energy savings compared to no skylights. Advanced skylights hence perform 7.6% better than standard skylights in the range of 25deg – 65deg.

Site 2 (Solatube)

Solar Altitude	STANDARD Skylight - % Ltg Energy Savings	ADVANCED Skylight - % Ltg Energy Savings	ADV vs STD	
0	18.3%	**19.3%**	1.0%	
5	29.0%	**56.7%**	27.7%	
10	29.8%	**48.1%**	18.3%	8.3%
15	34.7%	**43.1%**	8.4%	
20	50.2%	**67.8%**	17.5%	
25	**50.5%**	24.6%	-25.9%	
30	44.6%	**78.6%**	33.9%	
35	**45.7%**	37.6%	-8.2%	
40	48.5%	**76.5%**	28.0%	
45	**61.8%**	48.6%	-13.2%	7.6%
50	**57.0%**	55.0%	-1.9%	
55	61.8%	**78.9%**	17.1%	
60	57.3%	**59.2%**	1.9%	
65	**85.1%**	72.6%	-12.5%	
70	NA	**59.4%**	NA	
75	NA	**68.3%**	NA	
80	NA	**76.2%**	NA	
Angles 0 to 65 (weighted)	**42.0%**	**51.6%**	**9.6%**	

Figure 23: Comparison of percent lights off at Site 2 Advanced skylights vs Standard skylights by solar altitude

6.1.3 Performance Analysis Over a Single Day

To illustrate when the savings from advanced skylights occur over the course of a day, we compared illuminance data recoded using a Hobo data logger. We chose two comparable days, one from the standard skylight monitoring period and the other from advanced skylights monitoring period. The Hobo data logger was placed horizontally at 5ft height from floor, he middle of four skylights.

Figure 24 graphs the solar radiation and solar altitude of the two comparable days in terms of Solar Radiation under the standard and advanced skylights conditions. The dashed lines represent the base case (standard skylights) while the solid lines represent the advanced skylights. The dates being used for comparison here are September 6, 2008 (standard) and April 29, 2009 (advanced). These days were chosen because they are the closest comparison of solar altitude and solar radiation values available considering the different seasons in which the monitoring periods took place.

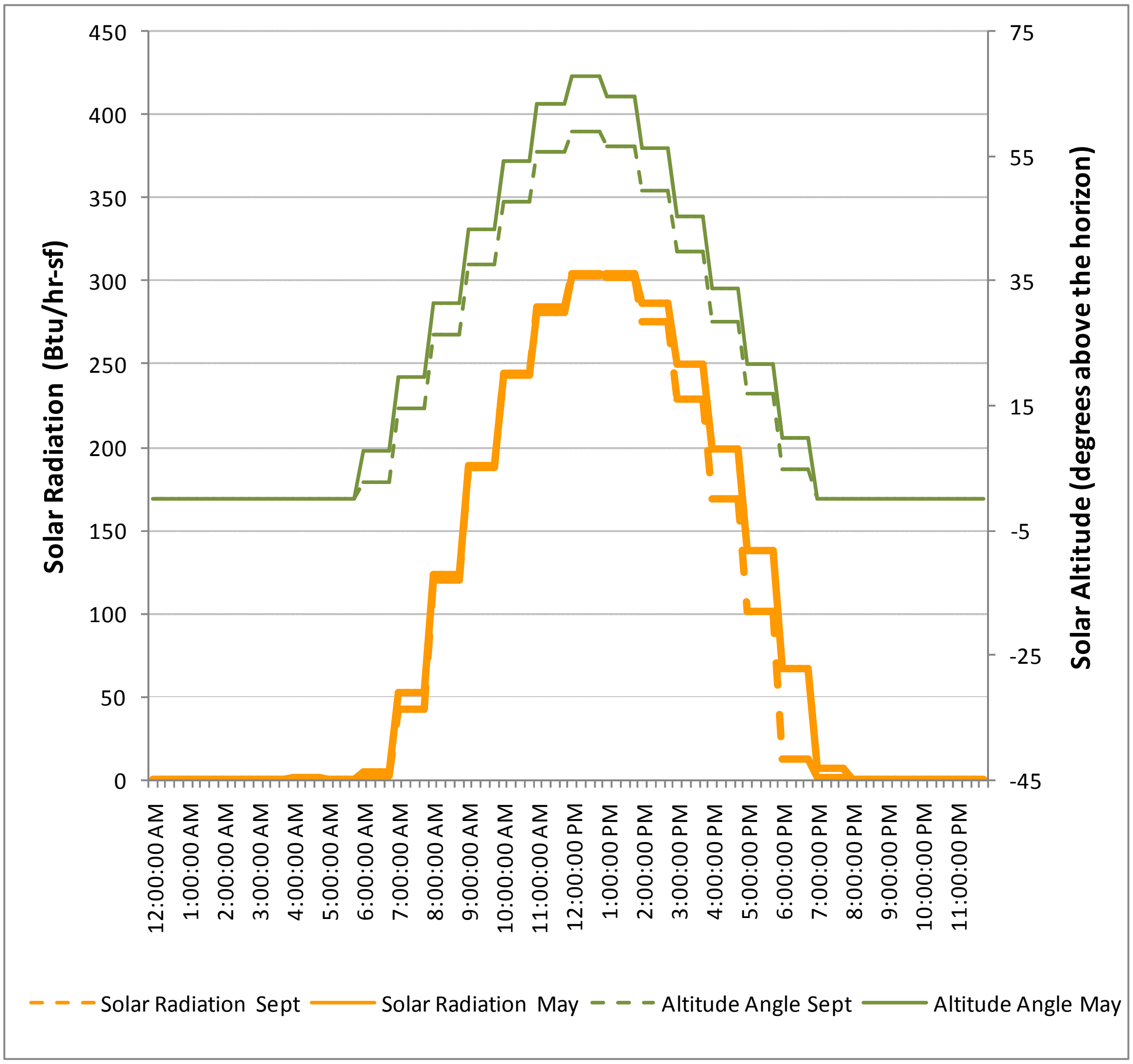

Figure 24: Solar Altitude and Solar Radiation values for the two comparable days – 9/6/2008 and 4/29/2009.

For these two days, Figure 25 compares the light levels inside Site 2 as captured by the hobo-loggers fixed in a horizontal position at about eye-level in the middle of the store. The shaded blue area indicates the excess light admitted by the standard skylights in the middle of the day. The shaded green areas highlight the ‘shoulder’ areas when the advanced skylights permit more light into the store than the standard skylights. The additional light levels during the ‘shoulder’ periods are the advantage of advanced skylights. The flatter, wider curve of illuminance with the advanced skylights demonstrates the longer, more uniform distribution of light into the space throughout the course of the day, as opposed to the standard skylights’ relatively steep spike in the middle of the day, and shallow shoulders (extended in the afternoon due to the use of the solar collar facing west inside the standard skylight dome). Another advantage to the flatter illuminance curve of the advanced skylights is that less excess light in the middle of the day and afternoon reduces the solar heat gain of the skylights and can help mitigate summer cooling costs.

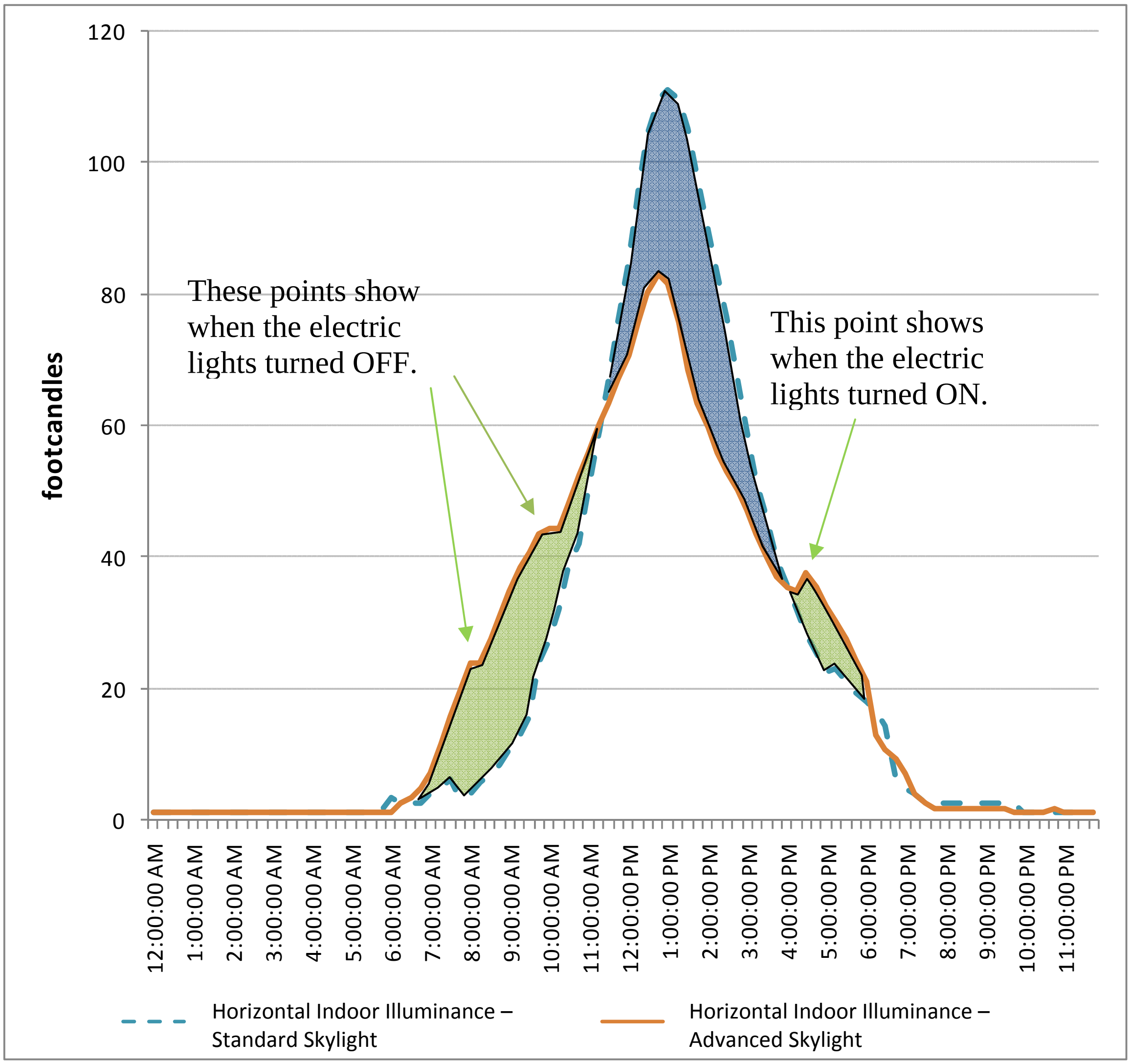

Figure 25: Comparison of light levels inside Site 2 on 9/6/2008 - Standard skylights case (dashed blue line) and 4/29/2009 - Advanced skylights case (solid orange line).

6.2 Annual Daylighting Performance – Lighting and HVAC Energy

The results for lighting energy savings were extrapolated (as described in Section 5.1.5), using solar radiation and solar altitude for the remaining hours of the year and normalized for a 5,000 sf retail store with the same lighting control strategy as found in Site 2. Results from this analysis are presented in Figure 26 and Figure 27 along with HVAC analysis done using DOE2.

The analysis was done for two climate zones CZ 3 – coastal region, PG&E's most populous climate zone with a mild cloudy/fogy weather, and CZ 12 – central valley region, sunny and hot weather. These climate zones were chosen to represent the range of climate in PG&E territory.

Lighting energy results show that advanced skylights save 8% and 11% lighting energy compared to standard skylights in climate zones 12 and 3 respectively. The lighting energy savings are larger in magnitude compared to cooling and heating savings. The HVAC energy results indicate that over the course of the year, advanced skylights is reducing cooling energy need in the space, compared to standard skylights. They does so by two means – reducing internal heat gains from photocontrolled electric lights, and rejecting high angle sun, associated with high heat gains. This result intuitive and in-line with our expectation of the advanced skylight's performance. The same two reasons also explain the additional heating energy requirement for the advanced skylights case, compared to the standard skylights case. However, the magnitude of heating energy difference is less compared to cooling and lighting, and so the overall effect of negative heating energy savings is small.

Lighting energy savings are much greater when compared to no skylights, 49% and 52% for CZ 3 and CZ 12. When compared to having no skylights, having advanced skylights reduced cooling energy need in the summers and increased heating energy need in winter. The explanation is the same for these results, as for the comparison with standard skylights.

These results indicate that the design of the 750DS Solatube advanced skylight has been very well optimized for increased daylighting, by admitting low angle sun into the building, and reduce cooling energy use by rejecting high angle sun away from the condition space below.

Overall the advanced skylights save 0.70 kWh/sf-yr (10%) in CZ 3 and 0.53 kWh/sf-yr (7%) in CZ 12 compared to standard skylights. They save 3.54 kWh/sf-yr (36%) in CZ3 and 3.43 kWh/sf-yr (31%) in CZ 12 compared to no skylights.

Peak demand was calculated using PG&E's definition of peak period of 12PM to 7PM on weekdays between June 1 and Sept 30. To calculate peak demand reduction a daily peak hourly demand in kWh was calculated for the advanced skylights case and compared to that from the standard and no skylights cases. This daily peak was then averaged over the entire peak period to report "Average during PG&E Peak period" and averaged over the 10 hottest days to report the "Average for 10 hottest days". Peak demand reduction was 2.75 kW to 2.96 kW, compared to no skylights, and 0.83 kW to 0.91 kW compared to standard skylights.

Advanced Skylight Type 2 SOLATUBE 750DS
ENERGY USE estimation from DOE2 for a 5,000 sf Retail Store

	CZ 3				CZ 12			
"No Skylights" Case	Lighting Only	Cooling Only	Heating Only	Total	Lighting Only	Cooling Only	Heating Only	Total
Annual Energy Use (kWh)	35,588	12,557	557	48,702	35,588	16,699	2,981	55,268
Peak Demand (kW) [Average during PG&E peak period]	7.50	5.80	-	13.30	7.50	8.91	-	16.41
Peak Demand (kW) [Average for 10 hottest days]	7.50	8.51	-	16.01	7.50	11.45	-	18.95
"Standard Skylights" Case								
Annual Energy Use (kWh)	20,239	13,042	1,212	34,492	18,564	17,351	4,848	40,763
Peak Demand (kW) [Average during PG&E peak period]	4.94	6.45	-	11.39	4.55	9.80	-	14.35
Peak Demand (kW) [Average for 10 hottest days]	5.14	9.31	-	14.45	4.11	13.15	-	17.26
"Advanced Skylights" Case								
Annual Energy Use (kWh)	18,038	11,631	1,310	30,978	17,033	16,034	5,043	38,111
Peak Demand (kW) [Average during PG&E peak period]	4.73	5.83	-	10.56	4.46	8.99	-	13.45
Peak Demand (kW) [Average for 10 hottest days]	4.98	8.51	-	13.49	4.17	11.67	-	15.84

* PG&E Peak period is defined as 12PM to 7PM on weekdays between June 1 and September 30
* Typical retail store assumed to have operating hours from 7AM to 8PM, Lighting power density of 1.5 W/sf and area of 5,000 sf. Lights on photocontrols with 2-level switching, as found in Site 2.
Store has 28, 21"dia skylights (SFR is 1.34%)

Figure 26: : Advanced Skylight: Solatube – Energy Use

Advanced Skylight Type 2 SOLATUBE 750DS
ENERGY SAVINGS estimation from DOE2 for a 5,000 sf Retail Store

	CZ 3				CZ 12			
Compared to **"No Skylights"**	From Lighting Only	From Cooling Only	From Heating Only	Total Savings	From Lighting Only	From Cooling Only	From Heating Only	Total Savings
Annual Energy Savings (kWh)	17,550	926	-753	17,723	18,554	664	-2,062	17,156
Percent Energy Savings (%)	*49%*	*7%*	*-135%*	*36%*	*52%*	*4%*	*-69%*	*31%*
Peak Reduction (kW) [Average during PG&E peak period]	2.77	-0.03	-	2.75	3.04	-0.08	-	2.96
Percent Peak Reduction (%)	*37%*	*0%*	-	*21%*	*41%*	*-1%*	-	*18%*
Peak Reduction (kW) [Average for 10 hottest days]	2.52	0.01	-	2.52	3.33	-0.22	-	3.11
Percent Peak Reduction (%)	*34%*	*0%*	-	*16%*	*44%*	*-2%*	-	*16%*
Compared to **"Standard Skylights"**								
Annual Energy Savings (kWh)	2,201	1,411	-98	3,514	1,530	1,316	-195	2,651
Percent Energy Savings (%)	*11%*	*11%*	*-8%*	*10%*	*8%*	*8%*	*-4%*	*7%*
Peak Reduction (kW) [Average during PG&E peak period]	0.21	0.62	-	0.83	0.09	0.81	-	0.91
Percent Peak Reduction (%)	*4%*	*10%*	-	*7%*	*2%*	*8%*	-	*6%*
Peak Reduction (kW) [Average for 10 hottest days]	0.16	0.81	-	0.97	-0.06	1.48	-	1.42
Percent Peak Reduction (%)	*3%*	*9%*	-	*7%*	*-2%*	*11%*	-	*8%*

* PG&E Peak period is defined as 12PM to 7PM on weekdays between June 1 and September 30
* Typical retail store assumed to have operating hours from 7AM to 8PM, Lighting power density of 1.5 W/sf and area of 5,000 sf. Lights on photocontrols with 2-level switching, as found in Site 2.
Store has 28, 21"dia skylights (SFR is 1.34%)

Figure 27: Advanced Skylight: Solatube - Energy and Demand reduction

6.3 Payback Analysis

For this project, we calculated the simple payback and net present value (NPV) for a 15 year period for the advanced skylight compared to "no skylights" and "standard skylights". To calculate simple payback, we used the energy savings estimated in this report and applied a energy cost of $0.18/kWh, a "blended" energy rate which represents energy cost as well as peak demand savings.

The incremental cost for the 750DS dome advanced skylights (skylight only) in a retrofit case was taken as **$80.38** per skylight (costs report by Solatube Inc). Labor cost for retrofitting the 750DS Dome was considered negligible.

The cost of a standard skylights (skylight only) was taken as $30 4.5 (costs report by Solatube Inc). To this cost, the cost of labor for installation was estimated at $90 per skylight from a 2007 study done for ASHRAE by the Heschong Mahone Group, Inc[1].

The incremental cost for a 750DS dome advanced skylight (skylight and installation labor) in a new construction case was taken as **$475.88** per skylight.

Figure 28 provides the remaining assumptions in the NPV calculation as well as the simple payback in years for climate zones 3 and 12.

	CZ3	CZ12
Compared to **"No Skylights"**		
Incremental Cost ($)	$13,297	$13,297
Maintenance Savings ($)	$0	$0
Energy savings ($)	$3,300	$3,389
n (years)	15	15
d (discount rate)	5%	5%
e (energy and labor escalation)	3%	3%
NPV ($)	$31,811	$32,959
Simple Payback (years)	4.03	3.92

* Calculations for 28, 21"dia skylights

	CZ3	CZ12
Compared to **"Std Skylights"**		
Incremental Cost ($)	$2,251	$2,251
Maintenance Savings ($)	$0	$0
Energy savings ($)	$647	$506
n (years)	15	15
d (discount rate)	5%	5%
e (energy and labor escalation)	3%	3%
NPV ($)	$6,097	$4,276
Simple Payback (years)	3.48	4.45

* Calculations for 28, 21"dia skylights

Figure 28: Simple Payback and NPV Calculations

[1] Heschong Mahone Group June 2008. ASHRAE 90.1 Skylighting Requirements Code Change Proposal - Code Change Proposal on behalf Pacific Northwest National Laboratory.

6.4 Occupant Satisfaction

The goal of the occupant survey was to assess the level of acceptance of the advanced skylights. In order to complete this task, surveys were conducted online by 8 employees regardless of rank or job duties.

6.4.1 Survey instrument

The survey instrument consists of multiple choice questions broken up into the following categories: Respondent Information, Work Environment, Electric Lights, Daylight from Skylights, and Comparative Assessment. All qualitative questions have numerical responses that range from 1-7. The responses were formatted so that lower scores always indicate poor performance, and higher scores always indicate better performance. A score of 4 is considered “neutral.” Some qualitative and quantitative questions are supplemented with text boxes. The text boxes allow respondents to elaborate their answers, and give insight to factors that preset answers cannot capture. The survey form used for these on-site interviews is presented in Appendix A – Survey Instrument.

6.4.2 Response rate and Data Analysis

To maximize the number of completed surveys, HMG designed a survey online using SurveyMonkey.com and emailed a link to the store manager to distribute to the employees. Within two weeks of distribution, eight employees completed the survey. Each employee that completed a survey received a $5 gift card.

We received a total of 8 responses; however 2 respondents skipped the final section which included the comparative assessment between the standard and advanced skylights. The responses were downloaded and analyzed in Excel. Weighted average scores were calculated for applicable questions.

6.4.3 General Observations from Occupant Survey Analysis

Respondent Verification

Approximately 63% of the respondents have worked onsite for over a year. With another 25% having worked onsite for over 5 months, 88% of the respondents had a chance to become acclimated to seasonal changes in daylight. This important factor allows workers to observe their environment over time and gain experience on how the change in daylight impacts daily business activity.

To further gather meaningful responses on daylight, employees surveyed should work a significant amount of hours during the day. 100% of the employees surveyed work more than 5 hours in a typical day, and 75% of employees surveyed work the majority of their hours during the day.

50% of the employees described their workstation as a checkout register or the sales floor. The remaining described their work as being a mix of the receiving area, a private office and all. After observing the business on multiple days of operation though, it was decided that all of the employees are in the store enough to provide useful feedback.

Lighting Conditions

100% of the occupants surveyed rated the store's "visual attractiveness" higher than “neutral.” The average weighted score for visual attractiveness was 5.9 out of 7. In addition to visual attractiveness, comfort is another important factor when lighting systems are considered. The average score for "lighting conditions being comfortable" in the store was 5.7 out of 7, with 100% of the occupants surveyed rating the store's "lighting condition" higher than “neutral.”

Electric lighting and daylighting are major variables that contribute to the visual attractiveness and lighting comfort in the store. The average score for "quality of electric lighting" of the store was 5 out of 7, with 75% of the occupants rating the store's "electric lighting" higher than “neutral.” The average score for "quality of daylight from the skylights" was substantially higher, at 5.9 out of 7. The current data shows a likely upward trend in the average score of “quality of daylights from skylights.” 89% of respondents rated the “daylight from skylights” higher than neutral.

Overall, respondents did not find particular parts of the store to be too dark or too bright. 100% of the respondents rated the store as being not excessively bright at any one place compared to 75% for any one place being not too dark. The remaining two surveys said that part of the store was “too dark” sometimes. Comments from employees formed a coherent picture, with the front of the store described as being too dark by multiple employees when it is cloudy and the electric lights have not been turned on.

Electric Lights

Employees rated the satisfaction of working with “some of the electric lights off” and “all the electric lights off” 5.4 out of 7, and 3.5 out of 7 respectively. As might be expected, the percentage of employees that rated the working experience above “neutral” was much higher with some of the lights off; 75% with some lights off to 38% with all lights off. This corresponds with the comments about parts of the store being too dark.

When asked about how they “feel about the electric lights turning off automatically”, half of the respondents, said that they “don't bother me”, or “are appropriate to the space”. On the other hand, one person (13% of respondents) found the automatic lighting controls “slightly annoying “. Comments include that “it can be disconcerting when [the skylights] all go off at once that “occasionally we may need to turn on the pendant lights” before the automatic control would Lighting would be more uniform if every other lighting fixture in a particular row were wired to turn off while switching, or the lights were set to dim, rather than step.

Daylight from Skylights

Questions about daylight from skylights aimed to clarify three issues related to comfort: proximity of skylights to employees, the intensity of light coming through skylights, and visual and thermal comfort affected by skylights.

Skylights were in close proximity to employees, with 100% of respondents stating that their work area was 15 feet or less from a skylight. The average score was high at 5.88 out of 7 for employees being "happy with the amount of daylight from skylights," with 100% answering they were "often" to "always" happy with the amount of daylight from skylights.

Light from skylights also showed high level of acceptance when asked if they were often too bright, or too dim. 87.5% of the occupants surveyed, rated the store as being "occasionally" to "never" too bright and the remainder said they were "sometimes" too bright. None of the occupants surveyed rated the store as being "occasionally" to "never" too dim.

Glare from skylights did not come out as much of a factor in the survey. 87.5% of the occupants surveyed were "occasionally" to "never" uncomfortable due to glare from skylights in the store. Heat from skylights was noticed even less as 87.5% of the occupants surveyed are "never" "uncomfortable due to heat from skylights" in the store.

Comparative Assessment

This section was answered by six of the eight employees at Site 2. 67% of respondents answered that the new skylights have made "the overall brightness of the store" "better", while the remaining 33% were neutral. When asked "how often is the store dimmer, over the course of an average day" 83% of respondents answered "occasionally" to "never".

When asked if the new skylights have "improved visual comfort" 50% of respondents were neutral while the other half answered "less glare" to "much less glare". The majority of respondents at 83% were "neutral" as to whether the new skylights "improved thermal comfort" while the remaining 17% felt there was "less heat". Overall the impact of the new skylights has been positive on employees, with 67% feeling "the visual attractiveness of the store" was made "better" by the new skylights, and the remaining third "neutral".

7. COMPARABLE TECHNOLOGIES

The Solatube 750DS was tested in this study. The following products are comparable products, which can also be categorized as “advanced skylights” that are currently available in the market.

7.1.1 The Natural Lighting Co.

The Active Daylighting™ System from Natural Lighting Co. uses four low-profile solar powered sun-tracking mirrors to redirect sunlight into a reflective light well. It comes with a diffusing lens at the bottom and has an option to include the So-Dark Motorized Shade Screen™ which is built directly into the skylight frame. This allows the skylight to be manually darkened with the flip of a switch. Cost per unit (not including shade screen) is approximately $1,300. More information is available at the website www.daylighting.com.

Figure 29: 4’ x 4’ Active Daylighting Skylight from the Natural Lighting co

7.1.2 Solar Tracking Skylights, Inc.

Solar Tracking Skylights use mirrors that align to the exact position of the sun and reflect light down into the space that would otherwise be lost, particularly during the parts of the day when the sun is at a low incident angle. The units are self contained and require no external power. A photovoltaic cell is mounted directly above the center of the mirrors which provides enough power to move the mirrors for tracking purposes.

This company was originally supposed to be included in this study, but a suitable site could not be found that met the criteria and timeframe for this project. Cost per unit for the 4’ x4’ STS4848 model is approximately $950. More information is available at the website http://www.solar-track.com.

Figure 30: Photo of Solar Tracking Skylight.

7.1.3 Monodraught Ltd

Monodraught Ltd is a British-based company that has specialized in the development of natural ventilation systems and low energy concepts for the building environment. This includes their line of large commercial SunPipe systems, wich are available in diameters of 530, 740, 1000, and 1500mm. According to the Monodraught website (http://www.sunpipe.co.uk/sunpipe/commercial/large_sunpipes.php) the 750 mm diameter Diamond dome is calculated to produce approximately 1000 lux at floor level in buildings greater than 7 meters in height. The larger systems, 1000mm diameter and greater, are manufactured as hemispherical domes. Smaller sizes utilize the diamond domes, which maximize the penetration of sunlight through the flat prisms and to capture the early morning and late afternoon sun through the arrangement of vertical prisms on the circumference. Cost per unit was quoted at £735 which at the time of writing converts to $1,214.81.[1]

[1] As of August 12, 2009 the conversion rate according to Economist.com was 1 USD = 0.6067 GBP.

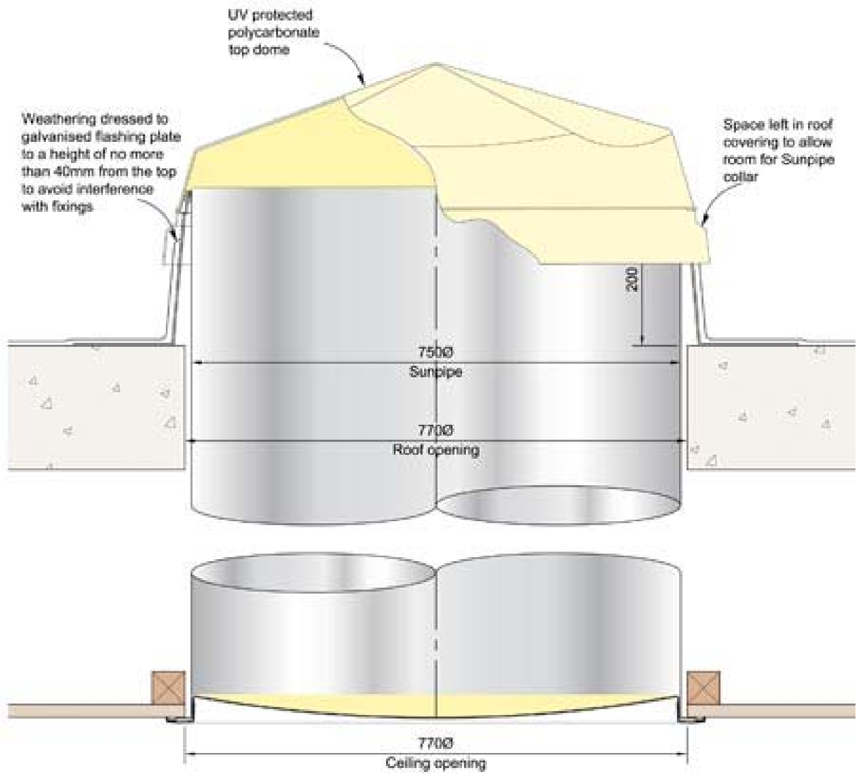

Figure 31: Drawing of the 750mm Diamond SunPipe System©

7.1.4 Sunflower Corporation

An alternative daylighting system is the Sundolier™ available from the Sunflower Corporation based in Boulder, Colorado. This product works in low bay ceiling (8 to 20 feet high) and high bay applications. The Sunflower Corporation claims that the Sundolier™ can illuminate up to 3,000 square feet with one unit which requires a single 24” roof penetration. The unit is made up of two distinct parts; the “harvester” as it is called, is located on the roof and uses two axis active tracking to capture the daylight, and the in-room fixture distributes the daylight evenly throughout the space

The price of the unit can vary depending upon the application, but approximate unit cost is around $15,000. According to their estimates, the cost per square foot of daylit area is in the $6.50 to $24 range. More information is available at the company website: www.sunflowerdaylighting.com.

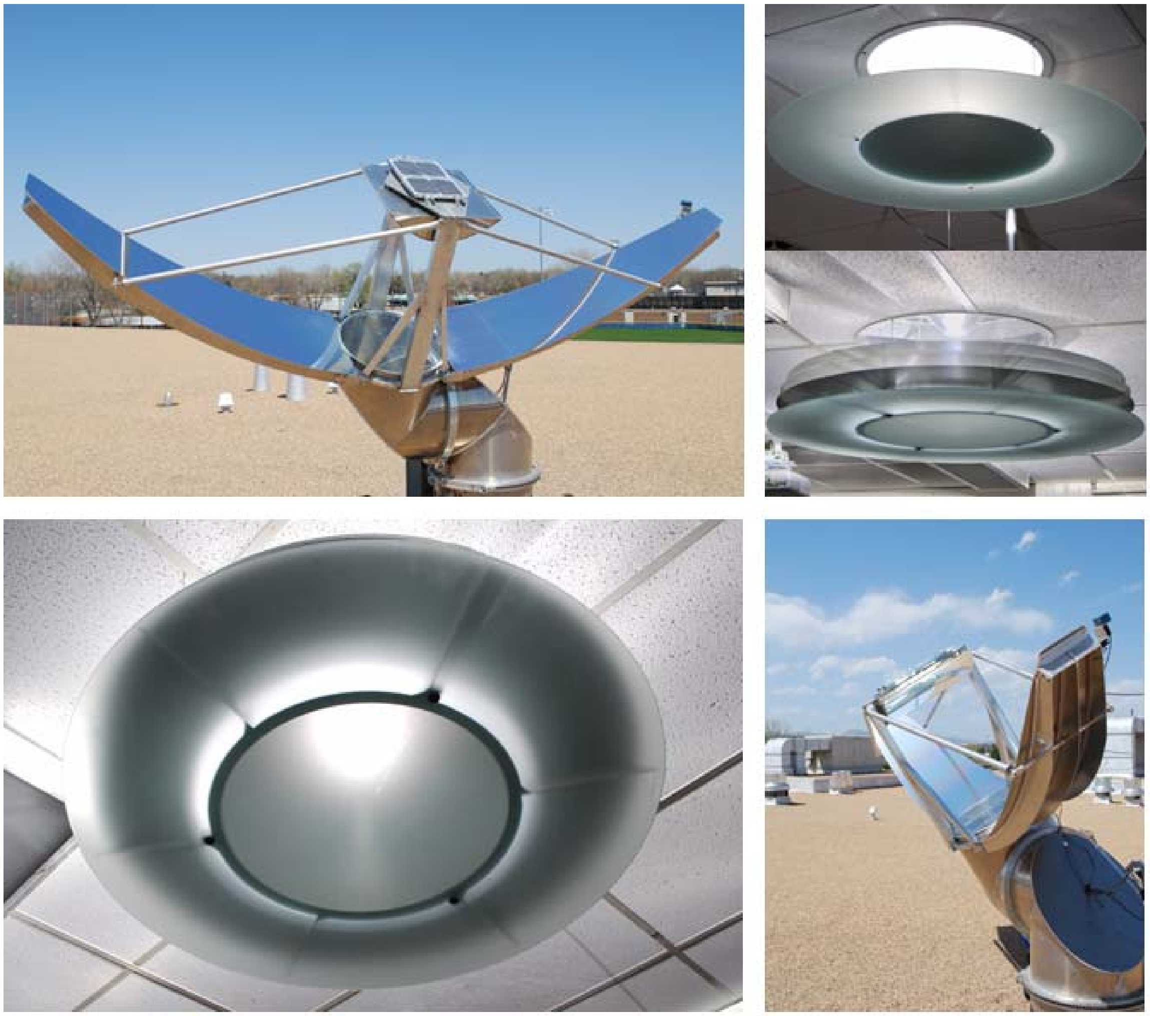

Figure 32: The Sundolier™ from the Sunflower Corporation

8. CONCLUSIONS

8.1 General Conclusions

Analysis of the Solatube 750DS advanced skylight's performance was done for two climate zones that represent a range of climatic conditions for PG&E's territory. CZ 3 is a cloudy, mild, coastal climate zone with high density of population, while CZ 12 is a sunny, hot, inland climate zone that presents ideal conditions for better performance from the advanced skylights.

The range of savings from the Solatube 750DS advanced skylights compared to a base case with no skylights, for a typical 5,000 sf retail store were 3.54 kWh/sf-yr (36%) for CZ 3 to 3.43 kWh/sf-yr (31%) for CZ 12. Compared to a base case with standard skylights, the savings were 0.70 kWh/sf-yr (10%) for CZ 3 to 0.53 kWh/sf-yr (7%) for CZ 12. Peak demand reduction was 2.75 kW to 2.96 kW, compared to no skylights, and 0.83 kW to 0.91 kW compared to standard skylights.

From our detailed analysis of daylighting performance by solar altitude angle and solar radiation, it was seen that for low solar altitude angles (0 – 20 deg), the Solatube 750DS skylights performed better than standard skylights, with about 8.3% greater electric lighting energy savings on average. Above 20deg, the performance reduces slightly to and average of 7.6%. Our HVAC analysis showed that the advanced skylights were very effective at rejecting high angle sun and reducing solar heat gain into the conditioned space. This results in net cooling energy savings over a year, compared to standard skylights.

In conclusion it can be said that the Solatube 750DS skylight was found to be performing per our expectations. As per it's design intent, the advanced skylight is redirecting low-angle sun into the building, which increases the total full load equivalent hours of daylighting, compared to standard skylights. It is also rejecting solar radiation from high angle sun, hence reducing cooling need, and marginally increasing heating needs.

Our occupant assessment analysis found overall positive feedback on the visual and thermal comfort questions. The survey found that 100% of the respondents rated the visual attractiveness of the store higher than neutral, with an average score of 5.9 out of 7 and 89% of the respondents rated quality of daylight from the skylights highly. They also indicated a high level of satisfaction with working with SOME of the electric lights turned off. Notable, there was no negative feedback on the issue of glare or too much daylighting from the Solatube advanced skylights. 87.5% of the occupants surveyed were "occasionally" to "never" uncomfortable due to glare from skylights. These results indicate a high level of acceptance with the advanced skylights technology among occupants.

8.2 Recommendations for Next Steps

Simple payback analysis showed a reasonable payback of about 4 yrs for the Solatube 750DS advanced skylights compared to a base case with no skylights and an equally good payback of 3 yrs (CZ 3) to 4 yrs (CZ 12) compared to standard skylights. These low payback values indicate that the cost of retrofitting the 750DS skylight is low, and benefits are high. However, careful skylighting design is required to ensure that uniform daylighting is achieved. With greater daylighting output from the advanced skylights, compared to standard skylights, fewer of these high efficacy advanced skylights are required in a space, which provides a challenge to the designer to achieve uniform and sufficient daylighting. To further advance this technology in the market, we recommend implementing a demonstration project, which will showcases the advanced skylight's energy efficiency features in multiple applications. Examples of such applications can be:

1. Spaces with plenums and dropped ceilings, which are typically not suited for standard skylight applications due to reduced efficacy from light wells
2. Spaces with aisles and stacks, such as libraries which require special design attention to ensure shadowing does not occur, and daylighting illuminance is required on a vertical surface
3. Spaces with low ceiling heights such as offices and classrooms, that also require high levels of illuminance and uniformity at the workplane
4. Spaces which have the need for high illuminance in specific areas and lower ambient lighting in others such as high-end retail stores.

The demonstration project will server a dual purpose. One, to further document energy savings from this type of skylighting technology, and second, to provide a source of information to designers on best-practices for designing skylit spaces using advanced skylights.

Advanced skylights have a unique ability to redirect sun light in a more-or-less perpendicular direction into the building. This makes them particularly suited to applications with dropped ceilings and light wells, compared to standard skylights. Previously, analysis done by the Heschong Mahone Group to support the prescriptive requirements for skylights in Title 24[1] showed that buildings with dropped ceilings and light wells did not pass the Energy Commission's cost effectiveness test because of reduced skylight efficacy, and increased construction costs of light wells.

Our recommendation is to re-examine calculations for cost effectiveness based on increased energy savings from advanced skylights such as the 750DS, documented in this report. This analysis can be done specifically for the following building types, that do not fall under the current Title-24 prescriptive skylighting requirement:

1. Buildings with less than 8,000 sf of open area. These buildings are currently not required to have skylights in Title-24.

[1] Codes And Standards Enhancement Initiative (CASE) 2008 California Energy Commission Title 24 Building Energy Efficiency Standards - Final Report Updates to Skylighting Requirements

2. Buildings with ceiling height less than 15', and with dropped ceiling and light wells, which reduce a skylight's efficacy due to multiple bounces of light inside the light well. We expect that the advanced skylights will particularly excel in these applications, when compared to standard skylights because of their unique ability to redirect light perpendicular to the light well.

As a result of this analysis a proposal for a code change in Title-24, or the Energy Commission's new 'Reach Code' can be made to include the above building types under the prescriptive skylighting requirement, with the use of light-redirecting skylight technology, as found in advanced skylights such as the Solatube 750DS.

9. APPENDIX A – SURVEY INSTRUMENT

1. Introduction

Please fill out this survey. There are a few multiple-choice questions. It will take you 5-10 minutes to complete. We want to know how you feel about the daylighting (from skylights) in your store and how you use it.

Remember...
- there are no wrong answers.
- please select only one answer per question, unless the question specifically states - "Check more than one if applicable"

As a gesture of thanks for completing this survey, you will receive a $5 gift card for Starbucks.

This information will be used to understand how well your daylighting system is performing, relative to other systems, in this study funded by Pacific Gas & Electric. Your responses will remain anonymous and confidential and will not be available to your supervisor or company. If you have any questions about this study or survey, call Mudit Saxena at 916-962-7001 or email him at saxena@h-m-g.com.

Thank you for your time!

2. About You

1. How long have you been working at this store?

- ◯ a. Just today
- ◯ b. a week
- ◯ c. a month
- ◯ d. 2-4 months
- ◯ e. 5-11 months
- ◯ f. a year or more

2. In a typical day, how many hours do you spend in this store?

- ◯ a. an hour or less
- ◯ b. 2-4 hours
- ◯ c. 5-7 hours
- ◯ d. 8 or more hours per day

3. What percentage of your hours are at night?

- ◯ a. 0%
- ◯ b. 0%-25%
- ◯ c. 25%-50%
- ◯ d. 50%-75%
- ◯ e. 100%

4. How would you describe the work you do? (Check more than one if applicable)

- ☐ a. Cashier
- ☐ b. Floor work
- ☐ b. Yard work
- ☐ c. Manager/Supervisor
- ☐ d. Recieving clerk
- ☐ e. Data processor

5. What is your age?

- ◯ a. 30 or under
- ◯ b. 31-50
- ◯ c. Over 50

6. Which of the following best describes your personal workstation?

- ◯ a. Checkout Register
- ◯ b. Sales Floor
- ◯ c. receiving Area
- ◯ d. Private or shared office
- ◯ e. Other (please specify)

3. Your Workstation

1. Do you find this store visually attractive?

○ 1-Not attractive at all ○ 2 ○ 3 ○ 4-Neutral ○ 5 ○ 6 ○ 7-Very attractive

2. Do you feel that the lighting conditions in this store are comfortable?

○ 1-Never ○ 2-Almost Never ○ 3-Occasionally ○ 4-Sometimes ○ 5-Often ○ 6-Almost Always ○ 7-Always

Please explain further (optional)

3. Overall, please rate the quality of the 'electric lighting' in the store

○ 1-Very poor ○ 2 ○ 3 ○ 4-Neutral ○ 5 ○ 6 ○ 7-Excellent

4. Overall, please rate the quality of the daylight from the 'skylights' in the store

○ 1-Very poor ○ 2 ○ 3 ○ 4-Neutral ○ 5 ○ 6 ○ 7-Excellent

5. Do you ever feel that any part of the store is too dark?

○ 1-Always ○ 2-Almost always ○ 3-Often ○ 4-Sometimes ○ 5-Occasionally ○ 6-Almost never ○ 7-Never

Please explain where and when areas are too dark

6. Do you ever feel that any part of the store is too bright?

○ 1-Always ○ 2-Almost always ○ 3-Often ○ 4-Sometimes ○ 5-Occasionally ○ 6-Almost never ○ 7-Never

Please explain where and when areas are too bright

4. Electric Lights

1. Are you satisfied working in the store with SOME of the overhead electric lights turned off?

◯ Don't Know/Not Applicable ◯ 1-Very Dissatisfied ◯ 2 ◯ 3 ◯ 4-Neutral ◯ 5 ◯ 6 ◯ 7-Very Satisfied

2. Are you satisfied working in the store with ALL of the overhead electric lights turned off?

◯ Don't Know/Not Applicable ◯ 1-Very Dissatisfied ◯ 2 ◯ 3 ◯ 4-Neutral ◯ 5 ◯ 6 ◯ 7-Very Satisfied

3. How do you feel about the electric lights being turned off automatically?

◯ Don't Know/Not Applicable

◯ a. The automatic control is very annoying

◯ b. The automatic control is slightly annoying

◯ c. The automatic control doesn't bother me

◯ d. I like the automatic control--it's appropriate to the space

◯ e. I never notice the lights being controlled

◯ f. Please explain further:

5. Daylight from Skylights

1. About how close is your workarea to a skylight?

- ◯ a. Directly under a skylight
- ◯ b. About 5 feet from a skylight
- ◯ c. 10-15 feet from a skylight
- ◯ d. 20-30 feet (or more) from a skylight
- ◯ e. I can't see a skylight from where I work

2. Are you happy with the amount of daylight from skylights in this store?

◯ 1-Never ◯ 2-Almost Never ◯ 3-Occasionally ◯ 4-Sometimes ◯ 5-Often ◯ 6-Almost Always ◯ 7-Always

3. Do you ever feel the skylights are too bright?

◯ 1-Always ◯ 2-Almost Always ◯ 3-Often ◯ 4-Sometimes ◯ 5-Occasionally ◯ 6-Almost Never ◯ 7-Never

4. Do you ever feel the skylights are too dim?

◯ 1-Always ◯ 2-Almost Always ◯ 3-Often ◯ 4-Sometimes ◯ 5-Occasionally ◯ 6-Almost Never ◯ 7-Never

5. Do you ever feel discomfort due to glare from skylights?

◯ 1-Always ◯ 2-Almost Always ◯ 3-Often ◯ 4-Sometimes ◯ 5-Occasionally ◯ 6-Almost Never ◯ 7-Never

6. Do you ever feel discomfort due to heat from skylights?

◯ 1-Always ◯ 2-Almost Always ◯ 3-Often ◯ 4-Sometimes ◯ 5-Occasionally ◯ 6-Almost Never ◯ 7-Never

6. Comparative Assessment

The following questions ask you to compare the lighting condition in this store now to the lighting condition in this store before the "new" skylights were installed.
NOTE: THESE QUESTIONS SHOULD BE SKIPPED IF YOU HAVE ONLY SEEN THE STORE WITH THE "NEW" SKYLIGHTS.

1. Have the new skylights impacted the overall brightness of the store?

1-Much worse | 2-Worse | 3-Slightly worse | 4-Neutral | 5-Slightly better | 6-Better | 7-Much better

2. How often is the store BRIGHTER, over the course of an average day?

1-Always | 2-Almost Always | 3-Often | 4-Sometimes | 5-Occasionally | 6-Almost Never | 7-Never

3. How often is the store DIMMER, over the course of an average day?

1-Always | 2-Almost Always | 3-Often | 4-Sometimes | 5-Occasionally | 6-Almost Never | 7-Never

4. Have the new skylights improved visual comfort?

1-Much more glare | 2-More glare | 3-Slightly more glare | 4-Neutral | 5-Slightly less glare | 6-Less glare | 7-Much less glare

5. Have the new skylights improved thermal comfort?

1-Much more heat | 2-More heat | 3-Slightly more heat | 4-Neutral | 5-Slightly less heat | 6-Less heat | 7-Much less heat

6. Have the new skylights changed the visual attractiveness of the store?

1-Much worse | 2-Worse | 3-Slightly worse | 4-Neutral | 5-Slightly better | 6-Better | 7-Much better

7. You're Finished!

THANK YOU!!! for completing this survey.

IT'S TIME FOR A COFFEE!!

Please submit the survey and a $5 Starbucks gift card will arrive for you June 1st!

- The Daylighting Survey Team :)