Pacific Gas and Electric Company

Emerging Technologies Program

Application Assessment Report #0817

Advanced Skylights- Passive: Ciralight Suntracker

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PG&E Emerging Technologies Advanced Skylights- Active: Ciralight Suntracker

Project Report for Site I – Ciralight Suntracker Skylight

HMG Project No: 0515q ET Adv Skylights

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TABLE OF CONTENTS

TABLE OF FIGURES

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

1. **Site 1**: An installation of **Ciralight’s Suntracker** skylights at a warehouse style retail store in Martinez, CA.
2. **Site 2**: An installation of **Solatube’s DS750** dome skylight at a bookstore in Santa Cruz, CA.

This report describes the first of the two studied sites. The Ciralight skylight is an active system that employs three mirrors that rotate on a vertical axis to track the sun, to intersect and redirect lower angle sunlight.

1.1 Lighting Energy Savings

We calculated *lighting energy savings* for the standard skylights case (DOE 2 estimate), no-skylights case (DOE 2 estimate), and advanced skylights case (on-site monitoring) 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 1 (Ciralight)

Solar Altitude	STANDARD Skylight - % Ltg Energy Savings	ADVANCED Skylight - % Ltg Energy Savings	ADV vs STD	
0	0.3%	**10.0%**	9.7%	
5	2.5%	**21.0%**	18.5%	
10	4.9%	**25.5%**	20.5%	13.8%
15	10.1%	**28.6%**	18.5%	
20	19.4%	**34.8%**	15.5%	
25	31.9%	**34.0%**	2.1%	
30	**47.1%**	41.2%	-5.9%	
35	**64.0%**	51.9%	-12.1%	
40	**67.0%**	59.8%	-7.3%	
45	**70.0%**	68.4%	-1.6%	-6.2%
50	**70.0%**	67.1%	-2.9%	
55	**70.0%**	69.1%	-0.9%	
60	70.0%	**70.6%**	0.6%	
Angles 0-60 (weighted)	**33.3%**	**39.0%**	**5.7%**	

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

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. Advanced skylight had higher energy savings compared to standard skylights between angles 0 – 25 deg by an average of 13.8%. However, we also found that at solar altitudes between 30 – 60 deg , the advanced skylights were rejecting more incoming daylight compared to standard skylights resulting in lower lighting energy savings by an average of 6.2%.

Overall for all angles, weighted over the study period, the advanced skylights performed better than standard skylights with **5.7%** greater lighting energy savings.

These results indicate that the Ciralight product was optimized for low solar altitude angles (0 – 25 deg), but the mirrors geometry and angles did not work as well for the mid range angles (30 – 50 deg). However, despite the reduced performance in mid range altitude angles, the advanced skylights were found to have net positive savings compared to standard skylights. We believe that by fine tuning the mirror angles for the Ciralight system, there is scope for an even greater energy savings through daylighting. This report however has not looked at performance of other comparable active advanced skylight products in the market (such as Solar Tracker, Natural Lighitng, Sundolier, etc) that may have better optimization of mirror angles, and so should not be considered as a sweeping conclusion for all active skylight types.

The results for lighting energy savings were extrapolated 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 1. Results from this analysis are presented in Figure 2 and Figure 3 along with HVAC analysis done using DOE2, as described in Section 1.2 below.

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 1, HVAC energy use could not be properly measured on-site due to the number of packaged HVAC system at the study site, and their interactions. So, to estimate HVAC energy use for Site 1, all three case: advanced skylights, standard skylights, and no-skylights, were modeled as three separate DOE 2 simulations 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. These results indicate that over the summer months, the advanced skylight is rejecting enough high angle sun to balance the heat gained from admitting low angle sun, hence making the net cooling energy load in the advanced skylights case very similar to the standard skylights case (a difference of only 2%). For winter, the results indicate that there is a net rejection of heat by advanced skylights compared to standard skylights, although the magnitude of increase in heating load is small compared to lighting and cooling. The advanced skylights save total energy by 3% or 1,294 kWh in climate zone 3, and 4% or 1,796 kWh in climate zone 12.

It should be noted here that energy savings are as much a function of the skylight design, as the building design, HVAC system, and lighting controls performance. By comparing advanced to standard skylights in this study, we are only changing one of the four variables (skylight design), keeping the rest constant. While the skylight might be optimized for better performance, the building design is not. A more appropriate building design for advanced skylight would likely have fewer skylights (a lower skylight to floor area ratio), which would likely result in overall better HVAC performance for the advanced skylight.

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 1 CIRALIGHT SUNTRACKER
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)	22,202	14,888	1,027	38,118	21,814	20,089	4,410	46,313
Peak Demand (kW) [Average during PG&E peak period]	6.82	7.21	-	14.03	6.80	10.99	-	17.79
Peak Demand (kW) [Average for 10 hottest days]	7.09	10.30	-	17.39	6.75	14.61	-	21.36
"Advanced Skylights" Case								
Annual Energy Use (kWh)	20,728	14,562	1,534	36,824	19,643	19,857	5,017	44,517
Peak Demand (kW) [Average during PG&E peak period]	5.40	6.94	-	12.34	4.93	10.86	-	15.79
Peak Demand (kW) [Average for 10 hottest days]	5.52	10.31	-	15.83	4.56	14.54	-	19.10

* 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 1.
Store has 11, 3.93' x 3.93' skylights (SFR is 3.38%)

Figure 2: Advanced Skylight: Ciralight – Energy Use

Advanced Skylight Type 1 CIRALIGHT SUNTRACKER
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)	14,860	-2,005	-977	11,877	15,944	-3,158	-2,036	10,750
Percent Energy Savings (%)	*42%*	*-16%*	*-175%*	*24%*	*45%*	*-19%*	*-68%*	*19%*
Peak Reduction (kW) [Average during PG&E peak period]	2.10	-1.14	-	0.96	2.57	-1.96	-	0.61
Percent Peak Reduction (%)	*28%*	*-20%*	-	*7%*	*34%*	*-22%*	-	*4%*
Peak Reduction (kW) [Average for 10 hottest days]	1.98	-1.80	-	0.18	2.94	-3.08	-	-0.14
Percent Peak Reduction (%)	*26%*	*-21%*	-	*1%*	*39%*	*-27%*	-	*-1%*
Compared to **"Standard Skylights"**								
Annual Energy Savings (kWh)	1,474	327	-507	1,294	2,171	232	-607	1,796
Percent Energy Savings (%)	*7%*	*2%*	*-49%*	*3%*	*10%*	*1%*	*-14%*	*4%*
Peak Reduction (kW) [Average during PG&E peak period]	1.42	0.27	-	1.69	1.87	0.13	-	2.00
Percent Peak Reduction (%)	*21%*	*4%*	-	*12%*	*27%*	*1%*	-	*11%*
Peak Reduction (kW) [Average for 10 hottest days]	1.57	-0.02	-	1.56	2.19	0.07	-	2.27
Percent Peak Reduction (%)	*22%*	*0%*	-	*9%*	*32%*	*1%*	-	*11%*

* 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 1.
Store has 11, 3.93' x 3.93' skylights (SFR is 3.38%)

Figure 3: Advanced Skylight: Ciralight - 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 83% of the respondents rated the visual attractiveness of the store highly and 87% 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 Ciralight advanced skylights. 82.6% of the occupants surveyed were "occasionally" to "never" uncomfortable due to glare from skylightsThese 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 Ciralight Global, and the energy savings compared to no skylights from Figure 3. The result was a simple payback of about **5 yrs** for CZ 3 and CZ 12.

In the standard skylights comparison, we took the incremental cost of the advanced skylight compared to a standard 4’x4’ double glazed acrylic domed skylight, and the energy savings compared to standard skylights from Figure 3. The result was a simple payback of **24 yrs** for CZ 3 and **18 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
2. Natural Lighting Inc.
3. Sundolier
4. Ciralight Inc

Passive Skylights

1. Solatube Inc.
2. Monodraught Skylights

2.1.2 Product Description: Ciralight Suntracker

Figure 4: Ciralight Suntracker

Ciralight's Suntracker is an active system, which employs 3 mirrors at fixed angles to redirect daylight, mounted on a rotating axis. The axis rotates to track the azimuth of the sun. A photovoltaic powered GPS controller adjusts for sun movement every ten minutes. According to the manufacturer, the tracking system begins operating when the Sun is ten degrees above the horizon. This system then rotates three mirrors that reflect sunlight down, through the light well, into the building.

Our host site (study space), a hardware retail store in Martinez, CA, had 32 Ciralight Suntracker advanced skylights. The skylight has a diffuser (flat) at the top of the light well, just below the mirrors. Another diffuser (inverted pyramid) is at the bottom of the light well. The two diffusers help diffuse the light that is redirected from the mirrors. The manufacturer claims the double diffuser design helps reduce possible 'hot-spots' that can form from highly specular surfaces like the mirrors.

Figure 5: Shot of interior showing Ciralight skylights at Site 1

2.2 Ciralight Suntracker - Cost Information

The cost of the Ciralight installation was difficult to assess because Site 1 performed the upgrade of skylights at the same time as other upgrades in the store. Thus the invoices included only total costs. The pricing information in Figure 6 was provided by Ciralight Global and is only an estimate of the costs. These costs do not include shipping.

QTY	Part#	Description		Retail Price	Extended
25	2200-	SuntrackerTwo Base Unit 4'x4' (Single Mirror)-includes the Dome Assembly, Mid Tray Assembly, Single Mirror Assembly and GPS Suntracking Controller (Does not include Curb)		$900.00	$22,500.00
25	4510-	Bottom Lens, Pyramid-Prismatic Acrylic 4'x4'		$72.00	$1,800.00
25	4710-	24" Regal, White Lightwell 4'x4'		$135.00	$3,375.00
25	4810-	Standard R20 Curbs 4'x4'	Curbs may be purchased from local vendor	$375.00	$9,375.00
				Sub Total	**$37,050.00**

Figure 6: Cost information as provided by Ciralight Global

2.3 Existing State of Technology

As one of the two advanced skylights that were assessed in this study, the Ciralight Suntracker has been available in the market for over 20 years under other names and owners, and has gone through many iterations and refinements over time. We learned in the middle of our project that the Ciralight has changed owners and is now being marketed under the ‘Ciralight Global’[1] brand name. We confirmed with the new owners that they are continuing to market and sell the Suntracker skylight in the US market. They also confirmed that along with the 3-mirror design skylight that was studied in this study, they are also marketing a 1-mirror design skylight, which they claim has better optimization of mirror angle for overall improved performance.

Other companies such as Solar Tracking Skylights Inc., and Natural Lighting Inc., have similar ‘active’ skylight products that are currently available in the market and are ready for broader market adoption.

The above mentioned manufacturers have a network of distributors and field representatives that create the market outreach and help educate potential users of their 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’s Emerging Technologies group to understand and quantify the benefit that these advanced skylight technologies provide over standard skylights

[1] http://www.ciralightglobal.com

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 2 month period
b. New advanced skylights – for a minimum of 2 month period

2. RETROFIT

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

- '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. No skylights – for a 1 month period
b. New advanced skylights – for a minimum of 2 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 2 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 B – 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 7 provides the timeline for the monitoring period for Site 1. A total of 16 weeks and 4 days were monitored from September 6th 2008 to December 31st 2008. Further monitoring took place for an additional 11 weeks, from April 23rd 2009 to July 10th 2009.

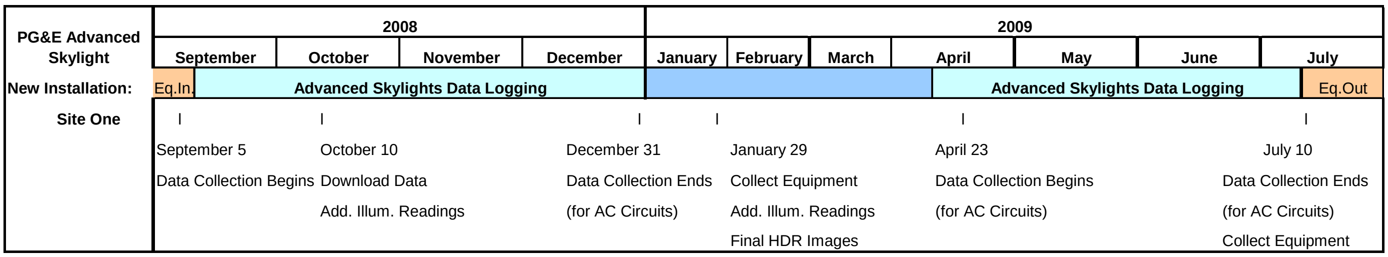


Figure 7: Project Timeline

For our first study period (Sep-Dec) the highest solar altitude angle at 12:00pm we captured in our study period was 58 deg and the lowest was 28.56 deg. The highest solar altitude angle at the summer solstice for this location is 75.29 deg.

3.6 Limitations and Equipment Malfunction During Study Period

For the two study periods (Sep-Dec and Apr-Jul), our intent was to monitor - indoor light levels, lighting circuit energy use, and HVAC energy use. However, during the second study period (Apr – Jul), the lighting circuit energy use data was not accurately captured due to malfunction of a Hobo data logger. For this reason, data from that period could not be used in the lighting energy savings analysis. However, indoor lighting levels for the second study period were successfully monitored and used in the analysis.

4. DESCRIPTION OF HOST SITES

4.1 Site 1: Ciralight Suntracker

Host Site 1 was selected after discussions with Ciralight on potential candidates for all three evaluation types: Swap, Retrofit and New Installation. The selected was a warehouse style hardware retail store in Martinez, CA (Title 24 Climate Zone 12).

Site Selection Criteria: Site 1 – Ciralight

The site selected as Site 1 – Ciralight, 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 1.7 Watts/sf.
- The site had hours of operation that spanned early morning and late evening hours, and was open 7 days a week, 12 months a year.
- Building was located in PG&E territory, sunny climate zone (CZ12)

Some of the criteria were not met:

- The site did not have a dropped ceiling
- The area of the store was greater than 8,000 sf - at 14,196 sf, and the ceiling height was greater than 15ft – at 19ft.

This site was chosen, as most of the important criteria were met, and the two criteria not met were not critical to the analysis. One disadvantage of choosing this site was that since it was a large site, it had multiple rooftop HVAC units, which could not be all monitored due to limitations on number of loggers available and project budget.

Selected Methodology: Site 1 – Ciralight

For Site 1 – Ciralight, the site already had advanced skylights from Ciralight installed. Hence the “New Installation” methodology was selected. The *Base Case* condition with standard skylights was estimated using a DOE 2 simulation using eQUEST version 3.63, while the *Advanced Skylights Case* was monitored.

History of Skylight Installations at Host Site

We were told by the hosts, that the site was retrofitted with standard skylights in 1997. Then in 2001, So-Luminaire, the parent company of Ciralight, installed their version of an advanced skylight. Then in 2007, Ciralight replaced the old So-Luminaire advanced skylights with the new Suntracker skylights, which uses active tracking technology and mirrors inside the skylight dome. This was the technology that was studied in this project.

The Suntracker skylights had been in place for one and a half years before our study began.

Description of Store

The store is a warehouse type hardware retail store that covers approximately 14,196 square feet. The ceiling height is 19ft in the middle of the store and slopes down to 14ft at the sides. There are 32 Ciralight 4' x 4' (46.5" x 46.5" opening dimensions) Suntracker skylights (see Figure 8). 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 1.7 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 23.5 fc on average, in an aisle at the mid point of two skylights, 2.5 ft from the floor.

The store is open from Monday-Saturday 7am-8pm and Sunday 8am-7pm.

Figure 8 shows the plan and section of the Site 1 store.

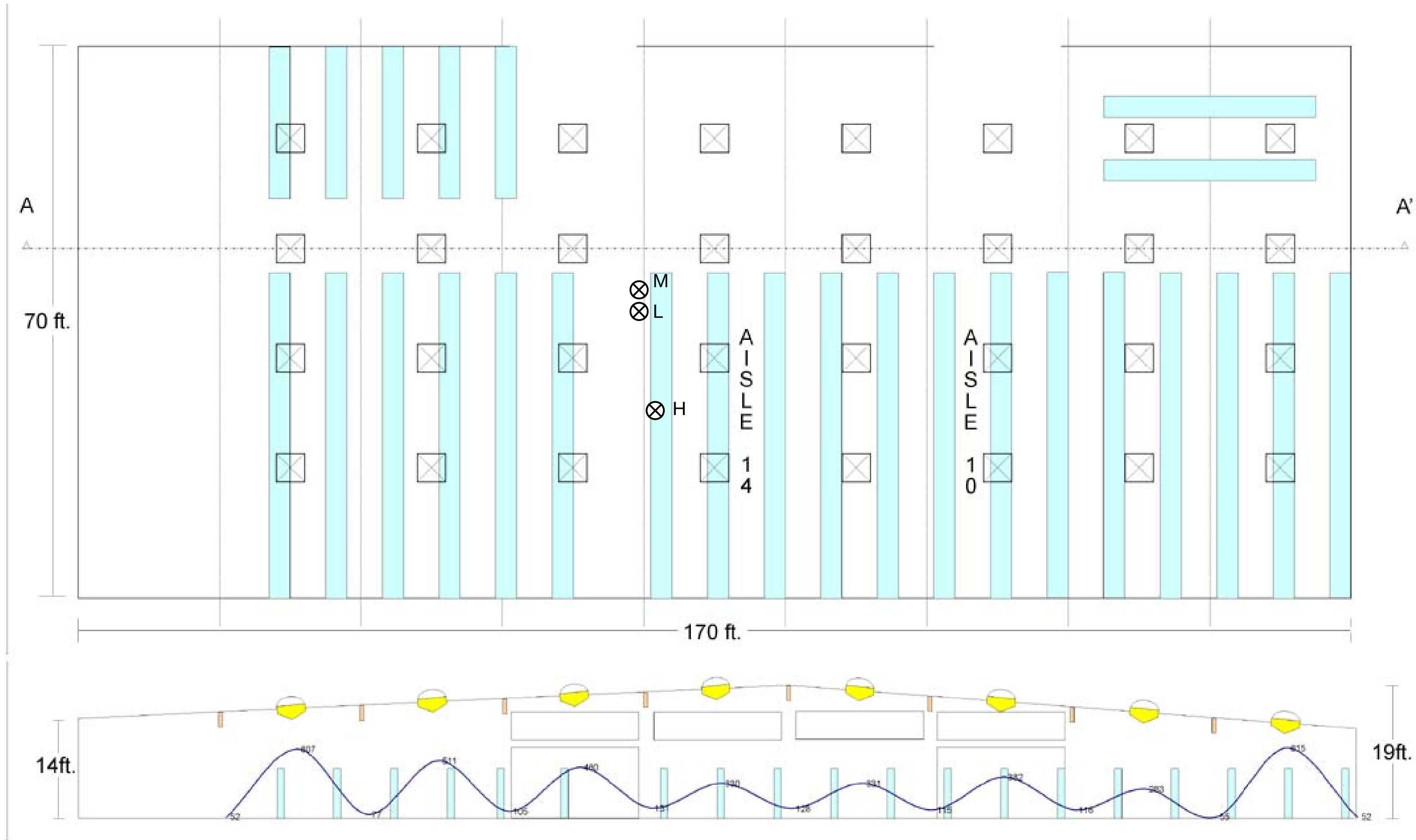


Figure 8: Plan and Section view of Site 1

In Figure 8, the section A-A' (shown as the dotted horizontal line A-A' in the plan view) shows the slightly sloping roof going down from 19 feet to 14 feet. The blue line in the section represents illuminance (in foot candles) measured at noon on a clear sunny day in September 2008 using a hand-held illuminance meter at about 2.5' height. The average illuminance reading was 256 fc, with highest reaching 615 fc where the ceiling height is the lowest. The lowest readings in-between skylights was 55 fc. As can be seen in the graphic, at high ceiling heights (19ft) creates more uniform and diffuse distribution of daylight, while at lower ceiling heights (14ft) the daylight is more intense below the skylight, and also has most contrast with daylight between skylights.

4.2 Monitored Data

Figure 9 shows the output from the three circuits plotted over the course of a typical sunny day (9/26/08). 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).

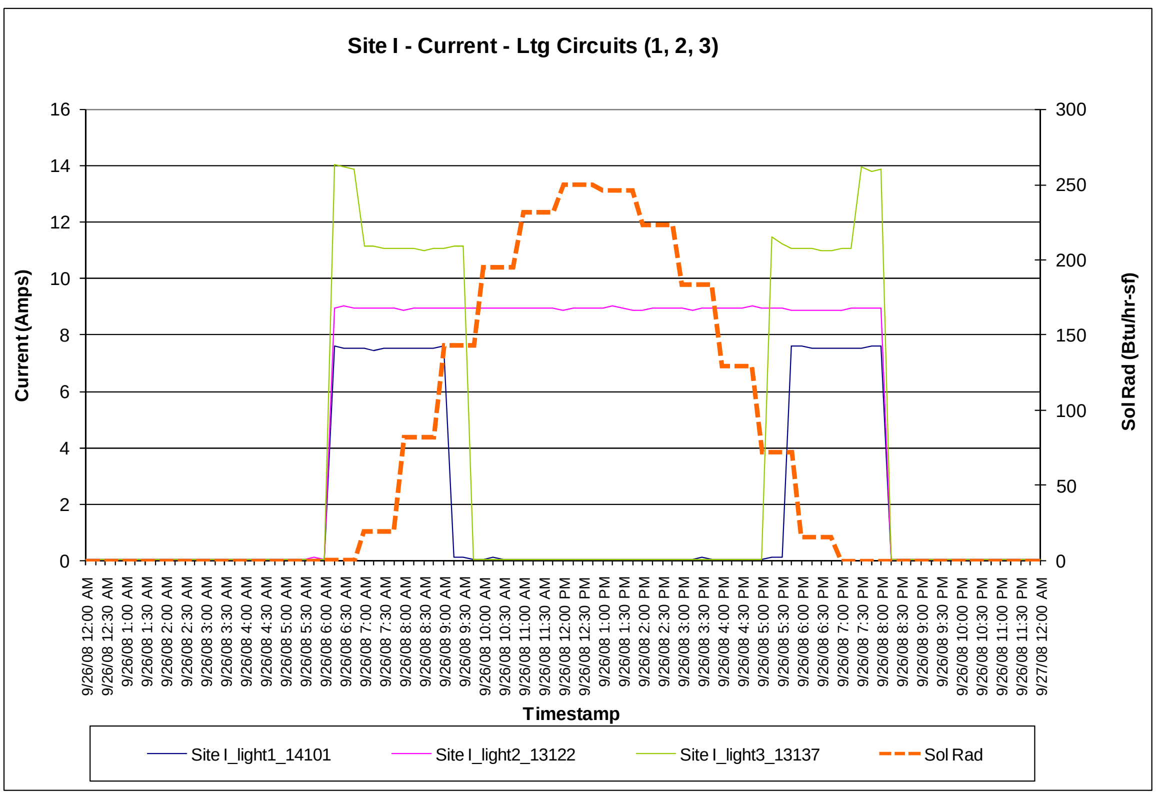


Figure 9: Monitored electric lighting energy usage data from three lighting circuits

The lighting system (4' T-8 lamps, 2 lamps per fixture) were arranged in three circuits. Two of these circuits were photocontrolled, while one was on manual on-off controls. Circuit 1 (Site I_light1_14101) had an automatic on-off control (100% - 0%), circuit 2 (Site I_light2_13122) was manual on/off, and Circuit 3 (Site I_light3_13137) had an automatic 2-step control (100% - 78.5% - 0%). Figure 9 shows that, as expected, when enough daylight is present, circuits 1 and 3 turn off completely, while circuit 2, which is on manual control remains on until the end of the work day.

Hobo data recorders were also placed measuring vertical illuminance (facing west) at three levels along aisle 14 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 8 along aisle 14 by letters L. M and H. The graph in Figure 10 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).

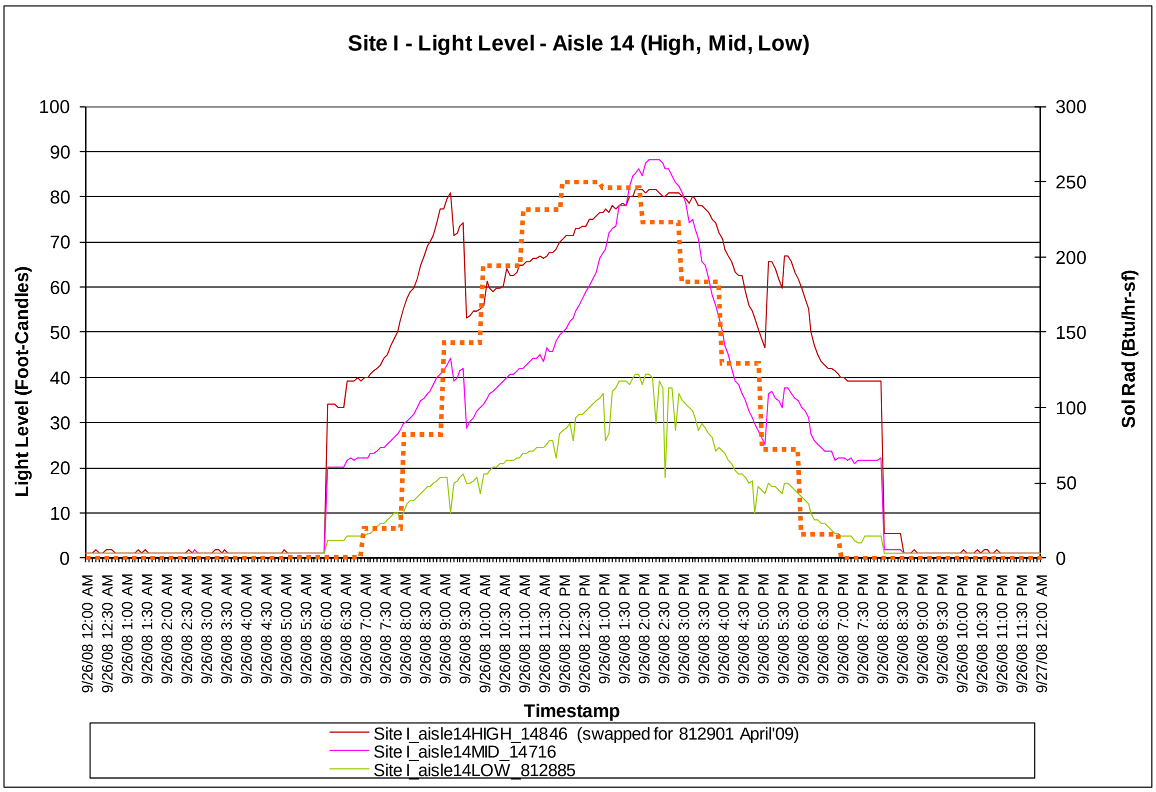


Figure 10: Monitored net indoor illuminance (daylight + electric light) from Hobo data recorders place at three levels in an aisle

As seen in Figure 10, the Hobo data logger at mid level (magenta line) recorded early morning and night time readings of 23.5 fc, while in the middle of the day, the illuminance levels reached as high as 88 fc. The times when automatic photocontrolled lights switched on or off can be seen as ‘spikes’ in the data at about 9:00am and 6:00pm.

5. DATA ANALYSIS

5.1 Lighting Analysis

The analysis for electric lighting energy use and savings was done for three cases:

- For the advanced case, monitored data on electric lighting circuits was used
- For the standard case, hourly output of lighting energy use from DOE 2 was used. In order to model a comparable and equivalent lighting control system in DOE 2, indoor lighting level data collected on-site was used to determined a lighting set point.
- For the no-skylight case, hourly output of lighting energy use from DOE 2 was used. No photocontrols were modeled in this case.

To ensure that results from the DOE 2 simulations and on-site monitoring were comparable we modeled the DOE 2 simulation to match the lighting power density, lighting controls and set point found at the site during the monitoring period. We also created a custom weather file for the DOE 2 simulation to match the monitoring period. 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 radiation conditions where the performance of advanced skylights was better or worse than standard skylights. Finally the data from the monitoring period was extrapolated for an entire year, using a multi variate regression analysis to determine annual energy savings and peak demand reduction.

5.1.1 DOE 2 Model

After collecting the monitored data at Site 1 we needed energy use data for an equivalent site with standard skylights. This was accomplished by creating a DOE 2 model representative of the participant site. A representative model of Site 1 was created in eQUEST version 3.63 (DOE 2.2) along with a 3 step lighting control. We used the latest version of eQUEST (v. 3.63) that has the ability to model domed acrylic skylights, for the base case condition that captures the added effect of refraction by the dome shape to admit some low altitude angle sun.

In order to model a comparable and equivalent lighting control system in DOE 2, we used the indoor lighting level data collected by a Hobo data logger at 2.5ft height to determine a set point. A Hobo data logger was placed in the store approximately equidistant from four skylights, in a aisle, 2.5 ft above the ground. Observing the exact light levels from the Hobo data logger at which the lights turned on and off, and also the night time illuminance, the set point was determined to be 23.5 fc. In the DOE 2 model, the photosensor was also placed in a location that was also equidistant from four skylights, and at 2.5ft from the ground, with a set point of 23.5 fc.

5.1.2 Custom TMY2 Weather File

In order for the DOE 2 simulations to more accurately reflect the actual monitored sites, we had to create new weather files using local data, rather than the building climate zones or major city TMY2 files that are available online. The first step was identifying the TMY2 file on which to base the new weather file. For Site 1 located in Martinez, we chose to use the Sacramento TMY2 file as the basis because they are located in the same building climate zone (Climate Zone 12). Accuracy of the weather file was increased by replacing specific variables with actual weather data recorded by a nearby weather station. Hourly 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 Concord station (2.5 miles from site location in Martinez) to fill in global horizontal radiation, global horizontal illuminance, dry bulb temperature and dew point temperature 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.

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.

5.1.3 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.

There were five distinct levels of light that became apparent. All of the electric lights on or all of the lights off were two levels. When the stepped lights dimmed 20%, this accounted for a 10% reduction in light overall. When the first circuit shut off while the second circuit was dimmed, this amounted to a 35% reduction in lighting overall, however this was a relatively rare occurrence, accounting for approximately 2% of all occupied hours for which data was available. The next level occurred when both circuits on photocontrols shut off, accounting for a 70% reduction.

5.1.4 Frequency Bins

The first step in the analysis required the construction of a frequency table showing the number of occurrences at various combinations of solar altitude and radiation. This was accomplished by using Excel to roundup the radiation and altitude values into bins of 5 degrees and 10 Btu/hr-sf respectively. Figure 15 (upper table) shows the frequency table of all the occupied hours that were monitored at Site 1. Solar radiation is measured in Btu/hr-sf and solar altitude is measured in degrees above the horizon. The color coding

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

from light to dark illustrates which combinations have the lowest and highest number of data points.

5.1.5 Analysis of Hourly DOE-2 Results and Actual 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 open at 6am, close at 8pm, modified according to actual data indicating lights on and daylight savings time.

5.1.6 Annual Data Extrapolation

Because of the monitoring equipment malfunction for the second study period (Apr – Jul) the monitoring period for Site 1 was limited to Fall 2008 (September 6th to December 31st 2008). Annual lighting schedules were extrapolated from the four months of 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 statistical model was also considered, but deemed less practical for this particular model).

Figure 11 compares the percent of lights turned off at 15 degree solar altitude angle bins across the different scenarios. 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 (September to December). The rightmost column, "Standard Extrapolated" gives the percent of lights off under standard skylights as modeled in a DOE-2 simulation.

Percent of lights off at 15 degree altitude bins

Ciralight	Fall (Sept-Dec)		
Altitude Angle	**Advanced monitored**	**Advanced extrapolated**	**Standard simulation**
0-15	20%	35%	4%
15-30	37%	48%	35%
30-45	58%	65%	66%
45-60	68%	70%	70%

Figure 11: Comparison between monitored and extrapolated savings estimates

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

The extrapolated data was necessary for comparison of standard and advanced skylights during the same time period. As can be seen in Figure 11 the extrapolation results tend to increase the percent savings at lower sun angles, when compared to our monitored data. At higher sun angles, due to saturation of lighting energy savings (at 71%), the difference between the monitored and extrapolated data is negligible. The margin of error between the actual and extrapolated data remains within 15%, which we deemed acceptable for this exercise. The extrapolated data allows us to compare the 8760 hourly predictions against the DOE 2 simulation to calculate savings throughout an entire year from the four months of data that were collected.

5.2 HVAC Analysis

As explained earlier, HVAC energy use could not be monitored for Site 1. So, to estimate HVAC energy use for Site 1 with advanced, standard and no-skylight cases, three separate DOE 2 simulations using eQUEST 3.63 were created.

- The standard skylight case was modeled in DOE 2 with a packaged single zone air conditioner and gas heater, and using default skylight properties for a double glazed, domed white acrylic skylight. These properties were visible light transmittance 0.50, solar heat gain coefficient (at 0deg incident angle) 0.467 and glass conductance 1.27 Btu/hr-sf-degF. These values were obtained from DOE 2's glazing library. Electric lights were modeled with a three level stepped switching control (1/0.66/0.33) and a setpoint of 23.5 fc to match what was seen on site.
- The advanced skylight case was also modeled in DOE 2 with the same packaged single zone air conditioner and gas heater. Skylight properties were modified based on monitored data. Angular dependent SHGC was modeled using the SKY-TRANS-ANG and SKY-TRANS-MULT functions in eQUEST, which were developed using monitored data on indoor illuminance and outdoor solar radiation. Daylighting was turned "off" for this run, and instead electric lights were put on a custom, hourly, stepped-switching lighting profile, to mimic the lighting load expected with the advanced skylights. The advanced skylight run was modeled with the same glass conductance as in the standard case of 1.27 Btu/hr-sf-degF. This approximation was made on the basis that the advanced skylight has a single glazed acrylic dome and a second acrylic sheet at the throat of the light well. The solar heat gain coefficient (at normal incident angle) was 0.312. This value was obtained from Ciralight's literature on skylight properties from the Ciralight website[1]. Since daylighting was turned off for this run, visible light transmittance of the skylight was irrelevant. This method ensured that both the solar and electric lighting loads are representative of the loads expected from advanced skylights
- The no-skylights case was also modeled in DOE 2 with the same packaged single zone air conditioner and gas heater, no skylights. The building was modeled with

[1] http://www.ciralight.com

daylighting turned off (no photocontrols), which meant that electric lights were fully on during all occupied hours of the year for this case.

5.2.1 Angular dependent SHGC for Advanced Skylight Case

In order to model heat gains from an advanced skylight appropriately in eQUEST, we modified the angular dependent solar heat gain coefficient of a standard dome skylight to a profile developed using illuminance data monitored on site. We could not find SHGC values by altitude angle for the Ciralight Skylights published by Ciralight, and so these values had to be determined using our monitored data for the site.

To develop a profile of SHGC by incident angle, we developed a ratio of indoor daylight illuminance to outdoor solar radiation for a clear day by altitude angle. This ratio was then applied to the published SHGC value from Ciralight at 0 deg Incident angle (90 deg Altitude angle), to determine SHGC at other angles.

To develop the profile we first plotted the indoor daylight illuminance captured by one of our Hobo data loggers (at eye level) by solar altitude bins (5 deg), as shown in Figure 13 below). To ensure that the illuminance reported here is daylight only ($Adj\ Ill_i$) , we subtracted the electric lighting component from the Total Illuminance ($Total\ Ill_i$) based on the following formula for each hour (i).

$$Adj\ Ill_i = Total\ Ill_i - \left[(1 - \%\ Lights\ off_i\ ) \times Electric\ Lights\ Illuminance\ at\ Full\ Power) \right]$$

Figure 12: Equation to Calculate Adjusted Illuminance

In Figure 12*:*

“% Lights off” for each hour was determined from the monitored data on energy use from the lighting circuits.

“Electric Lights Illuminance at Full Power” was determined by noting *Total Ill* during occupied hours after sun set (night time hours).

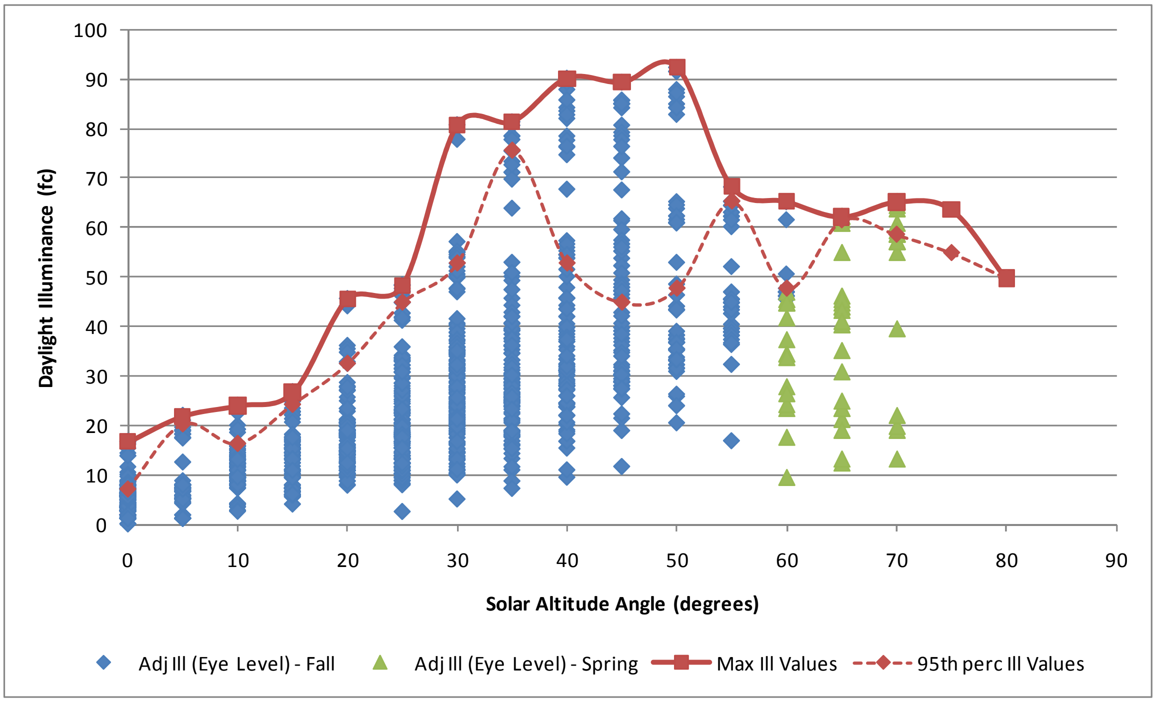


Figure 13: Daylighting Indoor Illuminance plotted by altitude bins

From this graph the we determined the highest values (*Max Ill Values*) and the 95th percentile values (*95th perc Ill Value*) for each altitude bin was determined, and their corresponding outdoor global horizontal solar radiation values. Our hypothesis is that *Max Ill Values* represent values for a clear day, as opposed to cloudy days which make up the rest of the values for any altitude bin.

We then calculated the ratio of *Max Ill Values* to their corresponding outdoor solar radiation, and apply the ratio to the SHGC value of 0.312 at 0 deg incident angle (90 deg altitude angles). Where appropriate, we used the *95th perc Ill Values* instead of *Max Ill Values.* The graph in Figure 14 shows the SHGC values finally used for the advanced skylight case HVAC analysis.

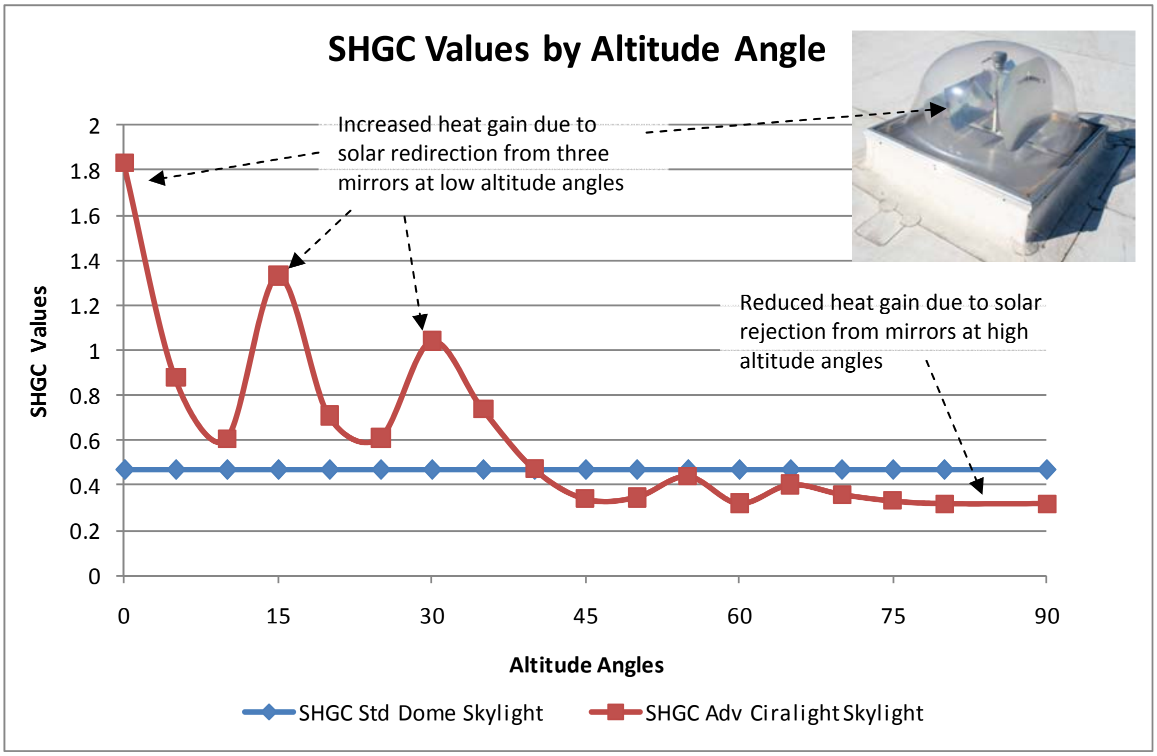


Figure 14: Angular Dependent SHGC Values

As seen in Figure 14, SHGC for the advanced skylight is higher than that of standard skylight for low angle sun. The effect of the three mirror design is evident from the increased heat gain at 0, 15 and 30 deg angles. At higher altitudes above 40 deg, we see that the SHGC decreases to lower than standard skylight's. This is also an effect of light redirection by the mirrors, as solar radiation is rejected by the mirrors at high angles.

Caveats on Analysis Methodology

While we have tried our best to correct for limitations of our data, the angular dependent SHGC calculation in Figure 14 may still be overestimating the SHGC of the advanced skylight due to the effect of electric lighting still included in the indoor illuminance valued used in the calculation. Although we have used an equation shown in Figure 12, this may not have accounted of all of the electric lighting illuminance.

6. PROJECT RESULTS

6.1 Daylighting Performance – Electric Lighting Energy Use

Results from monitoring lighting circuit energy use for advanced skylights and hourly output of lighting energy use from DOE 2 simulations for 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

The first table in Figure 15 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 15.

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, 70% was the maximum level that the lights are switched off by the automatic photocontrols. As would be expected, the percent lights off increases along with solar radiation.

Figure 16 depicts the same type of information for the advanced skylights case.

The test period for Site 1 spanned four months, September to December of 2008. Due to the proximity to the winter solstice, there are no data points for those high solar angles between 60 and 75 degrees, which occur during the summer heating season. As explained earlier, due to equipment malfunction data collected during high solar altitude period could not be used in this analysis.

Frequency Table

STANDARD 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	Total Hours	% of total
0	156	29																												
5	56	4	10	14	3																									
10	64	11	3	8	11	20	17	4																						
15	17	23	25	7			3	6	12	7	1																		511	36%
20	3	8	12	13	12	11	6	10	4	10	19	19	2																	
25	1	10	11	4	10	13	6	10	23	17	7	1	8	20	14	3	1													
30	1	5	8	8	9	6	7	5	11	8	9	20	21	25	13	30	10	6											490	35%
35		1	3		4	1	3	4	3	2	3	2	3	12	15	12	16	25	16	7										
40			2	2	1		1	2	1	1		3	3	1	5	6	8	6	16	11	21	9	2							
45												2				2	1	1	3	7	14	17	9	14	3				306	22%
50						1							3			2	1		1		4	8	6	15	10	8	1			
55																	1				2		1	3	9	12	10	1		
60																											4	8	111	8%
65																														
70																														
75																														
80																														

Total: 1418

Percent lights OFF Table

STANDARD 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
0	0%	0%																										
5	4%	0%	0%	0%	0%																							
10	9%	5%	0%	1%	1%	0%	2%	3%																				
15	9%	8%	17%	6%			0%	2%	10%	10%	10%																	
20	10%	10%	19%	18%	34%	36%	20%	46%	10%	10%	10%	10%	10%															
25	10%	10%	10%	10%	22%	19%	50%	64%	57%	52%	36%	10%	10%	22%	23%	30%	10%											
30	10%	22%	10%	25%	30%	20%	10%	58%	43%	63%	57%	58%	67%	58%	38%	54%	46%	50%										
35		70%	47%		40%	10%	70%	40%	50%	40%	70%	40%	70%	60%	66%	70%	70%	68%	70%	70%								
40			40%	70%	10%		70%	40%	10%	70%		70%	70%	70%	58%	70%	70%	70%	70%	70%	70%	70%	70%					
45												70%				70%	70%	70%	70%	70%	70%	70%	70%	70%	70%			
50						70%							70%			70%	70%		70%		70%	70%	70%	70%	70%	70%	70%	
55																	70%				70%		70%	70%	70%	70%	70%	70%
60																											70%	70%
65																												
70																												
75																												
80																												

Phase 1 (Lights off ~10%)

Phase 2 (lights off ~70%)

Figure 15: Frequency table and Percent Lights OFF table of occupied hours for Site 1 Standard Skylight 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	Total Hours	% of total
0	129	29																												
5	15	4	10	14	3																									
10	64	11	3	8	11	20	17	4																						
15	17	23	25	7			3	6	11	8	1																		443	33%
20	3	8	12	13	12	11	6	10	4	10	18	20	2																	
25	1	10	11	4	10	13	6	10	23	17	7	1	8	19	15	3	1													
30	1	5	8	8	9	6	7	5	11	8	9	20	21	25	13	30	10	6											490	36%
35		1	3		4	1	3	4	3	2	3	2	3	12	15	12	16	26	15	7										
40			2	2	1		1	2	1	1		3	3	1	5	6	8	6	15	11	21	9	2							
45												2				2	1	1	3	6	14	18	8	15	3				305	23%
50						1							3			2	1		1		4	8	6	15	10	8	1			
55																	1				2		1	3	9	12	10	1		
60																											4	8	111	8%
65																														
70																														
75																													Total:	
80																													1349	

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
0	10%	11%																										
5	9%	10%	15%	37%	39%																							
10	3%	7%	11%	26%	37%	62%	67%	62%																				
15	13%	11%	11%	19%			51%	71%	71%	72%	71%																	
20	11%	10%	11%	10%	11%	11%	20%	16%	56%	59%	67%	71%	71%															
25	12%	11%	12%	10%	16%	15%	20%	20%	20%	44%	31%	35%	71%	63%	67%	71%	10%											
30	11%	13%	10%	10%	10%	11%	11%	22%	15%	41%	37%	30%	50%	54%	66%	65%	71%	72%										
35		10%	15%		11%	11%	11%	32%	31%	24%	31%	32%	51%	33%	43%	55%	68%	68%	72%	71%								
40			17%	23%	11%		11%	11%	35%	11%		52%	39%	72%	57%	43%	50%	61%	72%	72%	72%	71%	71%					
45												11%				53%	71%	71%	71%	71%	67%	72%	71%	71%	71%			
50						34%							39%			53%	10%		71%		71%	71%	71%	71%	71%	71%	71%	
55																	70%				71%		10%	71%	71%	71%	71%	71%
60																											71%	71%
65																												
70																												
75																												
80																												

Phase 1 (Lights off ~10%)

Phase 2 (lights off ~70%)

Figure 16: Frequency table and Percent Lights OFF table of occupied hours for Site 1 Advanced Skylight Case

Full Load Equivalent OFF Hrs

STANDARD 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	Total Hours	% of total
0	0.60																													
5	2.20																													
10	5.70	0.50		0.10	0.10		0.30	0.10																						
15	1.60	1.90	4.20	0.40				0.10	1.20	0.70	0.10																		19.8	4%
20	0.30	0.80	2.30	2.30	4.10	4.00	1.20	4.60	0.40	1.00	1.90	1.90	0.20																	
25	0.10	1.00	1.10	0.40	2.20	2.50	3.00	6.40	13.1	8.9	2.50	0.10	0.80	4.40	3.20	0.90	0.10													
30	0.10	1.10	0.80	2.00	2.70	1.20	0.70	2.90	4.70	5.00	5.10	11.6	14.1	14.5	4.90	16.2	4.60	3.00											170.9	36%
35		0.70	1.40		1.60	0.10	2.10	1.60	1.50	0.80	2.10	0.80	2.10	7.20	9.90	8.40	11.2	16.9	11.2	4.90										
40			0.80	1.40	0.10		0.70	0.80	0.10	0.70		2.10	2.10	0.70	2.90	4.20	5.60	4.20	11.2	7.70	14.7	6.30	1.40							
45												1.40				1.40	0.70	0.70	2.10	4.90	9.80	11.9	6.30	9.80	2.10				203.3	43%
50						0.70							2.10			1.40	0.70		0.70		2.80	5.60	4.20	10.5	7.00	5.60	0.70			
55																	0.70				1.40		0.70	2.10	6.30	8.40	7.00	0.70		
60																											2.80	5.60	77.7	16%
65																														
70																														
75																													Total:	
80																													472	

Full Load Equivalent OFF Hrs

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	Total Hours	% of total
0	12.8	3.1																												
5	1.4	0.4	1.5	5.2	1.2																									
10	1.7	0.7	0.3	2.1	4.1	12.4	11.4	2.5																						
15	2.2	2.6	2.7	1.3			1.5	4.3	7.8	5.7	0.7																		89.6	17%
20	0.3	0.8	1.3	1.3	1.3	1.2	1.2	1.6	2.2	5.9	12.1	14.3	1.4																	
25	0.1	1.1	1.3	0.4	1.6	1.9	1.2	2.0	4.5	7.5	2.2	0.4	5.7	11.9	10.1	2.1	0.1													
30	0.1	0.6	0.8	0.8	0.9	0.6	0.7	1.1	1.6	3.2	3.3	5.9	10.5	13.4	8.6	19.4	7.1	4.3											182.3	35%
35		0.1	0.5		0.4	0.1	0.3	1.3	0.9	0.5	0.9	0.6	1.5	4.0	6.5	6.6	10.9	17.6	10.8	5.0										
40			0.3	0.5	0.1		0.1	0.2	0.4	0.1		1.5	1.2	0.7	2.8	2.6	4.0	3.7	10.8	7.9	15.1	6.4	1.4							
45												0.2				1.1	0.7	0.7	2.1	4.3	9.4	12.9	5.7	10.7	2.1				178.2	34%
50						0.3							1.2			1.1	0.1		0.7		2.8	5.7	4.3	10.7	7.1	5.7	0.7			
55																	0.7				1.4		0.1	2.1	6.4	8.5	7.1	0.7		
60																											2.8	5.6	75.69	14%
65																														
70																														
75																													Total:	
80																													526	

Figure 17: Full load equivalent OFF hours for Site 1- Standard Case (top) and Advanced Case (bottom)

Figure 17 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 1 saved 526 full load equivalent hours out of a total of 1349 occupied hours (total from frequency table in Figure 16), which is 39.0% savings compared to no skylights. The standard skylights modeled in DOE 2, saved 471.7 full load equivalent hours from a total of 1418 occupied hours(total from frequency table in Figure 15), which is a 33.3% savings compared to no skylights. The advanced skylights hence had 5.7% greater lighting energy savings compared to the standard skylights for the monitoring period of September 6th 2008 to December 31st 2008.

The vast majority of that savings results from the low angle sunlight that is captured by the advanced skylights. As can be seen in the rightmost column of Figure 15 and Figure 16, over 70% of the hours contained in this analysis took place when the sun was less than 35 degrees above the horizon. Therefore the additional savings from advanced skylights below 30 degrees translated into greater energy savings than standard skylights, which performed better in the 30-55 degree range.

6.1.2 Performance Analysis by Altitude Angle

To explain the results from our analysis further, Figure 18 graphs the full load equivalent hours off for the advanced skylights case against the standard skylight case by solar altitude and Figure 19 presents the percent lighting energy savings by solar altitude in a table.

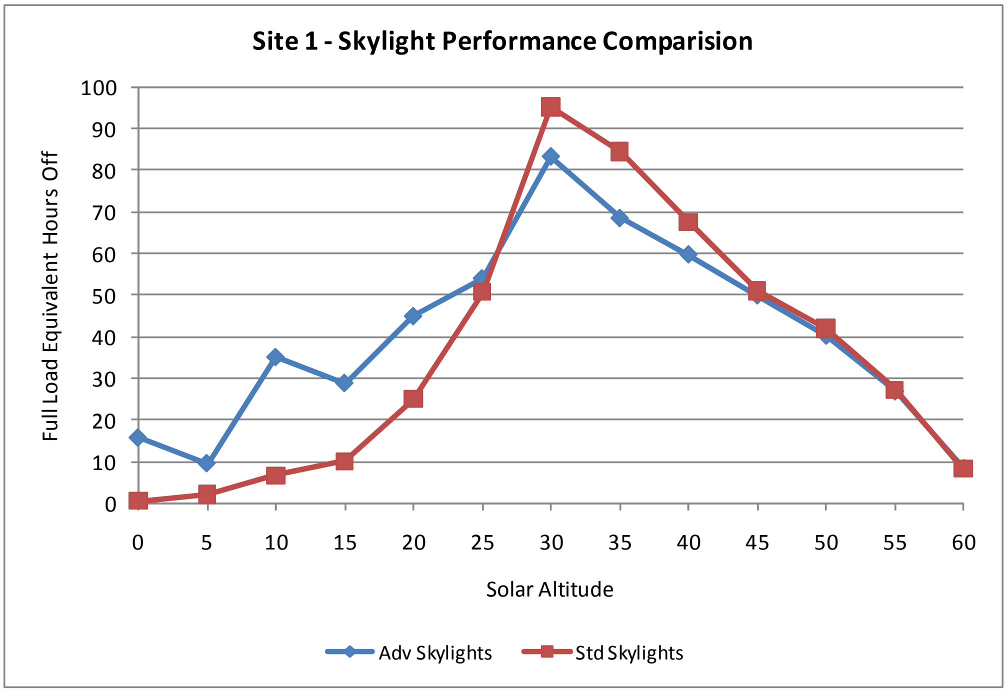


Figure 18: Full Load Equivalent Hours Off by Solar altitude, Site 1 actual vs DOE 2

Both Figure 18 and Figure 19 shows the advanced skylights perform better at solar altitude angles less than 25 degrees. However, the standard skylights are then marginally superior in the 25-50 degree range. Summing the area under the curve shows that the advanced skylights at Site 1 saved 525.71 full load equivalent hours, while the standard skylights modeled in DOE 2 saved 471.7 full load equivalent hours.

Site 1 (Ciralight)				
Solar Altitude	STANDARD Skylight - % Ltg Energy Savings	ADVANCED Skylight - % Ltg Energy Savings	ADV vs STD	
0	0.3%	**10.0%**	9.7%	
5	2.5%	**21.0%**	18.5%	
10	4.9%	**25.5%**	20.5%	13.8%
15	10.1%	**28.6%**	18.5%	
20	19.4%	**34.8%**	15.5%	
25	31.9%	**34.0%**	2.1%	
30	**47.1%**	41.2%	-5.9%	
35	**64.0%**	51.9%	-12.1%	
40	**67.0%**	59.8%	-7.3%	
45	**70.0%**	68.4%	-1.6%	-6.2%
50	**70.0%**	67.1%	-2.9%	
55	**70.0%**	69.1%	-0.9%	
60	70.0%	**70.6%**	0.6%	
Angles 0-60 (weighted)	**33.3%**	**39.0%**	**5.7%**	

Figure 19: Comparison of percent lights off at Site 1 Advanced skylights vs Standard skylights by solar altitude.

A closer observation of these results shows that the standard skylights are outperforming the advanced skylights at high solar altitudes when the solar radiation is less intense, such as on cloudy or foggy days. This result is intuitive, as one would expect the mirrors and the structure supporting the mirrors becoming an obstruction to daylight from a diffuse cloudy sky. Since the standard skylights have no such obstructions, they perform very well during cloudy hours. Figure 20 highlights (with a solid blue line) the hours with low solar radiation and high solar altitude for the standard and advanced skylights case where we see this effect.

Another area where the standard skylights outperform advanced skylights are at high altitude angle and mid-range solar radiation (90 to 180 Btu/hr-sf), highlighted by dashed blue line in Figure 20. This result was not intuitive. We suspect that some of the hours in this area are cloudy/foggy hours, which reduce performance of advanced skylights, however, that does not explain overall lower performance in this range. We have two hypothesis to explain this result:

1. Our first hypothesis was that the mirrors in the Ciralight Suntracker have not been optimized for this range (30deg – 50deg). Hence more sunlight at that angle is getting rejected by the mirrors, resulting in lower lighting savings. This may also be the result of self shadowing of the three mirrors
2. Our second hypothesis was that this result could be due to failure of the tracking mechanism in the Ciralight skylights. When mirrors do not align with the position of the sun, this could result in rejection of sunlight. To determine if this was indeed the case, we visually monitored the tracking mechanism of the skylights

during one of our site visits on July 12th 2009. We used a dry-erase marker to mark the position of the mirrors on the skylight dome at different times of the day. From our observations, we found that in 31 out of 34 skylights the tracking mechanism was working properly. The tracking mechanism had failed in only 2 out of 34 skylights. One skylight had been covered over with a tarp due to water leakage, and so could not be checked. We do not think that tracking mechanism failure in 2 out of 34 skylights can cause the results we observed, unless the photosensor was located in the lightwell of one of the 2 skylights that have the tracking mechanism failure. We were unable to determine which skylight had the photosensor, and so could not rule out the second hypothesis completely.

We also notice that all hours greater than 190 Btu/hr-sf tend to have daylight saturation (lights at 70% off) for both standard and advanced skylights.

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
0	0%	0%																										
5	4%	0%	0%	0%	0%																							
10	9%	5%	0%	1%	1%	0%	2%	3%																				
15	9%	8%	17%	6%			0%	2%	10%	10%	10%																	
20	10%	10%	19%	18%	34%	36%	20%	46%	10%	10%	10%	10%	10%															
25	10%	10%	10%	10%	22%	19%	50%	64%	57%	52%	36%	10%	10%	22%	23%	30%	10%											
30	10%	22%	10%	25%	30%	20%	10%	58%	43%	63%	57%	58%	67%	58%	38%	54%	46%	50%										
35		70%	47%		40%	10%	70%	40%	50%	40%	70%	40%	70%	60%	66%	70%	70%	68%	70%	70%								
40			40%	70%	10%		70%	40%	10%	70%		70%	70%	70%	58%	70%	70%	70%	70%	70%	70%	70%	70%					
45												70%				70%	70%	70%	70%	70%	70%	70%	70%	70%	70%			
50						70%							70%			70%	70%		70%		70%	70%	70%	70%	70%	70%	70%	
55																	70%				70%		70%	70%	70%	70%	70%	70%
60																											70%	70%
65																												
70																												
75																												
80																												

Phase 1 (Lights off ~10

Phase 2 (lights off ~70

Percent lights OFF Table

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
0	10%	11%																										
5	9%	10%	15%	37%	39%																							
10	3%	7%	11%	26%	37%	62%	67%	62%																				
15	13%	11%	11%	19%			51%	71%	71%	72%	71%																	
20	11%	10%	11%	10%	11%	11%	20%	16%	56%	59%	67%	71%	71%															
25	12%	11%	12%	10%	16%	15%	20%	20%	20%	44%	31%	35%	71%	63%	67%	71%	10%											
30	11%	13%	10%	10%	10%	11%	11%	22%	15%	41%	37%	30%	50%	54%	66%	65%	71%	72%										
35		10%	15%		11%	11%	11%	32%	31%	24%	31%	32%	51%	33%	43%	55%	68%	68%	72%	71%								
40			17%	23%	11%		11%	11%	35%	11%		52%	39%	72%	57%	43%	50%	61%	72%	72%	72%	71%	71%					
45												11%				53%	71%	71%	71%	71%	67%	72%	71%	71%	71%			
50						34%							39%			53%	10%		71%		71%	71%	71%	71%	71%	71%	71%	
55																	70%				71%		10%	71%	71%	71%	71%	71%
60																											71%	71%
65																												
70																												
75																												
80																												

Phase 1 (Lights off ~10

Phase 2 (lights off ~70

Figure 20: Comparison of percent lights off, between standard skylights (top) and advanced skylights (bottom)

6.2 Annual Daylighting Performance – Lighting and HVAC Energy

The results for lighting energy savings were extrapolated (as described in Section 5.1.6), 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 1. Results from this analysis are presented in Figure 21 and Figure 22 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 7% and 10% lighting energy compared to standard skylights in climate zones 3 and 12 respectively. The lighting energy savings are larger in magnitude compared to cooling and heating savings. The HVAC energy results indicate that over the summer months, the advanced skylight is rejecting enough high angle sun to balance the heat gained from admitting low angle sun, hence making the net cooling energy load in the advanced skylights case very similar to the standard skylights case (a difference of only 2% and 1% in the two climate zones). For winter, the results indicate that there is a net rejection of heat by advanced skylights compared to standard skylights, although the magnitude of increase in heating load is small compared to lighting and cooling.

Lighting energy savings are much greater when compared to no skylights, 42% and 45% for CZ 3 and CZ 12. When compared to having no skylights, having advanced skylights increases cooling energy need in the summers as well as heating energy need in winter. These results are intuitive as cooling energy is expected to increase with the introduction of skylights, mainly due to reduced roof u-factor. These results also indicate much of the winter sun is being rejected by the advanced skylight. This may be function of weather as the Ciralight type advanced skylight is not designed to redirect solar radiation scattered in a foggy or cloudy winters. Instead they are better designed to manage direct-beam solar radiation, which may have been missing in most winter days.

Overall the advanced skylights save 0.26 kWh/sf-yr (3%) in CZ 3 and 0.36 kWh/sf-yr (4%) in CZ 12 compared to standard skylights. They save 2.38 kWh/sf-yr (24%) in CZ3 and 2.15 kWh/sf-yr (19%) 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 0.96 kW to 0.61 kW, compared to no skylights, and 1.69 kW to 2.00 kW compared to standard skylights.

Advanced Skylight Type 1 CIRALIGHT SUNTRACKER
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)	22,202	14,888	1,027	38,118	21,814	20,089	4,410	46,313
Peak Demand (kW) [Average during PG&E peak period]	6.82	7.21	-	14.03	6.80	10.99	-	17.79
Peak Demand (kW) [Average for 10 hottest days]	7.09	10.30	-	17.39	6.75	14.61	-	21.36
"Advanced Skylights" Case								
Annual Energy Use (kWh)	20,728	14,562	1,534	36,824	19,643	19,857	5,017	44,517
Peak Demand (kW) [Average during PG&E peak period]	5.40	6.94	-	12.34	4.93	10.86	-	15.79
Peak Demand (kW) [Average for 10 hottest days]	5.52	10.31	-	15.83	4.56	14.54	-	19.10

* 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 1.
Store has 11, 3.93' x 3.93' skylights (SFR is 3.38%)

Figure 21: Advanced Skylight: Ciralight – Energy Use

Advanced Skylight Type 1 CIRALIGHT SUNTRACKER
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)	14,860	-2,005	-977	11,877	15,944	-3,158	-2,036	10,750
Percent Energy Savings (%)	*42%*	*-16%*	*-175%*	*24%*	*45%*	*-19%*	*-68%*	*19%*
Peak Reduction (kW) [Average during PG&E peak period]	2.10	-1.14	-	0.96	2.57	-1.96	-	0.61
Percent Peak Reduction (%)	*28%*	*-20%*	-	*7%*	*34%*	*-22%*	-	*4%*
Peak Reduction (kW) [Average for 10 hottest days]	1.98	-1.80	-	0.18	2.94	-3.08	-	-0.14
Percent Peak Reduction (%)	*26%*	*-21%*	-	*1%*	*39%*	*-27%*	-	*-1%*
Compared to **"Standard Skylights"**								
Annual Energy Savings (kWh)	1,474	327	-507	1,294	2,171	232	-607	1,796
Percent Energy Savings (%)	*7%*	*2%*	*-49%*	*3%*	*10%*	*1%*	*-14%*	*4%*
Peak Reduction (kW) [Average during PG&E peak period]	1.42	0.27	-	1.69	1.87	0.13	-	2.00
Percent Peak Reduction (%)	*21%*	*4%*	-	*12%*	*27%*	*1%*	-	*11%*
Peak Reduction (kW) [Average for 10 hottest days]	1.57	-0.02	-	1.56	2.19	0.07	-	2.27
Percent Peak Reduction (%)	*22%*	*0%*	-	*9%*	*32%*	*1%*	-	*11%*

* 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 1.
Store has 11, 3.93' x 3.93' skylights (SFR is 3.38%)

Figure 22: Advanced Skylight: Ciralight - 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 Ciralight advanced skylight (skylight only – no light well, no curb) in a new construction case was taken from the costs report to us by Ciralight Global as **$900** per skylight.

The cost of standard skylights (skylight only – no light well, no curb) was taken from a 2007 study done for ASHRAE by the Heschong Mahone Group, Inc[1] which represents an average cost collected from four national standard skylight manufacturers[2] as $300 per skylight.

The incremental cost for the Ciralight advanced skylight (skylight only – no light well, no curb) in a retrofit case was taken as **$672** per skylight

To these skylight costs, **$145** per skylight was added, to represent cost of labor for installation and cost of curbs. This cost estimate is taken from the same 2007 ASHRAE study by HMG[1].

Figure 23 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 ($)	$12,287	$12,287
Maintenance Savings ($)	$0	$0
Energy savings ($)	$2,281	$2,232
n (years)	15	15
d (discount rate)	5%	5%
e (energy and labor escalation)	3%	3%
NPV ($)	$17,936	$17,311
Simple Payback (years)	5.39	5.50

* Calculations for 11, 4'x4' skylights

	CZ3	CZ12
Compared to **"Std Skylights"**		
Incremental Cost ($)	$7,392	$7,392
Maintenance Savings ($)	$0	$0
Energy savings ($)	$307	$412
n (years)	15	15
d (discount rate)	5%	5%
e (energy and labor escalation)	3%	3%
NPV ($)	-$2,641	-$1,285
Simple Payback (years)	24.10	17.95

* Calculations for 11, 4'x4' skylights

Figure 23: 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.

[2] Four national skylight manufacturers referenced in the study were: Crystalite, Sun-Optics, Vistawall and Wasco

6.4 Daylighting Sufficiency and Uniformity

To assess daylight sufficiency we analyzed the high dynamic range (HDR) images taken every hour over the course of a full day from 7:00 am to 6:00 pm on a sunny January day (Jan 14th 2009). The HDR photos were taken looking into aisles 10, 14 and 19 to represent aisles with skylights. From these images we selected a section of an aisle and calculated the average illuminance on the vertical surface of the aisle as shown by the solid black line and hash in Figure 24. This was done for each aisle and each hour. The data was then plotted on a graph shown in Figure 25.

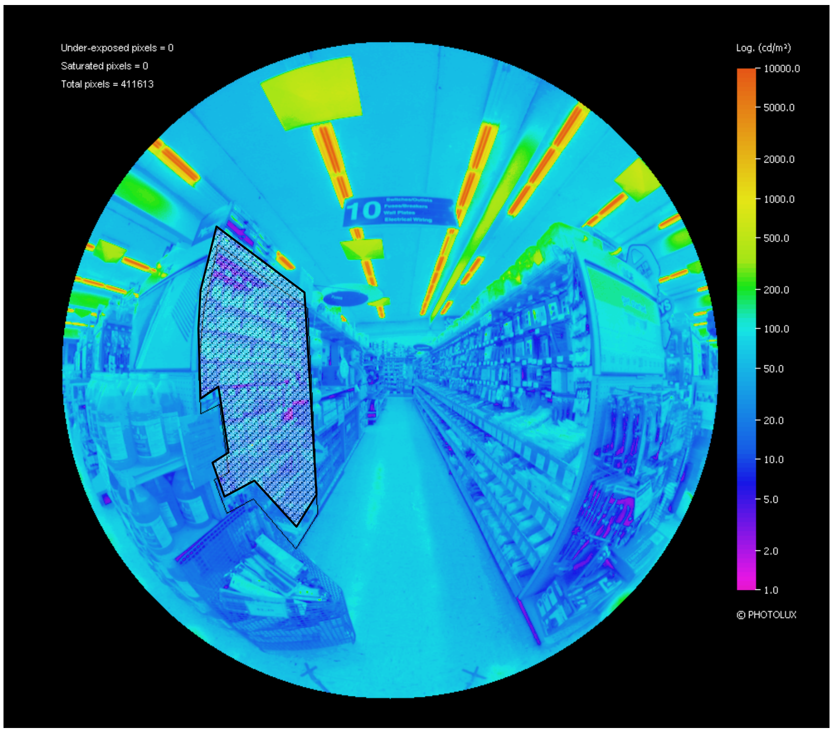


Figure 24: HDR Image of Aisle 10 showing area where average illuminance was calculated

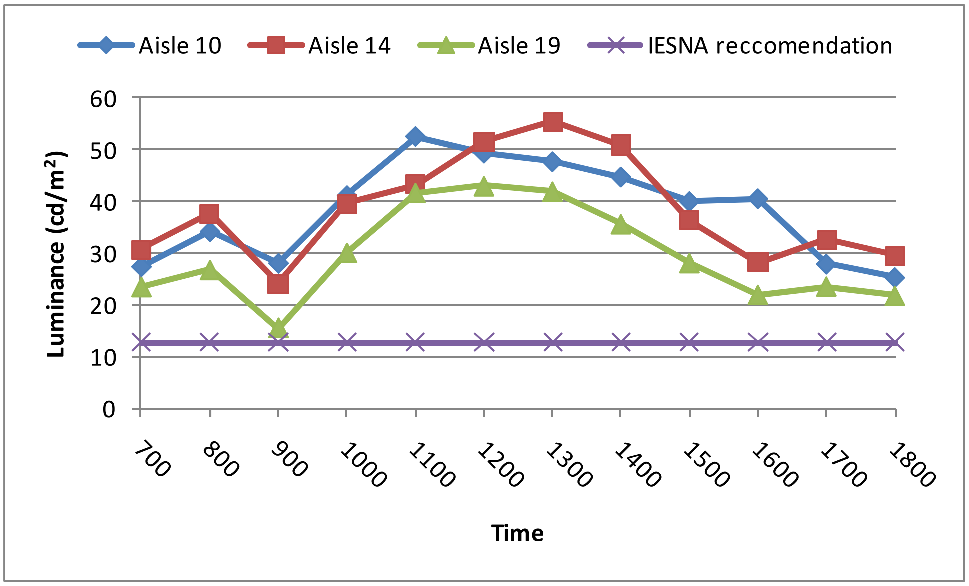


Figure 25: Illuminance of aisle shelf from HRD Images

6.4.1 Temporal Uniformity

Figure 25 shows the luminance in three aisles over the span of a sunny day in January (January 14th 2009). The average luminance for all three aisles was 35.3 cd/m^2 across the day. According to the IESNA Recommended Practice for Lighting Merchandise Areas (A Store Lighting Guide) General Illuminance values should be in the range of 750-850 Lux for a warehouse store.[1] We converted illuminance values in Lux to luminance in cd/m^2 for ease of comparison using the equation in Figure 26, In this equation, "L" is the average luminance measured in candelas per meter squared (cd/m^2). The uppercase "E" represents average illuminance in footcandles (or Lux divided by ten), while the lower case "e" represent reflectance, which is approximately equal to 0.5. The recommended value of 800 lux converts to 12.73 cd/m^2 which is shown by the purple line in Figure 25. The luminance captured by our HRD camera for an entire day was well above the IESNA recommended values at Site 1.

$$\overline{L} = \frac{\overline{E} \cdot e}{\Pi}$$

Figure 26: Equation used to convert Illuminance to Luminance

[1] General is the common selling floor where merchandise is presented and routine appraisal occurs. Excerpted from Buaer, Bernard et al. 2001. *Recommended Practice for Lighting Merchandise Areas*. Iesna RP-2-01. New York, New York: IESNA.

6.4.2 Spatial Uniformity

To study spatial uniformity for daylight, we plotted illuminance taken using a hand held illuminance meter level across a section of the building. This section A-A’ shown in Figure 8 (see dotted horizontal line A-A’ in the plan view) shows the slightly sloping roof going down from 19 feet to 14 feet. The blue line in the section represents horizontal illuminance measured at noon on a clear sunny day in September 2008 using a hand-held illuminance meter at about 2.5’ height.

The average illuminance reading was 256 fc, with highest reaching 615 fc where the ceiling height is the lowest. The lowest readings in-between skylights was 55 fc. As can be seen in the graphic, high ceiling heights (19ft) create more uniform and diffuse distribution of daylight, while under lower ceiling height (14ft) the daylight is more intense below the skylight, and also has most contrast with daylight between skylights. While these ranges are higher than the 1:6 or 1:10 ratios commonly used for electric illuminance, based on occupant responses to our questionnaire and our personal observations, we found that the spatial daylighting uniformity in the store is well within acceptable limits and did not cause any visual discomfort.

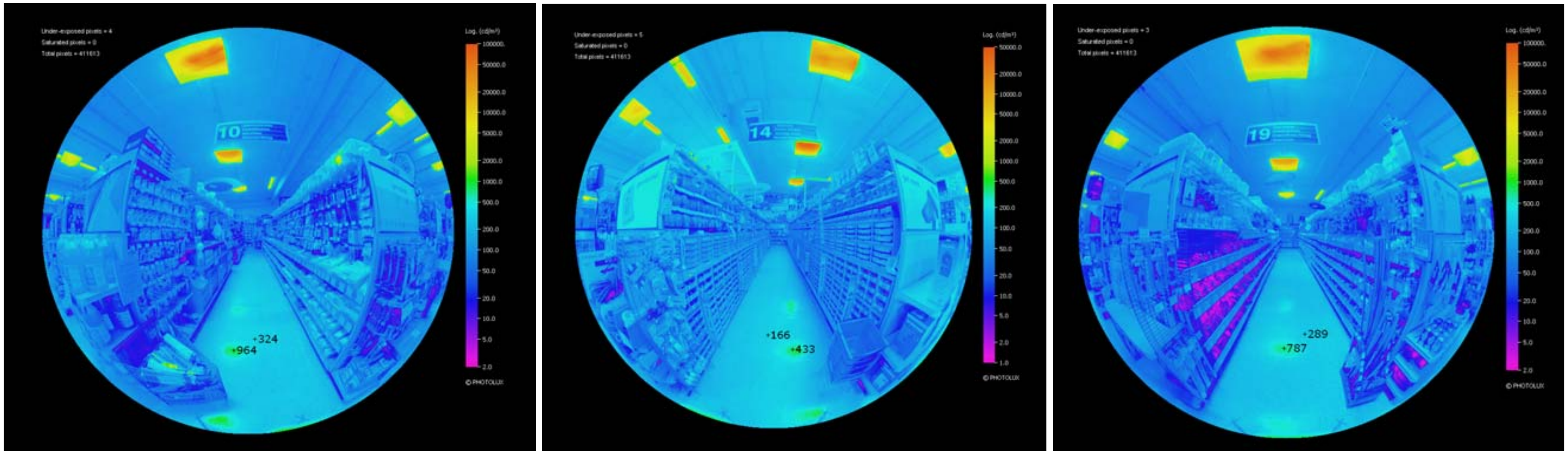


Figure 27: HDR Images of aisle 10, 14 and 19 at 12:00 noon on January 26th 2009

Another interesting metric of uniformity we explored was being able to measure a daylighting ‘hot-spot’ just below a skylight and its intensity compared to the surrounding area. Luminance was compared at the floor below a skylights and not at the roof at the skylight diffuser, because in normal view, the skylight diffusers are not as significant a part of an occupant’s view as the floor is. We measured a spot on the HDR image in the middle of the reflection of the skylight on the floor and a spot next to this reflection at noon on a sunny day in January. A high contrast ratio between the hot-spot and the surrounding area would mean a lower visual quality.

The ratio between the luminance at the hot-spot and the surrounding surfaces were:

1:2.95 for aisle 10

1:2.60 for aisle 14

1:2.72 for aisle 19

Most lighting designers consider a contrast ratio of 1:3 within comfort range. All three aisles were within this range. Also our personal observations were that these ratios were well within acceptable range for a retail store.

6.5 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 handed out to 25 employees regardless of rank or job duties.

6.5.1 Survey instrument

The survey instrument consists of multiple choice questions broken up into the following categories: Respondent Information, Work Environment, Electric Lights, and Daylight from Skylights. All qualitative questions have a numerical response that ranges 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 B – Survey Instrument.

6.5.2 Response rate and Data Analysis

To maximize the number of completed surveys, HMG arranged for the store manager to distribute the surveys. Of the twenty-three employees available, eighteen completed surveys and returned them the same day. The store manager distributed the remaining surveys the following day and returned the five completed surveys through the mail. Each employee that completed a survey received a $5 gift card.

We received a total of 25 responses, of which 2 were eliminated (for being less than 1hr/day in the store) for a total of 23 responses. The responses were compiled and then entered into Excel to be analyzed. Weighted average scores were calculated for applicable questions.

6.5.3 General Observations from Occupant Survey Analysis

Respondent Verification

Approximately 70% of the respondents have worked onsite for over a year. With another 17% having worked onsite for over 5 months, 87% 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. 87% of the employees surveyed work more than 5 hours in a typical day, and 90% of employees surveyed work the majority of their hours during the day.

69% of the employees described their workstation as a checkout register or the sales floor. The remaining described their work as being a mix of sales floor and outdoor yard or docking. After observing the business on multiple days of operation though, it was decided that the other employees are in the store enough to provide useful feedback.

Lighting Conditions

83% of the occupants surveyed rated the store's "visual attractiveness" higher than “neutral.” The average weighted score for visual attractiveness was 5.5 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 5.08 out of 7, with 69.5% 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 5.25 out of 7, with 69.6% of the occupants rating the store's "electric lighting" higher than “neutral.” The average score for "quality of daylight from the skylights" was only slightly higher, at 5.53 out of 7. The current data shows a likely upward trend in the average score of “quality of daylights from skylights.” 87% of respondents rated the “daylight from skylights” higher than neutral.

Overall, respondents found particular parts in the store to be too dark more often than too bright. 91% of the respondents rated the store as being not excessively bright at any one place compared to only 52% for any one place being not too dark. Comments from employees formed a coherent picture, with two specific aisles stated as being too dark by multiple employees.

Electric Lights

Employees rated the satisfaction of working with “some of the electric lights off” and “all the electric lights off” 5.2 out of 7, and 4.5 out of 7 respectively. Yet, the percentage of employees that rated the working experience above “neutral” are about even; 61% with some lights off, and 63% with all lights off. Although satisfaction is slightly higher in magnitude with some lights off, the same number of people still responded positively with all the lights off.

When asked about how they “feel about the electric lights turning off automatically”, a majority of them, 61% of the respondents, said that they “don't bother me”, or “are appropriate to the space”, or they “never notice the lights being controlled.”. On the other hand, 39% found the automatic lighting controls “slightly annoying “ or “very annoying”. Comments include that the lights “turn off when at times they don’t need to” and “are slightly annoying on cloudy days.” Further responses reflect annoyance at a lack of control and one respondent mentioned receiving customer complaints. These frustrations are likely due to the switching control system and the layout of the automatic switching lighting circuits. This control system is further magnified due to the uneven wiring of the lighting circuits, with rows of consecutive fixtures turning off at the same time. Lighting would be more uniform if every other lighting fixture in a particular row were wired to turn off while switching.

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 86% of respondents stating that their work area was 15 feet or less from a skylight. The average score was high at 5.81 out of 7 for employees being “happy with the amount of daylight from skylights,” with 87% 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. 78% of the occupants surveyed, rated the store as being “occasionally” to “never” too bright and only 22% said they were “sometimes” too bright. Less people, 57% 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. 82.6% of the occupants surveyed were "occasionally" to "never" uncomfortable due to glare from skylights in the store. Heat from skylights was noticed by a few more respondents, but it was not seen as a major source of discomfort. 74% of the occupants surveyed are "occasionally" to "never" "uncomfortable due to heat from skylights" in the store.

7. COMPARABLE TECHNOLOGIES

The Ciralight Suntracker skylight 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 28: 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 29: Photo of Solar-Tracker 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.

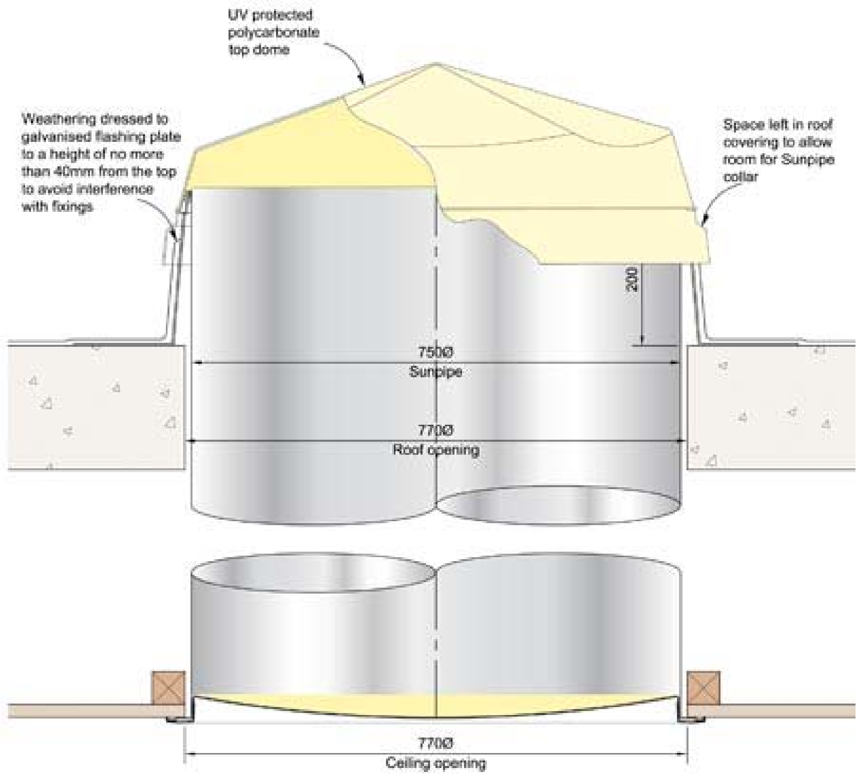


Figure 30: Drawing of the 750mm Diamond SunPipe System©

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 sunlight, and the in-room fixture distributes the sunlight 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.

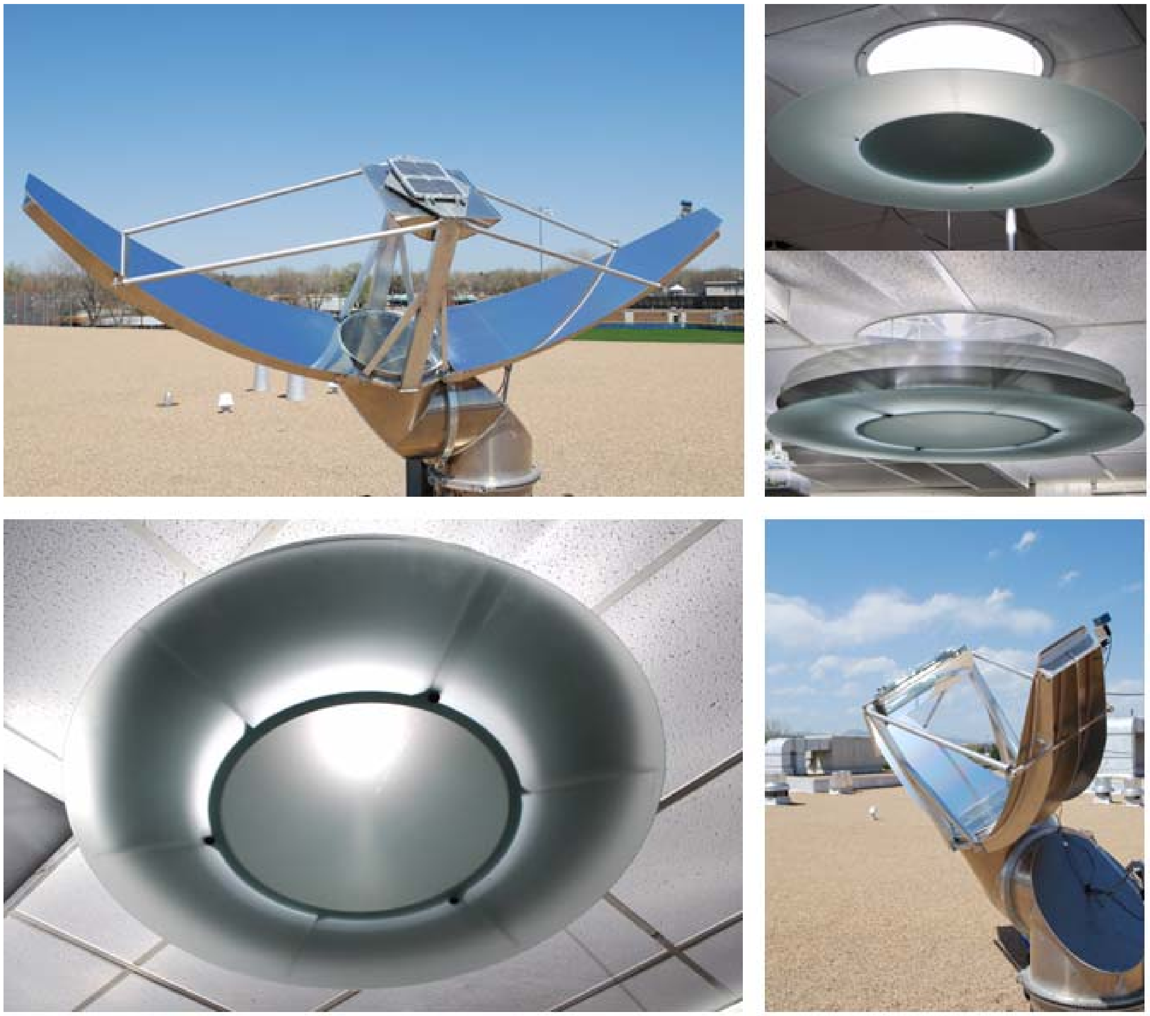


Figure 31: The Sundolier™ from the Sunflower Corporation

8. CONCLUSIONS

8.1 General Conclusions

Analysis of the Ciralight 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 Ciralight advanced skylights compared to a base case with no skylights, for a typical 5,000 sf retail store were 2.38 kWh/sf-yr (24%) for CZ 3 to 2.15 kWh/sf-yr (19%) for CZ 12. Compared to a base case with standard domed acrylic skylights, the savings were 0.26 kWh/sf-yr (3%) for CZ 3 to 0.36 kWh/sf-yr (4%) for CZ 12. Peak demand reduction was 0.96 kW to 0.61 kW, compared to no skylights, and 1.69 kW to 2.00 kW compared to standard skylights.

From our detailed analysis of daylighting performance by solar altitude angle and solar radiation, it was evident that the angle of the mirrors for the Ciralight product were optimized for low solar altitude angles (0 – 25 deg), but in the mid altitude angels (30 – 50 deg) their performance was below par of standard skylights. At high altitude angles (great than 55 deg), the daylighting performance for the advanced skylights was equivalent to the that of standard skylights. However, despite the reduced performance in mid range altitude angles, the Ciralight advanced skylights were found to have net positive savings compared to standard skylights. We believe that by fine tuning the mirror angles for the Ciralight system, there is scope for an even greater energy savings through daylighting. It is important to note, however, that this report did not look at performance of other comparable products in the market (such as Solar Tracker, Natural Lighting, Sundolier, etc) that may have better optimization of mirror angles, and so should not be considered as a sweeping conclusion for all active skylight types.

Our occupant assessment analysis found overall positive feedback on the visual and thermal comfort questions. 87% of respondents to our survey answered that they were "often" to "always" happy with the amount of daylight from skylights. Notable, there was no negative feedback on the issue of glare or too much daylighting from the Ciralight advanced skylights. 82.6% of the occupants surveyed were "occasionally" to "never" uncomfortable due to glare from skylights.

Our analysis on illuminance sufficiency found that the skylights are providing daylight levels above IESNA recommendations for lighting merchandise areas of 750-850 Lux for an entire day.

8.2 Recommendations for Next Steps

Simple payback analysis showed a reasonable payback of about 5 yrs for the Ciralight advanced skylights compared to a base case with no skylights, and a much higher payback of 24 yrs (CZ 3) to 18 yrs (CZ 12) when compared to standard skylights. The analysis shows that there is a need for an incentive program, such as a cash rebate for the purchase of this type of advanced skylight technology, to encourage retrofitting advanced skylights in buildings that already have standard skylights. This is a recommended next step for the advancement of this technology in the retrofit market. The incentive program should be designed to target buildings with the following characteristics:

1. Buildings that have existing older standard skylight installation, which are likely to be less efficient, and hence get greater savings with advanced skylights
2. Buildings with high lighting power density, so that greater savings can be achieved
3. Buildings with long operating hours, that cover early morning and late afternoon, to capture low angle sun, where advanced skylights have been shown to outperform standard skylights.
4. Buildings with plenums and dropped ceilings, which are typically not suited for standard skylight applications due to reduced efficacy from light wells.

Efforts for implementation and outreach for this incentive program should be focused in sunny climate zones, where this type of skylight technology was found to be more cost effective (CZ 12 had lower payback than CZ 3).

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.

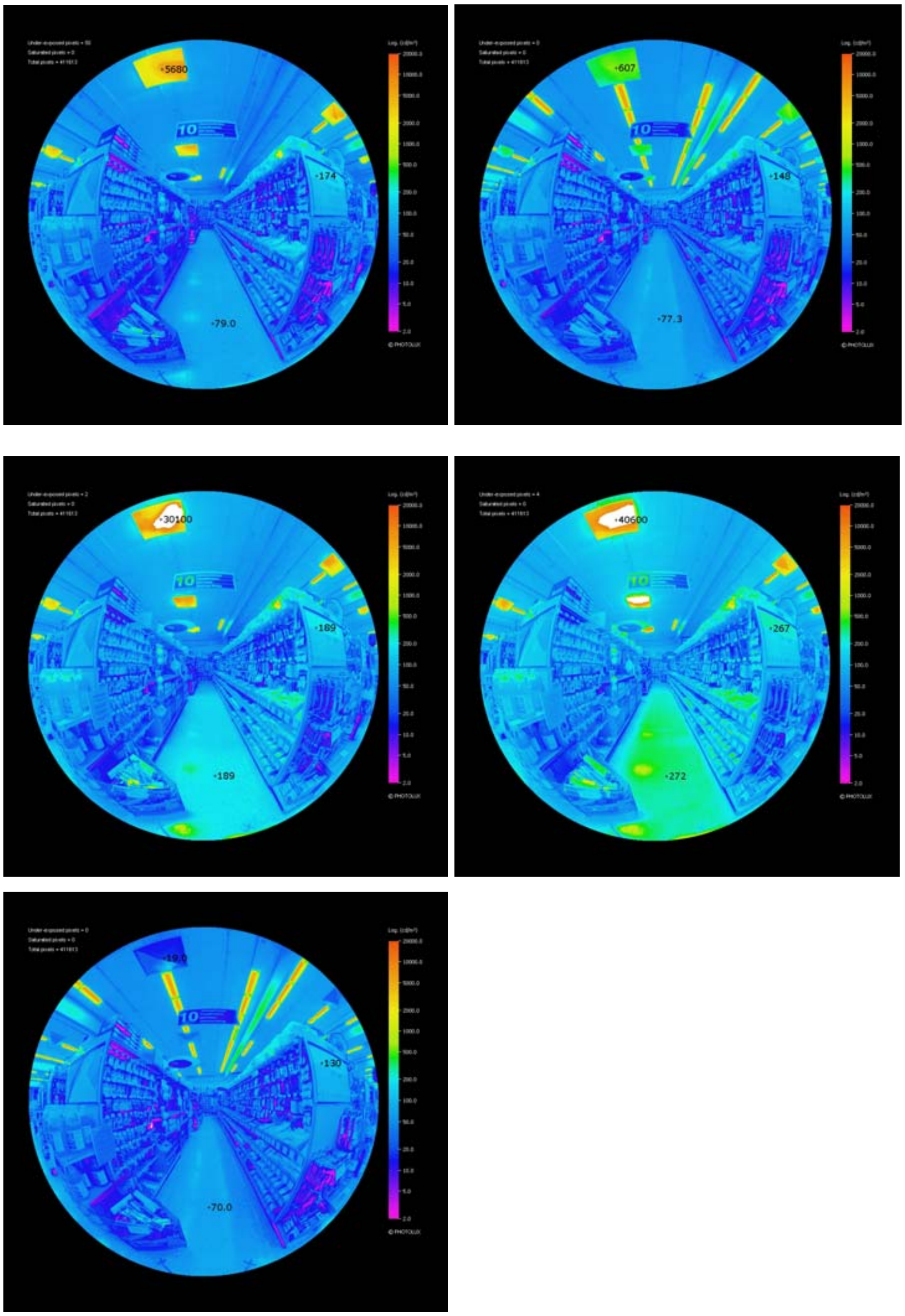
Our recommendation is to re-examine calculations for cost effectiveness based on increased energy savings from advanced skylights such as the Ciralight skylight, documented in this report. This analysis can be done specifically for the following building types, that do not fall under the current Title-24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

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

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 the Ciralight Suntracker advanced skylights.

9. APPENDIX A – HDR PHOTOGRAPHS



Hours 0700,0900,1200,1500, and 1800 – Upper left, Upper right, Lower Left, Lower Right, Bottom

10. APPENDIX B – 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. You're Finished!

THANK YOU!!! for completing this survey.

IT'S TIME FOR A COFFEE!!

Please hand over this survey to the person who gave it to you, and collect your $5 gift card from Starbucks from them!

- The Daylighting Survey Team :)