

Updates to Treatment of Skylighting in the IECC

Technical Document in Support of Proposed Amendments to the International Energy Conservation Code (IECC)

September 26, 2005

Submitted on behalf:
The Skylighting Collaborative



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ACKNOWLEDGEMENTS

This project was commissioned by the Skylighting Collaborative, a group of skylighting manufacturers who wish to promote the energy efficiency benefits of skylighting with photocontrols. This group includes the American Architectural Manufacturers Association (AAMA) Skylight Council (Acralight, CrystaLite,., CYRO, Eastman Chemical, Naturalite, Plaskolite, Structures Unlimited., SunTuf, Wasco), Velux Skylights, Sunoptics Skylights, Lighting Control & Design, and The Watt Stopper Co.

This project was managed and performed by Jon McHugh and Mudit Saxena of the Heschong Mahone Group (HMG). Paul Reeves of Partnership for Resource Conservation performed the building simulations under subcontract to HMG.

We would like to acknowledge the input from the following people: Jeffrey Johnson, Charlie Curcija, Randy Heather, John Hogan, Bob Keller, Ivan Johnson, John Lawton, Chris Magnuson, Stephan Moyon, Doug Paton, Eric Richman, Steve Richter, Julie Ruth, Arman Shehabi, Garrett Stone, Roland Temple, Dick Troyer, Carl Wagus, and Jay Woodward,

EXECUTIVE SUMMARY

Traditionally energy codes have treated skylights as a fenestration opening in the building envelope that is increasing both the solar and thermal transmittance of the envelope. Since these features increase cooling and heating loads respectively, the primary feature of these traditional energy codes try to minimize: 1) the total skylight area, 2) the solar heat gain coefficient (SHGC) and 3) and the thermal transmittance (U-factor).

However, there are thousands of commercial buildings in the United States that are saving energy with high transmission, diffusing skylights coupled with automatic photocontrols that are turning off electric lighting whenever there is sufficient daylight. In these well-designed buildings, the lighting energy cost savings is greater than the increased heating and cooling energy consumption. Wal-Mart alone owns and tracks the energy savings of 1,200 of these daylight buildings.

The traditional energy codes such as the IECC (International Energy Conservation Code) are ironically an obstacle to saving energy with skylights. By requiring low SHGC skylights, the IECC is inadvertently pushing specifiers towards using low visible transmittance skylights. With lower visible light transmittance skylights, less daylight is able to enter the building and thus there is less opportunity to turn off electric lighting. If one is controlling electric light is response to daylight admission into the space, the statistic of merit for increasing the balance between daylight admission and solar heat gains is the ratio of visible transmittance to solar heat gain coefficient.

The current IECC also limits the skylight area to 3% of the roof area. This skylight area is substantially less than the optimal skylight area for spaces with relatively high ambient light levels such as retail stores. This creates a compliance problem for the designers of energy efficient daylight stores. Thus we recommend that the area limitation for skylights be doubled to 6% when the skylights are diffusing and multi-level photocontrols are used to control general lighting in the space.

In mild climates (IECC climate zones 1-3), diffusing skylights in conjunction with photocontrols are a very cost-effective energy efficiency measure in large open spaces. These large open spaces are those buildings with ceiling heights greater than 15 feet and with single rooms larger than 25,000 sf. This is representative of spaces in warehouses and big box retail stores. These spaces should be daylight in at least half of their area and the ratio of skylights to daylight floor area be at least 3%.

1. PROPOSED CODE LANGUAGE

Proposed language to be added is underlined and proposed language to be deleted is in strikethrough format.

SECTION 202 GENERAL DEFINITIONS

DAYLIT AREA UNDER SKYLIGHTS. The daylit area under a skylight is the outline of the opening beneath the skylight, plus in each direction the lesser of: 70% of the ceiling height, one half of the distance to the edge of the nearest skylight, or the distance to any opaque partition which is further away than 70% of the distance between the top of the partition and the ceiling. (See Figure xx).

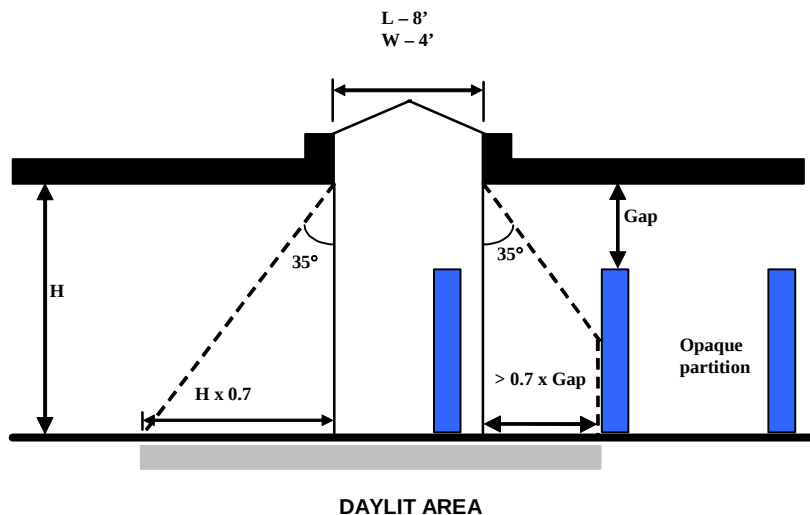


Figure xx: Daylit Area under Skylights

GENERAL LIGHTING. Luminaires that provide ambient diffuse lighting in a space. General lighting includes but is not limited to, lighting by linear fluorescent luminaires (direct, indirect and direct/indirect), high bay or low bay luminaires.

Lighting not considered general lighting includes: emergency lighting, electric signs, display lighting, decorative lighting (such as chandeliers), theatrical lighting, or wall sconces less than 150 W.

MULTI LEVEL PHOTOCONTROLS. Systems that reduce the lighting power draw in at least two steps or by continuous dimming in response to availability of daylight within the interior space.

805.2.3 Automatic daylighting controls. When the total, combined daylit skylight area exceeds 3% of the gross roof area12,500 square feet, the ambient lighting in the daylit area shall be separately controlled by at least one multi-level photocontrol. The multi-level photocontrol shall reduce electric lighting in response to available daylight uniformly as described in Section 805.2.2.1 and shall be capable of automatically reducing ambient lighting power in the daylit area to 35% of rated power or less. The multi-level photocontrol shall be located so that calibration and setpoint adjustment controls are readily accessible

802.2.5 (Supp.)Skylights. Skylights shall comply with all of the following applicable requirements.

802.2.5.1 Not high diffusion or without photocontrols. Skylights that do not meet the diffusion or photocontrol requirements of Section 802.2.5.2 shall be limited to 3 percent of the gross roof assembly area and shall have a maximum thermal transmittance (U-factor) and SHGC of the skylight assembly as specified in Table 802.2(2) under the heading "Skylights: Not high diffusion or no photocontrols (3% maximum)".

802.2.5.2 High diffusion with photocontrols. Skylighting systems having a glazing material or diffuser with a measured haze value greater than 90% when tested according to ASTM D1003 (notwithstanding its scope of maximum haze), and a ratio of visible transmittance to solar heat gain coefficient ($T_{vis}/SHGC$) greater than 1.0, with all ambient lighting in daylit areas under skylights controlled by multi-level photocontrols as defined in Section 805.2.3, shall be limited to 6 percent of the gross roof assembly area and, a maximum thermal transmittance (U-factor) of the skylight assembly as specified in Table 802.2(2) under the heading "Skylights: High diffusion with multilevel photocontrols, $T_{vis}/SHGC > 1.0$, (6% maximum)."

Skylights whose visible transmittance is in the scope of NFRC 200 (planar glazing, no diffusion i.e. "specular transmittance") shall have their visible transmittance determined in accordance with NFRC 200 by an accredited independent laboratory and labeled and certified by the manufacturer. For all other skylights, visible transmittance (T_{vis}) shall be defined as the solar photometric transmittance of the skylight glazing material(s) determined in accordance with ASTM E972 by an accredited independent laboratory and certified by the manufacturer. Visible light transmittance test results of covered skylights and haze test results of skylight glazing or diffuser shall be included with construction documents submitted with each application for a permit.

802.2.5.3 Minimum Skylight Area in Large Enclosed Spaces. In occupancy groups M, S-1, S-2, I-1, I-2, E-1, and A-2.1, when a low-rise enclosed space greater than 25,000 square feet is directly under a roof and has an average ceiling height greater than 15 feet and a ambient lighting power density greater than 0.5 Watt/sf the following requirements shall apply:

At least half of the space shall be in the daylit area under diffusing high diffusion skylights with multi-level photocontrols as described in Section 802.2.5.2.

The minimum total skylight area to daylit area ratio (SDR) shall be greater than those listed in table 802.2(2) under the heading "Low-rise enclosed spaces > 25,000 sf: Minimum skylight area - diffusing with multi-level photocontrols".

Exceptions: Refrigerated warehouses, houses of worship, theatrical spaces, and museums.

Table 802.2(2)

BUILDING ENVELOPE REQUIREMENTS

Climate Zone	1	2	3	4 except Marine	5 and Marine 4	6	7	8
Windows (40% maximum)								
Factory-assembled glazed fenestration products								
U-Factor	1.20	0.75	0.65	0.40	0.35	0.35	0.35	0.35
SHGC	0.40	0.40	0.40	0.40	0.40	0.40	NR	NR
Site-built products								
U-Factor	1.20	0.75	0.65	0.50	0.45	0.45	0.45	0.45
SHGC: PF < 0.25	0.25	0.25	0.25	0.40	0.40	0.40	NR	NR
SHGC: 0.25 < PF < 0.5	0.33	0.33	0.33	NR	NR	NR	NR	NR
SHGC: PF ≥ 0.5	0.40	0.40	0.40	NR	NR	NR	NR	NR
Skylights <u>Not high diffusion or no photocontrols</u> (3% maximum)								
Glass								
U-Factor	1.60	1.05	0.90	0.60	0.60	0.60	0.60	0.60
SHGC	0.40	0.40	0.40	0.40	0.40	0.40	NR	NR
Plastic								
U-Factor	1.90	1.90	1.30	1.30	1.30	0.90	0.90	0.60
SHGC	0.35	0.35	0.35	0.62	0.62	0.62	NR	NR
<u>Skylights: High diffusion with multilevel photocontrols, Tvis/SHGC > 1, (6% maximum)</u>								
<u>Maximum U-Factor</u>	<u>1.60</u>	<u>1.05</u>	<u>0.90</u>	<u>0.90</u>	<u>0.75</u>	<u>0.75</u>	<u>0.75</u>	<u>0.60</u>
<u>Low-rise enclosed spaces > 25,000 sf: Minimum skylight area high diffusion with multi-level photocontrols</u>								

Climate Zone	1	2	3	4 except Marine	5 and Marine 4	6	7	8
Minimum SDR	3%	3%	3%	NR	NR	NR	NR	NR

NR = No Requirement

CHAPTER 9

REFERENCED STANDARDS

ASTM

Standard Reference Number	Title	Referenced in code section number
D1003-00	Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics	802.2.5
E972-96(2002)	Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight	802.2.5
E1084-86(2003)	Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight	802.2.5
E1175-87(2003)	Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere	802.2.5

NFRC

Standard Reference Number	Title	Referenced in code section number
200-204	Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence	802.2.5

2. DEFINITION OF “DAYLIT AREA UNDER SKYLIGHTS”

If there is a requirement to control electric lighting in response to daylight, which lights should be controlled? Diffusing skylights can be thought of as being like diffusing luminaires. Luminaires can provide relatively uniform illumination if they are spaced closer together than the product of their mounting height and their spacing criterion. The spacing criterion is calculated from the luminous intensity distributions that are measured during photometric testing of luminaires. Skylights spaced further apart than their spacing criterion require “fill light” from additional light sources to maintain uniformity. Since the skylight is not providing sufficient light where fill light is needed, this area outside of the daylit area as defined by the spacing criterion should not be controlled by the automatic daylighting control. As a result the controlled electric lighting should be within one half of the spacing distance or one half of the spacing criterion times the mounting height. The floor to ceiling height is a close proxy for the mounting height. The area where electric lighting is controlled is called the “daylit area under skylights”.

Photometric measurements of diffusing skylights or skylights with a diffusing lens on the bottom of the light well found that for most samples and for most sun angles, the spacing criterion was calculated to be between 1.2 and 1.4 (McHugh et al. 2002). As a result, the daylit area is defined as the skylight “footprint” plus additional distance in each longitudinal and lateral dimension – and that additional distance is one half of the spacing criterion or 70% of the floor to ceiling height.

The background information from the photometric testing of skylights by the CEC sponsored Public Interest Energy Research (PIER) program is given below. Since the distribution of light emitted from a skylight changes when the sun position changes, a separate photometric test was performed for each 10 degree increment in solar elevation (angle of sun above the horizon). Thus for each skylight tested, there would be photometric measurements made for when the sun was at 10 degrees, 20 degrees etc. to the maximum solar elevation on the day of the test (all measurements were in the summer or early fall). The data from these tests was compiled into IES LM 63-1995 photometric files and processed into photometric reports that include the spacing criterion. Unlike electric lighting fixtures, a skylight has more than one set of spacing criterions based upon the sun angle. Thus this evaluation of spacing criterion for skylights is based upon the spacing criterion for several skylights over a range of sun angles.



Figure 1: Compound parabolic skylight

rotated so that the "ribs" of the skylight were parallel to the major axis in one set of tests and perpendicular in the other set of tests. An example of a compound parabolic skylight shape is shown in Figure 1

The graphs in Figure 2 display the distribution of Spacing Criterion in the direction along the primary axis of the skylight (North-South) and across this axis (East-West) for four foot wide by four foot long white skylights above a minimal one-foot light well. The skylights tested were a single glazed white acrylic dome skylight, a double-glazed clear over white acrylic dome skylight, and a single glazed white PET compound parabolic skylight.

The compound parabolic skylight was

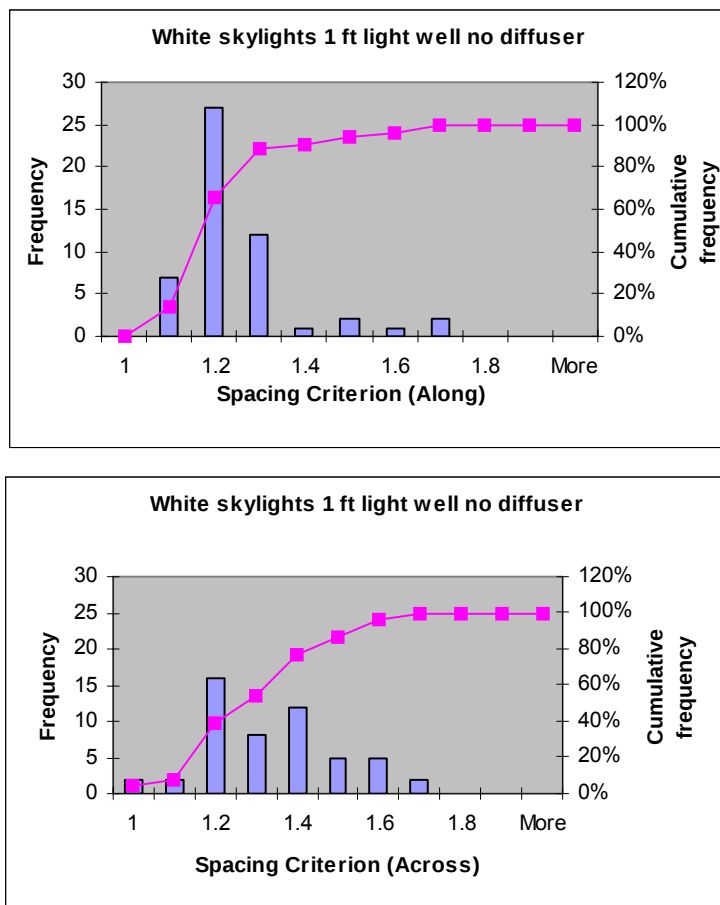


Figure 2: Frequency distribution of spacing criteria for white skylights

Each spacing criterion data point is for one of the four skylight conditions (single glazed white dome, double glazed white dome, and PET compound parabolic white dome in two orientations) and for each 10 degree increment in solar elevation over the course of a clear sky day from sunup to sundown.

The distribution of spacing criteria in Figure 2, clearly indicates that for these typical white diffusing skylights, the spacing criterion most of the time is 1.4 or less. The spacing criterion is a basic indication that for uniform light distribution the luminaires (in this case skylights) should be spaced no further apart than around 1.4 times the mounting height.

A second set of skylight photometric test results was also evaluated for its spacing criteria. This second set of skylights contained skylights having a prismatic diffuser at the bottom of a 3 foot or 6 foot light well. The skylight and well combinations were: a glass skylight with a 6 foot tall light well with white painted walls, a white acrylic dome with a 3 foot tall light well with a specular (metallic foil) surface and a white acrylic dome with a 6 foot tall light well with a specular (metallic foil) surface.

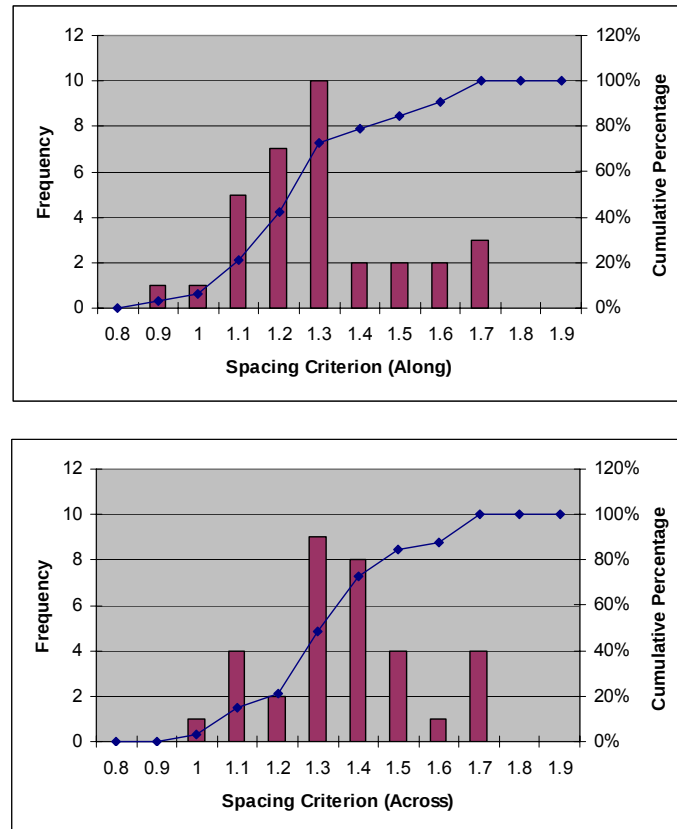


Figure 3: Frequency distribution of spacing criteria for skylights with diffuser at bottom of light well

The graphs in Figure 3 plot the frequency distribution of spacing criteria in the across and along directions for skylight configurations that have a flat bottom diffuser. These results are similar to Figure 2, in that most of the time the spacing criteria for skylights with bottom diffusers are equal to or less than 1.4.

Thus the area that can be controlled together as a "daylit zone" under skylights should be based on this definition. If we modify the existing definition of daylit zone as the skylight "footprint" plus additional distance in each longitudinal and lateral dimension – that additional distance would be one half of the spacing criterion or 70% of the floor to ceiling height. The "spread angle" that describes how the skylit area increases with ceiling height is the arctangent of 0.7 or 35 degrees.

3. REQUIREMENT FOR MULTI-LEVEL PHOTOCONTROL

The purpose of this part of the proposal is to assure that photocontrol systems are adequately commissioned initially and that they are easy to re-commission in response to changes in the use of a space or changes to the lighting system being controlled. Photocontrols without correct commissioning save significantly less energy than those calibrated correctly and may be disabled by unsatisfied building occupants, eliminating all energy savings potential. The additional requirements for automatic daylighting controls in this proposal were added to address each of the following issues.

First, from discussions with people who commission photocontrols, photocontrols with the adjustment knobs mounted on the light sensor were hard to commission for the following reasons:

- The photosensor is often mounted up high – attached to the ceiling or up in a skylight well. This makes it hard to access initially and even harder to access later on when furniture or machinery blocks easy access to the ceiling. In many of the skylit zones discussed in this code change proposal, ceiling heights are 20 feet or more.
- The body of the commissioning agent is shielding the photosensor. What might be a correct adjustment while the commissioning agent is on the ladder in front of the sensor is an incorrect adjustment once that agent is on the ground.

In response to these calibration issues, this proposal requires that the “photocontrol shall be located so that calibration and setpoint adjustment controls are readily accessible. The light sensor shall be remote from where calibration adjustments are made.”

This proposal also requires that the photocontrol be “multi-level”. That means that there are at least two control steps and of course this would not preclude continuous dimming. One reason for this requirement is that multi-level control is less distracting than “On/Off” control that turns all of the lights on and off.

The other reason for requiring multi-level photocontrols is that multi-level controls on average save more energy than single level controls. A control that can turn off a fraction of the lights in steps is able to turn some of the lights off when the interior daylight levels are less than the design footcandle levels.

It is also important that the control be able to reduce the controlled lighting power below some fraction of rated power so a significant amount of lighting power is being consumed when full daylighting is available. An example of excessive power draw at minimum light output is dimming metal halide lighting. Currently, dimming metal halide typically consumes a little over 50% of rated power while it is dimmed to minimum light output, typically around 25% of light output.

In conducting the cost-effectiveness calculations for photocontrols, we priced out several systems that would meet all of the requirements listed above: linearity (photodiode type sensor), sensor separate from control (also allows controls to be readily accessible), and multi-level or continuously dimming controls.

The average lighting energy savings range from 1.7 kWh/sf·yr to 2.8 kWh/sf·yr depending upon climate and lighting power density of the space. This translates to approximately an annual energy cost savings of \$0.28/sf to \$0.09/sf per year depending upon the energy savings and utility electricity rates. For a minimum daylit area of 2,500 the energy savings correspond to a range of \$700/yr to \$230/yr.

For a space of 2,500 sf, the cost of the simplest multi-level switching photocontrol systems cost approximately \$1,000 to \$1,500. Thus the energy savings associated with photocontrols would pay for the cost of the control system in 1.4 to 4.3 years. This payback is less than the ASHRAE scalar of 8, used to determine the cost-effectiveness of measures for the ASHRAE 90.1 energy standard referenced by the IECC.

Multi-level photocontrols are selected over the less expensive single step controls because the discounted incremental energy cost savings over the life of the control are greater than the incremental cost of the control. The cost increased by 25% when an additional level of control is added to the photocontrol system. A multi-level control serving a single zone costs approximately \$270 more than an on/off (single step) control. In an analysis a grocery store in IECC climate zones 1, 3, and 5, adding a second stage of control to 2,500 sf zone increased cost savings from \$210 to \$90. Thus the simple payback of adding the second stage of control ranges between 1.25 to 3.0 years. Thus when the life cycle cost scalar is 8, the benefit cost ratio of this measure ranges between 6.4 to 2.7 – well above the cost benefit ratio of 1.0 to be considered cost-effective. In warehouses, the zone of control has to be 4 times as large to have similar cost-effectiveness of multi-level controls. In addition, the multi-step control results in smaller fluctuations of light and minimizes occupant distraction.

4. DEFINING GLAZING DIFFUSION WITH “HAZE”

Diffusion is an important metric for determining how well skylights can light a space. Non-diffusing skylights allow intense beams of sunlight to enter the space, which often results in glare and poorly distributes light. A skylight with lower visible transmittance but higher diffusion will let less light enter into an interior space than a high transmittance non-diffusing skylight but often the illuminance between skylights will be higher from the system using diffusing skylights. Diffusing skylighting systems create relatively uniformly daylit spaces which can have electric lighting reduced while maintaining excellent visibility. In comparison, non-diffusing skylighting system cannot reduce electric lighting levels as much because the occupants have adapted to the high light levels receiving beam daylight and thus the other areas in the space appear dim.

This proposal allows greater flexibility in skylight selection and area if in return one can be reasonably assured that the building will consume less energy because light from skylights will indeed displace electric lighting. This assurance comes in the form of the requirement that skylights are diffusing and the electric lighting system is controlled automatically to respond to available daylight. So how does one specify or define what is a diffusing skylight?

As described below, one can differentiate between diffusing and non-diffusing skylights by using the metric of haze. Haze is the ratio of diffusely transmitted light to total light transmitted. The measurement of haze according to the ASTM D1003 standard is relatively inexpensive (one lab routinely performs this test for less than \$10/sample). Many of the skylight manufacturers have or will be performing this test as a haze requirement is contained in the California Title 24 energy code (§ 143(c), Table 146 A).

Visible transmittance and transmission haze measurements of glazing materials can be made with repeatable accuracy in accordance with ASTM D1003-00 *Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics*, Procedure A. The measurements performed for the author as part of the Public Interest Energy Research (PIER) program were made using BYK Gardner Haze Gard Cat. #4725 (McHugh, Dee & Saxena 2004). The transmission haze values were determined by the ratio of the diffuse transmittance to the total transmittance for each specimen. See Figure 4 for a diagram of the haze and luminous transmittance test apparatus.

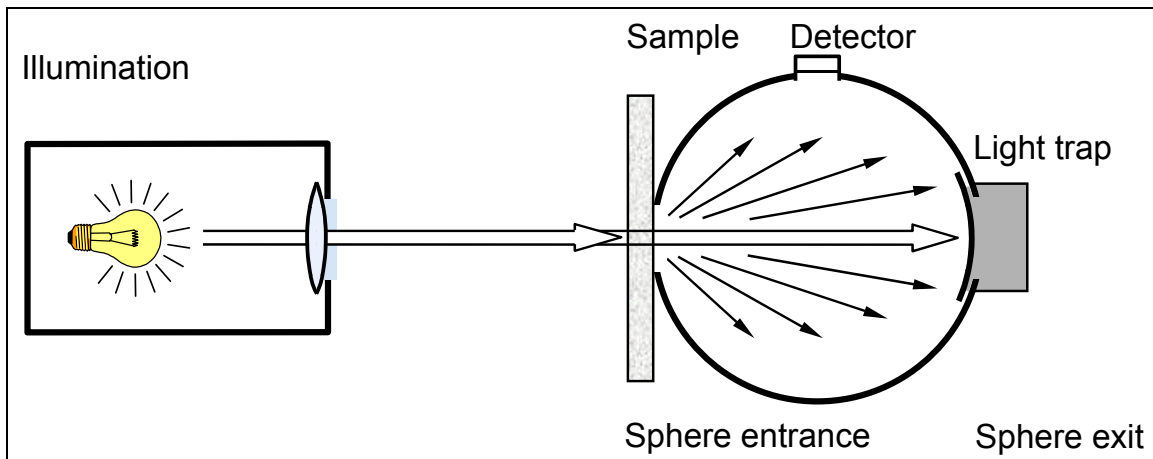


Figure Courtesy of BYK-Gardner

Figure 4. Measurement of Total Transmittance with light trap covered

The Haze Gard consists of a light source, and integrating sphere with a light trap a light trap shield and three detectors. The light source matches the spectral distribution of CIE illuminant C. The light trap captures all light that is within a 2.5° acceptance angle of the beam of light emitted by the light source. If there is no glazing in place and the light trap is unshielded virtually all of the light is captured by the light trap. When there is no glazing in place and the light trap is shielded the integrating sphere detector shown on the top of Figure 4 measures the maximum amount of light reflected in the integrating sphere.

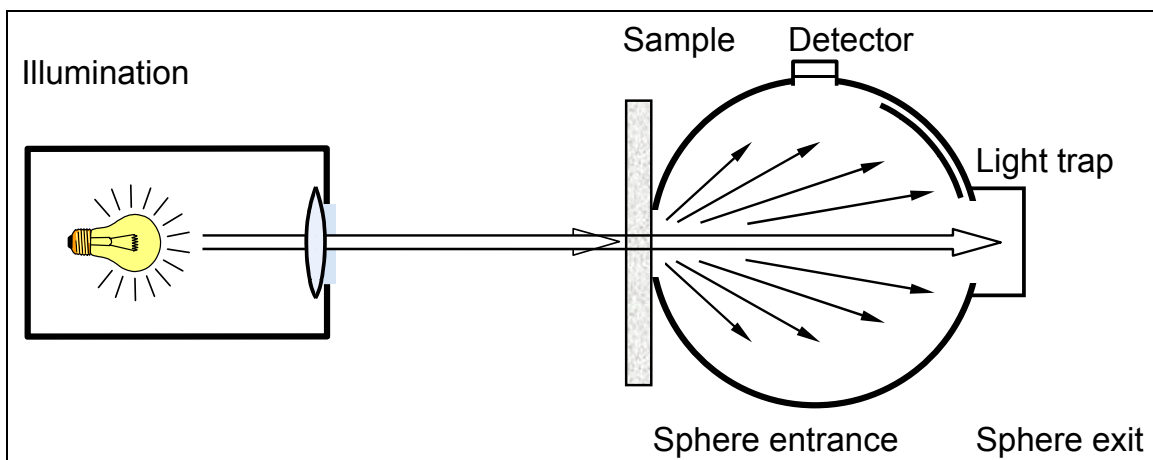


Figure Courtesy of BYK-Gardner

Figure 5. Measurement of Diffuse Transmittance with light trap open

Total light transmitted by the glazing is measured with the light trap obstructed by a cover having the same reflectance as the rest of the integrating sphere (see Figure 4). Total transmittance is the ratio of the measured illuminance by the sphere detector with the glazing sample in front of the sphere aperture and the light trap covered, to measured illuminance by the sphere detector with the glazing sample removed and the light trap covered.

Diffuse transmittance, T_{Diffuse} , is measured with the light trap uncovered as shown in Figure 5. In this configuration the sphere detector measures only the light not trapped – light which is scattered more 2.5° . Diffuse transmittance is used to quantify transmission haze, which is the wide-angle scattering of transmitted light through transparent and translucent materials. Haze is the ratio of diffuse transmittance to total transmittance and is expressed by the following relation:

$$\text{Haze} = \frac{T_{\text{Diffuse}}}{T_{\text{Total}}}$$

The ASTM D1003 standard states that “material having a haze value greater than 30% is considered diffusing and should be tested in accordance with practice E167,” *Standard Practice for Goniophotometry of Objects and Materials*, American Society for Testing and Materials. The problem with ASTM E166 (for transmitting materials) and E167 (for reflecting materials), is that this standard has no simple term for diffusing or non-diffusing glazing. There is no concept of haze in ASTM E166, it merely defines the method of generating a photometric distribution. This result of a measurement of a photometric distribution is not particularly useful in a code or a specification context where an unambiguous criteria is desired. If ASTM E166 were used as a method of defining diffusion, some derivative metric would have to be created such as a root mean square error from a Lambertian (perfectly diffusing) distribution. Such a definition currently does not exist.

The concern with measuring haze from a highly diffusing sample is that it does cause some error but this error is small. In a paper by Weidner and Hsia (1979), the uncertainty in percentage haze is on the order of 0.2% of full scale for a highly diffusing (Lambertian) sample and as high as 2% if the haze samples have a concentrated directional scattering. For a yes/no determination of whether a glazing material is diffusing or not, 2% error is acceptable for this very gross distinctions in haze.

As shown in Table 1, prismatic acrylic (except double-glazed prismatic with a 1" gap), clear acrylic and twinwall polycarbonate glazings have the highest transmittances, T_{vis} . The bronze acrylic skylight and the fiberglass assembly have the lowest transmittances.

Table 1. Results of DSET Laboratories' Standard Visible Transmittance test.

Test	Materials	Thickness in Inches	% T_{vis}	% Haze
1	White Acrylic	0.118	62.6	100
2	Clear Acrylic	0.118	94.9	0.3
3	Clear Acrylic outside, White Acrylic inside – 1/16" gap	0.298	59.4	100
4	Clear Acrylic outside, White Acrylic inside – 1" gap	1.236	58.0	100
5	Bronze Acrylic	0.116	28.2	1.5

Test	Materials	Thickness in Inches	% T _{vis}	% Haze
6	White PET	0.117	48.8	100
7	Thicker prismatic prisms facing light	0.225	95.3	96.7
8	Thicker prismatic prisms away from light	0.225	84.8	98.1
9	Thinner prismatic prisms facing light	0.117	96.6	97.2
10	Thinner prismatic prisms away from light	0.117	87.7	97.2
11	Thicker prismatic outside, thinner inside – 1/16" gap	0.404	80.0	99.7
12	Thicker prismatic outside, thinner inside – 1" gap	1.342	45.5	100
13	Twinwall polycarbonate (clear)	0.241	83.6	33.2
14	Fiberglass assembly (crystal over crystal no fill)	2.750	29.2	92.2
15	Fiberglass sheet (crystal)	0.067	79.1	69.0
16	Prismatic diffuser prisms facing light (clear)	0.180	93.3	97.4
17	Prismatic diffuser prisms away from light (clear)	0.180	85.8	97.2

The materials that provide best wide-angle diffusion are those with high haze values and include prismatic glazing and diffusers, white acrylic, double-glazed acrylics, white PET, and fiberglass assembly. Those samples with the lowest measured haze are the clear acrylic and the bronze acrylic. Though not measured, the glass used in the skylights test would have extremely low haze values. Many of the materials that provide high levels of wide angle scattering, also provide high levels of narrow angle scattering as defined by clarity. The lower the clarity number, the greater the narrow angle scattering. Ideally a diffusing glazing provides both high levels of haze and low levels of clarity.

The following analysis were derived from the data:

- Prismatic lenses with prisms facing the light perform about 10% better than when the prisms face away from the light.
- Layered diffusing materials have a higher tested visible transmittance when the gap between layers is smaller. This is an artifact of the test method and not an actual reduction in the amount of light transmitted. The reasons for this are discussed later in this section.
- Though they are a commonly used skylight glazing material, pigmented white acrylic materials perform satisfactorily, with a T_{vis.} around 60%.

Table 2. Ranking of test specimens according to haze rating.

Test	Material	Specimen Code	% Haze
1	White Acrylic	A	100
3	Clear and White Acrylic 1/16" gap	A + B	100
4	Clear and White Acrylic 1" gap	A + B	100
6	White PET	D	100
12	Thinner and Thicker prismatic 1" gap	E + F	100
11	Thinner and Thicker prismatic 1/16" gap	E + F	99.7
8	Thicker prismatic prism away fr light	E	98.1
16	Prismatic diffuser prism facing light	J	97.4
9	Thinner prismatic prism facing light	F	97.2
10	Thinner prismatic prism away from light	F	97.2
17	Prismatic diffuser prism away from light	J	97.2
7	Thicker prismatic prism facing light	E	96.7
14	Fiberglass assembly	H	92.2
15	Fiberglass sheet	I	69
13	Twinwall polycarbonate	G	33.2
5	Bronze Acrylic	C	1.5
2	Clear Acrylic	B	0.3

As can be seen in Table 2, there is a very obvious demarcation in haze ratings of existing skylight materials. Most of the test specimens are either above 92% or below 70% haze. The haze properties of less diffusive materials fall rapidly below 70%. Thus the concern expressed about the 2% error generated by measuring the haze of highly diffusing glazings is not important when making a clear separation between diffusing and non-diffusing glazings.

5. METHODOLOGY

The primary purpose of the IECC analysis was to investigate three issues:

1. What is the minimum amount of skylight area in large open areas needed to assure that one obtains sufficient and cost-effective energy savings from skylighting and daylighting controls?
2. What lighting control methods and minimum daylit areas will provide cost-effective trade-off between controls costs and energy savings?
3. What is the maximum allowable skylight area before the losses from skylights outweigh the gains? This maximum area should not prohibit good daylighting design under conditions that reduce light from skylights including: deep light wells, dirty ambient conditions, high stacks.

We considered three building types in the analysis: Warehouse, Grocery and Retail to cover the range of commercial buildings and set up six models as described below:

1. Warehouse – Heating and Cooling: Warehouse with full air conditioning
2. Warehouse – Heating only: Warehouse with only heating
3. Grocery – Big Box: A warehouse style grocery store, with exposed roof structure
4. Grocery – Dropped Ceiling: A grocery store with a false ceiling
5. Retail – Fluorescent: Retail store with fluorescent lighting
6. Retail – HID: Retail store with HID lighting

Parametric runs for each of the above six models were setup as described in Section 6. Figure 6 below shows a typical graph of savings from skylights SFR values going from 0% to 12%. From each parametric run for a given climate zone, a “Max Savings” figure was identified, and along with that, the corresponding SFR for this max savings. The corresponding SFR to the “90% Min” and “90% Max” was also noted. This gave an idea of how steep the curve to the max savings was. Another point identified was the SFR value at which the savings start to become negative. These values were identified for each of the 24 skylight types in each climate zone.

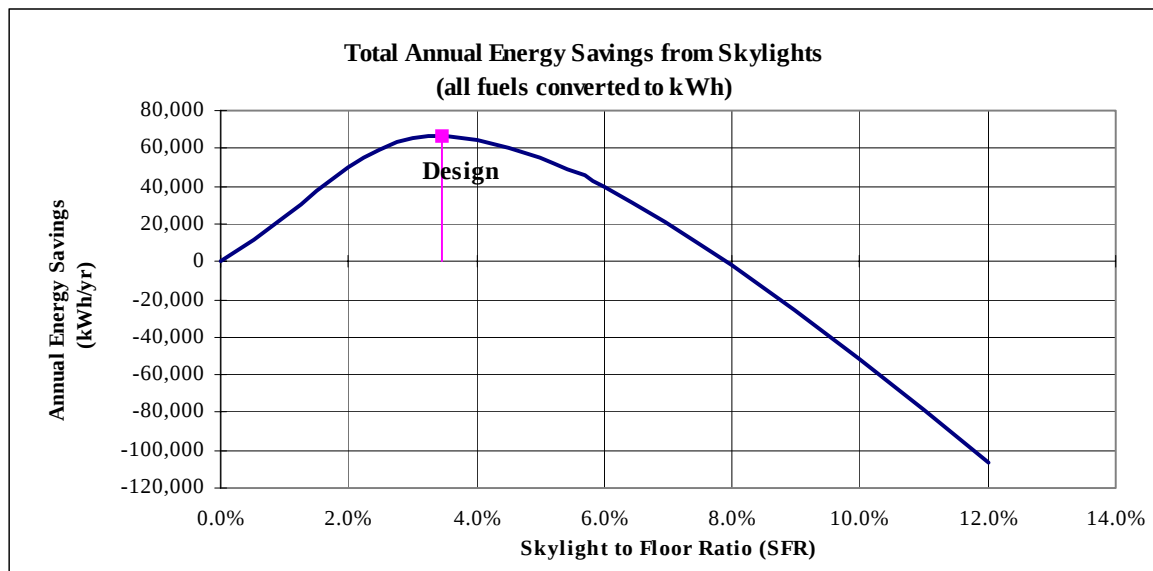


Figure 6: Typical graph of energy savings from skylights across increasing SFR

For the purpose of analysis of this data, we decided to group the savings data from the simulation runs with the skylight's visible and thermal properties and then mathematical sort those groups by the savings. The better performing skylights sorted to the top of the group while the poor performing skylights sorted to the bottom, along with their corresponding properties. This helped us identify the appropriate metric to use as criteria for the code change proposal. Figure 7 show one such group for CZ2A for Warehouse with heating and cooling.

Three properties for each skylight were: visible transmittance (Tviz), solar heat gain coefficient (SHGC), and thermal resistance (U-value). To better capture the relation between Tviz and SHGC, a fourth variable Tviz/SHGC we introduced. This metric was found to be the most effective in identifying the better performing skylights from the poor performing ones.

In Figure 7 each skylight is identified by the "Skylight ID" and "Skylight Code", which is then followed by the skylight properties, namely "SHGC", "UFactor", "Tviz" and "Tviz/SHGC". The next column is "Max Savings" which indicates the maximum savings between 0% to 12% SFR. The column next to that, "Max Savings' SFR" identifies the SFR value at which this max savings was found. The next two columns "90% Min SFR", and "90% Max SFR" give corresponding SFR values for the 90% range from the maximum saving value. This gave an idea of how steep the curve to the max savings was. And finally another point identified was the SFR value at which the savings start to become negative under "Exact SFR at point of -ve savings".

CZ 2A		Skylight ID	Skylight Code	SHGC	Ufactor	Tviz	Tviz/SHG C	Max	Max	90% Min	90% Max	Exact
Houston								Savings -	SFR -	SFR -	SFR -	point of -
								WAR hc	WAR hc	WAR hc	WAR hc	ve savings WAR hc
50	ID-313	bCLRLairCLRNfla	0.38	0.53	0.65	1.72	13,073	0.03	0.02	0.05	0.1	
80	ID-311	bCLRLargCLRNfla+PRM	0.35	0.4	0.62	1.77	13,056	0.03	0.02	0.05	0.1	
60	ID-308	bCLRLairCLRNfla+PRM	0.35	0.43	0.62	1.76	13,017	0.03	0.02	0.05	0.1	
10	ID-409	bCLRairCLRairHWHtdom	0.56	0.67	0.69	1.23	12,731	0.02	0.02	0.03	0.1	
30	ID-405	bCLRairHWHtdom	0.58	0.71	0.61	1.05	12,369	0.02	0.02	0.03	0.1	
200	ID-303	mEVGNfla+PRM	0.41	0.8	0.59	1.44	12,356	0.02	0.02	0.04	0.1	
130	ID-312	bEVGLargWHTNfla	0.26	0.47	0.38	1.45	12,291	0.03	0.03	0.07	0.1	
90	ID-310	bCLRLargWHTNfla	0.35	0.47	0.47	1.35	12,281	0.03	0.02	0.05	0.1	
70	ID-307	bCLRLairWHTNfla	0.35	0.52	0.47	1.34	12,261	0.03	0.02	0.05	0.1	
180	ID-406	bPRMairPRMdom	0.69	0.71	0.72	1.04	12,202	0.02	0.02	0.03	0.093883	
120	ID-309	bEVGLairWHTNfla	0.27	0.52	0.38	1.39	12,201	0.03	0.03	0.07	0.1	
0	ID-411	bCLRairCLRairCLRairCLRdom	0.65	0.6	0.71	1.09	12,187	0.02	0.02	0.03	0.091643	
100	ID-305	bCLRNairCLRNfla+PRM	0.61	0.52	0.7	1.15	12,134	0.02	0.02	0.03	0.1	
170	ID-410	bPRMairPRMairPRMdom	0.61	0.67	0.63	1.03	12,117	0.02	0.02	0.03	0.1	
40	ID-403	bCLRairMWHTdom	0.58	0.71	0.55	0.94	12,037	0.02	0.02	0.03	0.1	
210	ID-401	mPRMdom	0.8	1.33	0.82	1.03	11,991	0.01	0.01	0.02	0.077975	
220	ID-402	mWHTdom	0.59	1.33	0.61	1.04	11,873	0.02	0.02	0.03	0.099159	
190	ID-302	mCLRNfla+PRM	0.71	0.8	0.79	1.11	11,869	0.02	0.02	0.03	0.087905	
140	ID-306	bEVGNairWHTNfla	0.37	0.69	0.41	1.12	11,448	0.03	0.02	0.05	0.1	
160	ID-404	bLWHTairCLRdom	0.35	0.71	0.29	0.84	11,239	0.04	0.03	0.06	0.1	
110	ID-304	bCLRNairWHTNfla	0.62	0.69	0.54	0.87	11,188	0.02	0.02	0.03	0.096011	
150	ID-408	bLWHTairCLRairCLRdom	0.31	0.67	0.27	0.87	11,168	0.04	0.03	0.06	0.1	
230	ID-301	mWHTNfla	0.67	1.29	0.61	0.91	11,039	0.02	0.02	0.03	0.08371	
20	ID-407	bCLRairCLRairMWHTdom	0.56	0.67	0.41	0.74	10,918	0.02	0.02	0.04	0.1	

Figure 7: Parametric runs grouped and sorted by Max Savings.

We identified the top half of the group as “better performing” skylights and the bottom half as “poor performing” skylights. Averages of SHGC, Tviz, U-value and Tviz/SHGC for the better and poor performing skylights were calculated. To determine the strongest metric that determines a better skylight in that specific climate zone, ratios of “Better/Poor” and “Poor/Better” were taken and the four metrics were ranked in terms of their strength based on the ratio. In Figure 8 below, climate zone 2A, the two strongest metrics are U-factor and Tviz/SHGC. SHGC was less significant and the least significant was Tviz.

	SHGC	Ufactor	Tviz	Tviz/SHG C
Better	0.413636	0.566364	0.563636	1.412727
Poor	0.571538	0.821538	0.564615	0.98
B/P	0.723724	0.689394	0.998266	1.441558
P/B	1.381741	1.450549	1.001737	0.693694

Figure 8: Identifying the strongest metric

We then compared the results from this study looking both at the ratios of better to worse performing skylights and then compare the results of good performing systems to the current IECC skylight properties requirements. In addition we evaluated the range of skylight areas across all building types by climate zone that would include both optimal savings while excluding skylight areas that would increase energy consumption (negative savings). As one would expect warehouses need less skylight area than retail because, less light is needed. To determine this range of acceptable skylight areas, we looked at all skylights that met the minimum skylight properties revised requirements and considered both the SFR at which the savings went negative and where savings were optimal. To

give assurance that the optimal savings metric was not overestimating skylight areas when there has to be trade-off between too many skylights in low light areas and the optimal skylight area in high light areas we also looked at the minimum skylight to floor area ratio needed to obtain 90% of the optimal savings.

This 90% of optimal savings metric was also useful for our last proposal, what should the minimum skylight area be to assure most of the possible savings from skylights.

This can be evaluated by considering the SFR's for all building types in a given climate zone. This would assure that the limitations selected for skylight area and properties would allow both optimal savings and at the same time prevent energy consumption increases relative to no skylights at all.

5.1 Analysis for Minimum and Maximum Allowed Skylights

In order to ensure that the minimum requirement of skylight to daylight area ratio (SDR) of 3% for climate zones 1, 2 and 3 produces cost effective results, we performed a benefit to cost analysis for all eight climate zones. We determined savings and costs for the three building cases: Warehouse (Heating & Cooling), Warehouse (Heating only) and Big Box Retail (Fluorescent Lighting). We used minimally compliant skylights for each climate zone.

ASHRAE and IESNA in developing the 90.1 energy standard have used a scalar (essentially a series present worth factor) of 8. It is possible to use scalars up to 12, but using the precedence of ASHRAE 90.1, the lifecycle energy cost savings analysis was done using a scalar of 8.

For the cost calculations, we used the cost for the minimally compliant skylights for each climate zone, photocontrols, and for providing increased tonnage to offset the increased cooling loads due to skylights. Cost for skylights and photocontrols is described in detail in Section 7.2 and Section 7.3. To estimate the increased tonnage of the air conditioner we used the equipment sized by DOE2 for each run. To get the cost of this upgrade, we used the RS Means Mechanical Cost Data that the average cost of increasing the tonnage of a commercial rooftop air conditioner was approximately \$1000 per extra ton.

Table 3. Benefit to Cost Ratios at 3% SDR for Each Climate Zone

	Miami, FL CZ 1	Houston, TX CZ 2	San Francisco CA CZ 3	Albuquerque, NM CZ 4	Chicago, IL CZ 5	Helena, MT CZ 6	Duluth, MN CZ 7	Fairbanks AK CZ 8
WAREHOUSE (Heating & Cooling)								
Lifecycle Energy Cost Savings (Scalar 8)	\$94,338	\$95,002	\$151,202	\$72,677	\$60,037	\$58,848	\$55,549	\$104,929
Costs for Skylight, Controls & Increased Tonnage	\$61,457	\$65,958	\$65,183	\$69,800	\$62,941	\$65,785	\$63,803	\$129,606
Benefit to Cost Ratio	1.54	1.44	2.32	1.04	0.95	0.89	0.87	0.81
WAREHOUSE (Heating Only)								
Lifecycle Energy Cost Savings (Scalar 8)	\$104,337	\$101,091	\$158,275	\$83,421	\$65,547	\$66,066	\$63,065	\$99,014
Costs for Skylight & Controls	\$50,747	\$56,789	\$56,789	\$56,789	\$56,789	\$56,789	\$56,789	\$133,488
Benefit to Cost Ratio	2.06	1.78	2.79	1.47	1.15	1.16	1.11	0.74
BIG BOX RETAIL (Fluorescent Ltg)								
Lifecycle Energy Cost Savings (Scalar 8)	\$64,132	\$55,737	\$93,304	\$50,323	\$21,928	\$28,388	\$26,229	\$26,211
Costs for Skylight, Controls & Increased Tonnage	\$26,886	\$33,597	\$32,809	\$41,106	\$52,842	\$36,048	\$29,164	\$82,141
Benefit to Cost Ratio	2.39	1.66	2.84	1.22	0.41	0.79	0.90	0.32

Finally a benefit to cost ratio was calculated for the three cases as shown in Table 3. From the results in the table, it can be clearly seen that for the climate zones selected for the minimum skylight area requirement, namely climate zones 1, 2 and 3, benefit/cost ratios are above 1.5 for almost all cases, making them cost effective by a comfortable margin. In the remaining climates, we find that skylights do not save enough energy to achieve a benefit/cost ratio greater than 1.5, with most cases not being cost effective (benefit/cost <1).

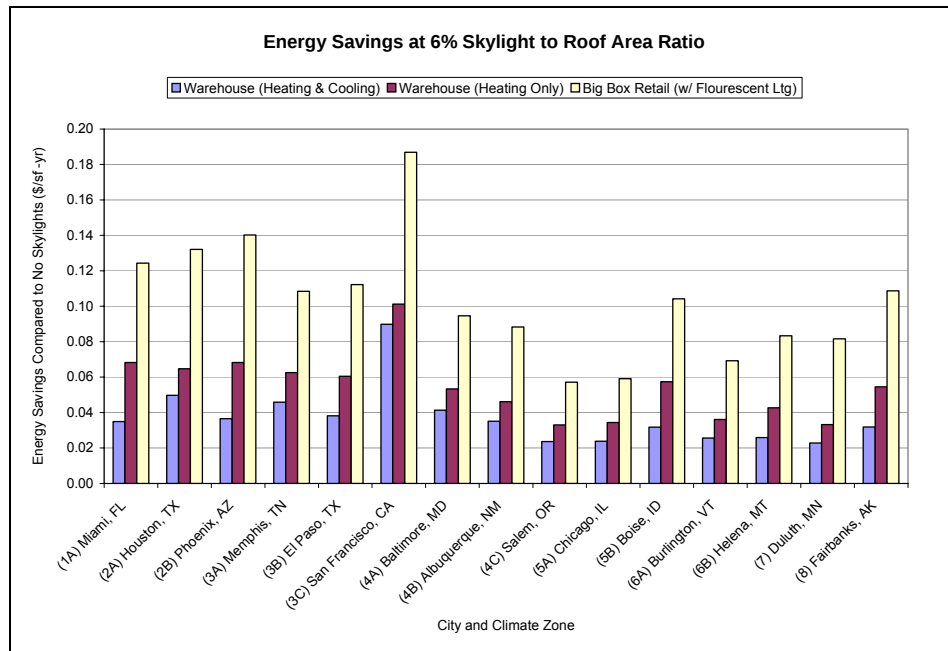


Figure 9: Energy Cost Savings with Minimally Compliant Skylights for Each Climate Zone at Maximum Allowed Skylight to Roof Area Ratio of 6%

To ensure that the maximum allowed skylight to roof area ratio (SRR) of 6% does not create a condition of negative energy savings, we calculated the energy savings at 6% SRR for all climate zones.

Figure 9 shows energy savings from the DOE2 simulation runs with a minimally compliant skylight for each climate zone and the maximum skylight to roof area ratio (SRR) of 6%. Energy cost savings were calculated with respect to a case with no skylights. It is readily apparent that for 6% SRR, there are positive energy savings for all climate zones across all buildings types.

6. SIMULATION MODELS

This section describes the simulation models that were used to estimate the energy impacts of various combinations of skylights and photocontrols to identify energy and cost saving combinations.

6.1 Primary Issues

The purpose of the IECC analysis is to investigate three issues:

4. What is the minimum amount of skylight area in large open areas needed to assure that one obtains sufficient and cost-effective energy savings from skylighting and daylighting controls?
5. What lighting control methods will provide the optimum trade-off between controls costs and energy savings?
6. What is the maximum allowable skylight area before the losses from skylights outweigh the gains? This maximum area should not prohibit good daylighting design under conditions that reduce light from skylights including: deep light wells, dirty ambient conditions, high stacks.

6.1.1 Specific issues

Key issues that this analysis needs to address are:

1. Interrelation of T_{vis} , SHGC and U-factor especially in plastic skylights. Glass skylights have greater flexibility due to low-e coatings and gas fills.
2. The substantially better low sun angle performance of projecting skylights as compared to flat skylights. Dome skylights maintain almost constant effective visible transmittance over most sun angles. In contrast the transmittance of flat glass skylights drops off markedly when the solar elevation is below 25 degrees.
3. The substantially higher U-factor of projecting skylights as compared with flat skylights.
4. The interrelation between electric lighting LPD, space geometry and reflectances and the design footcandle levels for spaces. Light levels are calculated from the maintained and depreciated average light output of the lighting system. This can be calculated by the Lumen Method calculations in SkyCalc.
5. The great disparity in energy costs between electricity (lighting and cooling) and natural gas (heating) and the great disparity of peak demand costs (kW) and electrical usage (kWh).
6. The impact of skylight sizing and controls on sizing of HVAC units.

6.2 Climate data

The IECC requirements are specific to 8 climate zones where 1 is the warmest and mildest climate and climate zone 8 is the coldest. In addition, these climate zones are further subdivided by A, B and C based on humidity.

Table 4. Climate zones simulated in IECC skylighting proposal study

Zone#+	City, State
1A	Honolulu, HI
1A	Miami, FL
2A	Houston, TX
2B	Phoenix, AZ
3A	Memphis, TN
3B	El Paso, TX
3C CA-3	Los Angeles, CA
3C	San Francisco, CA
4A	Baltimore, MD
4A NE-4	New York City, NY
4B	Albuquerque, NM
4C	Portland, OR
4C	Salem, OR
4C	Seattle, WA
5A NE-5	Boston, MA
5A	Chicago, IL
5B	Boise, ID
6A	Burlington, VT
6B	Helena, MT
7	Duluth, MN
8	Fairbanks, AK

The cities that are bolded in Table 4, are the standard cities used to develop standards for the climate zones. We also included other cities with significantly higher electricity prices than the rest of their climate zone or because we had conducted additional studies on those areas and this data could be used for comparison. See the section “Energy Costs” for a further description on the relative pricing of energy by region of the country.

6.3 Skylight parametrics

6.3.1 Skylight area

Skylight area is parametrically increased from 0% to 10% of roof area in increments of 1%.

6.3.2 Glass skylight properties

The description and skylight visible transmittance (T_{vis}), solar heat gain coefficient (SHGC) and thermal transmittance (U-factor) properties are contained in Table 5 below. U-factors are given for the entire skylight

including a 3.5 inch (nominal 4”) tall curb. The glass properties are derived from the library of glass properties in the Window5 program. The total horizontal U-factors are mostly from NFRC ratings of glass skylights. Some of the U-factors however do not exist in the NFRC library – for instance the glass over acrylic prismatic diffuser. This material was included as it provides both high transmittance and acceptable diffusion (haze > 90%).

The angular visible light transmittance and solar heat gain coefficient of glass skylights will be modeled as described by their Window 5.0 file.

Table 5. Glass Skylight Material Properties

Glazing layers	ID #	Frame	Glazing Description	SHGC	Tvis	Total Horizontal U-factor	U-factor Center Glass	U-factor Edge Glass
Single	301	metal	Med.Wht Interlayer	0.666	0.608	1.285	1.149	1.148
Single over acrylic diffuser	302	metal	Clear - Prismatic	0.709	0.785	0.803	0.539	0.632
Single over acrylic diffuser	303	metal	Evergreen - Prismatic	0.410	0.591	0.803	0.539	0.632
Double	306	thermally broken metal	Evergreen - Air - Med.Wht	0.366	0.409	0.688	0.556	0.614
Double	304	thermally broken metal	Clear - Air - Med.Wht	0.622	0.543	0.688	0.556	0.614
Double over diffuser	305	thermally broken metal	Clear - Air - Clear - Prismatic	0.609	0.702	0.522	0.350	0.424
Dbl low-e clear	313	thermally broken metal	ClearL - Air - Clear	0.383	0.659	0.533	0.416	0.479
Dbl Low-e	309	thermally broken metal	EvergreenL - Air - Med.Wht	0.265	0.369	0.519	0.412	0.475
Dbl Low-e	307	thermally broken metal	ClearL - Air - Med.Wht	0.353	0.474	0.519	0.413	0.476
Dbl low-e w/ argon	312	thermally broken metal	EvergreenL - Arg - Med.Wht	0.255	0.369	0.471	0.339	0.415
Dbl low-e w/ argon	310	thermally broken metal	ClearL - Arg - Med.Wht	0.351	0.474	0.471	0.340	0.416
Dbl Low-e over acrylic diffuser	308	thermally broken metal	ClearL - Air - Clear - Prismatic	0.349	0.613	0.430	0.284	0.374
Dbl Low-e w/ argon over acrylic diffuser	311	thermally broken metal	ClearL - Arg - Clear - Prismatic	0.347	0.613	0.402	0.247	0.349

Glazing description: Layers from outside to inside, "L" after glazing color indicates the layer with the low-e film

6.3.3 Plastic skylight properties

The description and skylight visible transmittance (Tvis), solar heat gain coefficient (SHGC) and thermal transmittance (U-factor) properties are contained in Table 6 below.

Table 6. Plastic Skylight Material Properties

Glazing layers	ID #	Frame	Glazing Description	SHGC	Tvis	Total Horizontal U-factor	U-factor Center Glass	U-factor Edge Glass
Single	401	metal	Prismatic	0.802	0.826	1.330	1.056	1.055
Single	402	metal	Medium white	0.589	0.615	1.330	1.113	1.112
Double	406	thermally broken metal	Prismatic - Prismatic	0.690	0.719	0.710	0.516	0.573
Double	403	thermally broken metal	Clear - Med.Wht	0.584	0.550	0.710	0.530	0.587
Double	405	thermally broken metal	Clear - High.Wht	0.584	0.615	0.710	0.530	0.587
Double	404	thermally broken metal	Low.Wht - Clear	0.345	0.290	0.710	0.529	0.586
Triple	410	thermally broken metal	Triple Prismatic	0.614	0.631	0.666	0.333	0.411
Triple	407	thermally broken metal	Clear - Clear - Med.Wht	0.560	0.414	0.666	0.339	0.415
Triple	409	thermally broken metal	Clear - Clear - High.Wht	0.560	0.690	0.666	0.339	0.415
Triple	408	thermally broken metal	Low.Wht - Clear - Clear	0.309	0.270	0.666	0.339	0.415
Quadruple	411	thermally broken metal	Quadruple Clear	0.653	0.712	0.600	0.244	0.348

The angular visible light transmittance and solar heat gain coefficient of plastic skylights will be modeled with a constant transmittance as found by the PIER skylight testing and as modeled by the SkyVision software of the National Research Council of Canada.

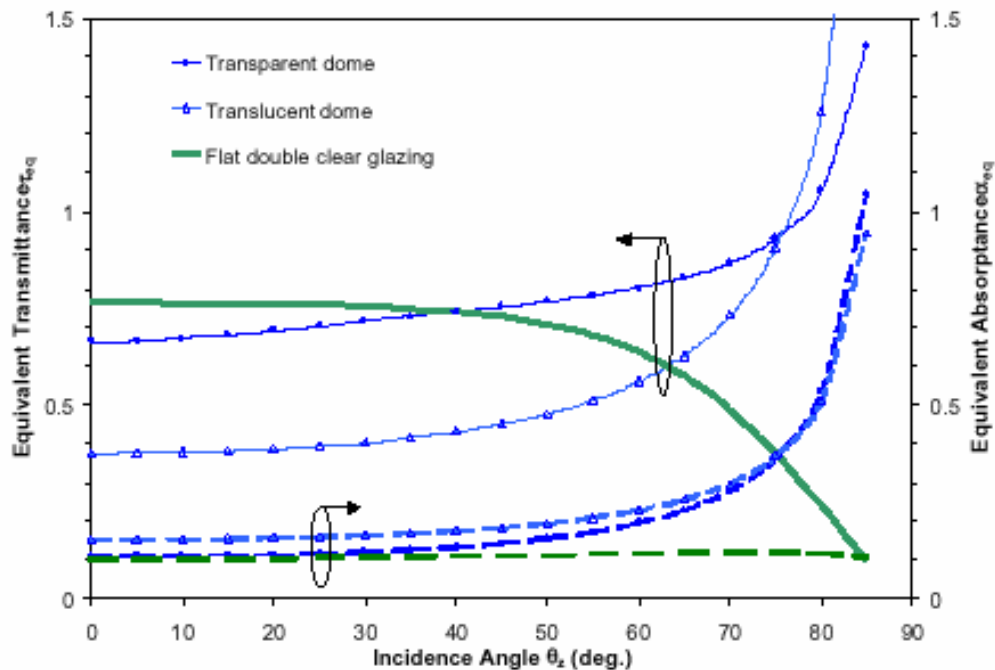


Figure 10. Dome Skylight Equivalent Transmittance (Laouadi & Atif 2001)

6.4 Building Models

The buildings of interest are those with large open spaces. These building types include warehouses, grocery stores and big box retail.

6.4.1 Warehouse description

(2 HVAC)(2 LPD's)[(10 controls)(12 skylights)(10 SFR's) + current code] = 4,804 runs per climate

We do the above for 3 climates and cut controls down to 4 types for the other climates resulting the following runs.

(2 HVAC)(2 LPD's)[(4 controls)(12 skylights)(10 SFR's) + current code] = 1,924 runs per climate

The warehouse modeled is 82,944 sf with 32 ft ceiling height. The stacks in this space are 15 feet tall and have an effective reflectance of 40%. The walls, floor and ceiling of the space have reflectances of 50%, 20% and 60% respectively.

We are interested in looking at the impact of skylights on three types of space conditioning:

1. Unconditioned warehouse – if we have time we can plot this to show that the best skylight is a single glazed one but we can use SkyCalc to demonstrate this sufficiently.

2. Heated only warehouse – gas unit heaters
3. Heated and cooled warehouse – air cooled rooftop units

We are also looking at the impact of lighting power density (LPD's) on optimal skylight area and suggest that we investigate two LPD's that correspond to the tenant level of 1.0 W/sf and the whole building level of 0.6 W/sf.

Lighting systems and controls. There are two likely types of lighting systems with their associated controls:

1. High or medium bay HID lighting
 - a. Single level on/off control
 - b. Two level on/off control
 - c. Two level 2/3 and 1/3 off control
 - d. Three level on/off control
 - e. HID dimming 52% power at 25% light output
2. T-5 fluorescent aisle lighting systems
 - a. Single level on/off control
 - b. Two level on/off control
 - c. Two level 2/3 and 1/3 off control
 - d. Three level on/off control
 - e. Fluorescent dimming 20% power at 10% light level

The “current code” run has 3% skylights having the SHGC and U-factors required by the standard with the Tvis of the default skylight determined to comply with the code and no lighting controls.

6.4.2 Big box retail description

(10 controls)(12 skylights)(2 Internal gains)(10 SFR's) + current code = 2,401 runs per climate

We do the above for 3 climates and cut controls down to 4 types for the other climates resulting the following runs.

(4 controls)(12 skylights)(2 Internal gains)(10 SFR's) + current code = 961 runs per climate

The big box retail store is modeled is 46,656 sf with 24 ft ceiling height. The stacks in this space are 15 feet tall and have an effective reflectance of 40%. The walls, floor and ceiling of the space have reflectances of 50%, 20% and 60% respectively.

The building we are considering is heated and cooled with roof top air cooled roof top units. Outside air rates are determined as according to ASHRAE 62

Lighting power density of general lighting set to 1.5 W/sf (from UES).

Lighting systems and controls. There are two likely types of lighting systems with their associated controls:

1. High or medium bay HID lighting
 - a. Single level on/off control
 - b. Two level on/off control
 - c. Two level 2/3 and 1/3 off control
 - d. Three level on/off control
 - e. HID dimming 56% power at 25% light output
2. T-8 fluorescent industrial strips
 - a. Single level on/off control
 - b. Two level on/off control
 - c. Two level 2/3 and 1/3 off control
 - d. Three level on/off control
 - e. Fluorescent dimming 20% power at 10% light level

The “current code” run has 3% skylights having the SHGC and U-factors required by the standard with the Tvis of the default skylight determined to comply with the code and no lighting controls.

6.4.3 Grocery store description

(5 controls)(12 skylights)(2 Light wells)(10 SFR's) + current code = 1201 runs per climate

We do the above for 3 climates and cut controls down to 2 types for the other climates resulting the following runs.

(2 controls)(12 skylights)(2 Light wells)(10 SFR's) + current code = 481 runs per climate

The grocery store is modeled is 46,656 sf with 24 ft ceiling height. The stacks in this space are 7 feet tall and have an effective reflectance of 40%. The walls, floor and ceiling of the space have reflectances of 50%, 20% and 60% respectively. The grocery store is modeled with two light wells: one that is two feet deep and another that is 8 feet deep. The light well shall have a diffuse reflectance of 80%. SkyCalc shall be used to calculate well efficiency.

The building we are considering is heated and cooled with roof top air cooled roof top units. Outside air rates are determined as according to ASHRAE 62. These simulation models included heat recovery from refrigerated cases for spacing heating as it is commonly used in grocery stores.

Lighting power density of general lighting set to 1.5 W/sf (from UES).

Lighting systems and controls. The most likely lighting system for groceries is fluorescent strip lighting and associated controls:

1. T-8 fluorescent industrial strips
 - a. Single level on/off control
 - b. Two level on/off control
 - c. Two level 2/3 and 1/3 off control
 - d. Three level on/off control
 - e. Fluorescent dimming 20% power at 10% light level

The “current code” run has 3% skylights having the SHGC and U-factors required by the standard with the Tvis of the default skylight determined to comply with the code and no lighting controls.

6.5 Modeling Skylights

Modeling skylights in DOE-2 is traditionally performed by treating as skylight as if it were a piece of glass that is flush with the roof surface. However, this is not the case. The skylight curb projects from the surface of the roof and some skylights, such as domes, project out of the plane of their frame. Since some skylights have curved surfaces, their angular transmittances are quite different than that of a flat piece of glass. For flat glass as the angle of incidence increases, the visible light transmittance decreases. However, it has been shown that for dome skylights, the skylights have a near constant effective visible transmittance over a wide range of sun angles (McHugh, Dee et al 2004, Laoudi et al. 2001, Linforth 1958).

In addition, the NFRC rating of skylights defines U-factor as the total heat transfer of the entire skylight including a nominal 4” wood curb per degree Fahrenheit temperature difference divided by the rough opening of the skylight. All curb mounted skylights – even flat skylights will have a greater surface area than their rough opening.

6.5.1 Method of Modeling Flat Glass Skylights

The DOE-2.2 energy simulation program will import skylight properties files from Window 5.0 after they have been processed for format by E-Quest, a user-friendly front end to DOE-2.2. The process of importing the glazing properties into DOE-2 strips off the frame description. The frame information has to be manually introduced separately into the DOE-2 program.

For each skylight modeled, we will use the two pieces of data: the overall NFRC rating of the U-factor of the entire skylight and curb and an associated Window 5.0 file of the glazing assembly. The glazing assembly material properties include the impacts of number of glazing layers, the conductivity of fill gas and of spacer materials, and the emissivity of the glazing surfaces. Window 5.0

provides a center of glass U-factor. The edge of glass area, which is within 2.5 inches of the edge of the glazing, has a different U-factor than the center of glass U-factor. The edge of glass U-factor can be calculated as follows:

The skylight is modeled using Window 5.0 to generate glazing characteristics

Glazing characteristics are added to a THERM files that generates frame and edge of glass U-factors. The edge of glass is defined as being within 2.5" of the frame.

The THERM model is added to the Window glazing model to develop skylight overall U-factors and center of glass U-factor.

Overall skylight glazing U-factor, $U_{\text{glazing-total}}$ is calculated from the Ufactor center of glass, U_{cog} , and the U-factor edge of glass, U_{eog} , as follows:

$$U_{\text{glazing}} = \frac{U_{\text{cog}} \times A_{\text{cog}} + U_{\text{eog}} \times A_{\text{eog}}}{A_{\text{cog}} + A_{\text{eog}}}$$

where,

A_{cog} = area of center of glass, ft^2

A_{cog} = (skylight width – [5/12]) x (skylight length – [5/12]) ft^2

A_{eog} = area of edge of glass, skylight rough opening area minus center of glass area, ft^2

The rated U-factor for the skylight curb and frame, $U_{\text{cf,rated}}$, is defined per unit area of the skylight opening and is simply the overall skylight U-factor minus the U-factor of the glazing. This U-factor includes the exterior film coefficient of 0.218 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h/Btu}$) and the interior film coefficient 0.6 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h/Btu}$) for a 20° slope.

The frame and curb heat transfer is going to be modeled as four walls, which is defined without film coefficients and to reduce errors associated with film coefficients we are going to model this as having the size of the curb. At the design wind speed the conductance area product of the curb and frame as extracted from the rating per unit of rough opening area $U_{\text{cf,rated}} A_{\text{ro}}$ will be equal to conductance area product of the curb and frame from the revised U-factor per unit surface area of the curb, $U_{\text{cf,rev}} A_{\text{curb}}$. Thus the revised U-factor is calculated as follows:

$$U_{\text{cf,rev}} = U_{\text{cf,rated}} \frac{A_{\text{ro}}}{A_{\text{curb}}}$$

where

A_{curb} = area of surface of curb ([3.5/12] x Skylight length x Skylight width)

Since DOE-2 models the air films separately for walls, the U-factor of the curb used for the DOE-2 calculation, $U_{\text{cf, DOE-2}}$ has the film coefficients stripped off as follows:

$$U_{cf,DOE-2} = \frac{1}{\left[\frac{1}{U_{cf,rev}} - 0.6 - 0.218 \right]}$$

As the skylight area increases and the fraction of skylight area that is edge of glass decreases, the U-factor of the curb will be adjusted so that the total U-factor is close to that of the NFRC standard skylight (4'0" by 4'0").

Since flat skylights are typically placed on a canted curb to impart a 3/12 slope to the glazing, additional heat losses are attributed to this cant section. For a 4' by 4' skylight the cant section has 2 sf on the east and west sides and 4 sf on the north side. Thus these cant areas are normalized per unit skylight area:

$$A_{cantE} = 2/16 \times A_{ro}$$

$$A_{cantW} = 2/16 \times A_{ro}$$

$$A_{cantS} = 4/16 \times A_{ro}$$

The U-factor for the cant is that of 1-1/2" Wood $R_{cant} = 1.5$ (ft²·°F·h/Btu),

$$U_{cant} = 0.6667 \text{ (ft}^2 \cdot \text{°F} \cdot \text{h/Btu)}$$

The tilted skylights are on small pieces of wall that are of equal size to the skylights that are tilted at 20° to the south. Light-ref-pt-1 is moved until it is at the minimum point between two skylights.

The nominal NFRC rated skylight model is created in Window 5.0 as described above and the Window 5.0 creates a "Report" in "DOE-2 format" that is used as part of DOE-2's window library. The Window 5.0 report file is imported into the E-Quest DOE-2.2 front end program which places the data in the correct format for being used by DOE-2.2. The first line of the file in the E-Quest library is then edited to be compatible with the stand-alone version of DOE2.2.

An example header line is as follows:

\$LIBRARY-ENTRY 2002

GLASS-TYPE-CODE Double Clr/Tint

Unlike the rest of the DOE-2 inputs data a dollar sign (\$) on the header line does not indicate a comment line. The advantage of creating a window library entry in DOE-2 is that the angular transmittance of solar radiation and light is more accurately captured.

6.5.2 Method of Modeling Dome Plastic Skylights

The calculation method for plastic skylights is very similar to that for flat glass skylights. U-factors for the curb and frame are calculated in the same manner. Dome skylights do not need to be tilted thus there is no calculated cant area.

Creating a Window 5.0 model will have to be an approximation as the appropriate plastic glazings may not be available in the glass library. We will use materials that have similar conductive properties to plastic. The visible light transmittance and solar transmittance properties are not as important as we will

be editing the resulting Window 5.0 DOE-2 report to insert measured visible light transmittances and SHGC's that are invariant to sun angle. This issue is described in the beginning of the report.

6.5.3 Method of Modeling Adjustments to Tvis and SHGC

Since we are modeling diffusing skylights but want to capture the angle dependant quality of skylight transmittance, diffusion is created by adding internal shades. The visible light transmittance of the shade is the product of:

- Dirt depreciation factor 85%
- Well efficiency
- The ratio of the coefficient of utilization of the actual space, CU_{actual} , as compared to the coefficient of utilization of the DOE-2 model, $CU_{\text{DOE-2}}$. The coefficient of utilization is the fraction of light leaving the bottom of the light well that makes it to the work surface. The coefficient of utilization is a function of the geometry of the space and the reflectances of surfaces. The CU's are calculated using the Lumen Method calculation procedure contained in the SkyCalc software¹.

The product of the above factors is the value used for the DOE-2 keyword VIS-TRANS-SCH which is the visible transmittance of the shade. The product of the glazing transmittance and the VIS-TRANS-SCH is the overall transmittance of the glazing system.

When light wells are modeled, not only is the visible light transmittance reduced, but due to stratification effect the SHGC is reduced (Klems 2002, McHugh, Saxena et al.) For the deep light well modeled here, solar heat gain will be reduced by 30%; the Shading-Schedule of the interior blind will be 70%². The product of the angular SHGC of the glazing and the Shading-Schedule is other overall solar heat gain transmittance of the skylight and light well.

¹ Freely available at <http://www.h-m-g.com>

² McHugh, Saxena et al. found that solar gains were reduced by 31% to 35% for 6 foot deep light wells under 4 foot by 4 foot single and double white dome skylights.

7. ECONOMIC ANALYSIS

7.1 Energy Costs

The energy costs used in this analysis were those developed by the New Building Institute in the development of their envelope models for the IECC. These models weight the costs of electricity and gas in different states by their fraction of population that contributes to a given IECC climate zone. Key findings from this study are that more populated regions in the Northeast (NE4- NE6) have higher electricity costs. California in particular has high electricity costs in comparison to the rest of the country as does Alaska and Hawaii.

Table 7. NBI Weighed Costs by Climate Zone

Mod Zone	Mod Zone Pop	Nat Gas Prices		Elect Prices	
		Hi \$/Therm	Low \$/Therm	Hi \$/kWh	Low \$/kWh
1-humid	2,673,923	\$1.01	\$0.73	\$0.071	\$0.062
2-dry	3,295,171	\$0.84	\$0.62	\$0.075	\$0.069
2-humid	16,286,072	\$0.83	\$0.59	\$0.075	\$0.065
3-dry	2,623,125	\$0.73	\$0.49	\$0.078	\$0.068
3-humid	19,522,701	\$0.78	\$0.58	\$0.068	\$0.062
3-marine	6,228,690	\$0.86	\$0.57	\$0.120	\$0.093
4-dry	1,226,131	\$0.69	\$0.46	\$0.078	\$0.071
4-humid	25,166,819	\$0.90	\$0.66	\$0.064	\$0.058
4-marine	4,318,131	\$0.84	\$0.54	\$0.067	\$0.051
5-dry	6,263,611	\$0.79	\$0.48	\$0.061	\$0.055
5-humid	32,024,248	\$0.78	\$0.55	\$0.074	\$0.066
6-dry	1,245,871	\$0.75	\$0.46	\$0.058	\$0.054
6-humid	8,192,774	\$0.71	\$0.51	\$0.064	\$0.057
7	1,027,695	\$0.69	\$0.47	\$0.063	\$0.056
8	102,206	\$0.32	\$0.19	\$0.101	\$0.093
AK/NE 7	414,451	\$0.38	\$0.23	\$0.105	\$0.094
CA 3-dry	20,562,838	\$0.86	\$0.57	\$0.120	\$0.093
HI 1-humid	906,086	\$1.68	\$1.63	\$0.151	\$0.134
NE 4-humid	14,015,840	\$0.77	\$0.69	\$0.115	\$0.105
NE 5-humid	11,426,220	\$0.88	\$0.73	\$0.104	\$0.094
NE 6-humid	1,822,106	\$0.88	\$0.68	\$0.130	\$0.108

7.2 Skylight Costs

Skylight costs were derived from and manufacturers' cost for installed skylights as well as the costs developed by the envelope committee³ for ASHRAE standard 90.1. The ASHRAE figures all were in terms of incremental costs above a single glazed skylight with a metal frame. We then fit a regression line through the data to average the costs. In general the ASHRAE costs were quite close to the average of the manufacturers we interviewed. An example of this is shown in Figure 11 and Figure 12, where the squares represent the ASHRAE cost values and the diamonds represent the manufacturer estimates of installed costs.

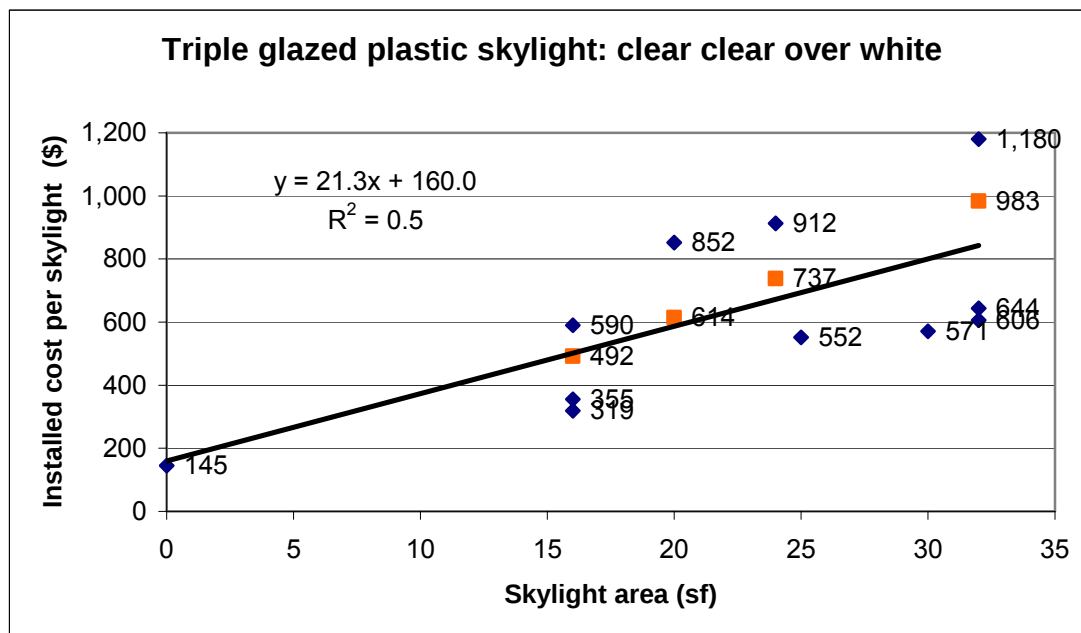


Figure 11. Regression plot of cost of triple glazed plastic dome skylight with respect to size

³ We thank Joe Deringer for his assistance in obtaining this data.

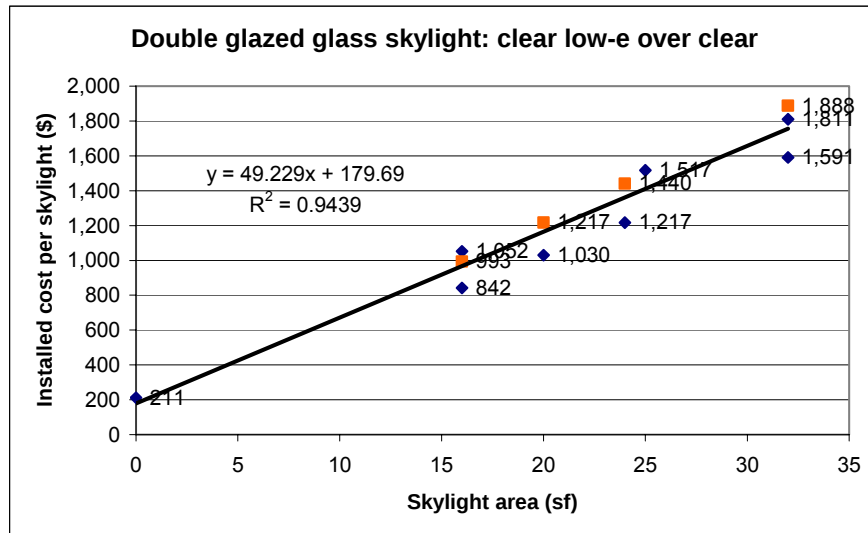


Figure 12: Regression plot of cost of double glazed glass skylight with respect to size

Based upon these regression equations, we then were able to estimate the costs of the skylighting system for each prototype building for each of the skylight to floor ratios from 1% to 10%. These results are given in the tables below.

Table 8. Installed skylight costs for warehouse prototype

GLASS		Warehouse									
Skylight Fraction Index >>		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Area per skylight >>		23.04	46.08	69.12	92.16	115.2	138.24	161.28	184.32	207.36	230.4
G Med.Wht Interlayer		\$945	\$1,705	\$2,465	\$3,225	\$3,985	\$4,744	\$5,504	\$6,264	\$7,024	\$7,784
G Clear - Prismatic		\$1,148	\$2,125	\$3,101	\$4,077	\$5,053	\$6,030	\$7,006	\$7,982	\$8,959	\$9,935
G Evergreen - Prismatic		\$1,295	\$2,415	\$3,535	\$4,655	\$5,774	\$6,894	\$8,014	\$9,133	\$10,253	\$11,373
G Clear - Air - Med.Wht		\$1,328	\$2,466	\$3,603	\$4,741	\$5,878	\$7,015	\$8,153	\$9,290	\$10,428	\$11,565
G Clear - Air - Clear - Prismatic		\$1,443	\$2,710	\$3,977	\$5,244	\$6,511	\$7,778	\$9,045	\$10,313	\$11,580	\$12,847
G Evergreen - Air - Med.Wht		\$1,572	\$2,929	\$4,285	\$5,641	\$6,997	\$8,353	\$9,709	\$11,065	\$12,421	\$13,777
G ClearL - Air - Med.Wht		\$1,378	\$2,598	\$3,818	\$5,039	\$6,259	\$7,479	\$8,700	\$9,920	\$11,140	\$12,361
G ClearL - Air - Clear - Prismatic		\$1,370	\$2,537	\$3,703	\$4,870	\$6,036	\$7,203	\$8,369	\$9,536	\$10,703	\$11,869
G EvergreenL - Air - Med.Wht		\$1,622	\$3,061	\$4,500	\$5,939	\$7,378	\$8,817	\$10,256	\$11,695	\$13,134	\$14,573
G ClearL - Air - Clear		\$1,314	\$2,448	\$3,582	\$4,717	\$5,851	\$6,985	\$8,119	\$9,254	\$10,388	\$11,522
G ClearL - Arg - Med.Wht		\$1,309	\$2,563	\$3,817	\$5,071	\$6,325	\$7,580	\$8,834	\$10,088	\$11,342	\$12,596
G ClearL - Arg - Clear - Prismatic		\$1,309	\$2,484	\$3,659	\$4,835	\$6,010	\$7,186	\$8,361	\$9,536	\$10,712	\$11,887
G EvergreenL - Arg - Med.Wht		\$1,640	\$3,100	\$4,559	\$6,019	\$7,479	\$8,938	\$10,398	\$11,858	\$13,317	\$14,777
PLASTIC		Warehouse									
Skylight Fraction Index >>		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Area per skylight >>		23.04	46.08	69.12	92.16	115.2	138.24	161.28	184.32	207.36	230.4
P Prismatic		\$590	\$1,071	\$1,553	\$2,034	\$2,515	\$2,996	\$3,478	\$3,959	\$4,440	\$4,921
P Medium white		\$530	\$907	\$1,284	\$1,661	\$2,038	\$2,415	\$2,792	\$3,169	\$3,546	\$3,923
P Clear - Med.Wht		\$579	\$1,015	\$1,452	\$1,888	\$2,325	\$2,761	\$3,198	\$3,634	\$4,071	\$4,507
P Low.Wht - Clear		\$579	\$1,015	\$1,452	\$1,888	\$2,325	\$2,761	\$3,198	\$3,634	\$4,071	\$4,507
P Clear - High.Wht		\$579	\$1,015	\$1,452	\$1,888	\$2,325	\$2,761	\$3,198	\$3,634	\$4,071	\$4,507
P Prismatic - Prismatic		\$650	\$1,186	\$1,722	\$2,258	\$2,794	\$3,330	\$3,866	\$4,402	\$4,938	\$5,474
P Clear - Clear - Med.Wht		\$652	\$1,144	\$1,635	\$2,127	\$2,619	\$3,111	\$3,603	\$4,095	\$4,586	\$5,078
P Low.Wht - Clear - Clear		\$652	\$1,144	\$1,635	\$2,127	\$2,619	\$3,111	\$3,603	\$4,095	\$4,586	\$5,078
P Clear - Clear - High.Wht		\$652	\$1,144	\$1,635	\$2,127	\$2,619	\$3,111	\$3,603	\$4,095	\$4,586	\$5,078
Triple Prismatic		\$775	\$1,439	\$2,102	\$2,766	\$3,429	\$4,093	\$4,757	\$5,420	\$6,084	\$6,748
Quadruple Clear		\$640	\$1,125	\$1,611	\$2,097	\$2,582	\$3,068	\$3,553	\$4,039	\$4,525	\$5,010

Table 9: Installed skylight costs for retail and grocery big box prototypes

GLASS		Retail and Grocery Big Box									
Skylight Fraction Index >>		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Area per skylight >>		12.96	25.92	38.88	51.84	64.8	77.76	90.72	103.68	116.64	129.6
G Med.Wht Interlayer		\$612	\$1,040	\$1,467	\$1,895	\$2,322	\$2,750	\$3,177	\$3,605	\$4,032	\$4,459
G Clear - Prismatic		\$721	\$1,270	\$1,819	\$2,369	\$2,918	\$3,467	\$4,016	\$4,565	\$5,114	\$5,664
G Evergreen - Prismatic		\$805	\$1,435	\$2,065	\$2,695	\$3,325	\$3,955	\$4,585	\$5,214	\$5,844	\$6,474
G Clear - Air - Med.Wht		\$831	\$1,470	\$2,110	\$2,750	\$3,390	\$4,030	\$4,670	\$5,309	\$5,949	\$6,589
G Clear - Air - Clear - Prismatic		\$889	\$1,601	\$2,314	\$3,027	\$3,740	\$4,452	\$5,165	\$5,878	\$6,590	\$7,303
G Evergreen - Air - Med.Wht		\$979	\$1,742	\$2,505	\$3,268	\$4,030	\$4,793	\$5,556	\$6,319	\$7,082	\$7,844
G ClearL - Air - Med.Wht		\$844	\$1,530	\$2,217	\$2,903	\$3,590	\$4,276	\$4,962	\$5,649	\$6,335	\$7,022
G ClearL - Air - Clear - Prismatic		\$860	\$1,516	\$2,172	\$2,828	\$3,484	\$4,141	\$4,797	\$5,453	\$6,109	\$6,765
G EvergreenL - Air - Med.Wht		\$992	\$1,802	\$2,611	\$3,421	\$4,230	\$5,039	\$5,849	\$6,658	\$7,468	\$8,277
G ClearL - Air - Clear		\$818	\$1,456	\$2,094	\$2,732	\$3,370	\$4,008	\$4,646	\$5,284	\$5,922	\$6,560
G ClearL - Arg - Med.Wht		\$760	\$1,466	\$2,171	\$2,876	\$3,582	\$4,287	\$4,993	\$5,698	\$6,404	\$7,109
G ClearL - Arg - Clear - Prismatic		\$794	\$1,456	\$2,117	\$2,778	\$3,439	\$4,100	\$4,761	\$5,423	\$6,084	\$6,745
G EvergreenL - Arg - Med.Wht		\$1,001	\$1,823	\$2,644	\$3,465	\$4,286	\$5,107	\$5,928	\$6,749	\$7,570	\$8,391
PLASTIC		Retail big box									
Skylight Fraction Index >>		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Area per skylight >>		12.96	25.92	38.88	51.84	64.8	77.76	90.72	103.68	116.64	129.6
P Prismatic		\$380	\$650	\$921	\$1,192	\$1,462	\$1,733	\$2,004	\$2,275	\$2,545	\$2,816
P Medium white		\$365	\$577	\$789	\$1,001	\$1,213	\$1,425	\$1,637	\$1,850	\$2,062	\$2,274
P Clear - Med.Wht		\$388	\$633	\$879	\$1,124	\$1,370	\$1,616	\$1,861	\$2,107	\$2,352	\$2,598
P Low.Wht - Clear		\$388	\$633	\$879	\$1,124	\$1,370	\$1,616	\$1,861	\$2,107	\$2,352	\$2,598
P Clear - High.Wht		\$388	\$633	\$879	\$1,124	\$1,370	\$1,616	\$1,861	\$2,107	\$2,352	\$2,598
P Prismatic - Prismatic		\$416	\$717	\$1,019	\$1,320	\$1,622	\$1,923	\$2,225	\$2,526	\$2,828	\$3,129
P Clear - Clear - Med.Wht		\$437	\$713	\$990	\$1,267	\$1,543	\$1,820	\$2,097	\$2,373	\$2,650	\$2,926
P Low.Wht - Clear - Clear		\$437	\$713	\$990	\$1,267	\$1,543	\$1,820	\$2,097	\$2,373	\$2,650	\$2,926
P Clear - Clear - High.Wht		\$437	\$713	\$990	\$1,267	\$1,543	\$1,820	\$2,097	\$2,373	\$2,650	\$2,926
Triple Prismatic		\$485	\$858	\$1,231	\$1,604	\$1,978	\$2,351	\$2,724	\$3,098	\$3,471	\$3,844
Quadruple Clear		\$427	\$700	\$974	\$1,247	\$1,520	\$1,793	\$2,066	\$2,339	\$2,613	\$2,886

Note that typical construction practices limit skylight sizes to 32 sf per skylight. So that even though the estimates are based upon 36 skylights that increase in size, the cost data here is smoothed and provides a cost break on larger skylight areas. This reflects that the costs of a skylight include both fixed costs and variable costs.

Table 10. Installed skylight costs for grocery with dropped ceiling prototype

GLASS		Grocery w/ dropped ceiling									
Skylight Fraction Index >>		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Area per skylight >>		4.41	8.82	13.23	17.64	22.05	26.46	30.87	35.28	39.69	44.1
G Med.Wht Interlayer		\$330	\$476	\$621	\$767	\$912	\$1,058	\$1,203	\$1,349	\$1,494	\$1,639
G Clear - Prismatic		\$359	\$546	\$733	\$919	\$1,106	\$1,293	\$1,480	\$1,667	\$1,854	\$2,041
G Evergreen - Prismatic		\$390	\$604	\$819	\$1,033	\$1,247	\$1,462	\$1,676	\$1,890	\$2,105	\$2,319
G Clear - Air - Med.Wht		\$409	\$626	\$844	\$1,062	\$1,279	\$1,497	\$1,715	\$1,933	\$2,150	\$2,368
G Clear - Air - Clear - Prismatic		\$418	\$661	\$903	\$1,146	\$1,389	\$1,631	\$1,874	\$2,116	\$2,359	\$2,601
G Evergreen - Air - Med.Wht		\$476	\$735	\$995	\$1,255	\$1,514	\$1,774	\$2,033	\$2,293	\$2,552	\$2,812
G ClearL - Air - Med.Wht		\$391	\$625	\$858	\$1,092	\$1,325	\$1,559	\$1,792	\$2,026	\$2,260	\$2,493
G ClearL - Air - Clear - Prismatic		\$427	\$650	\$873	\$1,097	\$1,320	\$1,543	\$1,766	\$1,990	\$2,213	\$2,436
G EvergreenL - Air - Med.Wht		\$458	\$734	\$1,009	\$1,285	\$1,560	\$1,835	\$2,111	\$2,386	\$2,662	\$2,937
G ClearL - Air - Clear		\$397	\$614	\$831	\$1,048	\$1,265	\$1,482	\$1,699	\$1,916	\$2,134	\$2,351
G ClearL - Arg - Med.Wht		\$295	\$535	\$775	\$1,015	\$1,255	\$1,495	\$1,735	\$1,975	\$2,215	\$2,455
G ClearL - Arg - Clear - Prismatic		\$358	\$583	\$808	\$1,033	\$1,258	\$1,483	\$1,708	\$1,933	\$2,158	\$2,383
G EvergreenL - Arg - Med.Wht		\$460	\$739	\$1,019	\$1,298	\$1,577	\$1,857	\$2,136	\$2,415	\$2,695	\$2,974
PLASTIC		Grocery w/ dropped ceiling									
Skylight Fraction Index >>		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Area per skylight >>		4.41	8.82	13.23	17.64	22.05	26.46	30.87	35.28	39.69	44.1
P Prismatic		\$201	\$293	\$385	\$477	\$570	\$662	\$754	\$846	\$938	\$1,030
P Medium white		\$225	\$297	\$369	\$442	\$514	\$586	\$658	\$730	\$802	\$875
P Clear - Med.Wht		\$226	\$309	\$393	\$477	\$560	\$644	\$727	\$811	\$894	\$978
P Low.Wht - Clear		\$226	\$309	\$393	\$477	\$560	\$644	\$727	\$811	\$894	\$978
P Clear - High.Wht		\$226	\$309	\$393	\$477	\$560	\$644	\$727	\$811	\$894	\$978
P Prismatic - Prismatic		\$217	\$320	\$422	\$525	\$627	\$730	\$833	\$935	\$1,038	\$1,140
P Clear - Clear - Med.Wht		\$254	\$348	\$442	\$537	\$631	\$725	\$819	\$913	\$1,007	\$1,101
P Low.Wht - Clear - Clear		\$254	\$348	\$442	\$537	\$631	\$725	\$819	\$913	\$1,007	\$1,101
P Clear - Clear - High.Wht		\$254	\$348	\$442	\$537	\$631	\$725	\$819	\$913	\$1,007	\$1,101
Triple Prismatic		\$238	\$365	\$492	\$619	\$746	\$873	\$1,000	\$1,127	\$1,255	\$1,382
Quadruple Clear		\$247	\$340	\$433	\$526	\$619	\$712	\$805	\$898	\$991	\$1,084

7.3 Lighting Control Costs

The installed costs of adding a photocontrol system to each of our prototype buildings is given in Table 11. The costing of controls for the 82,944 sf warehouse, and the big box retail and big box grocery, which are both 46,656 sf each, is based upon 4 controls zones. That is there are 4 different desired illuminance levels in different areas of these buildings. This is perhaps conservative in that there may only be really two zones in a warehouse: one zone that is for shipping and receiving that has higher light levels but also usually without stacks to absorb light, and a second zone for lighting in the stacks. The prototype for the grocery with a dropped ceiling is only 15,876 sf and thus we consider the costs for this prototype to have only two control zones.

Table 11. Cost of photocontrol systems for each prototype building

STEPPED CONTROLS

Type	Cost	
	All Bldg Types	
2 Position+OFF On-Off		\$2,849
3 Position+OFF On-50%-Off		\$4,522
3 Position+33%ON On-67%-33%		\$4,522
4 Position+OFF On-67%-33%-Off		\$5,737

DIMMING CONTROLS

Type	Cost				
	Warehouse HID	Retail Big Box HID	Retail Big Box Flo	Grocery Big Box Flo	Grocery Dropped Ceiling Flo
Dimming Continuous Dimming	\$17,637	\$29,409	\$33,493	\$33,493	\$12,109

On/off control is a single control step, two levels (100%, 50%) plus off is a two step control as is 2/3 or 1/3 switching (no off) is also a two step control, three levels (100%, 67%, 33%) plus off is a 3 level control. Potentially in a 4 zone building with three level plus off control their need to be as much as $3 \times 4 = 12$ separately controlled outputs.

Dimming controls for fluorescent systems have a dramatically different light and power relationship than those for HID systems. A fluorescent dimming system consumes approximately 20% of rated power at minimum (10%) light output. A metal halide system typically consumes in excess of 50% of power at minimum (25%) light output. Thus a fluorescent dimming system is better suited for savings energy than HID systems.

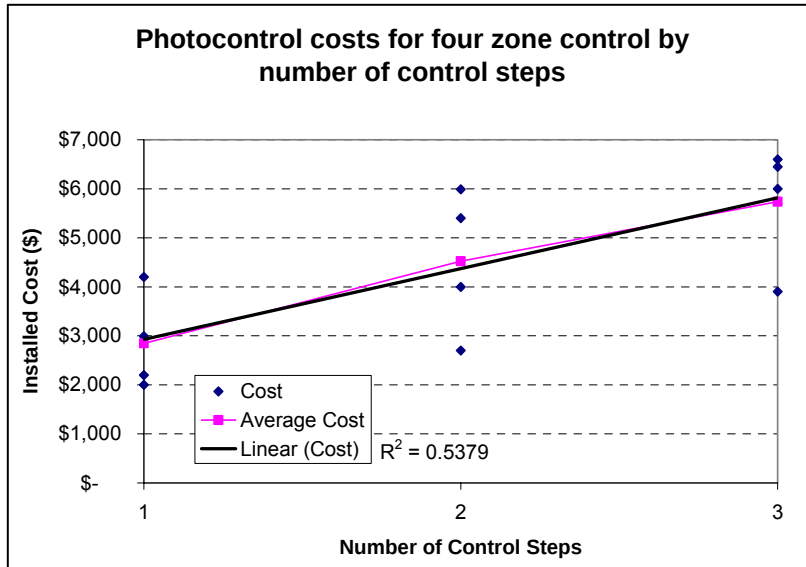


Figure 13: Plot of installed costs of a four zone switching photocontrol system by number of control steps

REFERENCES

- ASTM D1003-00 *Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics*, American Society for Testing and Materials, West Conshocken, Pennsylvania.
- ASTM E972-96(2002) *Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight*, American Society for Testing and Materials, West Conshocken, Pennsylvania.
- ASTM E1084-86(2003) *Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight*. American Society for Testing and Materials, West Conshocken, Pennsylvania.
- ASTM E1175-87(2003) *Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere*, American Society for Testing and Materials, West Conshocken, Pennsylvania.
- California Energy Commission, 2005 Building Energy Efficiency Standards (Title 24). Publication # 400-03-003-ET15.
http://www.energy.ca.gov/2005_standards/rulemaking/documents/15-day_language/2003-10-21_400-03-001-ET15F.PDF
- Klems, Joseph H. 2000. "U-Factors of Flat and Domed Skylights," *ASHRAE Transactions*, Vol 106, Pt. 2, pp. 614-621.
- Klems, Joseph H. 2002. "Solar Heat Gain through a Skylight in a Light Well," *ASHRAE Transactions*, Vol 108 Pt. 1, pp. 512-524.
- Laouadi, A.; Atif, M. R. 2001 "Prediction model of optical characteristics for domed skylights under standard and real sky conditions," *7th International IBPSA Conference* (Rio de Janeiro, Brazil, 8/13/2001), pp. 1101-1108, August 20, 2001 (NRCC-44741)
<http://irc.nrc-cnrc.gc.ca/fulltext/nrcc44741/nrcc44741.pdf>
- Linforth, E. 1958. "Efficiency of domed acrylic skylights". *Illuminating Engineering* 53(10), pp 544-546.
- McHugh, J, Lewin, I, Domigan, J, 2002. "Skylights as luminaires: PIER skylight photometric test results." *Proceedings of the IESNA Conference 2002*, 427-442. IESNA, New York
- McHugh, J., Dee, R & Saxena, M. 2004. *Visible Light Transmittance of Skylights*, PIER Report, California Energy Commission, Contract Number 400-99-013.
- McHugh, J., Pande, A., Ander, G. & Melnyk, J. 2004. "Effectiveness of Photocontrols with Skylighting," *Proceedings of the 2004 IESNA Annual Conference*, IESNA, New York.

- McHugh, J., Saxena, M., Dee, R. & Tait, D., *Solar Heat Gain Coefficient of Skylights*, PIER Report, California Energy Commission, Contract Number 400-99-013, 2004
- NFRC 200-204 *Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence*, National Fenestration Rating Council, Silver Spring, MD
- Rubin, M., von Rottkay, K., and Powles, R., 1988. "Window Optics," *Solar Energy*, **62**, 1988, pp. 149-161. <http://windows.lbl.gov/pub/OM/39911.htm>
- Winkelmann, F.C., "Daylighting Calculation in DOE-2," Lawrence Berkeley Laboratory Report, (Chapter III.2.9 of the DOE-2 ENGINEERS MANUAL), 1983, LBL-11353 (III.2.9)
- Weidner, V.R. & Hsia, J.J. 1979. "NBS reference hazemeter: its development and testing," *Applied Optics* 15 May 1979, Vol 18, No 10, pp. 1619-1626.