Skylights: Calculating Illumination Levels and Energy Impacts

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Abstract

Daylighting from skylights provides a highly valuable, if variable source of illumination, which is dependent upon the local climate, the design of the skylights, and the design of the building. When skylights are properly sized and designed, excellent lighting conditions result, and the energy savings from reducing electric light usage can greatly outweigh the energy impacts on heating and cooling of the building. In order to integrate this daylight source into lighting designs, the designer should be able to predict illumination levels throughout the year and understand the energy impacts of design choices.

SkyCalc, an Excel spreadsheet application, was developed to provide this information. Three levels of inputs allow the designer to describe a skylit building, its lighting and its operation, simply or in great detail. The program then uses local hourly weather files simulation to calculate and graph average hourly daylight illumination inside of the space for each month and whole building energy impacts. Results from many *SkyCalc* skylighting simulations are presented to illustrate how design considerations (climate, skylight glazing material, building type and operating schedule, and lighting control system) affect optimum sizing of skylights for whole building energy performance (lighting, heating and cooling energy use). For example, dimming and switching control systems were found to have very different performance based on the interaction between target illumination levels and local climate conditions.

This paper will report on both methodology imbedded in the tool and the analysis of the results.

Introduction

Skylights in commercial buildings, can greatly improve habitability and lighting quality. When correctly sized and with appropriate lighting controls, they can also save a tremendous amount of energy. Considering that nationally, approximately 60% of commercial building floor area is directly under a roof (single story buildings alone make up 41% of total commercial floor area),[1] there is a huge area that could be potentially skylit.

To be successful, however, designers must size a skylighting system correctly. An undersized skylighting system will not justify the cost of the electric lighting controls and will never attain the pleasing effect of a well daylit space. An oversized skylighting system will over-light the space, admit too much solar heat during the day and lose too much heat on cold winter nights. To create a successful skylit building that fully realizes its energy savings potential, a designer should optimize the skylighting system, taking into consideration the local climate, building geometry and operation, skylight characteristics, lighting system and controls operation. The variability of illumination available from daylight, combined with the operating schedules of each building, can make this a complex task.

A deceptively simple spreadsheet application, using simple user inputs combined with data from sophisticated building simulations (DOE-2.1E) has been developed to simplify the task. This program is available free from a website[2], and is fully documented in the accompanying *Skylighting Guidelines*. We report on the use of this program, named *SkyCalc*, to study the lighting and energy impacts of various skylighting specification choices.

History

The Lumen Method for Toplighting, published in the *IESNA Handbook*, has provided a simple way to calculate average interior daylight illuminance expected from evenly spaced skylights for any given hour, once the exterior daylight level is known[3]. However, this method provides guidance for only one point in time, and does not provide information on overall energy or cost savings.

The variation inherent in daylighting strongly suggests the use of a computer program that compiles results for hourly weather data run for the whole year. The DOE-2 building energy simulation program is one of a few computer programs that has the capability to model interior daylight illumination levels on an hourly basis thoughout the year, <u>and</u> to calculate the impacts on total building energy consumption (lighting, heating and cooling energy use). The accuracy of energy savings predictions from such a program is vastly greater than estimates derived from the lumen method, but due to the complexity of DOE-2, the program tends to be limited to a small cadre of expert users.

In 1984, researchers at Lawrence Berkeley Laboratories used DOE-2 to investigate the whole building energy savings (lighting, cooling and heating) from skylights under a range of conditions. The results were used to generate regression equations that predicted electricity usage, fuel consumption and peak electrical demand for various skylighting designs, and the optimal effective aperture size needed to minimize energy consumption[4]. From these studies, it was clear that there were substantial energy savings across the country that could be achieved with skylighting.

To improve the accessibility of these results to designers, the *AAMA Skylight Handbook*[5] was written in 1987 to convert these results into design guidelines, nomographs and a step-by-step calculation. This hand calculation method was also automated in a DOS-based spreadsheet application named AAMASKY1. Both techniques made many assumptions in order to simplify the calculations. For example, they reduced the climatic input to five representative cities and used monthly averaged weather data. While useful at the time, AAMASKY1 was made obsolete by advances in computing, leaving practitioners with only the very approximate and tedious hand calculation method.

Most current computer daylighting programs, such as SUPERLITE or Lumen-Micro, do not calculate the effects skylights have on HVAC energy consumption. Thus, they do not have the capability of optimizing the design of skylighting systems in terms of overall energy consumption or cost-savings.

The Development of *SkyCalc*

Given this context, there seemed to be a need for a simple calculation tool that would help a designer to optimize a skylighting design for both illumination level and annual energy performance. The authors developed *SkyCalc* to fill this need. In writing a new skylighting design program we identified the following desirable features:

- A very quick learning curve for the first time user
- Ability to use local, hourly climatic data
- Menus of default skylight, lighting system and building characteristics
- Easy modification of the inputs at a simple or highly detailed level
- Illumination calculation procedures that account for space geometry, surface reflectances, and the presence of shelving or partitions
- Accurate modeling of photo control response
- Accurate modeling of building operating schedules
- Accurate calculation of heating and cooling impacts of skylights

The extensive defaults contained in *SkyCalc* convert simple user inputs such as “white paint” into values the spreadsheet can use, such as “reflectance = 80%.” This

combination of simple user inputs and sophisticated defaults creates a detailed description of the building, its loads, electric lighting and skylighting systems.
SkyCalc was designed as an Excel spreadsheet application. It was reasoned that the vast majority of computer users are familiar with this software, and thus could very quickly master the operation of the program. The program is deceptively simple. One page of inputs (a Workbook Tab) describes a building and its skylighting system. A second page of graphic outputs reports on the optimum sizing for the given skylighting design. Another graph displays the interior daylight illumination achieved with the design, averaged by hour of the month. In order to generate this information, however, *SkyCalc* uses hourly interior illuminance and thermal load data from a DOE-2.1E simulation of a "reference building" run in the climate of interest using a full year of typical weather data[6]. S*kyCalc* currently contains pre-processed climate data for 15 different California cities. National weather data should be available shortly.
SkyCalc then performs arithmetic manipulations on these inputs to calculate the energy impacts for the user-defined building. It also calculates the energy impacts for a full range of skylight apertures in order to graph optimization curves, which indicate the ideal skylight sizing for the given conditions.

Daylighting Calculations

The daylighting calculations in *SkyCalc* are a hybrid of: 1) the Split Flux Method contained in the DOE-2 building energy simulation of the "reference building" and 2) the Lumen Method based adjustments to the reference building which correct for differences between the reference building and a given building design.
The DOE-2.1E program converts solar radiation climatic data into values of both hourly beam sunlight and diffuse sky light. Skylights are treated as a flat diffusing single layer glazing. Light and solar heat gain transmittance are adjusted according to incident angle[7].
The DOE-2 program generates a file of hourly daylight illumination levels for the reference building. The Split Flux method can calculate illuminance at any interior location. The reference building has been modeled so illumination is measured at a "light sensor" location that provides conservatively low illuminance values – equidistant between the four reference skylights rather than directly beneath a skylight.[8]
The Lumen Method accounts for all the losses suffered as the exterior light makes its way from the sky to the work plane inside of a building. These losses include:

- The opaque fraction of the roof
- Absorption and reflection from the skylight glazing
- Absorption and reflection from dirt or dust on the skylight glazing
- Absorption or redirection upward by the sides of the skylight well
- Absorption by room surfaces, including partitions or stacks

Mathematically this cascading set of losses can be represented as follows to calculate the interior illuminance, E_i:

$$E_i = SFR\left(E_{kh}\tau_{diff} + E_{Dh}\tau_D\right)GF\ WF\ CU$$

where,

SFR	=	skylight area to floor area ratio
E_{kh}	=	sky diffuse horizontal illuminance
τ_{diff}	=	skylight diffuse transmittance
E_{Dh}	=	sunlight direct horizontal illuminance
τ_D	=	skylight direct beam transmittance
GF	=	glazing light loss factor due to dirt build-up, between 0.7 and 0.5
WF	=	light well efficiency, fraction of light transmitted by skylight that exits the bottom of the light well, the shaft that ducts light from the underside of the skylight to the ceiling plane (Figure 2)
CU	=	skylight coefficient of utilization, the fraction of light exiting the light well that makes it to the work plane.

Simple ratios are used to relate the illuminances in a skylight design to the reference building. The two factors to be compared are the effective apertures and coefficients of utilization. The effective aperture, EA, accounts for losses due to the skylighting system, including the light well, while the coefficient of utilization, CU accounts for losses in the room itself. The adjusted interior illuminance for a building design modeled in *SkyCalc*, E_{Design} is related to the interior illuminance that DOE-2 calculates for the reference building, E_{Ref} as follows:

$$E_{Design} = E_{\mathrm{Re}\,f}\,\frac{CU_{Design}EA_{Design}}{CU_{\mathrm{Re}\,f}EA_{\mathrm{Re}\,f}}$$

where,

EA	=	SFR × Tvis × WF × GF
T_{vis}	=	visible light transmittance of skylight at normal incidence angle

SkyCalc calculates the light well efficiency as a coefficient of utilization for a cavity that has a Lambertian emitter as the top plane (the underside of the skylight), a ceiling reflectance of 99%, a wall reflectance equal to the average reflectance of surfaces in the light well and a floor reflectance of 0%. The length and width for this calculation are measured at the bottom of the light well. The height of the light well is the distance from the bottom of the light well to the top of the curb as shown in Figure 2.

As shown in Figure 3, this method of calculating well efficiency closely correlates with the well efficiency table in the IES Handbook at low well cavity ratios.[9] At high well cavity ratios, the shape of the divergence from the values in the IES handbook is similar to that published by Serres and Murdock.[10] This method allows for a direct calculation of well efficiency without interpolation of a non-linear function.

The lumen method algorithm as published in Chapter 9 of the 8th Edition of IES Lighting Handbook is used to calculate the Coefficient of Utilization from skylights and the light well efficiency. The key assumptions of this method are:

- Light emanating from the bottom of the light well or skylight is perfectly diffuse (Lambertian distribution)
- The skylights are uniformly spaced (spacing no greater than 1.5 times the mounting height)
- Each surface in the room is diffusely reflecting
- Each major surface of the room is uniformly illuminated

Thus, this method will not accurately model clear skylights, non-uniform spacing, or high partitions.

The calculation of Coefficients of Utilization for Lambertian emitters such as skylights is simplified by recognizing that the direct ratio, DG, for a Lambertian emitter is the same as the form factor between the ceiling cavity and floor cavity, $F_{CC \rightarrow FC}$. In addition, all of the flux leaving the skylight is downwards, thus $\Phi_{down} = 1$ and $\Phi_{up} = 0$

When the space of interest has shelving or partitions, the design coefficient of utilization is the product of two intermediate coefficients of utilization: 1) the upper cavity between the ceiling and the top of the partition and 2) the lower cavity from the top of the partition to the floor.

SkyCalc's lumen method adjustment to the DOE-2 pre-processed illuminances for the reference building results in daylight interior illuminances for every hour of the year. Figure 4 shows a summary plot from *SkyCalc,* the monthly average illuminance for each hour of the day. These interior daylight illuminances are also used in an hourly calculation of energy savings.

Electric Lighting Energy Use

SkyCalc calculates a lighting power density based upon a target design illuminance, a selected light source and luminaire type, and a description of the geometry and reflectances of the space. Selecting a given building type results in the selection of a default target illuminance for the space. Selection of a luminaire type determines the maintained efficacy of an efficient light source for that fixture. *SkyCalc* then calculates a coefficient of utilization for the light fixture in the defined room configuration. Given the CU and the source luminous efficacy, *SkyCalc* is able to calculate a lighting power density. Designers can override these defaults or define their own light source and fixture types. Internal consistency of the calculations is enhanced when both electric lighting and daylighting illumination levels are calculated from the same room cavity descriptions.

When a particular building type is selected in the initial inputs, a corresponding default lighting schedule is also activated. These schedules are multipliers that define what fraction of the lights are on for each hour of a typical weekday and a typical weekend. These default schedules, and all others used in *SkyCalc*, are derived from a sample of actual buildings of each type surveyed by Southern California Edison, similar to the one shown in Figure 5.

Electric Lighting Controls

SkyCalc contains three major classes of daylighting controls: dimming controls, switching controls and step ballast controls. The performance curves for each type are based on the averaged performance of currently available ballasts.

Dimming controls can continuously modulate the light output from full on to some minimum level. Dimming ballasts generally have lower efficiency at lower light output, which is approximated as a linear function. As shown in Figure 6, a 10% dimming fluorescent ballast may actually consume 20% of its rated power input while producing only 10% of its rated light output.

Switching controls switch off individual luminaires, or lamps inside of luminaires, as the daylight level increases. Figure 7 shows a performance diagram for a switching daylight control. Percentage light output is equivalent to power output. Note that deadbands between switch-on and switch-off levels are not modeled in *SkyCalc.*

Step ballasts also reduce light output, but operate only at two or three discrete levels of light output. At reduced power, efficiency is lower. The shape of the control diagram is similar to switching controls, with discrete jumps in power input relative to interior daylight level.

Electric Lighting Savings Calculation

Lighting electric power usage is determined by the interrelationship between the predicted daylight illumination levels, the lighting power density, the selected control algorithm, and the lighting schedule. The lighting energy savings, LES_i for any hour, i, is given by the relation:

LES_i = $LPD \times A \times LCS_i \times [1-DCF_i]$

where,

LPD = lighting power density, W/ft2

A = floor area of building described in *SkyCalc*

LCS_i = lighting control schedule for hour i, between 0 and 1.0

DCF_i = the daylight control fraction, a control specific function of the interior illuminance for hour i (see plots in Figure 6 and Figure 7)

An hourly calculation is necessary for a reasonable estimate of savings when modeling non-linear control functions such as switching and step ballast controls.

HVAC Model

Thermal losses due to skylights are modeled using a simple UA (conductance area product) equation. This steady state heat transfer method does not consider thermal storage of heat in the mass of the building.

In contrast, the solar heat gain model, which scales the hourly solar loads from the DOE-2 reference building by the relative area of the skylights and their solar heat gain coefficient, does reflect the thermal capacitance of the reference building. The other thermal loads of occupancy and equipment are also added in to arrive at the total zone heating or cooling load for a given hour.

At this point in the calculation, the loads for each hour and the sum of electricity consumption for electric lighting for both the base case building and the skylit building have been generated and stored. The maximum cooling load is also stored for sizing of the heating and air conditioning systems.

The HVAC systems model then evaluates the energy consumption required by the hourly building loads. This model allows the user to specify an outside air economizer that can displace some or all of the cooling load when the outside air is cool enough. This model also varies the heat pump efficiency depending upon outside temperature.

SkyCalc assumes that all of the input power to the electric lighting system ends up as heat gain in the space. Thus, depending upon the conditions for each hour, the electric lighting energy savings due to daylighting either reduces cooling requirements or increases heating requirements.

Savings are calculated by subtracting the energy consumption of the daylit building by component (lighting, cooling and heating) from the base building without skylights. Note that the total energy consumption of the building is not reported, only the savings due to skylights.

Skylight Area Optimization

After a particular skylight configuration is defined, *SkyCalc* helps the user find the optimal area of skylights for maximum energy savings and maximum cost savings. *SkyCalc* does this by plotting a graph of energy savings and cost savings for a range of skylight to floor ratios (SFR) from 0% to 12% for the given building design. The highest point on the graphs is the optimal sizing for maximum energy savings and maximum cost savings. Often these are not the same, since heating fuel is typically less expensive than the electricity used for lighting and cooling. Thus, maximum cost savings is often found with larger skylight areas than for maximum energy savings.

We have used *SkyCalc* to run multiple calculations for a generic building, with only one of these variables changing at a time. The resulting graphs give a sense of the relative importance of each design variable; they are not, however, absolute answers for any system.

We have made these comparisons using California weather, since this study was funded in California. Currently 16 climate zones in California are available. Our intent is to expand this work to include all national climates in the near future.

Total Building Energy Model

The combined heating, cooling and lighting energy model summarized over all of the hours in a year provides the basis for optimum skylight sizing. Figure 8 illustrates this relationship between these three different components. As skylight sizing is increased,

- Electric lighting savings, the primary driver of overall savings rise sharply until about 5% SFR and flatten off towards an asymptote of maximum savings;
- Heating savings are continuously negative due to reduced electric lighting heat gains and lower overall thermal resistance of the roof;
- Cooling savings are initially positive as electric lighting is reduced and then become negative as further increases in skylight area yield less lighting energy reductions than energy needed to reject solar gains.

By comparing the energy savings curves to the energy cost saving curves in Figure 8, we see that the relative cost of heating is substantially less than the cost of electricity used for cooling and lighting. Thus, the slope the heating cost curve is less than that of the cooling cost, and the resulting total cost savings curve has less of a downward slope. The net result is that the energy curve optimizes at about 3% SFR in this case, while the cost curve optimizes at about 4%.

Luminous efficacy of light sources

Key to understanding the initial drop in cooling energy as skylights are introduced at low skylight to floor ratios, is the relative luminous efficacy of various light sources. Luminous efficacy, the ratio of lumens of light to power (heat) is higher for sunlight and skylight than for any source of electric lighting. Figure 9 plots the average maintained luminous efficacy for standard light sources[11,12]. For the same amount of light, sunlight generates less heat than electric lighting; diffuse light from the sky even less.

Daylight Saturation

If daylight is more efficacious than electric lighting, why does Figure 8 show negative cooling savings above 5% while lighting savings are still growing? Daylight illuminance is highly variable and depends upon weather as well as time of day and season. By increasing the skylight to floor ratio (SFR), lighting savings are increased during times with less sunlight and cooling loads would be reduced during these periods. At other times of year, the target illuminance for the space may have already been met with daylight at a low SFR. Any additional skylight area during time with plenty of available daylight does not provide additional electric lighting savings but may add unnecessary heat to the space.

A room is said to be saturated with daylight when the illuminance levels from daylight meet or exceed the design target illuminance for that space. Daylight saturation is influenced by three primary factors:

- **Desired illuminance levels:** the amount of light needed for the visual tasks to be performed
- **Skylight effective aperture:** a measure of the amount of light that will make it through a given skylight design, based on the gross skylight-to-floor ratio (SFR), the visible transmittance of the glazing material and the light well design
- **Daylight availability:** the characteristics of available daylight outdoors, as influenced by latitude and local climate conditions

The graphs in Figure 10 were generated by *SkyCalc* for an office in San Bernardino (CA Climate Zone 10, Rialto) with a lighting power density of 1.5 W/sf (16 W/m^2), a design target illumination at 50 footcandles (538 lux), 10% dimming controls, and double glazed, white acrylic skylights. All other *SkyCalc* defaults were used throughout. The graphs illustrate how increasing the number of skylights (increasing the SFR) results in greater daylight saturation. The light shaded areas indicate the hours of the day when daylight is available (more hours in summer, less in winter) to provide at least 10% of the target illuminance in the space. The white areas indicate the hours of daylight saturation (more than 50 fc of daylight) on an average day in each month.

In the top graph, at a SFR of two percent, the average monthly conditions show that the target illumination level of 50 footcandles (538 lux) is never met. In the bottom graph, the office achieves full daylight saturation for three to eight hours a day, for every month of the year with an SFR of 6%. *SkyCalc* tells us that 50 footcandles (538 lux) or more would be available for 2,159 hours per year, about one half of the possible daylight hours. Average illumination levels rise up to 129 footcandles (1,388 lux) in the middle of summer, over two and one half times the target illumination level.

Thus, as effective aperture increases, the hours of daylight saturation increase, but at an ever diminishing rate, approaching saturation for 100% of the maximum daylight hours available.

Savings by Glazing Type

The selection of the glazing assembly for a skylighting system can have a profound effect on its energy performance. There are three interrelated variables that need to be addressed: visible transmittance (T_{vis}), solar heat gain coefficient (SHGC), and unit U-value.

We have combined the first two variables into a single value: skylight efficacy (SE). A high SE represents a glazing assembly with relatively high light transmission and comparatively low heat gain. This could be achieved for example with a glazing material that has a T_{vis} equal to or higher than its SHGC. A low SE represents a glazing assembly that allows more solar heat gain in and relatively less light. This could be achieved with glazing materials that absorb much of the light and/or a deep light well that also acts to absorb much of the light. The unit U−value is dependent primarily on the number of insulating layers in the glazing assembly, and secondarily on the insulating properties of the skylight frame. To model these three variables we used the following assumptions:

- **Low SE** (single glazed, SE=0.5; double glazed, SE=0.4) with a four foot by four foot (nominal 1,200 by 1,200 mm) white acrylic skylight and a six foot (1.8 m) deep light well.
- **High SE** (single glazed, SE=1.0; double glazed, SE=0.8) with a four foot by four foot (nominal 1,200 by 1,200 mm) clear , but diffusing, acrylic skylight, and a one foot deep light well.
- **Very high SE** (SE=1.5) with triple-glazed low-e green glass with a one foot (0.3 m) deep light well.

In Figure 11 we see how differences in transmission, solar heat gain coefficient, and insulation levels effect energy performance of this office building in San Bernardino. In this relatively mild climate, moving from single to double glazed skylights improves the energy savings and increases the optimum skylight aperture, but relative energy cost savings are minimal between the two. Triple glazing improves both performance and savings, but savings only increase about 10% above the high SE single glazed alternative. Since double and triple glazing inevitably cost more than single glazing, a cost/benefit analysis would certainly suggest that in this climate single glazing is sufficient.

It is the high SE skylights that are clearly the best performing systems in this climate. Such a glazing material increases energy cost savings by 38% over the low SE option whether for a single or double glazed assembly. It improves lighting savings while reducing cooling losses. It is clear that in this sunny, warm climate, a single glazed high SE skylight will produce significantly more savings than a double glazed low SE product.

Savings by Control Type

The comparison of savings due to variations in control types is also instructive. Figure 12 looks at five control types: 5% and 20% dimming, on/off and 2 level switching plus off, and a hi/lo ballast. All systems were compared for a fluorescent lighting system at 50 footcandles (538 lux) and 1.5 W/sf (16 W/m^2).

The on/off system and the two level plus off system have the interesting effect of starting with negative savings at the lowest skylight apertures, because in this sample building the lighting levels rarely get high enough to turn off the lights. Thus, there are insufficient lighting savings to counterbalance the resulting heating and cooling losses. However, at the larger apertures, these two systems outperform the others, and see some of the largest potential energy savings. This is because, with these switching systems the electric lights are turned completely off when there is sufficient daylight; while with dimming and hi/lo systems, some percentage of the electric lighting power is always left on.

It should be pointed out that on/off switching systems also tend to be simpler and less expensive than dimming systems. Thus, the cost effectiveness of a switching system in this climate is probably also significantly higher than the dimming or hi/lo systems.

The results could be very different in another climate, with lower daylight illuminance levels, or in another building, with a higher design target illumination. In either of those cases full daylight saturation would be achieved less often, and dimming systems may perform significantly better than the simpler switching systems.

Switching systems also perform the best in daylight climates that are very consistent, with either fully sunny days or fully cloudy days, so that there are fewer occasions for switching between levels. Climates with frequent days of highly variable clouds will see better energy savings with dimming systems.

Conclusion

Skylighting is attractive both as a method to provide daylight illumination into buildings and as a way to save energy. Due to the inherent variability of daylight, there is enormous variation in the performance of skylighting system. However with *SkyCalc*, a designer now has a tool with which to learn a great deal more about the energy effects of skylighting system specification choices.

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Endnotes

[1] Calculated from Table BC-9 Building Size, Floorspace, 1995 in *A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption and Energy Expenditures,* DOE/EIA-0625(95).

[2] Both *SkyCalc* and *The Skylighting Guidelines* can be downloaded free from the website: <http://www.energydesignresources.com>.

[3] Chapter 8 in Rea, M. (ed.), 1993, *Lighting Handbook 8th Edition*, IESNA, New York.

[4] Arasteh,D. et al. 1985, "Energy Performance and Savings Potential with Skylights," *ASHRAE Transactions*, Vol. 91, Part 1, Atlanta.

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[6] Heschong, L. et al., 1998, "The *SkyCalc* User's Guide," *Skylighting Guidelines* , <http://www.energydesignresources.com>. See p. 6-22 for description of the reference building.

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[8] Arasteh, D., Johnson, R. and Selkowitz, S., 1984, *The Effects of Skylight Parameters on Daylighting Energy Savings*. Draft Lawrence Berkeley Laboratory Report, LBL-17456.

[9] Figure 8-12 "Efficiency factors for various depths of light well," in Rea, M. (ed.), 1993, *Lighting Handbook 8th Edition*, IESNA, New York.

[10] Serres, A., & Murdoch, J., Winter 1990, Figure 5 "On the Efficiency of Skylight Wells," *Journal of the Illuminating Engineering Society*, pp. 73-86.

[11] Electric lighting maintained lamp/ballast luminous efficacies in Appendix A, 1997, *Lighting Efficiency Technology Report Vol. II: Scenarios Report*, Heschong Mahone Group for the California Energy Commission, CEC Contract #400-95-012.

[12] Direct beam efficacy is for a 60° solar altitude. See Littlefair, P.J., 1985, "The luminous efficacy of daylight: a review," *Lighting Research and Technology*, Vol. 17, No. 4, pp. 162-182.

Discussions

This paper provides an excellent introduction and initial documentation of a very useful skylight optimization and screening tool, SkyCalc. The authors have done a wonderful job of presenting the calculation process and useful analyses that can be used with the SkyCalc tool. As presented by the authors, SkyCalc uses a very defensible method of calculating estimates of energy savings due to both the lighting reductions and the impacts on the building envelope. Having had the chance to work with the SkyCalc tool, this reviewer has found it to be quite robust, allowing the user to quickly analyze and screen any number of skylighting options during initial building conceptual design, at varying levels of complexity, and establish a skylight design/concept which can be modeled in greater detail using more detailed energy modeling tools.

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Authors note: numbers were added in square brackets [#] to the following comments to indicate the order of our responses.

The *SkyCalc* tool provides a simple, yet very useful simulation and graphical analysis package to designers, enabling one to quickly understand critical skylight design parameters that affect energy and cost savings. The tool is sophisticated: it uses the DOE-2.1E building energy simulation program as its illuminance, heat gain, and energy calculation engine with additional refinements to account for light well and furniture light losses. Yet, the input description requires little expertise or investment in time. One need only specify information that is readily accessible to the architect or facility manager. The performance data output is clear and helpful: the program lays out graphically how choices of skylight area, glass type, or control type can be optimized for a specific building design. The authors should be well commended for addressing a critical need in the daylighting industry that has immense potential in the commercial sector: how to design skylights with electric lighting controls to achieve optimum energy-efficiency and operating cost savings. The assumptions behind the tool, however, were not well documented. The authors use a “hybrid” of the DOE-2.1E split-flux method and the IES Lumen Method, however after many hours studying the text, I was unable to determine how the methods were applied [1]. One critical aspect of their method was the use of a reference building description, then application of a multiplier to translate the resultant illuminance data to a design-specific case. The multiplier includes “effective aperture”, which is defined by skylight area and visible transmittance of the glazing. If the design-specific case uses a different skylight geometry (hence area), this multiplier will not accurately predict interior daylight illuminance levels. For example, if a 2x2 ft skylight was defined as the base case and a 8x8 ft skylight as the design-specific case, the direct daylight illuminance “received” at the reference point would be significantly different [2]. In the same manner, if the baseline glazing is clear glass, a design-specific triple-pane, low-e glazing would have significantly different angle-dependent solar-optical properties [3]. It would seem improbable that the authors would actually apply such a multiplier as they have described in their text in such a way (perhaps it is only the well factor and dirt depreciation factor that changes?), if the DOE-2.1E program is embedded in *SkyCalc*. Clarification is needed.

The thermal calculations were also not well documented and should be clarified. Were the algorithms in DOE-2 used for the prediction of hourly skylight and lighting heat gains or were other algorithms or simplifying assumptions introduced; i.e., were conductive heat gains (UAΔT) calculated within DOE-2 (with its inherent absorbed inward-flowing fractions of solar radiation and wind speed-dependent air-film coefficients) or separately by *SkyCalc* [4]? What type of HVAC system was used to handle the load and were the systems tailored to building type? The HVAC design is known to have a significant effect on predicted energy use [5].

Limitations of the calculation tool should be explained (or embedded as cautions in the tool), some of which may be attributed to the limitations of DOE-2. For example, (a) horizontal, flat, translucent skylights only, no transparent or domed skylights are modeled; (b) illuminance and thermal loads from skylights with deep light wells cannot be modeled accurately due to DOE-2 limitations (section on “savings by glazing type” models a 3x3 ft skylight with a 6 ft deep light well, which I hope is a typographical error); (c) no reference point locations where the interreflected contribution to the total daylight illuminance is significant (e.g., a 2x2 ft skylight with a reference point 30 ft away cannot be accurately modeled by DOE-2); (d) fixed splayed light wells (well angle=90°?) and rectangular (or square?) skylight geometry (assumptions not given; Figure 2 shows a well geometry that Serres and Murdoch did not model); (e) hour-by-hour illuminance data not used to determine energy savings; and (f) open plan interior with a maximum defined partition height assumed. [6]

The authors are known for their comprehensive approach to daylighting design. Would they care to comment on how their tool could be extended to address qualitative criteria such as glare and uniform illuminance distributions [7]?

Eleanor S. Lee

Lawrence Berkeley National Laboratory

Authors’ response

To Dr. Neall Digert

Thank you for your review of our paper and software. As you have pointed out the analyses take little time to create or to run. With *SkyCalc* one can quickly evaluate the feasibility of a given design before investing the time in more complex models.

To Eleanor S. Lee

Thank you for comments and questions to “Skylighting: Calculating Illumination Levels and Energy Impacts” I will respond to each question in the order they were delivered. To simplify the reader’s task, the responses below are numbered to reference the above questions that were numbered with square brackets.

(1) Hourly DOE-2 outputs of interior illuminance, solar heat gain, and other zone loads for “the reference building” have been preprocessed for 15 California cities. These DOE-2 outputs are modified by the *SkyCalc* program to account for how the

actual building design deviates from the reference building. The DOE-2 reference building illuminances using the split flux method are adjusted in *SkyCalc* (using the Lumen Method) to represent the actual building dimensions and reflectances.
(2)Though we stated that the reference building uses flat diffusing skylights, we did not explicitly state that this program is only intended for modeling diffusing skylights for uniform illumination of the spaces below. It is not intended for designing systems that try to deliver direct beam sunlight into the occupied space or for systems that are trying highlight a small fraction of the space below. It should also be emphasized that tool is explicitly for commercial buildings not residential buildings.
3) As mentioned earlier, the glazing in the reference building is defined as diffusing. The DOE-2 simulation program models the angle-dependant solar optical properties for single pane glass and then diffuses the resulting light. The calculations within *SkyCalc* adjust the transmitted light by the ratios of the normal transmittances of the reference glazing and the glazing specified. As Ms. Lee has pointed out, the angular transmissivity of glazing assemblies can vary depending upon type of glazing and number of glazings. The Window 4.0 program does do these types of calculations but only for non-diffusing planar glazings. For commercial skylights we are typically concerned with diffusing curved glazings that are not even necessarily parallel. We are planning to release next year *SkyCalc*2 which will improve the angular transmittance calculations by taking into account the shape of skylights. Currently, the model is conservative; the energy savings from curved skylights are greater than the flat skylight model represents.
Ultimately what we would like to see is an industry testing standard that evaluates angular transmittance of light and solar heat gain in addition to measurements of light diffusion and thermal transmittance (U-factor). To make testing requirements financially viable for skylight manufacturers we need tools like Window 4.0 and FRAME that can be calibrated against test results for a given model to certify the results for an entire line of similar skylights.
4) The DOE-2 outputs used by *SkyCalc* are:
foot-candles from light-ref-pt-1 (Loads - Space 49), variable name RDAYIL(1)
dry-bulb temperature (Loads Global 4), variable name DBT
Total zone load sensible (Loads - Space 42), variable name QZS
Solar load (Loads - Space 33), variable name QSOL
Increases in skylight area increase daylight illuminance, increase solar heat gains and increase thermal transmission due to conduction. Increased solar gains are calculated by ratios of the product of the skylight area and the solar heat gain coefficent in the proposed design to that of the reference building. The solar heat gain for a given hour, Solar Gain_h, is:

$$Solar\ Gain_h = QSOL_h \frac{SkyArea_{Design} SHGC_{Design}}{SkyArea_{\mathrm{Re}\,f} SHGC_{\mathrm{Re}\,f}}$$

where $QSOL_h$ is the DOE-2 output of the hourly solar gain for the reference building.
The adjustments in thermal gains due to skylight conduction use a simple conductance area product approach and are not correlated with wind speed. The

conductances used in the analysis are based upon the table of skylight conductances in the fenestration chapter of the 1997 ASHRAE Fundamental Handbook. These conductances are based upon winter design conditions (higher wind speeds) and thus estimates of energy savings using *SkyCalc* will be slightly conservative.
5) The system modeled is an air-cooled constant volume system similar to a typical roof top system. If the user chooses, the efficiency of the system can be changed. This HVAC system is defaulted to have an air side economizer. The user has the option to turn the economizer off. The efficiency of the system is considered constant regardless of outside air temperature or part load. The efficiency of the heat pump option does vary with load. We are not concerned here with modeling the actual energy consumption of the HVAC system, just the change in HVAC consumption resulting from skylights. A lot of the variations in energy consumption with HVAC system type drop out when just the change in energy consumption is considered.
This tool is intended to be a simple and easy to use. Creating an elaborate HVAC model would add more inputs than is necessary to this simple tool. The beauty of SkyCalc is that one can open the familiar format of an Excel spreadsheet, take about 5-10 minutes to enter a basic description of the building, the lighting system, and skylights and in one minute have a result that indicates the optimal sizing of skylights to a reasonable degree of accuracy. The level of accuracy of the HVAC model is kept in line with the level of accuracy of the inputs.
6) Many of the limitations or caveats listed in this section of the comments are described in the text of the paper and indeed warnings are displayed in the spreadsheet when high partitions are modeled. However, it should be noted that limitation (e) is incorrect, the energy savings calculations are based upon an hour by hour analysis of illuminances, lighting control functions and resulting HVAC loads.
7) SkyCalc was developed as a companion piece to the *Skylighting Guidelines,* a guide for effective skylighting design, specification and application. Outside of the Skylight Spacing Calculator which advises not to space skylights further apart than 1.5 times the ceiling height, *SkyCalc* does not give any qualitative advice. The *Skylighting Guidelines* however, does provide guidance on lighting quality issues.

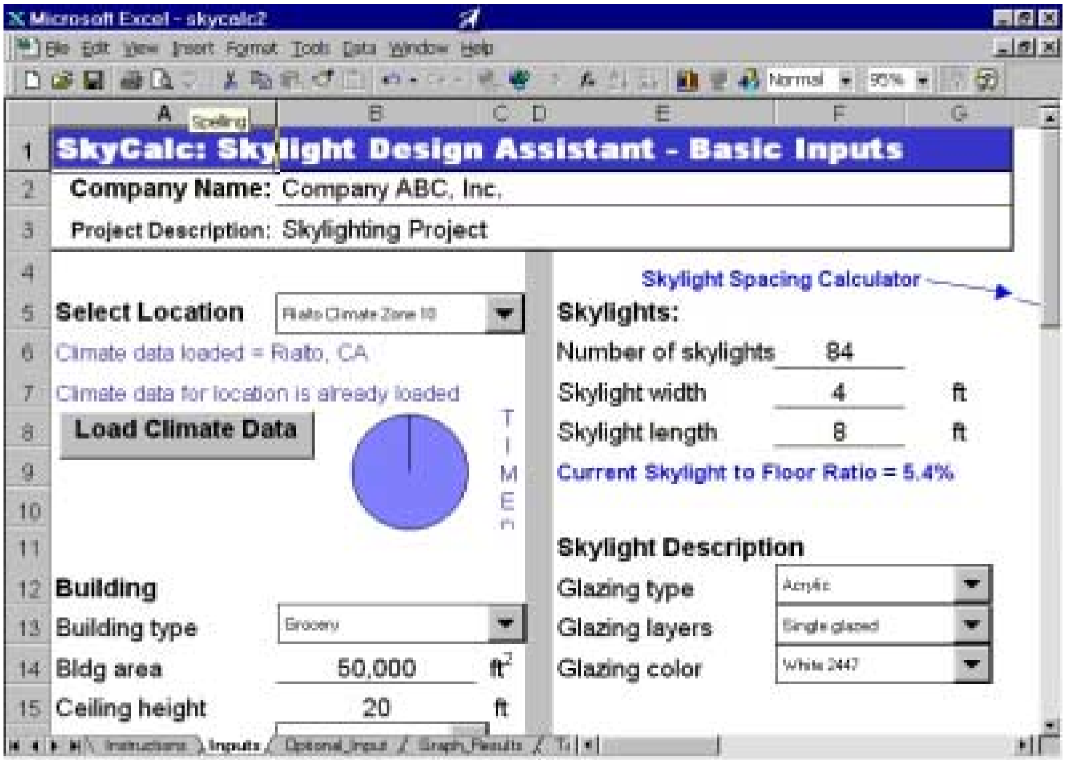


Figure 1: SkyCalc *Basic Inputs*

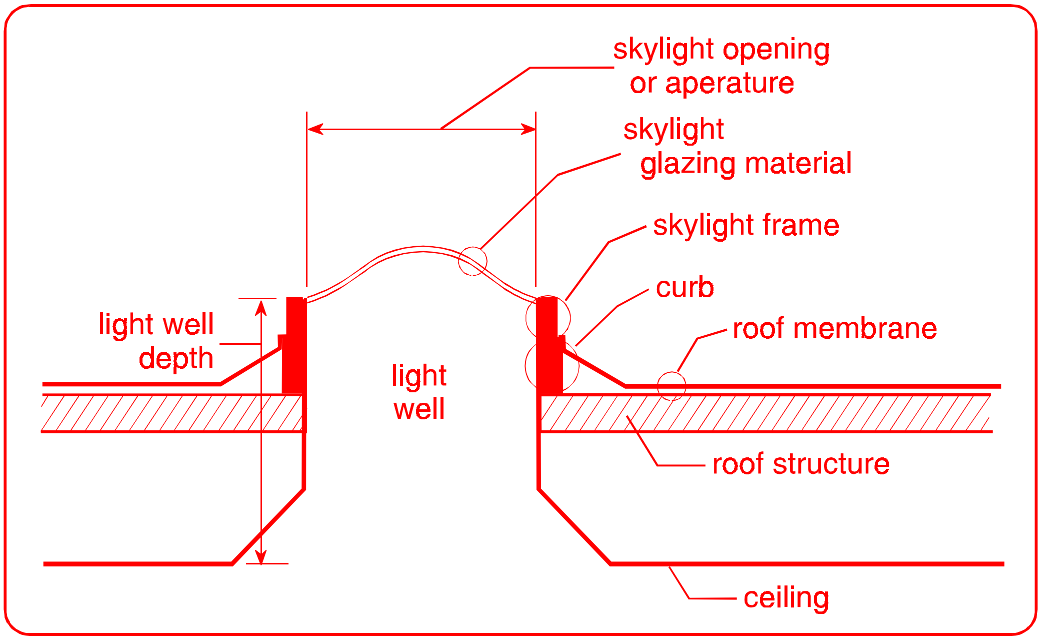


Figure 2: Components of a Typical Skylight

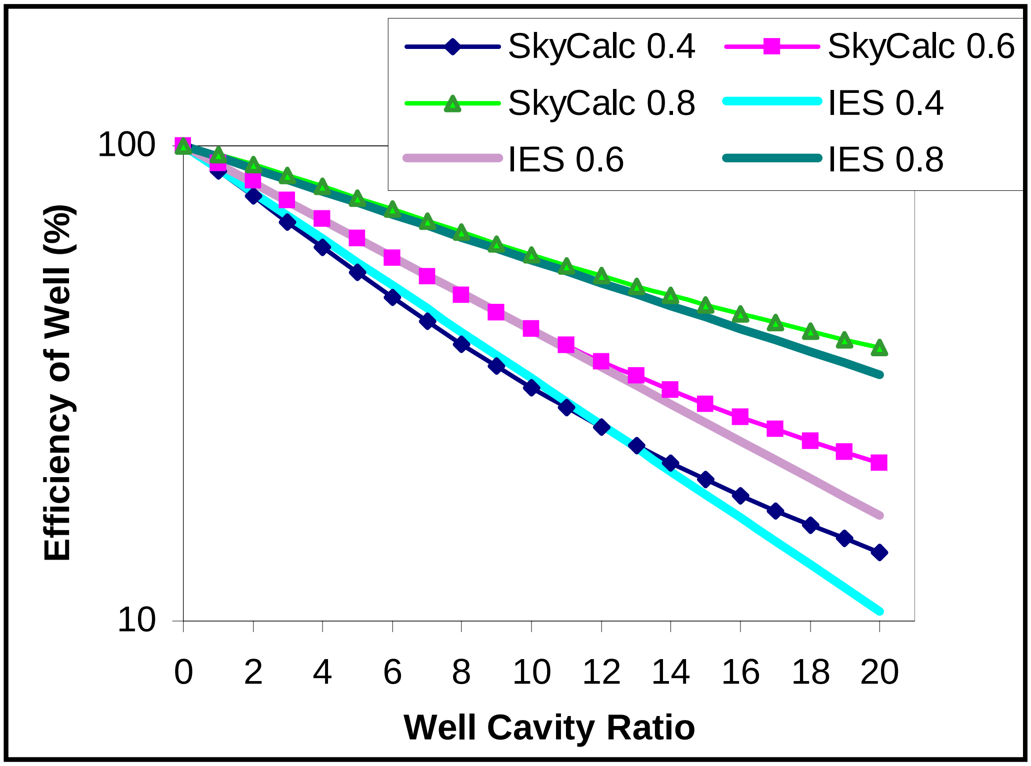
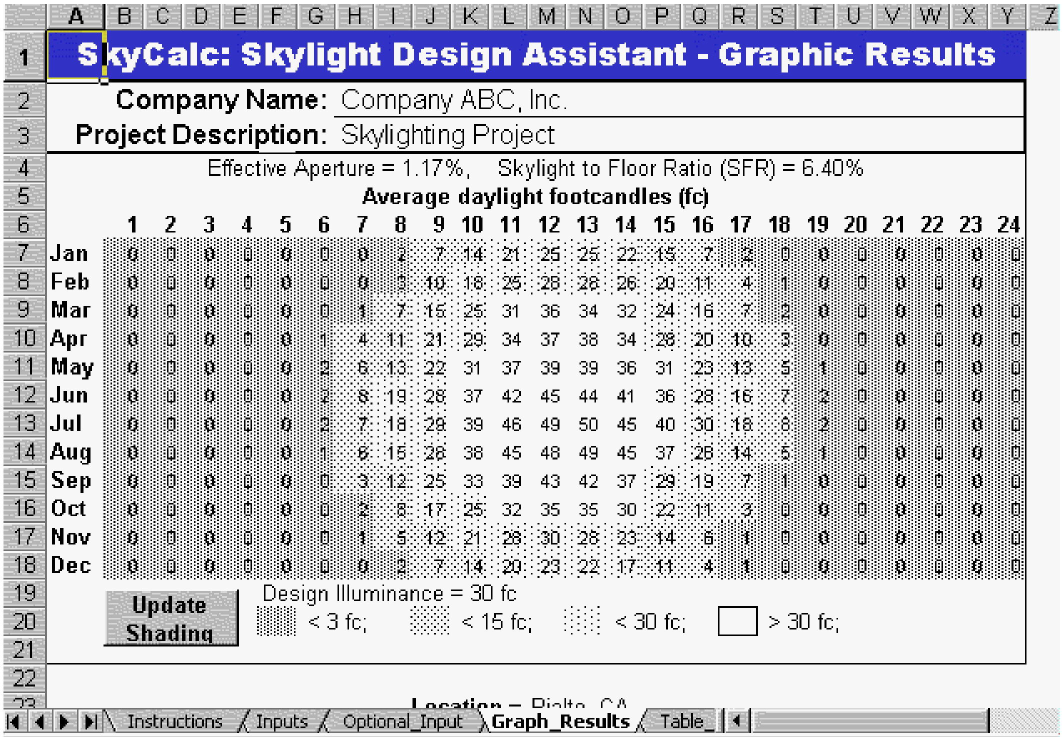


Figure 3: Well Efficiency Factors for Various Well Reflectances in SkyCalc *and the IES Handbook*



SkyCalc: Skylight Design Assistant - Graphic Results

Company Name: Company ABC, Inc.

Project Description: Skylighting Project

Effective Aperture = 1.17%, Skylight to Floor Ratio (SFR) = 6.40%

Average daylight footcandles (fc)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	2	7	14	21	25	25	22	15	7	2	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	3	10	18	25	28	28	26	20	11	4	1	0	0	0	0	0	0
Mar	0	0	0	0	0	0	1	7	15	25	31	36	34	32	24	16	7	2	0	0	0	0	0	0
Apr	0	0	0	0	0	1	4	11	21	29	34	37	38	34	28	20	10	3	0	0	0	0	0	0
May	0	0	0	0	0	2	6	13	22	31	37	39	39	36	31	23	13	5	1	0	0	0	0	0
Jun	0	0	0	0	0	2	8	19	28	37	42	45	44	41	36	28	16	7	2	0	0	0	0	0
Jul	0	0	0	0	0	2	7	18	29	39	46	49	50	45	40	30	18	8	2	0	0	0	0	0
Aug	0	0	0	0	0	1	6	15	28	38	45	48	49	45	37	28	14	5	1	0	0	0	0	0
Sep	0	0	0	0	0	0	3	12	25	33	39	43	42	37	29	19	7	1	0	0	0	0	0	0
Oct	0	0	0	0	0	0	2	8	17	25	32	35	35	30	22	11	3	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	1	5	12	21	28	30	28	23	14	6	1	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	2	7	14	20	23	22	17	11	4	1	0	0	0	0	0	0	0

Update Shading

Design Illuminance = 30 fc

< 3 fc; < 15 fc; < 30 fc; > 30 fc;

Location = Rialto, CA

Instructions / Inputs / Optional_Input / Graph_Results / Table_

Figure 4: Plot of Average Illuminances

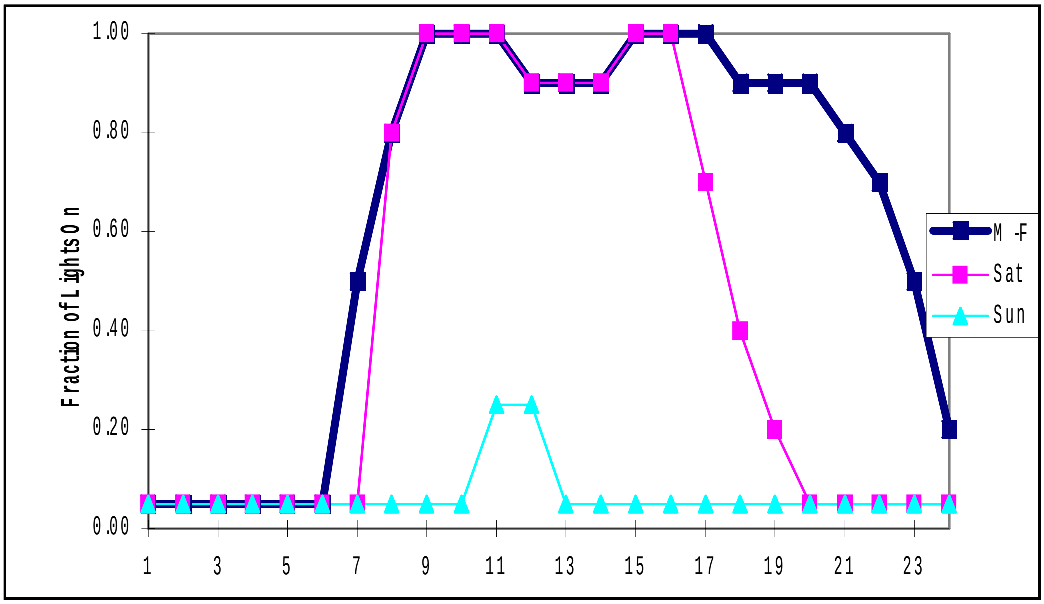


Figure 5: Lighting Control Schedule for University Classrooms

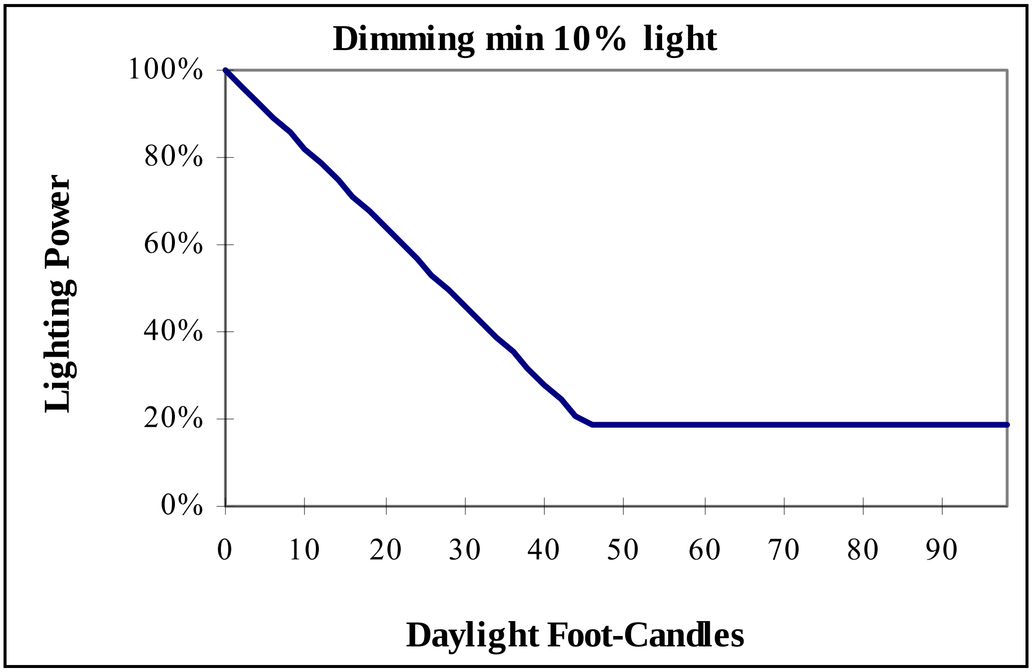


Figure 6: SkyCalc *Plot of Dimming Control Performance*

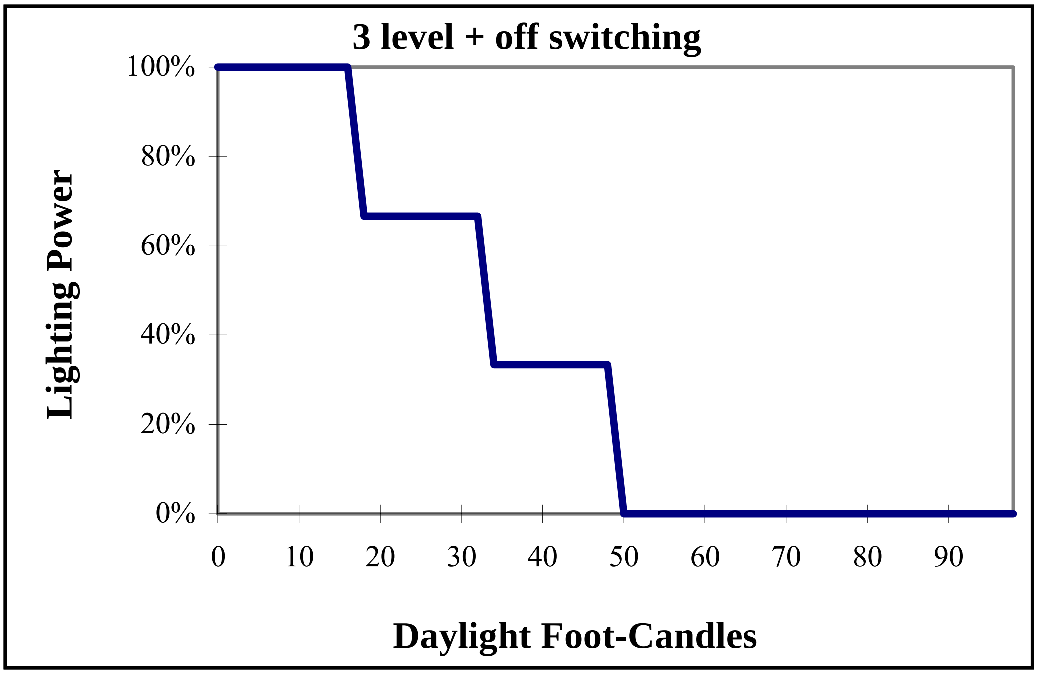
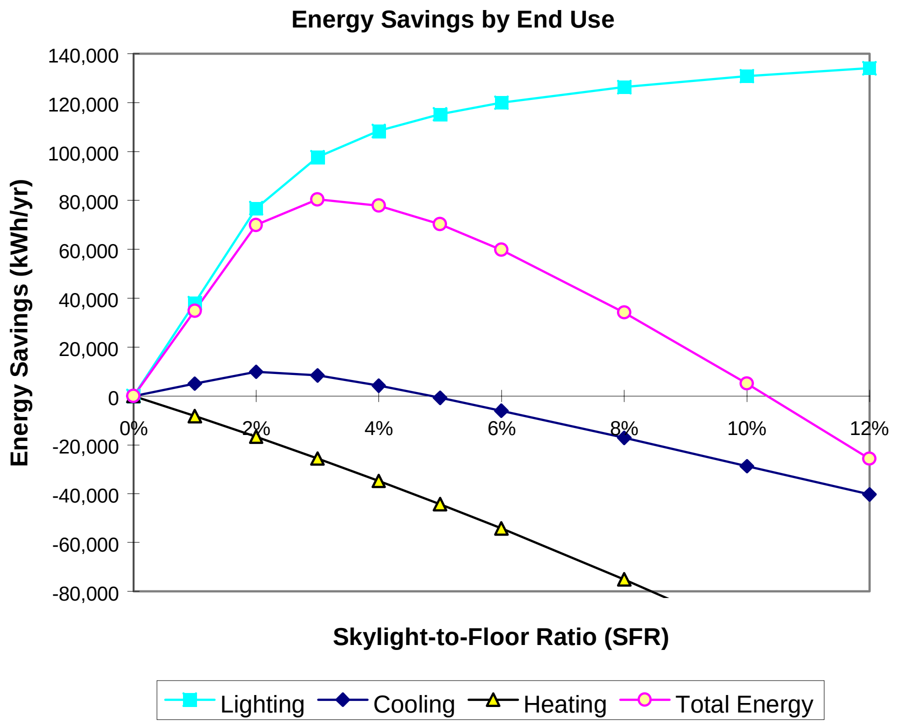


Figure 7: SkyCalc *Plot of Three Level Daylight Switching Performance*



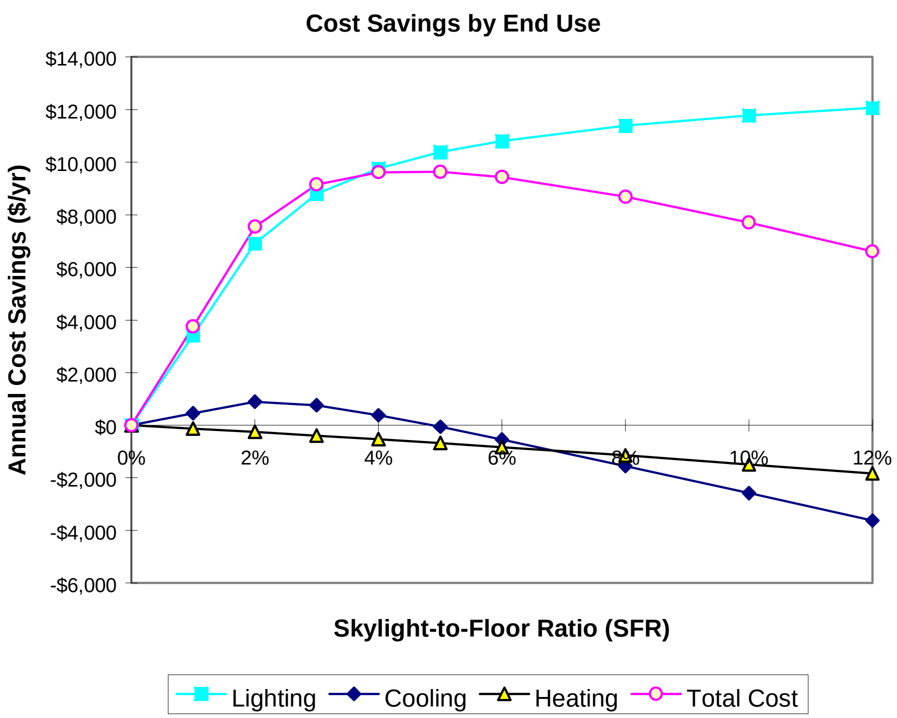


Figure 8: Annual Energy and Cost Savings, by End Use - San Bernardino Office

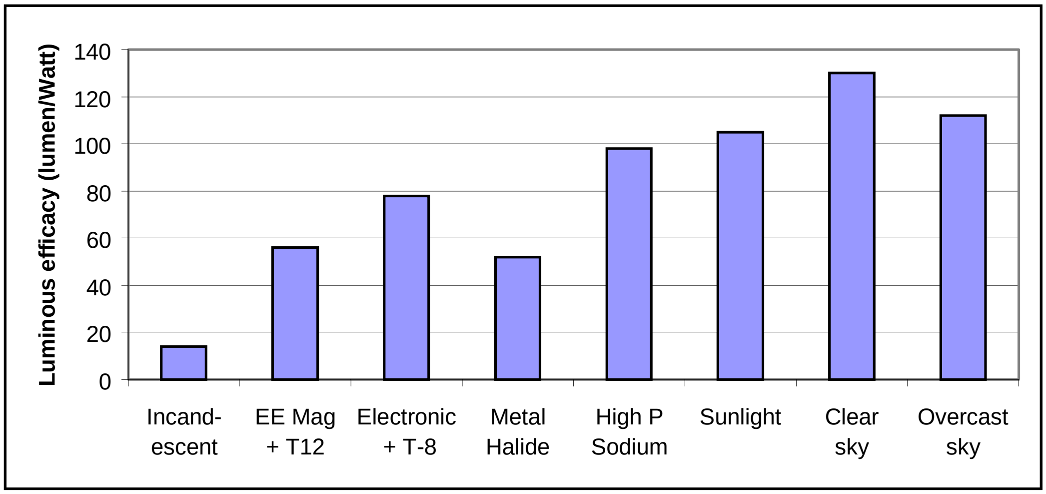


Figure 9: Average Luminous Efficacy of Light Sources

Effective Aperture = 0.62%, Skylight to Floor Ratio (SFR) = 1.98%

Average daylight footcandles (fc)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Jan	0	0	0	0	0	0	0	1	6	12	18	21	22	19	13	6	2	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	3	8	16	21	24	24	22	17	10	3	1	0	0	0	0	0	0
Mar	0	0	0	0	0	0	1	6	13	21	26	31	30	27	21	14	6	1	0	0	0	0	0	0
Apr	0	0	0	0	0	1	3	10	18	25	29	32	33	29	24	17	9	3	0	0	0	0	0	0
May	0	0	0	0	0	1	5	11	19	26	32	34	33	31	27	20	11	4	1	0	0	0	0	0
Jun	0	0	0	0	0	2	7	16	24	32	36	38	38	35	31	24	14	6	1	0	0	0	0	0
Jul	0	0	0	0	0	2	6	15	25	34	40	42	42	39	34	25	15	6	2	0	0	0	0	0
Aug	0	0	0	0	0	1	5	13	24	32	39	41	42	39	32	23	12	4	1	0	0	0	0	0
Sep	0	0	0	0	0	0	3	10	21	28	33	36	36	32	25	16	6	1	0	0	0	0	0	0
Oct	0	0	0	0	0	0	2	7	15	21	27	30	30	26	18	9	3	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	1	4	11	18	24	26	24	19	12	5	1	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	2	6	12	17	20	19	14	9	4	1	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 5 fc; < 25 fc; < 50 fc; > 50 fc;

Effective Aperture = 1.26%, Skylight to Floor Ratio (SFR) = 4.03%

Average daylight footcandles (fc)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Jan	0	0	0	0	0	0	0	3	12	25	37	44	44	38	26	12	3	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	1	5	17	32	43	48	49	44	35	20	7	1	0	0	0	0	0	0
Mar	0	0	0	0	0	0	3	11	27	43	54	63	60	55	42	28	12	3	0	0	0	0	0	0
Apr	0	0	0	0	0	1	7	19	36	50	60	65	67	60	49	35	18	6	0	0	0	0	0	0
May	0	0	0	0	0	3	11	23	38	53	65	69	68	63	54	41	22	9	2	0	0	0	0	0
Jun	0	0	0	0	0	4	15	32	49	64	73	77	76	71	63	48	28	11	3	0	0	0	0	0
Jul	0	0	0	0	0	3	12	31	51	69	81	86	86	78	69	51	31	13	3	0	0	0	0	0
Aug	0	0	0	0	0	2	10	27	48	65	79	84	85	78	65	46	25	9	1	0	0	0	0	0
Sep	0	0	0	0	0	0	5	21	43	57	68	74	74	65	50	32	12	2	0	0	0	0	0	0
Oct	0	0	0	0	0	0	3	13	30	43	55	61	60	53	37	19	5	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	1	8	22	37	49	52	49	40	24	10	2	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	4	13	24	35	41	39	29	19	8	2	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 5 fc; < 25 fc; < 50 fc; > 50 fc;

Effective Aperture = 1.90%, Skylight to Floor Ratio (SFR) = 6.05%

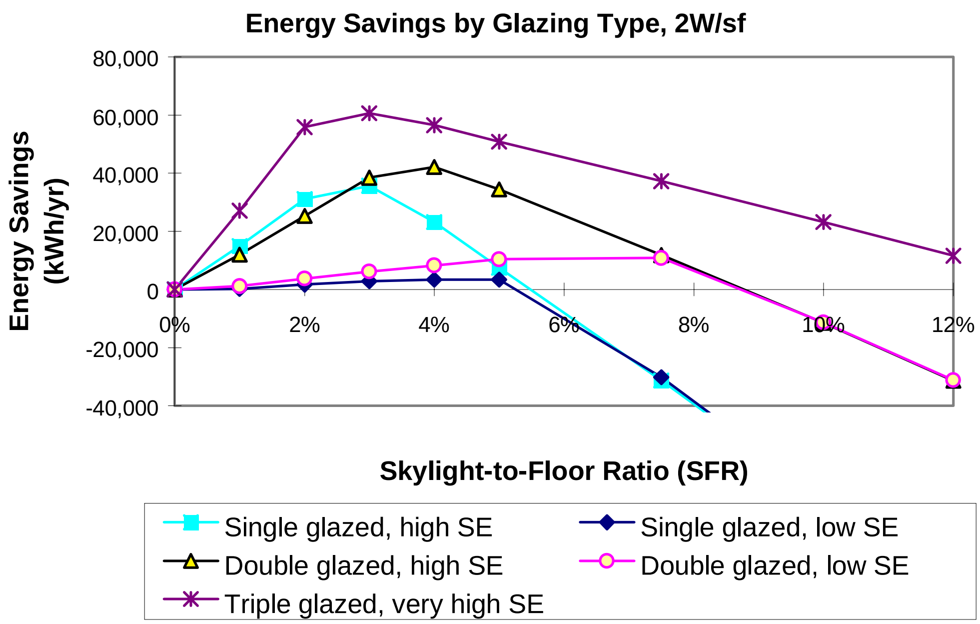
Average daylight footcandles (fc)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Jan	0	0	0	0	0	0	0	5	18	38	56	65	66	57	39	18	5	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	1	8	25	47	65	72	73	67	53	30	10	2	0	0	0	0	0	0
Mar	0	0	0	0	0	0	4	17	40	65	81	95	90	83	63	43	18	4	0	0	0	0	0	0
Apr	0	0	0	0	0	2	10	29	54	75	90	97	100	90	73	52	26	9	1	0	0	0	0	0
May	0	0	0	0	0	4	16	34	57	80	97	103	101	95	81	61	34	13	3	0	0	0	0	0
Jun	0	0	0	0	0	6	22	48	74	96	110	116	114	106	94	72	42	17	4	0	0	0	0	0
Jul	0	0	0	0	0	5	18	46	77	103	121	129	129	118	104	77	47	20	5	0	0	0	0	0
Aug	0	0	0	0	0	3	15	40	72	98	119	126	127	117	97	69	37	13	2	0	0	0	0	0
Sep	0	0	0	0	0	1	8	31	64	86	101	111	111	98	76	48	18	3	0	0	0	0	0	0
Oct	0	0	0	0	0	0	5	20	45	65	83	92	91	79	56	28	8	1	0	0	0	0	0	0
Nov	0	0	0	0	0	0	2	12	33	56	73	78	73	59	36	15	3	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	6	19	36	52	61	58	44	28	12	2	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 5 fc; < 25 fc; < 50 fc; > 50 fc;

Figure 10: Daylight Saturation in Office in San Bernadino, for Three SFR Levels



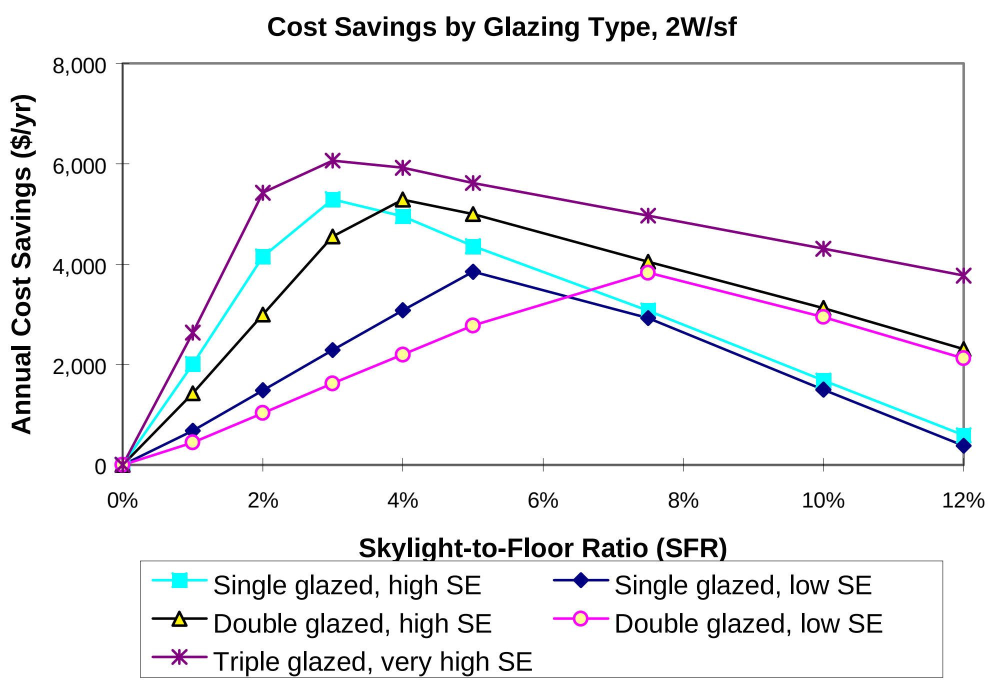
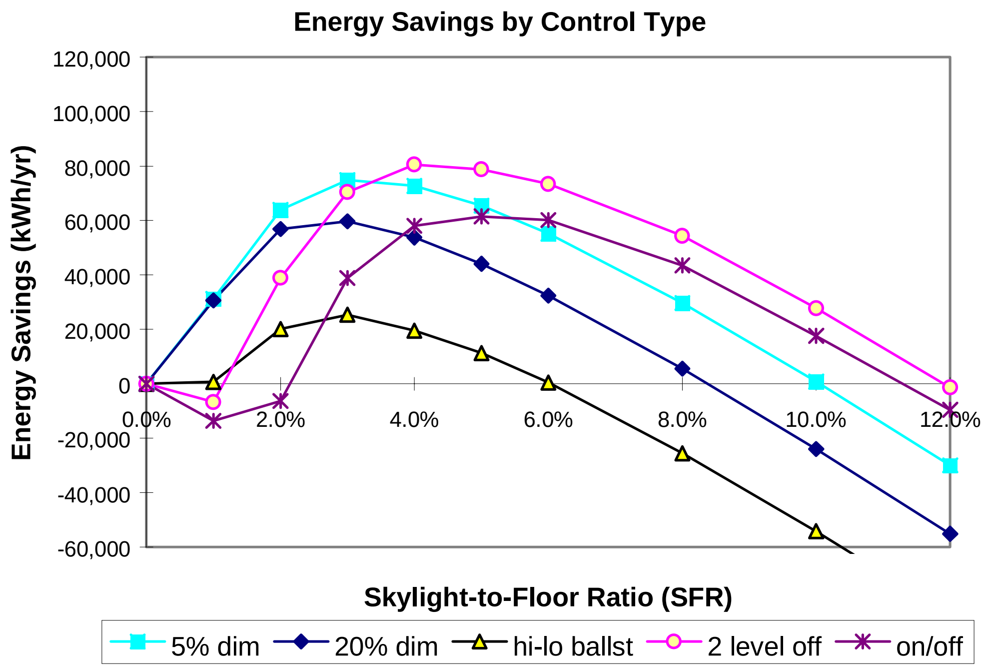


Figure 11: Annual Energy and Energy Cost Savings, by Glazing Type



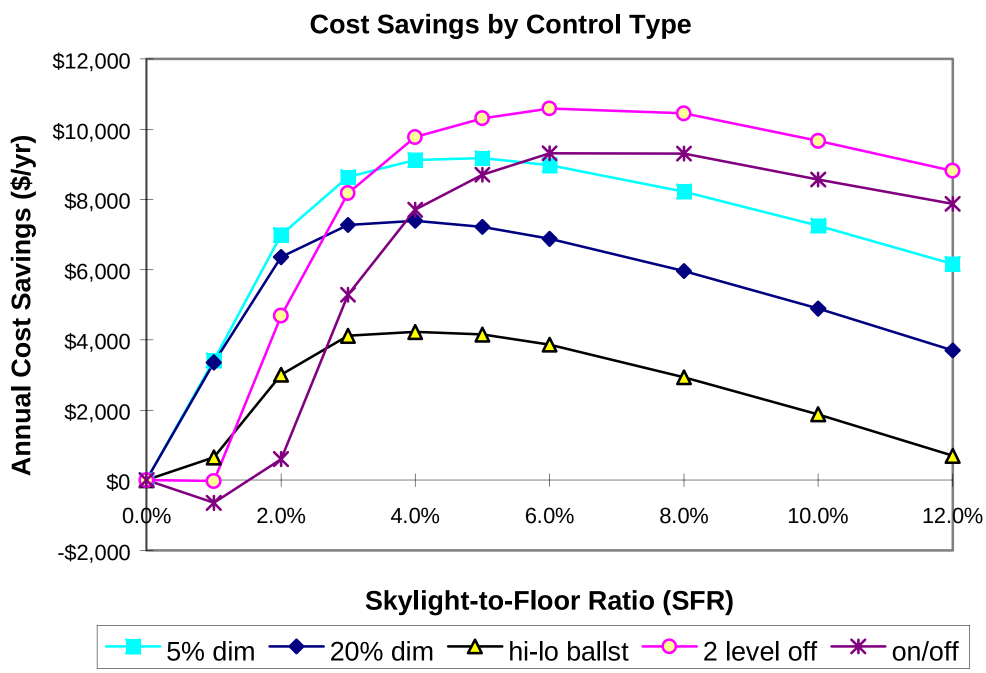


Figure 12: Annual Energy and Energy Cost Savings, by Control Type