Commercial Building Toplighting: Energy Saving Potential and Potential Paths Forward

Final Report

Prepared by

TIAX LLC

For

U.S. Department of Energy

BUILDING TECHNOLOGIES PROGRAM

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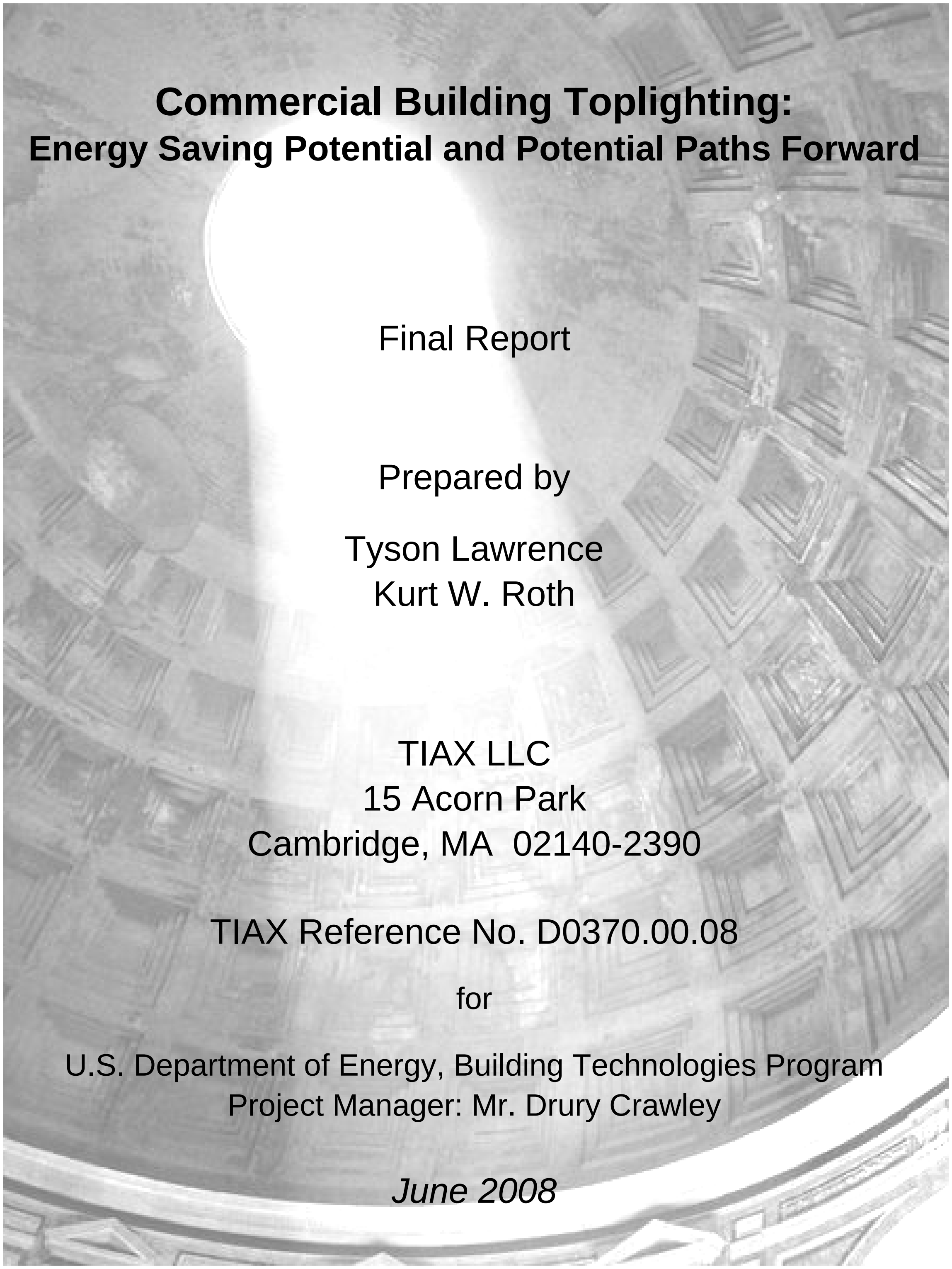
June 2008



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Prepared by

Tyson Lawrence
Kurt W. Roth

TIAX LLC
15 Acorn Park
Cambridge, MA 02140-2390

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U.S. Department of Energy, Building Technologies Program
Project Manager: Mr. Drury Crawley

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1 EXECUTIVE SUMMARY

Studies have repeatedly found that daylighting has the potential to realize very large reductions in lighting energy consumption. For example, the TIAX Controls and Diagnostics Report found that dimming electric lights in daylit spaces could reduce annual lighting energy consumption in existing commercial buildings by 40-60% (New Buildings 2001, New Buildings, 2003). Daylighting can be achieved through sidelighting (windows) or toplighting (skylights). This report focuses on toplighting, i.e., the combination of skylights and electric lighting controls. Despite the potential of daylighting, only approximately 2 to 5% of commercial building floor space currently has sufficient skylight area installed for toplighting-based daylighting (PG&E 2000). To gain a deeper understanding of how to increase toplighting deployment and associated energy savings, the U.S. Department of Energy, Building Technologies Program (DOE/BT), contracted TIAX to develop an overview of the potential for toplighting across the U.S. including an estimate of toplighting energy saving potential and a review of possible actions to accelerate the market adoption of toplighting. Well beyond providing “a number”, the analysis also illuminates the building attributes (e.g. ceiling height), market drivers, technology characteristics, and trends that influence the toplighting market. TIAX and DOE/BT decided upon the following project approach:

1. Review literature and contact industry stakeholders to identify key issues that impact the implementation of toplighting-based daylighting
2. Develop a base case (favorable, but realistic) to evaluate energy performance
3. Estimate the cost of adding toplighting in the base case scenario
4. Model the national annual energy savings potential of daylighting
5. Identify potential solutions to barriers limiting toplighting implementation
6. Select the most promising potential solutions and confirm their attractiveness
7. Identify steps that DOE can take to implement the most attractive solutions
8. Publish the findings in a report, including feedback from government and industry.

Key Issues

The study identified three key benefits of toplighting and two key issues that limit penetration of energy-saving toplighting products (see Tables 1-1 and 1-2).

Table 1-1: Key Benefits of Toplighting

Key Benefits
Energy Savings
Potential to Enhance Sales and Productivity
Potential to Increase Building Market Value

Table 1-2: Key Issues Limiting Toplighting Penetration

Key Issues
Cost versus Energy Benefit
– Equipment
– Implementation
Awareness and Education
– Inadequate Knowledge Leads to Faulty Design
– Concerns About Leaks and Controls Operation

Energy savings is the most easily quantifiably of the benefits and the benefit that is most important to the DOE. In the cases studied, we found that an economically optimum toplighting system using skylights saved 35-55% of annual lighting energy while having a much smaller impact on both heating and cooling energy consumption. Stated another way, depending on climate and building type, toplighting (skylights with lighting controls) can save between \$0.11-\$0.32 per ft^2 per year.

Industry representatives and decision makers also identified several qualitative benefits of skylights (e.g. architecture, productivity, or sales enhancements) as very important factors that influence installation decisions. In fact, in the majority of building types, skylights are not generally installed with the goal of saving energy. Instead, skylights are installed for aesthetic or programmatic (i.e., building purpose) reasons. Several recent studies have attempted to quantify these benefits. So far, results are far from definitive; however it can be stated that these effects, whether real or not, do influence some installation decisions. This may be because, while benefits are uncertain, the potential economic upside resulting from increased sales or productivity is so much greater than the incremental cost of skylights that decision makers decide to take the gamble.

Similarly, the increase in building market value resulting from the use of skylights is difficult to quantify. However, like the potential for improved occupant performance and increased building value is likely to positively influence many purchase decisions. Consider this – both windows and skylights are almost always more expensive and less insulating than opaque building envelope options. Despite the higher costs, the widespread use of windows in buildings continues, indicating that value is placed on daylight and view, and possibly that windows and skylights contribute to the prestige and comfort of a building and its occupants much like other expensive architectural details.

Our study focuses on the relationship between cost and energy savings, i.e., simple payback period, because currently only a small fraction (2-5%) of commercial building floor space has sufficient skylight area for daylighting. This suggests that building owners usually do not consider skylights *without* lighting controls to be an attractive investment, i.e., that the non-energy benefits of skylights do not compensate for the increased installation and energy costs. That led us to evaluate the attractiveness of skylights *with* controls (toplighting) as a stand-alone energy-efficiency measure, for which simple payback period is a commonly used evaluation metric. This enables DOE/BT to evaluate the value proposition of toplighting based solely on its energy impact. This is not to say that toplighting has negligible non-energy benefits, but that market decisions suggest that they are less than the cost of skylights alone. As such, our estimates are conservative estimates of the overall economics of toplighting (skylights with lighting controls).

We found that simple payback periods resulting from *energy effects only* range from 4 to 10 years in high, open, ceiling cases, and 30 to 40 years in cases with lower, drop ceilings where expensive light wells are required (see Figure 1-1). The long paybacks in buildings that use drop ceilings and, thus, require the construction of a light well for each skylight, essentially preclude the use of the skylights in these cases for economically motivated energy-use reduction. In open-ceiling buildings that facilitate shorter payback periods, industry representatives indicate that the limited implementation of toplighting is largely a result of a lack of awareness and education, and concerns about risk of leaks and not achieving promised cost/energy savings ratios.

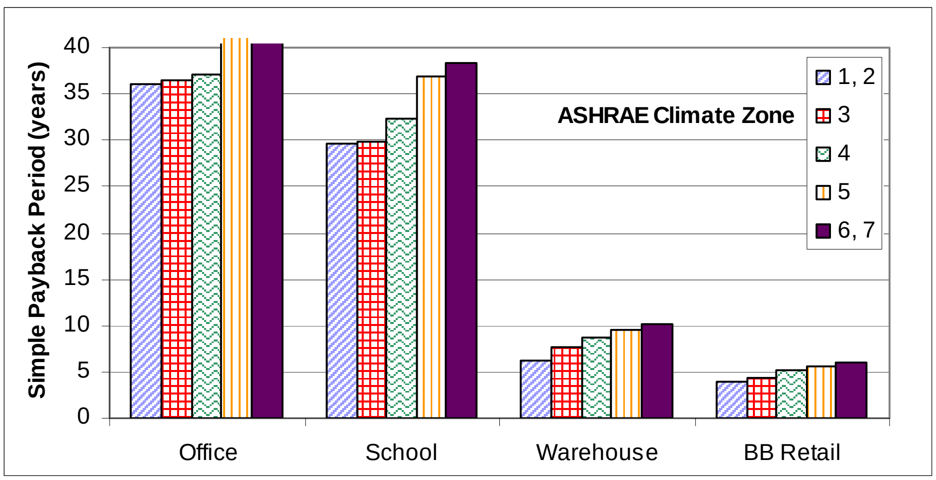

Figure 1-1: Simple Payback Resulting From Energy Savings, by Climate Zone and Building Type

Cases in which skylights are installed for non-energy reasons also represent an important energy saving opportunity. In our modeling adding controls added \$0.16-\$0.38/ft^2 of floor area, or 8-24% of the total cost of the skylight and controls installation, and resulted in savings of \$0.11-\$0.32/ft^2/year. *If skylights are already present, or will be installed for non-energy reasons, it is very often worthwhile to invest in non-dimming lighting controls and, if possible, to tweak skylight design choices to facilitate toplighting.* However, the total number current skylight installations is relatively small, and in many cases designers wish to use clear skylights for aesthetic reasons, which are not compatible with effective toplighting due to resulting glare (high contrast).

National Energy Savings Potential

To generate a national estimate for energy saving potential, we developed a base-case scenario for use in modeling. The base case is a standard toplighting installation scenario for a new, energy-efficient, building that has favorable characteristics for toplighting, but is generally consistent with current practice. We varied the base case as appropriate for each of the 4 building types modeled to reflect the unique characteristics of each (office, school, warehouse, and big box retail). Each was modeled using SkyCalc™ in 5 cities representing the 7 most populous ASHRAE climate zones in the United States.

We estimated the installed cost of each base-case system from the available literature and industry interviews. We calculated the economically optimum skylight area for each climate and building type. This resulted in a skylight to floor[1] ratio (SFR) of 4% in all cases except for warehouses (lower lighting-power densities resulted in a 3% SFR) and in Phoenix (higher annual insolation decreased the optimal SFR for all building types, except big box retail[2]). The cost estimates also include a 3-step + off lighting control system and necessary additional wiring. In the office and school cases the resulting installed cost is about $4.70/ ft^2 (using 4'x 4' skylights and light wells). The cost for the warehouse and big box retail is about $1.25/ ft^2 (using 4'x 8' skylights) (see Figure 1-2). Key takeaways from these cost figures are:

- Smaller, more expensive, skylights and light wells result in very high cost in drop ceiling cases (office/school)
- Simple lighting controls and wiring upgrades represent $0.16-$0.38/ft^2; thus, if skylights are available adding lighting controls will likely be an economically sound decision (HMG 2007, PG&E 2006, and discussions with manufacturers).

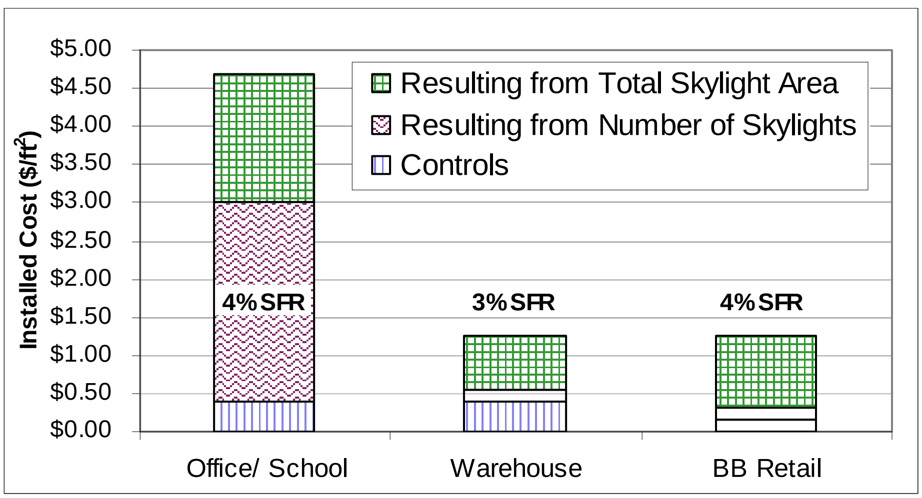

Figure 1-2: First Cost per Unit Floor Area of Optimum Toplighting System, by Building Type

National primary energy savings technical potential, assuming complete penetration of all floor space directly below a roof in the four building types examined, is about **0.4 quads**. While big-box retail offers the greatest savings per square foot, because the total floor areas of the other building types are higher, the total savings potential is not generally highest for retail across climate zones (see Figure 1-3). The floor area of non-mall retail was used as a proxy for big-box retail floor area in all calculations.

[1] Floor space under the roof.
[2] In Phoenix the optimum SFR is 3% for offices and schools and 2% for warehouses due to higher solar insolation.

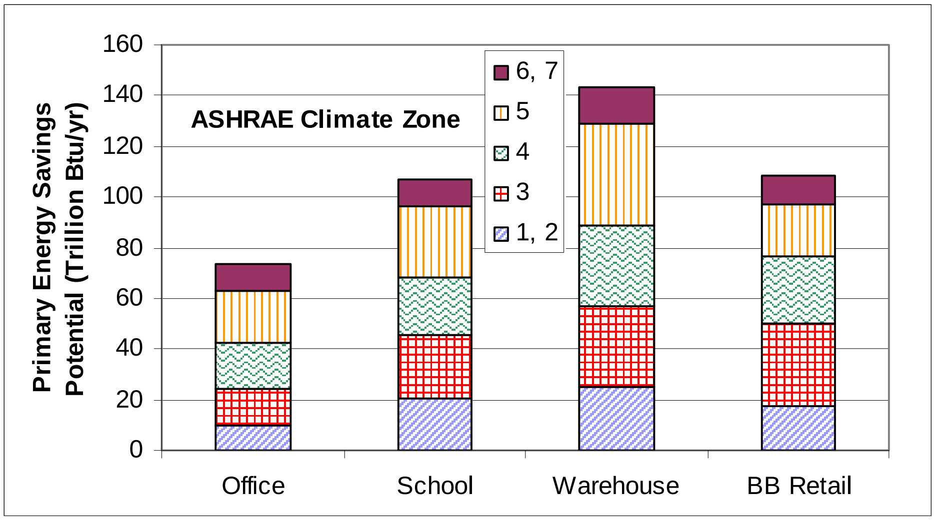

Figure 1-3: Annual Primary Energy Savings Technical Potential, by Climate Zone and Building Type

These savings results are consistent with results from earlier studies (e.g., TIAX 2005).

Potential Solutions and Recommendations to Overcome Barriers to Greater Market Penetration

To move toward the theoretical national energy savings potential, the major barriers limiting large-scale implementation of toplighting must be overcome. We identified several possible paths forward where the DOE could take action (see Table 1-3).

Table 1-3: Potential Solution Overviews

Solution	Applicable Building Types	Key Features of Solution
Code Changes	Big-Box Retail & Warehouse	• Codes limiting solar heat gain and U-value should be loosened for skylights used with lighting controls • Codes requiring skylights in certain applications could increase awareness and reduce costs • Rating systems should be updated to reflect performance in a toplighting application
Education	Big-Box Retail & Warehouse	• Improve tools and resources available to practitioners • Reduce risk of leaks, real and perceived • Reduce chances of poor design not achieving energy savings • Reduce cost of design • Increase awareness of benefits
Research	School & Office	• Develop a dramatically less expensive solution to bring light into spaces with low, drop ceilings (unlikely to achieve favorable economics)

Recommendations

There exists a real, immediate, opportunity for national energy savings in buildings with high, open ceilings. We recommend action to exploit this potential, including ensuring that codes do not stand in the way of energy-saving toplighting solutions, increasing awareness of benefits through training, and making appropriate resources available to practitioners to achieve effective designs with limited risk and cost. In the case of buildings with low, drop ceilings, the long payback will be very difficult to overcome. For example, in offices, typical payback periods would still exceed 11 years even if the cost of implementing skylights could be reduced to be equivalent to those for a high open ceiling case (i.e., in which fewer, larger skylights are installed without light wells). In schools, due to slightly higher lighting power densities, paybacks would approach 9 years. Improving economics and performance of skylights in buildings with low ceilings may tip the balance in cases where skylights are under consideration mainly for their aesthetic and programmatic benefits, but such efforts are unlikely to form a basis for *energy cost savings alone* to drive installation decisions.

2 INTRODUCTION

Daylighting has the potential to realize large reductions in commercial building lighting energy consumption. For example, TIAX found that dimming electric lights in daylit spaces could reduce lighting annual energy consumption in existing commercial buildings by 0.2 to 0.25 quads (TIAX 2005). At present, the portion of floor space with adequate daylight for effective daylighting limits the ultimate savings potential of this approach. That is, estimates suggest that windows (side lighting) can currently provide only approximately 15 to 20% of commercial building lighting (LRC 2001), and skylights (toplighting) can currently provide only approximately 2 to 5% (PG&E 2000).

Lighting energy accounts for a significant portion of commercial building energy consumption (see Figure 2-1). When properly implemented, daylighting can reduce lighting energy usage by 40-60% (New Buildings 2001, New Buildings 2003). In addition to energy saving benefits, some building owners, researchers, and toplighting practitioners feel there are additional benefits such as increased health and wellbeing for occupants potentially leading to higher productivity, sales, or happiness (see Section 3.2).

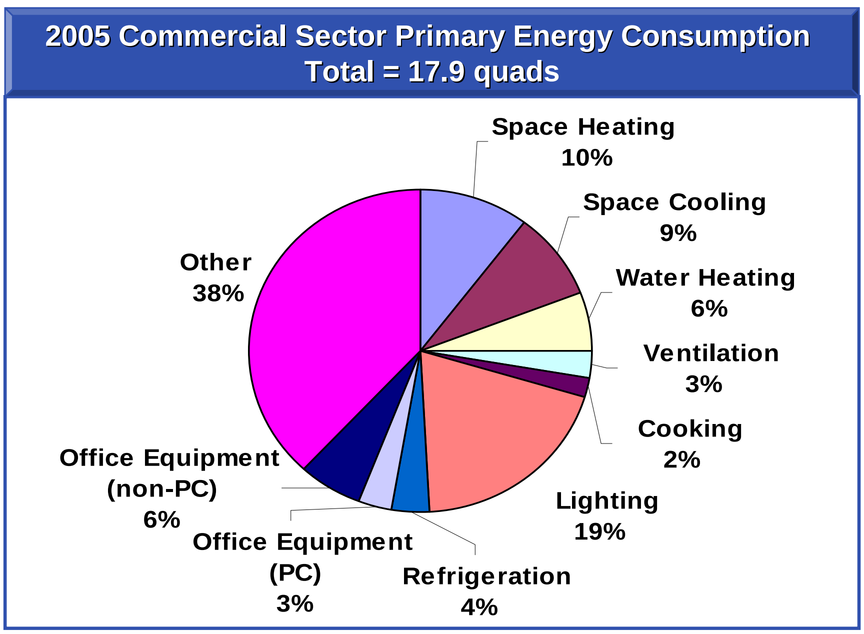

Figure 2-1: Commercial Building Energy Consumption by End Use Circa 2005 (*EIA 2006)*

Prior studies note several challenges associated with daylighting including:

- The cost of windows/skylights and lighting control systems
- Added design complexity to ensure siting and interior space facilitates daylighting
- Glare (large intensity variations) management
- Implementation of effective lighting controls

In many instances, toplighting (skylights) eases some of these challenges relative to sidelighting (windows)—glare is easier to reduce, and lighting control can be simpler and more reliable due to more consistent light distribution throughout the day. Furthermore, toplighting has the potential to provide greater energy savings per unit area, because it can provide up to 30% more light per ft^2 of glazing (New Buildings 2001, New Buildings 2003). Also, there is greater market expansion opportunity in toplighting. Initial estimates indicate that only approximately 2 to 5% (PG&E, 2000) of commercial floor space currently has sufficient skylight area for toplighting, compared to 60% of commercial floor space that is directly under a roof and, therefore, a potential toplighting opportunity (EIA 1998).

The U.S. Department of Energy, Building Technologies Program (DOE/BT) recognizes the large gap between current implementation of toplighting and its theoretical potential as an opportunity for significant national energy savings. Specifically, DOE/BT identified the need to develop a better understanding of why toplighting is used infrequently, what DOE could do to increase utilization, and the national energy savings that could result from such efforts.

2.1 Study Approach

To gain understanding of the issues outlined above and support its strategic planning efforts, DOE/BT contracted TIAX to develop an overview of the potential for toplighting across the U.S. The study includes an estimate of toplighting energy saving potential, an assessment of the barriers to and drivers for greater use of toplighting, and a review of possible actions to accelerate the market adoption of toplighting. Well beyond providing "a number", the analysis also illuminates the building attributes (e.g. ceiling height), market drivers, technology characteristics, and trends that influence the toplighting market. TIAX and DOE/BT agreed to the following project approach:

1. Review literature and contact industry stakeholders to identify key issues that impact the implementation of toplighting-based daylighting
2. Develop a base case (favorable, but realistic) to evaluate energy performance
3. Estimate the cost of adding toplighting in the base case scenario
4. Model the national annual energy savings potential of daylighting
5. Identify potential solutions to barriers limiting toplighting implementation
6. Select the most promising potential solutions and confirm their attractiveness
7. Identify steps that DOE can take to implement the most attractive solutions
8. Publish the findings in a report, including feedback from government and industry.

This report describes the methodology, results, findings, and recommendations of the study.

2.2 Report Organization

This report is organized as follows:

- Section 3 provides background on toplighting and presents key factors that impact the implementation of toplighting identified by industry stakeholders.
- Section 4 summarizes the methodology used to assess toplighting energy savings potential.
- Section 5 presents energy and energy cost savings analyses by region and building type.
- Section 6 presents possible solutions that could overcome the barriers to toplighting implementation.
- Section 7 presents the conclusions of this report, potential solutions to barriers limiting penetration, and recommendations to DOE/BT.
- Appendix A presents the TIAX interview process of toplighting stakeholders
- Appendix B presents additional detailed results of energy and economic modeling

3 TOPLIGHTING BACKGROUND AND FACTORS IMPACTING TOPLIGHTING IMPLIMENTATION

3.1 Toplighting Background

Toplighting is the practice of adding architectural elements on or near the roof of a building to allow sunlight to enter the occupied space. Simple skylights are the most common and most cost-effective method of accomplishing this (see Figure 3-1). Other options[3] are shown in Figure 3-2.

Source: Sunoptics Prismatic Skylights

Figure 3-1: Simple Plastic Domed Skylights

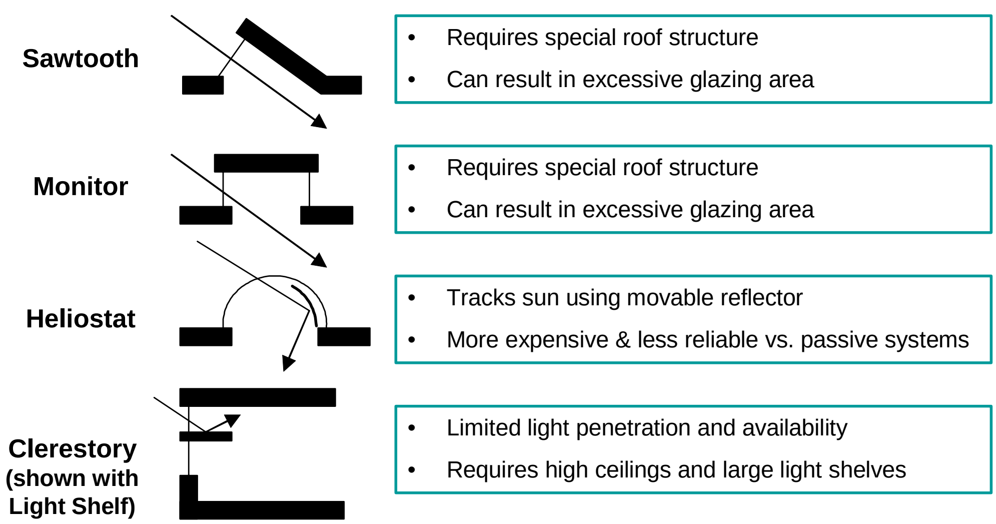

Figure 3-2: Alternative Toplighting Methods

[3] Because light shelves do not access the 'top' of the building and cannot be used in the core of buildings, one could reasonably categorize them as side lighting instead of toplighting. On the other hand, light shelves and clerestories are functionally more similar to toplighting than side lighting, i.e., they do not provide view, they direct light into the space from above, and they are less susceptible to glare problems. Consequently, we decided to include them as an alternative toplighting approach.

Figure 3-3 depicts a typical skylight system. The skylight system consists of:

- **Glazing** (1 to 3 layers) **and Frame**
- **Curb** on which the skylight is mounted to raise it above the roof surface
- **Light well** to bring light through the roof structure, insulation, and plenum space between the roof and a drop ceiling if present

In some cases, the light well may splay out as it nears the ceiling to allow the light to begin to spread through the room earlier, thereby improving light distribution when ceiling height is not adequate. Another option to aid light distribution is a diffusing sheet at the bottom of the light well.

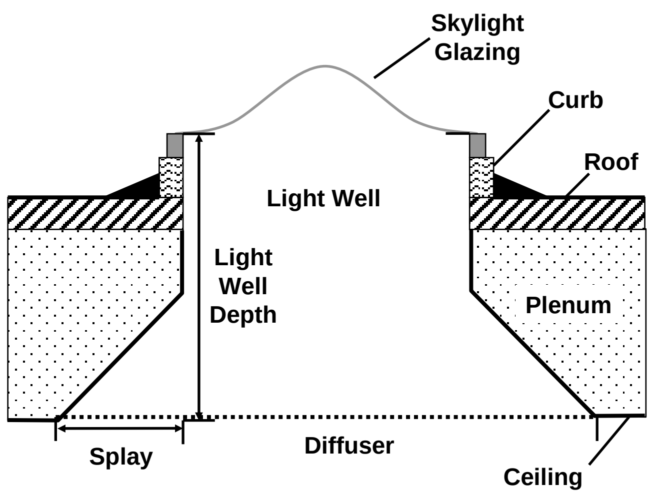

Figure 3-3: Typical Skylight System

To achieve energy savings, skylights or other toplighting architectural features must be combined with lighting controls that dim or turn off some or all of the electric lights in response to available daylight. Lighting control systems consist of one or more photocells that detect light levels and a controller that dims or turns off luminaires. Photocells can be placed outside, directly below skylights, or inside distant from any skylights. Their location depends on building type and system design, as well the potential influence of sidelighting (not considered in this study). While there have been many reports of unsatisfactory results in sidelighting daylighting control systems, toplighting control systems are generally simpler and more reliable. A recent study of toplighting in buildings primarily with high ceilings[4] concluded that lighting controls achieved, on average, 98% of theoretical energy savings as calculated using SkyCalc™ (Pande et al. 2006). The use of toplighting to save energy is much less common in buildings with lower ceilings; as a result, good data are not as readily available to verify lighting control performance in those applications.

[4] Although this reference did not report the floor-to-ceiling heights of the buildings, industrial buildings and warehouses accounted for 50 and 38 percent of the sample, respectively. Both building types almost always have higher ceilings, whereas the office and educational buildings accounting for the remainder of the sample may not have had higher ceilings.

3.2 Key Issues

To understand what may prevent toplighting from achieving greater market penetration, we evaluated the drivers that would promote the use of toplighting. Review of available literature, and interviews with industry experts identified three key benefits of toplighting (see Table 3-1; Appendix A contains the questionnaires used for both rounds of interviews).

Table 3-1: Key Benefits of Toplighting

Key Benefits
Energy Savings
Potential to Enhance Sales and Productivity
Potential to Increase Building Value

Energy savings is the most easily quantified of the benefits and the benefit of greatest interest to DOE/BT. Our modeling results found that 35-55% of lighting energy can be saved, with minimal incremental heating and air conditioning energy consumption, by installing an economically optimum toplighting system. Stated another way, depending on climate and building type, \$0.12-\$0.32/ft^2 can be saved per year including losses. Economic results are discussed in further detail in Section 5.

Industry representatives and decision makers also identified the more qualitative non-energy benefits of skylights as very important. In fact, in the majority of building types, current skylight installations are not generally undertaken with the goal of saving energy. Instead, skylights are installed for aesthetic or programmatic reasons. Some stakeholders acknowledged the potential for skylights to improve worker/student productivity or retail sales as an important benefit that influences installation decisions. Several recent studies have attempted to quantify the benefits of daylight (see Table 3-2).

In addition, two studies found positive correlations between view and call center worker productivity (Heschong et al. 2004) and student performance (Aumann et al. 2004). These studies imply that, to the extent that the potential non-energy benefits of daylight noted in Table 3-2 exist, access to a view may account for some portion of that benefit. Consequently, since skylights do not provide direct views, this suggests skylight-based daylighting alone (i.e., without sidelighting) might not provide all of the posited non-energy benefits of daylighting.

Table 3-2: Potential Sales, Productivity, and Learning Benefits (CEC 2003a, NAS 2006)

Benefit	Details
Increased Retail Sales	A recent study conducted for the PIER program at CEC found daylit stores experienced an average of a 0 to 6 percent increase in sales.
Enhanced Productivity	• Studied potential benefits include: – Health (circadian system) – Worker Perception/Happiness – Visual Clarity and Color Perception – Reduced Eye Strain (if glare free) • PIER studies found a "significant and positive" increase in mental function and attention.[5] • Furthermore, glare, common with sidelighting, was found to have an even more significant negative effect.
Enhanced Learning	• Results are inconclusive. • One study of a single California school district found that moving a student from a classroom without daylight to a classroom with maximum daylight would be expected to increase performance by 21%. These results have been disputed by other researchers (Boyce 2004). • Furthermore, when HMG repeated this study in the Fresno school district no positive correlation between daylight and performance was found. Associated negative factors such as increased noise or glare in daylit classrooms where sited as possible sources of the discrepancy.

While there is still insufficient information to conclude that there are sales, productivity or learning gains, these perceived benefits, whether real or not, affect some installation decisions.

Louis Kahn, a 20th century architect, famously said "*No space, architecturally, is a space unless it has natural light.*" This is a sentiment shared by many in the architectural and building community. It is reasonable then to conclude that spaces with high-quality natural light will be more valuable. However, the increase in building value is very difficult to quantify. This value of daylighting can be observed in the rental market, construction and resale, and in corporate image:

- **Rental:** Anecdotal evidence suggests that the complete absence of *windows* reduces the rental value of a space by 10-20% (RPI 2003-2006; it is not clear, however, that a lack of toplighting has an impact of this order of magnitude.
- **Construction and Resale:** In most cases, windows and skylights are both more expensive and less insulating than opaque building envelope options. Despite the higher costs, the widespread use of windows and, to a lesser extent, skylights in buildings continues, indicating that value is placed on daylight and view, and

[5] "The Backwards Numbers test is widely accepted in psychological research as a valid test of mental function and attention span. An increase in daylight illumination levels from 1 to 20 footcandles resulted in a 13% improvement in performance in the ability to instantly recall strings of numbers." (CEC 2003a)

possibly that windows and skylights contribute to the prestige of a building and its occupants much like other expensive architectural details.

- **Visitors:** The increased aesthetic or architectural appeal of a building has value to its occupants, but also is of significant value for impressing a corporate image upon visitors, whether they be customers, business partners, or potential employees.

Increased building value, if any, will depend on design and market conditions. Recent McGraw-Hill reports suggest that, overall, current green building techniques reduce building operating costs by 8% to 9%, increase building value by about 7.5%, have approximately 3.5% higher occupancy ratios, 3% higher anticipated rent ratios, and an overall ROI improvement of about 6.6% (MHC 2005). Much as in the case of improved occupant performance, we are not able to generally quantify the increase in building value that will result from adding toplighting, but we can conclude that it is likely to positively influence decisions to add skylights.

Decision makers must find these benefits more valuable than the costs of design, materials, installation, maintenance and associated risk. Discussions with stakeholders identified many factors that contribute to the cost and risk associated with toplighting (see Table 3-3).

Table 3-3: Barriers Limiting Toplighting Penetration

Key Issues
Cost vs. Energy Benefit – Equipment – Implementation Awareness and Education – Inadequate Knowledge Leads to Faulty Design – Concerns About Leaks and Controls Operation
Other Issues
Lack of Integrated Costing (i.e. taking into account reduction in cooling systems from daylighting)
Maintenance Concerns
Resistance from contractors (increases complexity of roof and risk)
Design Challenges (Glare, Distribution, Integration with mechanical systems [duct and piping runs])
Inadequacy of Current Design Tools
Inadequacy of Current Skylight Rating Systems
Code Issues
Security
Safety

Industry experts identified two issues, first cost versus energy cost savings and the awareness and education of stakeholders, as the most important issues.

Our study focuses on the relationship between cost and energy savings, i.e., simple payback period, because currently only a small fraction (2 to 5%) of commercial building floor space has sufficient skylight area for daylighting. This suggests that building owners usually do not consider skylights *without* lighting controls to be an attractive investment, i.e., that the non-energy benefits of skylights do not compensate for the increased installation and energy costs. That led us to evaluate the attractiveness of skylights *with* controls (toplighting) as a stand-alone energy-efficiency measure, for which simple payback period is an commonly used evaluation metric. This enables DOE/BT to evaluate the value proposition of toplighting based solely on its energy impact. This is not to say that toplighting has negligible non-energy benefits, but that market decisions suggest that they are less than the cost of skylights alone. As such, our estimates are conservative estimates of the economics of toplighting (skylights with lighting controls).

We found that simple payback periods range from 4-10 years in high, open, ceiling cases, and 30-40 years when expensive light wells are required. The long paybacks in buildings that use drop ceilings, and thus require the construction of a light well for each skylight, essentially preclude the use of the skylights in these cases for economically motivated energy use reduction. Economic results are discussed further in Section 5.

We calculated these payback results using a relatively simple design strategy of evenly spaced, plastic domed skylights and short, splayed light wells. Particularly in buildings with low, drop ceilings, such as offices and schools, building design and programmatic requirements may require more sophisticated (expensive) implementations. Toplighting provides better distribution and less glare than sidelighting, but can still present problems if not properly designed. A skylight can be ten times as bright as an electric luminaire, and can produce contrast ratios as great as 100:1 between the ceiling and skylight (PIER 2007). The higher the visible transmission (efficiency) of the skylight and the larger the skylight (economically more efficient), the worse these problems become if not accounted for in the design of the skylight system. This is not a major issue in high-ceiling applications where skylights are out of the normal range of view. However, in low-ceiling cases such as offices and schools, brightness can be a major problem, particularly from diffusers located below ceiling level (Johnson 2008). Various accessories can increase distribution and reduce glare, but must be designed carefully and generally add cost (see Figure 3-4).

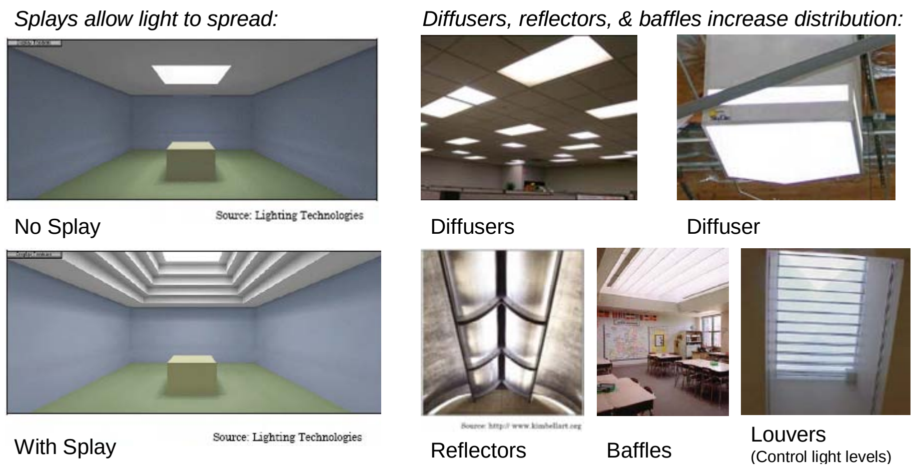

Figure 3-4: Skylight Implementation Options

In open-ceiling buildings offering more reasonable payback periods, industry representatives indicate that low implementation of toplighting is largely a result of a lack of awareness and education, as well as concerns about risk of leaks and not achieving anticipated payback periods. Experts frequently mentioned that inadequate design tools and skylight rating systems increase the cost of designing an effective toplighting strategy beyond what many builders can bear or result in poor energy savings outcomes. They said existing tools do not provide designers with a simple and accurate means of understanding the energy and lighting impacts of design decisions. As many as 4 different software packages may be required to complete a design (e.g. Daysim requires use of Radiance, a CAD package, and EnergyPlus). Software packages may be expensive or require significant training. Many offerings do not allow for a full range of building designs (see Table 3-4).

Table 3-4: Examples of Existing Daylighting Design Tools (Kelecher 2007)

Existing Design Tools Have Limited Capabilities
• *SkyCalc™* models energy savings from toplighting, but does not include sidelighting, sloped roofs, or some types of skylight, and does not provide CAD models of light distribution and levels to inform lighting design. • *EnergyPlus* performs an energy savings analysis, but does not provide sophisticated daylighting design capability and is complex. • *Lumen-Designer, Radiance, Adeline, Lightscape*[6] and others provide light level modeling, but most are limited in their sophistication and do not provide energy analysis. • *Daysim* adds weather and user models to Radiance calculations and allows export to CAD. It is complex, and analyzing HVAC effects "requires the use of advanced simulation programs such as *Esp-R, TRNSYS*, and/or *EnergyPlus*." (Daysim manual) • CAD software such as *AutoCAD*[7], *Ecotect, Sketchup*, etc. are generally radiosity based, and have limitations in accuracy. • *Sensor Placement and Orientation Tool, SPOT*, calculates energy savings and assists with sensor placement, but is not capable of analyzing complex geometries.

[6] According to the Autodesk website, "Autodesk has purchased Lightscape and has successfully incorporated Lightscape's most powerful lighting features into VIZ" (http://usa.autodesk.com/adsk/servlet/item?siteID=123112&id=6547440&linkID=8393668).
[7] Appears now to be Revit® Architecture 2008 and AutoCAD® Revit® Architecture Suite 2008 (http://images.autodesk.com/adsk/files/revit_arch2008_autocad_revit_arch_suite2008_qanda.pdf).

Note: The SkyCalc™ model chosen for the analysis (presented in Sections 4 and 5) evaluates energy savings and losses resulting from toplighting for simple cases. Because our analysis focuses on simple representative buildings, the lack of model support for sidelighting, sloped roofs, some types of skylight, and CAD models of light distribution is not material to our analysis.

Inadequate standards and rating systems for manufacturing quality and performance can hamper computer-based and manual evaluation of available skylight products. For example, the accepted fenestration rating systems do not properly account for the greater consistency of effective light transmission over the course of a day through a domed skylight relative to that through a flat skylight. Many significant product options are not included in rating systems or their properties are not fully accounted for, making it difficult for designers to make meaningful comparisons. Some software packages offer methods to manually compensate for differences, i.e., specify a domed skylight, however these compensations are limited in their accuracy and applicability due to incomplete information (PIER 2003).

Inadequate training and access to knowledge can lead to improper design and/or installation, which can cause leaks and compromise energy savings. According to industry representatives, leaks and system deterioration should be very rare if systems are properly installed. However, even if leaks are very rare in practice, concerns about *possible* leaks remains an issue. Occupants perceive leaks from the roof as worse than leaks from a window, and roofers are hesitant to take on the additional liability associated with guaranteeing any additional flashed joints beyond what is necessary.

Some decision makers are also concerned that lighting controls will not achieve the promised energy savings. In fact, several energy codes, including the International Energy Conservation Code (IECC) and ASHRAE/IESNA 90.1-1999, dropped the requirement for photocontrols, reduced allowable skylight areas, and require low solar heat gain coefficients (SHGC) and U-values, due to reports of photocontrol failure. One study found that, contrary to these concerns, lighting controls for toplighting in high-ceiling applications have proven very effective, achieving 98% of theoretical energy savings. Occasionally, they could be better optimized, but they are rarely disabled. When they are overridden, it is usually by occupants shutting off lights to further increase energy savings. In spaces with lower ceilings and in sidelighting situations, however, lighting controls are not always well implemented and can be problematic, strengthening perceptions that lighting controls are a hassle (Pande et al. 2006).

Inadequate understanding and awareness of the benefits of toplighting can result in codes that fail to encourage energy savings. In California, Title 24 requires toplighting in certain circumstances, and it appears that the 2010 version of ASHRAE 90.1-2010 will incorporate similar requirements (Richman 2008). Most states codes discourage, however, skylights due to their thermal impacts. For example, the 2006 IECC (International Energy Conservation Code) limits skylights to 3% of the roof area, less than optimum for toplighting in many climates, and prescribes a Solar Heat Gain Coefficient (SHGC) of 0.35. This in turn effectively limits the Visible Transmission (VT) of useable skylights and, thus, decreases the economic and energy benefit of toplighting. In summary, codes and standards focused on thermal properties alone increase cost and discourage use of skylights combined with lighting controls as an energy-saving measure (Brenden 2006). These results and other have led to changes in the upcoming ASHRAE 90.1-2007 to make new allowances for toplighting including requiring photocontrols for toplit areas of over 5,000 ft^2, and permitting higher skylight-to-floor ratios and SHGCs *if* diffusing skylights and lighting controls are used and VT/SHGC is greater than 0.8 (HMG 2007).

Most of the other issues identified are usually peripheral to the decision-making process. Operation and maintenance costs are minimal. High-quality, properly installed skylights should be as durable as standard roofing materials. Dirt build-up impairs light transmission, however, because diffusing skylights are not transparent, dirt accumulation is less noticeable than with clear fenestration. An annual cleaning is recommended to maintain maximum efficiency. Domed skylights generally stay cleaner than flat skylights because they allow rainwater to run off, providing some cleaning. Security and safety were identified by some industry representatives as problems, but it was generally felt they were not major issues. Like any building penetration, skylights are a potential access point for theft. However, windows are generally more accessible and skylights can be alarmed or strengthened. Many standard plastic skylight products are resistant to damage from an assailant and also provide protection in severe weather. Improperly designed skylights can present safety hazards, so, most manufacturers now provide products that meet OSHA regulations that require skylights to withstand a man falling onto the glazing.

4 ENERGY AND ECONOMICS CALCULATION METHODOLOGY

We used a Microsoft-Excel®-Spreadsheet-based program called SkyCalc™ (Version 3.0) to calculate energy and cost savings resulting from the use of skylights and lighting controls. SkyCalc™ is recognized as an accurate and user friendly tool for analyzing the energy impact of basic toplighting installations. The software is well suited for the needs of this analysis in which we modeled a simple configuration in multiple locations and conducted sensitivity analyses by selectively varying inputs. The Heschong Mahone Group created SkyCalc™ with funding from the California Energy Commission. SkyCalc™ performs an annual calculation based on user inputs (described in Section 4.1 Base Case for Modeling); a database of default schedules, skylight performance characteristics, lighting efficacy, material properties; and hourly climate data generated by the DOE-2.1 building energy simulation program. The DOE-2.1 data reflect interior illuminances, sensible heat gains, solar heat gains, and outdoor dry-bulb temperatures for a reference building. The calculation is completed through cell equations, user defined functions, and subroutines. The lumen method, as defined by the 8th Edition of the Handbook of the Illuminating Engineering Society of North America, is used to calculate performance of luminaries and skylights. The schedules for each building type are based on data collected by Southern California Edison from a large set of monitored buildings. More detail on the use and calculation methods used by SkyCalc™ can be found at the Energy Design Resources website (EDR 2007). Based on the inputs given, SkyCalc™ returns the energy savings and loss characteristics of the building over a range of skylight-to-floor area ratios. We used SkyCalc™ default values for those inputs not described specifically in Section 4.1 Base Case for Modeling. Appendix B contains sample SkyCalc™ inputs and outputs.

4.1 Base Case for Modeling

We generated a set of base case inputs for consistency (see Table 4-1). The base case is intended to represent a standard installation in a new, energy-efficient, building that has favorable characteristics for toplighting consistent with current practice. It was created and validated through literature review and discussions with industry stakeholders, including manufacturers and installers. To further validate the base case, we conducted a sensitivity analysis (discussed below in Sections 4.2 – 4.8). We used the base case to generate energy and cost savings for four building types (office, school, big box retail, and warehouse) in five cities representing the five ASHRAE climate zones in the U.S. with the greatest populations (Phoenix, AZ, Zone 2; Memphis, TN, Zone 3; Baltimore, MD, Zone 4; Chicago, IL, Zone 5; and Burlington, VT, Zone 6).

Table 4-1: Base Case Characteristics Used For Input to SkyCalc™

Characteristic	**Value**			
	Office	**School**	**Warehouse**	**Big-Box Retail**
Building				
Applicable Building Area	10,000 ft^2	10,000 ft^2	10,000 ft^2	50,000 ft^2
Ceiling Height	10ft[a]	10ft[a]	20ft	20ft
Wall Color	Off-White Paint; Reflectance = 80%			
Shelf/Partition Height	5ft	n/a	15ft	7ft
Shelf/Rack Width	n/a	n/a	8ft	6ft
Aisle/Cubicle Width	8ft	n/a	12ft	10ft
Cubical Length	8ft	n/a	n/a	n/a
Electric Lighting				
Lighting System	Open cell fluorescent	Open cell fluorescent	Industrial fluorescent	Industrial fluorescent
Lighting Level	31fc	59fc	24fc	63 fc
Power Density	1.02W/ ft^2	1.21W/ ft^2	0.84W/ ft^2	1.49W/ ft^2
Fixture Height	10ft	10ft	16ft	16ft
Lighting Control	3 level + off switching (90% of lights controlled)[b]			
Skylights				
Glazing Type	Acrylic			
Glazing Layers	Double Glazed			
Glazing Color	Prismatic over High White (VT=65%, SHGC=53%, U=0.81)			
Skylight Well				
Light Well Height	4ft[a]	4ft[a]	1ft	1ft
Well Color	White Paint			
Utility Prices				
Average Electric Cost	$0.087/kWh			
Average Fuel Cost	$1.124/Therm			

a Drop ceiling used. To simulate a 2ft high splay, a ceiling height of 12ft and a well height of 2ft was entered in SkyCalc™.

b Levels are: 100%, 67%, 33%, and off.

4.2 Building Size

We selected the floor space of each building type to be generally representative of a single-floor building (or the top story) of that class of building. In general, the economics of toplighting-based daylighting will be somewhat better for larger buildings due to fixed costs and economies of scale related to equipment purchase and installation. Therefore, an attractive payback for a base-case building can be reasonably applied to any larger building. The sizes chosen are slightly lower than the mean for that building type, but higher than the median. For example, the mean office building size is about 15,000 ft^2 and the median size is closer to 5,000 ft^2 (EIA 2007). Because economics tend to improve with floor space, choosing a baseline square footage below the mean allows us to reasonably apply the results to the majority of square footage directly under a roof for each building type.

4.3 Ceiling Height

Ceiling height has a major impact upon the economics of a toplighting solution because a higher ceiling enables fewer, larger skylights to be used to achieve similar lighting levels. Effective toplighting requires that light from skylights be reasonably even across a space, as is required for light from electric fixtures (luminaires). A higher ceiling allows skylights to be spaced further apart because the additional height provides more distance for the light to spread horizontally outward from each skylight. For this analysis, we used the luminaire spacing criterion described in the IESNA Lighting Handbook (2000). It is based on a comparison of the light levels between two luminaires (skylights) with light levels directly below a luminaire (skylight). The luminaire-spacing criteria indicate that skylights should be spaced no further than 1.4 times the mounting height to maintain sufficiently even light levels.

When other criteria are considered, such as overlap between luminaires, vertical illuminance, shadowing and illuminance distribution above the workplane, it is generally found that luminaires must be installed at some spacing-to-mounting-height ratio less than the value of the luminaire spacing criterion (IESNA 2000).

Contrast brightness may limit permissible skylight size and spacing . Lighting designers and architects raised this concern during interviews, noting that large, bright, skylights can irritate occupants when viewed directly. Partitions can also shade nearby areas. Using the luminaire spacing criterion, without blocking partitions, as a best case scenario yields the following expression for the area that a single diffusing skylight can serve (see Figure 4-1; PG&E 2006):

$$\text{Lit Area} = ((1.4 \text{ x ceiling height}) + \text{skylight width})^2.$$

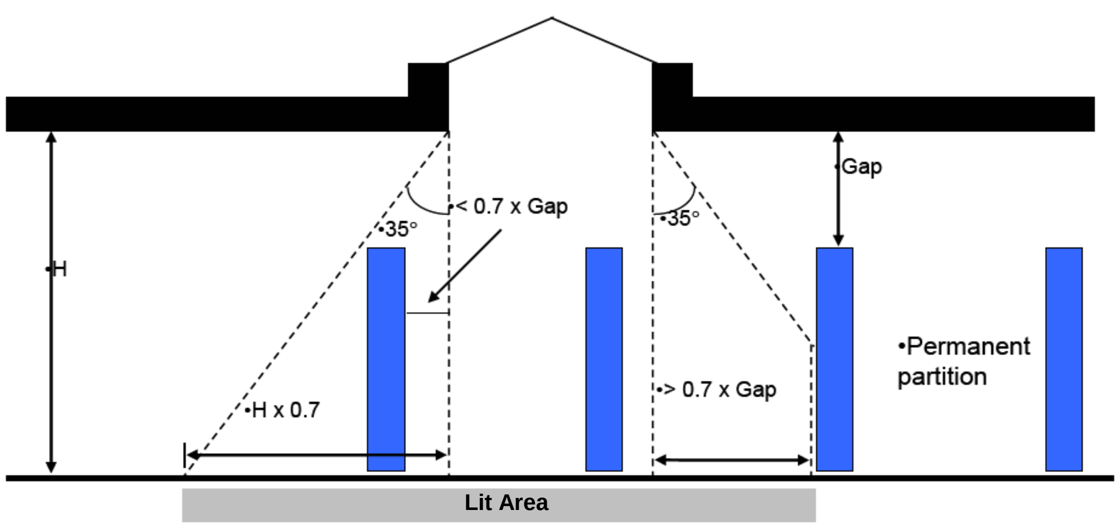

Figure 4-1: Skylight Spacing Criteria (PG&E 2006)

If the skylight design includes a splay, the ceiling height used in the equation should equal the ceiling height plus the height of the splay to account for the additional light spreading enabled by the splay. For example, in the analysis of the office case, a 10ft ceiling height plus a 2ft splay results in spacing equal to 16.8ft plus the skylight width. Figure 4-2 shows the relationship between ceiling height and the number of skylights required (assuming a minimum 3% SFR to provide sufficient illuminance). For this analysis, we selected ceiling heights of 10ft and 20ft as representative of buildings where skylights are feasible. Higher ceiling heights would improve economics because they tend to reduce the number of skylights required by increasing light spreading.

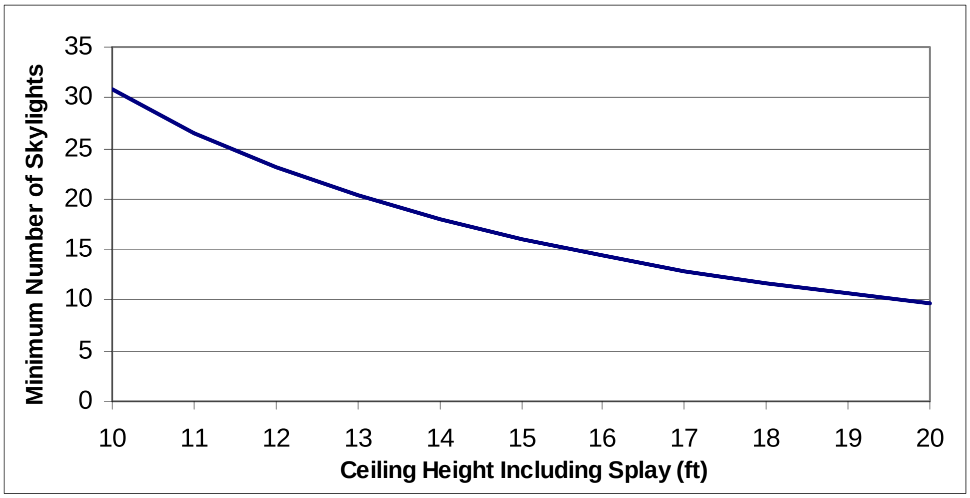

Figure 4-2: Number of Skylights Required for a 10,000 ft^2 Area Versus Ceiling Height

4.4 Lighting Power Density, Required Intensity and Efficacy

Required light level (illuminance) and the lighting power density (LPD) needed to generate the light level are very important factors in energy savings. In short, the LPD represents maximum energy savings potential, and the required light level determines how much daylight must enter the space to achieve that savings. The lighting power density values were set based on the ASHRAE 90.1-2004 standard for each building type. Figure 4-3 shows how savings changes in Burlington as required light level (lighting intensity) varies from 21fc to 105fc (this range of lighting intensity corresponds to a lighting power density range of 0.5W/ ft^2 to 2.5W/ ft^2). All of the figures in Section 4 are based on the Big-Box Retail building because it has the best economic potential. The relative sensitivity to inputs would be similar for the other building types.

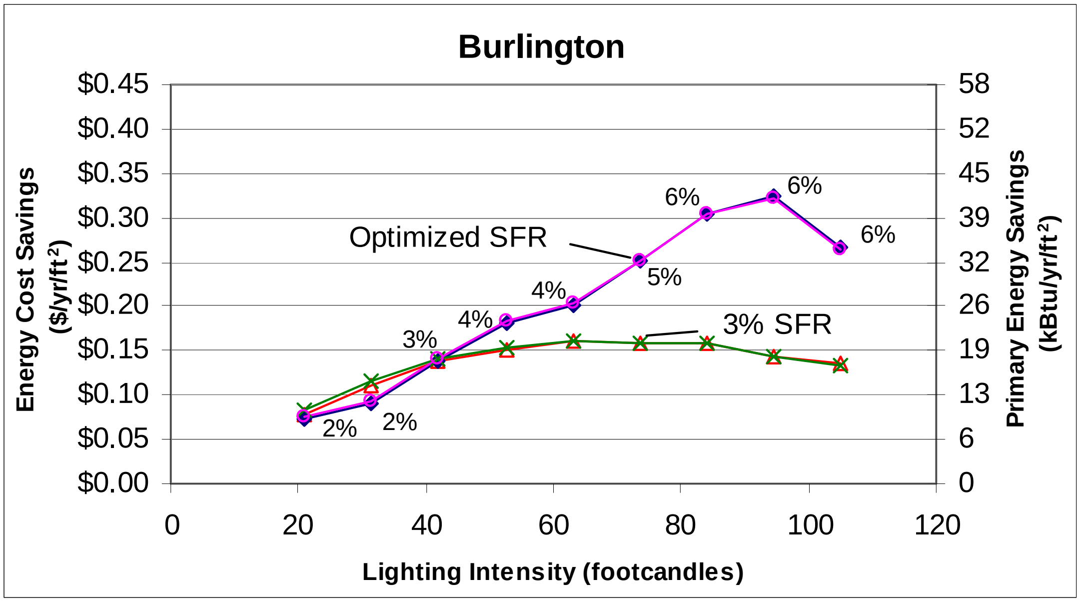

Figure 4-3: Energy Cost Savings as a Function of Required Lighting Intensity / Lighting Power Density, Big Box Retail, Burlington

As expected, as lighting power usage increases, so do savings from toplighting. There are four series graphed on this chart, energy and cost savings, each for two cases. The cost savings and primary energy savings series for each case are difficult to differentiate and lie almost directly on top of one another, because electricity dominates the change in energy consumption from toplighting at low skylight–to-floor ratios (SFRs). This is true even in Burlington (Vermont), where buildings have high heating loads. Consequently, the cost savings and primary energy savings are very nearly multiples of one another. For this reason, further graphs will still show cost savings and primary energy savings on different axes, but we have combined them into a single line (based on energy cost) for simplicity. In practice, this results in at most a few percent error, well within the expected accuracy of these calculations.

The lower two lines on the chart show the increase in savings (at least above 40 fc) that results from increasing lighting intensity requirements without changing the SFR. The upper lines show how savings increase if the SFR is optimized by selecting the highest integer SFR that lies within ½ year of the minimum simple payback period (see Section 5 for details). Usually, this value is 1% higher than the SFR that produces the minimum simple payback. The figure shows the optimum SFR value adjacent to each data point. Both lines show a steady increase in savings, followed by a decline at high intensities. The decline reflects the control system selected, 3-level + off control. Switched control achieves the greatest savings in applications in which there are many hours when lights can be completely shut off. As the lighting intensity increases, the number of hours that require a mix of daylighting and electric lighting increases, as does the number of hours when the available daylight is not sufficient to turn off the first “step” of electric lighting. Dimming control is able to capture additional savings in these cases (Note: the impact of control system on energy savings will be compared later in this section).

Figure 4-4 shows analogous results for savings in Phoenix. The key difference between Phoenix and Burlington is that greater solar insolation in Phoenix enables the toplighting system to achieve higher savings with a lower SFR. The combination of higher savings and the need for less skylight area (which, in turn, decreases toplighting system cost) translates into shorter simple payback periods (see Section 5.3 for a discussion of payback for each climate).

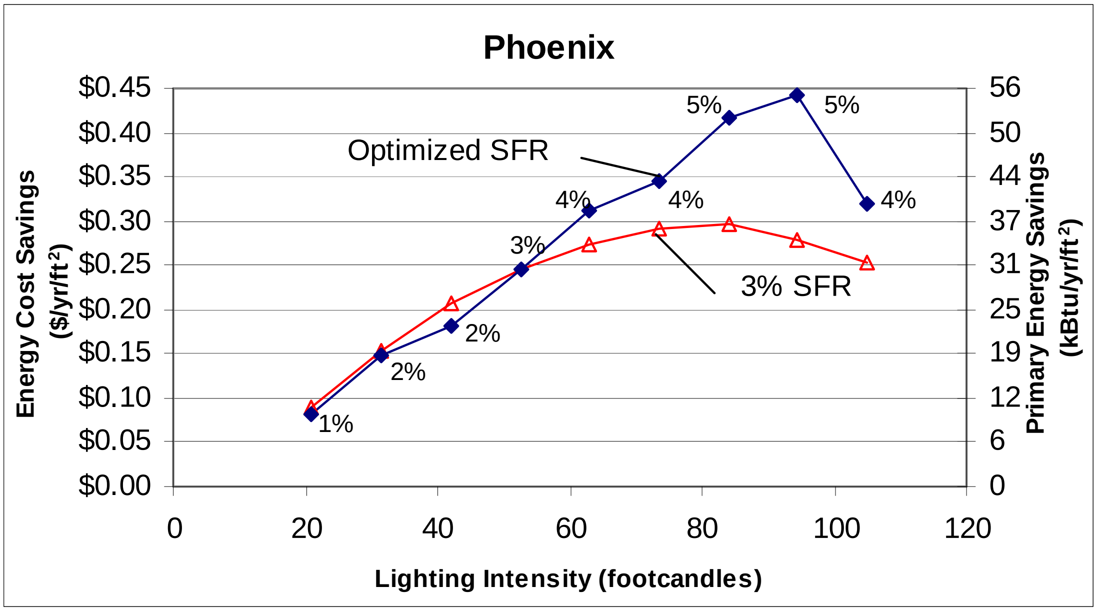

Figure 4-4: Energy Cost Savings as a Function of Required Lighting Intensity / Lighting Power Density, Big Box Retail, Phoenix

SkyCalc™ calculated lighting intensity from wall color, partitions/shelving characteristics, fixture technology (e.g. fluorescent), fixture height, and the ASHRAE lighting power density for each building type. We assumed that an energy-conscious designer that would choose to implement toplighting would also choose reasonably energy-efficient wall colors, partition design, and fixtures. The choices in each of these areas were developed through discussions with industry experts. In addition, we set fixture heights equal to ceiling height in the office and schools with drop ceilings, and at 4ft below ceiling height in the open-frame ceiling cases, i.e., warehouse and big-box retail. Less-efficient lighting technology, less reflective wall color, and increased partitions/shelving all would improve the economics of toplighting, but the rational designer would likely choose these energy-efficient measures before adding toplighting because they are simpler and lower-cost changes.

Figure 4-5 shows how various types of lighting can lead to different power densities and energy savings. Decreasing lighting efficacy (and thus increasing lighting power density while maintaining constant illuminance) linearly increases energy savings. In fact, at very low power densities (not shown in the figure) the total savings becomes negative, because in that case the increased cooling load resulting from adding skylights is greater than the cooling load and lighting energy savings resulting from shutting off lights.

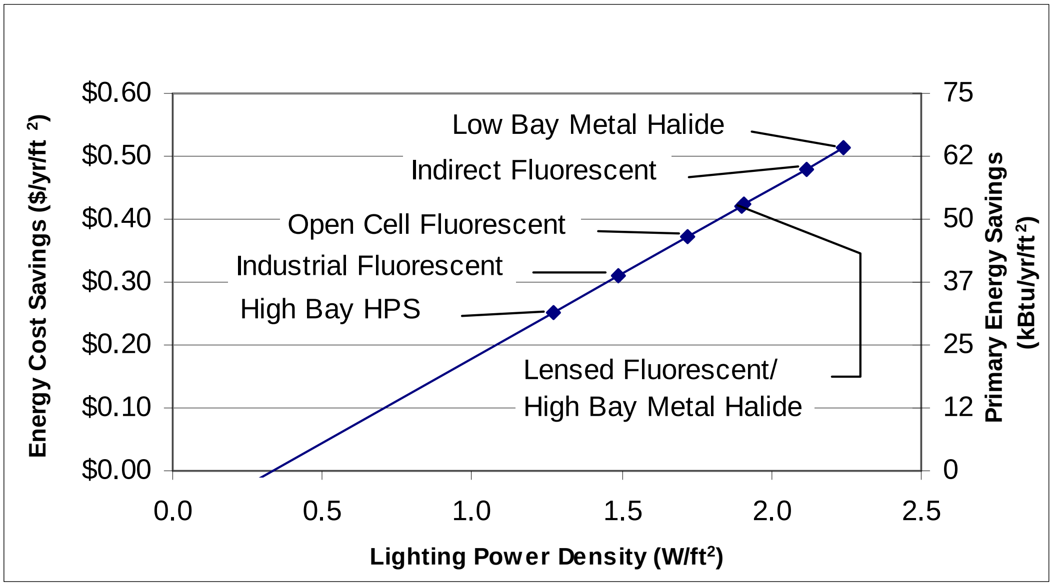

Figure 4-5: Annual Energy Cost Savings as a Function of Lighting Power Density / Light-Source Efficacy, Illuminance = 63 fc, Big Box Retail, Phoenix, 4% SFR[8]

4.5 Lighting Control

Effective lighting controls are key to achieving energy savings. For this analysis we chose a single-zone system because the areas analyzed are assumed to be single-use spaces without sidelighting. Because daylight levels *from toplighting* are relatively uniform throughout the space, the multiple zones that would be needed in sidelighting applications are not required. For example, the 10,000 ft^2 of office space represents a core open-plan space that does not receive significant sidelighting, requires a consistent level of lighting, and does not have private offices. We analyzed the energy impact of three different types of control: Dimming to 5% light level, switching (on/off) of 3 interleaved circuits, and switching of all lights together. Figures 4-6 and 4-7 show energy savings results for each type of switching control in Burlington and Phoenix, respectively.

[8] This chart was generated using SkyCalc default efficacies (CEC 1999).

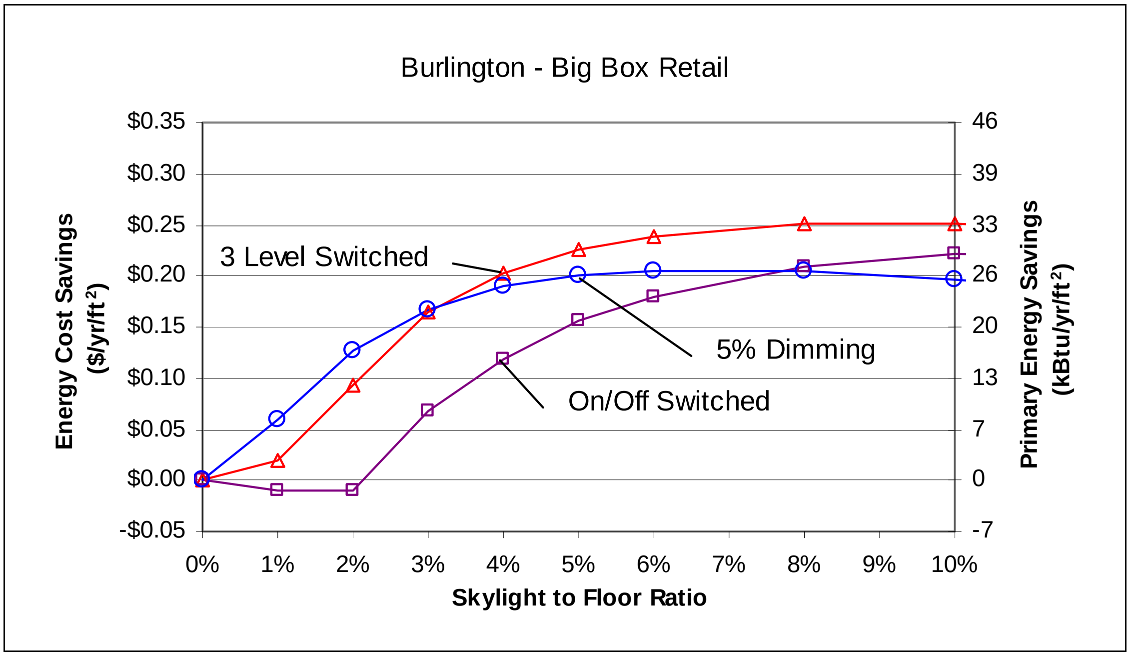

Figure 4-6: Effect of Lighting Control Type on Energy and Cost Savings, Big Box Retail, Burlington

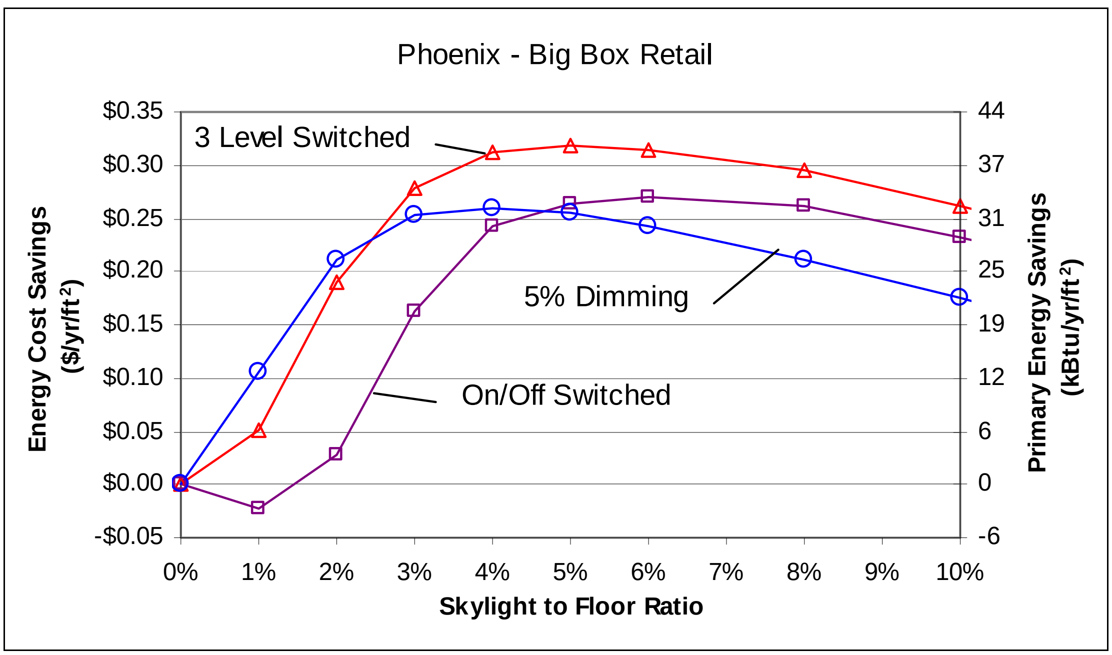

Figure 4-7: Effect of Lighting Control Type on Energy and Cost Savings, Big Box Retail, Phoenix

In the SFR range usually of interest for toplighting, 3 to 5 percent, the 3-level switched control system achieved the highest savings. The simple on/off control is insufficient because there are significant time periods when sunlight levels do not allow all of electric lights to be shut off. The dimming system achieves higher savings at low SFRs, because there are more hours when light levels are between steps in the multi-level switched system. When lights cannot be switched off, dimming allows the maximum savings to be achieved. However, dimming decreases efficacy, and does not allow for the lights to be completely shut off. In many cases, the minimum energy usage that can be achieved is approximately 20% of full power (at 5% light level). This results in losses at higher SFRs when there is often sufficient sunlight available for the electric lights to be shut off. Furthermore, dimming systems cost 2 to 3 times more (HMG 2007).

4.6 Skylight Characteristics

The primary factors influencing the economics of toplighting are climate and building type (primarily due to LPD, schedule, and light well needs); nonetheless, appropriate skylight technology selection is also crucial. The key performance attributes of a skylight for daylighting are good diffusing properties to aid in light distribution and avoid glare and high visible transmittance (VT). Other desirable properties that are much less important for daylighting applications are low solar-heat-gain coefficient (SHGC) and conductance (U-Value)[9]. Figure 4-8 illustrates the rational for this prioritization.

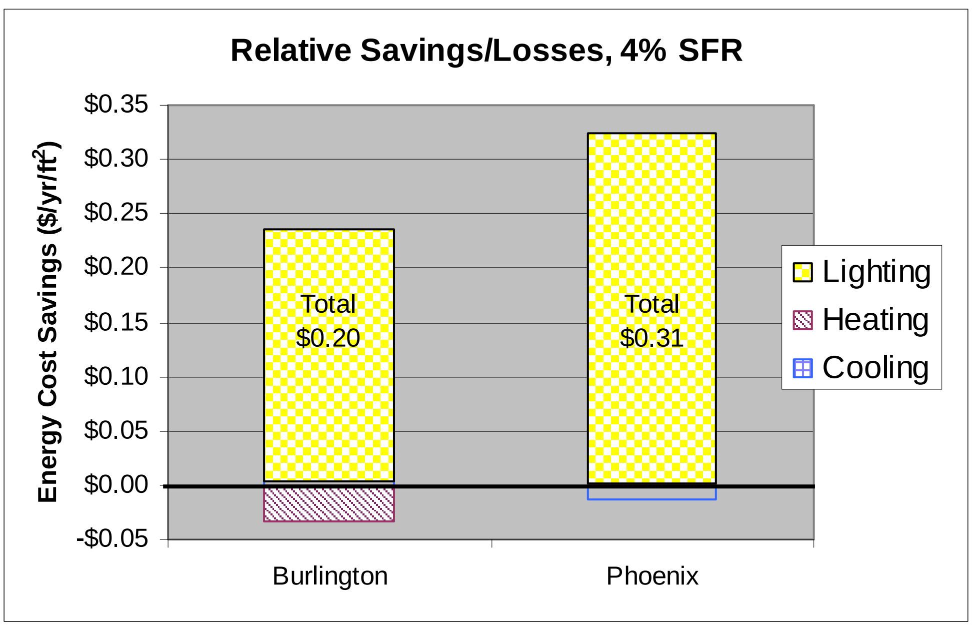

Figure 4-8: Relative Savings/Losses from Lighting and HVAC, Big Box Retail, Phoenix

Reduced lighting energy use ranks as, by far, the greatest factor in the annual savings at economically optimum SFRs. The reduction in lighting energy use is directly related to VT, i.e. the higher the VT, the lower the total skylight area needed to achieve a given lighting energy savings. Lower total skylight area reduces cost and energy losses. To further minimize energy *losses*, in most climates, the SHGC and U-value of the skylight should be as low as possible[3]. However, because heating and cooling energy losses are small relative to lighting energy savings, if reducing SHGC or U-Value results in any

[9] In very cold climates it may be somewhat advantageous to have a high SHGC.

significant reduction in VT it is generally not a beneficial tradeoff at SFRs in the range expected to be economically optimal, i.e., below 5%.

For simplicity, we used a single baseline skylight for all climates: a double-glazed, domed, acrylic prismatic design with a small amount of diffusing white added to the plastic of the second layer. This skylight achieves a high VT (VT= 65%) while also providing sufficient diffusion. It has an SHGC of 53% and a U-value of 0.81, representing a good compromise between useable light and potential for energy losses. Figures 4-9 and 4-10 show a comparison between the base case skylight and other realistic options, listed in Table 4-2, in Burlington and Phoenix, respectively.

Table 4-2: Skylight Characteristics for Performance Comparison

Skylight Type	VT	SHGC	U-Value
Baseline: Acrylic, Double Glazed, Domed	65%	53%	0.81
Acrylic, Single Glazed, Medium White	62%	59%	1.33
Glass, Double Glazed, Low-e, Argon, Clear over Clear + Prismatic Diffuser	61%	35%	0.4
Baseline Acrylic, Double Glazed – Flat	65%	53%	0.81

We chose the skylights in Table 4-2 to illustrate the effect of differences in available skylights while restricting the field to high-performance skylights that provide sufficient diffusion for visual comfort, making them realistic choices for energy conscious toplighting. A description of how each compares to the baseline unit follows.

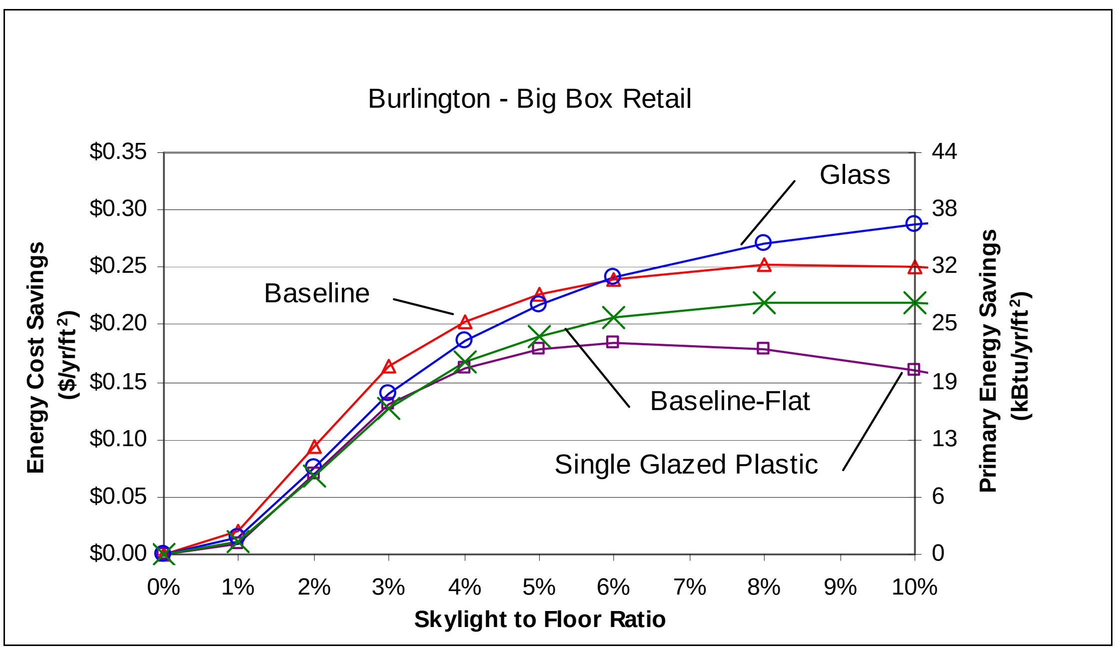

Figure 4-9: Effect of Skylight Type, Big Box Retail, Burlington

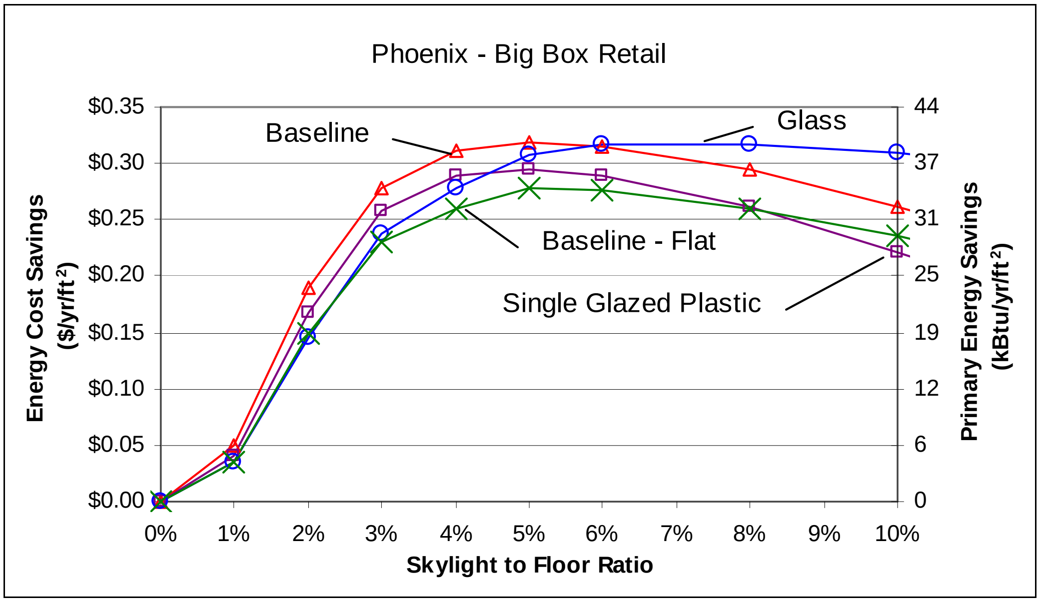

Figure 4-10: Effect of Skylight Type, Big Box Retail, Phoenix

The single-glazed acrylic skylight saves less energy at low SFRs because it has a lower VT than the baseline unit. Typically, a single-glazed skylight of the same type will have a higher VT; however, in this case the plastic has increased diffusing properties to ensure that sufficient diffusion occurs as the light passes through the single sheet. As a result, VT decreases. Many skylights provide higher VT values than the base case unit., but we excluded them because manufacturers indicated that they typically do not provide sufficient diffusion for visual comfort. At high SFRs, the relative energy performance of single-glazed plastic skylight performance suffers further due to higher SHGC and U-value.

The high-performance glass skylight saves less energy at SFRs up to about 6%, primarily because its flat profile decreases the quantity of light it captures at lower sun angles in the morning and evening. To understand the impact of this effect, we evaluated a flat skylight that otherwise has the same properties as the domed baseline unit (i.e., the "baseline-flat" case). The resulting decrease in savings is significant at SFRs of 3 to 4%, i.e., approximately a 17% decrease. On the other hand, at high SFRs, the flat skylight's performance relative to the baseline improves to only about a 10% decrease because the increased surface area of a domed skylight increases thermal losses, which become more significant as SFR increases. For this same reason, the glass skylight has better performance than the baseline unit at SFRs above 6%, i.e., at higher SFRs, the superior SHGC and U-value overcome the inferior light capturing characteristics.

This comparison leads to the conclusion that, for skylight to floor ratios that are likely to be economic optimums, i.e., 2 to 5%, the base-case skylight is a good choice to generate the highest possible energy cost savings. In a cold climate, the glass skylights achieve similar energy performance to the base case; however, because they cost approximately twice as much as baseline units, they would not be an economically attractive option.

Similarly, the single-paned plastic skylight may warrant consideration in warmer climates, but the cost savings of using single glazing is limited to about 10%. The difference in a drop ceiling situation is even smaller due to the high cost of skylight wells, i.e., the difference in cost is less than 2%.

4.7 Light Well

Before the light from a skylight can reach the living space it must pass through the roof structure and any plenum space between the roof and ceiling. In the warehouse or big box retail store, we estimate this to be about one foot; this includes the height of the skylight curb and the depth of insulation. A concrete roof would add an additional 4-6" of total depth. For these building types, we assume that there is no ceiling below the roof, obviating the need for a light well. In contrast, for the office and school examples, the baseline buildings include a drop ceiling that is approximately 3 feet below the roof, resulting in a total well height of 4 feet. Because a 4-foot well decrease the effectiveness of the toplighting assembly and to allow greater distribution of light, these toplighting assemblies include a 2-foot high splay (45^o) added to the bottom of the well. This results in 2ft of straight-walled well depth, followed by 2ft of depth that is splayed at 45 degrees (see Figure 4-11). The performance of this arrangement is generally equivalent what would be achieved by a 12-foot ceiling with a 2-foot straight-walled light well with no splay.

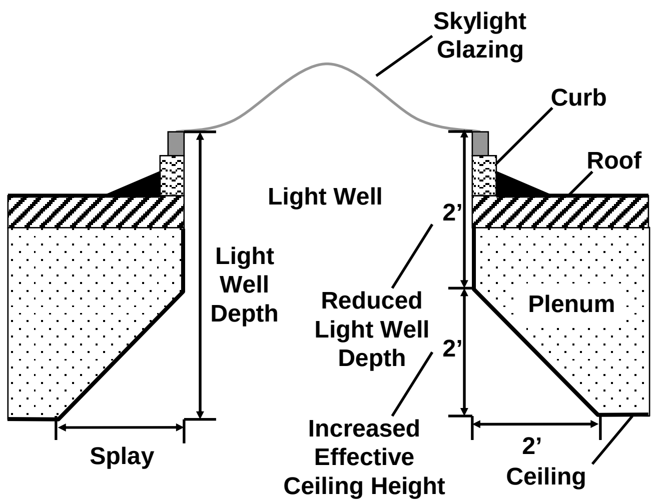

Figure 4-11: Skylight and Light Well Assembly Schematic

The addition of a light well to span a plenum space adds significant cost (e.g., approximately $1,000) and reduces the amount of useable light that enters the space. The 4ft well depth represents a favorable case in which the ceiling is fairly close to the roof. In some less favorable cases, this distance could be as great as 10ft. Figure 4-12 shows how the length of the straight-wall section of a light well reduces the effectiveness of the skylight assembly. The well efficacy shown is calculated for 80% reflective white paint using the equation described in the 2005 Building Efficiency Standards (CEC 2003b).

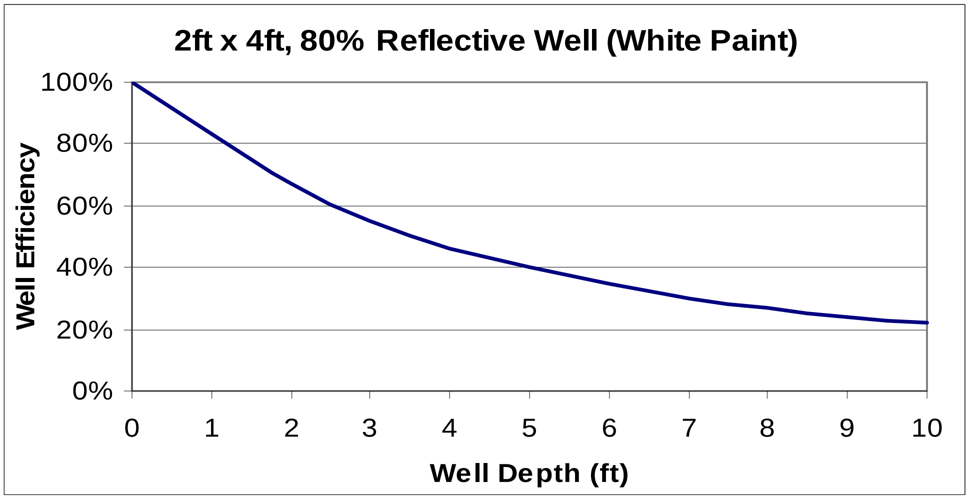

Figure 4-12: Well Efficiency as a Function of Well Depth

4.8 Energy Rates

As with any site-based energy-saving technology, energy rates have a major effect upon the system's economic viability. For this analysis, we used the most recent U.S. national commercial average rates available from the EIA (Energy Information Administration): 2005 average electricity rate, $0.087 / kWh; 2005 average natural gas rate, $1.124 / Therm (EIA 2005). Figure 4-13 shows how savings/ ft2 varies with electric rate. Gas rate is insignificant in Phoenix, because heating savings are less than 1% of lighting savings. Even in the case of the coldest climate analyzed, Burlington, heating losses equal only about 15% of lighting savings (at near-optimal SFRs). Therefore, electric rate has a much larger impact on energy cost savings from toplighting than the gas rate.

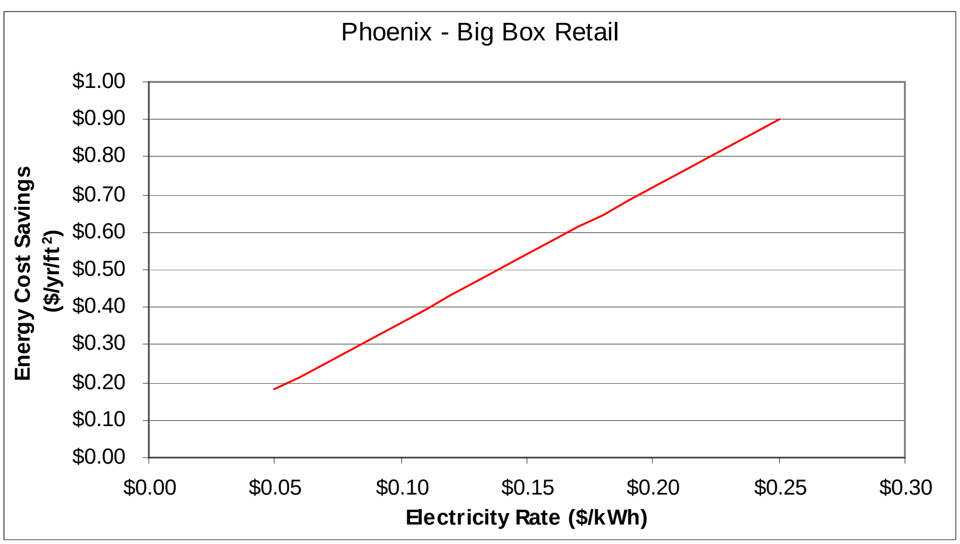

Figure 4-13: Annual Energy Cost Savings as a Function of Electricity Rate

5 Commercial Primary Energy and Energy Cost Savings Potential

The performance of toplighting varies significantly depending on climate and building type. To generate an estimate of the national energy savings potential and the economic attractiveness of toplighting across the U.S., we analyzed toplighting in 4 building types and 5 cities. Figure 5-1 shows how savings varies in the 5 cities modeled, using national average energy rates instead of local rates to isolate climate effects. The warmer cities tend to provide better savings because they have greater solar insolation that allows a greater reduction in lighting energy usage for a given skylight to floor ratio (SFR).

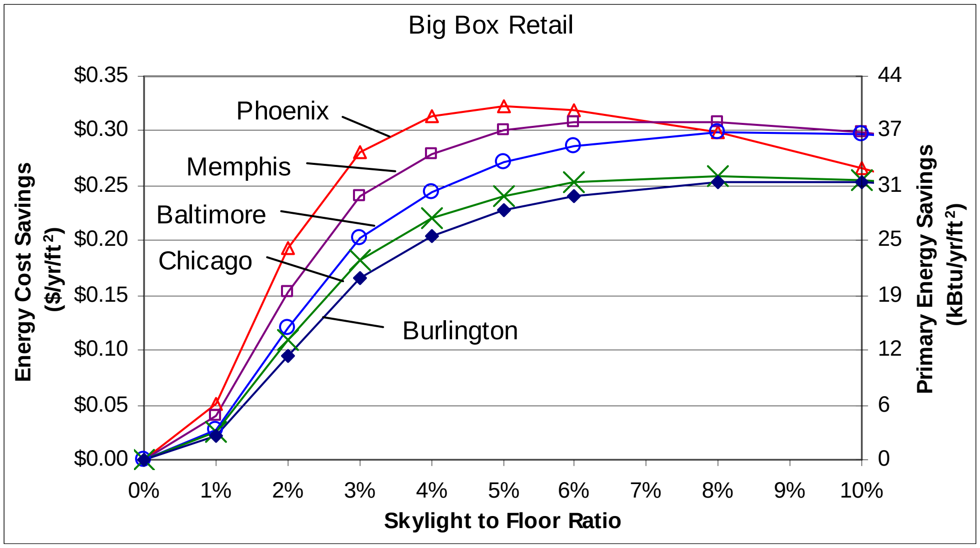

Figure 5-1: Total Annual Energy Cost Savings in 5 cities as a Function of SFR, Big Box Retail

As discussed in Section 4.6, heating and cooling losses are second-order effects at low SFRs. Figures 5-2 and 5-3 show that, even in the coldest climate modeled, the heating losses do not become significant until unreasonably high SFRs are selected.

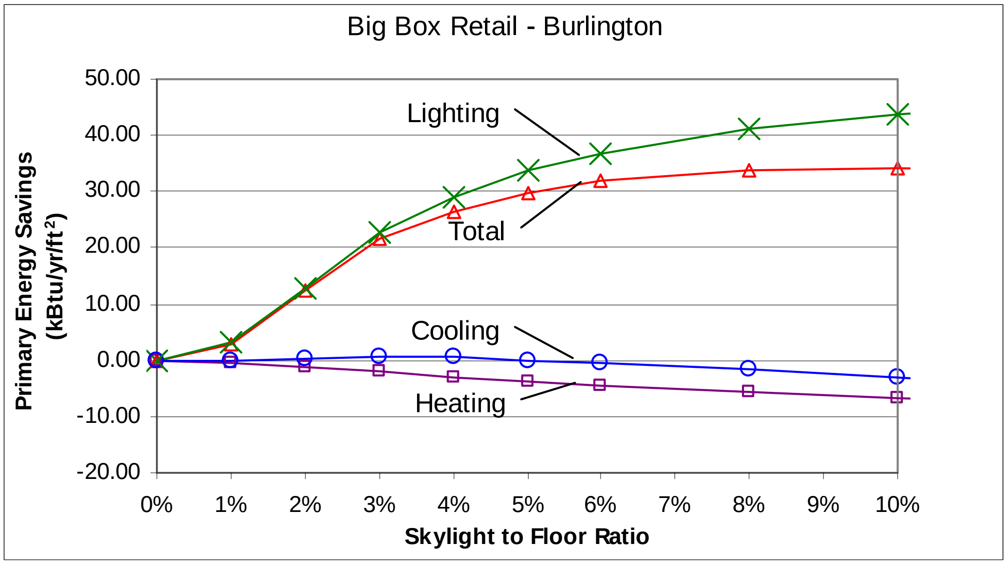

Figure 5-2: Annual Primary Energy Savings by End Use (lighting, cooling, heating) as a Function of SFR, Burlington

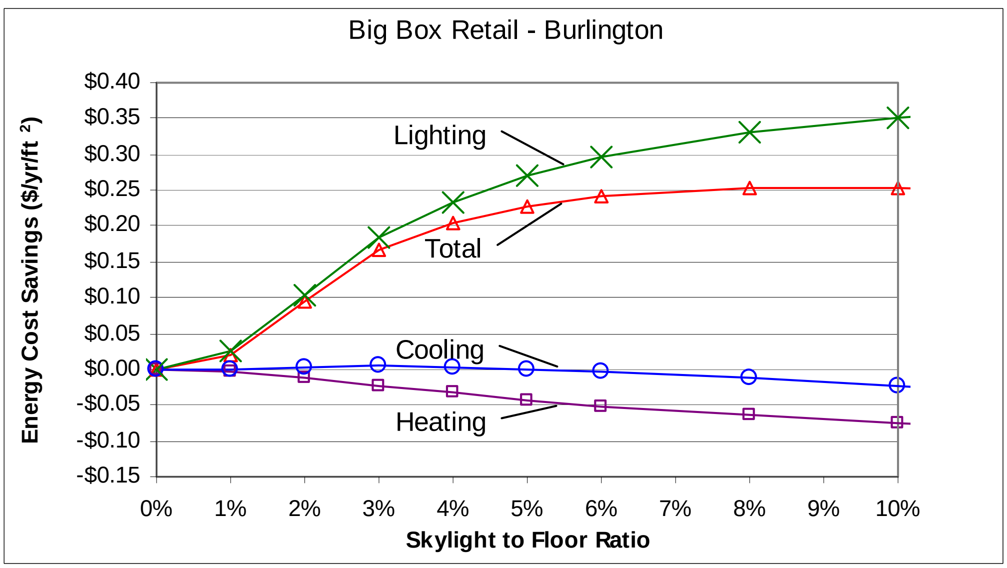

Figure 5-3: Annual Energy Cost Savings by End Use (lighting, cooling, heating) as a Function of SFR, Burlington

Figures 5-4 and 5-5 show an analogous result in the warmest climate, i.e., cooling losses do not become significant until high SFRs are selected. Increasing insulating characteristics of the skylight technology would marginally increase savings by reducing losses and possibly allowing a slightly higher SFR to be feasible, but, as can be seen in the figures, lighting is the dominant component controlling savings. When lighting savings start to plateau, it is no longer economical to add additional skylight area.

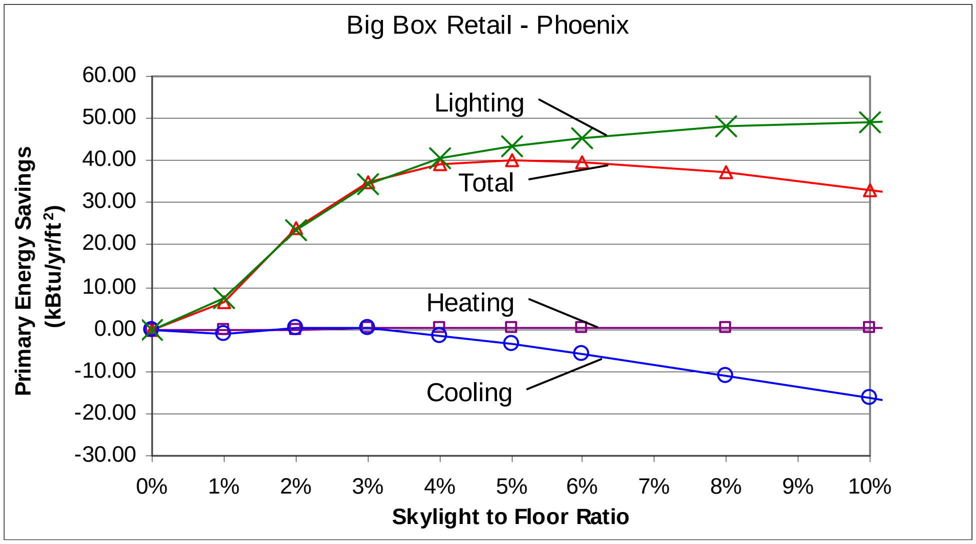

Figure 5-4: Annual Primary Energy Savings by End Use (lighting, cooling, heating) as a Function of SFR, Phoenix

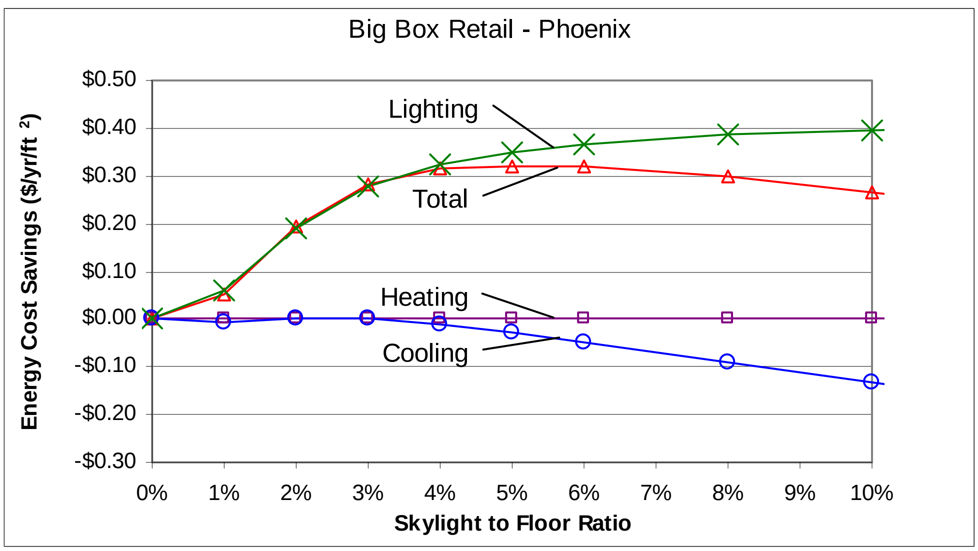

Figure 5-5: Annual Energy Cost Savings by End Use (lighting, cooling, heating) as a Function of SFR, Phoenix

The 4 building types selected (office, school, big box retail, and warehouse) represent building types that industry representatives view as having high potential for increased use of toplighting. Big-box retail and warehouse are, by far, the largest current market for toplighting systems. Offices are the most common commercial building type, and some studies have suggested daylight is important to learning, which has increased interest in use of toplighting in schools. Furthermore, these building types represent enough variation to allow practitioners to extrapolate results to other similar building types. For example, results for a police station are likely to be approximately 2/5 better than results for offices, because police stations generally use a 7-day lighting schedule rather than a 5-day schedule, but otherwise have similar characteristics.

Figure 5-6 shows a savings comparison of the 4 building types in Phoenix. Due to high lighting power densities (LPD), a 7-day schedule that overlaps with available solar insolation, and a lack of light-absorbing light wells, big-box retail provides by far the best savings opportunity. Warehouses share a 7-day lighting schedule and also do not have light wells, but have approximately ½ the lighting power density, which reduces the savings opportunity (by approximately ½ at 4% SFR). Schools and offices have very similar characteristics, i.e., both use light wells and both have a 5-day schedule. At optimum SFR, the 33% lower LPD in offices relative to big-box retail results in about a 30% reduction in savings, the shorter and less intense lighting schedule decreases savings by about 40%, and having 2 feet of straight light well depth instead of 1foot causes about a 10% decrease in savings. Overall, savings in the office case is approximately 35% of savings in the big-box retail case. The superior performance of schools is due to slightly higher power densities - 1.2 W/ft^2 versus 1.0 W/ft^2. In this case, the school modeled operates for 12 months of each year; if instead it were only used for 9 months (i.e., omitting June, July, August), savings in Phoenix would be reduced by approximately 26%. Locations with greater seasonal variation in solar insolation would see slightly higher reductions in savings, assuming the occupied 9 months spanned the colder months of the year. Because of lower lighting intensity requirements in warehouses, savings relative to SFR will tend to plateau more quickly, resulting in a lower optimum SFR.

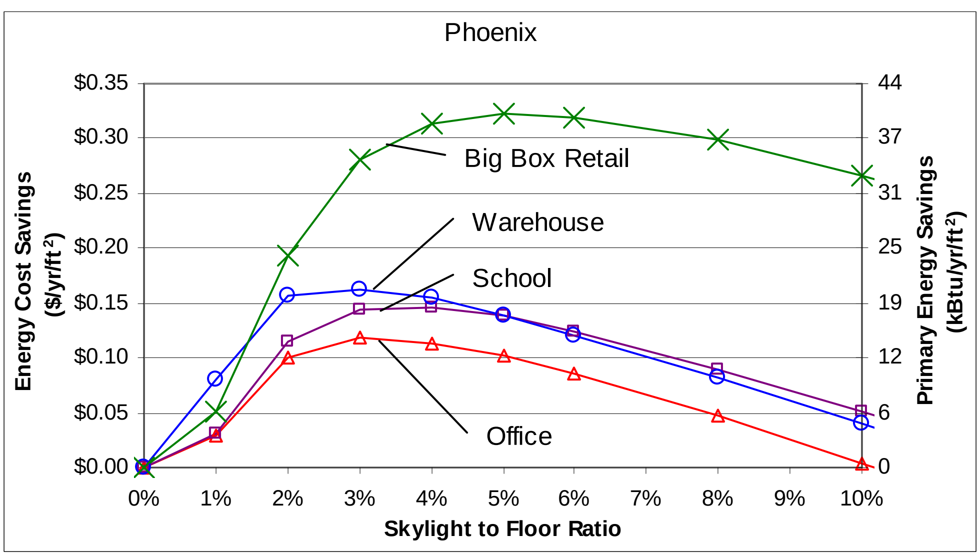

Figure 5-6: Total Annual Energy Cost Savings for 4 Building Types as a Function of SFR, Phoenix

We selected the cities used in modeling from the ASRHRAE 90.1 representative cities list (see Table 5-1). We used the 5 cities as an approximation for the 7 most populous U.S. climate zones by combining zones 1 and 2, and zones 6 and 7. Table 5-2 shows the climate zones and the representative city used for modeling.

Table 5-1: ASHRAE 90.1 Thermal Climate Zone Definitions

Zone No.	Climate Zone Name and Type	Thermal Criteria	Representative U.S. City
1A	Very Hot – Humid	5000 <CDD10^{o}C	Miami, FL
1B	Very Hot – Dry	5000 < CDD10^{o}C	---
2A	Hot – Humid	3500 <CDD10^{o}C< 5000	Houston, TX
2B	Hot – Dry	3500 <CDD10^{o}C< 5000	Phoenix, AX
3A	Warm – Humid	3500 <CDD10^{o}C< 3500	Memphis, TN
3B	Warm – Dry	2500 <CDD10^{o}C< 3500	El Paso, TX
3C	Warm – Marine	HDD18^{o}C < 2000	San Francisco, CA
4A	Mixed – Humid	2500 < CDD0^{o}C and HDD18^{o}C < 3000	Baltimore, MD
4B	Mixed – Dry	2500 < CDD10^{o}C and HDD18^{o}C < 3000	Albuquerque, NM
4C	Mixed – marine	2000 <HDD18^{o}C < 3000	Salem, OR
5A	Cool – Humid	3000 <HDD18^{o}C < 4000	Chicago, IL
5B	Cool – Dry	3000 <HDD18^{o}C < 4000	Boise, ID
5C	Cool – Marine	3000 <HDD18^{o}C < 4000	---
6A	Cold – Humid	4000 <HDD18^{o}C < 5000	Burlington, VT
6B	Cold – Dry	4000 <HDD18^{o}C < 5000	Helena, MT
7	Very Cold	5000 <HDD18^{o}C < 7000	Duluth, MN
8	Subarctic	7000 <Hdd18^{o}C	Fairbanks, AK

Table 5-2: Climate Zones and Representative Cities Selected for Modeling

Climate Zone	City
1, 2	Phoenix, AZ
3	Memphis, TN
4	Baltimore, MD
5	Chicago, IL
6, 7	Burlington, VT

Modeling each building in each city resulted in 20 unique modeling runs. In each modeling run the SkyCalc™ model starts with a user-specified design skylight-to-floor ratio (SFR) and scales skylight size up and down from there to achieve higher and lower SFRs. To make results as close to physical reality as possible, we selected integer sizes and numbers of skylights for the optimum SFR for each of the 20 cases. This resulted in a 4% SFR (25 - 4'x 4' skylights) for the office and school cases, except in Phoenix where 3% SFR is optimum, and 25 – 3'x 4' skylights were substituted. In the warehouse case, 15 – 4'x 5' skylights results in a 3% SFR, except in Phoenix where 10 4'x 5' skylights are used, resulting in a 2% SFR. The big-box retail base case is 5 times the floor area of the other building types (50,000 ft^2), requiring 63 – 4'x8' to produce the optimum 4% SFR in all cities (see Table 5-3).

Table 5-3: Optimum SFR, and Number and Size of Skylights by Climate Zone and Building Type

Climate Zone	City	Office	School	Warehouse	Retail
1, 2	Phoenix, AZ	3% - 25 3'x4'	3% - 25 3'x4'	2% - 10 4'x5'	4% - 63 4'x8'
3	Memphis, TN	4% - 25 4'x4'	4% - 25 4'x4'	3% - 15 4'x5'	4% - 63 4'x8'
4	Baltimore, MD	4% - 25 4'x4'	4% - 25 4'x4'	3% - 15 4'x5'	4% - 63 4'x8'
5	Chicago, IL	4% - 25 4'x4'	4% - 25 4'x4'	3% - 15 4'x5'	4% - 63 4'x8'
6, 7	Burlington, VT	4% - 25 4'x4'	4% - 25 4'x4'	3% - 15 4'x5'	4% - 63 4'x8'

Using cost estimates (see Section 5.2) we enhanced the SkyCalc™ model to generate a simple payback for a range of SFRs in each of the 20 cases. To represent a rational economic purchase decision, we optimized the SFR to the highest integer ratio that is within ½ year of the minimum simple payback period, usually 1% higher than the SFR that produces the minimum simple payback. This method provides a higher absolute energy cost savings while maintaining a payback period close to the theoretical minimum. We used the optimized SFR to calculate primary energy savings and energy-cost savings for each modeled case (see Figure 5-7). In most cases the sensitivity of payback to SFR is fairly low near the optimum. As a result, slight increases or decreases in SFR that might result from mismatches between building size and shape and available skylight sizes will have a minimal effect on results.

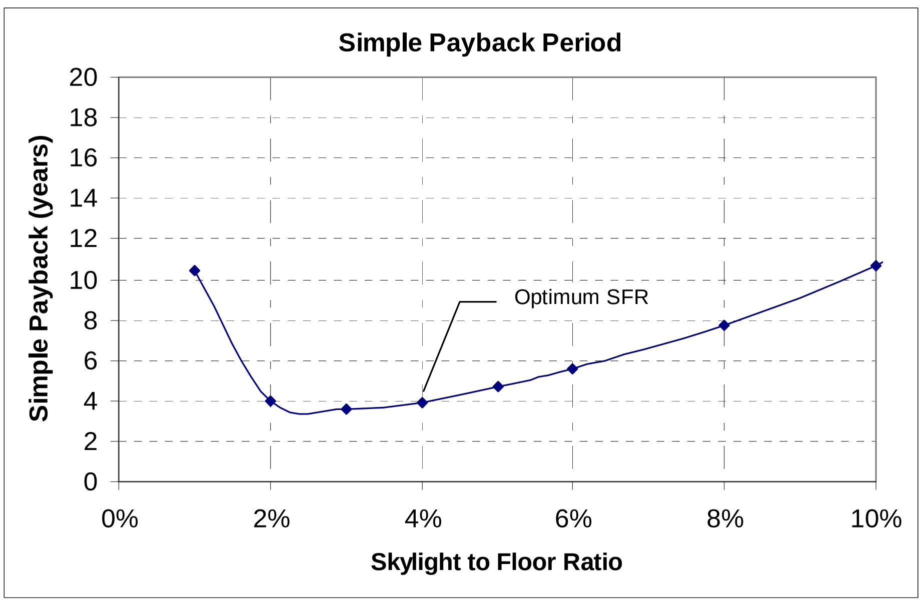

Figure 5-7: Simple Payback for Choosing Optimum SFR , Big-Box Retail, Phoenix

The following sections describe model outputs: Section 5.1 presents primary energy savings, Section 5.2 presents cost results, and Sections 5.3 presents payback results.

5.1 Primary Energy Savings

Savings potential per square foot varies both by climate and by building type. The most pronounced variation is by building type, with offices achieving only about half the savings per square foot that is possible in big-box retail buildings. Sunnier climates allow for greater savings with a given skylight area, particularly in the big-box retail case where savings potential is highest. Savings potential in Burlington, VT is about 70% of savings in Phoenix. Higher optimum SFRs in Memphis result in apparently incongruous increases in savings in Memphis over Phoenix (see Table 5-4).

Table 5-4: Annual Primary Energy Savings by Climate Zone and Building Type, kBtu/yr/ ft^2

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	15	18	19	39
3	Memphis, TN	16	20	20	35
4	Baltimore, MD	16	18	18	31
5	Chicago, IL	15	17	17	28
6, 7	Burlington, VT	15	16	16	27

Stated another way, the percent of lighting energy saved ranged from 34% to 54%(see Table 5-5). The percent savings does not correlate directly to primary energy savings, because schedule and lighting intensity requirements vary. In fact, while savings are highest in retail buildings, the percent of lighting energy saved is actually lowest in that case. The retail lighting schedule extends to 10pm, whereas the other schedules start to decrease around 5pm. This is a significant period during which sunlight is unavailable, resulting in a lower percentage lighting energy saved. Total primary energy savings is still higher in big-box retail, because total lighting power use is much higher. The warehouse case achieves the highest percentage lighting energy decrease because the 7-day lighting schedule produces higher savings and the lack of light wells allows for lower installation costs resulting in a higher optimum SFR relative to lighting intensity requirements.

Table 5-5: Percent Lighting Energy Saved by Climate Zone and Building Type

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	49%	49%	50%	47%
3	Memphis, TN	51%	51%	54%	41%
4	Baltimore, MD	47%	47%	49%	36%
5	Chicago, IL	45%	45%	48%	35%
6, 7	Burlington, VT	45%	45%	48%	34%

To generate regional technical energy savings potential estimates, we combined primary energy savings per square foot with an estimate of total, under roof, floor space for the associated building type and climate zone (see Table 5-6). While total office floor space is higher than the other building types, the area under a roof is lower, because offices are often multistory. We used the floor area of non-mall retail as a proxy for big-box retail floor area, because the available data did not include and estimate for big-box retail floor area.

Table 5-6: Estimated Top Floor Floor Space (*Millions* of ft^2, EIA 2003)

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	660	1,140	1,310	440
3	Memphis, TN	920	1,300	1,540	930
4	Baltimore, MD	1,130	1,220	1,740	880
5	Chicago, IL	1,440	1,690	2,310	710
6, 7	Burlington, VT	710	690	880	430

The national technical primary energy savings potential, i.e., assuming complete penetration of all floor space below a roof in the four building types examined[10], is about **0.4 quads**. While big-box retail offers the greatest savings per square foot, the total savings potential is not generally highest for retail across climate zones, because the total floor areas of the other building types are higher (see Table 5-7 and Figure 5-8).

Table 5-7: Annual Primary Energy Savings Technical Potential, Trillion Btu/yr, by Climate Zone & Building Type

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	10	20	25	17
3	Memphis, TN	15	25	31	33
4	Baltimore, MD	18	22	32	27
5	Chicago, IL	21	28	40	20
6, 7	Burlington, VT	11	11	14	11
	Total	**74**	**107**	**143**	**108**

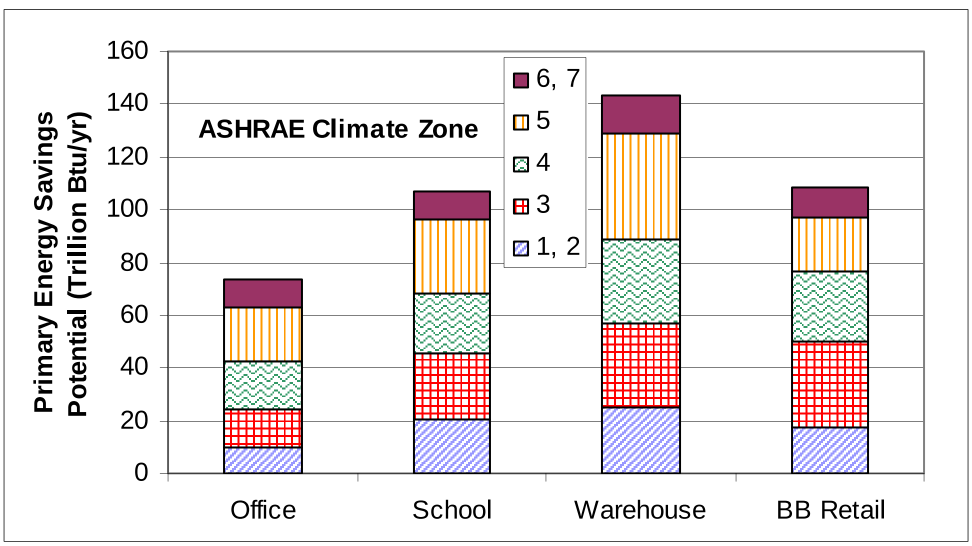

Figure 5-8: Annual Primary Energy Savings Technical Potential, by Climate Zone and Building Type

[10] Real-world factors, such as mechanical equipment, will limit the actual square footage that can be daylit.

5.2 Cost of Toplighting

We estimated the cost of the base-case system in new buildings using available literature and vetted our estimates through industry interviews (see Table 5-8; see Appendix A for the questionnaires used for the two rounds of interviews).

Table 5-8: Cost Verification Interviews

Base Case Cost Contributors
Skylight Manufacturers
Lighting Controls Manufacturers
Day Lighting Designers

Detailed cost inputs were (HMG 2007, PG&E 2006):

School/Office (4% SFR)[11]

- Controls: \$3,818 (10,000 ft^2)
  - \$2,500 – 3 level and off control, 1 zone/sensor, Single use space, no sidelighting
  - \$1,318 – incremental wiring costs
- Skylights: \$1,719 each (25 - 4' x 4')
  - \$1,048 (light well and other fixed cost)
  - \$42/ft^2 glazing (small size = high cost)

Warehouse (3% SFR)[12]

- Controls same as School/Office
- Skylights: \$580 each (15 - 4' x 5')
  - \$115 (fixed cost, ***NO*** light well)
  - \$23/ft^2 glazing (large size = low cost)

Big-Box Retail (4% SFR)

- Controls: \$8,228 (50,000 ft^2)
  - \$2,500 – 3 level and off control, 1 zone/sensor, Single use space, no sidelighting
  - \$5,728 – incremental wiring costs
- Skylights: \$860 each (63 - 4' x 8')
  - \$115 (fixed cost, *not including* light well)
  - \$23/ft^2 glazing (large size = low cost)

Installed cost per ft^2 for schools and offices is almost four times the cost per ft^2 in big-box retail stores and warehouses (see Figure 5-9).

[11] In Phoenix, due to higher solar insolation, the optimum SFR for offices and schools was 3%, resulting in the use of 25 - 4'x3' skylights instead.

[12] In Phoenix, due to higher solar insolation, the optimum SFR for warehouses was 2%, resulting in the use of 10 - 4'x5' skylights instead.

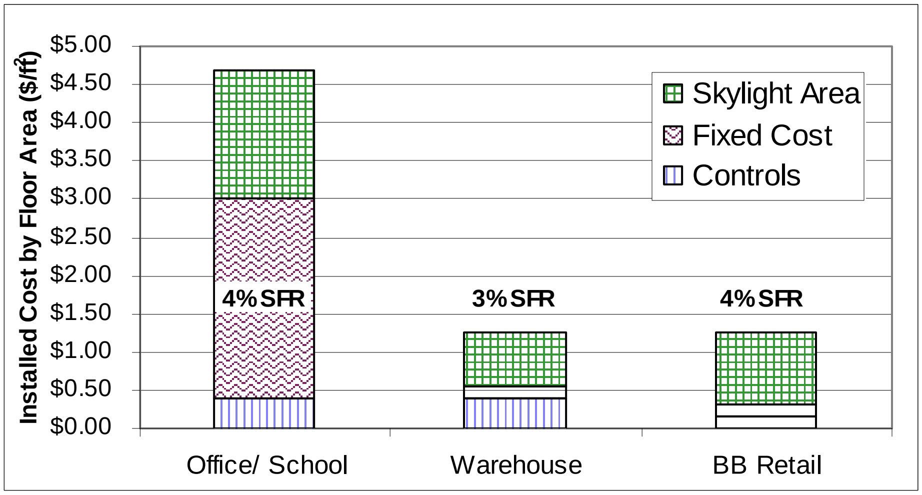

Figure 5-9: First Cost of Optimum Toplighting System, by Building Type

The addition of a light well and the higher cost of using a larger number of smaller skylights drives up cost in the office and school examples. The light well adds almost $1,000 to the fixed cost per skylight, and adds to the cost per unit area of skylight glazing. Controls account for a small portion of total cost in all building types, ranging from 8 to 24%, or $0.16 to $0.38/ft^2 of floor area. *As a result, if skylights are already present, or will be installed for non-energy reasons, it is almost always worthwhile to invest in non-dimming lighting controls and, if possible, to tweak skylight design choices to facilitate toplighting.* Sidelighting complicates the use of controls, increasing costs and chances of user dissatisfaction. Therefore, the addition of controls will be easiest and most effective in areas that are solely or primarily toplit.

Table 5-9 provides the total cost per ft^2 by building type and climate zone.

Table 5-9: First Cost of Optimum Toplighting System in New Buildings, $/ ft^2, by Climate Zone and Building Type

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	$4.26	$4.26	$0.96	$1.25
3	Memphis, TN	$4.68	$4.68	$1.25	$1.25
4	Baltimore, MD	$4.68	$4.68	$1.25	$1.25
5	Chicago, IL	$4.68	$4.68	$1.25	$1.25
6, 7	Burlington, VT	$4.68	$4.68	$1.25	$1.25

If a dimming control system were used, instead of the selected circuit based control system, costs would likely increase by ~$0.40-$1.00/ft^2 or more to upgrade to dimmable ballasts and install control wiring.

5.3 Simple Payback Period

We calculated the simple payback period for each case by dividing the first cost of the optimum system by the energy cost savings (see Figure 5-10 and Table 5-10).

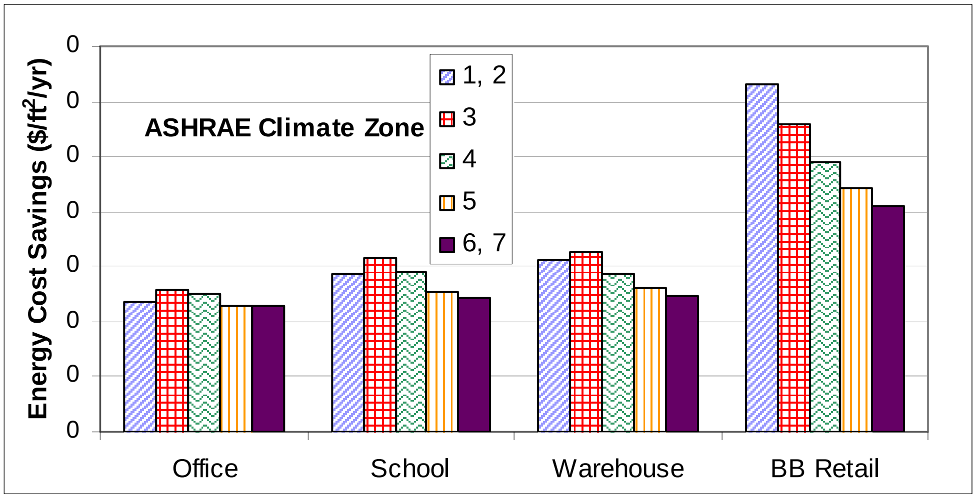

Figure 5-10: Energy Cost Savings, $/yr/ ft^2, by Climate Zone and Building Type

Table 5-10: Energy Cost Savings, $/yr/ ft^2, by Climate Zone and Building Type

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	$0.12	$0.14	$0.16	$0.32
3	Memphis, TN	$0.13	$0.16	$0.16	$0.28
4	Baltimore, MD	$0.13	$0.15	$0.14	$0.24
5	Chicago, IL	$0.11	$0.13	$0.13	$0.22
6, 7	Burlington, VT	$0.11	$0.12	$0.12	$0.21

The simple payback periods for the office and school cases range from 30 to 41 years, far too long for most building owners. However, in the warehouse and retail cases, paybacks were in a range (4 to 10 years) that could motivate some installations if other market barriers, such as awareness and education, can be overcome (see Figure 5-11 and Table 5-11).

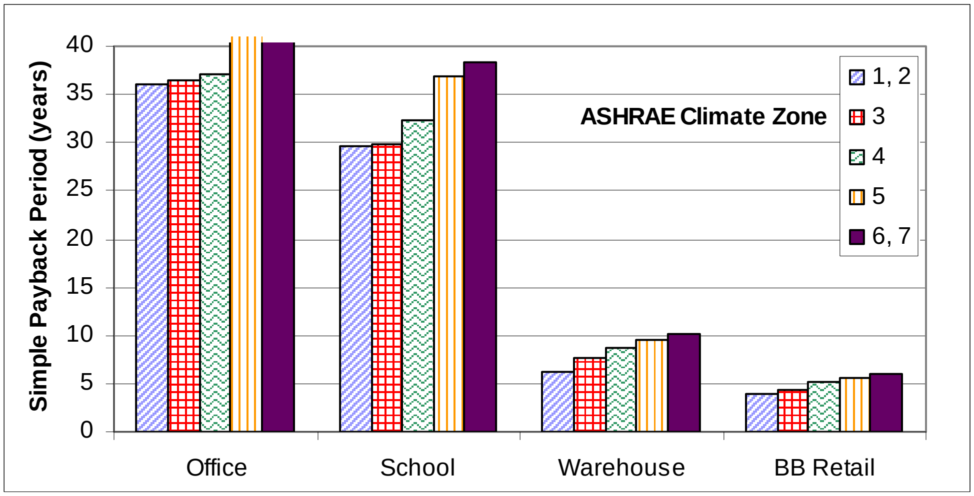

Figure 5-11: Simple Payback Resulting From Energy Savings, by Climate Zone and Building Type

Table 5-11: Simple Payback Period, years, by Climate Zone and Building Type

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	36	30	6.2	3.9
3	Memphis, TN	37	30	7.7	4.5
4	Baltimore, MD	37	32	8.7	5.1
5	Chicago, IL	41	37	9.6	5.6
6, 7	Burlington, VT	41	38	10.2	6.1

6 POTENTIAL SOLUTIONS TO FACILITATE GREATER USE OF TOPLIGHTING

6.1 Current Products and Research

We focused our exploration of innovative products and research on the office and school applications because traditional products are not cost effective in those cases. We evaluated:

- Light Tubes (Tubular Daylighting Devices)
- Fiber Optics
- Electrochromic Glass
- Heliostats
- Advanced Controls
- Translucent Panels with Increased Insulation
- Angularly Selective Glazing/Prismatic and Holographic Coatings

Light tubes are a highly engineered product that provide a number of significant advantages over traditional skylights (see Figure 6-1). They can include:

- Integrated reflectors to enhance light capture
- Fresnel lens or other enhancements to redirect low-angle light into the building
- Highly reflective (claims of up to 99.7%) factory-manufactured light wells
- Ceiling-level diffusers to reduce glare and hot spots
- Integrated shutters to control light output
- Largest current size is 22”dia, ~2.6 ft2

Source: Velux Skylights

Figure 6-1: Light-Tube Depiction

Oak Ridge National Laboratory has developed a fiber-optic-based hybrid lighting system that avoids large roof penetrations and can distribute light 30 to 50 feet into buildings, allowing light to reach another floor below the roof (see Figure 6-2; DOE 2007).

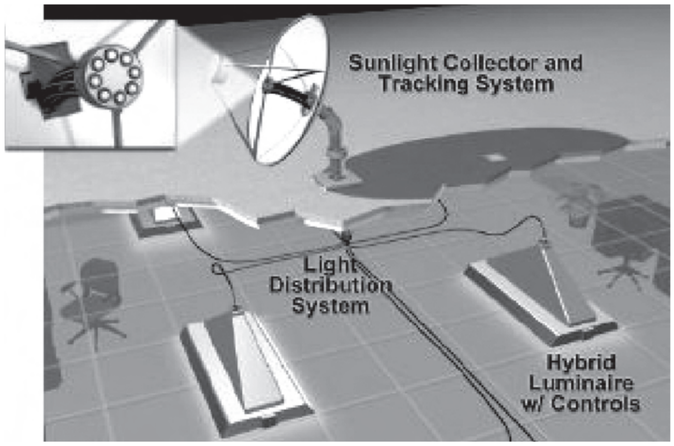

Figure 6-2: Fiber-Optic Hybrid Lighting Depiction (DOE 2007)

Currently available tubular daylighting and fiber optic systems are prohibitively expensive, but if costs decreased relative to traditional skylights, they could become preferred options in some applications, e.g., crowded plenums/roofs (see Table 6-1).

Table 6-1: Comparison of Toplighting Product Options

Product	Installed System Cost per Building ft^2 (Office/School)	Impact on Building Design	Maintenance and Cleaning
Skylights	~$5/ft^2	Can be Significant	Generally Minor
Light Tubes[13]	~$9/ft^2	Minimal	Generally Minor
Fiber Optics[14]	~$19/ft^2 (current) ~$4/ft^2 (projected 2012)	Very Minimal	Potentially Significant

Several other efforts are interesting, but most likely will not have a major impact in the short term. Electrochromic glass could allow better control of light from skylights, but is prohibitively expensive (e.g. $3,500 for 16ft^2). Heliostats are only effective with direct sunlight, and add cost and complexity (Littlefair 1990). Advances in lighting controls, such as auto calibrating photo sensors, have reduced the cost and risk associated with lighting control. New, more intelligent networked sensors will allow development of new control strategies. These advances will likely be most valuable in more complex sidelighting cases. Because toplighting controls are already fairly effective, the benefit may be limited to cost reduction resulting from use of a single controller for toplighting and occupancy control.

Translucent panels with high insulating value are attractive from a thermal perspective, but savings in a toplighting application is driven mostly by visible transmittance, not thermal properties (see Section 4.6). Translucent panels can achieve much higher insulating values than traditional skylights by adding fiberglass, aerogel, or other

[13] Source: Solatube, VT = 80%, SHGC = 48%, U-Value = 0.640, light well reflectance = 99%, resulting optimum SFR of 3% leads to 115 22" units for 10,000 sqft, installed cost $750/unit.

[14] "Hybrid Solar Lighting Illuminates Energy Savings for Government Facilities," FEMP Technology Focus, DOE/EE-0315, April 2007. http://www1.eere.energy.gov/femp/pdfs/tf_hybridsolar.pdf

insulating material; Kalwall is the most notable of these systems. Unfortunately, the highest-performing panels only have a visible light transmission around 20% as compared to 60% for a diffusing plastic skylight, and thus require much larger areas to achieve effective daylighting. Increased area offsets insulation gains and can be logistically difficult. Furthermore, their cost is still quite high, ~\$50/ft^2, about twice as much as a traditional double-glazed domed plastic skylight.

New technology to improve the distribution of light from skylights could reduce the number of light wells required and theoretically have a positive impact on cost. Angularly selective glazing using prismatic and holographic coatings are designed redirect light using features within or coated onto glazing materials. These features can gather light preferentially from certain angles or reflect light from a large area into a small opening. On the interior they could potentially be used to create wider distribution patterns or increase the size of the diffusing area. They are generally found to reduce the total amount of light entering a space, but if they could reduce the number of light wells the required increase in glazing area may be an acceptable tradeoff (Littlefair 1990). Reflectors, baffles, and other light distributing hardware perform a similar function and have been available for years. Again, if they could reduce the number of light wells, the required increase in cost may be an acceptable tradeoff. Ultimately it is unlikely that these technologies will be able to make skylights economical for offices/schools. At the limit, if these systems were able to double the light distribution with no added costs, and the light well had NO cost, payback in Phoenix would still be 11 years for offices, and 9 years for schools.

6.2 Suggested Solutions to Increase the Market Penetration of Toplighting

Overcoming the major issues limiting large-scale implementation of toplighting is crucial to realizing more of the national energy savings technical potential. We identified several possible paths forward where DOE could participate (see Table 6-2).

Table 6-2: Potential Solution Overviews

Solution	Applicable Building Types	Key Features of Solution
Code Changes	Big-Box Retail & Warehouse	• Codes limiting solar heat gain and U-value should be loosened for skylights used with lighting controls • Codes requiring skylights in certain applications could increase awareness and reduce costs • Rating systems should be updated to reflect performance in a toplighting application
Education	Big-Box Retail & Warehouse	• Improve tools and resources available to practitioners • Reduce risk of leaks, real and perceived • Reduce chances of poor design not achieving promised energy savings • Reduce cost of design • Increase awareness of benefits
Research	School & Office	• Develop a dramatically less expensive solution to bring light into spaces with low, drop ceilings (unlikely to achieve favorable economics)

For big-box retail and warehouse buildings, the economics of toplighting can drive implementation if the remaining barriers described in Section 3.2 are overcome. In particular, codes must allow for the most economic and energy-efficient solutions. Recent updates to ASHRAE 90.1-2007 are a great start in this process, but much more remains to be done to ensure that builders are not hampered by costs resulting from local code variances when trying to achieve effective toplighting. Publicly-available studies and information explaining the benefits and proper application of toplighting would encourage local code bodies to adopt the new ASHRAE modifications, and, in the near term, allow for toplighting-based variances. DOE-supplied information also could encourage the International Energy Conservation Code (IECC) and other code bodies to adopt similar measures.

Better rating systems are needed to accommodate the full range of toplighting products that are available, for example, tubular daylighting devices. The rating systems should accurately reflect the annual performance of products in a toplighting application. Current rating values do not fully account for the effective light transmission over the course of a day/year, light-well losses, and diffusion/distribution properties. Diffusion properties are a key characteristic of an effective toplighting product. Inadequate diffusion can lead to glare and eye-strain, inadequate lighting in the spaces between skylights, and hot spots resulting from concentrated solar heat gain. Research is needed to develop a rating system that would readily allow performance comparisons between product offerings, for example, light tubes and skylights.

Overcoming the cost associated with designing toplighting systems and the risk to stakeholders of implementation, are also key to increasing market penetration. Many builders and architects are unfamiliar with the benefits of toplighting and the proper methods to achieve these benefits. Beyond the cost of training, practitioners may choose not to pursue a new method such as toplighting due to the risk of design failures, for example, not achieving promised energy savings or poor lighting comfort. Solutions must address the following issues:

- Architects and building owners must understand the potential for energy savings (many see skylights only as an energy drain)
- Designers/architects need toplighting performance information
- Calculation of energy savings and simulation of photometrics (distribution and quality of light) should be easy and reliable
- Building owners' and maintenance professionals' concerns about complications and risk of problems from skylights must be reduced
- Roofers' fear of increased liability due to additional roof penetrations must be overcome
- Improper installations that set further bad precedents for the industry must be avoided

Support of a training and certification program, "real world" manuals, software tools that allow practitioners to quickly and inexpensively complete effective designs, and improved rating systems could help overcome inexperience, reduce risk and cost of design, and increase awareness of potential benefits. Specific actions to facilitate the penetration of effective toplighting include:

- *Training and Certification*
  - Similar to the National Council on Qualifications for the Lighting Professions, "Lighting Certified" Program, but focused on daylighting techniques
  - If industry buy-in is achieved, could be implemented rapidly using existing manuals, software, and rating methods
  - Has the greatest potential to improve installation quality immediately and encourage market penetration
- *"Real World" Manuals*
  - Manuals designed by industry for industry will facilitate training (current materials are often too abstract/academic for installers to easily use, or require practitioners to learn complicated equations or software)
  - Create a collaborative group of industry representatives
- *Software*
  - Simple, accurate design software could reduce cost and risk for architects, engineers, and lighting designers to design and specify toplighting systems that achieve energy savings without compromising occupants' visual comfort
  - New versions could allow for analysis of more complex geometry and new products
- *Rating Systems*
  - Rating systems that reflect real-world performance as described above (i.e., domed shapes gather more light over the course of a day) would facilitate merit

based comparison of technology and encourage manufacturers to develop effective products

Offices and schools have strong economic disincentives to install toplighting on top of the code and education barriers faced by the entire market. Achieving national energy saving in these cases would require providing large incentives or dramatic reductions in cost. For example, in offices, even if the cost of implementing skylights were equivalent to a high-open-ceiling case (in which fewer, larger skylights are installed without light wells), average payback periods would still exceed 11 years in the most favorable climates, i.e., Phoenix, AZ. In schools, due to slightly higher lighting power densities, paybacks would approach 9 years. Achieving this would require a two-fold improvement in the distribution characteristics of the skylight system without introducing any additional losses or cost, or introducing additional aesthetic or light-quality problems. Various reflecting and diffracting systems have the potential to improve distribution, but all produce additional losses and cost, and may present aesthetic or light-quality issues. Furthermore, this example assumes the complete elimination of light-well costs. Modular light wells, such as those described in a report prepared for the California Energy Commission, are an example of a technology shift that could reduce costs (CEC 2003c). While it may be possible to achieve reductions in cost through improved design and reduction of on-site labor, it is unlikely that reductions can approach the ten-fold reduction in fixed cost (from $1,000 to $100) assumed for this straw-man case.

Eliminating the light well all together by using an open-ceiling design similar to what is used in warehouses and big-box retail stores is another potential solution. However, this would be a very significant change for the building industry. Drop ceilings reduce cost during construction by reducing the required coordination between trades and allowing system installations in a quick-and-dirty, often haphazard, manner. They allow flexibility, quickly and cheaply produce a finished appearance, provide sound absorption, and can aid in light distribution.

To eliminate drop ceilings without compromising the economic advantages of drop ceilings, significant changes would have to be made to the management and design of utility installations. TIAX conducted a research effort for the Housing and Urban Development (HUD) Department on this topic of “Disentangling Utilities.” This effort resulted in suggested industry changes that could allow better coordination among trades, more organization, and better allowance for upgrade and repair. For example, greater use of modular construction could facilitate a logical order of utility installation and preplanning of routing and design. Unfortunately, the report also concluded that these changes would likely be difficult and slow due to the multitude of local subcontractors, code barriers, and general resistance to change in the building industry (Lawrence 2004).

In addition to the existing economic hurdles, widespread implementation of toplighting in low-ceiling applications would likely require the addition of diffusers, reflectors (indirect), or shades to address contrast and brightness issues (see Section 3.2). This will add cost and reduce the amount of light provided.

A potential solution for offices and schools that is often suggested is the use of tubular daylighting devices (TDDs). While these products can be used in open-ceiling applications, their primary market is in drop ceilings where they replace traditional skylights and site-built light wells with a easy-to-install kit that integrates all the components needed to bring light in from outside and distribute it below the ceiling. Most current products are circular and are available in diameters up to 22 inches. This results in an area of 2.64 square feet as compared to 16 square feet for the 4'x 4' skylight used for the office and school base case analysis in climates other than Phoenix. Therefore, to obtain the same SFR, 6 light tubes would be required for every skylight, resulting in approximately 150 light tubes in the office and school cases to achieve 4% SFR. According to manufacturers the installed cost of a light tube in a drop ceiling application is roughly $750 or approximately 45% the installed cost of a 4'x 4' skylight and light well of the type used in the base case analysis. With a cost of 45% of the base-case system and a size of 1/6th the area, even if overall light transmission equaled 100%, i.e., twice that of the base-case system, their payback would be 35% longer.

A possible solution would be to increase the size of the TDD. To analyze this possibility, we hypothetically increased the maximum size of a TDD by approximately three fold to 8 square feet (approximately 38" in diameter). Optimistically, we assumed that cost did not increase at all, still $750/unit, and that the unit avoided brightness and distribution issues without impacting cost or performance. To complete the calculation, we used manufacturer performance assertions for current TDDs of VT = 80%, SHGC = 48%, U-Value = 0.64, and light well reflectance = 99% (Solatube 2007). We performed the analysis in the most favorable climate and building type (Phoenix, School). The resulting optimum SFR is 2%, requiring 25 TDDs. Even with these very optimistic assumptions[15], acceptable payback periods still can not be obtained (see Figure 6-3). In this hypothetical example, savings increases almost 25%, and overall system cost per ft^2 is reduced almost 50%, resulting in a payback of 12 to 13 years. This would represent a large improvement, but still would not produce an economically attractive scenario.

[15] A manufacturer of TDDs noted several disadvantages to larger TDDs, namely: 1) the smaller size limits the size of roof penetrations, thus decreasing the amount of structural modification required; 2) in the context of suspended grid ceilings, they want their TDD to readily fit into the space of a standard 2'x2' ceiling tile; and 3) smaller diameters enable the TDDs to fit around plenum obstructions (e.g., ductwork, sprinkler lines, etc.) and increasing diameter would compromise this capability (Sather 2008).

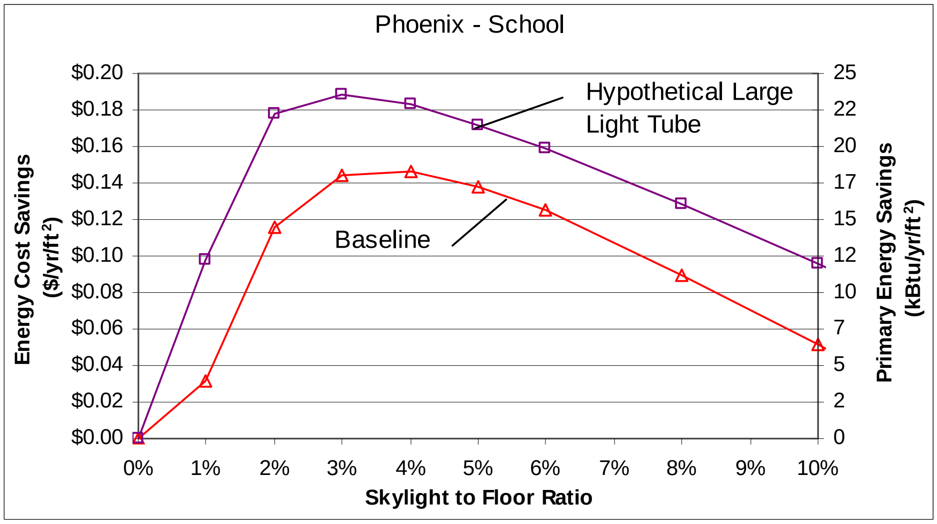

Figure 6-3: Energy Cost Savings Potential Using a Hypothetical Tubular Daylighting Device

Improving the economics and performance of skylights in buildings like offices and schools may tip the balance in cases where skylights are under consideration mainly for their aesthetic and programmatic benefits, but such efforts are unlikely to make skylights a cost-effective energy-savings measure for buildings like schools and offices.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Studies have repeatedly found that daylighting has the potential to realize very large reductions in lighting energy consumption, but this potential has not been fully realized. To gain a deeper understanding of how to increase toplighting deployment and energy savings, the U.S. Department of Energy, Building Technologies Program (DOE/BT), contracted TIAX to develop an overview of the potential for toplighting across the U.S. including an estimate of toplighting energy saving potential and a review of possible action to accelerate the market adoption of toplighting.

Key Issues

The study identified three key benefits of toplighting and two key issues that limit penetration of energy-saving toplighting products (see Tables 7-1 and 7-2).

Table 7-1: Key Benefits of Toplighting

Key Benefits
Energy Savings
Potential to Enhance Sales and Productivity
Potential to Increase Building Value

Table 7-2: Key Issues Limiting Toplighting Penetration

Key Issues
Cost versus Energy Benefit
– Equipment
– Implementation
Awareness and Education
– Inadequate Knowledge Leads to Faulty Design
– Concerns About Leaks and Controls Operation

We found that 35-55% of lighting energy can be saved, with minimal heating and air conditioning losses, by installing an economically optimum toplighting system. Stated another way, depending on climate and building type, \$0.12-\$0.32/ft^2 can be saved per year including losses. Economic results are discussed in further detail in Section 5.

Industry representatives and decision makers also identified several qualitative benefits of skylights (e.g. architecture, productivity, or sales enhancements) as very important factors that influence installation decisions. In fact, in the majority of building types, skylights are not generally installed with the goal of saving energy. As a result, they are often undertaken without lighting controls and proper design to maximize energy savings. *Adding lighting controls and designing for toplighting to cases in which skylights are installed for non-energy reasons represents a significant energy-saving opportunity*. In our modeling adding controls added \$0.16-\$0.38/ft^2 of floor area, or 8-24% of the total cost of the skylight and controls installation, and resulted in savings of \$0.11-\$0.32/ft^2.

However, the total number current skylight installations is relatively small, and in many cases designers wish to use clear skylights for aesthetic reasons, which are not compatible with effective toplighting due to resulting glare (high contrast).

We found that simple payback periods resulting from *energy effects only* for full toplighting installation range from 4 to 10 years in high, open, ceiling cases, and 30-40 years in cases with lower, drop ceilings where expensive light wells are required (see Figure 7-1). The long paybacks in buildings that use drop ceilings and, thus, require the construction of a light well for each skylight, essentially preclude the use of the skylights in these cases for economically motivated energy-use reduction. In open-ceiling buildings that facilitate shorter payback periods, industry representatives indicate that the limited implementation of toplighting is largely a result of a lack of awareness and education, and concerns about risk of leaks and not achieving promised cost/energy savings ratios.

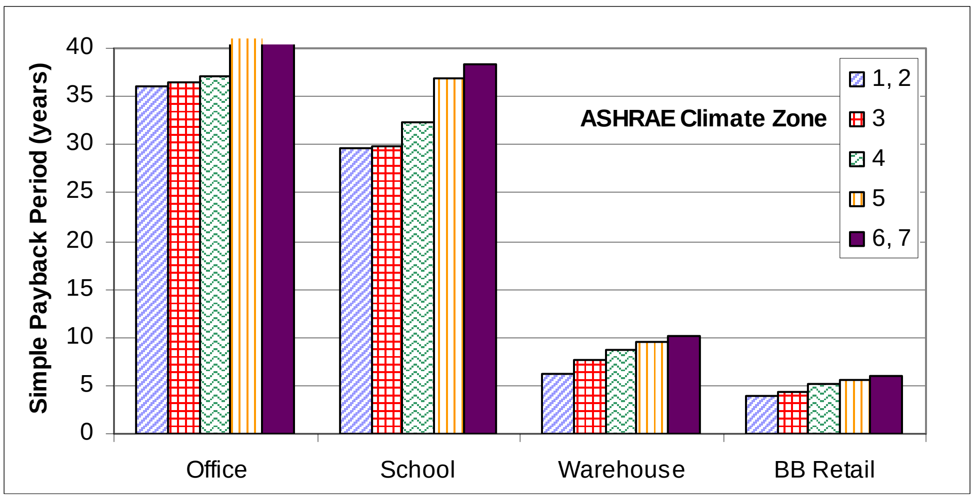

Figure 7-1: Simple Payback Resulting From Energy Savings, by Climate Zone and Building Type

National Energy Savings Potential

To generate a national estimate for energy saving potential, we developed a base-case scenario for use in modeling. The base case is a standard installation scenario for a new, energy-efficient, building that has favorable characteristics for toplighting, but is generally consistent with current practice. We varied the base case as appropriate for each of the four building types modeled to reflect the unique characteristics of each (office, school, warehouse, and big-box retail). Each was modeled using SkyCalc™ in five cities representing theseven most populous ASHRAE climate regions in the United States.

We estimated the cost of the base-case system from the available literature and industry interviews. We calculated the economically optimum skylight-to-floor area ratio (SFR) for each climate and building type. This resulted in a 4% SFR in all cases except for the warehouse (where lower lighting power density resulted in a 3% optimum) and in Phoenix, where greater sunlight resulted in lower optimum SFRs for all building types except the big-box retail[16]. A key result from the development of the base case was the identification of which skylight characteristics have the greatest impact on energy savings. Lighting savings dominate the energy impact of toplighting at SFRs near the optimum; heating and cooling impacts are at least an order of magnitude smaller even in extreme climates in all building types evaluated. Because lighting savings are the key, output visible transmission is much more important than thermal characteristics.

In addition to installed skylight costs, the cost estimates include the addition of a three-step (plus off) lighting control system and necessary wiring upgrades. In the office and school cases, the incremental cost equaled about \$4.70/ ft^2 (using 4'x 4' skylights and light wells), while the cost for the warehouse and big-box retail is much lower--about \$1.25/ ft^2 (using 4'x 8' skylights; see Figure 7-2).

These results lead to two key conclusions. First, smaller, more expensive, skylights and light wells result in very high costs in drop-ceiling cases. Second, simple lighting controls and wiring upgrades represent \$0.16-\$0.38/ft^2; thus, if skylights are available, adding lighting controls will likely be an economically sound decision, with a 0.5 to 4 year simple payback. (HMG 2007, PG&E 2006, TIAX interviews of manufacturers).

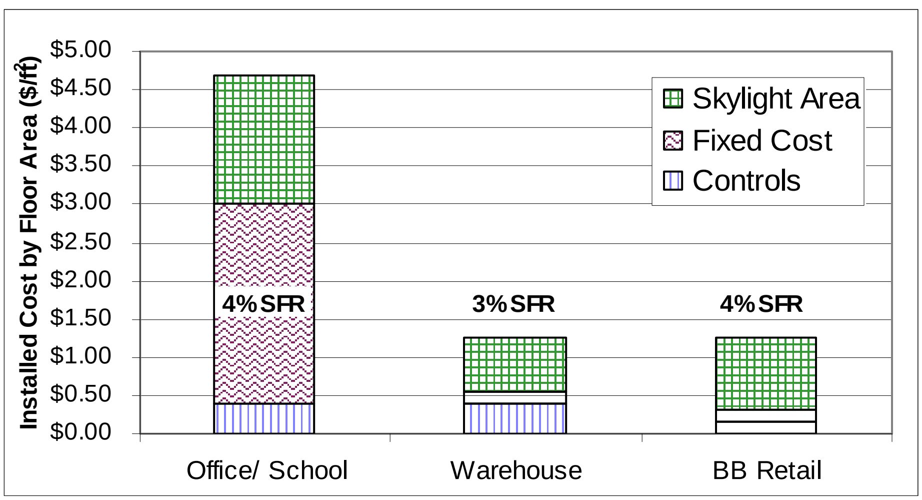

Figure 7-2: First Cost of Optimum Toplighting System, by Building Type

National primary energy savings technical potential, assuming complete penetration of all floor space directly below a roof in the four building types examined, equals about **0.4 quads**. While big-box retail offers the greatest energy savings per square foot, the total savings potential is not generally highest for retail[17] across climate zones because the total floor areas of the other building types are higher (see Figure 7-3). These energy savings results are in line with results from earlier studies (TIAX 2005).

[16] *In Phoenix the optimum SFR is 3% for offices and schools and 2% for warehouses due to higher solar insolation.*
[17] *The floor area of non-mall retail was used as a proxy for big box retail floor area in all calculations, because specifically big box retail floor area was not available.*

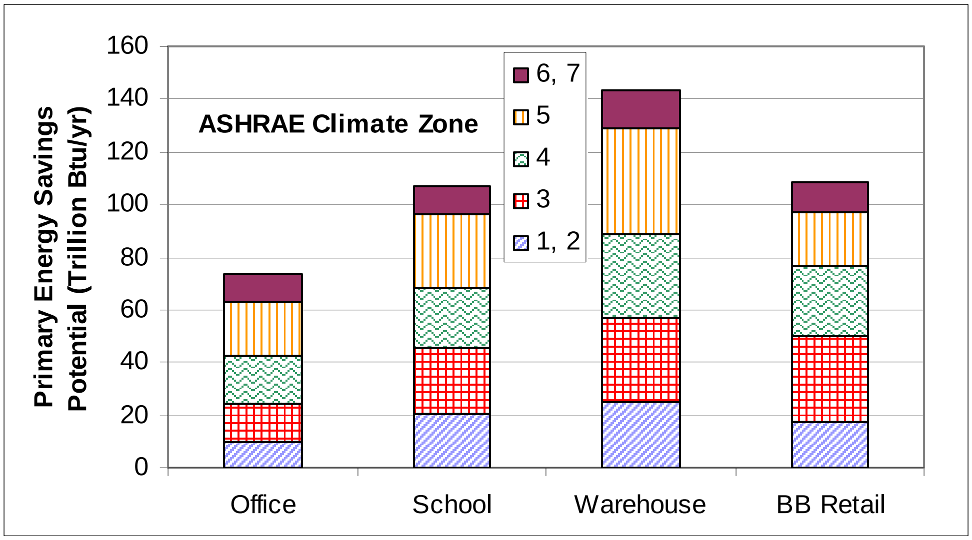

Figure 7-3: Annual Primary Energy Savings Technical Potential, by Climate Zone and Building Type

Potential Solutions to Overcome Barriers to Greater Market Penetration

To greatly increase the market penetration of toplighting and move toward the theoretical national energy savings potential, the major issues limiting large-scale implementation of toplighting must be overcome. We identified several possible paths to increase toplighting deployment (see Table 7-3).

Table 7-3: Potential Solution Overviews

Solution	Applicable Building Types	Key Features of Solution
Code Changes	Big-Box Retail & Warehouse	• Codes limiting solar heat gain and U-value should be loosened for skylights used with lighting controls • Codes requiring skylights in certain applications could increase awareness and reduce costs • Rating systems should be updated to reflect performance in a toplighting application
Education	Big-Box Retail & Warehouse	• Improve tools and resources available to practitioners • Reduce risk of leaks, real and perceived • Reduce chances of poor design not achieving promised energy savings • Reduce cost of design • Increase awareness of benefits
Research	School & Office	• Develop a dramatically less expensive solution to bring light into spaces with low, drop ceilings (unlikely to achieve favorable economics)

7.2 Recommendations

There exists a real, immediate opportunity for national energy savings in buildings with high open ceilings. We recommend action to exploit this potential, including ensuring that codes do not stand in the way of energy savings toplighting solutions, increasing awareness of benefits, and making appropriate resources available to practitioners to achieve effective designs with limited risk and cost:

- *Training and Certification*
  - Similar to the National Council on Qualifications for the Lighting Professions, "Lighting Certified" Program, but focused on daylighting techniques
  - If industry buy-in is achieved, could be implemented rapidly using existing manuals, software, and rating methods
  - Has the greatest potential to improve installation quality immediately and encourage market penetration
- *"Real World" Manuals*
  - Manuals designed by industry for industry will facilitate training (current materials are often too abstract/academic for installers to easily use, or require practitioners to learn complicated equations or software)
  - Create a collaborative group of industry representatives
- *Software*
  - Simple, accurate design software could reduce cost and risk for architects, engineers, and lighting designers to design and specify toplighting systems that achieve energy savings without compromising occupants' visual comforts
  - New versions could allow for analysis of more complex geometry and new products
- Rating Systems
  - Rating systems that reflect real-world performance as described above (i.e., domed shapes gather more light over the course of a day) would facilitate merit based comparison of technology and encourage manufacturers to develop effective products

In the case of buildings with low, drop ceilings, favorable toplighting economics will be difficult to achieve. For example, even if the cost of implementing skylights in offices were (very optimistically assumed to be) reduced to point where it was equivalent to a high open ceiling case, in which fewer, larger skylights are installed without light wells, payback periods would still exceed 11 years. In this hypothetical case, in schools, paybacks would approach 9 years. Improving the economics and performance of skylights in buildings of this type may tip the balance in cases where skylights are under consideration mainly for their aesthetic and programmatic benefits, but these types of efforts are unlikely to result in widespread deployment of toplighting as an energy-efficiency measure alone.

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APPENDIX A – TIAX STAKEHOLDER INTERVIEW PROCESS

We interviewed more than 20 industry experts using two questionnaires (labeled as Questionnaire A and B). Many of the experts listed below participated in both rounds of interviews.

QUESTIONAIRE A

Date:

Interviewee:

Title:

Company:

Business Type:

Location:

Type of Buildings:

Phone:

Subject: Questionnaire for Toplighting

Note: Interviews will be conducted in a conversational format, but attempts will be made to cover the questions described below.

Introduction:

Hello, my name is Tyson Lawrence. I am calling from TIAX LLC in Cambridge. We are conducting a study to help the Department of Energy Building Technologies Program better understand how to encourage the use of toplighting (skylights and controls to lower lighting) to reduce lighting energy consumption in commercial buildings. We are focusing our analysis on two base case buildings:
Both - new, owner occupied, flat roof , open plan
Office building - drop ceilings ~10ft high
Big box retail store - exposed structure ceilings ~20ft high.

There are four main areas I am reviewing:

1. How are decisions to install skylights made? (i.e. benefits that drive decisions)

2. Barriers to market penetration

3. Cost of equipment, installation, and maintenance

4. New toplighting technologies that may affect the previous answers

Specific Questions:

1. How are decisions to install skylights made?

    a. Who makes decisions to install skylights? Does this include lighting controls needed to save energy?

    b. What drives their decisions to install skylights? To include lighting controls system? (i.e. perceived benefits) Avoid listing to avoid leading the interviewee (e.g. energy savings, enhanced productivity, increased building value, safety, etc.)

    c. When people decide NOT install skylights, what are the main factors?

2. Barriers to market penetration

    a. What would you think are the most important (e.g., up to three) barriers to greater use of toplighting?

    I am going to read you our list of barriers in our order of importance. Please let me know how important you think each is, if you think we should change the order of importance, and if there are any you would add or remove.

    i. High Installed Cost Compared to Energy Savings Benefit

    ii. Design Challenges (Glare, Light Distribution)

    iii. Awareness of Stakeholders About Benefits/Availability Of Software Or Data To Confirm Benefits

    iv. Maintenance Concerns

    v. Concerns About Effectiveness of Dimming Systems

    vi. Concerns About Thermal Gains and Losses Through Skylights

    vii. Code Issues

    viii. Security

    ix. Safety

3. Cost of equipment, installation, and maintenance (It is our belief that the major limit to installation of toplighting systems is cost) Basic Characteristics: Double Paned, Single Dome, Acrylic, Frosted Diffuser,

	Equipment	Installation + Commissioning	Maintenance [$/year/unit]
Skylights (typical office, ~16sqft?)	$300	$100	~$15?
Skylights (typical big box, ~32 sqft?)	$600	$200	~$20?
Light wells (typical office, 6ft?)	$100	$900	$0?
Tubular Skylights (22" Diameter?)	~$350	~$150	~$10?
Circuit Controls (10,000 sqft)	$2100	~$400 (incremental)	$0?
Step Control Systems (10,000 sqft)	$2100	~$400 (incremental)	$0?
Dimming Controls (10,000 sqft) (including ballast incremental cost)	$4000?	~$400? (incremental)	$0?

4. Are circuit and stepped distinct? Prevalence of Stepped vs. Dimming?

5. Are you aware of any new technologies that may affect the previous answers? (for example modular skylight and well systems, fiber optics, etc.)

QUESTIONAIRE B

Date:

Interviewee:

Title:

Company:

Business Type:

Location:

Type of Buildings:

Phone:

Subject: Questionnaire for Toplighting

Note: Interviews will be conducted in a conversational format, but attempts will be made to cover the questions described below.

Introduction:

Hello, my name is Tyson Lawrence. I am calling from TIAX LLC in Cambridge. We are conducting a study to help the Department of Energy Building Technologies Program better understand how to encourage the use of toplighting (skylights and controls to lower lighting) to reduce lighting energy consumption in commercial buildings. A major output of our efforts will be a recommendation to DOE as to how they should be involved in this area, e.g., funding R&D or developing information to help transform markets. Ultimately, we will publish a Final Report to DOE/BT and will, with your permission, acknowledge your contributions. In all cases, however, we will treat any information that you provide to us as confidential. That is, no specific values or information will be attributed to HOK and we will only present aggregate findings from our research in the Final Report.

We are calling industry stakeholders to At establish a base case (standard installation scenario for a new, energy efficient, building that has favorable characteristics for toplighting, but is consistent with current practice)
AND
installation costs for the base case and common options. (Cost skylights and light well, per sqft and cost of lighting control system, per sqft)

Base Case

Building

1. New Construction, Owner Occupied
2. Flat Roof
3. Off-white paint
4. Office/Warehouse/School - 10,000 sqft, Retail - 50,000 sqft
5. Big Box Retail – 20ft open ceiling, shelving 6ft wide x 7ft high – 10ft aisle
6. Warehouse – 20ft open ceiling, shelving 8ft wide x 15ft high – 12ft aisle
7. Office – 10ft drop ceiling, 4ft partitions in 8ft x 8ft cubicles
8. School – 10ft drop ceiling, no partitions

Skylight

1. Acrylic (In cold climates?)
2. Double glazed (In cold climates?)
3. Diffusing (white plastic)
4. Single Dome
5. Big Box Retail/Warehouse – 4'x 8'
6. Office/School – 4'x 3'
7. Spaced at 1.5x ceiling height
8. No safety grate

Well Depth (plenum space between ceiling and roof)

1. Big Box Retail/Warehouse – 1ft
2. Office/School – 4ft – 1ft 45^{o} splay
3. White paint

Lighting

1. 3 step and on/off control, 90% controlled
2. Big Box Retail – 60 fc, industrial fluorescent, 1.5 W/sqft
3. Warehouse – 30 fc, pulse start metal halide, 0.8 W/sqft
4. Office – 40 fc, open cell fluorescent, 1.0 W/sqft
5. School – 50 fc, open cell fluorescent, 1.2 W/sqft

http://www.energycodes.gov/training/pdfs/lighting2004.pdf

HVAC - Utilities

1. Mechanical AC (no AC in warehouse)
2. Gas/Oil Furnace
3. Electricity $0.087 / kWh (2005 EIA Comm. Average)
   http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html
4. Heating $1.124 / Therm (2005 EIA Comm. Average)
   http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

Current Cost Estimates - Please confirm or edit the cost information in the below chart. If you can provide information for additional sizes of skylights, glass skylights or other components/options that would also be of value. We are planning to use high volume prices as an optimistic case representing skylight market growth. For proper light distribution the office/school will require 45+ skylights, the warehouse will require 15+ and the big box retail will require 65+ skylights.

	Equipment	Installation + Commissioning	Maintenance [$/year/unit]
Skylight - typical office, 4x3~12sqft?	$225	$75	~$15?
Skylight - typical big box, 4x8~32 sqft?	$600	$150	~$20?
Light well - typical office, 4ft?	$100	$900	$0?
Tubular Skylight - 22” Diameter	~$350	~$250	~$10?
Circuit Controls -10,000 sqft	$2100	~$400 (incremental)	$0?
Step Control Systems -10,000 sqft	$2100	~$400 (incremental)	$0?
Dimming Controls -10,000 sqft, incl. ballast incr. cost	$6000?	~$400? (incremental)	$0?

Cost of other skylight options?
i.e. glass (double and triple paned)

APPENDIX B – EXAMPLE SKYCALC™ INPUT AND OUTPUT

SkyCalc: Skylight Design Assistant - Basic Inputs

Company Name: Company ABC, Inc.

Project Description: Skylighting Project

Select Location User Generated w/ e-QUEST

Climate data loaded = Phoenix.wea3

Climate data needed =

Building

Building type	Retail	
Bldg area	50,000	ft^2
Ceiling height	20	ft
Wall color	Off-white paint	

Shelving/Racks or Partitions?

○ Partitions, ◉ Shelves/Racks, ○ None/Open

Shelf/rack height	7	ft
Shelf/rack width	6	ft
Aisle width	10	ft
No data required	0	ft

Check Lighting Power Density on Optional_Input tab

Electric Lighting

Lighting system	Industrial fluorescent	
Fixture height	16	ft
Lighting control	3 level + off switching	

Design Skylight to Floor Ratio = 4.0%

Skylights:

Number of skylights	63	
Skylight width	4	ft
Skylight length	8	ft

At least 66 skylights needed for uniform daylighting

Max skylight spacing = 30 ft (1.5 x ceiling ht)

Skylight Description

Glazing type	Acrylic
Glazing layers	Double glazed
Glazing color	Clear prismatic

Skylight Well

Light well height	1	feet
Well color	White paint	

Safety grate or screen ○ Yes, ◉ No

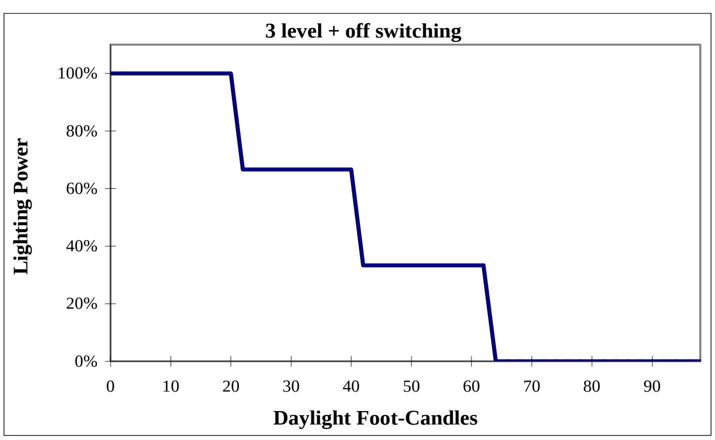
Heating and Air Conditioning Systems

Air Conditioning	Mechanical A/C
Heating System	Gas/Oil Furnace

Utilities

Average Elec Cost	$0.087	kWh
Heating Fuel Units	Therm	
Heating Fuel Cost	$1.124	/Therm

Lighting Control Graph - Lighting Setpoint = 63 fc



SkyCalc: Skylight Design Assistant - Optional Inputs

Company Name: Company ABC, Inc.

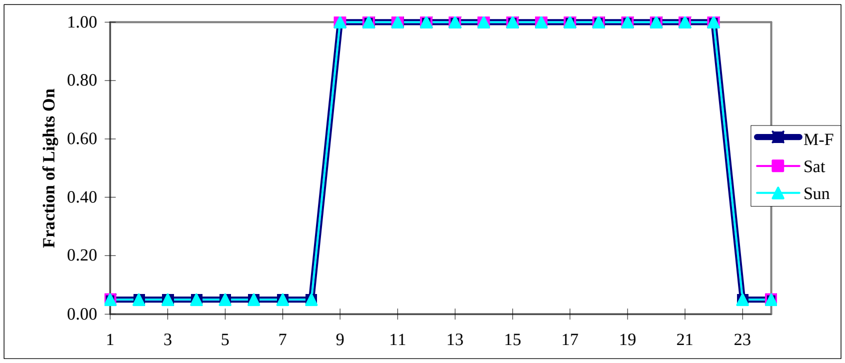
Project Description: Skylighting Project

Skylights	Default	User Revisions	Design Input
Skylight shape	Dome	Default	Dome
Height of dome (Rise) (ft)	1		1
Visible transmittance	74%	65%	65%
Solar heat gain coefficient	67%	53%	53%
Curb type	Wood	Default	Wood
Frame type	Metal w/ thermal brk	Default	Metal w/ thermal brk
Unit U-value (Btu/h•°F•ft^2)	0.970	0.810	0.810
Dirt light loss factor	70%		70%
Screen or safety grate factor	100%		100%
Light well reflectance	80%		80%
Well factor (WF)	92%		92%
Bottom of light well:			
Width (ft)	4.00		4.00
Length (ft)	8.00		8.00
Diffuser on bottom of well?	No	○ Yes, ◉ No	No

Building	Default	User Revisions	Design Input
Building width (ft)	158		158
Building length (ft)	316	Change width or area	316
Wall reflectance	70%		70%
Ceiling reflectance	70%		70%
Floor reflectance	20%		20%
Shelving reflectance	40%		40%
Roof U-value (Btu/h•°F•ft^2)	0.063		0.063

Electric Lighting	Default	User Revisions	Design Input
Lighting setpoint (fc)	65	63	63
Task height (ft)	2.50		2.50
Lighting power density (W/ft^2)	1.49		1.49
Fraction lighting uncontrolled	10%		0.10
Lighting schedule	Retail	Default	Retail
Room and luminaire depreciation	80%		80%

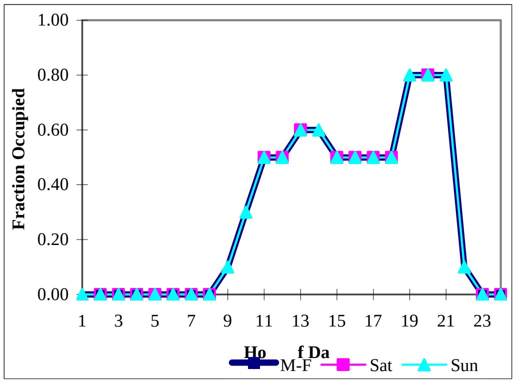
Lighting Schedule Graph



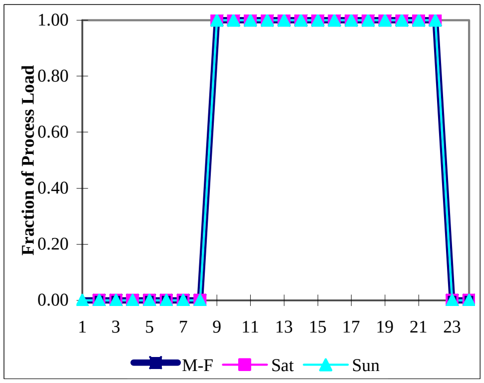
Company Name:	Company ABC, Inc.
Project Description:	Skylighting Project

Internal Loads	**Default**	**User Revisions**	**Design Input**
Number of people	333		333
Occupancy schedule	Retail	Default	Retail
Process (plug) loads (W/ft^2)	0.50		0.50
Process schedule	Retail	Default	Retail

Occupancy Schedule - Retail

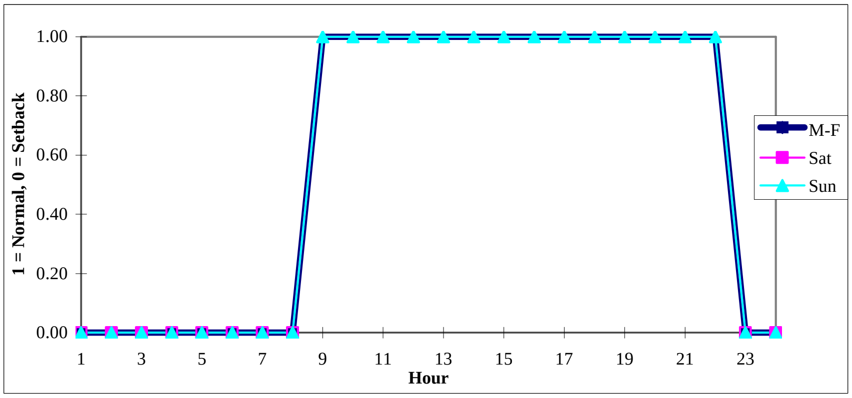


Process Schedule - Retail



HVAC	**Default**	**User Revisions**	**Design Input**
Heating setpoint temperature (°F)	68		68
Heating setback temperature (°F)	55		55
Cooling setpoint temperature (°F)	72		72
Cooling setup temperature (°F)	88		88
Economizer (Y/N)	Y	◉ Yes, ◯ No	Y
Economizer setpoint (°F)	67		67
HVAC schedule	Retail	Default	Retail
Design outside air (cfm)	6,000		6,000

HVAC Schedule - Retail



Annual Schedule	**Default**	**User Revisions**	**Design Input**
Starting Month	1		1
Ending Month	12		12

SkyCalc: Skylight Design Assistant - Graphic Results

Company Name: Company ABC, Inc.

Project Description: Skylighting Project

Dome Skylight Effective Aperture = 1.69%, Skylight to Floor Ratio (SFR) = 4.03%

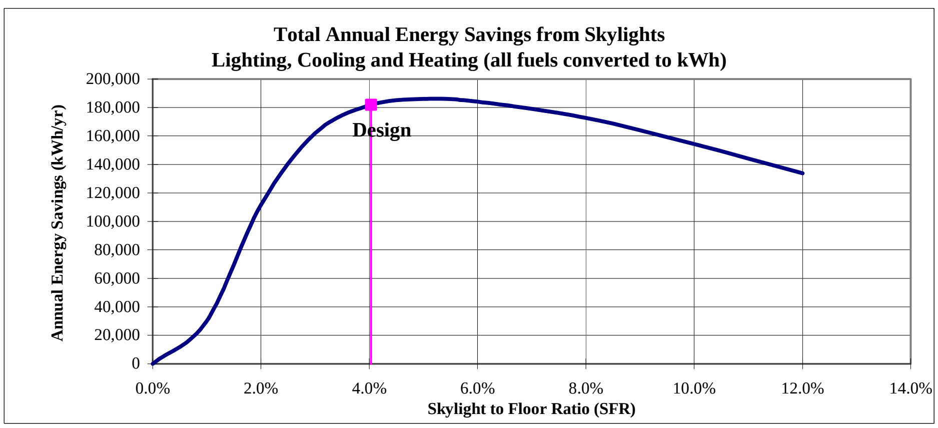
Average daylight footcandles (fc)

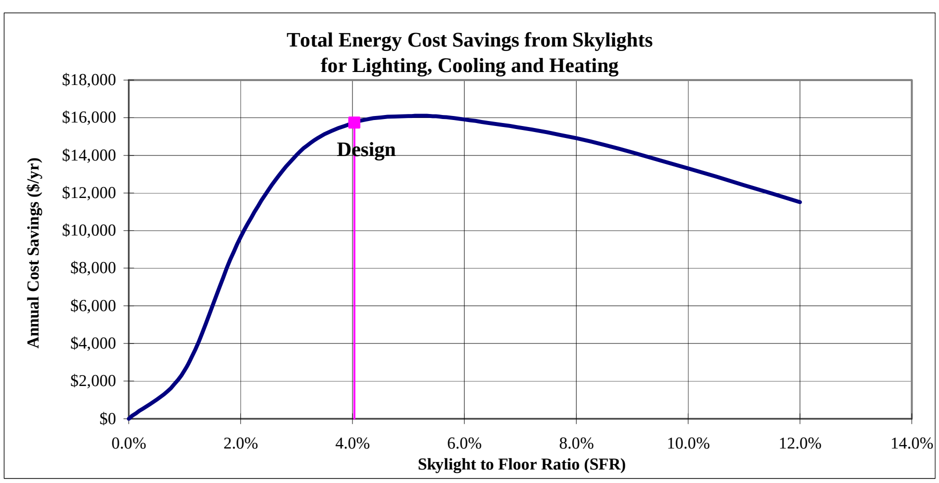
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	2	13	34	57	73	80	77	64	42	19	3	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	5	23	51	74	90	99	94	79	59	33	9	1	0	0	0	0	0
Mar	0	0	0	0	0	0	2	13	41	67	93	108	115	115	101	76	50	20	4	0	0	0	0	0
Apr	0	0	0	0	0	0	8	32	68	98	121	135	141	135	119	93	61	29	7	0	0	0	0	0
May	0	0	0	0	0	3	16	46	81	109	132	143	148	141	126	104	74	40	13	2	0	0	0	0
Jun	0	0	0	0	0	4	18	49	83	111	128	141	147	145	130	108	80	47	18	4	0	0	0	0
Jul	0	0	0	0	0	2	14	41	75	108	131	142	150	147	137	114	83	48	17	3	0	0	0	0
Aug	0	0	0	0	0	0	8	34	69	98	121	138	146	140	122	102	72	38	10	1	0	0	0	0
Sep	0	0	0	0	0	0	5	25	61	92	115	129	132	126	111	81	49	19	4	0	0	0	0	0
Oct	0	0	0	0	0	0	2	15	44	72	93	106	109	100	84	58	28	7	0	0	0	0	0	0
Nov	0	0	0	0	0	0	0	7	27	51	73	84	88	79	61	39	14	3	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	3	15	35	55	68	71	64	52	32	10	2	0	0	0	0	0	0

Design Illuminance = 63 fc

< 1 fc; < 32 fc; < 63 fc; > 63 fc;

Location = Phoenix





SkyCalc: Skylight Design Assistant - Tabular Results

Company Name: Company ABC, Inc.
Project Description: Skylighting Project

Electric Lighting Usage	**kWh/yr**		
Ltg. Energy without Skylights	394,940	Lighting Fraction Saved	47%
Lighting Energy w/ Skylights	208,068	Full daylighting (h/yr)	2,309

Savings from Design Skylighting System

Savings		Annual Energy Savings (kWh/yr)	Annual Cost Savings ($/yr)
Lighting		186,872	$16,258
Cooling		-6,675	-$581
Heating		1,672	$64
Total		**181,868**	**$15,741**
Total/sqft (kBtu and $)		39.14	$0.315

Skylighting System Description

Skylight unit size (ft^2)	32.0
Number of Skylights	63
Total Skylight Area (ft^2)	2,016
Skylight to Floor Ratio (SFR)	4.03%
Effective Aperture	1.7%
Floor Area per Skylight	794
Skylight U-value	0.810
Skylight SHGC	53%
Skylight T_{vis}	65%
Well Efficiency (WF)	92%
Dirt and Screen Factor	70%
Overall Skylight System Tvis	42%
Skylight CU	80%

Site Description

Climate Location	Phoenix.wea3	
Climate Zone	CZ2 (hot, 6,300 < CDD50°F <= 9,000	
Building Type	Retail	
Building Area	50,000	(ft^2)

Electric Lighting System Description

Lighting Type	Industrial fluorescent	
Lighting Control	3 level + off switching	
Light Level Setpoint	63	fc
Lighting Density	1.49	W/ft^2
Connected Load	74.6	kW
Fraction Controlled	90%	

As compared to the design with 63 skylights but no photocontrols

Savings from Functioning Photocontrol System

Savings		Annual Energy Savings (kWh/yr)	Annual Cost Savings ($/yr)
Lighting		186,872	$16,258
Cooling		44,776	$3,895
Heating		-25	-$1
Total		**231,622**	**$20,152**

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Building Technologies Program