

# Advancing the Art & Science of Daylighting Design

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## 1. INTRODUCTION

Designing a building that effectively uses natural lighting is, as with most design, both art and science. While people have built beautiful naturally-lit buildings for ages, their design relied heavily on the skill and experience of the designer. Seldom were accurate predictions of daylight levels available to inform the design process. Only recently have accurate analytical tools become practical in a project's budget. These tools facilitate the development of designs that meet the project goals and make the best use of materials and systems. In other words, the science of daylight analysis is now able to provide much better information about the performance of the building, and this can improve our designs.

The capabilities of desktop computers and modern design tools for buildings are amazing, from CAD software to energy analysis. We are now able to quantify, with good accuracy, the energy use of a building and its components. We are also able to make detailed analyses of lighting levels at any point in a space at any time of year for standard sky conditions. What we are still lacking, though, is an integrated software package that allows all of this to be done in one package, for every hour of the year.

With the current state of these tools, there is generally much duplication of effort. Despite all of the time put into making the CAD drawings to document a building's design, energy analysis software based on DOE2 and most daylighting software now requires the analyst to manually transfer building geometry and materials, essentially duplicating an effort. Furthermore, the outputs from daylighting models and building energy models typically require further processing to provide useful graphical results to inform the design process. This paper describes the process used to orchestrate the modeling and other tools to design daylighting systems for a school.

## 2. PROJECT OVERVIEW

The daylighting analysis described here was used in the design of the Clearview Elementary School in Hanover, Pennsylvania. The project began in 2000 and the school will be occupied in 2003. The school is a neighborhood school with 38,000 square feet of floor area including 15 classrooms, a multipurpose room, a cafeteria, music room, art room, media center, library, and administrative offices. Project architect was John Boecker of L. R. Kimball and Associates, and

the integrated design team was supported by 7Group, an LLC specializing in the design of green buildings. The authors worked for 7Group. The project team had an overall goal of designing a green building that could achieve a minimum LEED rating of gold.

In the schematic design phase, the building was oriented with a long east-west axis to expose every classroom to either north or south light, or to both. A two-story configuration was also chosen. As much as possible, the main classrooms were to be naturally lit. The daylighting considerations addressed at this critical stage were:

1. Both floors: What is the “best” amount of North glazing (area, transmittance, geometry)?
2. Second floor: What is the “best” additional aperture system to effectively light the south end of the classroom?
  - a. South-facing clerestory (features)
  - c. Skylight (features)
3. Corridor in classroom wing exposed to south for light and winter heat: How does the shading wall work?
4. Multi-purpose / cafeteria: What is the best skylighting system?

We were careful not to use the word optimum because of the difficulty in defining what that criterion means. Since optimum solutions are always a result of values and preferences, we chose to use the word “best.” While optimum implies some scientific certainty that rarely exists, best implies that some value judgments are involved. Because a primary design goal was for naturally-lit classrooms, we defined the best daylighting system as one that provides *sufficient natural light* (close to 50 fc) for the entire school year, with *little seasonal change* and with *reasonable maximums* on sunny days (100 fc), while keeping *energy cost as low as possible*. This clearly required analysis of both natural lighting levels and resultant energy use, considering the impact of lighting energy on HVAC design and energy use. Furthermore, the design team recognized that the best solution would also fit within the project budget where a goal was for the construction costs to be equivalent to those in a conventional school.

### 3. SOFTWARE AND ANALYSIS

#### 3.1 Lighting Software

The current state of lighting analysis software makes daylight design and analysis more difficult to perform than analysis in most other building design areas. A number of different tools exist, including Lumen-Micro ([www.lighting-technologies.com](http://www.lighting-technologies.com)), Radiance (<http://radsite.lbl.gov/deskrad>), DOE2 ([www.doe2.com](http://www.doe2.com)), Adeline (<http://radsite.lbl.gov/adeline/HOME.html>), Lightscape ([www.lightscape.com](http://www.lightscape.com)) and others. The major problems with many of these software programs are limitations on one or more of the following

- (1) The geometry they consider (such as rectangular boxes only),
- (2) The materials they handle (such as Lambertian reflectances only, or limitations on what type of transmitting materials one can consider), or
- (3) The complexity of the calculations they apply. (Particularly, how interreflected light is addressed and what daylight controls, such as blinds, shades and exterior obstructions, can be applied)

These limitations often restrict the building conditions that a designer can accurately and effectively model with these programs.

By far, the most complex calculation tool available – the one that can model the greatest array of space conditions - is Radiance, which was developed at the Lawrence Berkeley National Laboratory. Radiance is available in both a Windows and UNIX version. In Desktop Radiance (the Windows version), input is through an AutoCAD interface that contains a limited library of reflective materials, glazing materials and objects. Radiance can generate renderings of a space as well as conduct a luminance or illuminance analysis at a grid of points. The AutoCAD interface contains a fraction of the features and control available in the UNIX version, but a user can access nearly the full list of commands in the Desktop version by modifying the text and batch files that are generated, then re-executing the batch files. In a recent paper (Bryan 2002) reviewing four daylighting simulation programs (Lightscape 3.2, Desktop Radiance 1.02, Lumen Micro 2000, FormZ RadioZity 3.80), the authors conclude that “Desktop Radiance is the most accurate.” Other studies have shown that Radiance’s results agree well with system performance in actual daylighted spaces (Maraljevic 1995 and Ehrlich 2001)

Radiance is somewhat lacking in what it can provide in terms of output. It can produce excellent renderings, falsecolor images and falsecolor images with contours superimposed, although the contours are generally difficult to read. Numerical information in the form of illuminance grid readings are provided in an ASCII text file that contains a column of X, Y, Z coordinates and the resulting illuminance reading. To display a three-dimensional graph, a file must be imported into Excel, or some other program, and rearranged into a column and row format.

Perhaps the biggest challenge in using Radiance in the daylight design process is that for each run of the model, only one time of year and sky condition is modeled. Thus, while the designer can obtain snapshots of daylighting performance at key times of year, it does not allow for the determination of annual energy use and electric lighting savings. These snapshots are useful in guiding the design of the daylighting systems because one can study the distribution of natural light and the magnitude, as well as the seasonal variation, at selected times. This technique was used in this project and results of this work will be discussed later.

There are two programs that determine annual energy use and the impact of daylighting systems: DOE2 and SkyCalc (<http://www.energydesignresources.com/tools/skycalc.html>). SkyCalc is a very useful tool for the analysis of skylight systems. It is a spreadsheet-based tool that applies DOE2 runs from a series of base-case buildings to forecast the energy impacts of using a uniformly-distributed skylight system coupled with a specified electric lighting control scheme. The software provides graphical information showing the “optimum” glazing area for a particular skylight configuration to maximize energy or energy cost savings (these two values don’t always peak together due to the differences in heating and cooling costs). Our experience with this tool has shown that ***maximum energy savings are generally achieved when the maximum illuminance levels in a space at some time of the year are more than double the target illuminance level that is provided by the electric lighting system.*** If you allow the maximum daylight level at any particular time of the year to only reach the target level, then at other times, when there is less daylight, minimal energy savings will be obtained from control of the electric lighting system. While the school project described here does not apply skylights, this approach was applied in the design of the lighting system for this school.

DOE2 performs a more simplified daylight analysis than most of the other programs, and cannot handle very complex geometry, but provides an opportunity for daylight controls to be linked with HVAC system performance. It is designed for energy modeling and not for the purpose of designing and fine-tuning a daylight delivery system. In this project, DOE2 as incorporated in PowerDOE was used to investigate annual energy use, including the effect of the daylight systems.

### 3.2 Analysis Using Radiance and Spreadsheets

We decided to use Radiance for this project due to the complexity of the space, since no other software would be capable of handling a sloped ceiling, windows, a clerestory (or skylights) and the exterior obstructions that are present outside the clerestory. Radiance was first used to analyze different window conditions, including both a simple rectangular array and a configuration that provided more high-level glass on the exterior wall with reduced vision glass below. The analysis that was conducted included a work plane grid distributed across the desktops. Room surface luminances were also considered an important element in the design. In Desktop Radiance, luminances are easiest to investigate in the rendering program *rview*.

Once a suitable north-facing window design was determined for a typical classroom in this building, the design process focused on how to illuminate the more interior sections of the second-floor classrooms with daylight. One option considered was to apply skylights; and a second option was to apply clerestories. Diffuse skylights that were tilted toward the north with a slightly splayed interior well and flat ceiling were considered, with the northward tilt designed to reduce summer heat gain and winter peaks. In the clerestory option, a south-orientation was modeled; and since direct sunlight would strike the glazing, particularly during the fall and winter months, sunlight control was necessary, so diffuse glazing was studied. There are other ways to diffuse direct sunlight such as baffles within the space, but diffuse glazing has at least two advantages, no baffles are needed, and glazing with a very low U-factor is available. In the cases of the skylight and clerestory results presented here, a visible transmittance of 0.30 was used, and a U-factor of 0.27 Btu/hr-ft<sup>2</sup>-°F.

Figure 1 shows a cross-section through the classroom wing as it appeared in the preliminary design. The left side is facing north. The extreme right side is a partly-detached shading wall that helps block summer sun on the daylit and passively heated corridor.

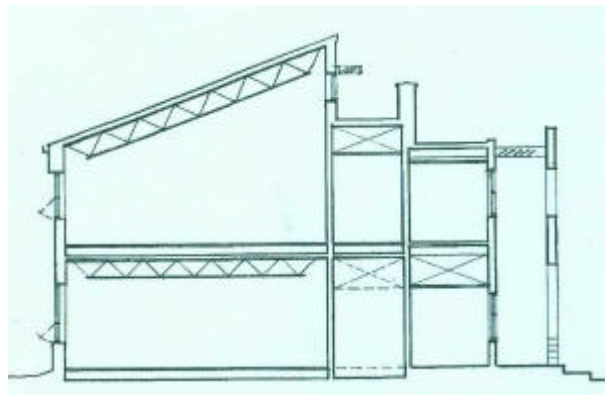


Figure 14 Cross-section through classroom wing, looking west.

To help visualize the natural lighting levels and their distribution about the classroom, 3-D illuminance plots were used. For this analysis, three representative days of the year were considered. The choice of which days to use is based on the solar cycle that reaches its limits on December 21 and June 21, the solstices (and on the time available for the analysis). We used January 21 to represent the four months centered on the winter solstice (October 21 through February 21, approximately), March 21 to represent the four months centered on the equinoxes (February 21 through April 21, and August 21 through October 21), and May 21 to represent the four months centered on the summer solstice (April 21 through August 21). The solar positions on the dates chosen approximate the average position during the time period they represent. For each day, two (solar) times were modeled, 9:00 a.m. to represent the four-hour period from 8:00-10:00 a.m. and 2:00-4:00 p.m. A time of 11:00 a.m. was used to represent the four-hour period from 10:00 a.m. to 2:00 p.m. Symmetry about noon is possible because the glazing orientations are essentially due north and south.

The floor of the 3-D plot represents the floor of the room with the north windows located on the left wall of the chart. The plots shown are all for the second-floor classrooms and compare the performance of north windows in combination with either two skylights or a south-facing clerestory, both with diffusing glazing.

Figure 2 shows the daylighting illuminance on the equinox at 11:00 a.m. under clear skies. The left chart is for a system of two skylights in combination with north glazing. Even with diffuse glazing in the skylight, there is a great deal of nonuniformity in the lighting levels. Peaks near the skylights are over 100 fc and minimums are under 50 fc. Compare this with the same time for the clerestory system, the right graph in Figure 2. Here the lighting is very uniform with levels in the range of 70-80 fc (electric lighting target is 50 fc).

In the winter, as shown in Figure 3, the skylight performance drops considerably on clear days due to the low sun angles, with natural light levels of about 30 to 45 fc, albeit more uniform. The clerestories perform quite well with daylight levels ranging from 50 to 80 fc.

In the summer, the difference in the two systems is most pronounced. Figure 4 shows the two systems in the summer. Here the skylights create extremely high peaks, exceeding 140 fc. The clerestory system again produces more uniform lighting with most of the room between 60 and 80 fc.

The one disadvantage of the north-facing window/south-facing clerestory situation is that performance is limited under overcast sky conditions. An overcast sky is brightest at zenith and therefore provides less available daylight on vertical surfaces. The clerestory design provides higher overall space luminances than the skylight system with a well, since daylight from the clerestory directly illuminates the ceiling, but this system also requires a larger room volume. Figure 5 shows the daylight distribution under an overcast sky on the equinox at 11:00 a.m.

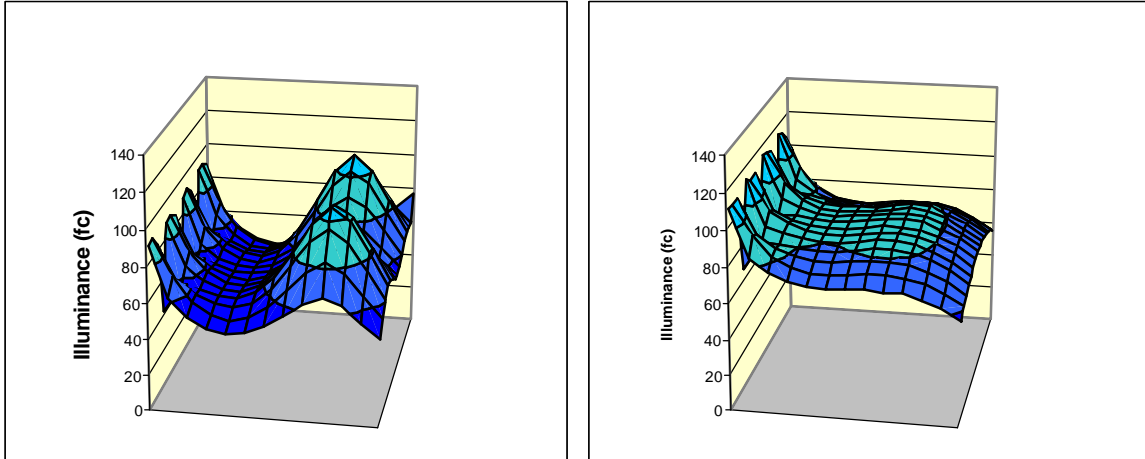


Figure 22 Daylighting distribution for skylight (left) and clerestory (right), Mar 21, 11 a.m., clear sky.

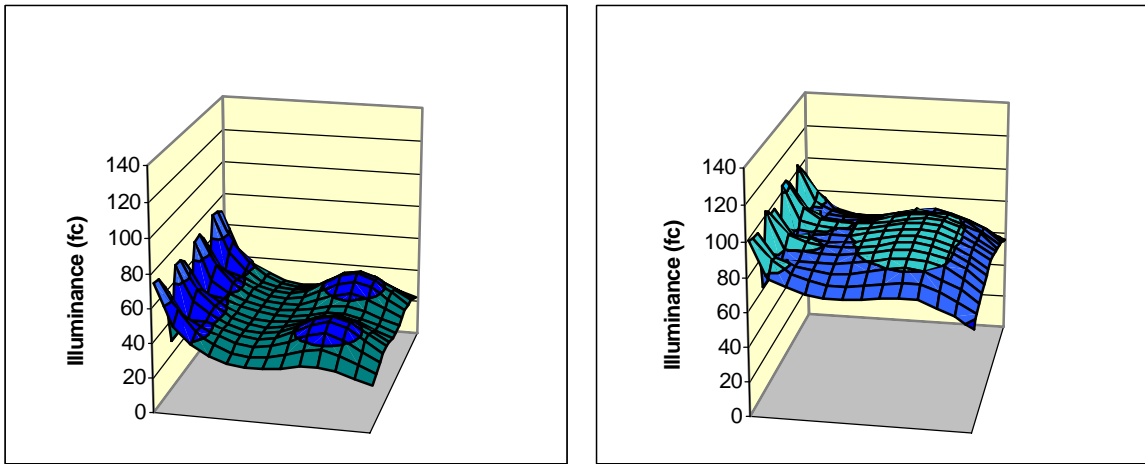


Figure 3 Daylighting distribution for skylight (left) and clerestory (right), Jan 21, 11 a.m., clear sky.

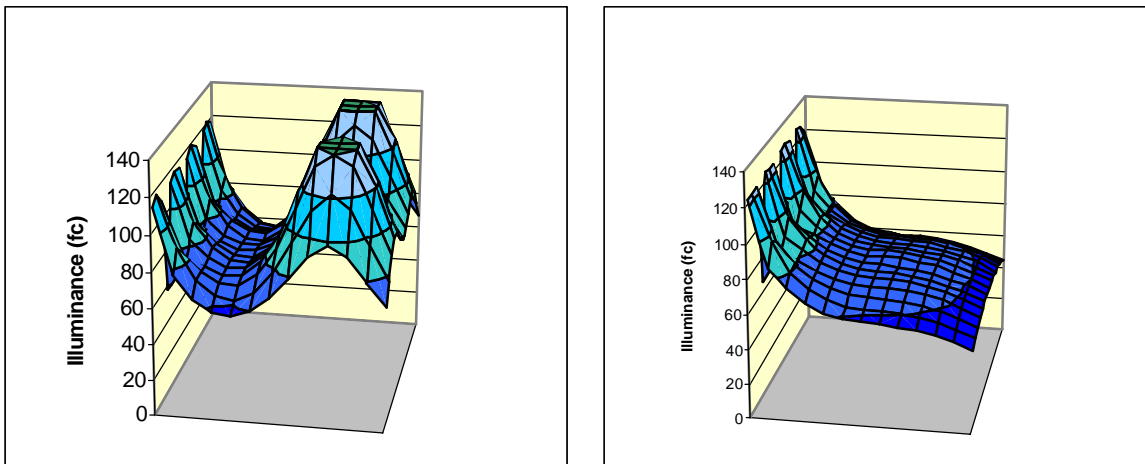


Figure 4 Daylighting distribution for skylight (left) and clerestory (right), May 21, 11 a.m., clear sky.

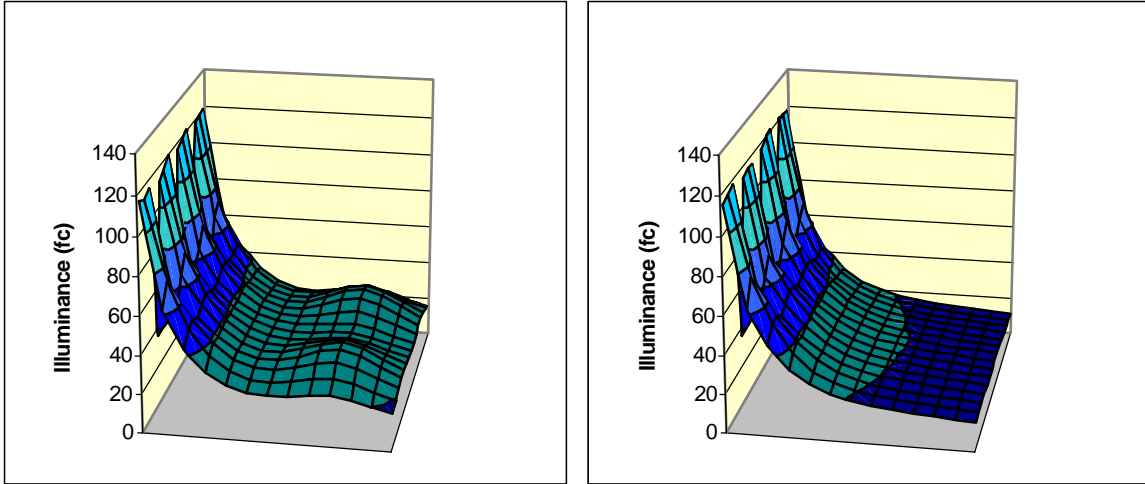


Figure 5 Daylighting distribution for skylight (left) and clerestory (right), Mar 21, 11 a.m., overcast sky.

To further compare the two systems and the seasonal variation, the results for 9 and 11 a.m. for each day were averaged to represent the average daily performance on those days. To get one number for the room, the uniformly-distributed points were averaged, resulting in Figure 6. This figure clearly shows that the daylighting from skylights in combination with the north windows varies significantly from winter to summer under clear skies, with best performance in summer (when the school is mostly unused at present). While this performance can be altered with reflectors or sloped skylights, or with other skylight patterns, it would be difficult to achieve the seasonal uniformity of the south-clerestory, north window combination, particularly on clear days. The skylight system does do somewhat better on completely overcast days, about 5 fc more in average illumination. Partly cloudy days would likely be somewhere inbetween the limits of clear and completely overcast, except through the north glazing, where the daylight conditions should be highest under a partly cloudy sky.

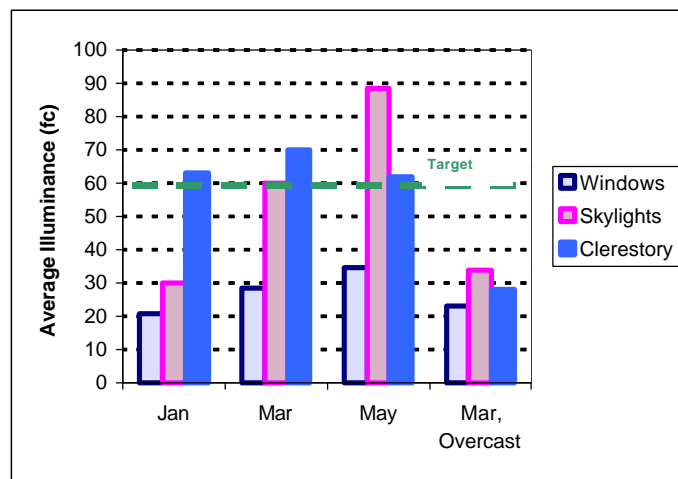


Figure 6 Seasonal variation of daylighting levels.

### 3.3 Energy Analysis with PowerDOE During Schematic Design

To help understand the energy use consequences of some of the daylighting systems being studied, a PowerDOE model was developed for one classroom. This greatly simplifies the model and the time to construct it, allowing this effort to fit into the modeling budget. The HVAC system was assumed to be a packaged rooftop unit with performance close to what was anticipated in the final design. This may not actually reflect the final performance, but it allows energy use to be factored into the daylighting design during preliminary design.

PowerDOE analysis during schematic design was used in two ways. The first was to study the impact of skylight size and number on annual energy use, and then to compare the best skylight system with the best clerestory system for the second-floor rooms. In the skylight study, four skylights were assumed, centered on the four quadrants of the room, with a flat roof and flat skylights. Varying skylight sizes were modeled and the energy use results were assembled in a spreadsheet. Electric and gas costs were put into the spreadsheet as variables to investigate their effect on the energy cost and savings. The results are summarized in Figure 7.

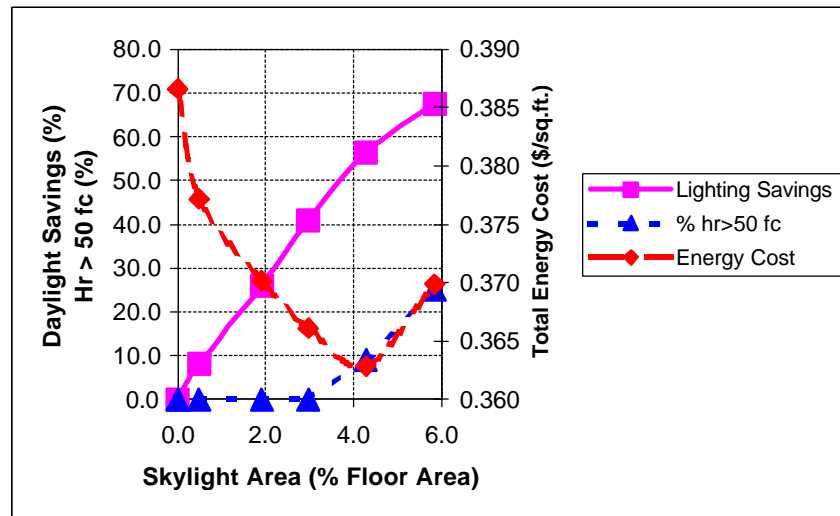


Figure 7 Effect of skylight area on annual lighting savings and energy cost.

This graph is for an electric cost of \$0.085/kwh and gas cost of \$0.70/CCF. As more skylight area is added more electric lighting is saved, and this trend starts to drop off when skylight area is over about 4.0% of floor area. At the same time, cooling and heating costs are increasing, tending to offset the lighting savings. This results in a minimum annual energy cost at a certain skylight size. In this case, it was just over 4.0% of floor area, equivalent to four 3 ft by 3 ft skylights in this room with a floor area of 840 ft<sup>2</sup>.

The sensitivity of annual energy use to skylight area (or to area of any daylighting aperture) is exaggerated in this graph to highlight the minimum. Note that the minimum at 4% skylight area is about 0.363 \$/ft<sup>2</sup>-yr, and at 2% and 6% skylight area is about 0.370 \$/ft<sup>2</sup>-yr, a relative increase of only 2%. For example, halving the skylight area from 4% to 2%, only increases energy cost for the classroom by 2%. For this case, that translates to an increase in annual energy cost of \$6 for the classroom. Clearly, the savings in skylight cost from halving the size (a reduction in size of 17 ft<sup>2</sup>) would greatly outweigh the small increase in energy cost. In fact, if one compares the

energy cost at the minimum with the cost with no skylights, you get an annual savings of about \$20. This leads to an observation about skylighting systems with these energy costs in this application – *providing natural light will add to the cost of the building and will typically not be justified on the basis of energy cost savings alone.*

Fortunately, providing adequate natural lighting levels has other more significant, if less quantifiable benefits. From an economics standpoint, workers in naturally lit spaces are more productive, and this increased productivity readily pays for the up-front costs of daylighting. In the case of schools, studies have shown increased student performance in daylit schools, in some cases over 20% (Heschong 2001). This is what led to the design goal stated earlier that focuses on providing sufficient natural light as a priority, with energy use as a secondary concern.

Later in the design development phase, a more detailed model was made of the room with the skylight system and a flat roof, versus a sloped roof and the clerestory. The base case was the room with a flat roof and north windows (all cases had the north windows). The annual energy use is shown in Figure 8. Even though the clerestory system uses slightly more annual energy than the skylight system, the clerestory system provided better natural light.

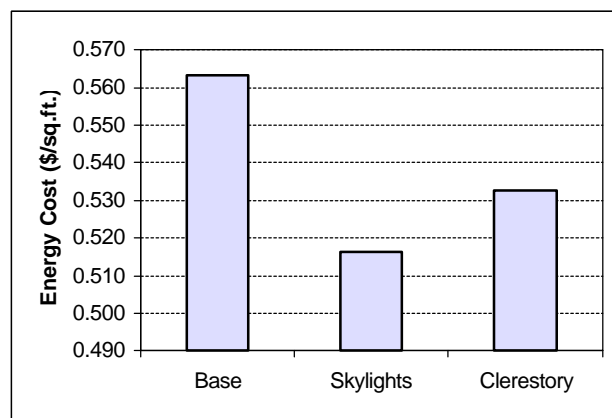


Figure 8 Annual energy cost for different daylighting systems.

#### 4. CONCLUDING REMARKS

The design of effective daylight systems for buildings requires the orchestration of various analytical tools that have yet to be well integrated. The analysis described here made use of primarily two software packages, Desktop Radiance for predicting the natural illumination, and PowerDOE for predicting annual energy use, including the effect of daylighting. A spreadsheet, Excel, was also instrumental in further analyzing outputs and providing graphical results.

The best design for classroom daylighting in this northeastern location was south-facing clerestories with diffusing glazing (with low U-factor) in combination with north-facing sidelighting. The general findings are:

- (1) Detailed and potentially accurate predictions of daylight distributions are possible on a desktop computer.

- (2) Finding the best design for daylighting requires modeling of both daylight levels and energy use, but daylight levels take precedence.
- (3) Combining daylight system types and tuning glazing characteristics results in the best overall performance.

## **5. REFERENCES**

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