Integrated Dynamic Skylight Solutions to Reduce Energy Consumption and Improve Indoor Lighting Quality in US Buildings

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ABSTRACT

Lighting is the largest percentage of electric energy demand in commercial buildings, with the greatest potential for substantial energy savings, peak load shaving, and human benefits. Proper integration of skylights into commercial building design represents an important potential approach for capturing these potentials. Sixty-five percent of all commercial buildings are 1 to 2 stories tall. However, currently only 2-5% of the total commercial building floor space has skylights installed. Energy simulation and side by side experiments were performed in the Intelligent Workplace Living Laboratory at Carnegie Mellon University to demonstrate how integrated day-lighting technologies can improve the thermal and lighting performance, achieve energy saving, and improve occupant comfort. Custom dynamic skylight shading control algorithms for an office building and retail store in Philadelphia were developed to maximize the energy savings and test additional technologies throughout the year. Research results show that integrated dynamic daylight and skylight technologies can provide a total energy savings of 0.8 – 13.9% and lighting savings up to 26% for office buildings and 58% for retail buildings, depending on the technology and control strategy, compared to an office or retail building with no skylights. This paper presents the methods and results of this research.

Introduction

Lighting is the largest percentage of electric energy demand in commercial buildings, with the greatest potential for substantial energy savings, peak load shaving, and human benefits. At the same time, 65% of all commercial buildings are 1 to 2 stories tall, however, currently only 2-5% of the total commercial building floor space has skylights installed. There is a huge opportunity for energy savings when retrofitting those buildings roofs if skylights were integrated.

The objectives of this modeling study is to evaluate the thermal performances of skylights and whether or not shading strategy with knowledge based control algorithm brings additional benefits. The control algorithm implemented in the simulation is based on knowledge acquired from field measurements during the first phase of this project (Pei 2013). In this modeling study, three skylight shading technologies have been compared to a baseline building without skylight as well as with static skylights: slimshade blinds, cellular fabric shades and electro-chromic(EC) glass. Because electro-chromic windows have different properties in their clear states than conventional skylights, a static skylight baseline with the property of the clear electromic window was also calculated to be able to compare the electrochromic shading strategy both to a conventional skylight and to a skylight with the same glass and U-value.

Background

Modeling studies have shown benefits of skylights in offices since the 1980's: In a single story commercial building, skylights reduced electric energy by 77% in the climate of Washington, DC compared to a base case without skylights (Treado, Gillette and Kusuda 1984). In a core room in an office located in Malargue,Argentina -which is a cold-to-temperate climate- a skylight strategy reduced energy consumption by 39% with 9% glass area (Garcia-Hansen, Esteves and Pattini 2002). Most recently conventional skylights reduced electrical energy consumption in a Boston single story office by 48% while integrated skylight with splay reduced it by 77% (Ghobad, Place and Hu 2012).

Contrasting with the limited amount of publications aboutexperimental skylight thermal performances, a variety of tools have been developed over the years to calculate these thermal performances such as skymode (York, Tucker and Coppiello 1984), skyvision (Laouadi, et al. 2003) or skycalc based on DOE2 (Heschong and McHugh 2000). Those numerous models are often not build upon each other and focus exclusively on skylights.Therefore a new model needs to be built if the user wants information about that building that are not related to skylight as opposed to our model beinf programed in Energy+.

Beyond the energy benefits of daylight, several studies demonstrate the health and productivity improvement through daylight for commercial buildings. For instance, retail stores where skylights provided a significant portion of daytime lighting had a 40% increase in sales, a measure of organizational productivity, as compared to stores with conventional lighting systems and no skylights (Heschong, Wright and Okura 2002). Additionally, in a software development company, occupants of windowed offices electric lighting was lower by 35% compared to occupants in interior offices with no access to daylight, in winter months (Figueiro, et al. 2002).This results reiterate the fact that daylighting reduces lighting consumption.

Modeling Assumptions

In this whole building energy modeling study, both the small conventional office and the small conventional retail space from the DOE reference building guidelines have been used (Deru, et al. 2011). The buildings were modeled in DesignBuilder and the loads were calculated with Energy+. They were both modeled for Philadelphia, PA weather which is in a climate 5a zone. A TMY3 weather file was used for this yearly simulation. The skylight were added with an area of 5% of the roof, according to ASHRAE recommendations.

In order to evaluate the skylight energy performance, lighting control strategies have been implemented in both models to dim the indoor lighting according to the daylight input. in the lighting control section of design builder, a linear control was selected, which means the overheads lights dim continuously from 100% light output to a minimum light output of 10%. Each zone has one virtual lighting sensor, placed at the height of 2ft. 8in.

Small Conventional Office Model

The small office model has a rectangular floor plan and a pitched roof. The total floor area is 5500 ft2. The building height is 10.17 ft. It has a core zone with four perimeter zones which is indicated by figure1. The exterior wall has an R-value of 8.13 and the roof has an R-value of 29.4. The windows have R-value of 1.75, SHGC of 0.39 and visible transmittance of 31%. With windows on the 4 facades, the perimeter zones receive sufficient daylight. Therefore the skylights were added above the core zone where they will have the most impact. The changing properties of the skylight can be found in Table 1.

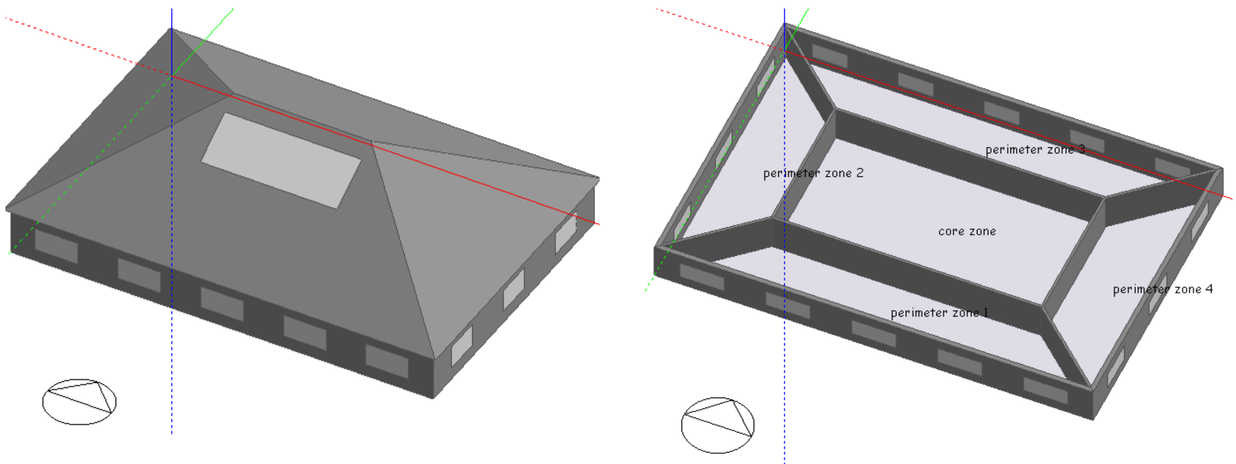


Figure 1. Small office building representation in design builder and its 5 zones.

Stand-Alone Retail Model

The stand-alone retail building has a rectangular floor plan and flat roof as illustrated in figure 2. The total floor area is 24692 ft2. The building height is 20 ft. The exterior wall has an R-value of 8.13 and the roof has an R-value of 15.8. Windows have R-value of 1.75, SHGC of 0.39 and visible transmittance of 31%as shown in table 1. Only the south wall has windows. It has a core zone with four perimeter zones. The core retail zone has the largest volume of the zones, but no windows. Hence the skylights were added to the core zone roof for this study. This zone was subdivided in 6 zones, one under each skylight to calculate the loads more accurately. The changing properties of the shaded skylight can be found in Table 1 and are similar to the office model in Table 1.

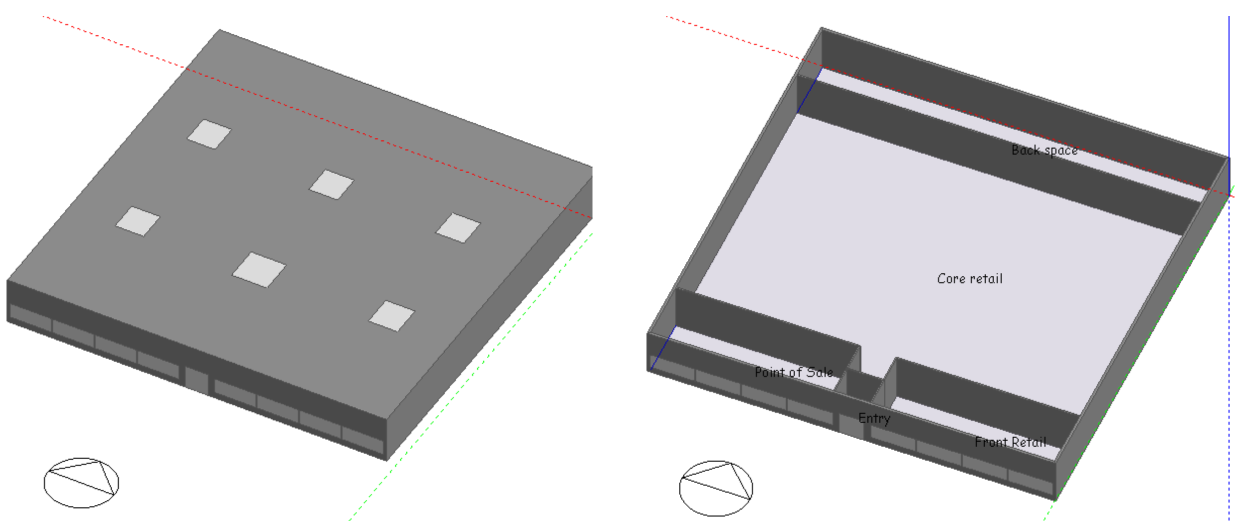


Figure 2. Retail model zoning and skylight location.

Table 1. Skylight properties for the different shading strategies for offices and retail skylights

	Slimblind shade			Cellular fabric shade			Dynamic glass		
	U-value	SHGC	Tvis	U-value	SHGC	Tvis	U-value	SHGC	Tvis
Shades on	0.35	0.17	31	0.3	0.23	29.5	0.29	0.17	21
Shades off	0.48	0.59	61	0.48	0.59	61	0.29	0.47	62

Knowledge-Based Dynamic Shading

The dynamic control strategy energy consumption is illustrated in figure 3. It is calculated by evaluating the hours of the year when shading should be used and when it should not, based on the season and the solar radiation. The loads are calculated for the 2 configurations. Then the adequat energy consumption values for each hour are summed based on the dynamic control strategy output.

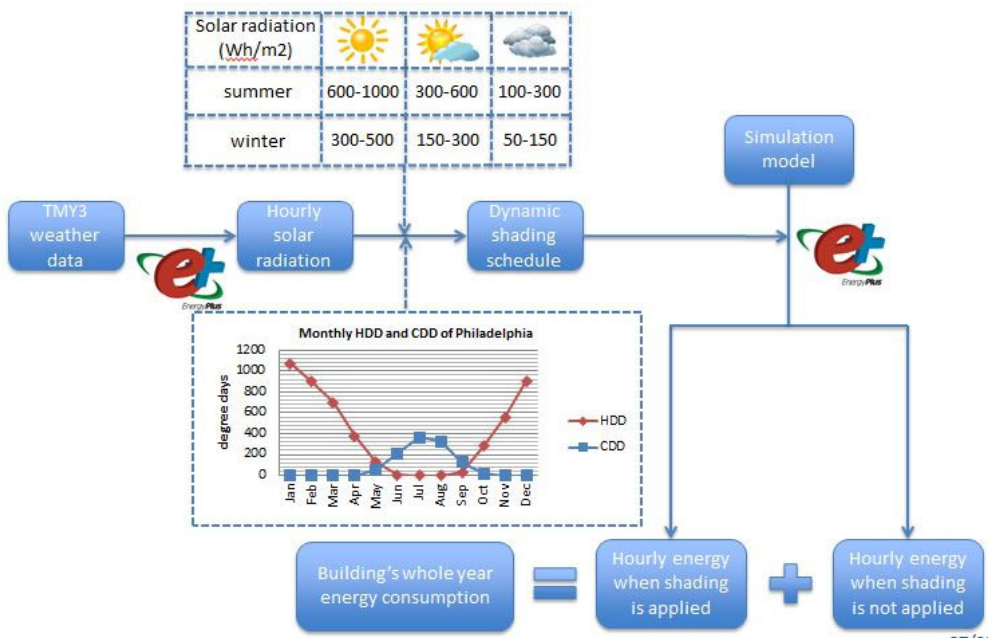


Figure 3. Knowledge base dynamic shading strategy.

The first step of this method is to develop a dynamic skylight shading schedule. As a typical city in northeast region of the U.S., the heating season for Philadelphia is from November to March. June to August, is the cooling season while April, May, September and October are identified as the swing season where needs for heating and cooling alternate. These seasons are illustrated in figure 4.

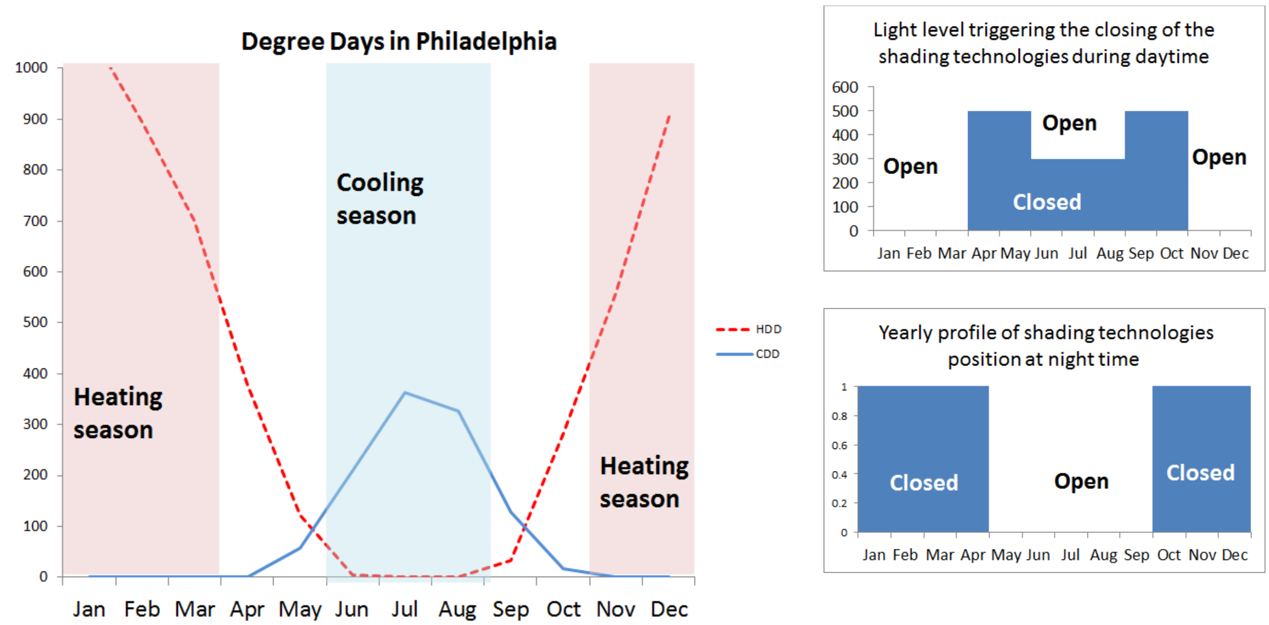


Figure 4. The climate of Philadelphia influences the control algorithms set points based on degree days.

In the cooling season, shading is needed during most time of a day to block extra daylight and solar heat,therefore the closing setpoint for shades is 300W/m^2. At night, it has been estimated that shading should be pulled up so that night radiation could cool down indoor temperature since the summer sky is usually clear and cool in the northeast climate (Patwardhan 2012). In heating seasons, shading is expected to be pulled up during daytime to receive free solar heat and daylight and should pulled down at night to prevent heat loss. During swing season, heat is needed from time to time,therefore the shade are only used when the solar radiation is higher than 500Wh/m2 during daytime and are kept pulled down at night to block the radiation to the night sky and trap the heat inside.

Results

Conventional Small Office Results

According to figure 5, static skylights increase site energy consumption by 3.8%. After applying slimshades and cellular shades with knowledge base control, both of the two shading strategies reduce the site EUI to 61.5 kBtu/ft^2, achieving 2% and 5.7% energy savings compared to no skylight and static skylight respectively.

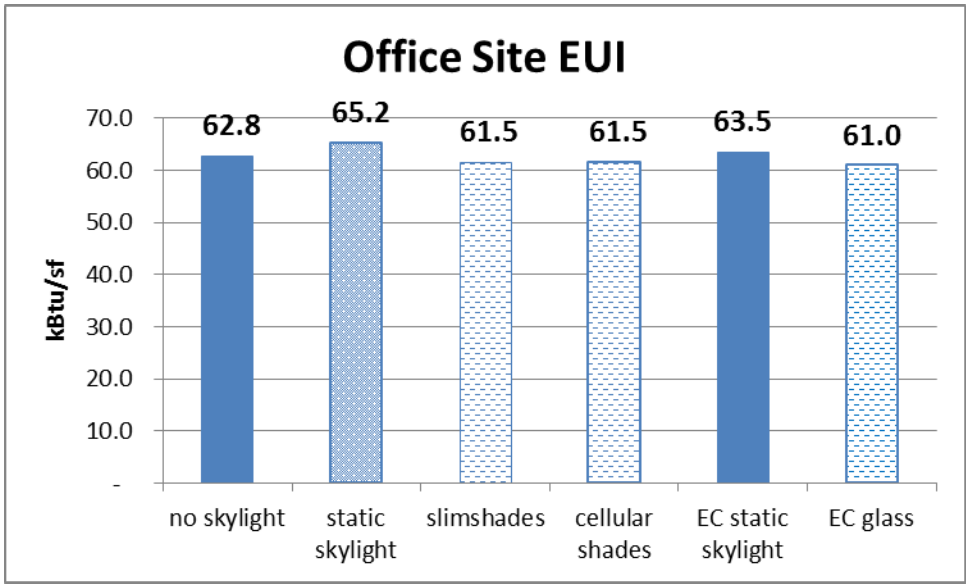


Figure 5. Site EUI of the DOE conventional office with different skylight shading strategies.

When analyzing the main energy end use breakdown, static skylights achieve heating and lighting energy saving. However, the cooling energy increases by 55%, resulting a total energy increaseas shown in figure 5. Although lighting energy reduces, which means internal heat gain from electric lighting should decrease, the cooling energy still increases a lot. It is probably because the SHGC of skylight is high, therefore too much solar heat has been received through the skylights. This assumption is further confirmed by the heating energy. Slimshade blinds and cellular shades have almost the same performance in saving cooling energy consumption, however, slimshade blinds results in slightly higher energy consumption for lighting. The same strategy applied to electro-chromic glass brings the EUI to 61kBtu/ft^2 by reducing the cooling load further than internal shades.

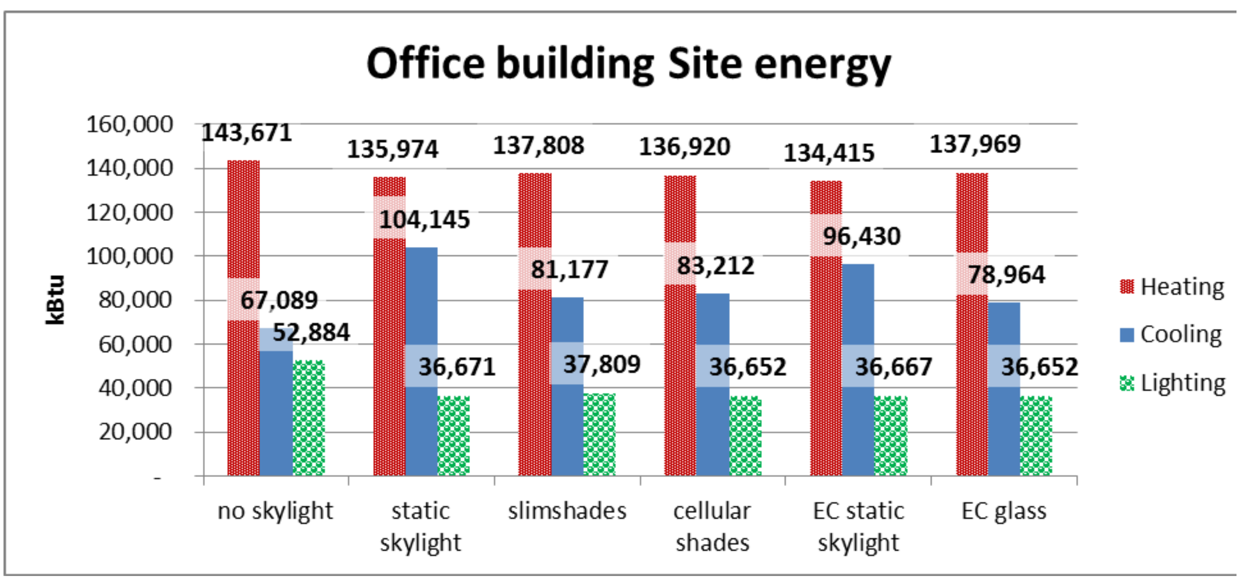
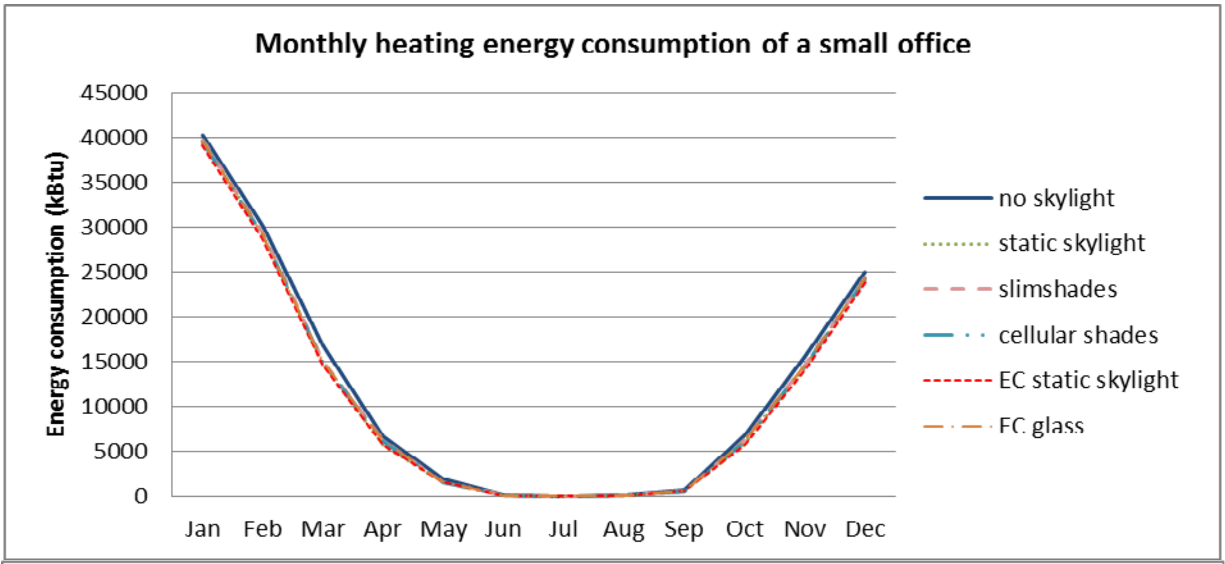
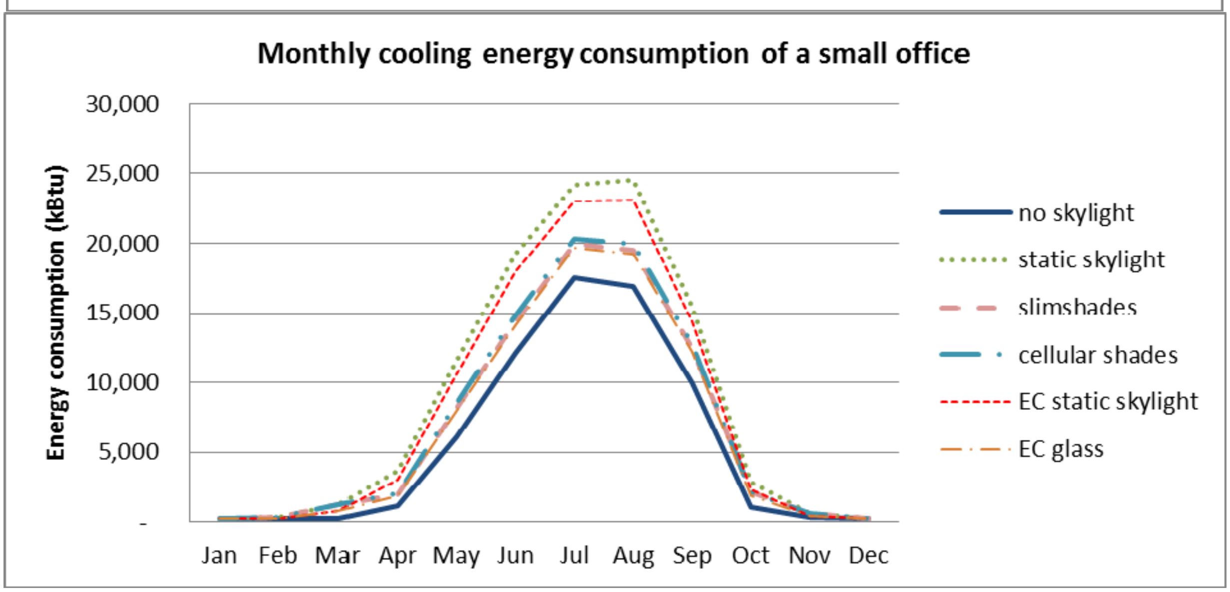


Figure 6. Small office energy end-use comparison.

The three graphs below represents the monthly profile of energy consumption of the small office model for heating cooling and lighting. This comparative study shows that shading has almost no effect on heating consumption. For cooling, the implementation of static skylight increases cooling energy consumption during summer months but the dynamic shading helps in making this increase smaller. In terms of lighting, the cellular shade profile almost overlaps with the static skylight one; indicating that this shading still allows sufficient daylight to come inside. Due to their very small visible light transmittance value, slimshade blinds block more daylight, which results in a higher consumption for electric lighting. The dynamic shading strategy seems to have more impact during summer; the winter strategy of closing the blinds at night does not have a significant impact noticeable in this energy modeling study.





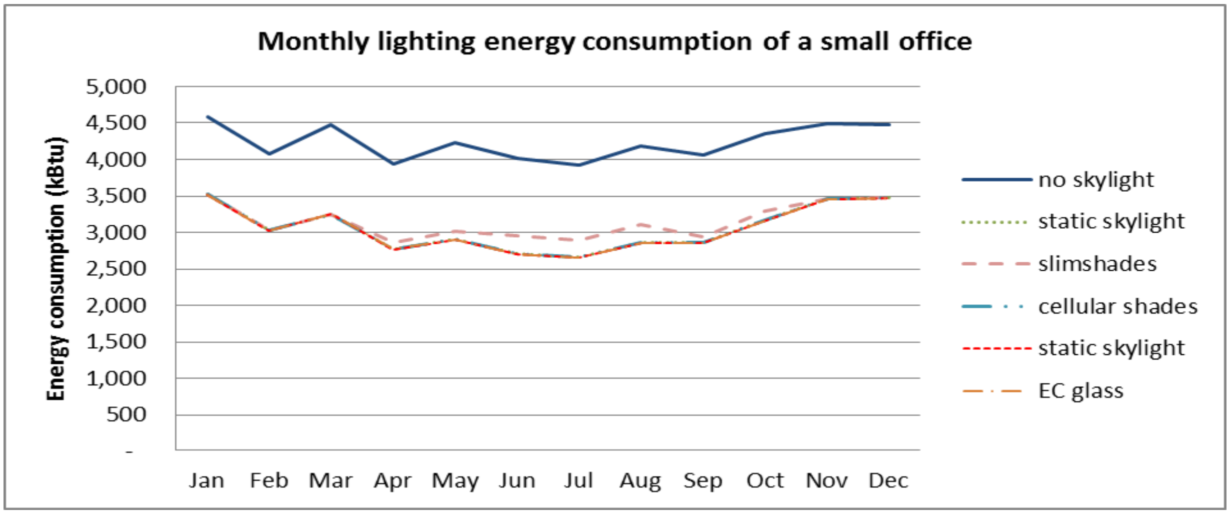


Figure 7. Monthly energy consumption by end-use in a small conventional office for different skylight shading strategies.

Stand Alone Retail Results

In the case of a retail building, static skylights achieve 10.8% site energy reduction compared to the baseline. The two dynamic shading have different energy performances: slimshades increase energy consumption by 1% and cellular shades reduce energy consumption by 3.5% compared to static skylight.Further information about the energy use intensity can be found in figure 8.

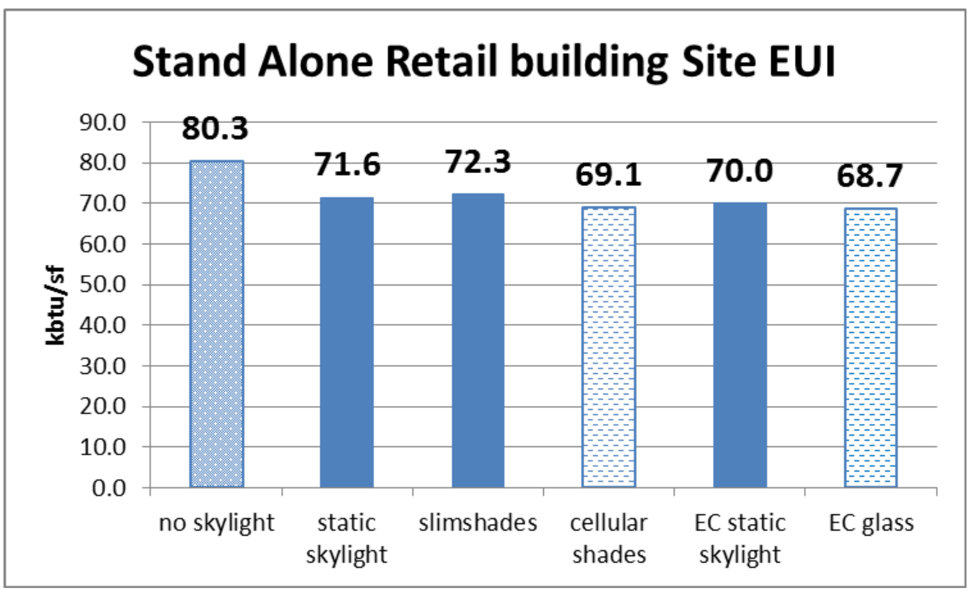


Figure 8. Stand-alone retail source EUI comparison.

Figure 9 presents the detail energy end use breakdown of each alternatives. Comparing the baseline and static skylight data, it is easy to find that most of the energy savings come from lighting energy consumption. Cooling energy consumption is also reduced most likely because the lighting energy consumption is almost halved which reduced the internal heat gain from lighting. However there is a small heating energy consumption penalty for the 3 skylight strategies. The slimshades consumes 21.5% more energy in lighting than cellular shades.The low light transmittance of the slim shades excessively blocking daylight was identified as a probable cause for this energy consumption increase. Electro-chromic glass reduces the EUI to 68.7kBtu/ft2 which reduced the energy consumption by 14.4%.

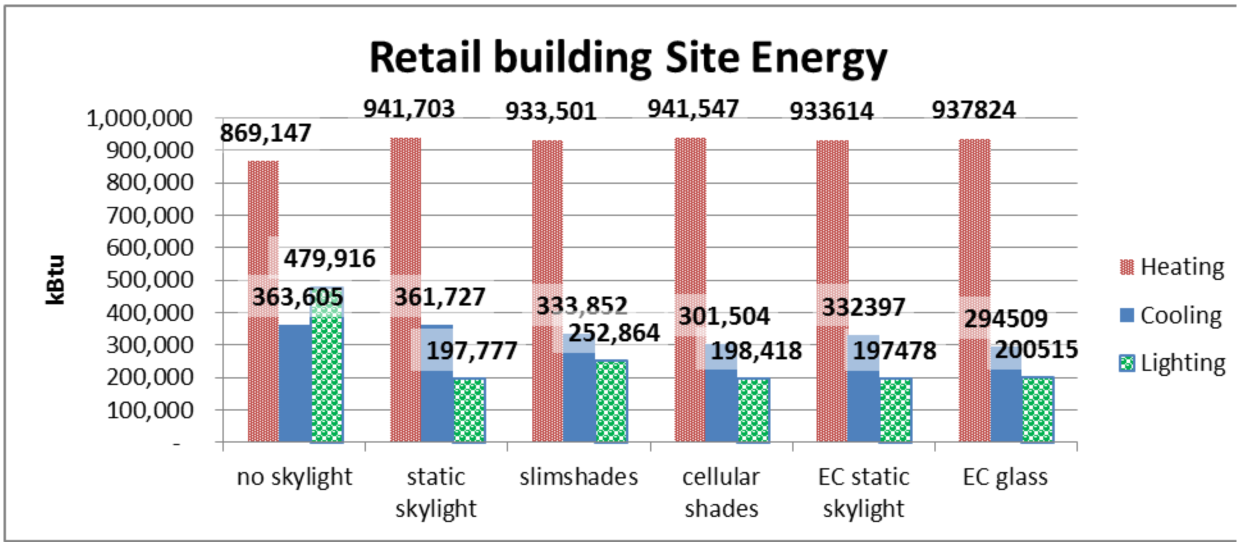


Figure 9. Retail model energy end use breakdown comparison.

Figure 10 presents the monthly change of the three main energy end use of these alternatives. Similar to the trend in small office, there is still almost no impact on building's heating energy consumption. Regarding to cooling, cellular shades consumes less energy than slimshades, even though slimshades have a lower SHGC than cellular shades. For lighting energy, the implementation of cellular shades doesn't impact the skylight's daylight performance. The lighting energy changing curve of cellular shades is overlapped with static skylight. However, slimshade blinds consume much more energy for lighting. As mentioned before, the low light transmittance blocks too much daylight, so the building has to use more electric lighting to reach the illuminance setpoint. Besides, it also explains why with a lower SHGC, slimshades still consumes more energy in cooling.

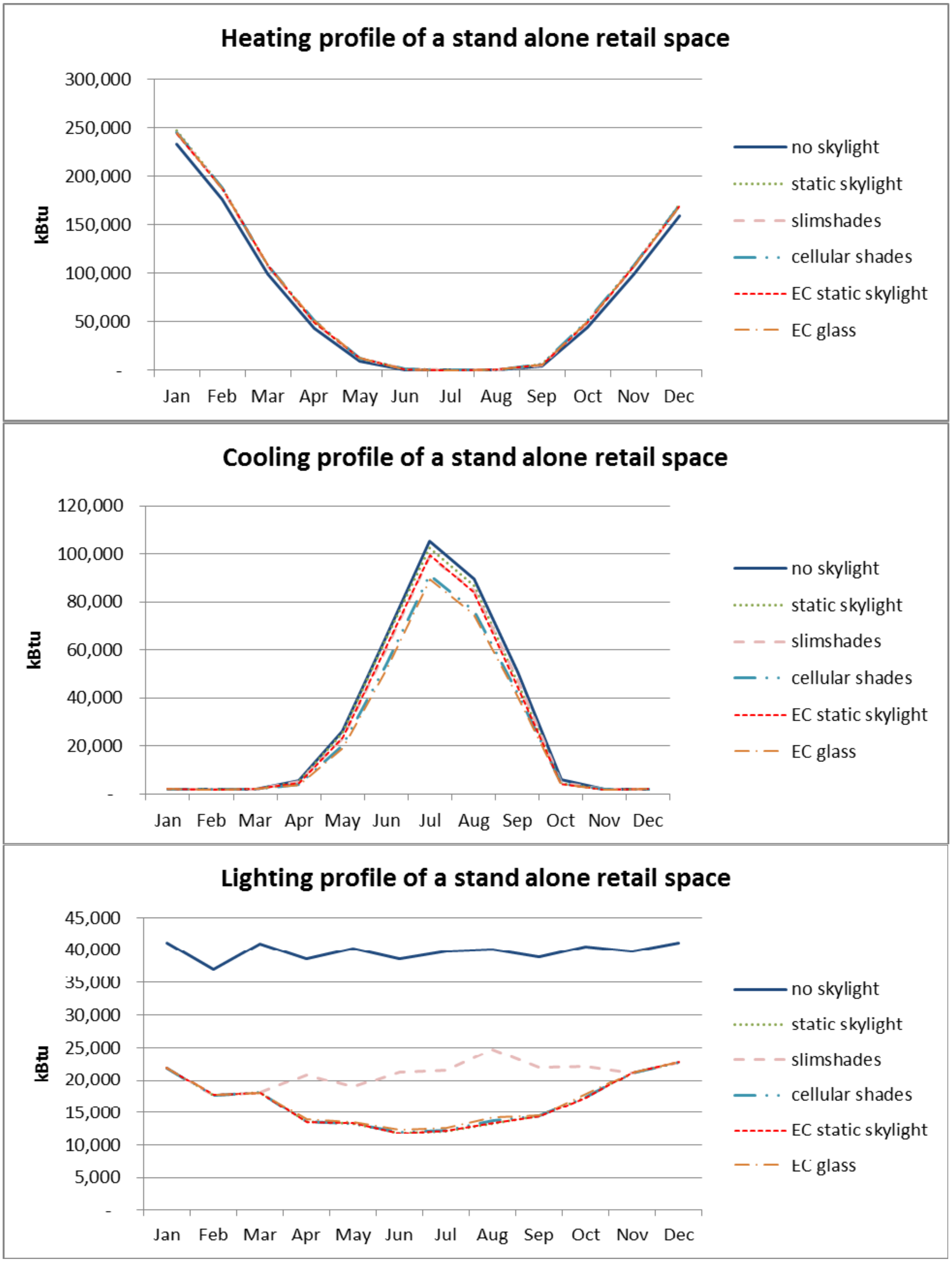


Figure 10. Monthly energy profile by end use of a small retail space for different shading strategy.

Discussion

There are two main differences between the small office and retail model results. Firstly, in small office, static skylights consume more energy than without it while in retail model, static skylights achieve 10.8% energy saving. Secondly, in the retail model, there is an energy performance difference between slimshade blinds and cellular shades,while in small office there is almost none. To explain those discrepancies, it is necessary to go back to the characteristics of the two models. As previously stated,the small office has a relatively small floor area and it is surrounded by windows on every facade. In this case, the four perimeter zones already has enough daylight coming from the windows, which will reduce the impact of the skylights. However, the retail model is a big rectangular box with windows only on its south wall. Most of the areas in the retail model don't have access to daylight, therefore, the skylights have a huge impact on the retail lighting performances. Finally the type of shading solutions installed will have difference performance, mainly because of the difference of visible light transmittance.

Conclusion

In this study, the impact of shaded skylights controlled with a knowledge based algorithm was evaluated for the climate of Philadelphia, for a small office and a stand alone retail space. An Energy+ model was created for both buildings. Shaded skylights showed a 2% energy reduction compare to the absence of skylight in an office. The energy savings were bigger for a retails space with 14% energy savings with cellular shades with the same control logic.
This study shows that the drawback of skylights can be avoided if they are dynamically shaded in an office. It also emphasized that skylights save energy for retails even without shading. Skylights are an element of the solution to reduce the US total energy reduction that needs to be more often considered in new design and retrofit of buildings.

References

Belzer, DB. An Exploratory Energy Analysis of Electrochromic Windows in Small and Medium Office Buildings – Simulated Results Using EnergyPlus. Seattle: PNNL, 2010.

Deru, Michael, et al. U.S. Department of Energy Commercial Reference Building Models of the National Building Stock. Technical Report, Golden,CO: NREL, 2011.

Garcia-Hansen, V, A. Esteves, and A. Pattini. "Passive Solar Systens for Heating,Daylighting and ventilation for rooms without an equator-facing facade." Renewable Energy, 2002.

Ghobad, Ladan, Wayne Place, and Jianxin Hu. "The Impact Of Systems Integration On The Daylighting Performance Of Skylights In Offices." Fifth National Conference of IBPSA-USA. Madison, WI, 2012. 577-284.

Heschong, Lisa, and Jonathan McHugh. "Skylights: Calculating Illumination Levels and Energy." JOURNAL of the Illuminating Engineering Society, 2000.

Laouadi, A., A. Galasiu, M. Atif, and A. Haqqani. "Skyvision: A Software Tool To Calculate The Optical Characteristics And Daylighting Performance Of Skylights." 8th International Building Performance Simulation Association Conference,. Eindhoven, Netherlands,, 2003. pp. 705-712,.

Patwardhan, Uma. "Reducing Energy Consumption & Improving Indoor Environmental Quality with Dynamic Solar Shading." MSSD Synthesis, Pittsburgh, 2012.

Pella. "Product performance." Between-glass window fashions. 2013. http://media.pella.com/professional/adm/Clad-Wood/DSBTGPerformance.pdf.

Treado, S., G. Gillette, And T. Kusuda. "Daylighting with Windows, Skylights, and Clerestories." Energy and Buildings, 1984.

York, D.A., E.F. Tucker, and C. Coppiello. "SKYMODE — Annual energy performance simulation model for skylights." Energy and Buildings, 1984: 353–360.