How Much Energy Do Sidelighting Strategies Save?

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Summary

Windows can introduce considerable heat gains and losses that may offset the benefits of electric light savings and cause an increase in yearly net energy use. The use of shading devices is necessary to prevent overheating and provide a glare-free visual environment. The common shading devices that have been in use in buildings are exterior overhang and interior blinds and roller shades.

This study examines the impacts of exterior overhang, roller shade, and blinds devices on the total yearly energy loads for a prototypical classroom space situated in Boulder, Colorado. The measured bi-directional transmittance characteristics for a roller shade were applied to the yearly daylight availability analysis. Coordinated modeling, with an advanced daylight and electric lighting simulation program and a building thermal simulation program based on hourly weather data was used to compute yearly total building energy use. Annual lighting, cooling and heating loads for a side-lit space using the shading devices were compared with those of a base case with no shading device. Of special interest was the performance of the new roller shades in comparison to blinds and exterior overhang as they are installed in the new New York Times building. It was found that the total energy performance of the roller shade with a total transmittance of 10.4% was similar to blinds tilted 45° with 60% reflectance. The roller shade consumed 12.5% more total building energy than exterior 1.2 m (4-ft) overhang.

1. Introduction

Most commercial windows are combined with either exterior overhangs or interior shades or blinds to block sunlight on the workplane. Exterior overhangs have been commonly used to block the high-angle, summer sun, but allow the lower winter sun to enter a building. Interior roller shades, blinds, and screens can attenuate heat gain, but they do not block sunlight. Roller shades are of particular interest here because they have been used more frequently and are now installed in the new New York Times building, a green building initially designed to earn a silver or gold LEED rating.

These windows and shading devices influence lighting loads as well as change solar heat gains and losses in very different ways. In order to ensure the selection of energy-efficient shading devices for a given window configuration, yearly lighting, cooling, and heating energy consumption on an hourly or sub-hourly basis must be identified. These energy use data can be accurately obtained by combined lighting and thermal simulations based on actual hourly weather data for a site.

A previous study about the impact of shading devices on energy use showed that shading devices reduce the cooling load of building by 23% - 89%, with the highest savings attained with devices with a low shading coefficient (Dubois 2001).

A tool called ParaSol-LTH has been developed to predict the energy performance of shading devices. However, it assumes a constant lighting load, ignoring lighting energy saving potential of windows equipped with shading devices, the effect lighting energy reduction on cooling and heating energy use, and the effect of daylight dimming (Wallenten et al. 2000).

2. Bi-directional Transmittance Measurement of Roller Shade

2.1. The cube

The bi-directional transmittance of a commonly used roller shade (see Figure 1), with its circular shape of diameter 3.5", was measured using the cube shown in Figure 2. The cube used for measurement of the shade has a frame of steel with dimensions 59"×59"×60", where 60" was the height of the cube. Five sides of the cube frame were closed with foam board panels, and one side was open in order to access the interior of the cube. The open side was covered with a black cloth during measurements. The light source used was ERCO beamer. The half angle of the sun is 0.025°, and the half angle of the source was 1.27°. The source was the best light source available to get a near parallel beam.

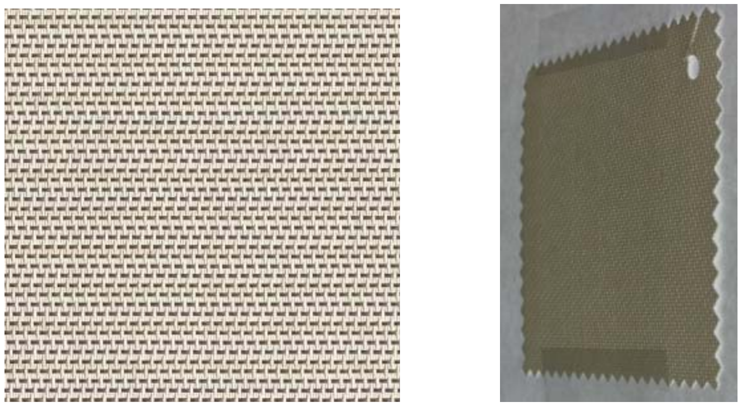


Fig. 1: Roller shade

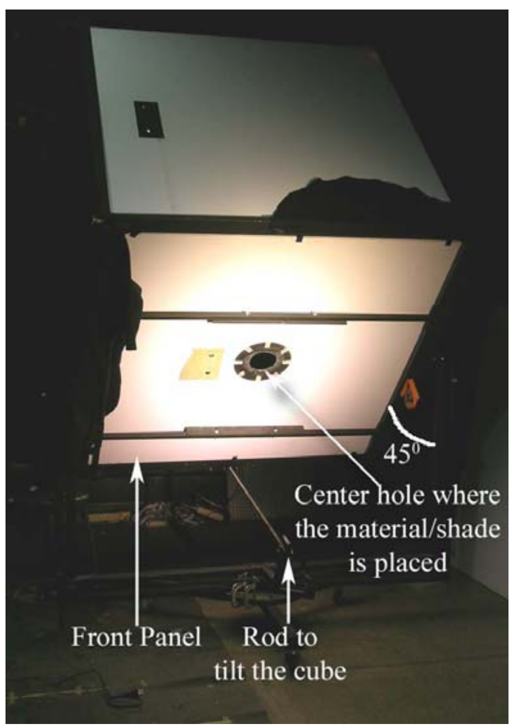


Fig. 2: The cube used for BTDF measurements

The front panel has a hole in the center which is 0.127m (5") in diameter. The shade, daylight system or the material whose BTDF is to be measured, is mounted so as to cover the hole.

One side of each of the five panels was covered with a black velvet material with reflectance measured at 2%. The other side was completely white with 7.6cm×7.6cm (3"×3") grids marked on the white side. At any given measurement position, the white side of only one of the four panels (the front panel has black velvet inside for all measurements) faces the inside, while all the other three panels have their black side facing inside. This was done to minimize any interreflections between the surfaces. A panel layout in which the side panel is white is shown in Figure 3.

Fig. 3: Configuration to avoid interreflections: one white panel and four black panels

2.2. Camera placement

The Nikon Coolpix 5400 camera, which was used as a multi-point luminance meter, was fixed at one of the three positions in the cube. The errors in the camera can be found in Anaokar and Moeck (2005). The four cube panels to be measured to obtain complete information about the transmitted distribution were the back panel, the side panel, the top panel, and the bottom panel. To capture the distribution on the back and bottom panel, the camera was attached to the front and top panel respectively as shown in Figure 4. To capture the distribution of the top panel, the camera was attached to the bottom panel; to capture the distribution of the side panel, the camera was attached to a holder at the open side of the cube. The panel on which the distribution is captured is called the active panel.

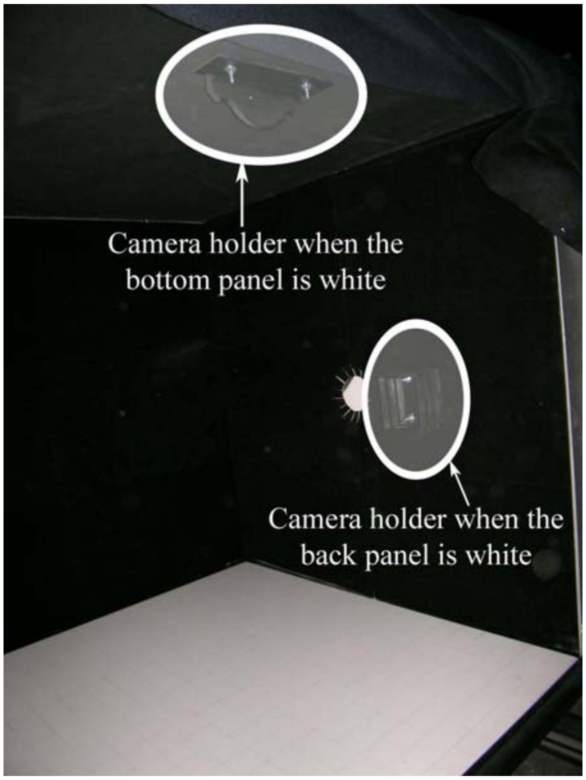


Fig. 4: Camera placement for back and bottom panel distribution

2.3. Angle measurements

In order to measure the BTDF of the shade, distribution of the transmitted light is needed for all the incident sun angles. The incident angles are represented by a tilt (θ) (corresponding to the sun altitude angle) of the cube as shown in Figure 2 and rotation (φ) (corresponding to the sun azimuth angle) of the shade as shown in Figure 5. The combination of the tilt and rotation correspond to a certain azimuth and altitude angle as shown in Equations 1 and 2.

$$\theta_{az} = \cos^{-1}\left(\cos\theta_{tilt} / \cos\theta_{alt}\right) \quad (1)$$

$$\boldsymbol{\theta_{alt}} = \sin^{-1}\left(\sin\boldsymbol{\theta_{tilt}} \times \cos\boldsymbol{\theta_{rot}}\right) \quad (2)$$

The different measurements are for incident varying for all θ from 0° to 70° and with φ from 0° to 180°.

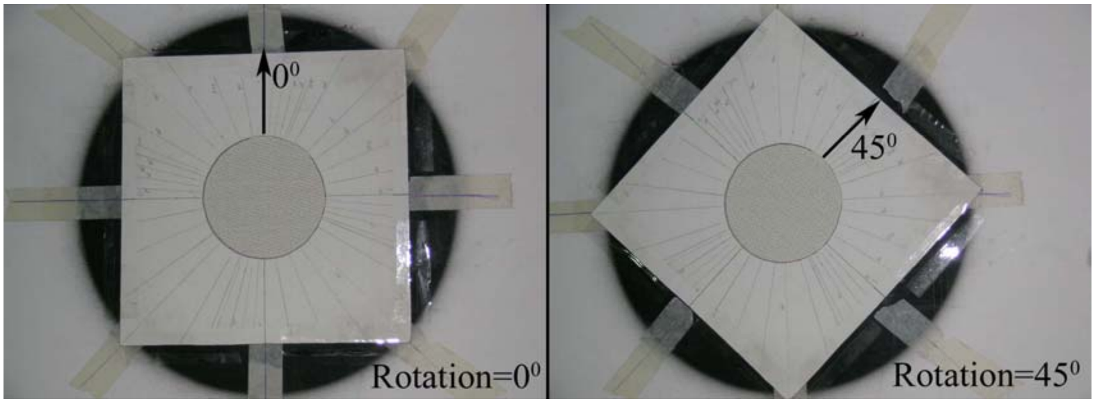


Fig. 5: Shade Rotation (φ)

2.4. Measurement procedure

The shade was attached to cardboard which was then mounted on the front panel of the cube. The shade and cardboard combination completely covered the hole such that all light that enters the cube is through the shade only.

2.5. Measurement of direct transmittance

An illuminance meter (Minolta T-10) was mounted on a tripod and placed directly behind the shade on the floor behind the cube. The back panel of the cube was removed for this measurement setup. The illuminance meter on the tripod was set up such that it lies in the direct component of the shade. The illuminance readings for the direct component through the shade were measured for all the different angle configurations. The shade was then removed, and the illuminance readings were measured again for light passing through the hole alone (without shade) for all the angle configurations again.

For each angle configuration, the ratio of the illuminance reading with and without the shade gave the direct transmittance of the shade for each angle configuration.

2.6. Measurement of total transmittance

A Munsell N6 matte gray card was attached at a known position on the active panel (one of the five panels of the cube which is reflective). The luminance on the gray card was measured using a Konica Minolta LS-100 Luminance meter. This luminance measurement was later used to calibrate the high dynamic range images created in Photosphere.

The camera was attached to the holder. The camera configurations, shown in Table 1, were used for each combination of tilt-rotation of the cube-shade. The shutter speed for each combination was changed from 1/2000 to 8 seconds.

Table 1: Camera Configurations

Camera	Nikon Coolpix 5400
Image resolution	1944 × 2592
Image size	5Mpixel
Image quality	Fine
White balance	Preset to the white panel with the source used
ISO	100
f-stop	2.8
Noise reduction	ON

Using the above configuration, at each tilt-rotation combination, 15 images of the distribution on the active panel were taken at the shutter speeds. These images were then combined using the image processing software Photosphere, developed by Greg Ward. The luminance of the gray card measured with the Luminance meter was then used to calibrate the high dynamic range (HDR) image.

The HDR images were converted to a photometric distribution file. This enabled the calculation of the total number of lumens transmitted in each angle configuration. Hence, the total transmittance of the roller shade was calculated using these lumen values.

2.7. Measurement of diffuse transmittance

Once the total transmittance was calculated for each angle configuration of the cube, the difference between the total and direct transmittance gives the diffuse transmittance of the shade at each angle. It was found that the average total transmittance was 10.4%, while the average direct transmittance varied from 0 to 3% as shown in Figure 6.

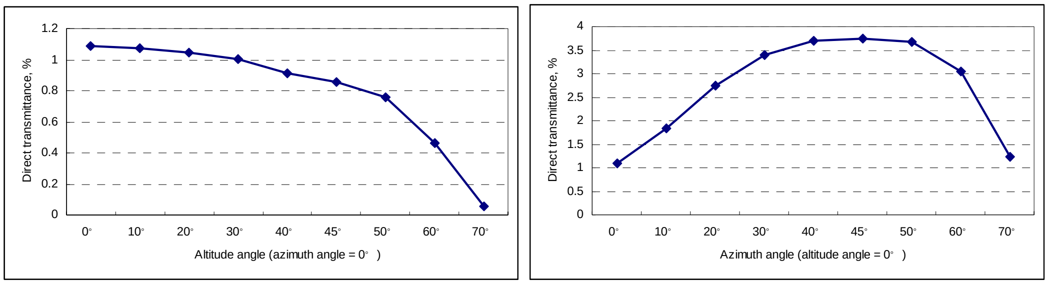


Fig. 6: Direct transmittance as a function of incident angle

2.8. Modeling of the shade in RADIANCE

To replicate the bi-directional transmissive characteristics of the shade, the shade was modeled using the trans material in RADIANCE (Larson and Shakespeare 1998) based on the hemispherical diffuse transmittance of 8.5% and the direct transmittance of 2%. Figure 7 compares the actual image of a shade installed in a building and the rendering image generated by RADIANCE.

Photo Radiance Radiance pseudocolor

Fig. 7: Comparison of the actual and rendering images of roller shade

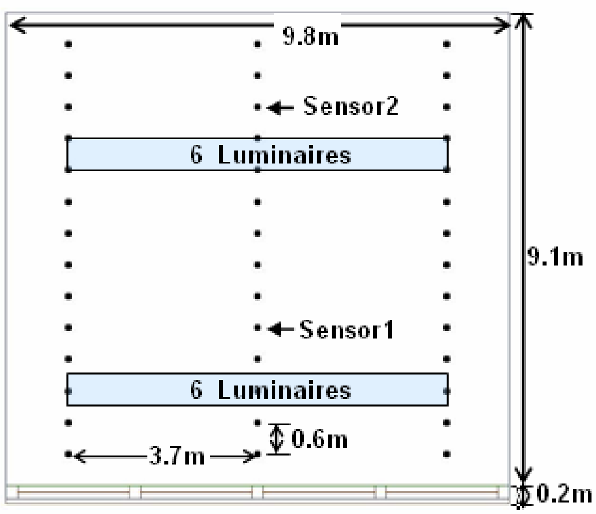
3. Simulation Study

This study compared the performance of roller shades installed in south-facing windows with the performances of blinds, exterior overhang, and clear windows without a shading device for a classroom in Boulder, Colorado. A lighting simulation program (RADIANCE) was combined with a building energy software (DOE 2.1E, James J. Hirsch and Associates 1998) to calculate accurate annual electric lighting energy consumption on an hourly basis over the whole year and capture the interaction between the electric lighting energy use and building cooling and heating energy use.

3.1. Typical classroom space

A one-floor, one-zone space with a floor area of 89.2 m^2 measuring 9.8 m width by 9.1 m depth (960 ft^2, 32 ft by 30 ft) was modeled. The reflectance values of the interior ceiling, wall, and floor were 75%, 55%, and 30%. The reflectance of blinds was 60% diffuse. The floor to ceiling height was 3.7 m (12 ft). The south façade of the building included double-paned clear windows separated by columns into upper and lower windows, and the total window area was 12.9 m^2, excluding window frame area. The window to wall ratio (WWR) was 0.36. The window provides the minimum of 1.5% daylight factor for 75% of the workplane area, covering 29.1%, 17.6%, 12.4%, and 41% of the workplane area with below 2%, between 2% and 3%, between 3% and 4%, and above 4% daylight factor, respectively. The minimum to maximum illuminance ratio was 8.4 for overcast sky. Figure 8 illustrates the classroom space and window configuration. The shade and blinds were situated inside glazing. The four different sidelighting strategies studied are as follows:

1. Base case – bare windows with no shading device
2. Roller shades with a total transmittance of 10.4% covering only the upper windows
3. Horizontal blinds oriented at a 45° angle, with the top surface facing outward to block direct sunlight from entering the building, covering both the upper and lower windows
4. Exterior 4-ft horizontal louvered overhang (see Figure 9)



Ceiling Reflectance: 75%

Wall Reflectance: 55%

Floor Reflectance: 30%

Glass Transmittance: 73%

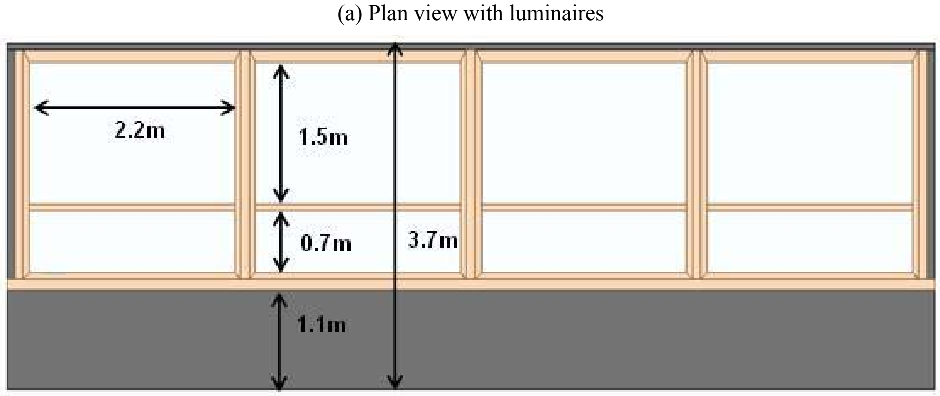
Photosensor Locations in meters:

Sensor 1: 4.9, 3.0, 0.8 (16,10,2.5)*

Sensor 1: 4.9, 7.3, 0.8 (16,24, 2.5)*

* Sensor locations in feet

(a) Plan view with luminaires



(b) Front elevation view

Fig. 8 : Classroom plan view and elevation view

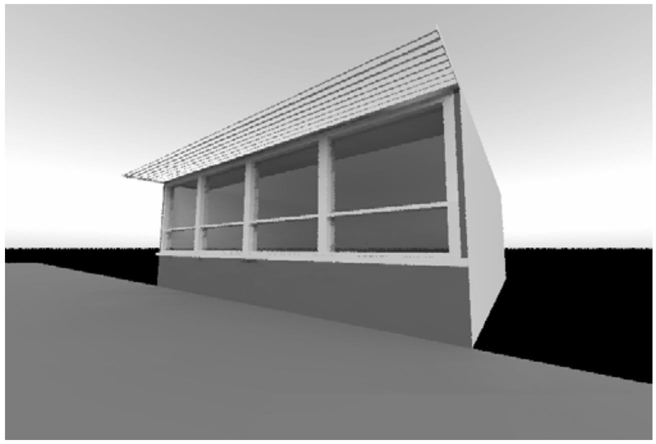


Fig. 9 : Exterior 4-ft louvered overhang

3.2. Daylighting and electric light simulation

TMY2 weather data (Marion and Urban 1995) was used for both daylight and thermal simulations. It should be noted that TMY2 beam radiation data are an average 10% higher than METEONORM weather data (Remund 1999), and TMY2 diffuse horizontal radiation data are lower than METEONORM data by an average 19% (see Figure 10).

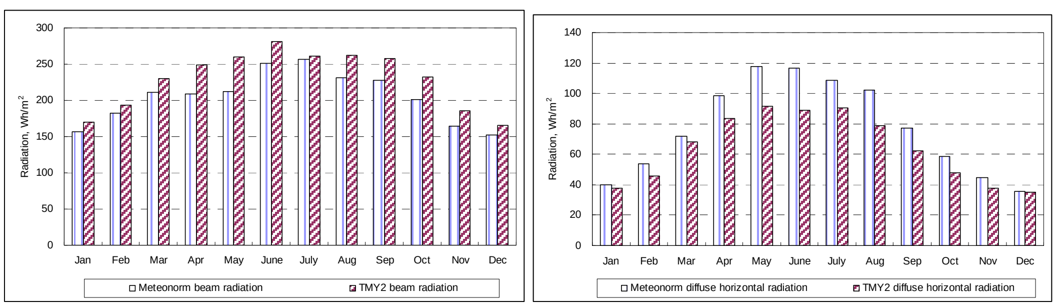


Fig. 10: Beam and diffuse horizontal radiation for Meteonorm and TMY2

To dynamically predict changing interior daylight levels, a series of hour-by-hour daylight simulation over the whole year, based on the Perez sky model (Perez et al. 1990) with its weather input taken from TMY2, was undertaken using RADIANCE. Illuminance levels were calculated over the workplane for 365 days during occupied hours from 8 A.M. to 5 P.M. for 42 points distributed along the grid lines located 1.2 m (4 ft) away from the east and west walls and at the center of the space as shown in Figure 8 (a). Each point was spaced 0.6 m (2 ft) apart.

For the electric lighting energy studies, (direct) luminaires were laid out in two rows with six luminaires per row on the ceiling plane. The illuminance values on the two sensor points as shown in Figure 8(a) were used to determine the amount of electric light output required to meet a target illuminance level of

538 lux. Each row of luminaires was dimmed independently according to the illuminance levels of the two sensors. The required lighting power density through electric light alone was 14 W/m^2 (1.3 W/ft^2). Lighting power density for non-occupied hours (from 6 P.M. to 7 A.M.) was set to zero. The space was assumed to be occupied from Monday to Friday. A continuous dimming system was used where the minimum light level was 5% of total light output, and a minimum of 19.6% of full ballast input power was consumed. The luminaires were always dimmed and never turned off during occupied hours. The change in lighting power consumption associated with the change in illuminance was assumed to be linear according to Figure 11. If the daylight level exceeded the target level, the luminaires were maintained at the minimum light output levels of 5%.

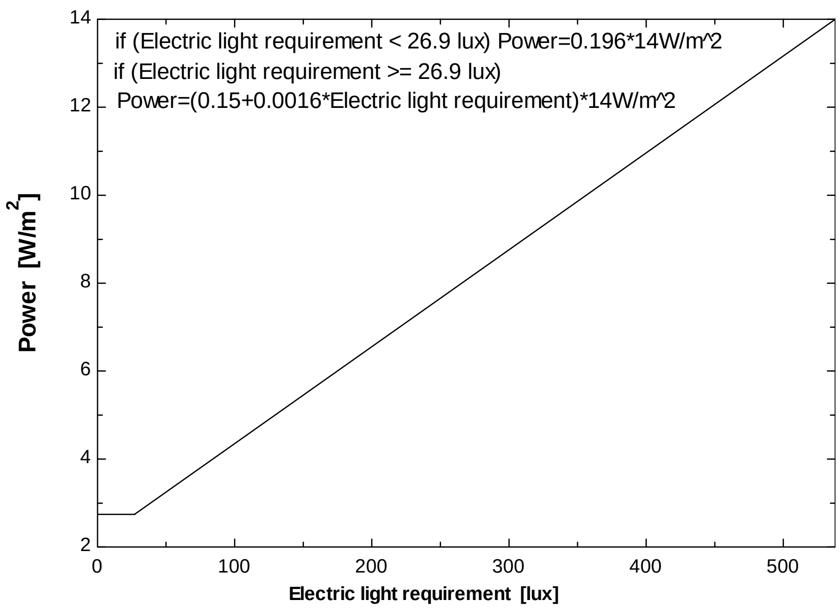


Fig. 11: Electric light dimming curve

3.3. Thermal simulation

DOE 2.1E (DOE 2) was used to compute hour-by-hour building cooling and heating loads. The south-facing wall was modeled as an exterior wall. To isolate the energy effect of the heat transfer and solar heat gain through the glazing material and shading devices, the other walls were modeled as interior walls by assuming adiabatic surfaces (Eley Associates 2003). U-values for the roof, exterior wall, and slab-on-grade floor construction, efficiency of cooling and heating equipments, and lighting power density complied with Energy Benchmark for High Performance Buildings (New Buildings Institute, Inc. 2005). The heat transfer from the floor to the ground through the slab was modeled in DOE 2 by specifying an effective U-value (Winkelmann 2002). Cooling and heating design temperatures were maintained at 23˚C (74˚F) and 21˚C (69˚F), respectively, with fans operating from 7 A.M. to 6 P.M. Table 2 summarizes the DOE 2 simulation assumptions for this study. Equipments loads of 0.52 W/ft^2 were computed based on the operation of four computers at 125 W per machine (ASHRAE 2001b). The occupancy density used was 20 students and one teacher (Stecher 2002). Full year occupancy was assumed from 8 A.M. to 4 P.M. A 75% adjustment was applied for child occupant heat gain (ASHRAE 2001b). Cooling and heating systems were selected based on the energy cost budget method (ASHRAE 2004b).

A double-clear, low-e glazing was applied in this study, and two other double low-e glazings were used for comparison. Their properties are shown in Table 3. For the roller shade case, shading coefficients of 0.34 and 0.81, obtained from the manufacturer, were applied to upper windows and lower windows, assuming that the shade only covers the upper windows. For the blinds case, a solar heat gain multiplier of interior blinds of 0.66 was applied, resulting in a shading coefficient of 0.53 for both upper and lower windows (ASHRAE 2001b 30.48 Table19). No blinds control was assumed. As previously stated, the exterior overhang has no additional interior blinds or shades.

Table 2: DOE 2.1-E Operating Assumptions

Model Parameter	**Value**	**Reference Document**
Shape	Rectangular, 9.8 x 9.1 m (32 x 30 ft) Ceiling height 3.7 m (12 ft)	
Conditioned floor area	89.2 m^2 (960 ft^2)	
Roof construction	U-value (W/m^2•K) = 0.17 (U-value (Btu/h•ft^2•F) =0.03)	New Buildings Institute, Inc. 2005: Table 2.1.2
Grade-on-Floor construction	U-value (W/m^2•K) = 0.11 (U-value (Btu/h•ft^2•F) =0.02)	New Buildings Institute, Inc.2005: Table 2.1.1
Exterior wall construction	U-value (W/m^2•K) = 0.35 (U-value (Btu/h•ft^2•F) =0.062)	New Buildings Institute, Inc.2005: Table 2.1.1
Infiltration rate	AIR-CHANGES/HR = 0.3	
No. of people	4.25 m^2/Person (45.71 ft^2 /Person)	Stecher 2002
Equipment power density	5.6 W/m^2(0.52 W/ft^2)	ASHRAE 2001b
Lighting power density	14 W/m^2(1.3 W/ft^2) for a full electric light operation	New Buildings Institute, Inc.2005: Table 2.7.1
Outdoor air	OA-FLOW/PER = 15	ASHRAE 2004a: Table 6-1, Minimum ventilation rates in breathing zone; classroom (age 9 or plus) OA-FLOW/PER = 13.4
HVAC system	Package rooftop air conditions Fan: Constant volume Cooling: direct expansion Heating: fossil fuel furnace	ASHRAE 2004b : Energy cost budget method, Figure 11.3.2 and Table 11.3.2A
Cooling source	Air conditioners, air-cooled 11.0 EER	New Buildings Institute, Inc. 2005: Table 2.5.1
Heat source	80% AFUE	New Buildings Institute, Inc. 2005: Table 2.5.4
Return system type	Duct	
Sizing options	Automatic sizing	
Sizing ratio	1.15 or higher	
Minimum supply air	12.8˚C (55˚F)	

temperature		
Maximum supply air temperature	48.9˚C (120˚F)	
Economizer low limit temperature	23.9˚C (75˚F) for Colorado	ASHRAE 2004a: Table 6.5.1.1.3B
OA- control	Temperature	

Table 3: Glazing Properties (U-value of 1.7 W/m^2K is the same for all glazing types)

Glazing type	Unobstructed window		Roller shade		Blinds		Exterior Overhang	
	VLT	S-C	VLT*	S-C	VLT	S-C	VLT	S-C
Double 1/4” clear low-e	0.73	0.81	0.04	0.34	0.73	0.53	0.73	0.81
Double 1/4” green low-e	0.62	0.55	0.03	0.27	0.62	0.36	0.62	0.55
Double 1/4” bronze low-e	0.44	0.55	0.03	0.27	0.44	0.36	0.44	0.55

* Visible light transmittance value of a roller shade for a given glazing type from a manufacturer’s catalog

4. Results

4.1. Energy use for double clear low-e glazing with 73% visible light transmittance

Base case electric lighting energy consumption, for the school without any shading devices (clear windows), was 35.1 kWh/m^2-yr (11.1 $MBtu/ft^2$-yr) assuming full electric light operation during the occupied hours. The annual electric lighting energy savings for roller shades, blinds, and overhang compared to the base case were 55%, 56%, and 67%, respectively, for double clear low-e glazing (see Figure 12). The base case introduces illuminance levels of 2000 lux or higher for 83 % of the total simulation hours for an average 9.1 % of the 42 calculation points. Case overhang consumes the least electric lighting energy because it receives maximum daylight including direct sunlight. With the 73% visible light transmissive glazing, the overhang allows illuminance levels of higher than 2000 lux from the sun only for more than 52% of the total simulation hours for an average 9.3% of the 42 measurement points. The shade and blinds allow the occurrence of 2000 lux or higher for 3.8% and 2.4% of the total simulation hours for average 1.4% and 0.2% of the 42 calculation points. An illuminance level of 2000 lux may cause office occupants to take actions to reduce the daylight level for both comfortable computer and paper-oriented tasks (Nabil 2005). The overhang has less control over maintaining proper indoor illuminance levels than blinds and shades. Both blinds and shades keep the illuminance levels below 2000 lux for most of the time as shown in Table 4.

Table 4: Frequency of different ranges of daylight availability for different shading devices for the two sensor positions

	Overhang		Roller Shade		Blinds	
Illuminance Range	Sensor Pt. 1	Sensor Pt. 2	Sensor Pt. 1	Sensor Pt. 2	Sensor Pt. 1	Sensor Pt. 2
E < 538lux	41.1%	53.4%	56.5%	93.6%	54.6%	90.2%
538lux < E < 2000lux	30.4%	45.9%	42.1%	6.4%	45.3%	9.8%
E > 2000lux	28.5%	0.7%	1.4%	0.0%	0.1%	0.0%

As shown in Figure 13, windows equipped with a roller shade, blinds, and overhang show a reduction in annual cooling energy use compared to the base case by 39%, 34%, and 51%, respectively. The shade and blinds diminish cooling load by 39% and 34%, while an overhang lowers it by 51% on average. Especially August, in which the maximum monthly cooling load occurs, provides 30%, 34%, and 47% reduction in cooling loads for shades, blinds, and overhangs. The shadow caused by an exterior 4-ft overhang covers the full windows for 35% of the noon time from April to August, which significantly lowers cooling loads during these months (see Figure 13). The overhang also casts shadows on the part of the window area during other months and times, leading to a reduction in cooling loads in other months and times. The shade and blinds show similar monthly cooling load profiles, but a slightly lower cooling load for the shade because the shading coefficient of the blinds (0.54 for double clear low-e) is higher than that of the window area averaged shading coefficient of the shade (0.48 for double clear low-e).

Figure 14 shows monthly heating loads. The base case consumes the lowest heating load because it has no device to block direct solar radiation from entering the interior space. The overhang takes advantage of solar heat gains during the winter months when the solar altitude angles are relatively low, leading to a lower heating energy demand than heating loads for the blinds and roller shade cases. The overhang, blinds, and shade consume almost twice as much heating energy use as the base case.

Figure 15 illustrates monthly total energy consumption for double-clear, low-e glazing. From November to February, the base case uses the least building energy because small heating loads overcome a high lighting energy consumption penalty. The base case, with high cooling loads from April to October, consumes the highest building energy, while the overhang consumes the least building energy during these months since an overhang best saves lighting and cooling energy uses among the four different window systems.

4.2. The effect of glazing properties on energy use

To investigate the impact of visible light transmittance and solar heat gain characteristics of the glazing on total building energy use, glazings with three different combinations of light transmittance and shading coefficient were selected. Figure 16 illustrates the change in total cooling, heating, and lighting energy use as a function of glazing type for window systems. Double-clear, low-e glazing, which has the highest visible light transmittance, provides the best energy savings among the three glazing types. As the transmittance decrease from 0.73 to 0.62 and shading coefficient changes from 0.81 to 0.55, heating and lighting loads increase at a faster rate than the rate at which cooling loads decrease. As the transmittance changes from 0.62 to 0.44 and shading coefficient remains the same as 0.55, cooling loads increase, and heating loads decrease due to heat generation from the increased electric lighting. With the same shading coefficient, double low-e glazing with a higher visible light transmittance saves more energy than with a lower transmittance because the higher transmittance provides more lighting energy saving potential. Double-green and bronze low-e glazing consume more total building energy than double-clear low-e glazing by 11% and 15% for a shade, 14% and 18% for blinds, and 15% and 15% for an overhang.

4.3. Glare analysis

The December average vertical sun illuminance values at a position 5 m away from the window towards the rear center line at an eye height of 1.2 m and directly looking at the window for the overhang and shade for December, are 5561 lux and 2439 lux, respectively. The overhang has a higher potential to deliver abundant daylight into interior spaces. When the sun angles are high, the overhang blocks direct sunlight penetration but still preserves light from the sky, maintaining comfortable visual environment. The shade cuts down both the sunlight and skylight, which results in much less indoor illuminance than the overhang. Therefore, the overhang case is likely to dim both luminaire rows, while the shade and blinds dim the luminaires near the windows only and keep the luminaire row deep inside the space on for most of the time.

The discomfort glare, due to the direct sunlight penetration, was analyzed for December using the Daylight Glare Index (DGI, Fisekis and et al. 2003) and the CIE Glare Index (CGI, Navvab and Altland 1997) for the shade and overhang cases. These glare indices were calculated for the position 5 m away from the window toward the rear center line at an eye height of 1.2m and directly looking at the window. As shown in Figures 17 and 18, the DGI varied from 22.3 to 26.5 for the shade and from 22.8 to 27.6 for the overhang. The CGI varied from 30.8 to 35.4 for the shade and from 29.2 to 38.9 for the overhang. The recommended thresholds of the DGI and CGI for acceptable condition are 22 and 16, respectively. The calculated glare indices are far beyond the recommended values. But it is not likely for occupants to experience serious discomfort glare problems because occupants rarely position their desks toward windows in real situations; they rather place them perpendicular to the windows. In that case, the discomfort glare indices will be significantly lower than the calculated values shown in Figures 17 and 18.

The lighting energy saving for the overhang is much better, while the glare effects are the same for all three systems. To best utilize both the sunlight and skylight in saving electric lighting energy use and to create direct sunlight-free interior environment, an overhang combined with interior shading devices is better than interior shading devices only. The interior shading devices will be operated when the overhang itself cannot prevent the sunlight penetration from entering an interior space.

5. Conclusion

This study measured the bi-directional transmittance of a roller shade and simulated its performance in lighting software. This study compared the energy performance of a roller shade with blinds, exterior overhang and bare window without interior shading devices for a side-lit classroom space. An accurate lighting simulation tool and a building energy simulation tool were used to determine the impacts of shading devices on yearly lighting and building energy consumption based on hourly weather data.

The following general conclusions are made in this study.

1. The measurement of the bi-directional transmittance of a shade was enabled with the use of a CCD camera and a cube.

2. The annual electric lighting energy savings for a roller shade, blinds, and an overhang were 55%, 56%, and 67%, respectively, compared to clear, double low-e glazing with no shading device (base case).

3. The lighting energy performance of the roller shade with a total transmittance of 10.4% is similar to blinds tilted 45° with 60% diffuse reflectance.

4. Windows equipped with roller shade, blinds, and overhang showed a reduction in cooling energy use compared to the base case by 39%, 34%, and 51%, respectively.

5. The overhang, blinds, and shade consume almost twice heating load as the base case.

6. For south-facing windows with a window-to-wall ratio of 36% for a classroom in Boulder, the maximum total building energy saving can be achieved with an exterior 1.2 m (4-ft) horizontal overhang. The blinds (60% diffuse reflectance) and shade (total transmittance of 10.4%) consume 7% and 15% more energy than the overhang.

7. When the sun angles are high, an exterior overhang can deliver more daylight (direct-sunlight free) to an interior space and consumes less cooling load than blinds and shade while preventing direct sunlight penetration.

8. Double-clear, low-e glass saves total building energy the best in comparison to double green low-e and double bronze low-e glazings for overhang, blinds, and shade systems by reducing 13% and 16 % on average.

9. Overhang and shade provide similar discomfort glare indices when looking directly at south-facing windows. However, glare indices are likely to be lowered in reality, where occupants avoid positioning their workspaces toward the windows.

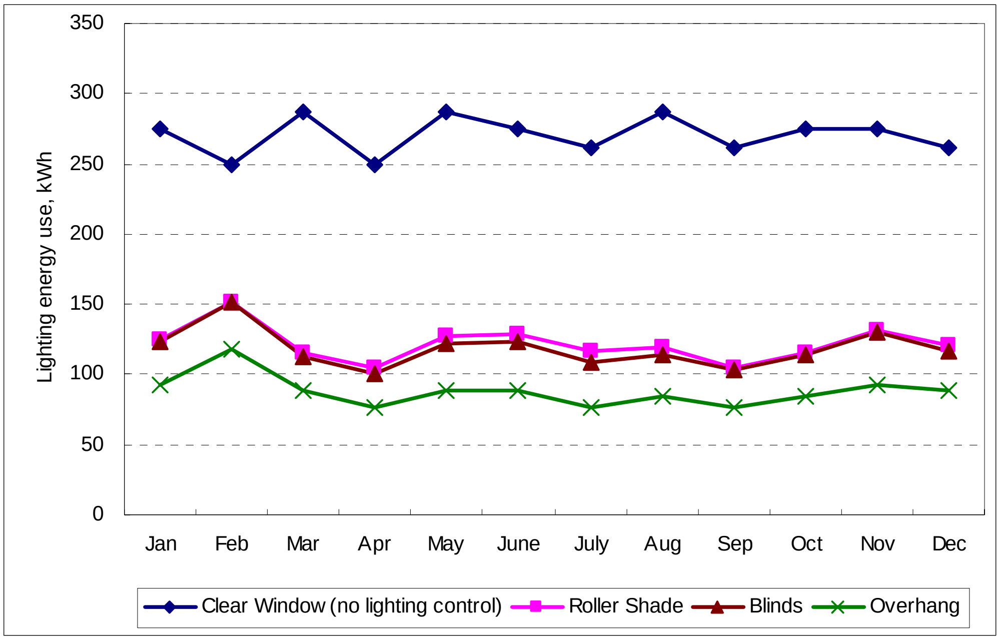


Fig. 12: Monthly lighting energy use in kWh for double clear low-e glazing

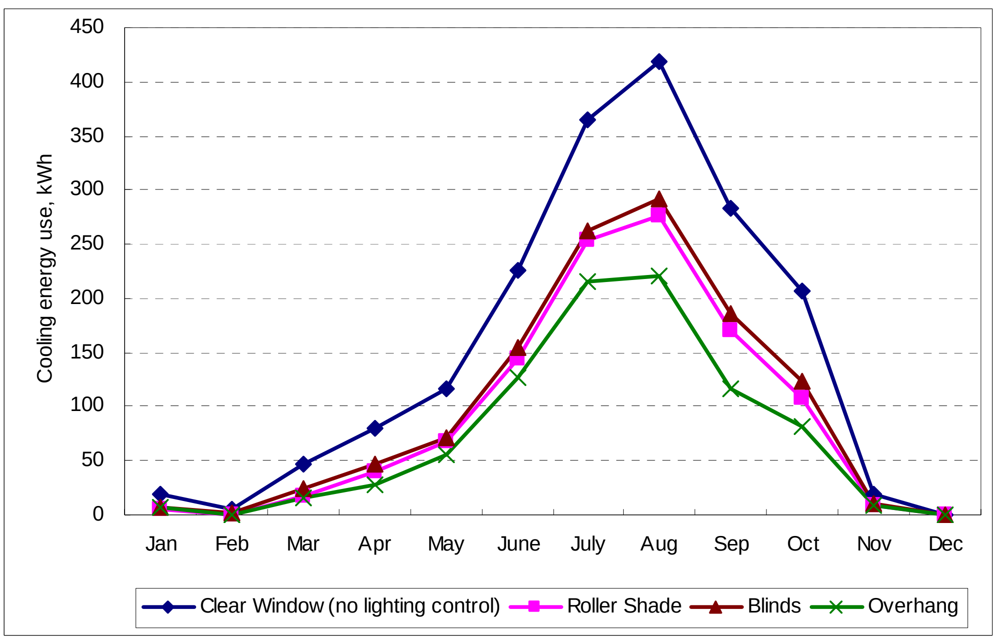


Fig. 13: Monthly cooling energy use in kWh for double clear low-e glazing

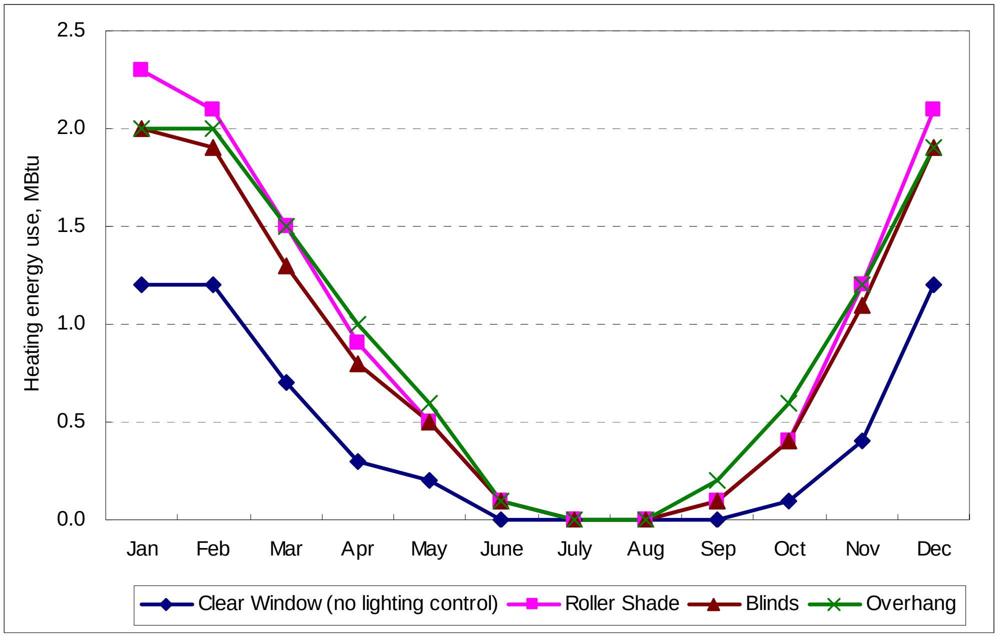


Fig. 14: Monthly heating energy use in MBtu for double clear low-e glazing

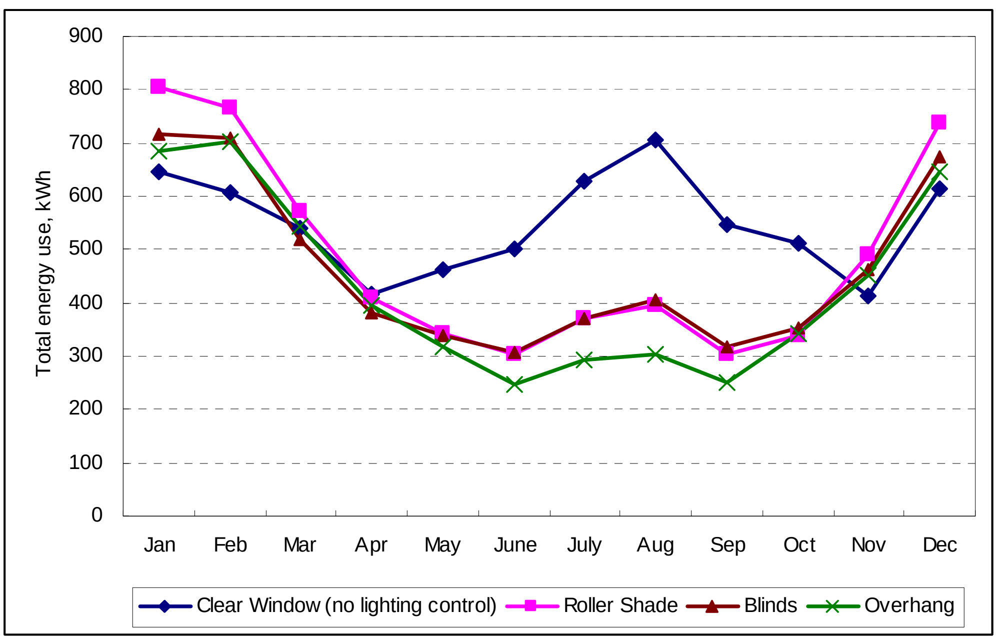


Fig. 15: Monthly total energy use in kWh for double clear low-e glazing

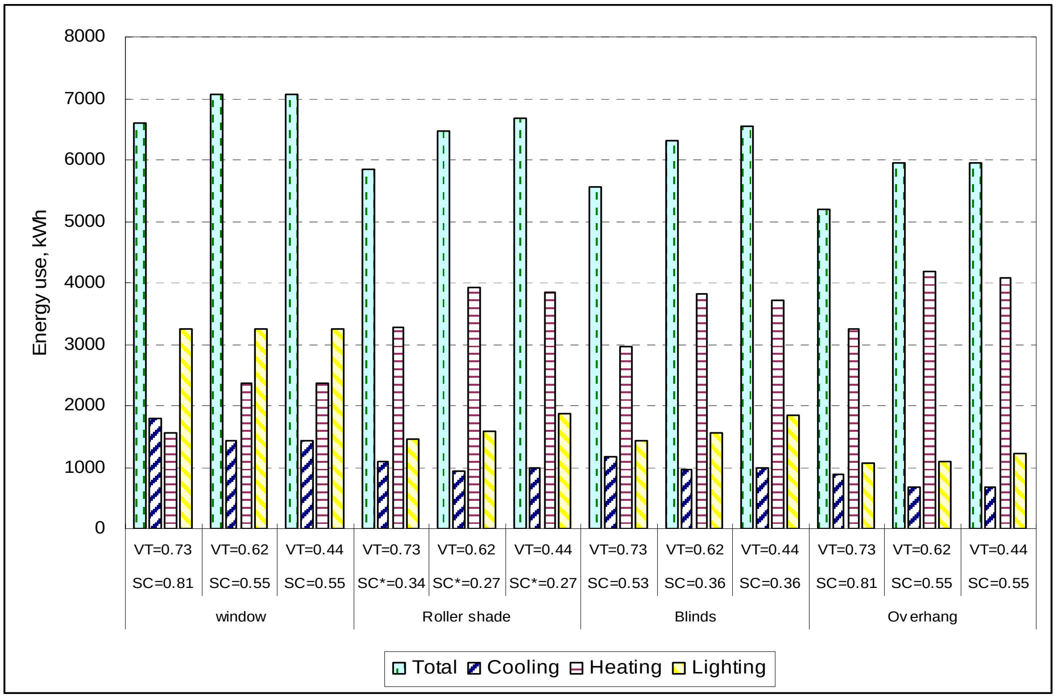


Fig. 16: Comparison of annual energy consumption for double clear, green, and bronze low-e glazings

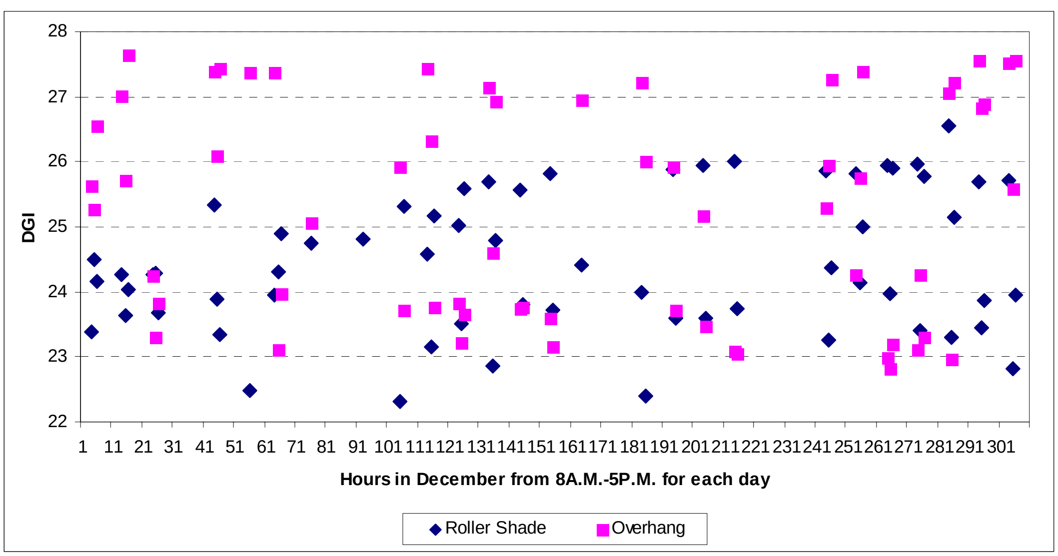


Fig. 17: Daylight glare index comparison for shade and overhang for December

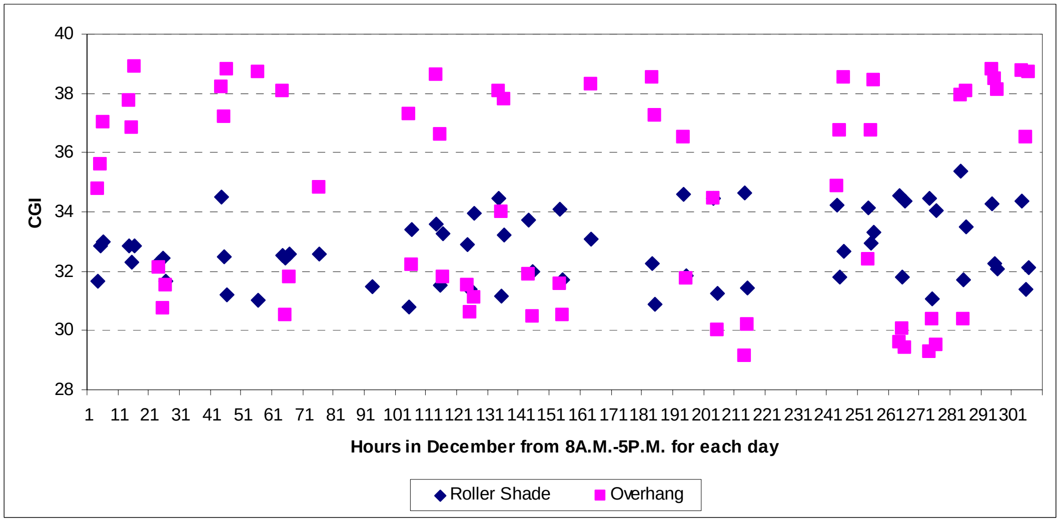


Fig. 18: CIE glare index comparison for shade and overhang for December

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