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Abstract

Sunlight redirecting systems have the potential to significantly offset electric lighting energy use in deep perimeter zones of buildings where the windows are subject to high daylight availability. New Radiance modeling tools have recently been developed and validated, enabling accurate and timely simulation analysis of the annual energy and comfort performance of these optically-complex, anisotropic systems. A parametric study was conducted using these tools to evaluate the performance of a commercially-available passive optical light shelf (OLS) in a 17.4 m deep (57 ft), south-facing open plan office zone in three climates. Daylighting efficiency, discomfort glare, and lighting energy savings with continuous dimming and bi-level switching controls were determined at varying depths within the zone. The OLS decreased lighting energy use significantly throughout the depth of the space and achieved these savings with minimal discomfort glare in the area near the window. Annual lighting energy use intensity was reduced to 1.71-1.82 kWh/ft^2-yr (22-27%) over the full depth of the perimeter zone across the three climates modeled (Phoenix, Washington DC, and Minneapolis) compared to a non-daylit zone at 2.34 kWh/ft^2-yr. There was a greater occurrence of discomfort glare (3-7% during daytime work hours) if the occupant was in a seated view position looking at the window from the back of the room. The system is passive, needing no adjustment during the day and over the seasons and can be used as a retrofit measure in existing buildings. These results are encouraging and demonstrate how the primary daylit sidelit area can be extended well beyond the defined limits provided by the newly adopted ASHRAE 90.1-2010 code (i.e., 1.0 times the head height of the window).

Keywords: Daylighting; Bidirectional scattering distribution functions; Radiance simulations; building energy efficiency

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1. Introduction

Electric lighting is one of the most significant energy end uses in commercial buildings in the United States, constituting 3.2 Quads (quadrillion or 3.2 x 10^{15} Btu) of primary or source energy of the total 18 Quads used in all commercial buildings [1]. While the industry has invested over a hundred million research dollars to derive cost-effective, energy efficient solid state lighting with a targeted performance of 130 lumens per watt by 2025 and a color rendering index that closely reproduces the visible portion of the solar spectrum [2], natural daylight at a photopic luminous efficacy of 683 lumens per Watt plays a niche but key role in our quest to achieving very low or net-zero energy buildings by lighting perimeter zones (or the top floors of buildings through skylights) with sunlight and diffuse skylight. With conventional technologies, daylight traditionally has only affected at most a small portion of the perimeter zone floor area since it rarely penetrates beyond about one to two times the height of the window wall (about 4.6 m (15 ft) in conventional office buildings) when interior shades are used to control direct sun and glare from the window. Electric light sources such as the fluorescent or light emitting diode (LED) lamps are required to light the remaining area of the building interior. With the increasingly stringent energy-efficiency standards, lighting designers are forced to use electric lighting more judiciously and have lowered ambient and task lighting levels to 200-300 lux and shut lights off in areas when spaces are unoccupied.

With advancements in technology, daylight could be extended deeper into the perimeter zone and provide supplemental temporal lighting in the core zone of buildings whenever the sun is above the horizon. The estimated technical potential for reducing US commercial building lighting energy use is 1 Quad [3]. Such technologies can not only improve the overall energy efficiency of the building but also improve the indoor environmental quality of buildings by increasing overall brightness throughout the room cavity and providing a connection to the outdoors (if not through direct views out the system then through variability in daylight levels as clouds pass over the sun, etc.). Since daylighting is not forced to an upper limit, light levels are often ten times that provided by electric lighting (even within the bounds of glare control). Spectrally selective low-e windows provide architects and engineers with the option to now specify high visible transmittance windows without the penalty of increased cooling energy use.

Reflective, sunlight redirecting systems are only one of many ways that daylight can be extended deeper into sidelit perimeter zones. In an overview of daylighting systems [4], the International Energy Agency Task 21 compiled a list of emerging daylighting technologies that improve daylighting performance through the various principles of optics: refraction, diffraction, reflection and any number of combinations of these modes of lighting. None of these systems were evaluated on an annual basis, unfortunately, because the simulation tools needed to model such systems were unavailable. Instead, full-scale field tests were conducted (in various locations around the world), illustrating performance for solstice and equinox periods and under clear and overcast sky conditions. Recently, new daylight modeling tools have been developed and validated that enable accurate annual simulations to occur in a timely manner [5] and enable accurate modeling of optically complex fenestration systems such as these daylighting systems [6], which scatter light in a non-specular fashion.

This study evaluates the performance of a commercially-available, passive optical light shelf which has been installed in many buildings over the years but has not yet achieved significant market penetration (<1% of the US commercial building stock) in part because of its unknown performance impacts on lighting energy use and visual comfort. Its performance is evaluated using parametric simulations of a south-facing open plan office perimeter zone in order to quantify impacts as a function of climate, distance from the window wall, and by lighting control strategy. The continuous daylight autonomy and useful daylight index are used to evaluate daylight availability resulting from this system compared to the same window with or without shades. Discomfort glare is also evaluated annually from three view points within the 17.4 m (57 ft) deep perimeter zone where the percentage of frequency of discomfort glare over the year was computed. Annual lighting energy use was determined where a continuous dimming system or a bi-level switching system was used to control the electric lighting.

2. Methods

2.1. Description of the modeled perimeter zone

A 297.5 m^2 (3192 ft^2) south-facing, furnished, open plan perimeter office zone was modeled using the Radiance simulation software [7]. The model was made purposely deep to assess the ability of fenestration systems to deliver daylight beyond the typical perimeter daylight zone (Table 1). The ceiling height is typical of US commercial office building construction. The height of the furniture was low (1.1 m, 3.7 ft) to reflect common trends in the industry to lower workstation heights in order to provide all occupants with access to outdoor views. Surface reflectances were moderate (Table 2) and are typical of commercial office finishes. Figure 1 depicts the layout of the space.

The façade was divided into upper daylight windows and lower view windows, where the total window-to-exterior-wall area ratio (WWR) was 0.35 (Figure 2). The clerestory windows form a near continuous strip of windows with a sill height of 2.2 m above the floor (7.25 ft). These windows have a center-of-glass visible transmittance (Tvis) of 0.62 and a WWR of 0.14. The lower view windows are discrete punched openings (WWR=0.21) with a visible transmittance of 0.30. Table 3 summarizes the center-of-glass properties of the window glazing.

The window configurations were defined by two reference cases and one test case for this study (Table 4):

- The first reference case ("Reference 1") has static, indoor Venetian blinds for both daylight and view windows. All Venetian blinds are comprised of curved, concave down, matte, 1.6 cm (0.63 in.) wide white slats (Rvis=0.70, Tvis=0.05) spaced 1.2 cm (0.47 in.) apart and set at a 45° tilt angle (lower edge of slat toward the exterior).
- The second reference case ("Reference 2") has no shading for the windows.
- "Test case 1" has a reflective, passive optical light shelf (OLS) placed inboard of the glazing in the upper daylight windows and the same Venetian blinds as Reference 1 in the lower view windows.

The passive optical light shelf is a commercial product (LightLouver LLC [8]), consisting of multiple 0.062 m (2.4 in.) wide, vertically-stacked, concave-up, reflective slats (Figure 3). A reflective film is applied to the concave-up surface and the sloping surface facing the space. The reflective slat geometry was designed to redirect incident sunlight uniformly onto the ceiling and to block sunlight below a 5° solar altitude angle to reduce glare. The system is completely static (passive) requiring no adjustment over the year and is typically installed in the upper portion of the window at a minimum of 2.1 m (7 ft) above the finished floor. The system completely obstructs view to the outdoors. The manufacturer defines a rule-of-thumb for sizing the height of the system: one vertical foot is needed for each 14 ft of daylit space (0.30 m for 4.3 m depth). Given the typical ceiling height defined for this model (2.9 m, 9.5 ft), the height of the system is only about half of the manufacturer's required height needed to meet the daylighting requirements of the deep perimeter zone (i.e., a ceiling height of 3.35 m (11 ft) would have been required).

A fluorescent lighting system was assumed with installed lighting power density values derived from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 90.1-2007 [9] space-by-space method for open plan offices (11.8 W/m^2, 1.1 W/ft^2) and the California Title 24-2008 [10] prescriptive requirements for indoor lighting area category method (9.8 W/m^2, 0.9 W/ft^2). These power densities were assumed to correspond to average workplane illuminance levels of 500 lux (36 fc) and 300 lux (28 fc), respectively. The illuminance levels were derived from the Illuminating Engineering Society of North America (IESNA) 9^{th} edition Lighting Handbook recommendations for open plan offices with intensive (300 lux) and intermittent (500 lux) visual display terminal (VDT) use.

The electric lighting system was controlled using two types of photoelectric controls: bi-level switching and continuous dimming. For the continuous dimming system, the ballasts were assumed to have a power range of 20-100% for a light output range of 10-100%. When the lighting was switched off, standby power was 3%. For the bi-level switching, power levels were 100%, 50% and 0% of full power with equivalent levels of light output at each power level. The relationship between percentage of light output and power level is shown for each type of lighting control in Figure 4.

The space was divided into three work area zones where daylight illuminance levels were determined on the work surfaces in each of these zones: Zone 1 contains the two rows of desks closest to the window (3.7 m, 12 ft to the centerline between workstations), Zone 2 contains the middle two rows of desks (8.5 m, 28 ft), and Zone 3 contains the two rows of desks furthest from the window (13.4 m, 44 ft). The distance from the window for each of these zoned areas is given in Table 1. The illuminance levels in the three zones were used to evaluate the daylighting effectiveness of the window systems and determine lighting energy use.

Table 1.
Geometric description of the open plan perimeter office zone

	Dimensions (m)	Dimensions (ft)
Zone dimensions	17.1 m wide, 17.4 m deep, 2.9 m high	56 x 57 x 9.5 ft
Floor area	297.5 m^2	3192 ft^2
Floor-to-floor height	3.66 m	12 ft
Furnishings	(24) 1.8 x 2.4 x 1.1 m cubicles with desk chairs and cabinets (12) 1.7 x 0.8 x 1.1 m desks with chairs and cabinets along the side walls	(24) 6 x 8 x 3.8 ft cubicles with desk chairs and cabinets (12) 5.5 x 2.5 x 3.7 ft desks with chairs and cabinets along the side walls
Upper clerestory windows (Tvis=0.62)	(7) 2.3 m wide (17.1 m total width), 0.55 m tall, sill height 2.2 m above the floor	(7) 7.58 ft wide x 1.75 ft tall, sill height 7.25 ft above the floor.
Lower view windows (Tvis=0.30)	(8) 1.14 m wide, 1.45 m tall, sill height 0.69 m above the floor	(8) 3.75 ft wide, 4.75 ft tall, sill height 2.25 ft above the floor
Window-to-wall area ratio (WWR)	Upper: WWR=0.14; Lower WWR = 0.21	
Façade orientation	South	
Work area zones:	Distance from window (m):	Distance from window (ft):
Zone 1	1.83-5.5 m	6-18 ft
Zone 2	6.7-10.4 m	22-34 ft
Zone 3	11.6-15.2 m	38-50 ft
Lighting control zones:	Distance from window (m):	Distance from window (ft):
Zone 1	0-5.8 m	0-19 ft
Zone 2	5.8-11.6 m	19-38 ft
Zone 3	11.6-17.4 m	38-57 ft
View locations:	1.22 m above the floor Distance from window (m):	4 ft above the floor Distance from window (ft):
View 1	4.9 m, looking south	16 ft, looking south
View 2	2.4 m, looking west	8 ft, looking west
View 3	14.6 m, looking south	48 ft, looking south

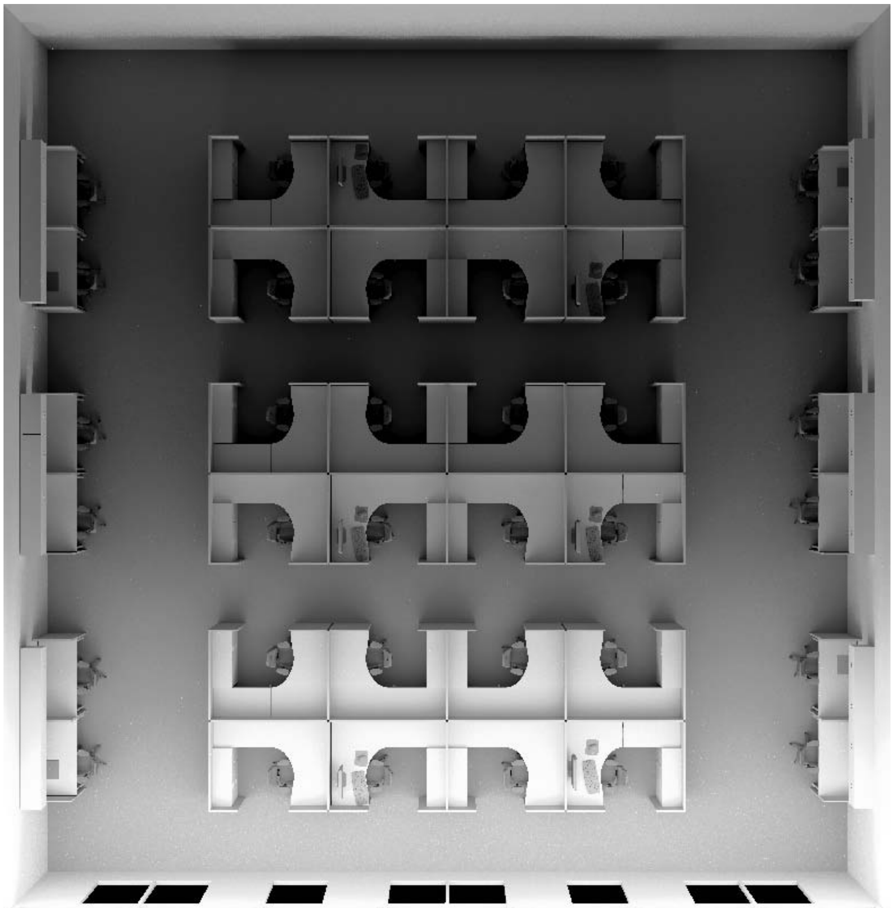

Fig. 1. A rendered floor plan view of the open plan office zone.

Table 2.
Model surface reflectance values

Surface	Visible Reflectance (R_{vis})
Floor	30%
Wall	60%
Ceiling	80%
Cubicle partitions	50%
Desks	65%
Chairs	20%

Fig. 3. Left: Side view of the OLS prior to being installed on the inward face of the clerestory glazing in the Windows Testbed Facility. Right: Oblique view of the OLS. In the Radiance model, the depth of the framing was not modeled.

Table 3.
Center-of-glass window glazing properties

Window	Description	T_{vis}	SHGC	U-value (W/m^{2}K)	U-value (Btu/h-ft$^{2°}$F)
Daylight Windows	Double glazed insulated units with clear glass and Viracon VRE67 low-e coating on surface 3	0.615	0.444	1.863	0.33
View Windows	Double glazed insulated units with clear glass and Viracon VRE30 low-e coating on surface 3	0.302	0.302	1.855	0.33

Table 4.
Window condition for the simulation cases

Case	Daylight (upper) window condition	View (lower) window condition
Reference 1	White Venetian blind with 45° slat tilt angle	White Venetian blind with 45° slat tilt angle
Reference 2	No Shading	No Shading
Test 1	Passive optical light shelf (OLS)	White Venetian blind with 45° slat tilt angle

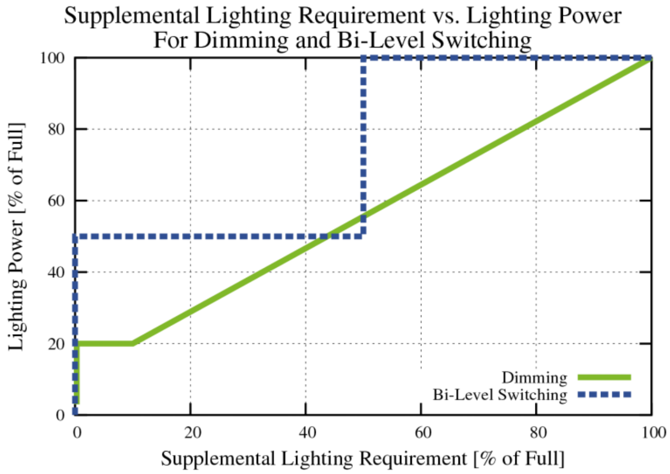

Fig. 4. Percentage of full light output versus percentage of full lighting power for dimming and bi-level switching systems.

2.2. Radiance simulation method

The Radiance ***rtcontrib*** method was used to perform annual daylight simulations in order to evaluate both the lighting energy savings and visual comfort of the reference and test cases [5]. This method separates light transport into three phases, one of which is the fenestration transmission described by bidirectional transmittance distribution function (BTDF). The other two phases, interior and exterior daylight propagation, are simulated independently of the fenestration and stored in a matrix form. The resultant illumination is obtained using matrix multiplication (Equation 1).

$$\mathbf{i} = \mathbf{V\ T\ D\ s} \qquad (1)$$

where:

V= view matrix, relating outgoing directions on window to desired results at the interior,
T = transmission matrix, relating incident window directions to exiting directions (BTDF),
D = daylight matrix, relating sky patches to incident directions on window, and
s = sky vector, assigning luminance values to patches representing sky directions.

This approach enables quick computation of the annual performance of any arbitrary optically-complex fenestration system. Facades can be changed without simulating the entire light path, just substituting a new sky vector or fenestration transmission matrix. The ***dctimestep*** tool within Radiance (version 4.0) calls this calculation for each time step to compute illuminance and luminance quantities defined by the user.

To generate the **s** sky vector, direct normal irradiance and diffuse horizontal irradiance values are taken from TMY2 weather data. The program ***gendaylit*** uses the irradiance data to generate a Perez sky definition for Radiance. The Radiance program ***genskyvec*** divides the sky into Tregenza or Reinhart patches and computes the average luminance of the patch. This study used the Reinhart MF:4 subdivision scheme which has 2305 patches.

The **D** daylight matrix was generated using the Radiance ***rtcontrib*** program for a window without near- or far-field obstructions. The exterior ground was uniformly diffusing with a reflectance of 0.1.

The **T** transmission matrix was defined using the Window 6.3.3 [12] where individual glazing layers were selected from the International Glazing Database and the shading and daylighting systems were defined separately using the methods described in Section 2.3. Window 6 was used to combine the glass and shading or daylighting layers to form a single window system whose bidirectional scattering distribution function (BSDF, which describes both transmittance and reflectance properties) characteristics were output by Window 6 for use by Radiance. Radiance used the front transmission data in the matrix calculation.

View matrices **V** were defined for four rendered views at a height of 1.2 m (4 ft) above the floor and three zones of workplane illuminance sensor points. Luminance renderings of three views were used to assess glare in the space. Figure 5 shows the rendering view points and Figure 6 shows the rendered views. Table 1 summarizes these locations. Workplane illuminance sensor points were defined by a grid of points spaced 0.6 m (2 ft) apart on the desks in each of the three zones (Figure 7). Table 5 summarizes the Radiance parameters used to generate the View matrices.

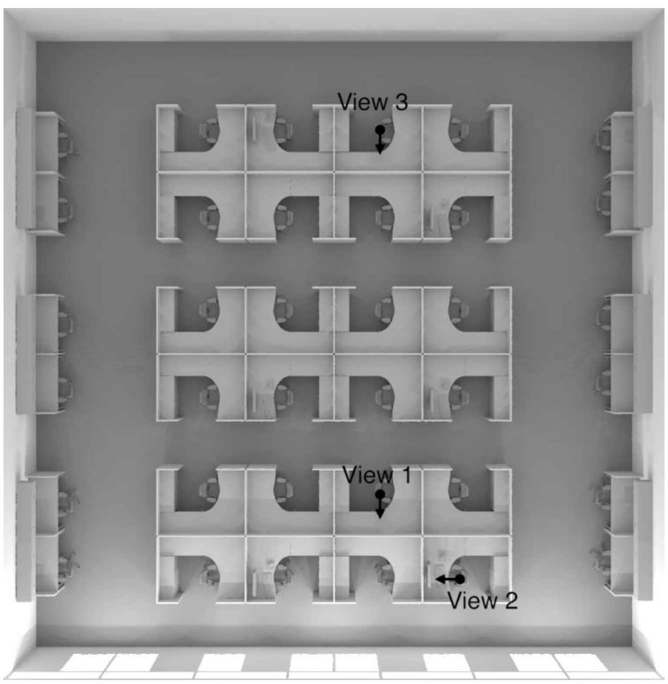

Fig. 5. Rendering viewpoints for glare assessment.

Fig. 6. Rendered views with the OLS (Phoenix Arizona, January 5, 12:30 PM). Left: View 1, center: View 2, right: View 3.

Table 5.
Radiance parameters used in simulations

Radiance Simulation Parameters	Illuminance View Matrix (Sensor Points)	Rendered View Matrix
ambient bounces (-ab)	5	4
ambient divisions (-ad)	10,000	10,000
ambient subdivisions (-as)	0	0
ambient accuracy (-aa)	0	0
limit weight (-lw)	1.00E-12	1.00E-10
direct source subdivision (-ds)	0.06	0.06
direct jitter (-dj)	0.9	0.9
direct threshold (-dt)	0	0
direct certainty (-dc)	0.75	0.75

2.3. Derivation of layer and whole window BSDFs

A synthetic BTDF with 145 incident and exiting directions was generated for the OLS daylighting system using a custom set of scripts[1] in Radiance. The geometry of the OLS was provided by the manufacturer and modeled in Radiance. The upper surface of the OLS is specularly reflective. The lower inside facing surface is also specularly reflective while the lower outward facing surfaces are matte gray. The surface properties were measured with a handheld spectrophotometer (Minolta CM-202). The specular surface has 85% reflectance and 96% specularity. The matte surface has 54% reflectance and 1% specularity.

The Radiance program ***genklemsamp*** was used to generate incident sample rays and ***rtcontrib*** was used to calculate distribution coefficients for each outgoing Klems division. A total of 9,280,000 sample rays were generated to sample the OLS; 64,000 sample rays per incident Klems division. The following Radiance parameters were used for sampling: -ab 2 -ad 1000 -st 0.005 -lw 1e-8.

Window 6.3.3 has the ability to model optically complex fenestration systems. Window has built-in models for standard glazings, Venetian blinds and woven shades (assuming Lambertian diffusing surfaces), and can import BSDF data for arbitrary fenestration layers then export whole window BSDF data in an XML file format. The Radiance program ***dctimestep*** imports the front transmission data block from the BSDF XML file exported by Window 6 to generate the transmission matrix part of Equation 1 defined in Section 2.2.

BSDF files were generated for each combination of window glazing and shading used in the annual assessments. An insulating glass unit (IGU) for the daylight and view glazing was created by adding layers from the International Glazing Database (IGDB) [12]. The built-in Window 6 Venetian blind model was used to model the reference case with blinds. The synthetically-generated BTDF file (145 incident and exiting directions) was imported into Window 6 to model the OLS.

[1]Since this computation was performed, Greg Ward developed a new Radiance utility, ***genBSDF,*** to generate a BSDF file from a Radiance model of the complex fenestration system.

2.4. Radiance parametric simulations

Radiance parametric simulations were run for the south-facing perimeter zone with three façade configurations and four electric lighting configurations in three climates: one predominantly cooling climate (Phoenix, Arizona), one predominantly heating climate (Minneapolis, Minnesota) and one mixed cooling / heating climate (Washington DC). The parametric configurations are summarized in Tables 6-8.

The Building Controls Virtual TestBed (BCVTB) [13] was used to coordinate the annual simulations. For each one hour time step, BCVTB called Python and C-shell scripts to run Radiance simulations (while the systems modeled in this study were static, the BCVTB can be used to model the control algorithms for automated shading systems and other operable façade elements). After completing all simulations for a timestep, the BCVTB then collected and logged results into text files for later analysis.

The view matrix simulations were run on a Linux cluster which has 202 nodes and 1616 CPU cores (2.66 GHz). Views were broken into 64 sub-renderings and rendered on one core each. Illuminance sensor points were divided into three zones with 64 points each. Each zone was run on a single core of the Linux cluster. To reduce repetition in sky vector generation, a year's worth of hourly sky vectors was pre-computed and compressed.

Table 6.
Simulation parameters

	Number of Parameters	Parameters Tested
Spaces	1	Open Plan Office
Fenestration Configurations	3	Ref 1, Ref 2, Test 1
Electric Lighting Systems	4	Switched 500, Dimmed 500, Switched 300, Dimmed 300
Climates	3	Minneapolis, Phoenix, Washington DC
Orientation	1	South

Table 7.
Electric lighting scenarios

Electric Lighting System	Work Plane Illuminance Set Point	Lighting Power Density	Daylight Linked Control Strategy
Switched500	500 lux (46 fc)	11.8 W/m^2 (1.1W/ft^2)	Bi-level switching 0/50/100% power output
Dimmed500	500 lux (46 fc)	11.8 W/m^2 (1.1 W/ft^2)	Continuous dimming 20-100% power output
Switched300	300 lux (28 fc)	9.7 W/m^2 (0.9 W/ft^2)	Bi-level switching 0/50/100% power output
Dimmed300	300 lux (28 fc)	9.7 W/m^2 (0.9 W/ft^2)	Continuous dimming 20-100% power output

Table 8.
Climates simulated

City	Latitude (°N)	Percent of Available Sun*	Annual Cooling Degree Days	Annual Heating Degree Days
Phoenix, AZ	33.45°	86.1%	4355	1040
Minneapolis, MI	44.88°	59.3%	699	7882
Washington DC	39.17°	55.1%	1560	3999

* Calculated from weather data file

2.5. Daylight sufficiency

Two metrics were used to assess daylight sufficiency: continuous daylight autonomy and useful daylight illuminance. Continuous daylight autonomy (CDA) [14] was computed by calculating the average percentage of the setpoint illuminance that is met by daylight during occupied hours over the year. Occupied hours were defined as 8:00-18:00 Standard Time (ST) and included all days of the year. CDA was calculated separately for each of the three lighting control zones. The minimum illuminance value of all 2x2 ft grid sensor points in each zone was used in the CDA calculation. The setpoint illuminance levels of 300 lux and 500 lux figure into the calculation, so CDA values will differ between these two cases with all other parameters being identical.

The useful daylight illuminance (UDI) metric quantifies the percentage of occupied hours when daylight illuminance in a space is useful [15]. UDI was computed by calculating the percentage of occupied hours when illuminance was between a minimum and maximum threshold. The minimum threshold was set at 100 lux, below which occupants derive little benefit from daylight. The maximum threshold was set at 2000 lux, above which visual and thermal discomfort is likely. UDI was also calculated separately for each lighting control zone. If a single sensor point in the zone was above the maximum threshold or below the minimum threshold then daylight was not considered useful at that time. Occupied hours were the same as those defined for the CDA metric.

2.6. Discomfort glare

The Daylight Glare Index (DGI) [16] was used to assess discomfort glare for each of the three rendered views. As a summary metric, the analysis reports the percentage of occupied daylight hours between 8:00-18:00 Local Time (LT, which accounts for Daylight Savings Time) for all days of the year when the DGI was greater than 22 (borderline between comfort and discomfort). Table 9 provides the subjective rating associated with the DGI values.

Renderings were produced for each hourly time step when daylight illuminance levels were greater than zero. The daylight renderings were combined with renderings of electric lighting to give an accurate adaptation luminance. Each electric lighting zone was dimmed according to the average illuminance in the zone for the given timestep.

The renderings were evaluated using the Radiance programs ***findglare*** and ***glarendx*** using a default resolution of 150x150 samples to detect glare sources (each sample represents approximately 0.00036 steradians) and a threshold for glare of seven times the average field-of-view luminance. Given the 145x145 subdivision of the sky, the ***rtcontrib*** method yields a direct source angular resolution of no less than 0.024 steradians (including the orb of the sun). Increasing the BSDF resolution would increase accuracy of the predicted DGI value but significantly increase computation time. For this analysis, this is anticipated to be a minor issue for the unshaded window (Reference 2) since the sun orb luminance produces intolerable glare even when averaged over a Klems patch. Both the reference

Venetian blind and the OLS block direct sun and direct views of the sky, so source resolution is not a relevant issue in this analysis. The OLS does produce bright regions on the ceiling and side walls: further study is needed to determine the significance of these potential glare sources. A single DGI value for each time step was produced for each rendering then used to produce an annual summary value.

Table 9.
Subjective response corresponding to DGI scale

Subjective Glare Assessment	DGI
Just perceptible	16
Just acceptable	20
Borderline between comfort and discomfort	22
Just uncomfortable	24
Just intolerable	28

2.7. Lighting energy use

Energy use was calculated for each of the four electric lighting scenarios. Three lighting control zones were defined, each 98.8 m^2 (1064 ft^2) in floor area. At full light output for the 500 and 300 lux scenarios, respectively, each control zone of electric lighting uses 1.17 kW or 0.96 kW for the 11.8 W/m^2 and 9.7 W/m^2 power densities. Annually, this equates to 3.1 MWh/yr or 2.5 MWh/yr assuming 10 hours of operation per day (8:00-18:00 LT) for 261 work days per year.

To calculate annual lighting energy use with daylighting controls, the average work plane illuminance in each of the three work area zones was calculated for each time step from the 2x2 ft grid of points rather than a simulated ceiling sensor response, thus the energy savings are idealized. If the average workplane illuminance was less than the setpoint light level, then the required illuminance level was determined by subtracting the illuminance from the setpoint light level. This was converted to the percentage of light output required by the electric lighting system in the three lighting control zones. The lighting power needed to provide this light output was then determined using the power-to-light-output relationships defined in Section 2.1 (Figure 4).

Annual lighting energy savings is defined as the reduction in lighting energy resulting from the daylighting controls compared to a case without daylighting controls. Savings were calculated for the (261) 10-h work days per year. Since this is an open plan office, we did not include reductions in lighting energy use due to occupancy, assuming that at least one person would be present in each lighting zone during operating hours. Outside of operating hours, we assumed that the lights were switched off.

3. Results

3.1. Daylight sufficiency

For this south-facing perimeter zone and for all climates, the unshaded window (Reference 2) had the highest continuous daylight autonomy (CDA), followed by the OLS (Test 1), then the window shaded by a Venetian blind (Reference 1) (Figure 8). Note that the CDA metric does not penalize excessive illuminance or glare conditions so the unshaded window logically produced the highest CDA values. The rankings were the same for each of the three zones.

In terms of distribution across the depth of the 17.4 m (57 ft) deep zone, for all window cases there was the typical asymptotic decrease in annual CDA as distance from the window increased (i.e., from Zone 1 to 3) that one sees from conventional window systems. One might expect to see an *increase* in daylight deeper in the space with the OLS system (particularly if this increase occurred consistently throughout the year) since this sunlight redirecting system is designed to reflect light to depths farther from the window, but this is not obvious when comparing CDA values for Zones 1 and 2 in the OLS (Test 1) and Venetian blind (Reference 1) cases.

For the useful daylight illuminance (UDI) metric (Figure 9), the relative ranking between systems remained the same. Note that the UDI of Zones 2 and 3 is near zero in all climates and cases because daylight levels were mostly below the minimum threshold of 100 lux at this depth in the space.

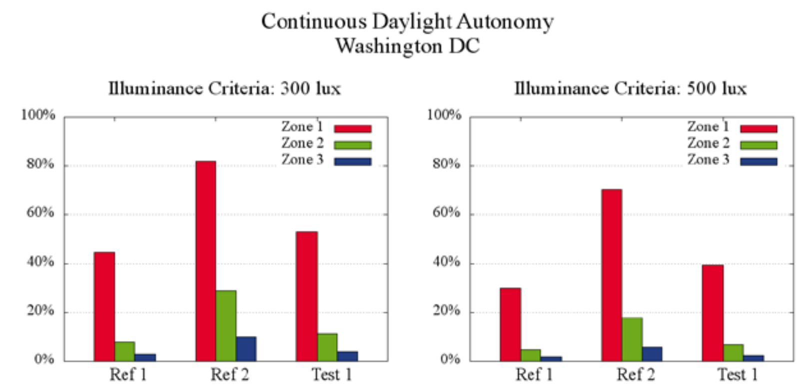

Fig. 8. Daylight autonomy graphs for Washington DC, Phoenix, and Minneapolis. Ref 1: 45° Venetian blind, Ref 2: clear glazing, and Test 1: OLS. Zone 1: 3.7 m, Zone 2: 8.5 m, Zone 3: 13.4 m (12, 28, 44 ft) from window to centerline between workstations.

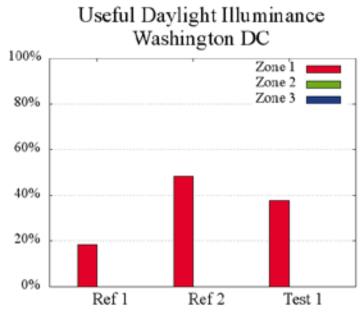

Fig. 9. Useful daylight illuminance graphs for Washington DC, Phoenix AZ, and Minneapolis MN.

3.2. Discomfort glare

From the three viewpoints, discomfort glare occurred least for the shaded windows with Venetian blinds. For the OLS, discomfort (DGI >22) occurred in the middle of the day around the equinox (September and March) for View 3 looking at the OLS from the back of the room with a slightly greater degree of visual discomfort than the shaded window. Glare occurred most frequently with the unshaded window (Reference 2): Views 1 and 2 in the zone closest to the window experienced intolerable glare (DGI >28) during the winter months when the sun was lowest and in direct view, despite the use of low transmittance glazing (Tvis=0.30) in the lower view windows. Figure 10 shows temporal plots of hourly DGI values for all three systems and the three view points over the year for Washington DC.

Figure 11 shows the percentage of occupied daytime hours (8:00-18:00 LT) when discomfort glare occurred (DGI>22) for each of the three view locations. In all climates, the shaded window (Reference 1) exhibited no discomfort glare for all three views. The OLS (Test 1) exhibited some glare for View 3 in the back of the room looking towards the window and no glare for Views 1 and 2 near the window. The unshaded window case (Reference 2) produced the most discomfort glare, particularly for the view locations looking directly at the window (Views 1 and 3) in all three climates.

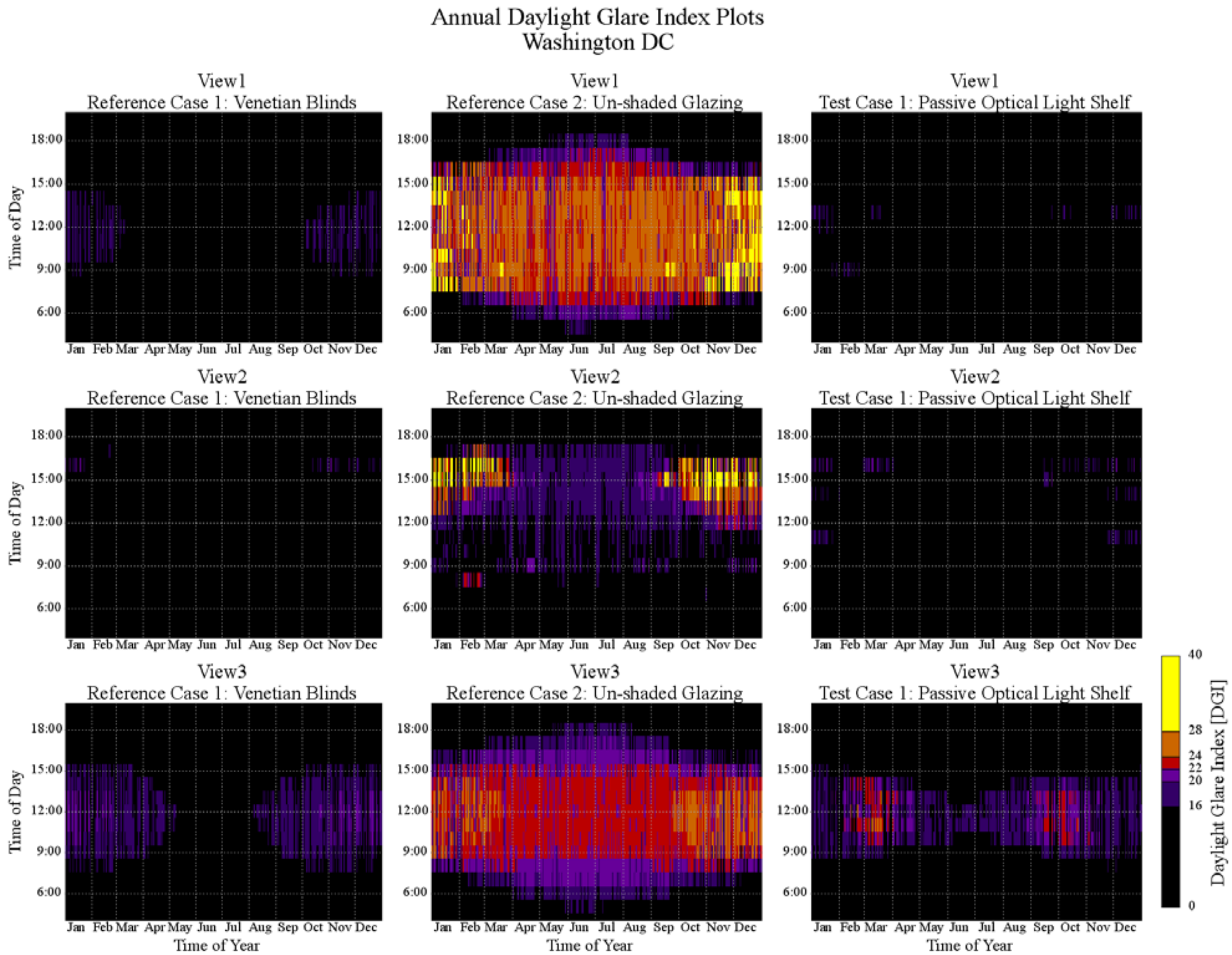

Fig.10. Annual plots of daylight glare index (DGI) for Washington DC. Plots are provided for three views (rows) and three simulation cases (columns). Data are given for local time (LT).

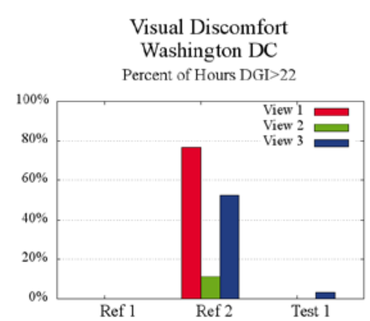

Fig. 11. Percent of operating hours where DGI reports discomfort (DGI>22). Reference 1: Venetian blinds. Reference 2: un-shaded glazing, 45° slat angle. Test 1: optical light shelf.

3.3. Annual lighting energy use savings

Figures 12 and 13 show temporal plots of the percentage of full lighting power use for each lighting control zone throughout the year for the Washington DC climate. Black regions indicate that lighting power use was below 5%. The analysis assumes that the lighting was automatically switched off after 18:00 LT until 8:00 LT the next morning. Figure 12 shows power use for a dimming system with the 300 lux setpoint. Lighting control Zone 1 (0-5.8 m, 0-19 ft from the window) exhibited the lowest power use and Zone 3 (11.6-17.4 m, 38-57 ft) the most in all three cases. Compared to the shaded window, the OLS was able to achieve greater reductions in lighting energy use in Zone 1 for a greater number of hours than the shaded window, particularly between March and September.

Peak electricity demand for the commercial building sector typically occurs in the afternoon on clear sunny days during the summer. The OLS reduced Zone 1 (5.8 m or 19 ft deep perimeter zone) lighting energy use by 40% compared to the Reference 1 Venetian blind with the same lighting controls for the occupied hours between 12:00-16:00 LT from June through September. For clear sunny summer days, demand reductions were even greater.

Figure 13 shows power use for a bi-level switching system with the 300 lux setpoint. For lighting power use to be reduced, daylight must account for at least 50% of the illuminance criteria. Daylight never reaches 50% of the illuminance criteria (150 lux) in Zone 3 for all three cases and Zone 2 for the Venetian blind case. The temporal plots show full lighting power use for the entire year in these instances.

Annual lighting energy use savings were calculated for the four electric lighting control scenarios. Savings were computed relative to the lighting system operating at full power from 8:00 to 18:00 LT on all 261 workdays per year. In all cases, the dimming control system with 300 lux setpoint provided the largest reduction in annual lighting energy consumption. Figure 14 contains charts of lighting energy use savings for all electric lighting scenarios in Washington DC. The lower 300 lux setpoint provided increased energy savings because less daylight was needed to meet this requirement. In addition, the dimming control systems provided greater savings, though in Zone 1 (closest to the window) the energy savings of the bi-level switching system was within about 10% of that of the dimming system, particularly for the lower setpoint.

Figure 15 contains charts of lighting energy savings for the dimming system with the 300 lux setpoint in three climates. In all climates, the OLS provided lower energy savings than the unshaded windows, but greater energy savings than the window shaded with the Venetian blinds. Compared to the shaded window, the OLS increased lighting energy savings in Zone 1 and extended lighting energy savings into Zone 2 and Zone 3.

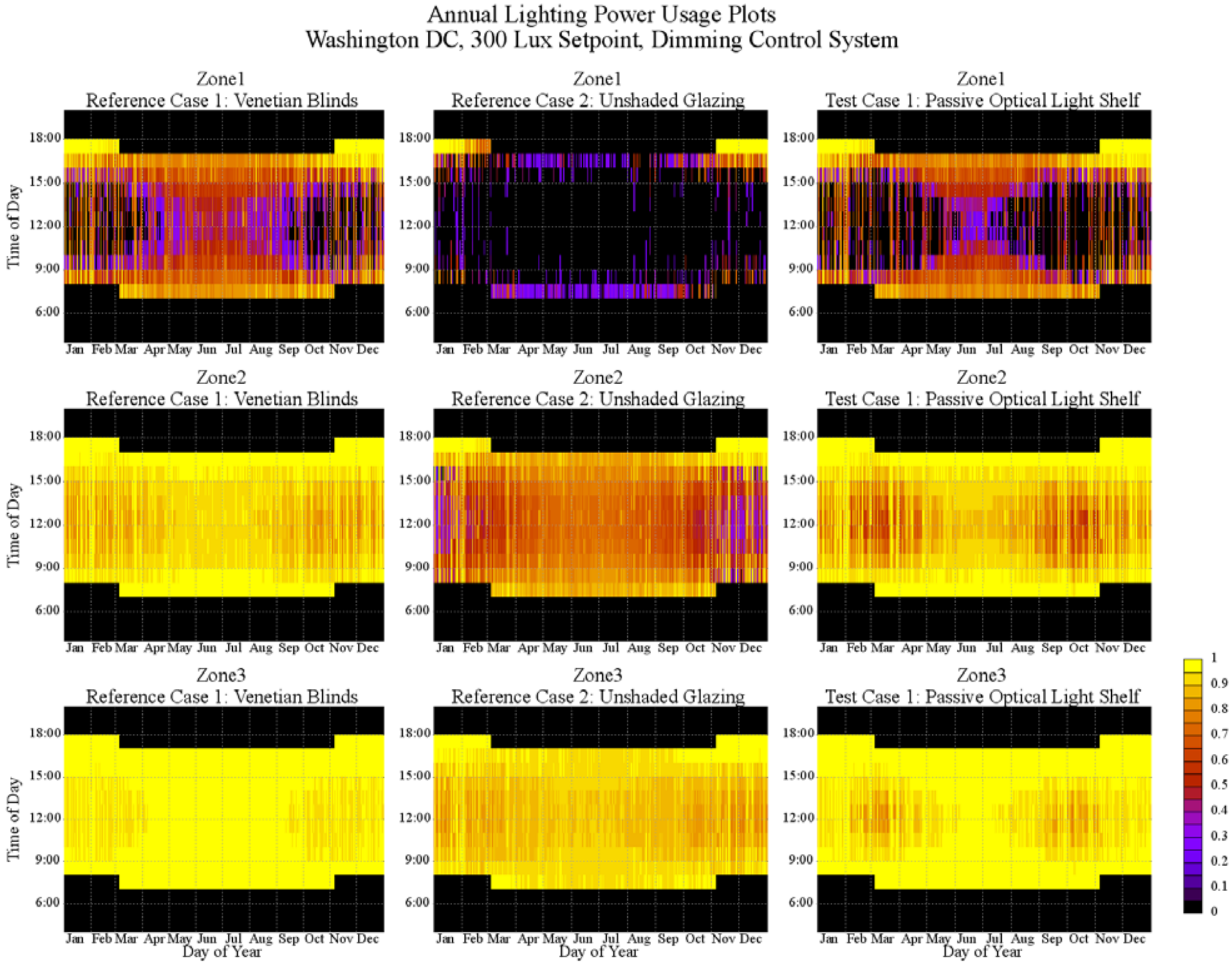

Fig. 12. Annual plots of lighting power use for a daylight dimming system in Washington DC. Plots are provided for lighting control zone (rows) and three simulation cases (columns).

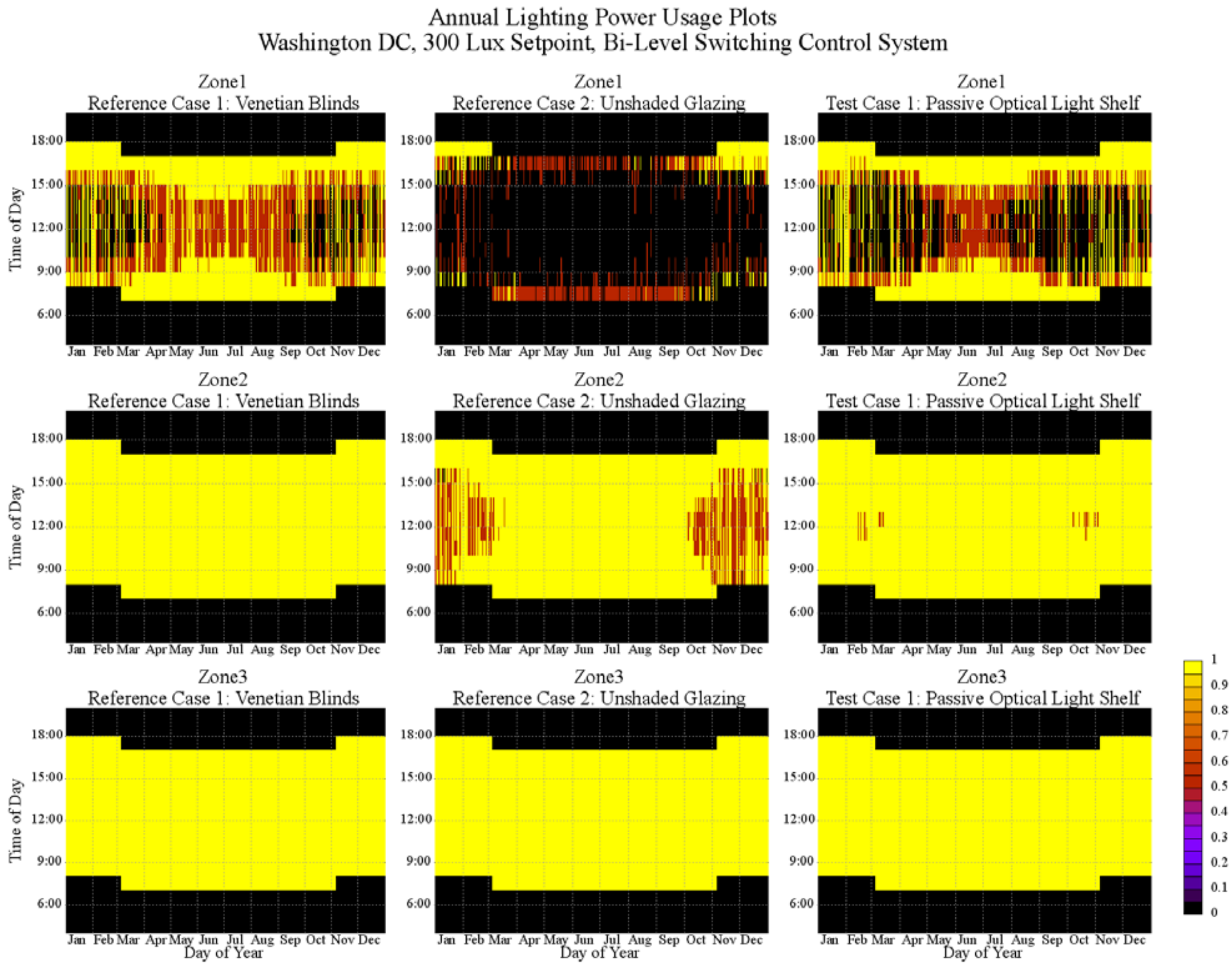

Fig. 13. Annual plots of lighting power use for a daylight-linked, bi-level switching system in Washington DC. Plots are provided for lighting control zone (rows) and three simulation cases (columns).

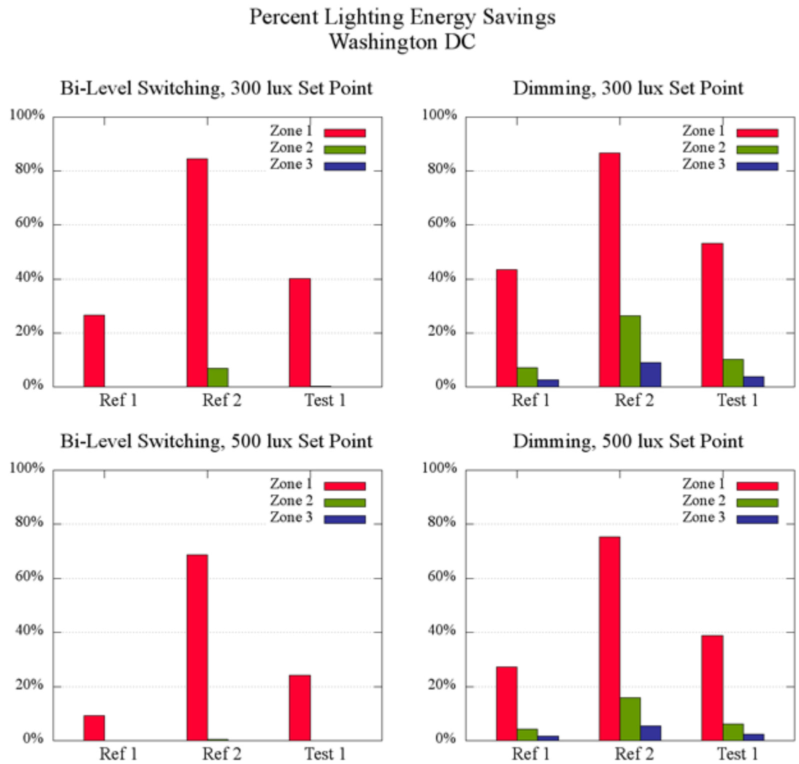

Fig. 14. Percentage annual lighting energy use reductions in each lighting control zone for Washington DC compared to no daylighting controls, where the lighting was on at full power from 8:00-18:00 LT on workdays throughout the year. Charts are provided for bi-level switching and dimming and for 300 lux and 500 lux set points.

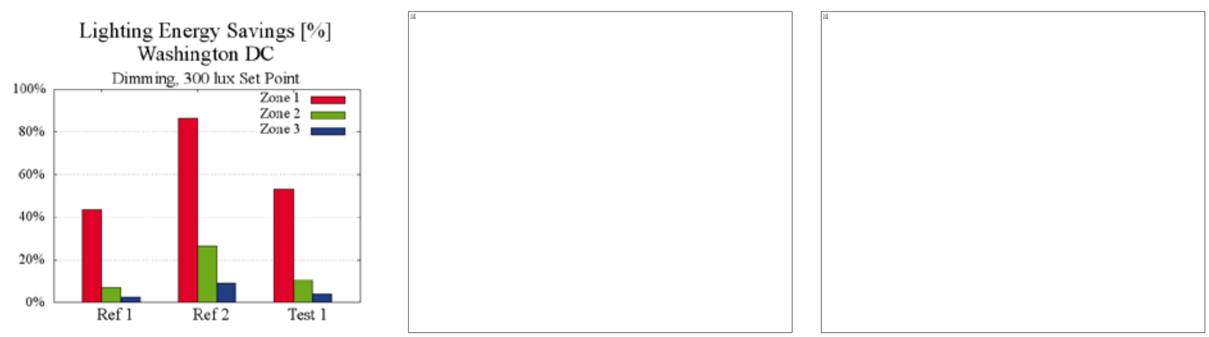

Fig. 15. Percentage annual lighting energy use savings for Washington DC, Phoenix and Minneapolis compared to no daylighting controls, where the lighting was on at full power from 8:00-18:00 LT on workdays throughout the year. Reference 1: Venetian blind, 45° slat angle, Reference 2: unshaded glazing, Test 1: optical light shelf.

4. Discussion

Summary data are given in Table 10 for the south-facing deep perimeter zone for the three modeled climates. Additional data for four additional climates are given in Appendix A. The unshaded window provided the greatest lighting energy savings compared to the same space with no lighting controls, however the frequency of visual discomfort made this case an unacceptable solution. Use of static Venetian blinds enabled a glare free environment, but the lighting energy savings were significantly reduced. Performance of the passive optical light shelf (OLS) fell between the shaded and unshaded cases in both energy savings and occurrence of glare.

More recent versions of building energy-efficiency codes and standards mandate use of photoelectric daylight controls in the area immediately adjacent to the window; e.g., ASHRAE 90.1-2010 defines the "primary sidelighted area" as a depth from the window of 1.0 times the head height of the window and 0.6 m (2 ft) on either side of the window. It is easy to see why this is the case as shown in Figure 15 for the shaded case (Ref 1). The bulk of the lighting energy savings are achieved in the first zone, in this particular case to a depth of 2.0 times the head height of the window due to the low height of the workstation partitions (1.1 m, 3.8 ft). Savings are 42-52% in this Zone 1 compared to a non-dimming system where the savings were calculated for the daytime weekday period when occupancy-based controls are unlikely to reduce the baseline energy use significantly. The lighting energy use intensity for the entire 17.4 m (57 m) deep perimeter zone was 1.82-1.93 kWh/ft^2-yr for the shaded window case with dimming controls and a 300 lux setpoint across the three climates. This is a total annual energy savings of 0.93-1.04 kWh/ft^2-yr (18-22%) achieved by a conventional shaded window.

The passive optical light shelf however is able to achieve significantly greater savings in Zone 1 nearest the window than the shaded window and achieve significant savings of 19-22% in Zone 2 compared to the non-dimming case across the three climates. Installations of lighting controls typically do not include dimmable lighting to this depth within the perimeter zone but could now potentially be cost-justified given the 1.04-1.15 kWh/ft^2-yr (22-27%) savings achieved by the OLS system over the entire depth of the perimeter zone.

In the assessment of discomfort glare, there are a few qualifiers related to this dataset. The DGI model is acknowledged to be poorly correlated to discomfort glare. The recently derived daylight glare probability (DGP) index [17] is more strongly correlated to end user response in full-scale daylit environments. As mentioned in Section 2.6, the Radiance simulations used the standard 145x145 resolution for both the bidirectional scattering distribution function dataset and subdivision of the sky, yielding a direct source resolution of no less than 0.24 steradians. Small-area, high intensity sources of glare were therefore muted by the low resolution, since intensity is spread out over a larger area than in reality. This lower resolution may not be sufficiently accurate for a glare assessment of the daylight-redirecting system. Further work is required to study how annual performance evaluations are affected by both the use of the DGP index and higher-resolution input data and settings for the view renderings.

As it stands with this analysis, however, the simulations indicate that discomfort glare for occupants seated at the rear of the room facing the OLS (View 3) will experience a greater frequency of "just uncomfortable" glare compared to the shaded window and on occasion levels of "just uncomfortable" to "just intolerable" glare (<1% frequency). The percentage of occupied daylight hours with a DGI greater than 22 was greatest in Phoenix (7%), which has the lowest latitude and the greatest percentage of available sunlight (Table 6) and for Washington DC and Minneapolis, the frequency was less (3%).

Table 10.
Summary of performance data for Venetian blind (Ref 1), unshaded glazing (Ref 2), and OLS (Test 1) for a 17.4 m (57 ft) deep, south-facing perimeter zone with savings compared to the same space without daylighting controls

Washington DC	Ref 1	Ref 1	Ref 2	Ref 2	Test 1	Test 1
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.54	11%	1.94	32%	2.41	16%
Continuous dimming, 300 lux	1.93	18%	1.39	41%	1.82	22%
Bi-level switching, 500 lux	2.77	3%	2.20	23%	2.63	8%
Bi-level switching, 300 lux	2.13	9%	1.63	30%	2.03	13%
Continuous daylight autonomy (% of year – Zone 1, 300 lux set point)	45%		82%		53%	
Useful daylight illuminance (% of year – Zone 1)	19%		48%		38%	
Percent occupied hours DGI>22						
View 1: facing window	0%		77%		0%	
View 2: side view of VDT	0%		11%		0%	
View 3: facing window, back of room	0%		53%		3%	
Phoenix	Ref 1	Ref 1	Ref 2	Ref 2	Test 1	Test 1
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.46	14%	1.86	35%	2.29	20%
Continuous dimming, 300 lux	1.82	22%	1.32	43%	1.71	27%
Bi-level switching, 500 lux	2.72	5%	2.16	25%	2.53	11%
Bi-level switching, 300 lux	2.02	13%	1.57	33%	1.93	18%
Continuous daylight autonomy (% of year – Zone 1, 300lux set point)	54%		87%		63%	
Useful daylight illuminance (% of year – Zone 1)	29%		54%		48%	
Percent occupied hours DGI>22						
View 1: facing window	0%		72%		0%	
View 2: side view of VDT	0%		13%		0%	
View 3: facing window, back of room	0%		61%		7%	
Minneapolis	Ref 1	Ref 1	Ref 2	Ref 2	Test 1	Test 1
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.54	11%	1.94	32%	2.40	16%
Continuous dimming, 300 lux	1.92	18%	1.39	40%	1.81	23%
Bi-level switching, 500 lux	2.76	4%	2.19	23%	2.60	9%
Bi-level switching, 300 lux	2.12	10%	1.63	30%	2.01	14%
Continuous daylight autonomy (% of year – Zone 1, 300lux set point)	45%		80%		54%	
Useful daylight illuminance (% of year – Zone 1)	22%		44%		41%	
Percent occupied hours DGI>22						
View 1: facing window	0%		73%		0%	
View 2: side view of VDT	0%		13%		0%	
View 3: facing window, back of room	0%		52%		3%	

The OLS has been commercially available for about a decade with a low degree of market penetration (1-2%) in part because the methods to simulate the annual daylighting and comfort performance of the system have not been routinely available. This particular study was run using considerable computing power (1616 CPU core Linux cluster), which has been unavailable to typical architects and engineers. With the development and validation of Radiance modeling capabilities for optically-complex systems such as this daylight-redirecting system and the capability to model performance on annual basis in a timely manner, market penetration of these types of systems may increase through either evidence-based decisionmaking on architectural applications of the product or through market-pull utility programs or new codes and standards.

5. Conclusions

Static, reflective, sunlight-redirecting systems have been used over many decades to improve daylighting in buildings, particularly in the perimeter zones of commercial buildings. These systems can take the form of simple flat or curved light shelves with a mirrored upper surface, designed for a specific project by a manufacturer or consulting architect or engineer. The concept has also been developed into commercial systems, such as the one evaluated in this study, where an engineered profile has been designed to improve the efficiency and distribution of sunlight redirection and then manufactured into a product that can be installed in new buildings or retrofit into existing buildings inboard of the window glazing. No adjustment of the system is required on a seasonal basis. The reflective surfaces must be kept clean and unobstructed to maintain optical efficiency.

The modeling tools up until this time have relied on detailed ray-tracing simulations to assess the energy and visual comfort performance of these systems. To obtain an annual assessment of performance, one would need to either compromise on the accuracy of the simulation or wait a very long time for the computations to be completed, particularly with complex spaces with furnishings. This study uses a recently developed suite of Radiance tools to perform a detailed parametric study evaluating the annual performance of a passive optical light shelf system (OLS) in a south-facing, 17.4 m (57 ft) deep, open plan office perimeter zone in several climates. The technology is applicable to residential buildings as well.

Findings from the study indicate that the OLS can achieve lighting energy savings of 1.04-1.15 kWh/ft^2-yr (22-27%) over the full depth of the perimeter zone compared to a non-daylit perimeter zone with minimal occurrence of discomfort glare near the window in an open plan space with 1.1 m (3.8 ft) high partitions. The system increased lighting energy savings in the 0-5.8 m (0-19 ft) zone nearest the window compared to the same window with a conventional Venetian blind and extended these savings to the 5.8-17.4 m (19-57 ft) core zone. Significant energy reductions occur during the summer peak periods when electricity demand across grid-stressed regions in the US is highest. These savings were achieved in locations that ranged from the most northern (Minneapolis) to southern (Phoenix) latitudes in the US and for a range in solar availability (high: Phoenix, moderate: Washington DC and Minneapolis).

The new ASHRAE 90.1-2010 mandates use of daylighting controls in commercial buildings within the area immediately adjacent to the window (1x the head height of the window, 0.6 m or 2 ft on either side of the window) and this is certainly a major step towards increasing adoption of daylighting measures. With more advanced technologies, such as this passive optical light shelf system, there is a case to be made to expand the code's definition of "daylight area" for sunlight-exposed (i.e., south-, east-, and west-facing zones in the Northern Hemisphere), sidelit perimeter zones to include deeper, wider areas when such systems are applied.

Acknowledgments

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References

[1] US DOE Office of Energy Efficiency and Renewable Energy, 2010 Buildings Energy Data Book, US Department of Energy, Office of Energy Efficiency and Renewable Energy, Table 3.1.5, http://btscoredatabook.eren.doe.gov/

[2] US DOE Office of Energy Efficiency and Renewable Energy, Solid-State Lighting Research and Development: Multi-Year Program Plan, April 2012. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf

[3] Arasteh, D., S. Selkowitz, J. Apte, M. LaFrance. 2006. Zero Energy Windows, 2006 ACEEE Summer Study on Energy Efficiency in Buildings.

[4] Ruck, N., O. Aschehoug, S. Aydinli, J. Christoffersen, G. Courret, I. Edmonds, R. Jakobiak, M. Kischkoweit-Lopin, M. Klinger, E.S. Lee, L. Michel, J.L. Scartezzini, S. Selkowitz, 2000, Daylight in buildings: A source book on daylighting systems and components, http://gaia.lbl.gov/iea21/

[5] Ward, G., Mistrick, R., Lee, E.S., McNeil, A., Jonsson, J, 2010, Simulating the daylight performance of complex fenestration systems using bidirectional scattering distribution functions within Radiance. *Leukos, Journal of the Illuminating Engineering Society of North America* 7(4).

[6] McNeil, A., Lee, E.S. 2012. A validation of the Radiance three-phase simulation method for modeling annual daylight performance of optically complex fenestration systems. *Journal of Building Performance Simulation* 2012: 1-14.

[7] Ward Larson, G. and R. Shakespeare, 1998, Rendering with Radiance: The Art and Science of Lighting Visualization. San Francisco: Morgan Kaufmann.

[8] Rogers, Z.L., Holtz, M.J., Clevenger, C.M., Digert, N.E., Mini-optical light shelf daylighting system, US Patent 6,714,352 B2, March 30, 2004.

[9] American Society of Heating, Refrigerating and Air-Conditioning Engineers, 90.1-2007 Energy Standard for Buildings Except Low-Rise Residential Buildings, www.ashrae.org.

[10] California Energy Commission, Title-24 2008 Building energy efficiency standards for residential and nonresidential buildings, CEC-400-2008-001-CMF, http://www.energy.ca.gov/2008publications/CEC-400-2008-001/CEC-400-2008-001-CMF.PDF.

[11] Illuminating Engineering Society of North America (IESNA), The IESNA Lighting Handbook: Reference and Application, 9th edition, New York: New York.

[12] Mitchell, R., C. Kohler, J. Klems, M. Rubin, D. Arasteh, C. Huizenga, T. Yu, D. Curcija. 2008. Window 6.2/ Therm 6.2 Research Version User Manual, Lawrence Berkeley National Laboratory, LBNL-941, Berkeley, CA 94720. http://windows.lbl.gov/software/window/6/index.html

[13] Wetter, M. 2010. Co-simulation of building energy and control systems with the Build Controls Virtual Test Bed. Journal of Building Performance Simulation,

[14] Rogers, Z. 2006. Daylighting Metric Development Using Daylight Autonomy Calculations In the Sensor Placement Optimization Tool. Boulder, Colorado, USA: Architectural Energy Corporation: http://www.archenergy.com/SPOT/SPOT_Daylight%20Autonomy%20Report.pdf

[15] Nabil, N., J. Mardaljevic. 2005. Useful Daylight Illuminance: A New Paradigm for Assessing Daylight in Buildings. Lighting Res. Technol, 37(1):41-59.

[16] Hopkinson, R.G. and Bradley, R.C., Glare from Very Large Sources, *Illuminating Engineering* (55): 288-297, 1960.

[17] Wienold, J., Christoffersen, J., Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, *Energy and Buildings* 38(7):734-757, 2006.

Appendix A – Simulation results for four additional cities

Simulations were conducted for a total of seven cities. Appendix A contains simulation results for the four cities not included in the paper.

A.1. Selection Criteria

The climates of the seven cities selected for simulation represent the range of climates found in the US. Selection of cities was based on ASHRAE climate zones and NREL global radiation map (Fig. A1 and A2).

Table A1.
Climates

City	ASHRAE Climate Zone	Global Solar Radiation Range [kWh/m^2/day]
Phoenix, AZ	2	5.5 – 6.0
Los Angeles, CA	3	5.0 – 5.5
Dallas, TX	3	4.5 – 5.0
Washington DC	4	4.0 – 4.5
Chicago, IL	5	3.5 – 4.0
Minneapolis, MN	6	3.5 – 4.0
Seattle, WA	4	3.0 – 3.5

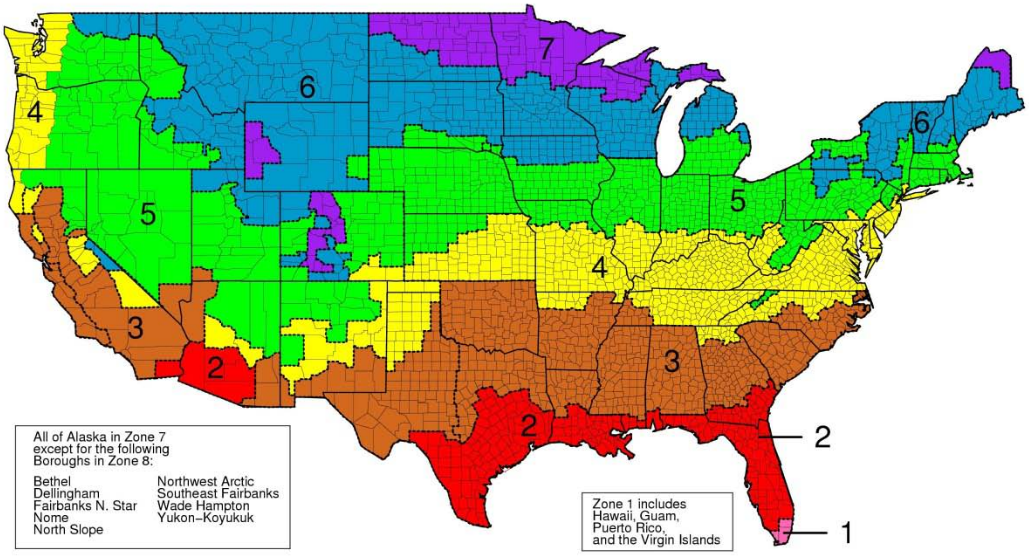


Fig. A.1. ASHRAE climate map.

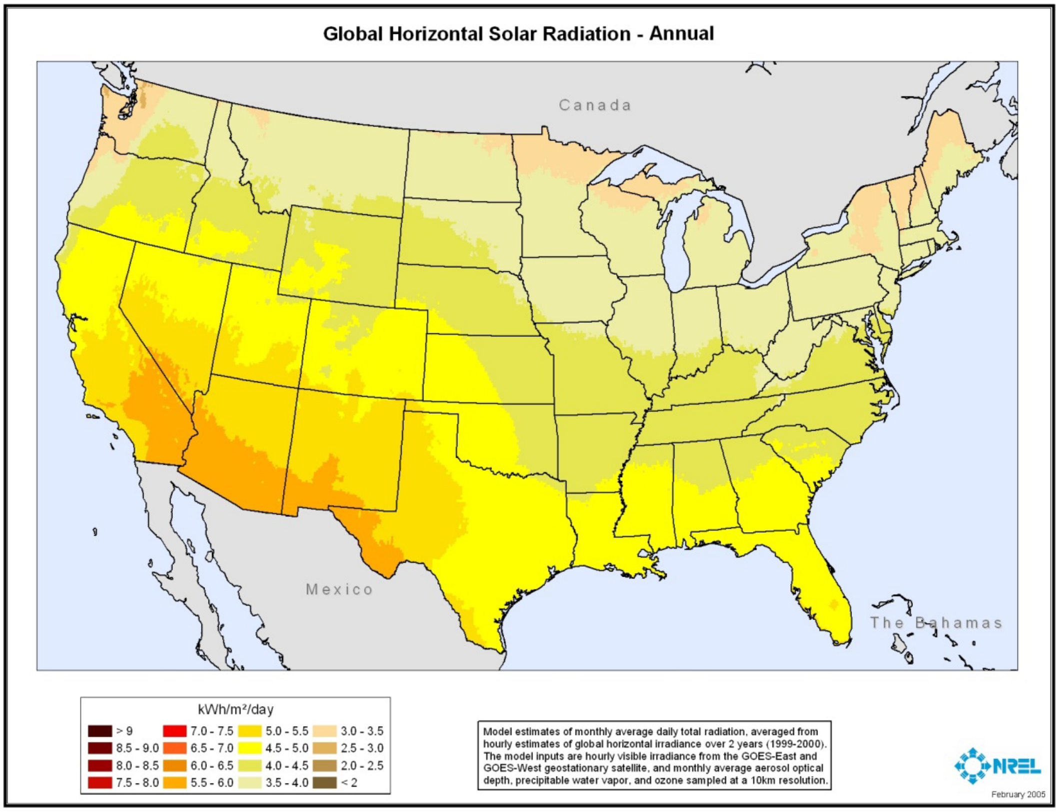


Fig. A.2. Annual global horizontal solar radiation map from NREL

A.2. Summary Table

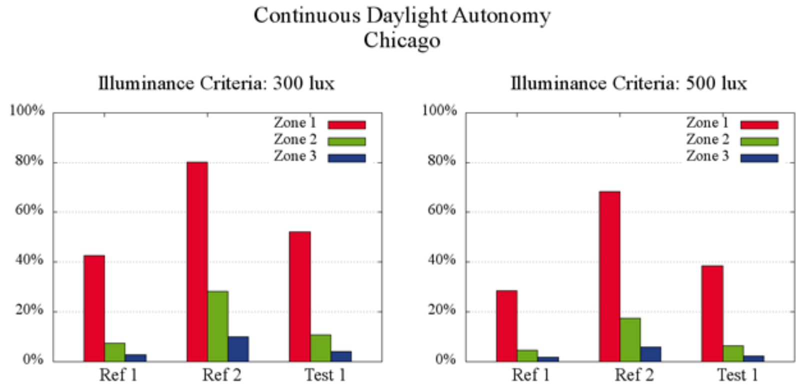
Table A2.

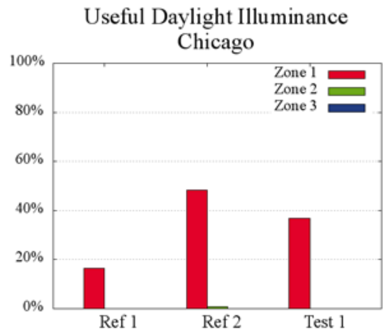
Summary of performance data for Venetian blind (Ref 1), No shading (Ref 2), and OLS (Test 1)

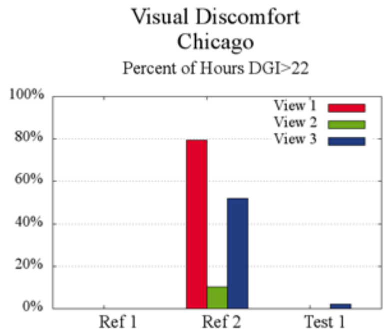
Chicago	Ref 1	Ref 1	Ref 2	Ref 2	Test 1	Test 1
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.56	10%	1.96	32%	2.43	15%
Continuous dimming, 300 lux	1.95	17%	1.41	40%	1.84	22%
Bi-level switching, 500 lux	2.78	3%	2.21	23%	2.64	8%
Bi-level switching, 300 lux	2.15	8%	1.64	30%	2.04	13%
Continuous daylight autonomy (% of year – Zone 1, 300 lux set point)	42%		80%		52%	
Useful daylight illuminance (% of year – Zone 1)	17%		48%		37%	
Percent occupied hours DGI>22						
View 1: facing window	0%		80%		0%	
View 2: side view of VDT	0%		10%		0%	
View 3: facing window, back of room	0%		52%		2%	
Dallas	**Ref 1**	**Ref 1**	**Ref 2**	**Ref 2**	**Test 1**	**Test 1**
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.53	12%	1.91	33%	2.38	17%
Continuous dimming, 300 lux	1.90	19%	1.37	42%	1.79	24%
Bi-level switching, 500 lux	2.77	3%	2.18	24%	2.62	9%
Bi-level switching, 300 lux	2.11	10%	1.61	31%	2.01	14%
Continuous daylight autonomy (% of year – Zone 1, 300lux set point)	47%		85%		57%	
Useful daylight illuminance (% of year – Zone 1)	20%		59%		39%	
Percent occupied hours DGI>22						
View 1: facing window	0%		76%		0%	
View 2: side view of VDT	0%		10%		0%	
View 3: facing window, back of room	0%		56%		4%	

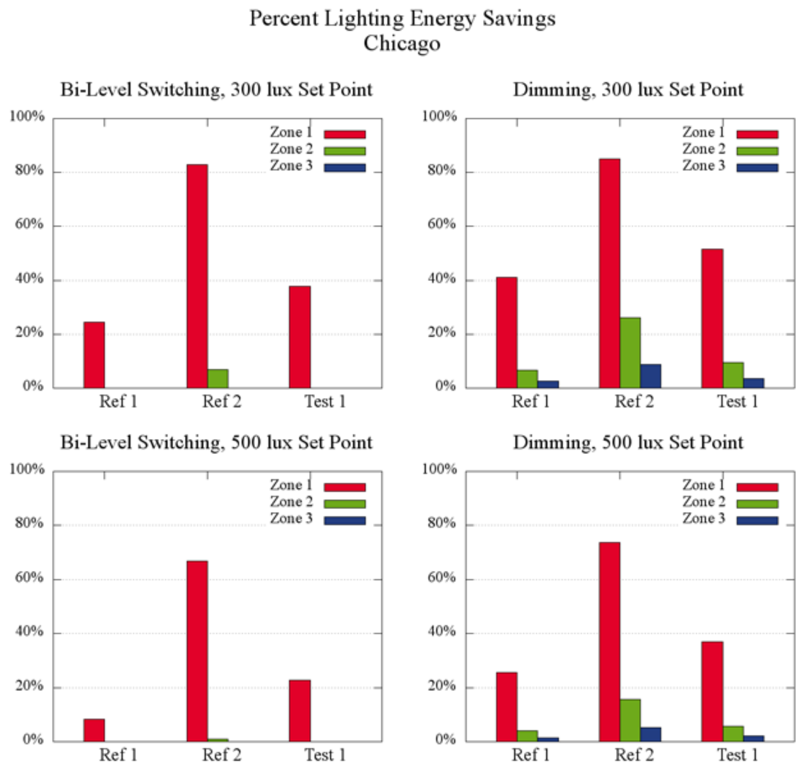
Los Angeles	Ref 1	Ref 1	Ref 2	Ref 2	Test 1	Test 1
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.51	12%	1.88	34%	2.34	18%
Continuous dimming, 300 lux	1.87	20%	1.34	43%	1.76	25%
Bi-level switching, 500 lux	2.75	4%	2.15	25%	2.58	10%
Bi-level switching, 300 lux	2.08	11%	1.58	32%	1.97	16%
Continuous daylight autonomy (% of year – Zone 1, 300lux set point)	50%		85%		60%	
Useful daylight illuminance (% of year – Zone 1)	24%		54%		44%	
Percent occupied hours DGI>22						
View 1: facing window	0%		85%		0%	
View 2: side view of VDT	0%		12%		0%	
View 3: facing window, back of room	0%		64%		4%	
Seattle	Ref 1	Ref 1	Ref 2	Ref 2	Test 1	Test 1
Lighting energy use (total of 3 zones)	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings	kWh/ft^2-yr	Savings
No lighting controls, 500 lux	2.86		2.86		2.86	
No lighting controls, 300 lux	2.34		2.34		2.34	
Continuous dimming, 500 lux	2.59	9%	2.03	29%	2.46	14%
Continuous dimming, 300 lux	1.98	15%	1.47	37%	1.87	20%
Bi-level switching, 500 lux	2.79	3%	2.28	20%	2.66	7%
Bi-level switching, 300 lux	2.17	7%	1.70	27%	2.06	12%
Continuous daylight autonomy (% of year – Zone 1, 300lux set point)	44%	39%		75%		48%
Useful daylight illuminance (% of year – Zone 1)	22%	16%		42%		35%
Percent occupied hours DGI>22						
View 1: facing window	0%		67%		0%	
View 2: side view of VDT	0%		9%		0%	
View 3: facing window, back of room	0%		45%		2%	

A.3 – Charts for Chicago



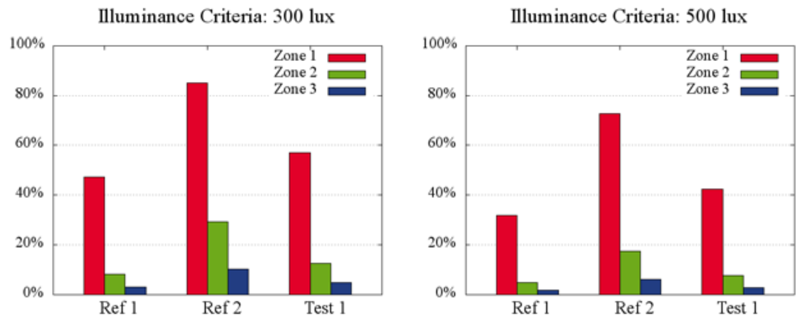




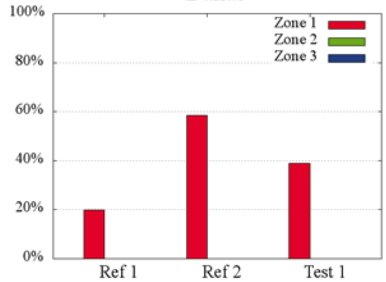


A.4 – Charts for Dallas

Continuous Daylight Autonomy
Dallas

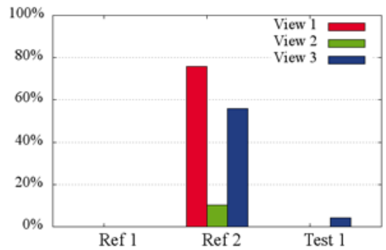


Useful Daylight Illuminance
Dallas

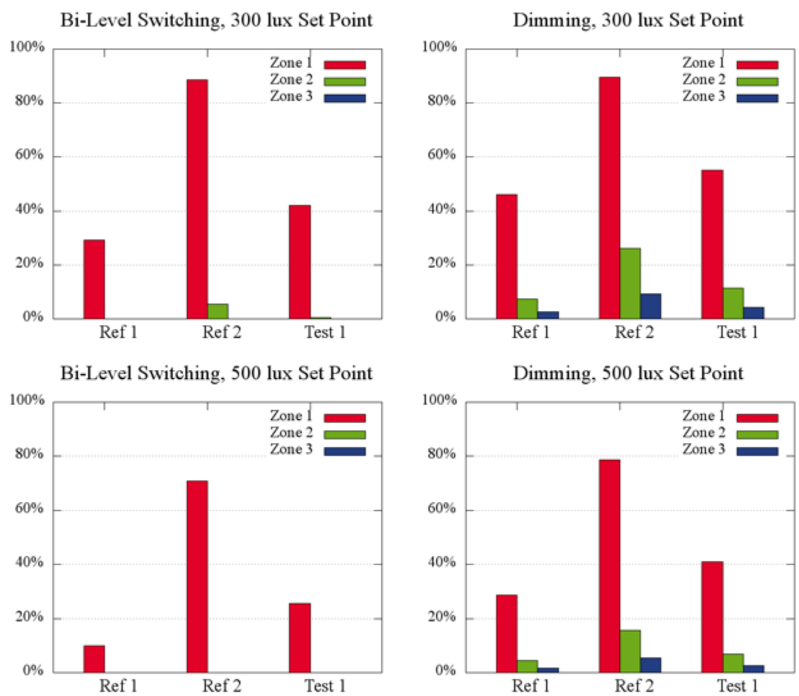


Visual Discomfort
Dallas

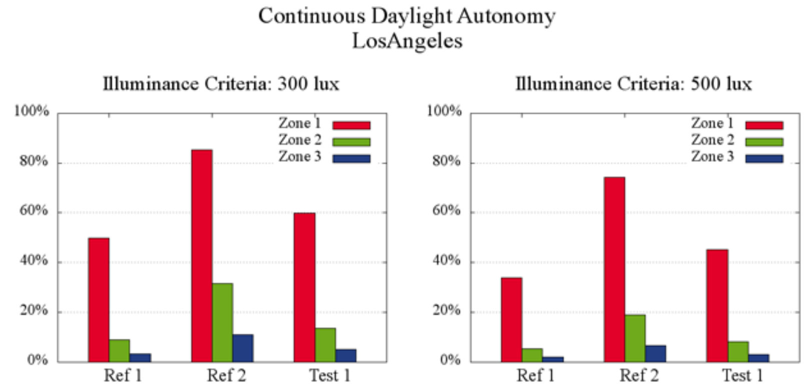
Percent of Hours DGI>22

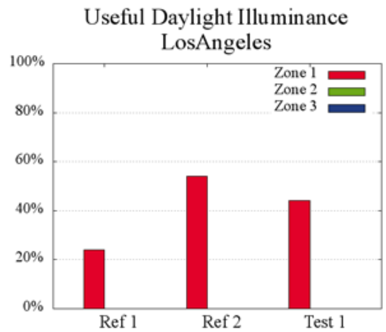


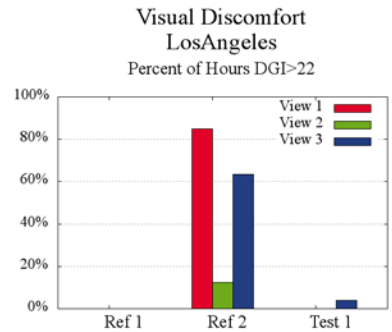
Percent Lighting Energy Savings
Dallas

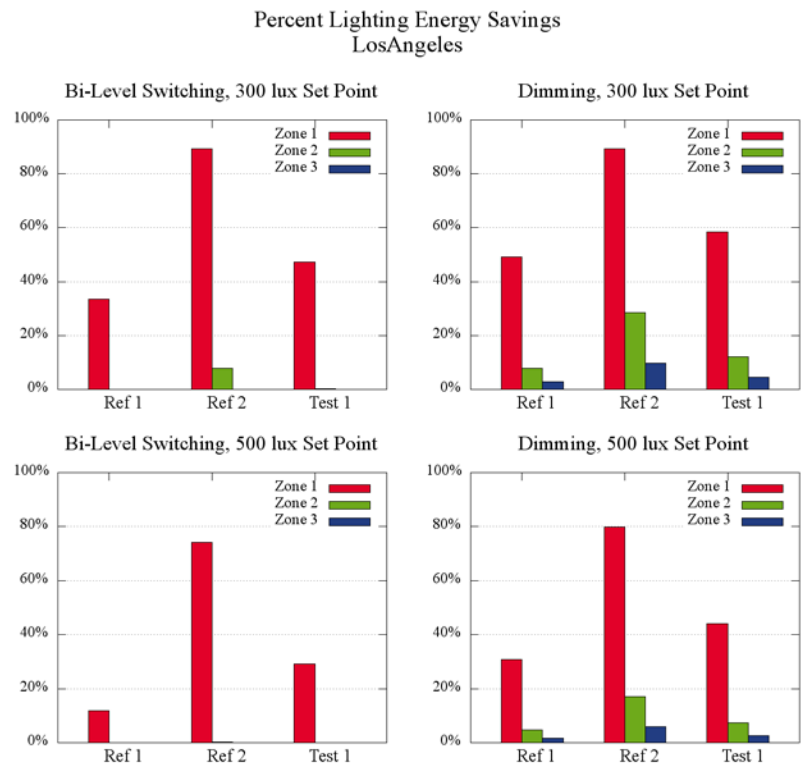


A.5 – Charts for Los Angeles









A.6 – Charts for Seattle