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Radiance-Mathematica optimization study of electrochromic window and daylighting control systems

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Abstract

A proof-of-concept lighting simulation study was conducted to evaluate lighting energy savings of EC window systems controlled to satisfy key visual comfort parameters directly or optimally as opposed to indirectly as was done in the testbed field studies and with prior DOE-2 simulations. Radiance was used to compute interior illuminance and luminance levels within a south-facing private office that was similar in geometry and furnishings to that of the Lawrence Berkeley National Laboratory (LBNL) windows testbed facility. Mathematica was used in conjunction with Radiance to select the EC window transmittance and Venetian blind height and slat angle that best satisfied various comfort variables via least-squares optimization with linear inequality constraints. With visual comfort requirements satisfied directly by the EC control system in a simulated case, annual lighting energy use savings were significant (48-67%) assuming a reference case (Tv=0.60) with a manually operated Venetian blind that is lowered once per day to address visual comfort requirements. This simulation study demonstrates that lighting energy use savings can be maintained at significant levels with a zoned EC system controlled to first address visual comfort concerns. In addition, the percentage of year that the occupant has a view out is significantly greater: 98% for the EC case versus 38% for the reference case.

Keywords: Building energy-efficiency; Daylighting; Control optimization, Electrochromic windows.

1. Introduction

Electrochromics (EC) are glazings whose optical transmittance can be controlled actively via a small applied electric potential. This leads naturally to their application in controlling the admission of daylight into buildings, since they can be darkened when too much light outside causes glare and be made lighter when more daylight is needed. This way the occupants of buildings can enjoy the advantages of both light and dark glazing, without the disadvantages of either. It is less straightforward whether using electrochromics can lead to lower lighting energy usage. When darkened, the glazing can prevent the admission of enough daylight for visual tasks, which, as in the case of standard tinted glazing, leads to higher electricity usage.

The objective of this simulation study is to quantify the annual energy performance impacts of EC windows controlled to meet basic visual comfort requirements then optimized to provide daylight. Most simulation studies have quantified energy impacts of EC windows controlled to maintain work plane illuminance above a given illuminance setpoint level, without direct consideration of visual comfort [Sullivan et al. 1994]. A field study was conducted with large-area EC windows, but the control algorithm provided less than optimal visual comfort control [Lee et al 2006]. A Radiance study was conducted where the EC was controlled for visual comfort, but the EC window was controlled based on seasonal thermal considerations [Wienold 2003]. This study compares the annual energy and daylighting performance of electrochromic and conventional window (visible transmittance, Tv, of 0.60) for a typical south-facing private office with a large-area zoned facade with interior Venetian blinds situated in Oakland, California. The façade was divided into upper and lower zones. The height and slat angle of the Venetian blind was controlled to block direct sun and provide daylight. The effect of adding an overhang to the façade was also determined. Lighting simulations were performed with *Radiance*, a lighting calculation and image rendering computer program [Larson 1998].

2. Method

2.1. Lighting simulation

2.1.1. Space geometry and surface properties

The space modeled is a south-facing private office situated in Oakland, California, 10 ft wide by 15 ft deep, with a 9-ft high ceiling and 2-ft high plenum (Figures 1-2). The reflectance of the interior surfaces are 50% for the walls, 70% for the ceiling, and 20% for the floor. The office has glazing on the south facade only, with a sill height of 22 inches. The window is divided into an upper portion for daylighting and a lower portion for view. Except for the optional overhang at the height of the division between the upper and lower windowpanes, no exterior obstructions were considered. Based on the available technology, it was assumed that the transmittance of the electrochromics could vary between 5% and 60%. The reference window had a transmittance of 60%.

The space contains typical office furniture (Figure 3). An L-shaped workstation (work surface has reflectance of 41%) is located in the southwest corner. A 17-inch LCD visual display terminal (VDT) sits on the work surface, with a chair opposite. Two sheets of white paper (reflectance of 75%) are placed to the left and right of the VDT for calculation purposes, and a red vase with yellow flowers is in front of the window for visual interest.

The façade was also modeled with 1-inch wide interior Venetian blinds. The blind heights were either fully up, lowered over the top window pane, or fully lowered over the whole window. The slat angle varied between horizontal (0°) to 80° (downward so view of ground from intererior) in 10° increments. Slats were spaced 0.7-inches apart. Slat reflectance was 85% with a specularity of 1%.

As an alternate case, a white (r=0.60) exterior overhang was placed 7 ft above the finished floor. The overhang was 3 ft deep and 1-inch in height. The width was continuous across the south façade.

A seated occupant's viewpoint was selected for the simulations. This view was situated 4 ft off the floor, 5 ft away from window, and 4 ft away from the facing wall (e.g., Figure 6). It was implemented in Radiance by a 180° hemispherical fisheye view looking towards the VDT.

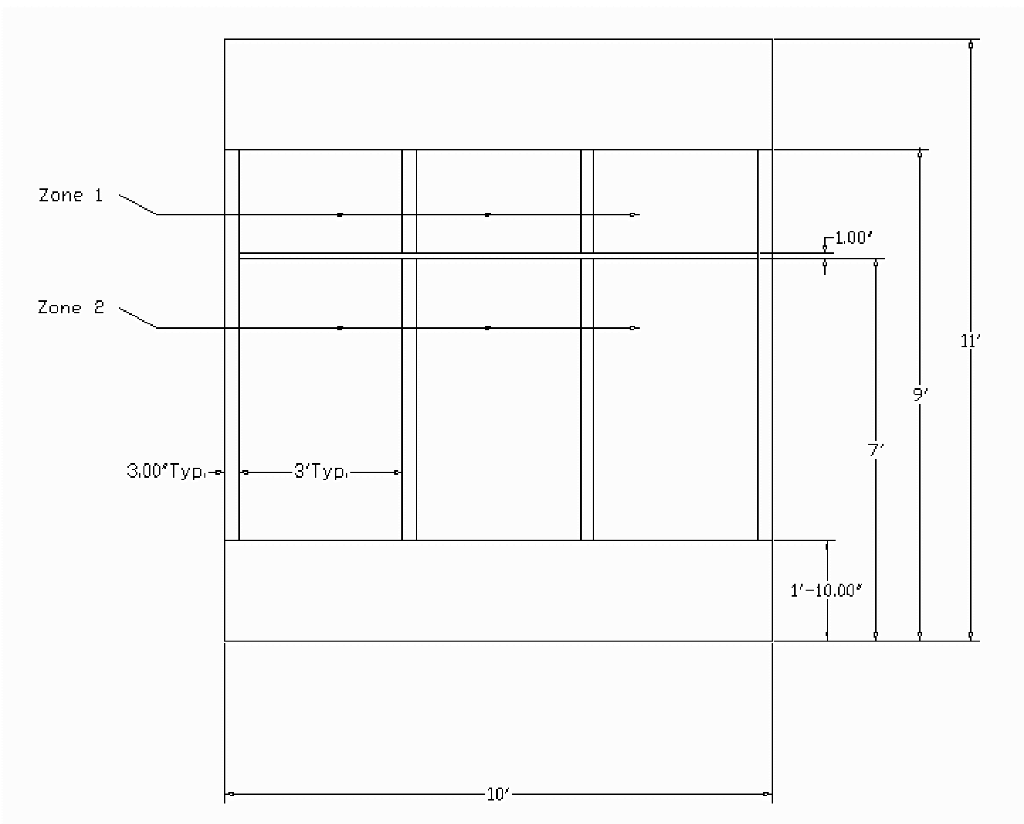


Figure 1. Section view of the office.

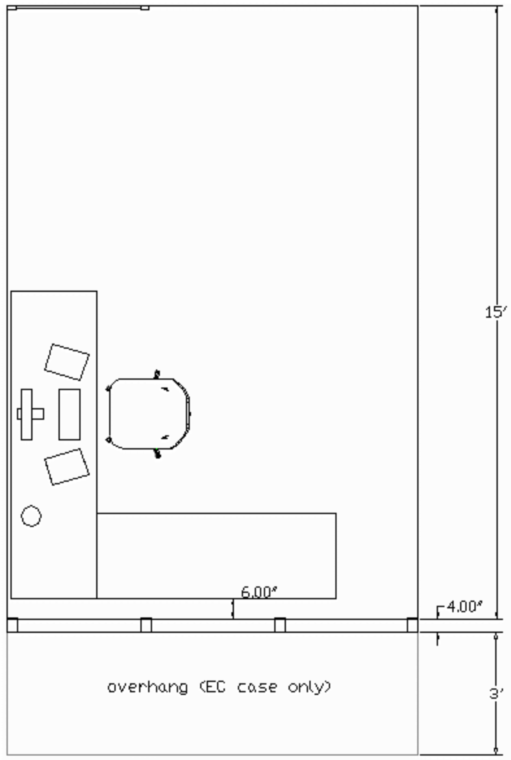


Figure 2 Plan view of the office.


Figure 3. General view of the office.

2.1.2. Daylight coefficient simulation

To enable rapid evaluation of different skies for each of our blind and overhang conditions, we employed a "daylight coefficient" approach, similar to the work of Reinhart and Walkenhorst [2001]. For each blind/overhang condition, we calculate the partial contributions of 145 solar positions and 145 sky patches distributed according to Tregenza and Waters' original proposal [1983]. This distribution is shown in Figure 4. In addition, we include a single patch for the ground contributions outside the local surface that captures shadows from the building structure.

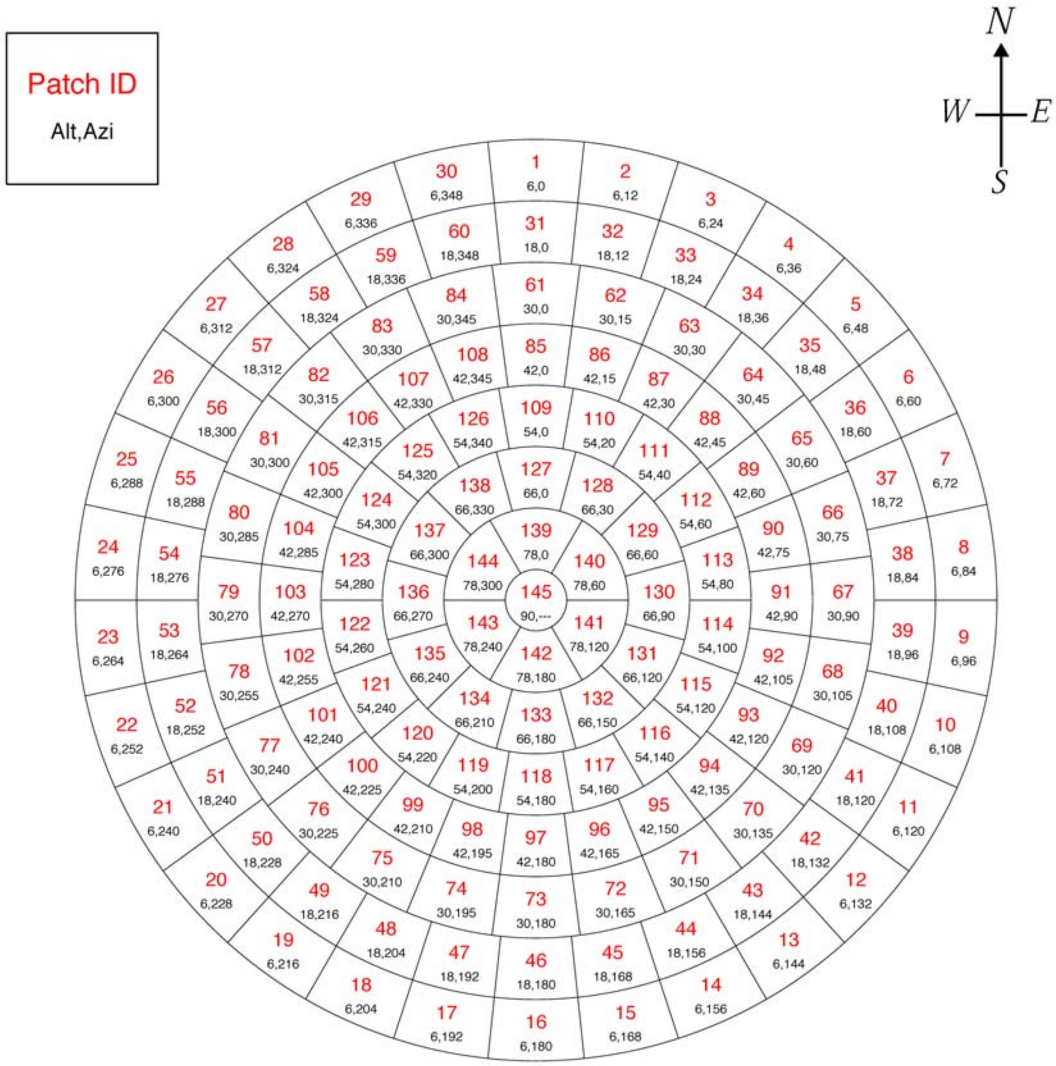


Figure 4. The arrangement of Tregenza patches over the sky dome. (Reprinted from [Mardaljevic, 2000].)

The *Radiance* program **rtcontrib** was employed in a “3-bounce” calculation of Tregenza sky patch contributions, which is adequate for a shallow space such as ours, but probably not optimal. No convergence tests or analyses were performed to guarantee that the results were accurate, as we were principally concerned with a comparison metric for this case study, and not high absolute accuracy. Previous simulations have shown that increasing the number of bounces only increases the overall levels rather than the distribution of light. As it was, it took two weeks on a render farm consisting of 8 two-processor nodes to perform the calculations. Future studies should probably include additional bounces, and place a ground plane outside to account for shading from the building structure.

In all, there were 40 configurations, each of which had data for 146 sky patch plus 145 solar position contributions. Because we intended to control the transmittance of the upper and lower glazings separately, we computed a set of runs for each, as well as separate runs for each Venetian blind angle (0-80° at 10° increments). As mentioned above, we also had three blind heights to consider. Finally, we had our building configured with and without an external overhang, which doubled the total number of runs again. Figure 5 shows example contributions from a single sky patch and its corresponding solar position. Figure 6 shows the combined result based on TMY weather data for Oakland, CA on December 21 at 12 noon.

Figure 5. Contributions through the lower glazing from sky patch 045 and the matching solar position with blinds fully deployed at 20° with overhang.

Figure 6. Combined result on Dec. 21 at 12 noon using TMY data for Oakland, CA.

The method by which our daylight coefficients are summed follows the daylight coefficient approach, using averaged sky values for CIE clear, intermediate, or overcast skies according to the thresholds outlined in Table 1. In the case of CIE Clear or Intermediate sky types, a sun is simulated that puts out light commensurate with the direct normal irradiance taken for that time point from the selected TMY weather data. Similarly, light coming from the sky dome and ground will correspond to the selected data point. A quick ray tracing sample is then taken of the simulated CIE sky to determine the appropriate daylight components, using 64 samples per Tregenza sky patch. This sampling was deemed sufficient to integrate local variations in each patch, including patches in the circumsolar region, but not including the sun, which is accounted for separately. For the direct solar component in the case of a clear or intermediate sky, the four closest pre-computed solar coefficients corresponding to the three nearest Tregenza sky patches are interpolated using a bilinear weighting. This was found to be adequate for simulations with Venetian blinds in a previous daylight coefficient study [Reinhart and Walkenhorst 2001], and we confirmed that it suited our needs based on some preliminary experiments.

Table 1
Defnition of sky types

CIE Sky Type	*Condition*
Clear	Direct normal irradiance is more than 200% of diffuse horizontal
Intermediate	Direct normal is between 5% and 200% of diffuse
Overcast	Direct normal is less than 5% of diffuse

Once the sky has been generated based on the selected blind deployment and angle, date, time, and weather data, the 146 daylight coefficient images are combined with the 4 nearest solar coefficients, appropriately weighted, to produce a resulting two *Radiance* image similar to that shown in Figure 6, one for the upper window's contribution and one for the lower window's. This image component calculation is reasonably fast, taking less than 10 seconds on a single CPU. Of course, it leverages all our pre-computed coefficients, which took months of CPU time, but this permits us to conduct studies over the course of a year in any climate and any building orientation on any part of the globe.

2.2. Window control

In order to evaluate the optimal daylight performance in our simulated office space, we need to define an algorithm for controlling both the Venetian blinds and the electrochromic windows. Since the optimal transmittance of the electrochromics will depend on the condition of the blinds and vice versa, we have a chicken-and-egg, or at least an iterative problem to solve. The algorithm we arrived to (Figure 7) comprised of several steps:

1. Blinds deployed to block direct sun. If the sun is visible by the occupant, the blinds are deployed at a height (either covering the top pane or the whole window) and angle (from horizontal to 80° tilt, in 10° increments) that are just enough to prevent the incidence of direct sunlight on the occupant's eye. Without this first step, the possibility of providing visual comfort would be very slim to nil.
2. Optimization of electrochromics transmittance. After the blinds ensure no direct sunlight reaches the occupant's eye, the transmittance of the electrochromic panes is optimized to provide adequate illuminance on task areas without creating visual discomfort. Two criteria for visual comfort were used in this study. The first is the luminance ratios between the computer screen and different parts of the occupant's field of view. The second is the total vertical illuminance at the occupant's eye. More detail about these is provided below.
3. Additional blind deployment. If visual comfort criteria are not met, even with the electrochromics set to their minimum transmittance of 5%, the blinds are further deployed. If the blinds aren't already fully closed, the angle is incremented by 10°. In case the blinds are fully closed, the blinds are lowered to the next lower height and the slats set to open position. The algorithm then goes back to step 2, and the iterations take place either until all visual comfort criteria are met, or until the blind is fully lowered and closed.

For the reference window, the control algorithm is similar but omits the transmittance optimization step 2 – transmittance is set to 60% (Figure 8).

In each case the control algorithm is used to determine electrochromics transmittance and blind position and angle for every daylight hour of the year.

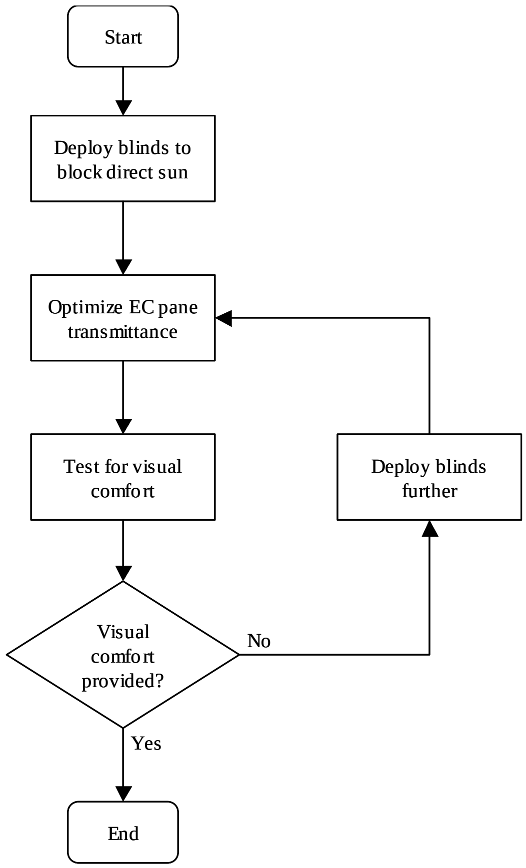


Figure 7. Control algorithm flow chart for electrochromic case.

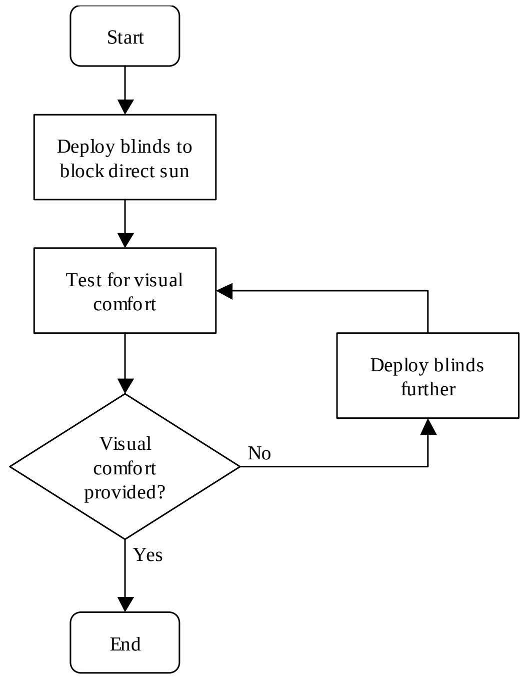


Figure 8. Control algorithm flow chart for reference case.

2.2.1. Blind deployment to block direct sun

The blinds will be required first to block direct sun from the view of the office's main occupant, who we assume is sitting at the desk with a view corresponding to the one shown in Figure 6. In the case of an overcast sky, we assume there is no sun visible, and leave the blinds fully raised. If the sky is intermediate or clear, we perform a quick computation of the sun's position and compare the sky regions visible in the upper and lower panes as shown in Figure 9. If the sun is visible in the corresponding lower pane section, we fully lower the blinds and set the slat angle just enough to exclude direct sun from entering the room. If the sun is visible through the upper pane, then we only deploy the blinds enough to cover the upper window.

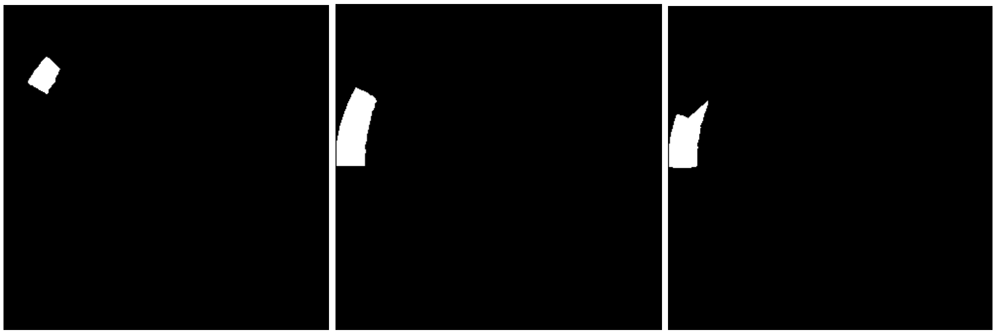


Figure 9. Sky visible through upper and lower panes, and lower pane with overhang.

2.2.2. Optimization of electrochromic window transmittance

Once blinds have been deployed, and therefore no direct sunlight arrives at the occupant's eye, the electrochromic windows are set to a transmittance level that provides optimum use of daylight without exceeding the boundaries of visual comfort.

This is done by calculating the set of window transmittances (upper and lower) that comes as close as possible to meeting a work plane illuminance target without exceeding two types of visual comfort constraints: 1) luminance ratios between the computer monitor and the surrounding field of vision and 2) total vertical illuminance at the eye.

This optimization is performed by an algorithm for least-squares optimization with linear inequality constraints [Lawson and Hanson 1974]. This algorithm takes into consideration the separate contribution from each window (Figure 10) and determines what combination of these will come the closest to meeting the target, within specified constraints.

Figure 10. Each window pane contributes independently to the amount of light present in the room. For June 12th at 1 PM standard time, the image on the left shows the contribution of the lower pane, the one on the right the contribution of the upper pane.

The target for the optimization is to provide as close as possible to 600 lux on the work plane; i.e., an amount of light that is comfortable for general reading and writing tasks on the desk areas adjacent to the keyboard. This target is defined for the center of each sheet of paper depicted in Figure 10.

This optimization is subject to several constraints. The physical characteristics of the electrochromics constrain visible transmittance to values between 5% and 60%. As specified by the Illuminating Engineering Society of North America for office lighting [IESNA 1999], visual comfort requires constraining the ratios between the luminances of the computer monitor and different areas of the occupant's field of view. For areas within a 30° cone centered on the direction of view, the maximum luminance ratio allowed is 3:1. For areas outside that cone but within a 60° cone, the ratio is 10:1. For the rest of the field of view, the ratio is 40:1. Other research into visual comfort [Osterhaus 1996] suggests an additional requirement that the total vertical illuminance at the eye should not exceed 800 lux.

To impose the luminance ratio constraints, the pixels of the 322x322 luminance map images are averaged into a 10x10 grid composed of larger pixels (Figure 11).

Assuming a monitor luminance of 200 cd/m^2, i.e. that of a current LCD computer monitor, each of these 100 "visual comfort pixels" is constrained to a certain luminance, according to its position in the field of view (Figure 12).

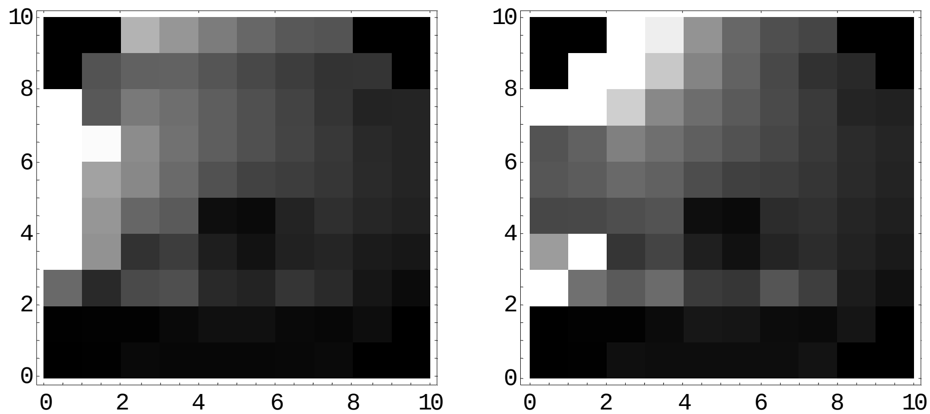


Figure 11. Luminance map obtained from images shown above in Figure 10, after pixel averaging.

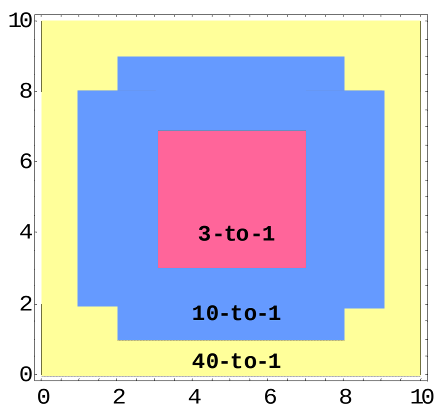


Figure 12 Luminance constraints for averaged pixels.

This reduction in the number of pixels is done for two reasons. The first is to reduce the running time of the optimization algorithm, which would be inordinately high if all 110,224 pixels of the original images were constrained. The second is that the human visual system does not respond to glare sources as small as the original pixels. Further research is necessary to determine the adequate level of pixel averaging, which may be variable according to position in the field of view. A limitation of this technique is that it may underestimate glare sources that are divided among neighboring pixels.

The following example shows the kind of result provided by this optimization. For June 12th at 1 PM (standard time) in Oakland, California, the result of the optimization is that the transmittance of the lower and upper electrochromic window panes should be set to 5 and 26%, respectively (Figure 13).

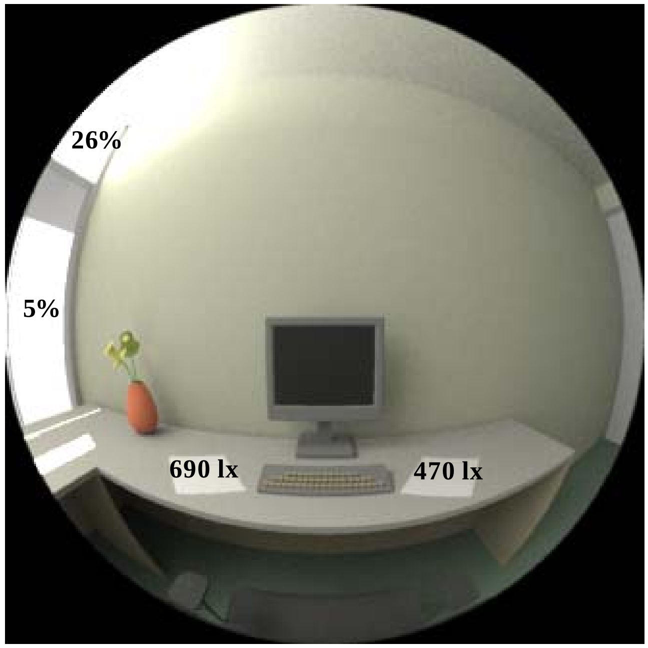


Figure 13. Occupant's view of the room for optimal pane transmittance of 5% for the lower pane and 26% for the upper pane.

With these levels of transmittance, the illuminance on the target points is approximately 690 (left) and 470 lux (right). The vertical illuminance at the eye is about 350 lux. The luminance of the "visual comfort pixels" is shown in Figure 14. All values are within the limits required by visual comfort.

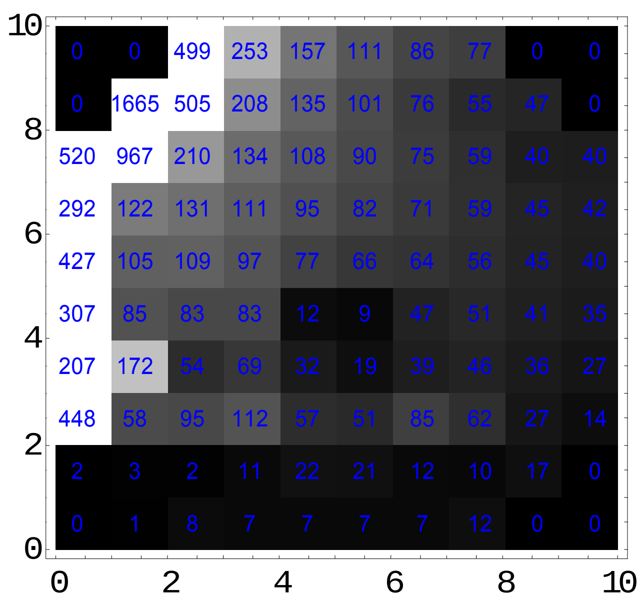


Figure 14 Luminance values for "visual comfort pixels" (cd/m^2).

2.2.3. Additional blind deployment

If, after the previous steps, the two criteria for visual comfort – luminance ratios and total vertical illuminance at occupant's eye – are not met, the blinds are deployed further. The flow chart for this part of the control algorithm is shown in Figure 15.

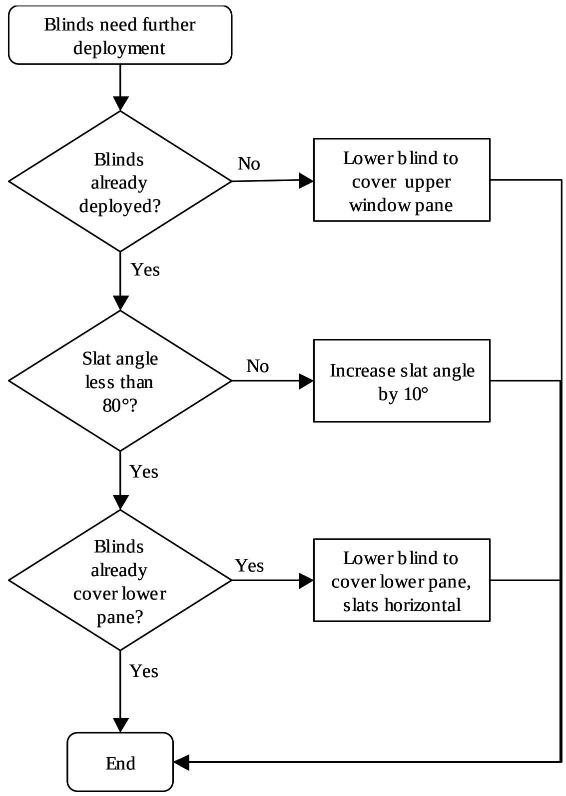


Figure 15. Flow chart for additional blind deployment.

Whenever possible, the closing of the slats takes precedence over lowering the blind; e.g., if the blind already covers the upper window pane and needs to be deployed further, the slat angle is increased by 10° successively until visual comfort criteria are met. If they still aren't met with the slats fully closed, then the blind is lowered over the lower window pane and the slats brought back to horizontal. After that the slat angle can still be successively incremented by 10° each time, if necessary until the blind is fully closed.

2.3. Lighting controls

In this simulation, electric lighting was provided by two 2x4 ft 4-lamp T8 recessed fluorescent luminaires with parabolic louvers, each having a maximum power consumption of 135 W. The power consumption as a function of light output for this system is plotted in Figure 16.

The luminaires were controlled by the simulated signal from two photosensors mounted on one of the luminaires in order to maintain an average work plane illuminance of 540 lux (approximately 50 footcandles). Lights went on only when more than the minimum light output (10% of maximum) was necessary. Sensor 1 was oriented vertically downwards towards the work space while sensor 2 was directed towards the back of the room. The areas monitored by each sensor are shown in Figure 17.

During daylight hours, electric lighting was controlled by the signal from sensor 1, except for times when the ratio between sensor 1 and 2 went above 0.8065 – the value of that ratio with the electric lights at full power and no daylight. For these times, the probability was high that direct sunlight was present in the area monitored by sensor 1. Therefore, the lights were instead controlled by the signal from sensor 2.

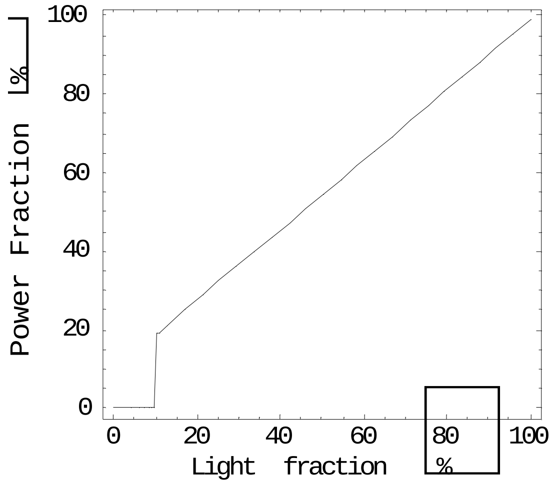


Figure 16. Luminaire power consumption vs. light output.

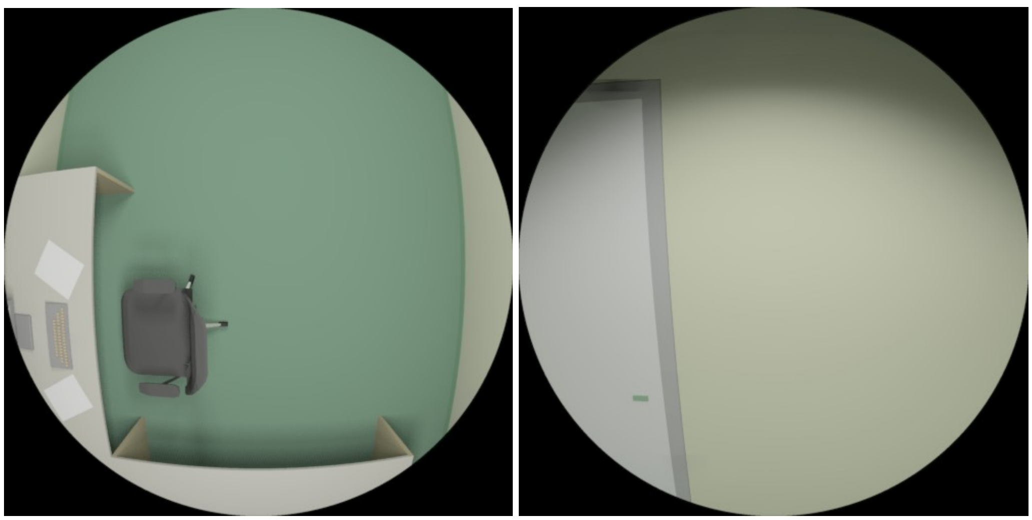


Figure 17. "Views" from sensors: a) sensor 1, b) sensor 2 (partial view of door).

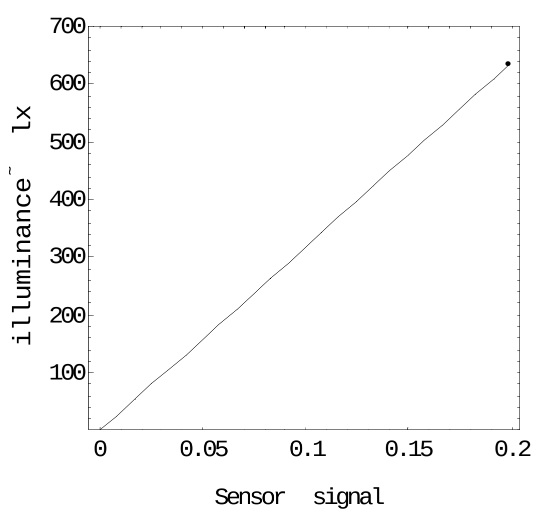
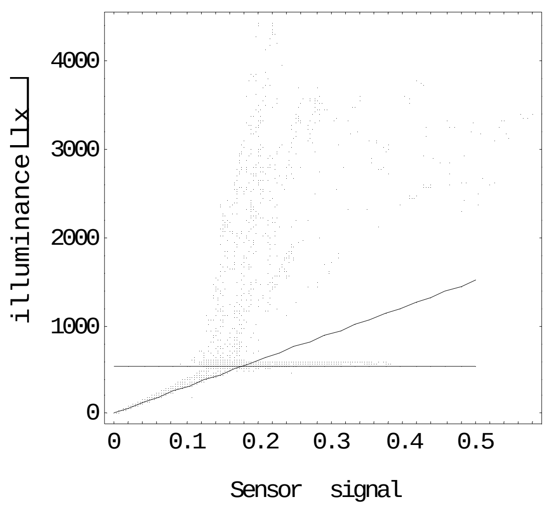


Figure 18. Work plane illuminance vs. sensor signal (V) for electric lighting system.

The work plane illuminance versus sensor signal function for the electric lighting system (Figure 18) was determined by calculating work plane illuminance and sensor 1 signal with the lights on at full power and no daylight, and by assuming a linear sensor response.

The sensor response to daylight was also determined. Hourly values of work plane illuminance due to daylight are plotted against sensor signal in Figure 19, for the whole year. The sloped line shown represents the selected work plane illuminance versus sensor signal function. It is below 90% of the points that are under the work plane illuminance setpoint. This ensures that, for 90% of the hours during which average work plane illuminance due to daylight is under the setpoint, the control system does not underestimate work plane illuminance. This was also done with the overhang added to the façade.

Using the illuminance versus sensor signal characteristics shown above, the amount of lighting power necessary to bring work plane illuminance up to the setpoint was determined for every daylight hour during which sensors indicated that work plane illuminance due to daylight alone was insufficient.



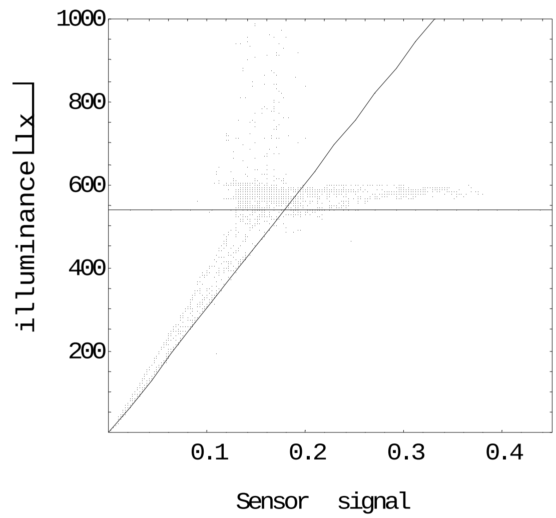


Figure 19, Work plane illuminance vs. sensor signal for daylight (electrochromic window, no overhang). The plot on the right shows the same data in more detail. The horizontal line is the illuminance setpoint for electric lighting control (540 lux). The sloped line is the illuminance versus sensor signal function.

3. Results

The results obtained show that annual lighting energy use is higher for the electrochromic window than for the reference window (Figure 20). For both cases, the introduction of the overhang results in a slight increase in energy use.

If the difference between the lighting energy usage of both windows is plotted hourly for the whole year (Figure 21), it can be seen that there is a significant amount of time when the electrochromic window requires more energy than the reference window. This happens either with or without the overhang.

Except for morning and early afternoon in winter and fall, the electrochromic window provides constant work plane illuminance throughout the year (Figure 22). This is expected because it is the target of the optimization algorithm. The higher values occur at times when direct sunlight hits the work plane. This effect is still present but much less marked when an overhang is present. The reference window generally provides higher average work plane illuminance, close to 1000 lux for most of the year.

Vertical illuminance at the eye is kept by the electrochromics at a very tolerable level, around 400 lux for most of the year (Figure 23). The value for the reference window is between 600 and 800 lux for most of the time, which is still below the specified threshold for glare.

Throughout the year, maximum window luminance is lower for the electrochromic window, usually around or under 2000 cd/m^2 (Figure 24). There are a handful of hours in the year during which spikes of up to 8000 cd/m^2 are observed. The reference window is usually brighter, very frequently with values in the 2000-5000 cd/m^2 range.

The histograms in Figure 25 show that, to achieve the specified visual comfort parameters, the reference window requires the blinds to be deployed much more frequently than the electrochromic window. By examining the pattern of blind usage throughout the year (Figure 26) it can be seen that indeed the reference window requires blinds deployed over the whole window consistently throughout the year approximately from 8:00 to 16:00. The electrochromic window, on the other hand, requires blind deployment over the whole window only in the early afternoon, from early November to late January. Furthermore, the required slat angle is horizontal, or nearly so. For a good part of the year this window requires no use of blinds at all.

The electrochromic window achieves visual comfort without blind deployment for most of the year because the glass transmittance can be lowered when necessary (Figure 27). The transmittance of the lower pane has most frequently values below 10%. The transmittance of the upper pane varies substantially more, having values close to 60% during a significant part of the year.

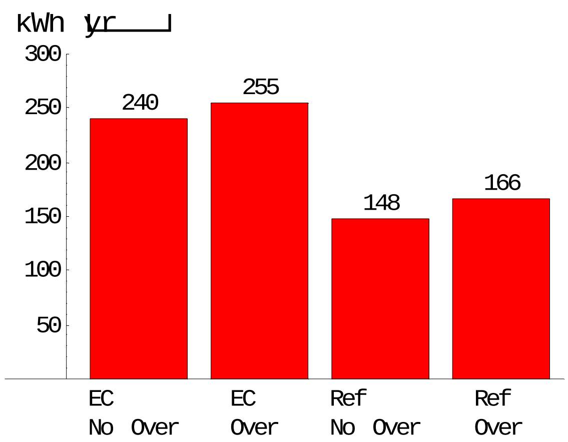


Figure 20 Annual lighting energy use for electrochromic (EC) and reference (Ref) windows, with and without overhang.

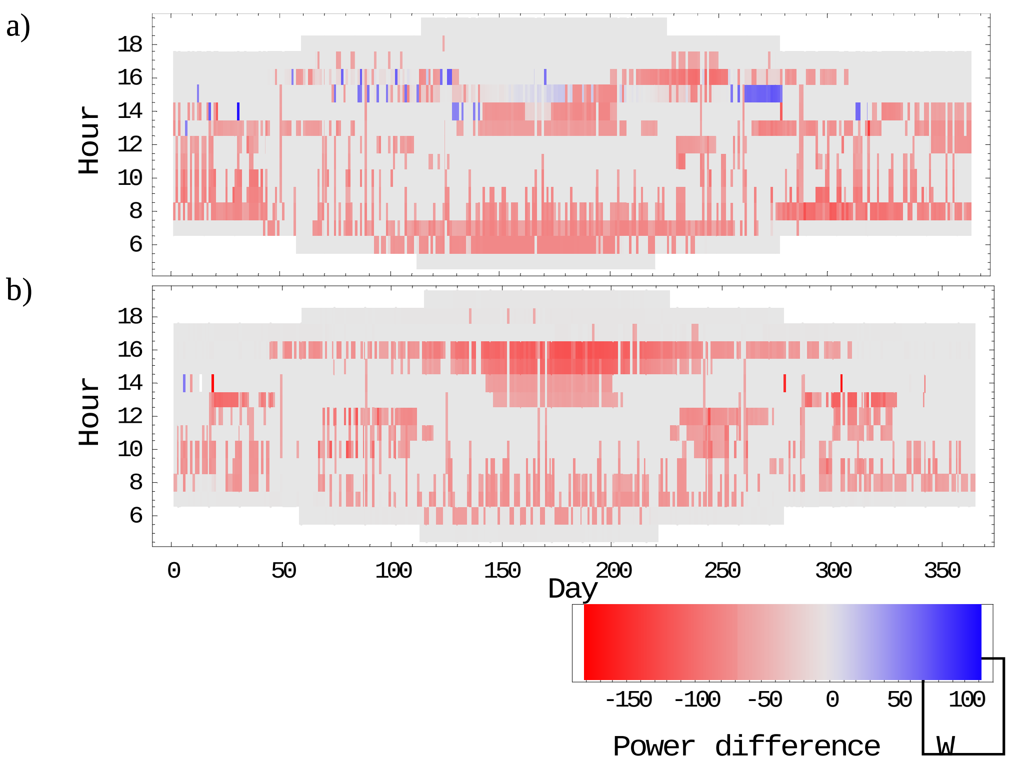


Figure 21. Year-round difference in lighting energy usage between reference and electrochromic window: a) without overhang, b) with overhang. Positive values (blue) mean reference window requires more power than the electrochromic window.

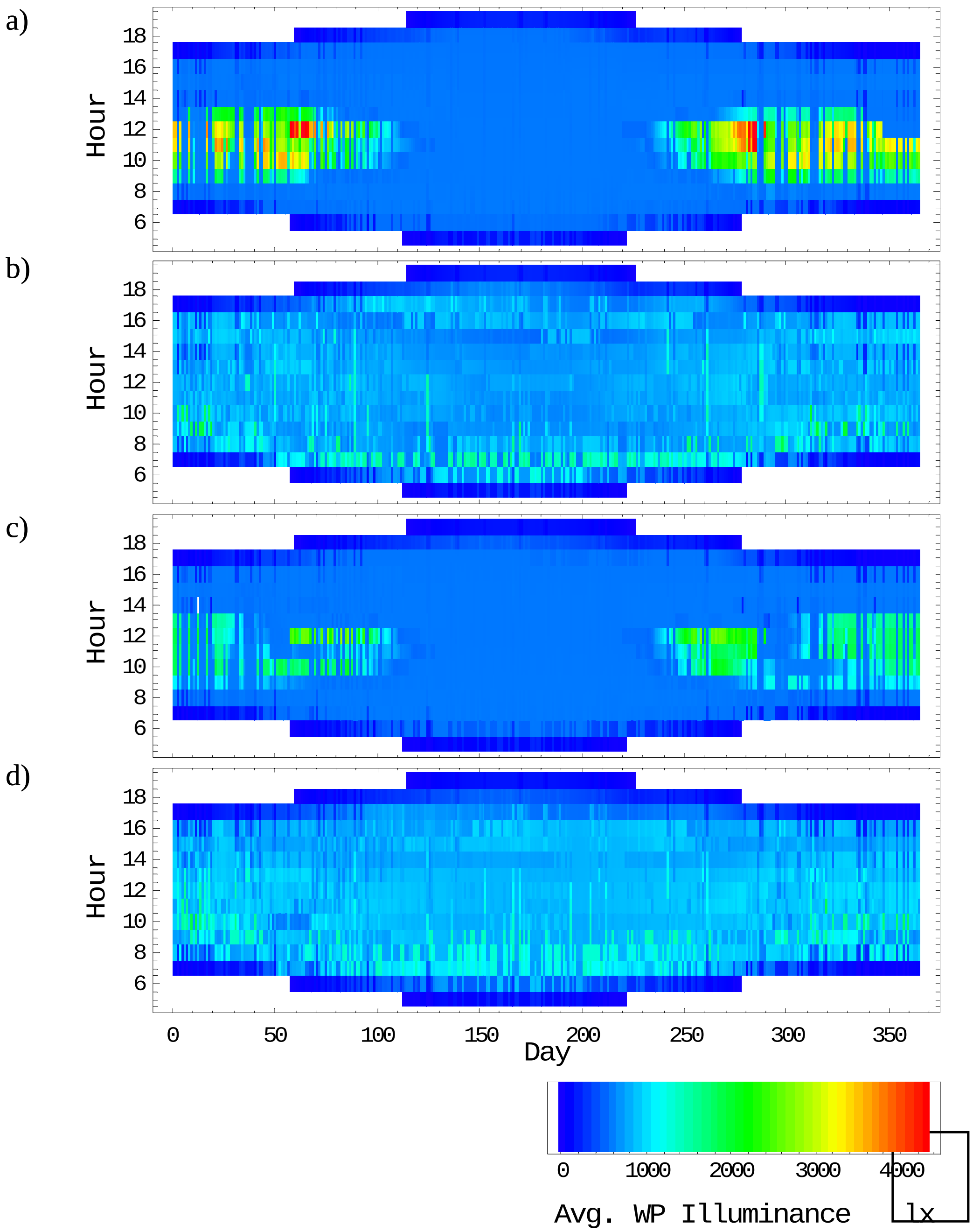


Figure 22. Average work plane illuminance: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

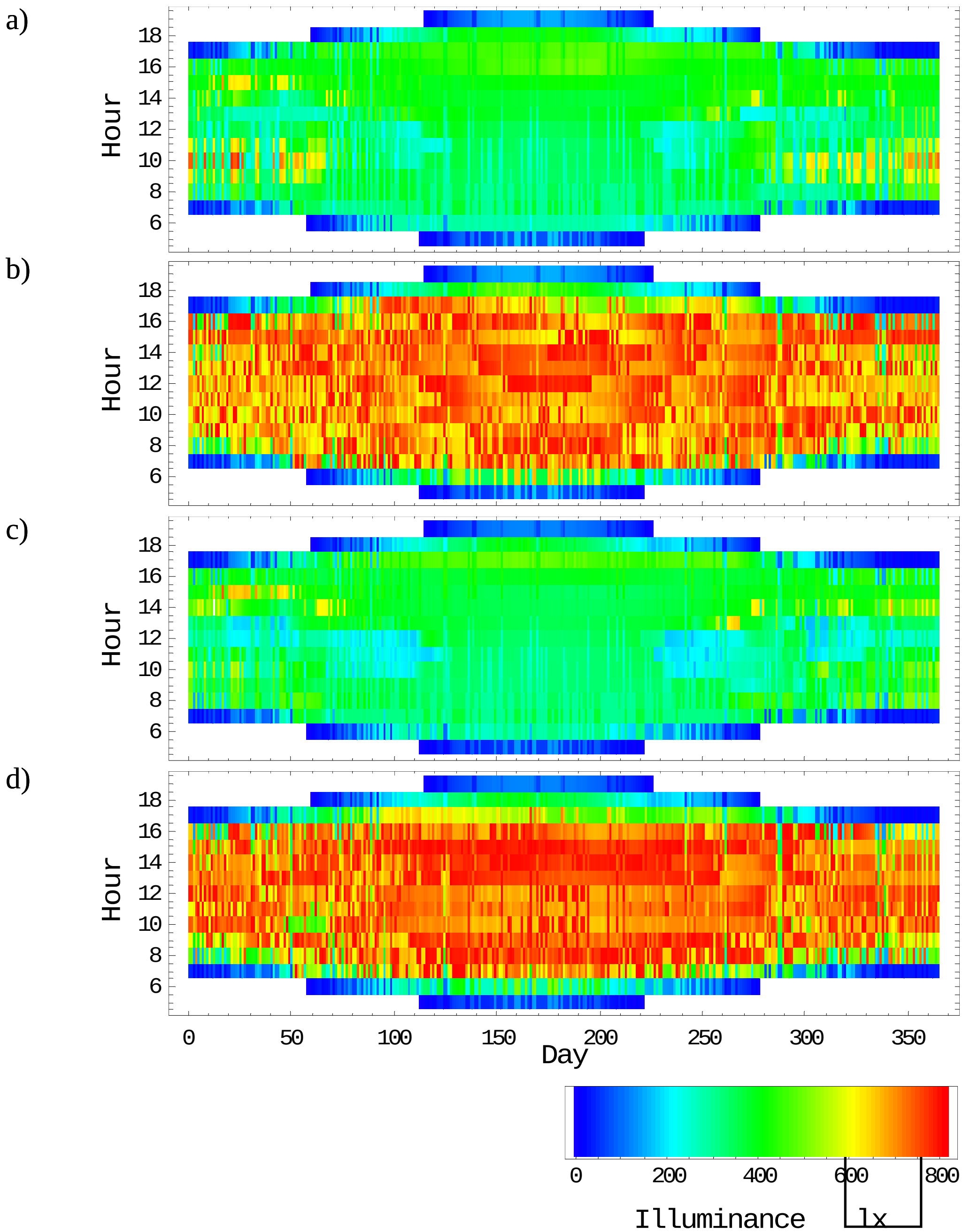


Figure 23. Vertical illuminance at the eye: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

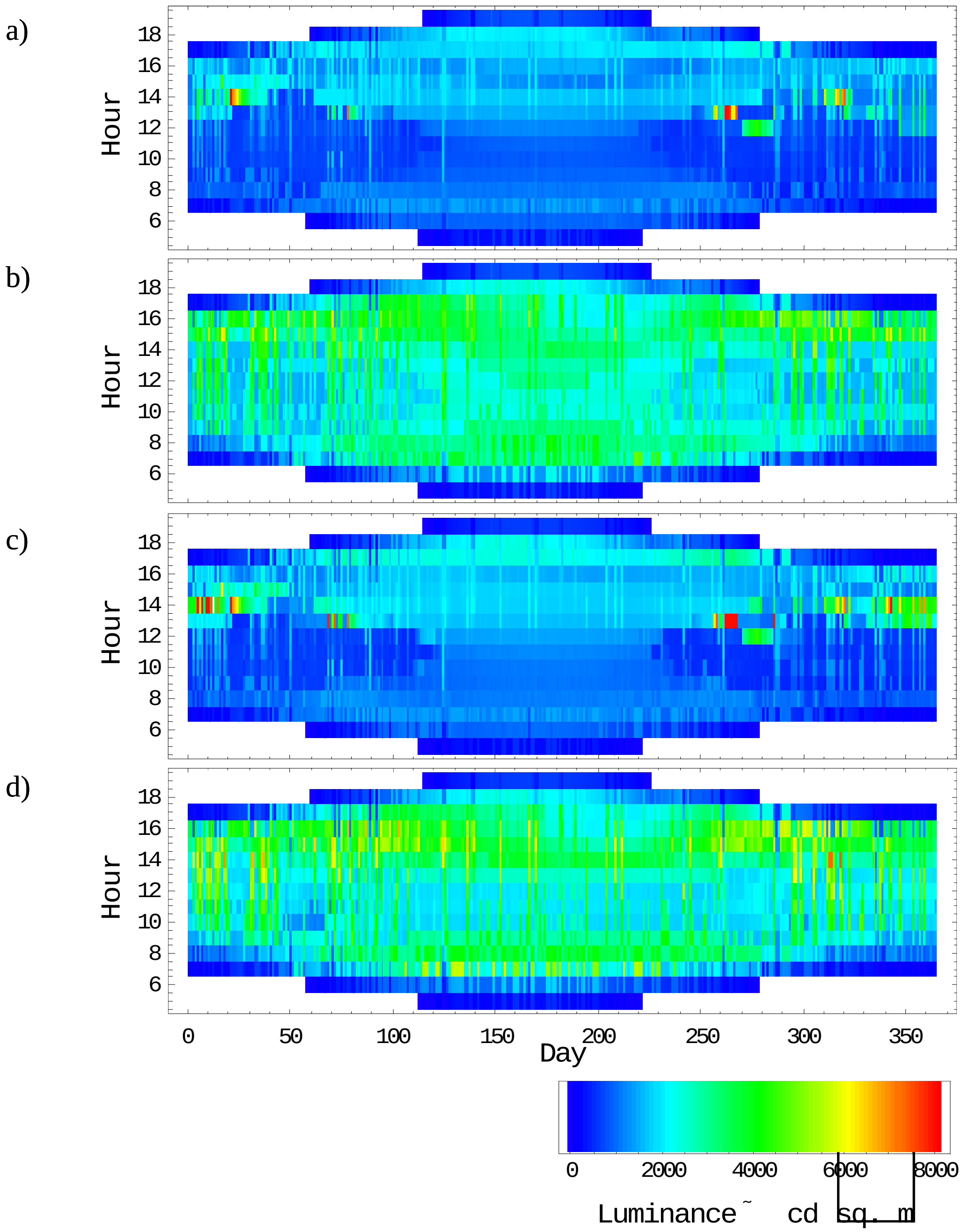


Figure 24. Maximum window luminance: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

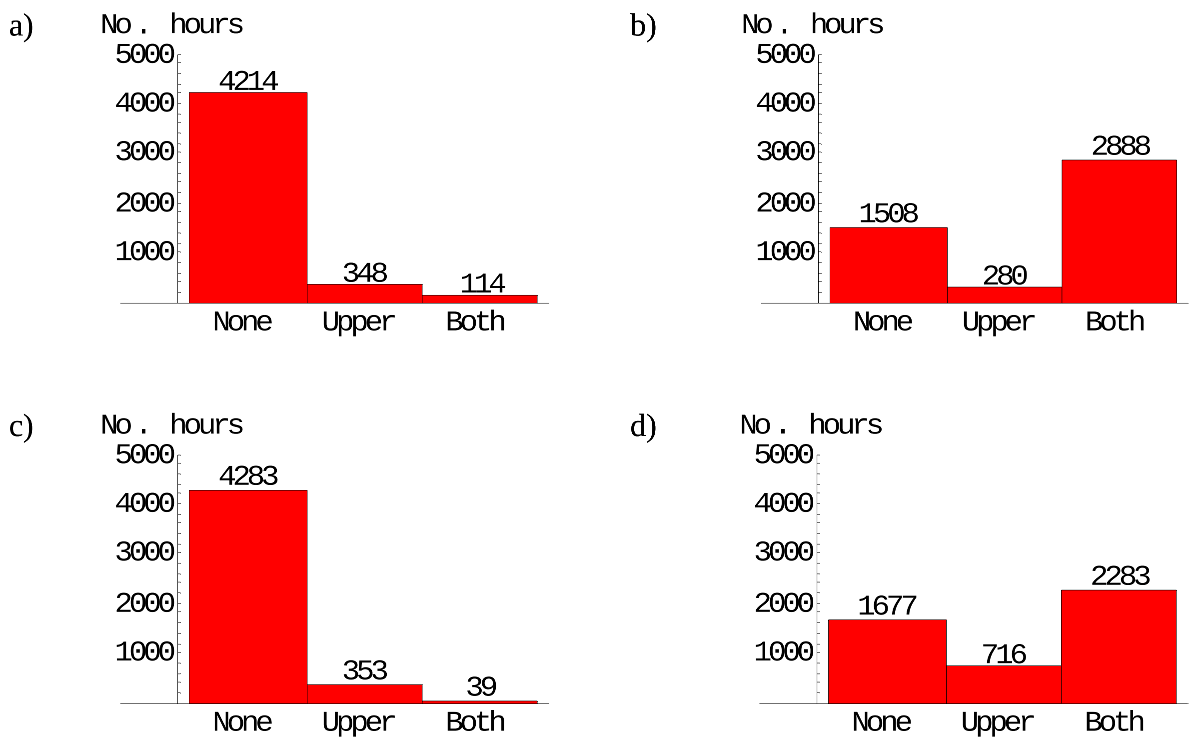


Figure 25. Histograms showing hours of blind deployment: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

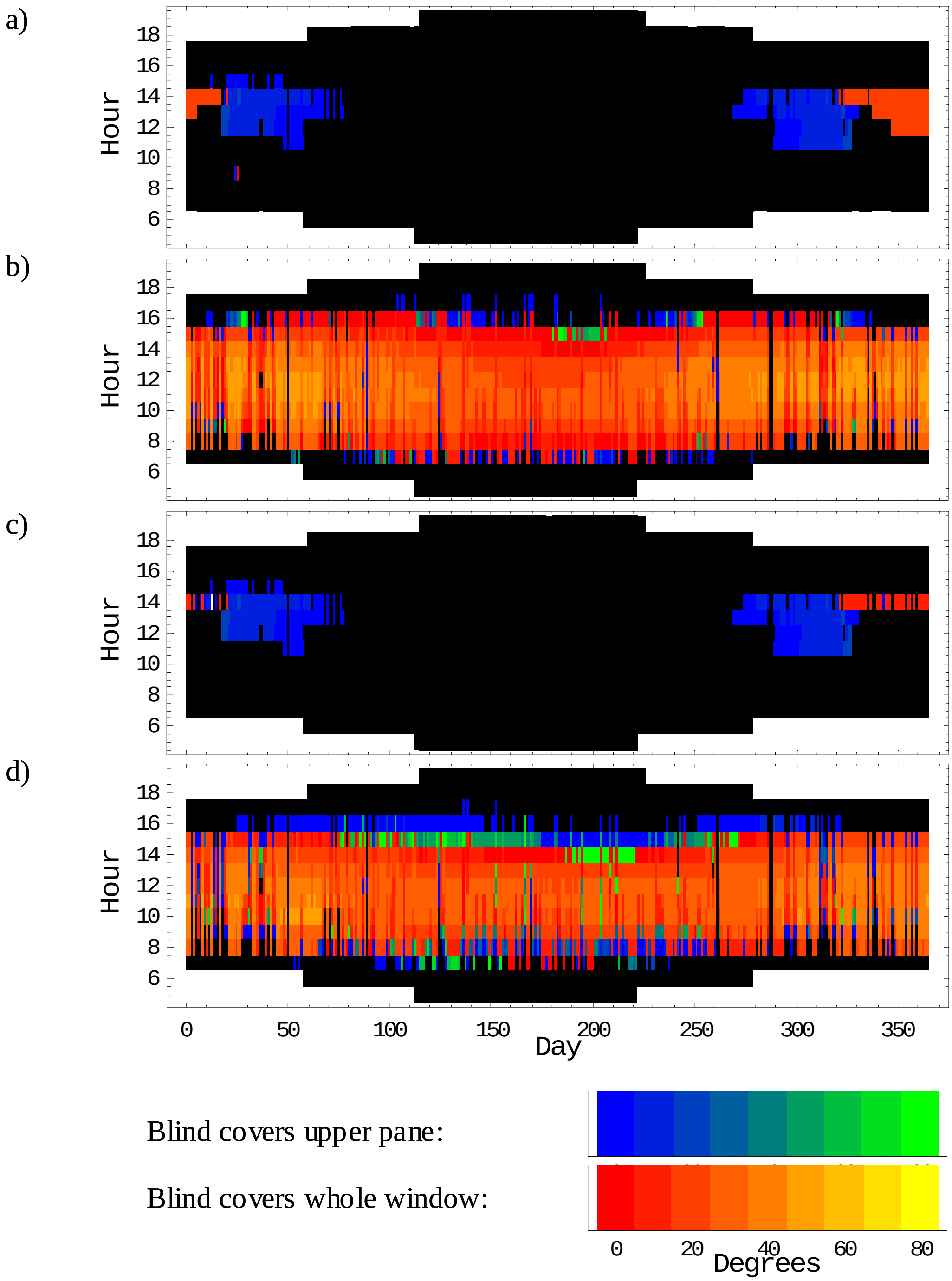


Figure 26. Blind deployment throughout year: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

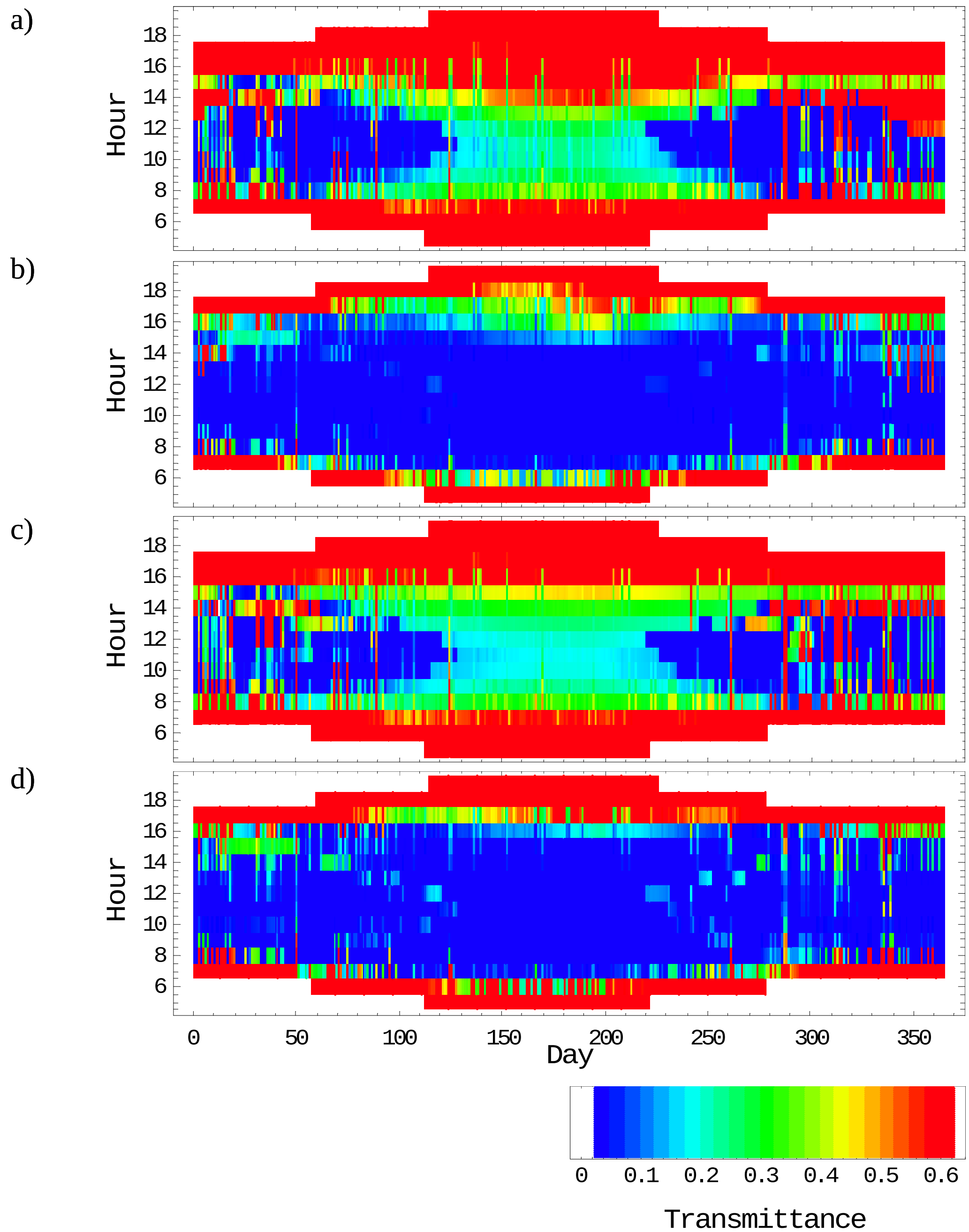


Figure 27. Electrochromic pane transmittance throughout year: a) upper pane, no overhang; b) lower pane, no overhang; c) upper pane, overhang; d) lower pane, overhang.

3.1. Effect of higher work plane illuminance setpoints for electrochromics

Given that the reference window was providing higher work plane illuminance than the electrochromic window, it was decided to investigate the effect of increasing the illuminance setpoint for the optimization of electrochromic pane transmittance from 600 lux to 800 lux and 1000 lux. As can be seen in Figure 28, this brought the energy performance of the electrochromics to levels very close to the reference case. This suggests that indeed the advantage of the reference window had indeed been that the electrochromic control algorithm was reducing the amount of useful daylight. Increasing the setpoint from 800 to 1000 lux did not bring significant improvements.

Again, the average work plane illuminance provided is fairly constant (Figure 29), although at the expected higher levels, given the higher setpoints. As before, this happens throughout the year except for morning and afternoon in winter and fall.

As the illuminance setpoint increases, vertical illuminance at the eye increases in the afternoons (Figure 30), not very significantly for 800 lux but frequently with values close to the maximum for 1000 lx.

Maximum window luminance also increases with setpoint (Figure 31), but instances of window luminance higher than 2000 cd/m^2 are still roughly half as frequent for electrochromics with a 1000 lx setpoint in comparison with the reference window.

The changes in blind deployment with increasing setpoint are negligible, occurring for less than a handful of hours for the whole year.

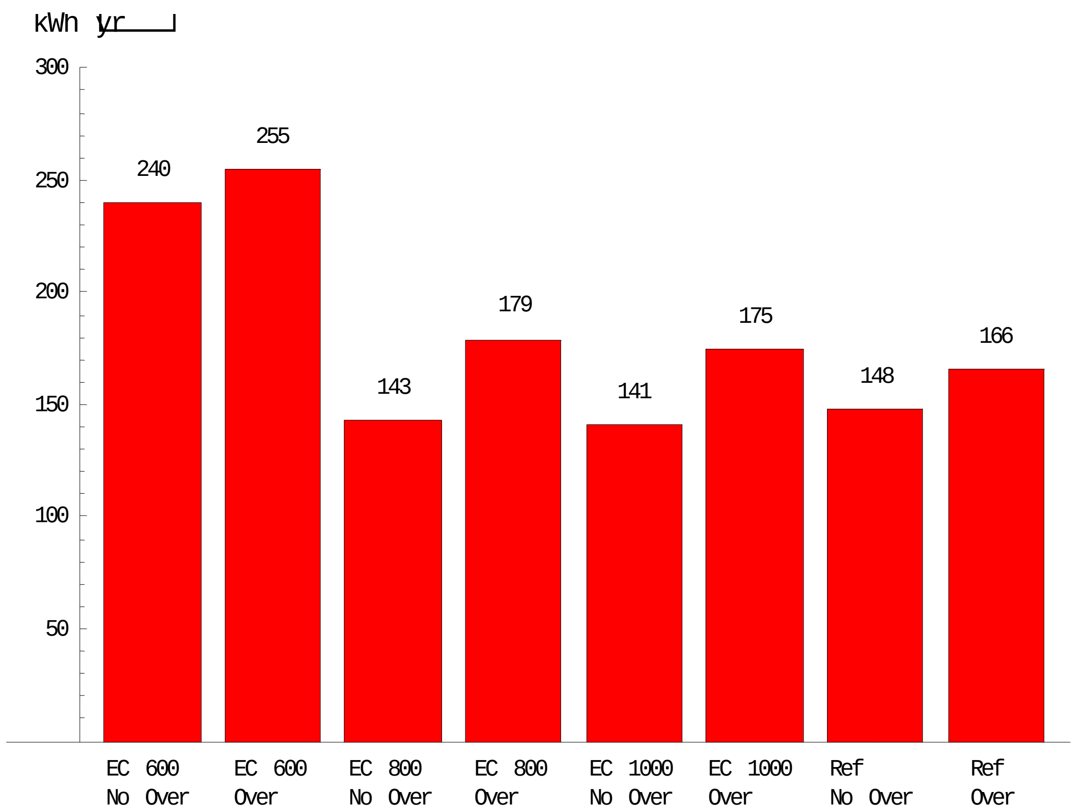


Figure 28. Annual energy use for electrochromic windows, with and without overhang, for work plane illuminance targets of 600, 800 and 1000 lux.

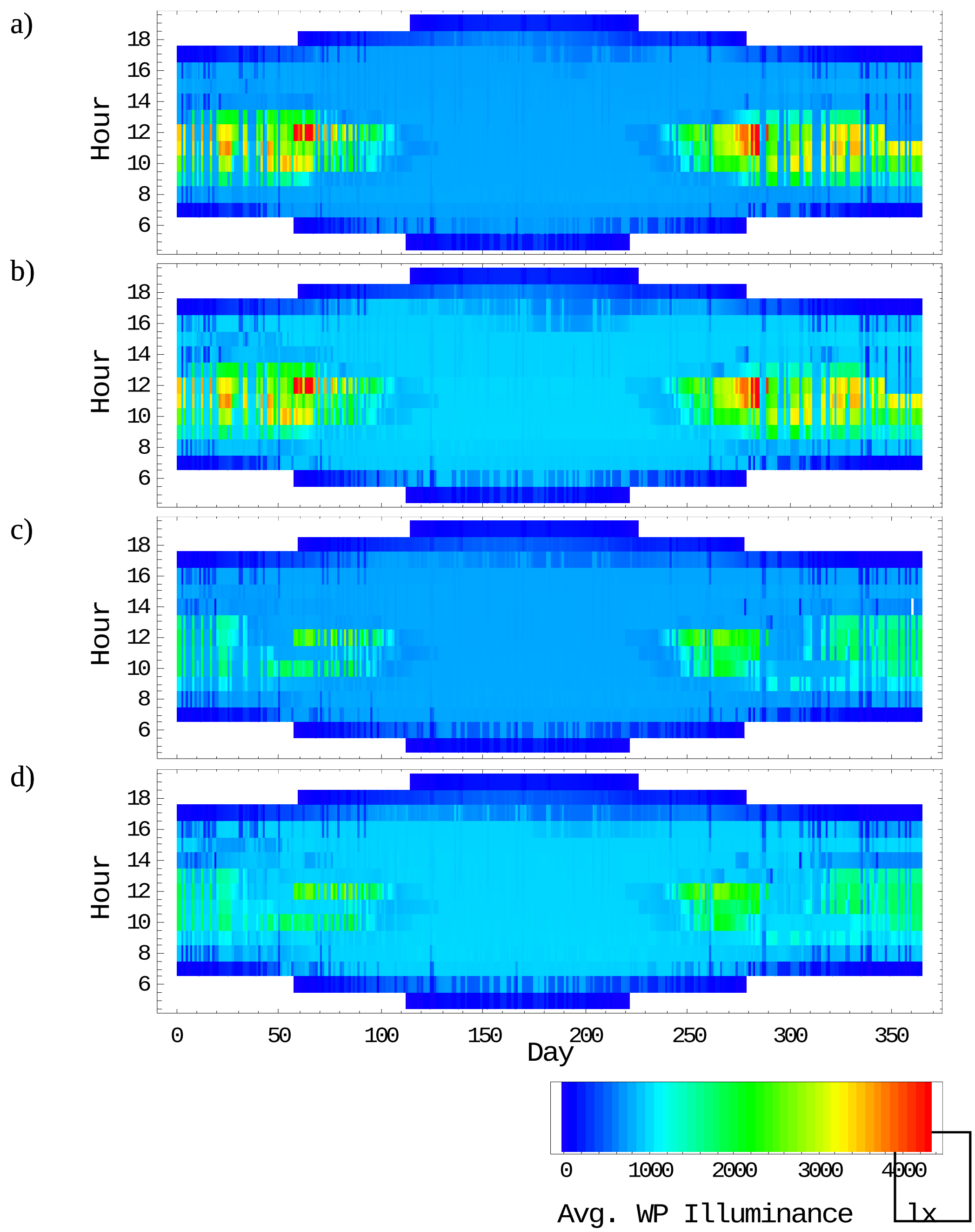


Figure 29. Average work plane illuminance with electrochromic windows: a) without overhang, 800 lux setpoint; b) without overhang, 1000 lux setpoint; c) with overhang, 800 lux setpoint; d) with overhang, 1000 lux setpoint.

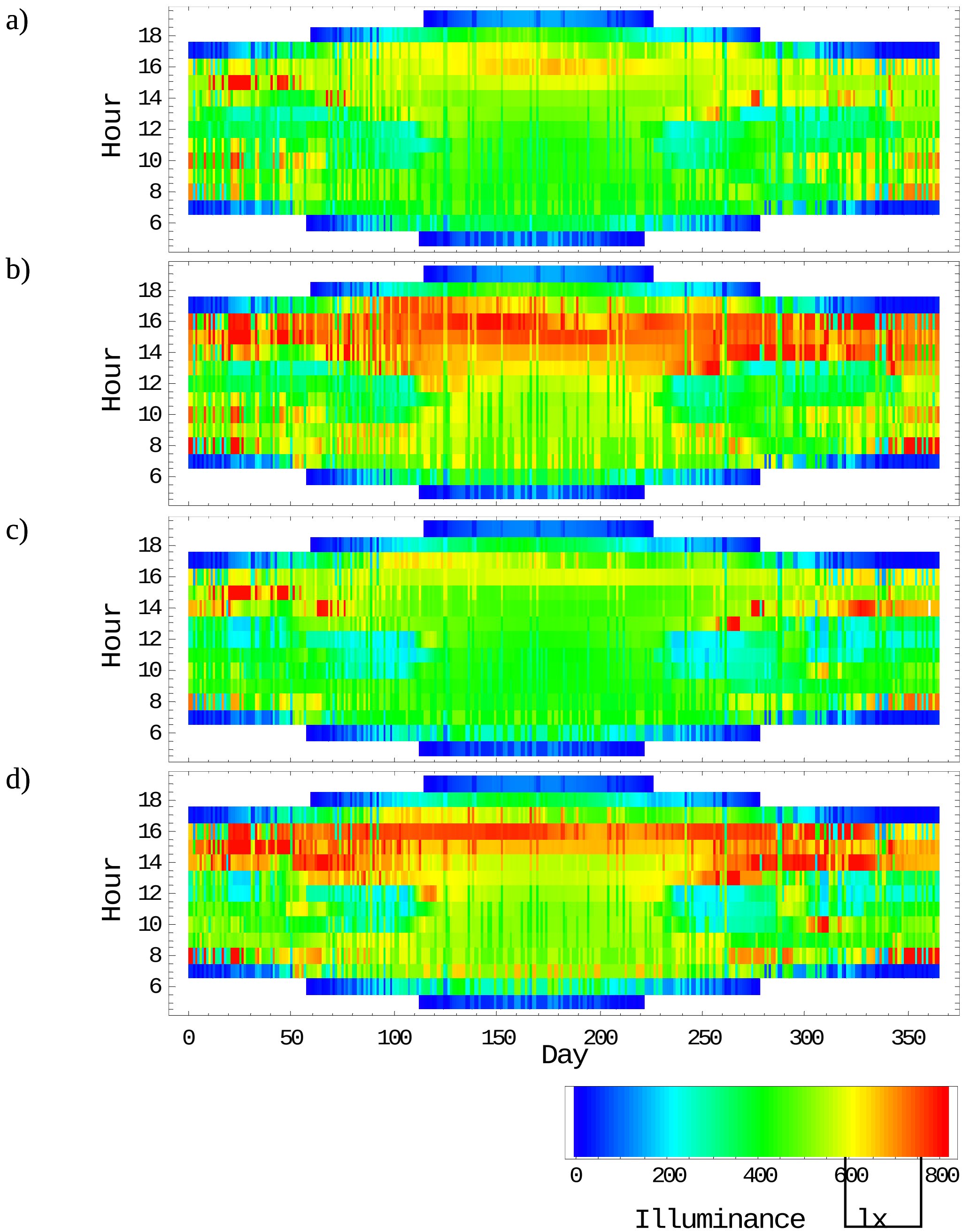


Figure 30. Vertical illuminance at the eye with electrochromic windows: a) without overhang, 800 lux setpoint; b) without overhang, 1000 lux setpoint; c) with overhang, 800 lux setpoint; d) with overhang, 1000 lux setpoint.

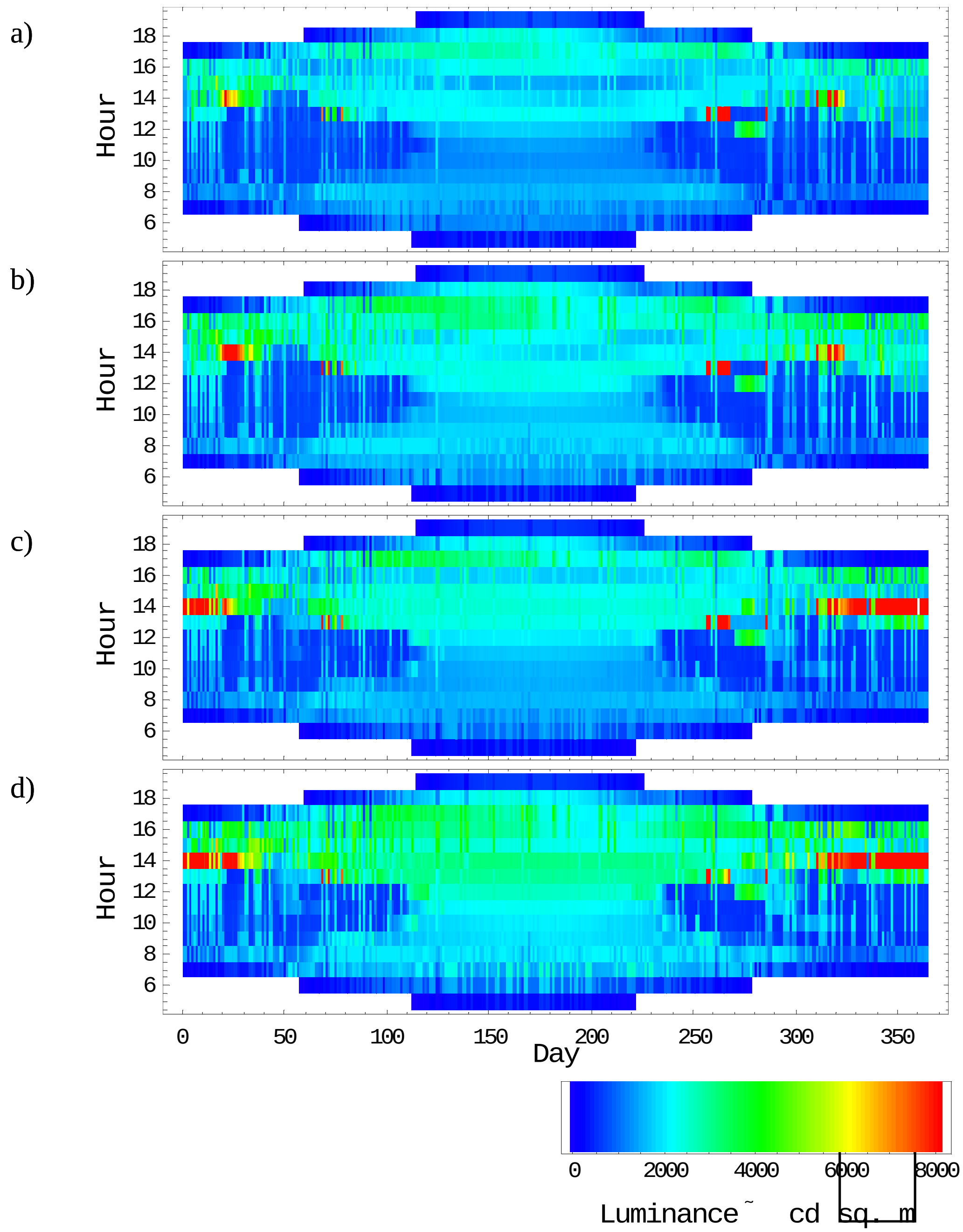


Figure 31. Maximum window luminance for electrochromic windows: a) without overhang, 800 lux setpoint; b) without overhang, 1000 lux setpoint; c) with overhang, 800 lux setpoint; d) with overhang, 1000 lux setpoint.

3.2. Daily blind control

Because blinds were adjusted hourly, the results above probably do not present an accurate picture of what would happen with a person in an actual office. Studies have suggested that office occupants, once they lower the blinds, tend to leave them lowered for the rest of the day, or even for days or weeks [Rubins et. al 1978].

A more realistic blind adjustment algorithm was then tested. For each day of the year, and for the whole day, blinds were set to the most deployed blind position that had been observed for the same day with the hourly blind adjustment mode. This resulted in the blind deployment shown in Figure 32 for an electrochromic control setpoint of

600 lux. The reference window now has the blinds down for almost the entire year, whereas the electrochromic window only for approximately half a year, and mostly only over the upper window pane. With this blind control algorithm, energy use was significantly lower with the electrochromic window (Figure 33). In Figure 34 it can be seen that the electrochromics provide comparative energy savings mainly during the early morning and late afternoon, especially during the summer months.

Average work plane illuminance was, for the electrochromic window, also constant, with reduced occurrence of high values (Figure 35). For the reference window the values were lower than previously, and clearly insufficient in the early morning and late afternoon, which probably explains the power consumption pattern seen in Figure 34.

For the electrochromic window, vertical illuminance at the eye had very similar values throughout the year as before (Figure 36). With the reference window the values were generally lower than before but still close to the 800 lux threshold during the middle of the day.

Maximum window luminance was, for the electrochromic window, very similar to that obtained with hourly blind control (Figure 37). The reference window had significantly lower values, which is consistent with the blind usage pattern.

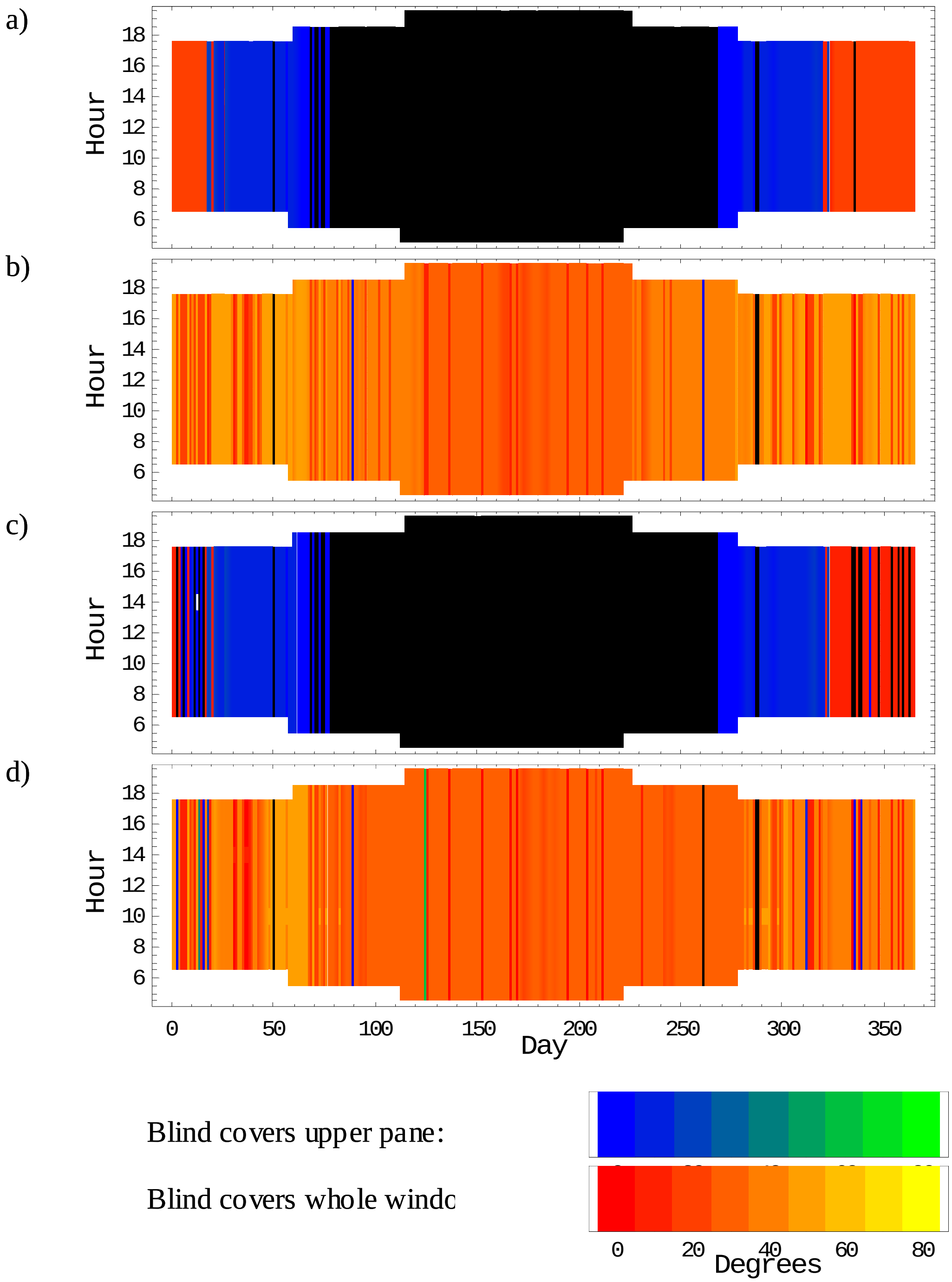


Figure 32. Blind deployment throughout year with daily blind control algorithm and electrochromic setpoint of 600 lux: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

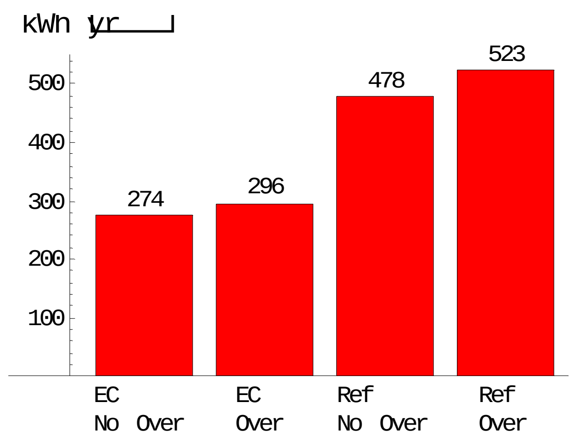


Figure 33. Annual energy use with daily blind control algorithm for electrochromic (EC) and reference (Ref) windows, with and without overhang.

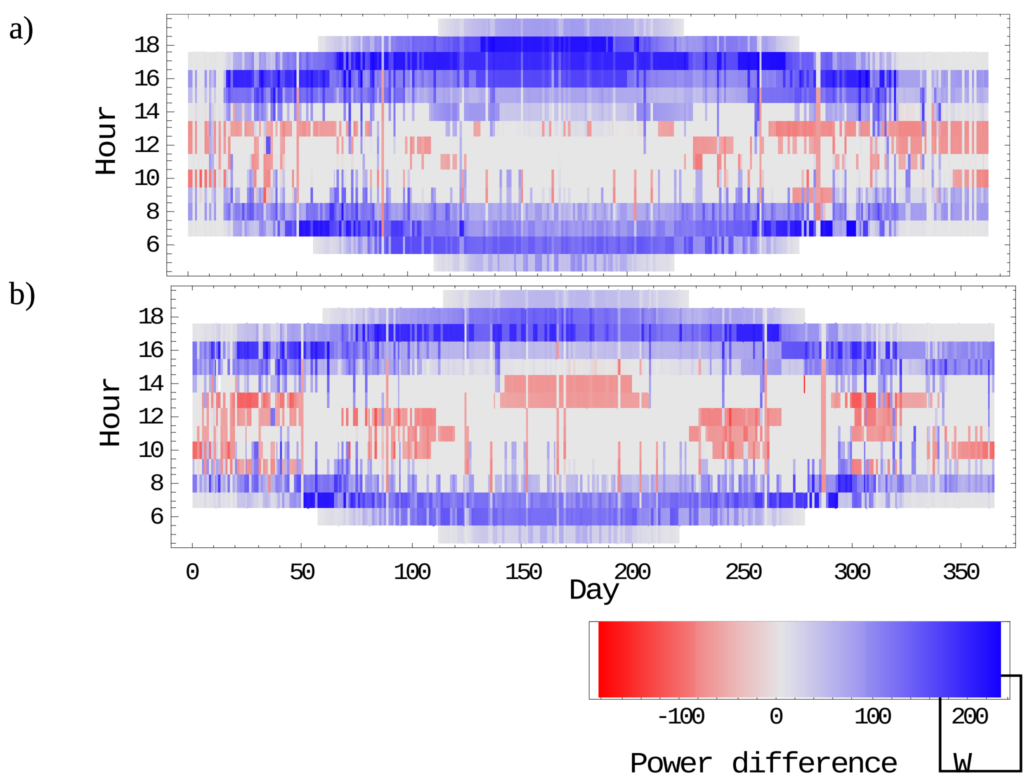


Figure 34. Year-round difference in lighting power usage between reference and electrochromic window, using the daily blind control algorithm: a) without overhang, b) with overhang. Positive values (blue) mean reference window requires more power than the electrochromic window.

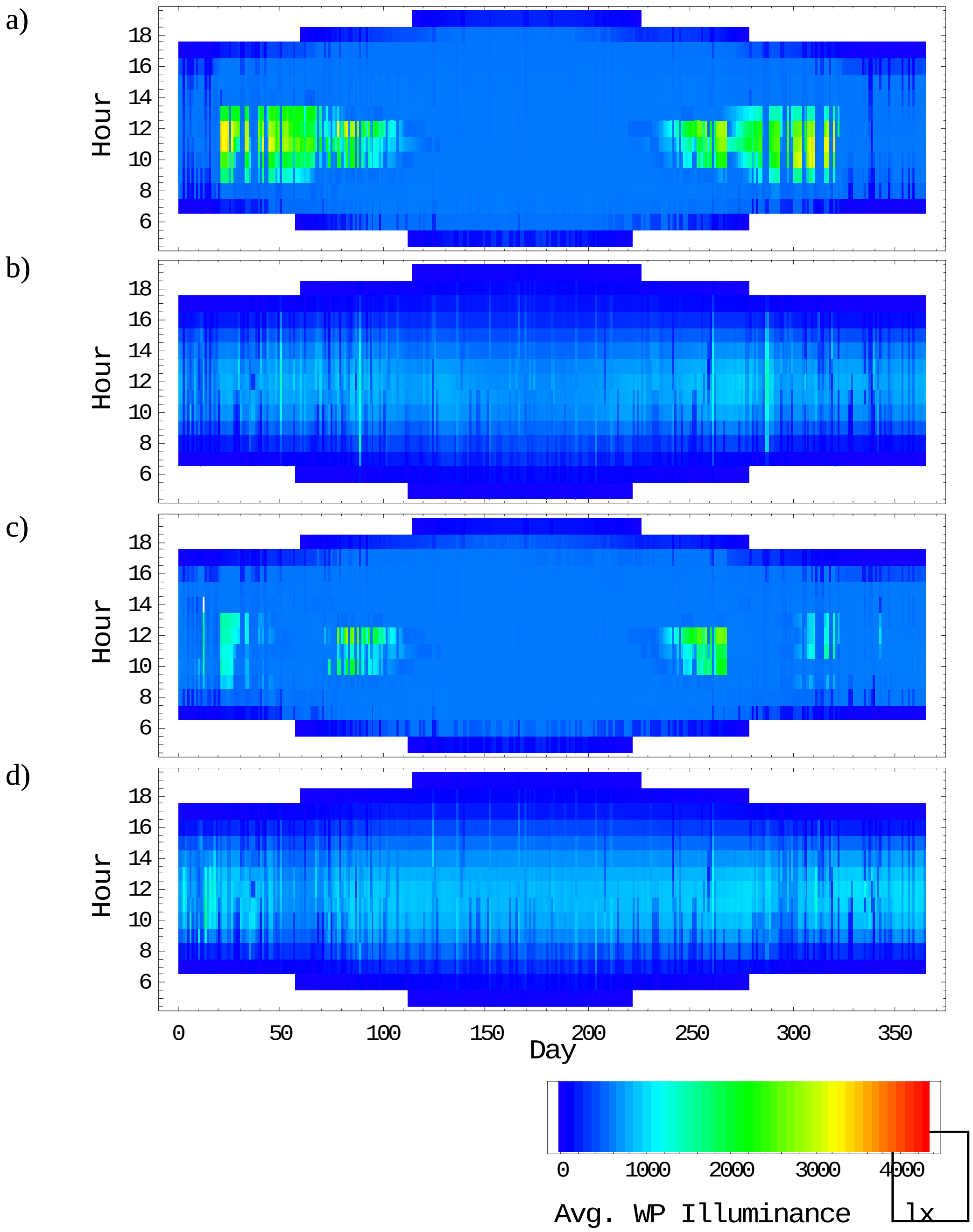


Figure 35. Average work plane illuminance with daily blind control algorithm: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

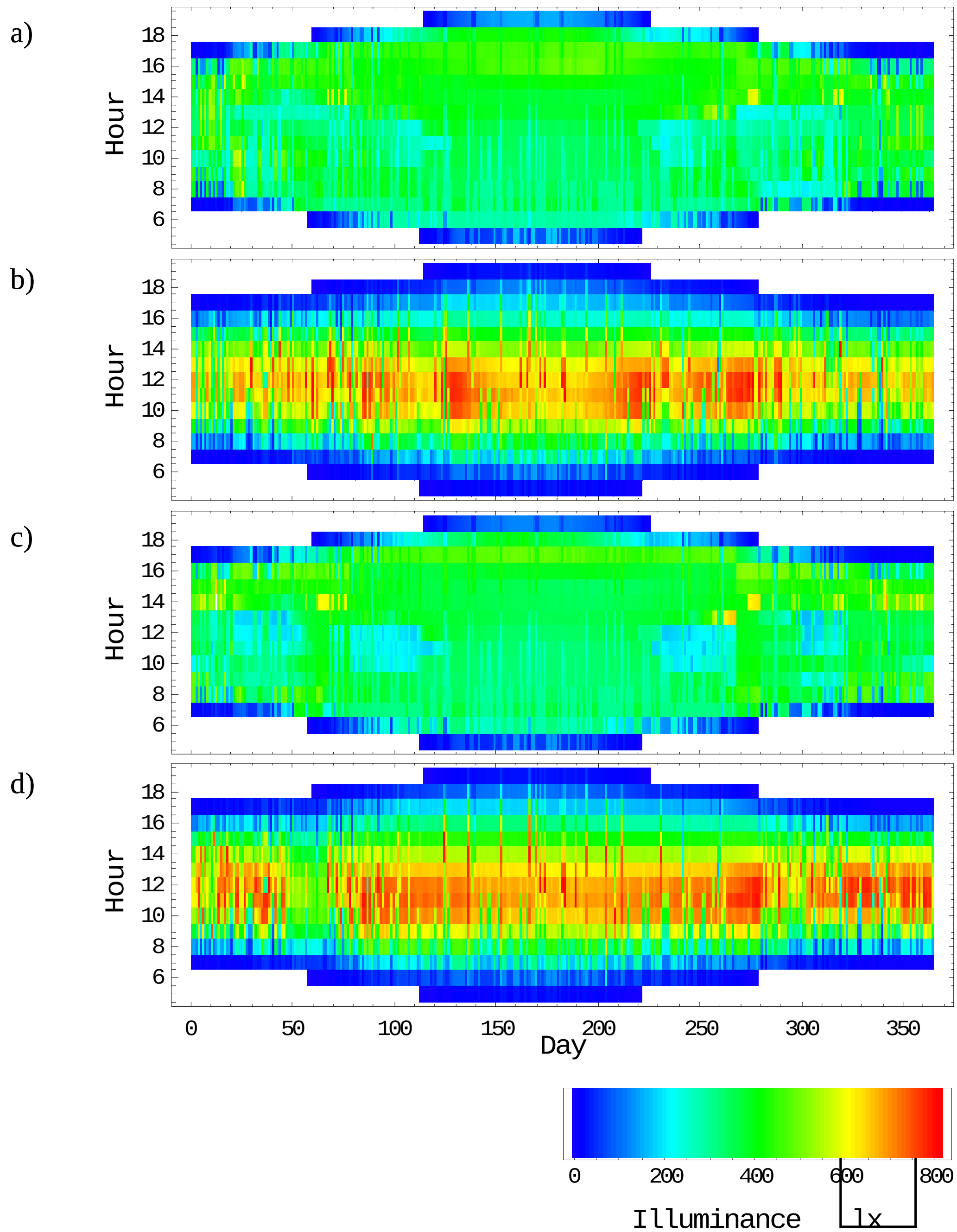


Figure 36. Vertical illuminance at the eye with daily blind control algorithm: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

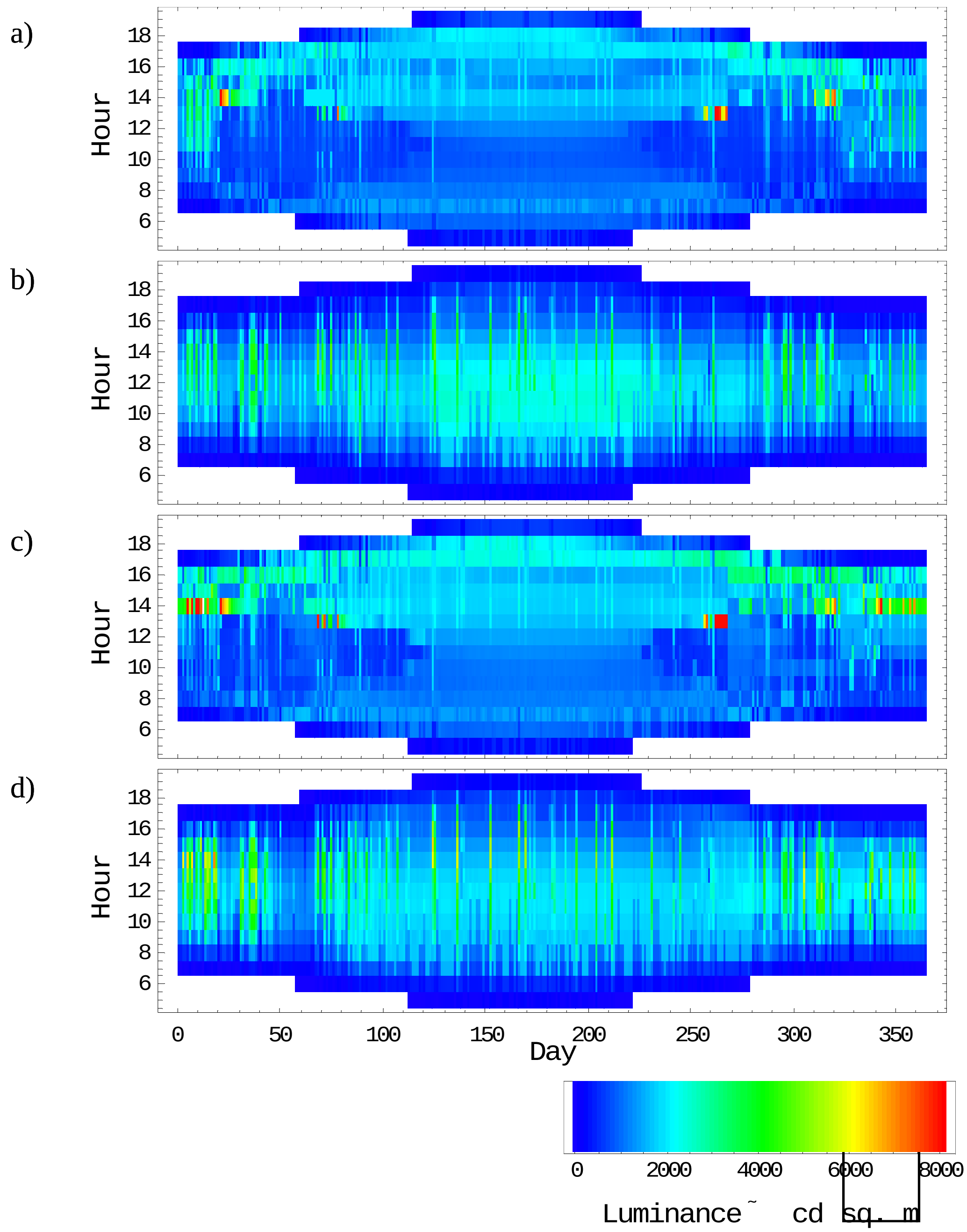


Figure 37. Maximum window luminance with daily blind control algorithm: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang.

4. Discussion

The results obtained indicate that if the Venetian blinds are continuously controlled to provide visual comfort, ordinary glass has a significant advantage over electrochromics in energy consumption – ordinary glass requires about a third less energy. The magnitude of that advantage can be almost eliminated, however by increasing the illuminance target for electrochromics control, although at the expense of visual comfort. This seems consistent with the fact that electrochromics control light by absorbing it, therefore preventing it from contributing to interior illumination, whereas Venetian blinds do so by redirecting light, some of which enters the space towards the ceiling and raises the light level without contributing to glare, thus comparatively reducing the need for electric light. This also can be taken to indicate that ordinary glass will not perform better than electrochromics if the interior shading is not light-redirecting, such as with fabric shades.

In practice, however, it is not reasonable to expect that building occupants will operate the Venetian blinds so frequently and with such regard for the balance between work plane illuminance and glare. Attempting to achieve this degree of control by automating the blind is also presented with significant technical challenges.

Results with a more realistic blind control, in which the blind position is adjusted daily instead of hourly, suggest that electrochromics can have a significant advantage over ordinary glass in terms of lighting energy consumption, requiring about 43% less energy.

Regardless of how the window is controlled, it is significant that electrochromics do not, for most of the time, require the obstruction of the view to the exterior by a shading device. With hourly adjustment, the electrochromics require very minimal deployment of blinds, whereas ordinary glass demands everyday use, and for most of the day. With daily adjustment, ordinary glass requires blinds all the way down throughout the whole year, with the exception of a handful of days, whereas electrochromics only from roughly mid-November to mid-January.

In all cases studied, adding an overhang to the façade increased lighting energy consumption. Depending on glass type and control algorithm that increase varied between 6% (original case) and 25% (same but with electrochromics controlled for 800 lx). This happens because less daylight enters the room. However, the presence of the overhang somewhat reduces the need to deploy blinds, this effect being quite significant in the case of electrochromics with daily blind control.

Some limitations should be had in mind when considering the results from this study. Energy consumption values were calculated for all daylight hours of the year. These values would be different if calculated for, say, 9:00-17:00, although it is anticipated that most of the general trends mentioned above would still be observed. The same could be said for operational schedules that include hours of darkness, which would probably reduce the relative differences in consumption between the cases studied.

Energy consumption values are also sensitive to the power/light output function of the electric lighting system, for example by considering standby power, instead of assuming zero power when the lights were off, as was done here. However, this would probably only cause a reduction in relative differences between cases.

Empirically derived models such as described in [Reinhart 2004] could be used for blind adjustment that would be more realistic than either of the models used here. In terms of realism, however, the daily blind adjustment used here is probably already a very significant improvement over hourly blind adjustment.

Since each additional viewing position requires weeks of computation, in this study only one position for the eyes of the occupant was considered. In reality, people move around and look around, and no two people sit in exactly the same position. In addition, sensitivity to glare also varies from individual to individual. The present study can still, however, give a very useful picture of how window systems compare to each other in terms of daylighting and visual comfort.

It was already mentioned in previous sections that the pixel reduction technique used in constraining luminance ratios may underestimate some glare sources and that some precision was traded for speed in the calculation of the daylight coefficients.

5. Conclusion

A Radiance-Mathematica simulation was conducted on a south-facing private office in Berkeley/Oakland, California. A zoned EC window was controlled to meet visual comfort requirements and to optimize daylight illuminance. Lighting energy use savings were computed using photosensor signal levels computed by Radiance to dim the recessed fluorescent lights in response to available daylight.

If the reference window (Tv=0.60) has an hourly-deployed (height and slat angle) Venetian blind, then annual lighting energy use is increased by 62% if an EC window is used. However, the reference window provided work plane illuminance levels well over the stipulated 600 lux. If the EC daylight illuminance control setpoint is raised from 600 lux to 800 lux, then annual lighting energy use savings was decreased by 3%.

Prior field studies indicate that manually-operated interior shades are rarely operated in this optimal manner. If the reference case blind is controlled one time per day at the first instance of visual discomfort, then annual lighting energy use is decreased by 42% if the EC window is used. With a 800 lux setpoint, annual lighting energy use is decreased by 67%.

This study indicates that, for a south-facing office in Oakland, electrochromics can provide lighting energy savings over the whole year, relative to ordinary clear glass. This, however, requires the window to be divided into independently-controlled daylight and view areas, and electrochromic transmittance to be continuously optimized. Further research is needed to determine whether the particular control method used here can be implemented in a physical room, since it depends on quantities that are challenging to measure, such as the separate contributions from the upper and lower panes.

Acknowledgments

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