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Electrochromic Window Demonstration at the John E. Moss Federal Building, 650 Capitol Mall, Sacramento, California

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GPG
Green Proving Ground Program

The Green Proving Ground program leverages GSA's real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other federal agencies, and the real estate industry. The program aims to drive innovation in environmental performance in federal buildings and help lead market transformation through deployment of new technologies.

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I. Executive Summary

A. INTRODUCTION

Dynamic windows have the potential to provide real-time optimization of perimeter zone energy use, peak demand, comfort, amenity, and cost criteria on a seasonal or even minute-to-minute basis in response to weather, occupant or regional grid demands. Electrochromic (EC) windows, a type of dynamic window, have the ability to adjust their tint dynamically in response to a small applied voltage. In previous studies, they have shown potential to reduce heating, ventilation and air conditioning (HVAC) energy consumption and increase occupant satisfaction. This technology is available in the U.S. as a commercial product from multiple vendors with high-capacity manufacturing facilities, and could be deployed broadly if successful in a pilot test.

B. STUDY DESIGN AND OBJECTIVES

FIELD STUDY

This Green Proving Ground (GPG) program study examines the energy and comfort performance of EC windows in south-facing perimeter zones of a typical U.S. General Services Administration GSA office building. The John E. Moss Federal Building is a large office building located in Sacramento, California. Built in 1961, it is nine stories high and has a gross floor area of 361,129 square feet (ft^2). The study took place in the areas adjacent to the South façade of the sixth floor from December 2015 to June 2016. The EC windows used in this study could tint to one of four visible transmittance levels (Table ES-1).

Table ES-1. Properties of the EC windows used in this study at their four tint levels.

Tint name	Visible transmittance (%)	Solar transmittance (%)	Solar Heat Gain Coefficient	U-factor
Clear	60	33	0.41	0.28
Light tint	18	7	0.15	0.28
Medium tint	6	2	0.1	0.28
Full tint	1	0.4	0.09	0.28

The technical objectives of the study are to determine from measurements of the indoor and outdoor environment, as well as an occupant survey, if the installation of the EC windows results in the following:

- Reduction in HVAC energy consumption
- Reduction in lighting energy consumption
- Reduction or no change in occupant perception of daylight glare

- Reduction of operable shading deployment

Strong evidence for all of these would indicate the suitability of EC windows for further deployment in other office buildings throughout the GSA building inventory.

This report details Phase II of this study. It was not possible to complete Phase I successfully due to technical issues encountered with the particular batch of EC windows used. The window manufacturer determined that a glitch during the production process caused tinting problems. They provided replacement windows which were used for Phase II of the evaluation.

LABORATORY TESTS

As a complement to the field study, and to evaluate aspects of EC window performance that are challenging to study in the field, such as HVAC loads and visual comfort, a parallel evaluation was undertaken at the Advanced Windows Testbed of the Lawrence Berkeley National Laboratory (LBNL).

C. RESULTS/FINDINGS

SUMMARY

Study findings are summarized in Table ES-2.

Table ES-2. Summary findings.

Objectives	Metrics	Data requirements	Success Criteria	M&V Results
Reduction in HVAC energy consumption	Ratio between HVAC energy use with and without EC windows	Metered data for perimeter zones (not available; used data from laboratory tests at LBNL's Advanced Windows Testbed)	Reduction in HVAC energy use	Daily HVAC load reduced by 29%–65% (0.43–3.48 Wh/ft^2); peak HVAC load reduced by 25%–58% (1.15–5.63 W/ft^2).
Reduction in lighting energy consumption	Ratio between lighting energy use with and without EC windows	Metered data (not available separately for the perimeter spaces; operational data from the lighting control system used instead)	Reduction in lighting energy use	62% increase in lighting energy use (probably due to issues specific to this demonstration and not attributable to EC technology as a whole)
Reduction or no change in occupant perception of glare	Occupants' self-reported change in glare between original conditions and conditions with EC windows	Responses from occupant surveys	No change or reduction in self-reported glare	No statistically significant change in self-reported glare levels (results indicate a possible decrease but number of responses was insufficient for establishing statistical significance)
Reduction of operable shading deployment	Ratio between number of lowered blinds with and without EC windows	Data from periodic surveys of the position of the blinds	Reduction in operable shading use	Slight reduction in blind use over the course of the study (90% of blinds lowered at the beginning of study; 79% of blinds lowered at the end)

INSTALLATION AND COMMISSIONING

The installation and commissioning of EC windows has additional complexities when compared to conventional windows: maintaining the physical integrity of the windows' EC properties throughout shipping and handling, controls hardware (wiring from the control system, to the windows and wall switches, sensors mounted on the façade or roof), configuring the control system, and managing the occupants' initial interaction with the windows. During this project, 11 windows did not function when they were installed, possibly due to mishandling during shipping. Replacements were provided by the manufacturer and successfully installed. In future installations, care should be taken to anticipate this type of issue and identify which of the participants (manufacturer, shipping company or installer) bears responsibility for addressing the malfunction.

a Control hardware

1. Wiring

In most retrofit situations, façades will not have been designed explicitly to allow room for running wiring to the windows. This can pose unexpected issues. For example, in this project it was found at installation time that the façade system would not allow the wires to be routed the way it was initially anticipated. This required a custom solution to be devised and implemented. Planning for these issues beforehand will save time and effort during the installation phase.

There is more than one type of cable used to connect EC windows to the control unit and, to minimize delays and effort, care must be taken to ensure that the correct wiring is provided, preferably before any wiring is installed.

2. Wall switches

EC windows can be manually controlled using wall switches or a smartphone app. The wall switches (using the smartphone app was not an option for this project) require additional labor and hardware that needs to be taken into account in the planning stages of the installation. In this project, the assignment of windows to switches was straightforward because most spaces were private offices and the open-plan workstations lined up well with the windows, but this might not necessarily be the case in other buildings.

3. Exterior sensors

The EC window control system relies on sensors mounted on the building exterior (façade or roof). It is important to be aware, during the planning stages, of possible issues in finding suitable locations for these sensors, and also that they will need to be connected with the control system via wire. Sensors need to be facing in the same direction as that of the façade that they are controlling and, ideally, facing a similar view (e.g., surrounding buildings, trees or other obstructions should affect the sensor in similar ways as they affect the façade being controlled).

b Control system configuration

When in automatic operation (i.e., not controlled manually via wall switch) the tint of the windows is determined by a central unit. Although there is, depending on location and façade orientation, one (or perhaps a few) standard operating modes that the manufacturer might default to based on its prior experience, there is actually a high degree of flexibility in how the control system is able to control windows and, although it is possible to perform adjustments after installation, it is important to specify early on what the expectations are for operation, both from the facility management and the occupant standpoints. Parameters to have in mind include:

- Depth of maximum solar penetration allowable before windows go to full tint (glare mode)
- Maximum allowable tint when in glare mode, if other than full tint
- When not in glare mode, how much windows should tint in response to exterior light levels
- Weekday vs. weekend/holiday operation
- For installations, such as the one shown in this project, with windows split into subpanes: the specifics of how subpanes will be controlled independently of each other when in automatic or manual operation.

c Managing occupant transition to EC windows

In replacing conventional windows with EC windows, particular attention needs to be paid to supporting occupants throughout the transition. This may involve:

- Providing information about how the windows operate (where applicable), how to use the wall switches to control them, and what they may and may not expect from the windows in terms of behavior and/or performance.
- Informing occupants of the ability to make modifications to the automated controls according to their needs or preferences. It is important for this to be available on a continuous basis, particularly in the first year of operation.
- Proactively seeking out occupants who may require special accommodations due to vision or other health issues and working with them to ensure the automatic and manual controls are configured according to their needs.

EC OPERATION AND OCCUPANT IMPACTS

a EC operation

Throughout the study, the EC windows were observed operating as configured by the manufacturer. The original configuration of the controls resulted in the windows spending most of the day at full tint, unless they were manually overridden using the wall switches. In April 2016, after five months of operation, the manufacturer readjusted the control algorithm at the request of GSA, based on feedback from the occupants that the space was too dark. After this, the windows spent most of the day at light tint (one step darker than clear).

b Use of wall switches

Occupants used the wall switches throughout the whole period from November 2015 to June 2016, with wide variations from week to week and from zone to zone. Throughout the study, on any given week, the wall switches were used to override automatic EC window control in between 18% and 64% of the window zones (windows were grouped into zones and each zone had one assigned wall switch). The use of the wall switches was higher in a relatively small number of zones, although the data does not allow a straightforward classification of zones into “high use” and “low use” categories; possible causes for this variation in wall switch usage might be natural variations in occupants’ propensity to modify their environment, or occupant response to environmental factors that were not identified during this study. Three zones accounted for 52% of the amount of time windows spent in manual override; eight zones accounted for 83% of time in manual override. The weekly average of time in manual override was, when taken throughout all zones that had occupancy, about one hour or less per day and per zone.

c Use of operable shading

Use of venetian blinds by the occupants was highly prevalent throughout the study, with at least 79% of the blinds lowered from their fully raised position and at least 67% of blinds lowered over 50% or more of the height of the window. This is a surprising finding, when considering that the EC windows spent, until April 2016, a substantial amount of time at full tint, which, at a visible transmittance of approximately 1%, is a very dark tint. This is probably due to a combination of two factors: (1) field measurements showed that EC windows were able to control glare most of the time, but not 100% of the time, so it is possible that the occupants in this building are adjusting the blinds according to worst-case conditions, and (2) occupants’ experience with the windows in Phase I of this project, during which windows were not able to tint all the way down to 1% visible transmittance, could have reduced the occupants’ expectations of the ability of EC windows to control glare.

d Occupant experience

The survey of the occupants that was performed during this study indicates that, overall, the occupants on the sixth floor prefer the EC windows to conventional windows. Responses also indicate an improvement in thermal comfort during warm/hot weather on the EC floor (sixth floor). While on average their overall aesthetic assessment of the EC windows wasn’t negative, occupants on the EC floor found their windows less aesthetically pleasing than occupants of another floor with conventional windows used for reference (eighth floor). Possible causes for this are (1) the EC windows spending a significant amount of time at full tint, (2) the fact that a light-colored line is visible between the subpanes when the EC windows are tinted or (3) the fact that subpanes were not all set to the same tint when the system was in glare mode. Occupants on the EC floor found that the outside was less visible through the window than on the reference floor. A probable cause for this result is the EC windows spending a significant time at full tint. In other aspects of the occupants’ indoor environment experience, such as visual comfort, light levels and general satisfaction, no statistically significant differences were found between pre- and post-installation conditions on the sixth floor, or post-installation conditions on the sixth floor and conditions on the eighth floor.

Occupant’s comments on the survey varied from the very satisfied (“Great product! I would love to have them @ home”) to the clearly not satisfied (“The windows are (…) unsatisfactory”). Two occupants pointed out that they use the EC windows in conjunction with the blinds to control glare. Issues mentioned by the occupants in comments included: the windows made the space seem too dark (three occupants), issues with the subpane tinting patterns (two occupants), need for personalized adjustments to the control algorithm (one occupant), and windows were slow to respond (one occupant).

e Visual comfort

Field and laboratory measurements showed EC windows as very capable in reducing glare to tolerable levels when at full tint, except in the most extreme conditions, such as low angle sun. However, it should be added that (1) windows at full tint are very dark and, while able to control glare in most situations, may be unappealing to the occupants — comments on the occupant suggests this could be the case and (2) when entering and exiting glare mode, if the tinting of the windows is not exactly timed with the appearance/disappearance of the sun from the field of view, occupants can experience extreme glare until the windows reach full tint — this was observed consistently in the laboratory tests.

f Thermal comfort

Measurements and occupant surveys did not suggest any significant negative impacts from the installation of EC windows. In fact, occupants of the EC floor reported an improvement in conditions during warm/hot weather.

ENERGY PERFORMANCE

a HVAC

Laboratory measurements performed during this study show significant reductions in HVAC cooling loads due to the installation of EC windows. Daily HVAC load was reduced by 29%–65% or 0.43–3.48 Wh/ft^2 per day, depending on time of year. Peak HVAC load was reduced by 25%–58% or 1.15–5.63 W/ft^2, also depending on time of year. Changing the control algorithm settings seemed to have only a minor effect on HVAC load.

b Lighting

Estimates using data from the lighting control system on the EC floor show a 62% projected increase in annual lighting energy consumption. This significant negative impact is probably related to two factors: (1) the significant amount of time windows spent at full tint from November 2015 to April 2016 and (2) the high prevalence of occupants using the venetian blinds. Altogether, this suggests that EC windows can, but do not necessarily, have a negative impact on lighting energy consumption. When installing EC windows in a space, special attention needs to be paid to the balance between glare control and lighting energy consumption.

COSTS

Manufacturer estimates of the cost of EC windows are \$61/ft^2, for large volumes in a mature market and including high-quality framing, controls, installation, equipment, project management and a 25% markup.

D. CONCLUSIONS

Measurements performed in this study show EC windows successfully controlling glare, except in some low-angle sun conditions and when the timing of the window transitions from/to full tint is not exactly synchronized with when the sun is directly visible. Laboratory measurements show significant reductions in HVAC loads, and low sensitivity of these reductions to how windows are controlled. Estimates show a significant increase in lighting energy use after the introduction of EC windows. When surveyed, a majority (60%) of occupants stated that they preferred the EC windows to the original ones. Use of venetian blinds was highly prevalent throughout study.

When considered in its totality, what the results from this study suggest is that, while the EC hardware itself is generally mature and able to perform well in controlling glare and thermal discomfort and in the reduction of HVAC cooling loads, the algorithms that control that hardware may require improvement, or at least extensive fine tuning, in terms of achieving an adequate balance between occupant satisfaction, glare control and lighting and cooling energy savings.

II. Introduction

A. PROBLEM STATEMENT

The United States Department of Energy estimates that 30% of the energy used to heat and cool all United States buildings, including federal facilities, is lost through inefficient windows, representing 4,100,000,000 MBtu of primary energy at a cost of $42,000,000,000 per year [Arasteh, 2006; DOE, 2010]. Daylight through windows offers an opportunity to reduce lighting energy use, with an estimated technical potential to save 1,000,000,000 MBtu of primary energy use in United States buildings.

While the standard windows of today are significantly more efficient than in the past, they are still energy liabilities. Even if all windows were converted to today's efficient products (e.g., low-emittance, dual pane windows), they would still require 2,000,000,000 MBtu of energy use to offset heat gains and losses.

B. OPPORTUNITY

Dynamic windows have the potential to provide real-time optimization of perimeter zone energy use, peak demand, comfort, amenity, and cost criteria on a seasonal or even minute-to-minute basis in response to weather, occupant demands or regional grid demands. Integrated with daylighting controls, these technologies have the technical potential to reduce U.S. commercial building heating and cooling energy use by a total of 980,000,000 MBtu, with an additional potential to reduce about 500,000,000 to 1,00,000,000 MBtu in lighting energy use over the business-as-usual case [Arasteh, 2006].

Electrochromic (EC) windows, a type of dynamic window, have the ability to adjust their tint dynamically. In previous studies, they have shown potential to reduce HVAC energy consumption and increase occupant satisfaction. This technology is available in the U.S. as a commercial product from multiple vendors with high-capacity manufacturing facilities, and could be massively deployed if successful in a pilot test.

The U.S. General Services Administration (GSA) Public Buildings Service (PBS) has jurisdiction, custody or control over more than 9,600 assets and is responsible for managing an inventory of diverse Federal buildings totaling more than 354 million square feet of building stock. The large majority of GSA's buildings include office spaces. The sheer size of this building portfolio represents a huge opportunity for potential energy savings.

This Green Proving Ground (GPG) program study examines the energy and comfort performance of EC windows in south-facing perimeter zones of a typical GSA office building.

III. Methodology

A. TECHNOLOGY DESCRIPTION

EC windows have the ability to change their tint dynamically. They achieve this through thin-film coatings applied to glass that can be actively controlled to change appearance reversibly from a clear to a dark blue tint when a small direct current voltage is applied via manual switch or an automated building control system. EC windows preserve the outward view while modulating transmitted light, glare and solar heat gains.

The EC coating itself is a nanometer-thick (1×10^{-9} m, 4×10^{-8} in), multi-layer film or stack deposited on glass. Transparent conductors form the outer layers of the stack, an active EC and passive counter-electrode layer form the middle layers and an ion-conducting electrolyte layer forms the center portion of the stack. The system works like a battery. A bipolar potential is applied to the outer transparent conductors, which causes lithium ions to migrate across the ion-conducting layer from the counter-electrode layer to the EC layer. A reversible electrochemical reaction takes place causing a tinted Prussian blue appearance. Reversing the potential causes the ions to migrate back, causing a bleached clear appearance.

EC windows have an exponential response time that is dependent on temperature and size of the window. A 4x5 ft window on a hot day can take 2–3 minutes to switch from clear to fully tinted. A 5x8 ft window on a cold day can take 5–10 minutes to reach 80% of full tint level, but then another 20–30 minutes to switch to its fully tinted state.

The material and physical composition of the EC window can vary and these dictate the unique properties of the EC window: its switching range, speed versus temperature characteristics, power consumption when being switched, durability, and color. Inorganic, EC windows, at this time, are fundamentally the same between the two known U.S. manufacturers that currently offer this technology: the EC materials exhibit approximately the same solar-optical properties when switched. For both manufacturers, the technology readiness level is the “late R&D” stage (cost reduction and performance improvement stage).

There have been several prior monitored demonstrations of EC windows focused on office settings. A full-scale field test in an office mockup provided rigorous analysis of the window heat gain and lighting impacts of an integrated EC window and dimmable lighting system, with occupant satisfaction evaluated over a short period (4–6 hour exposure per subject) [Clear, 2006; Lee, 2006]. A two-year monitored installation of EC windows in a large office building demonstrated end user acceptance of this technology, but the windows were shaded by a 10-foot deep overhang and conventional skylights confound the analysis of energy and occupant impacts [NREL]). An 18-month installation of EC windows and dimmable lighting in a conference room also demonstrated feasibility of the technology; end user acceptance was inferred by manual override switch activity, not direct subjective survey data [Lee, 2012]. A prior GPG program demonstration at the Denver Federal Center showed significant reductions in HVAC energy use and a decrease in perceived glare [Lee, 2014]. A recent field study of EC windows in a Department of Defense office building also showed significant HVAC energy reductions, as well as increased occupant satisfaction due to increased access to view [Tinianov, 2014]. Another GPG program EC demonstration was initiated in 2015 in an office building in Portland, Oregon.

B. TECHNICAL OBJECTIVES

The technical objectives of the study were to determine, from measurement and survey results, if the installation of the EC windows resulted in the following:

- Reduction in lighting energy consumption;
- Reduction in HVAC energy consumption;
- Improvement or no change in occupant comfort; and
- Reduction in the use of shades.

Strong evidence of these outcomes for all of these would indicate the suitability of EC windows for further deployment in other office buildings throughout the GSA building inventory.

C. DEMONSTRATION PROJECT LOCATION

The John E. Moss Federal Building is a large office building located in Sacramento, California. Built in 1961, it is nine stories high and has a gross floor area of 361,129 ft^2. The study took place in the areas adjacent to the south façade of the sixth floor (Figures III-1 and III-2). The areas adjacent to the south façade of floor contained a mix of private (Figure III-3) and open plan offices (Figure III-4).

Figure III-1. Exterior of the South façade.

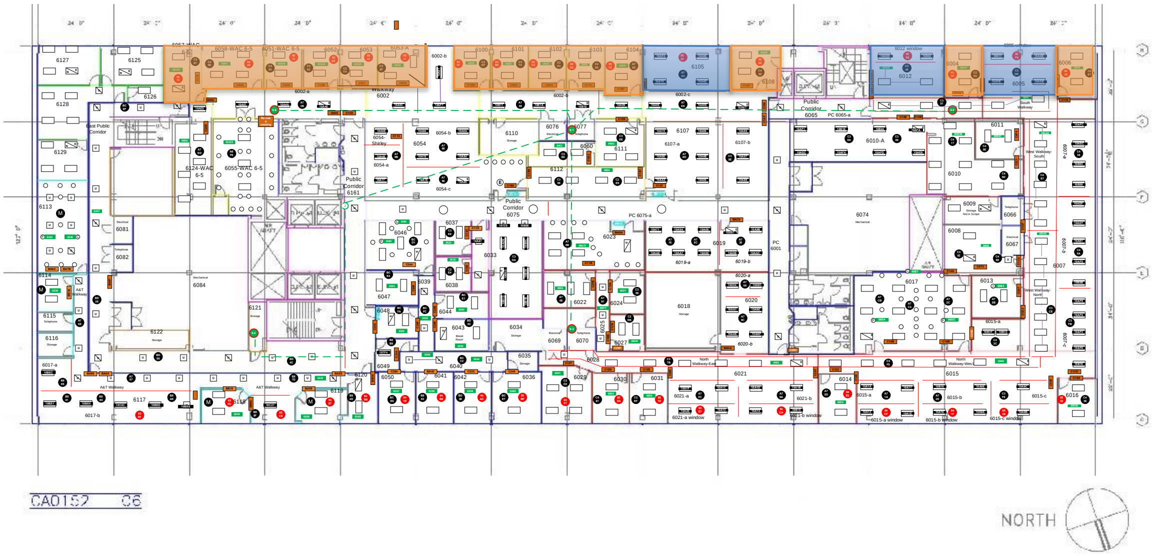


Figure III-2. Floor plan (sixth floor). South façade runs along the top of the figure. Areas studied are shaded in orange (private offices) and blue (open plan offices).

Figure III-3. Private office.

Figure III-4. Open plan area.

IV. M&V Evaluation Plan

A. TECHNOLOGY SPECIFICATION

WINDOWS

EC windows were installed on the south façade of the sixth floor of the Moss Federal Building. They replaced the original windows, which were double-pane low-emissivity units installed in 2006. The EC windows were composed of a 7.1 mm SageGlass SR2.0 laminate on the outboard position, a 12.2-mm air-filled gap and an inboard 6 mm clear float glass pane. Each EC pane was subdivided into three subpanes with the capability to tint independently of the others (Figure IV-1). The visible transmittance of these EC subpanes could be set to one of four nominal values: 60%, 18%, 6% and 1%. These levels are also referred to throughout the text as “clear,” “light tint,” “medium tint,” and “full tint,” respectively (Table IV-1).

Figure IV-1. Each window pane had three sub-zones that could be independently controlled.

Table IV-1. Name and visible transmittance of the four tint levels.

Tint name	Visible transmittance (%)	Solar transmittance (%)	SHGC	U-factor
Clear	60	33	0.41	0.28
Light tint	18	7	0.15	0.28
Medium tint	6	2	0.1	0.28
Full tint	1	0.4	0.09	0.28

SENSORS

The system used four exterior vertical illuminance sensors mounted on the south façade (Figure IV-2).

Figure IV-2. Location of sensors for electrochromic window control.

CONTROL ALGORITHM

The EC windows, 84 in total, were zoned as shown in Figure IV-3. Zones usually spanned a whole private office or an open-plan workstation. Within each zone, all windows are controlled identically, even if sub-zones are controlled independently of each other (see Figure IV-1, for example). Control modes are summarized in Table IV-2 and are explained in more detail below.

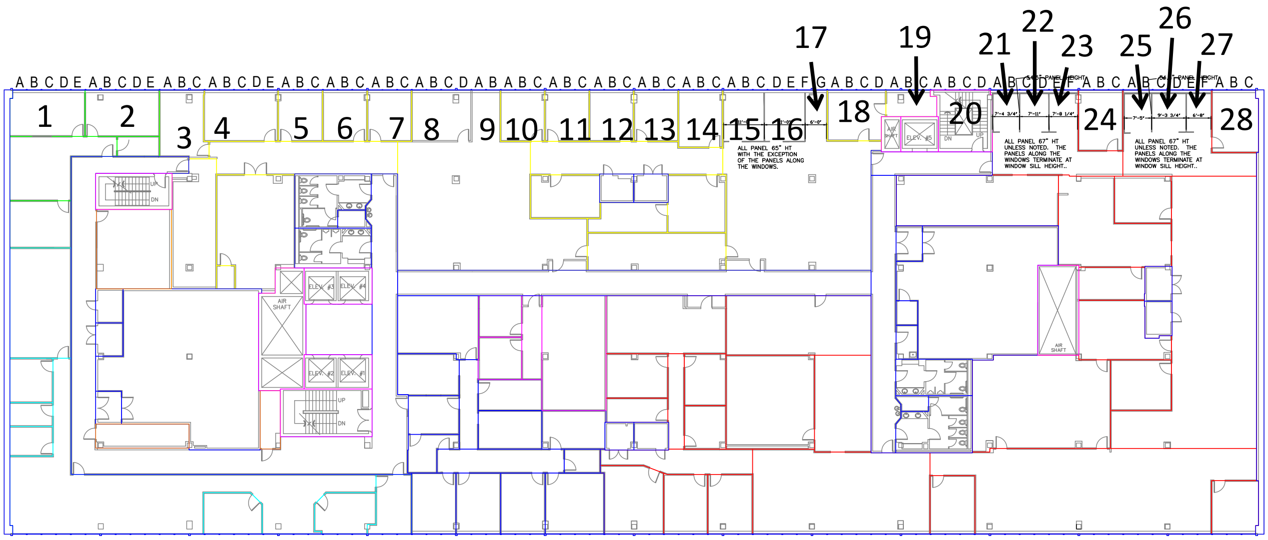


Figure IV-3. Floor plan depicting zoning of EC windows. Zones 1 and 2 were not part of this study.

Table IV-2. Summary of window control modes.

Control mode	Summary description	Priority
Daylight mode	Subpane automatically tinted/untinted according to exterior vertical illuminance	This mode had the lowest priority
Glare override	Subpane set to full tint when sun within defined altitude and azimuth ranges and exterior vertical illuminance above threshold	This mode overrode daylight mode only
Manual override	All three subpanes set to the tint selected manually using wall switch; this override was in effect for four hours, then returned to one of the automatic modes	This mode is able to override all other modes

a Daylight mode

In daylight mode, a subpane was automatically set to one of the four tint levels according to the signal from the exterior vertical illuminance sensors. This adjustment occurred continuously from sunrise to sunset. The control loop was open, i.e., there was no feedback to the control system regarding the effect that tint level changes may have on interior light levels. The sensitivity of each subpane to exterior light levels was determined by a control setpoint. The lower the setpoint, the darker the subpane would tint in response to exterior light levels. For this project, all three subpanes were initially set to the same setpoint, in accordance to GSA feedback. Consequently, when in daylight mode, all three subpanes of every window were controlled to the same tint (Figure IV-4). These setpoints were adjusted in response to occupant and GSA feedback throughout this project. See Table IV-3 for setpoint values.

Figure IV-4. EC windows in daylight mode (zone 18 on June 14, 2016). All subpanes are controlled to the same tint.

Table IV-3. Daylight mode setpoints throughout demonstration. Units are lux.

Subzones	**Daylight mode setpoints**	
	Installation to Jun 12, 2016	Jun 13, 2016 to end of study
Top	3000	1000
Middle	3000	1000
Bottom	3000	1000

b Glare override

During glare override mode, the control system sets one or more subpanes to full tint (Figure IV-5). A subpane is set to glare override mode when two conditions are satisfied:

(1) the sun is within preset azimuth and altitude angles and

(2) exterior vertical illuminance exceeds a preset threshold.

The control system will send the subpane back into daylight mode when either of the following two conditions are satisfied:

(1) the sun is not within the preset azimuth and altitude angles any more or

(2) exterior vertical illuminance fell below a preset threshold (which is not necessarily equal to the one for entering glare override mode).

Solar position is calculated by the control system based on astronomical formulas, date, time of day, geographical location of the building, and orientation of the window zone. The preset values were set by the manufacturer prior to or during commissioning, based on knowledge gained from past installations and computer simulations of light levels in the building, and adjusted throughout the project based on occupant and GSA feedback. See Table IV-4 for angle and exterior illuminance thresholds the manufacturer reported throughout the project.

Figure IV-5. EC windows in glare mode (zone 18 on December 17, 2015). The top and middle subpanes are at full tint due to glare mode. The bottom pane is in daylight mode.

Table IV-4. Glare control mode settings (values provided by manufacturer).

Subzone	Morning						Afternoon					
	Start		Stop		Threshold (klx)		Start		Stop		Threshold (klx)	
	Azimuth (°)	Altitude (°)	Azimuth (°)	Altitude (°)	Start	Stop	Azimuth (°)	Altitude (°)	Azimuth (°)	Altitude (°)	Start	Stop
Installation to Apr 13, 2016												
Top	109	18	289	55	10	6.5	109	55	289	18	10	6.5
Middle	109	0	289	55	10	6.5	109	55	289	0	10	6.5
Bottom	109	0	289	55	10	6.5	109	55	289	0	10	4
Apr 13, 2016 to end of study												
Top	150.6	6.7	274.4	53.7	17	10	150.6	53.7	247.4	6.7	17	10
Middle	150.6	0	274.4	43.4	17	10	150.6	43.4	247.4	0	17	10
Bottom	150.6	0	274.4	18.4	17	10	150.6	18.4	247.4	0	17	10

c Manual override

Building occupants can override any of the other two modes using wall switches (Figure IV-6). The switches also display the currently selected tint or if the window is under one of the two automatic control modes. When overridden, all the subpanes within a zone will stay at the set tint level for a preset duration. Override duration was set to four hours throughout the study. The EC windows used in this study can also be controlled via a smartphone app. This option was not chosen for this study due to IT security considerations.

Figure IV-6. The window tint within a zone can be controlled with wall switches such as this one. The blue light indicates the tint that the zone is manually set to (or automatic control).

B. TECHNOLOGY DEPLOYMENT

INSTALLATION

The electrochromics retrofit replaced the existing double-pane low-emissivity windows — which were a retrofit from the late 2000s (Figure IV-7). The replaced window area was approximately 1574 ft^2. For the study detailed in this report, window pane installation was initially completed in October 2015. Eleven windows were replaced between October and mid-December because they were found to be have cosmetic defects, possibly due to improper forklift handling during shipping. Initial commissioning of the controls was completed in November 2015. During the study period, one window needed to be replaced due to malfunction. Loose gaskets were repaired in two additional windows. These activities took place in March 2016.

Prior to this installation, in Phase I of this study, electrochromics had been installed on the sixth floor of the building, with the installation taking place between February and April 2014. Automated operation started at the end of April 2014. However, in the fall of that year, occupants began noticing that the tinting of the windows was not even, with the glass noticeably lighter on one side of the windows. In-situ transmittance measurements showed that the windows were lighter than their design tint levels, especially in the lighter areas. The window manufacturer determined that a glitch during the production process had caused these tinting issues. The manufacturer provided for the replacement of these windows with windows that functioned correctly, which were then used for the study described in this report. EC windows were kept operating until they were replaced for Phase II.

During the initial window installation process, it was unexpectedly discovered that routing the wires out of the electrochromics would need to be done horizontally through the side of the frame and not directly upwards into the ceiling as had initially been assumed. The window frames were not original — the windows of the building had been retrofit in 2006 — and up to date drawings were not available, making it difficult to anticipate this issue before installation. To address this issue, the frames were modified by drilling holes on their side (see Figure IV-8). Custom-made aluminum cover plates were installed to cover the holes, thereby creating an aesthetically pleasing appearance (Figure IV-9). These, in turn, were found to compress the wires in the afternoon, possibly due to thermal expansion, and cause problems with the control of the windows. This issue was addressed by installing plastic shims between the cover and the frame.

Another issue encountered during installation was that the wiring provided initially was incompatible with the windows that were eventually provided. Because the wiring had already been installed by the time the windows were delivered to the site, this caused the need to replace the existing wiring with new, compatible wiring provided by the manufacturer.

Figure IV-7. Original double-pane, low-emissivity, windows installed in the late 2000s.

Figure IV-8. Frame with drilled hole allowing wire to exit window through the side of the frame.

Figure IV-9. Aluminum cover plates were installed to conceal the wires coming out of the window frames.

COSTS

The EC windows and control systems for this installation were gifted by the manufacturer. Manufacturer estimates of the actual cost of EC windows are \$61/ft^2, for large volumes in a mature market, and including high-quality framing, controls, installation, equipment, project management and a 25% markup.

C. TEST PLAN

TEST SCHEDULE

A timeline of main study events is shown in Table IV-5. Measurements took place between the winter solstice of 2015 and the summer solstice of 2016.

Table IV-5. Main study events.

Activity	Completed by
Phase I	
Installation and commissioning of EC windows	Apr 30, 2014
NOTE: These windows were left in operation until Phase II	
Phase II	
Installation of EC windows	Oct 31, 2015
Initial control algorithm commissioning	Nov 10, 2015
LBNL instrumentation installation	Nov 10, 2015
Replacement of EC windows with cosmetic defects	Dec 16, 2015
Winter solstice measurements	Dec 17, 2015
Maintenance site visit	Feb 3, 2016
Glare algorithm adjusted by manufacturer	Apr 13, 2016
Equinox measurements	Apr 15–17, 2016
Occupant survey	May 26–Jun 6, 2016
Daylight mode algorithm adjusted by manufacturer	Jun 13, 2016
Summer solstice site visit	Jun 14, 2016
LBNL instrumentation decommissioning	Jun 14, 2016

ELECTROCHROMIC WINDOW OPERATION

The operation of the EC window system was evaluated using a) data from the window control system, provided by the manufacturer and b) measurements of subpane transmittance performed on one window.

a Control system data

Data from the window control system were provided by the manufacturer for each zone under study. Data included window tint level commands, estimated actual tint, daylight mode setpoint, operation mode (daylight, glare or manual override), as well as the signal from the exterior photosensors. Data files containing data at a 1-min interval were sent at regular intervals to the Lawrence Berkeley National Laboratory (LBNL) via a secure file transfer server.

b Window transmittance measurements

Photometer (illuminance) sensors were installed on the interior face of each of the three subpanes of one of the EC windows (easternmost window of zone 18). Data from these sensors was logged every two minutes for the duration of the study. The ratio between the signal from these photometers and that of a similar photometer installed on the roof, with its measurement surface parallel to the façade, provides an approximate measurement of the visible transmittance of each subpane.

c Occupant complaint log

The facility management team maintained a log of occupant complaints about the windows throughout the study period. This information was shared with the project team. Occupants were instructed to report any issues using GSA's technical support center and to provide the window reference number, which was posted on every window.

INDOOR VENETIAN BLIND USE

During site visits, GSA and LBNL personnel recorded the approximate position of the Venetian blinds in all accessible windows in the area under study. Blind position was recorded on November 10 and December 17, 2015, and February 3, March 16, April 15, June 7, and June 14, 2016. Information recorded including approximate blind height (limited to values of 0%, 25%, 50%, 75% and 100% of window height, where 0% is fully raised and 100% fully lowered) and slat angle (limited to "open" or "closed"). These data were used to compute the percentage of blinds that were lowered from their fully raised position, as well as the percentage of blinds that were lowered to cover over 50% or more of the height of the window.

OCCUPANT SURVEY

A survey of the occupants' perceptions of visual comfort, thermal comfort and general satisfaction with the windows was issued in May–June 2016. The occupants also were asked about their interaction with the EC windows and with the operable shading. Occupants in the area under study were asked to compare their perceptions of and experiences with the EC windows against the original windows. To have an additional reference group, a similar questionnaire (but not including any questions about EC windows) also was issued to occupants of the eighth floor of the building with the original non-switchable windows. Survey questionnaires were issued on paper, which, according to prior experience, provides higher response rates than online surveys.

VISUAL COMFORT

In addition to the occupant survey, visual comfort was measured during the winter solstice, equinox and summer solstice site visits, using high-dynamic-range (HDR) luminance mapping techniques. In this technique, multiple images taken with varying exposure times are combined, using software, to determine the luminance recorded by each pixel of the camera sensor, effectively using each of those pixels as if it were a luminance meter. Luminance data is then further processed into a single number representing Daylight Glare Probability (DGP), a metric for visual comfort [Wienold, 2006]. DGP values range from 0 to 1 and represents the percentage of people who would experience disturbing glare when viewing the scene captured in a luminance map. Table IV-6 shows the correspondence between DGP levels and qualitative perceptions of glare [Reinhart, 2011].

These measurements were performed using Canon EOS 60D SLR cameras with Sigma EX 4.5 mm f/1.8 fisheye lenses, controlled by a computer running Mac OS X custom software, and fitted with light sensors for continuous calibration (Figure IV-10). These cameras were mounted on lightweight tripods and placed 3.6 ft and 10.7 ft from the window, approximately at the two locations where occupants might sit facing the window.

Table IV-6. Correspondence between DGP and qualitative perceptions of glare.

DGP	Qualitative interpretation
< 0.35	Imperceptible glare
0.35 to 0.40	Perceptible glare
0.40 to 0.45	Disturbing glare
> 0.45	Intolerable glare

Figure IV-10. High-dynamic-range luminance mapping apparatus in operation at the study site (zone 18).

THERMAL COMFORT

Thermal comfort was assessed using three methods: (a) continuous measurements of indoor environmental variables (e.g., air temperature and relative humidity), (b) periodic measurements of window and room surface temperatures using infrared imaging and (c) occupant surveys.

a Continuous measurements

Sensors measuring room air temperature, mean radiant temperature, air velocity, and relative humidity were installed in an unoccupied office for the duration of the study. Data from these sensors was logged every two minutes for the duration of the study and then used to calculate two standard metrics [ISO, 2005]: Predicted Mean Value (PMV) and Percentage of People Dissatisfied (PPD).

PMV provides information on how occupants will on average perceive the temperature of the space. PMV values of -3, -2, -1, 0, 1, 2 and 3 correspond to the space being perceived as “cold,” “cool,” “slightly cool,” “neutral,” “slightly warm,” “warm,” and “hot,” respectively.

PPD is a value between 0 and 100% and represents the percentage of people who would be dissatisfied with the thermal conditions in the space.

The ASHRAE 55 standard for thermal comfort [ASHRAE, 2013] recommends PMV targets of between -0.5 and 0.5 and below 20% for PMV.

b Infrared thermography

During winter solstice, equinox and summer solstice site visits, infrared (IR) images of the interior surface of the windows were captured every 10 minutes. These images provide the distribution of temperature across the window surface and were used to estimate the likelihood of radiative discomfort arising from heat absorption and re-radiation by the windows. The ASHRAE 55 thermal comfort standard limits the radiant temperature asymmetry due to warm room surfaces to less than 23°C (41.4°F).

LIGHTING ENERGY USE

Data from the automated lighting control system were made available to the project team, providing a reported “intensity” level (0%–100%) for each zone and also including occupancy events (zone occupied/vacant) and manual override events. However, the goal of estimating the impact of EC windows was complicated by several factors:

- The mapping of lighting circuits did not match the areas by the façade that were of interest to this study, so we could not isolate these areas by measuring power at the lighting circuit panel.
- The lighting control system turned lights off when spaces were unoccupied and, therefore, it was not possible to have information about how lights would be controlled for periods during which spaces were unoccupied.
- Preliminary analysis of data from the lighting control system showed that occupants actively used the wall switches to override automatic operation, which also impeded the determination of how lights would be controlled had the lighting system been left to its own devices.

To circumvent these issues and still be able to provide an estimate of the lighting energy impacts of EC windows, we calculated typical weekday lighting profiles for each zone and for every two-week period throughout the study, as well as for an equivalent baseline period prior to the beginning of operation of EC windows. For each zone and two-week period, the typical lighting profile was calculated by placing dimming level data from a two-week period in 1,440 one-minute bins, according to the time of day of each available data point, and averaging the data points in each bin. Data points were excluded that corresponded to periods during which (a) lights were off because the space was unoccupied or (b) lights had been set to a particular level manually using the wall switches. For this reason, depending on how often a space was vacant or how often an occupant used the wall switches, profiles could have a significant number of empty bins. A profile was considered sufficiently complete if it satisfied both these conditions: (a) it had at least one data point in 90% or more of the bins between 9 a.m. and 5 p.m. and (b) the largest group of contiguous empty bins had no more than 30 bins, i.e., the profile data covered at least 90% of the working day, and the biggest gap was no longer than 30 minutes. Figure IV-11 shows a lighting profile derived for a private office for the period between April 9 and 22, 2014.

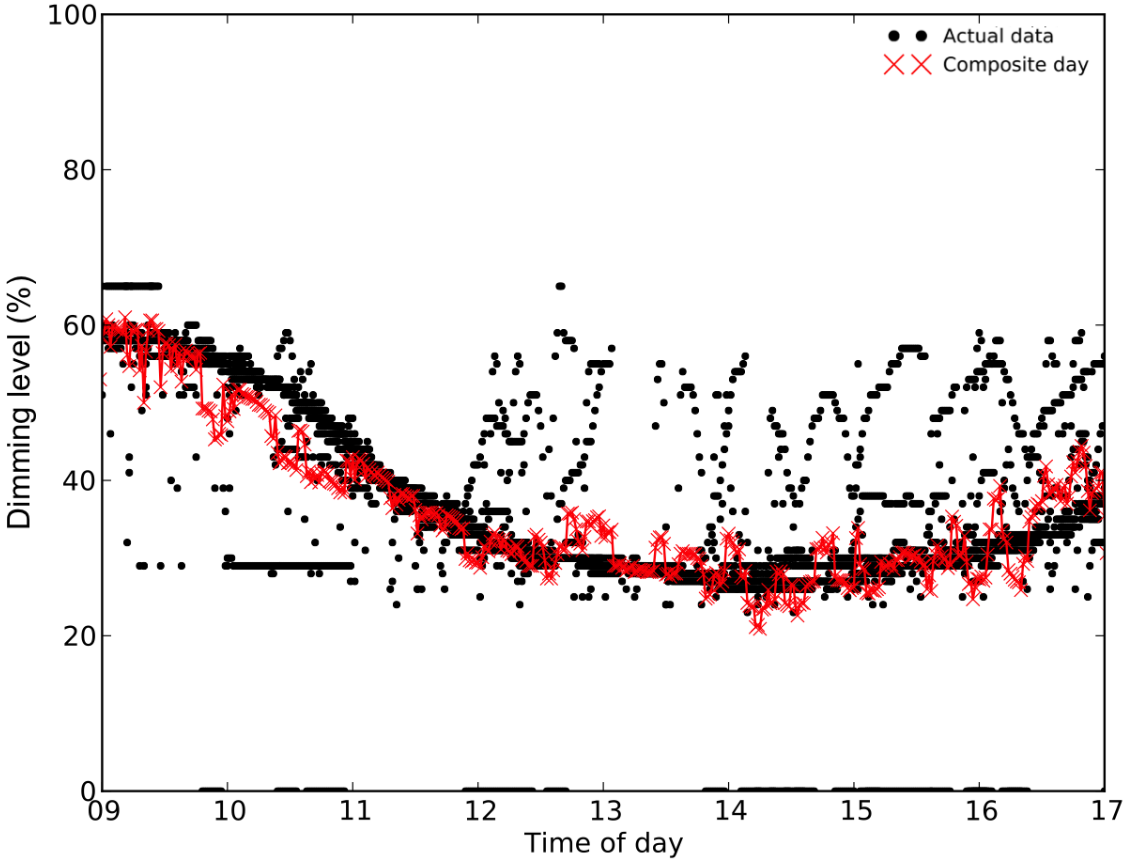


Figure IV-11. Weekday lighting profile for a private office during a two-week period. The dots represent the individual data points gathered in the 1-minute bins for the two-week period, and the red crosses the average value for each bin.

For each two-week period, these lighting profiles were used to calculate average power consumption using results from bench testing that measured luminaire energy consumption versus “intensity” level reported by the lighting control system. These bench tests, performed during a prior GPG program study of the advanced lighting control system that took place in the same building [Rubinstein, 2015], revealed that luminaire power consumption was 93% of full power when “intensity” reported by the control system was 65%. Minimum (standby) power was 23% of full power. The relationship between reported “intensity” and power consumption used in the calculations is shown in Figure IV-12.

The calculation method was as follows:

1. For each zone (including only zones in which daylight harvesting was enabled) and for each two-week composite period, power level was calculated for every timestep using the function shown in Figure IV-12. The arithmetic mean of these power levels was then calculated.
2. For each two-week period, the arithmetic mean calculated in the previous step was averaged between all the zones, weighted by the number of luminaires in each zone. This yielded the average power level during that two-week period for all the zones in which daylight harvesting was enabled.
3. The sum of average power levels calculated in the previous step was calculated for two solstice-to-solstice periods, one before EC windows were in operation and the other after EC windows were in operation. A comparison between these two sums yields the reduction (or increase) in annual lighting energy consumption due to the installation of EC windows.

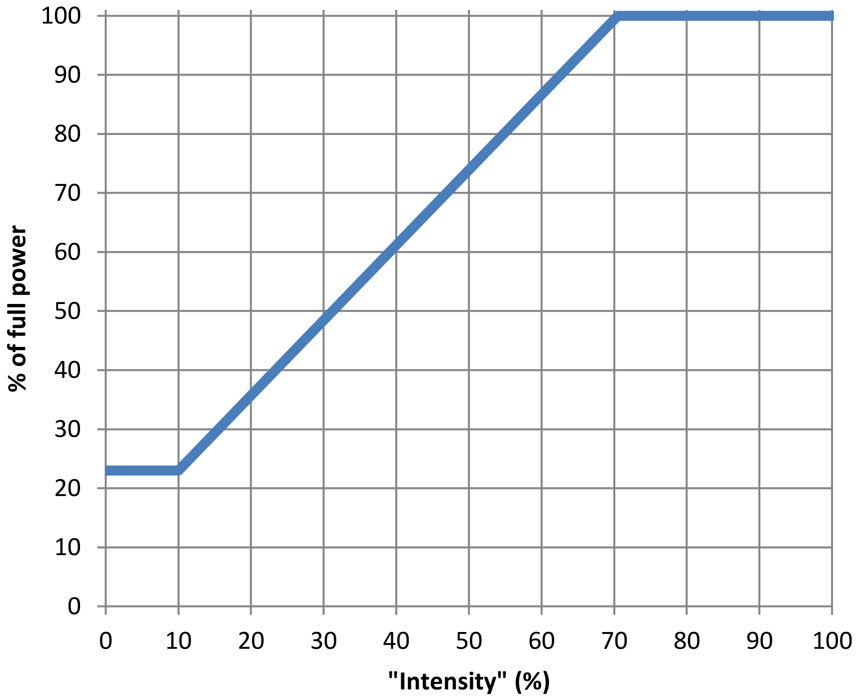


Figure IV-12. Relationship between luminaire power consumption and “intensity” reported by the lighting control system.

LIGHT AVAILABILITY

To measure workplane light availability in perimeter areas, we installed photometers at desktop height in three spaces: (a) an unoccupied office with the Venetian blinds pulled all the way up, (b) an unoccupied office with the blinds pulled all the way down and the slats set to a horizontal position and (c) an occupied office in which the occupant lowered the blinds over approximately half of the window area with the slats closed. This occupant also stated a preference for overriding the windows to their darkest tint and for overriding the lights to the off state. Two sensors were placed in each of these spaces, at 2 ft and 8 ft from the window. The data from these sensors was used to compute the percentage of time light levels were high enough to provide useful illumination without high probability of glare, generally taken to be between 100 and 2000 lux [Nabil, 2004], during the period from 9 a.m. to 5 p.m. on weekdays. In addition, since these spaces would have lights off most of the time due to vacancy or manual override, we also determined the percentage of time during which light levels were between 100 and 500 lx, indicating they would need to be supplemented by electric lighting, even if they were already above the 100 lux threshold for usefulness.

D. INSTRUMENTATION PLAN

To implement the test plan, the instrumentation described below was used. Some instruments were left to gather data continuously throughout the study, whereas others were used only during winter solstice, equinox and summer solstice site visits.

CONTINUOUS MONITORING

Instruments were installed for the duration of the study in four locations in the building: three private offices on the sixth floor and one location on the rooftop.

a Roof

Instruments installed on the roof (Figure IV-13) were:

- a photometer (Li-Cor LI-210) mounted vertically, with the measurement plane aligned with the façade;
- a pyranometer (Delta T SPN1) measuring global and diffuse horizontal exterior irradiance; and
- a shielded dry-bulb temperature and relative humidity sensor (Onset S-THB-M002) measuring outdoor air temperature and relative humidity.

The signal from these instruments was logged by an Onset HOBO RX3000 GSM data logger.

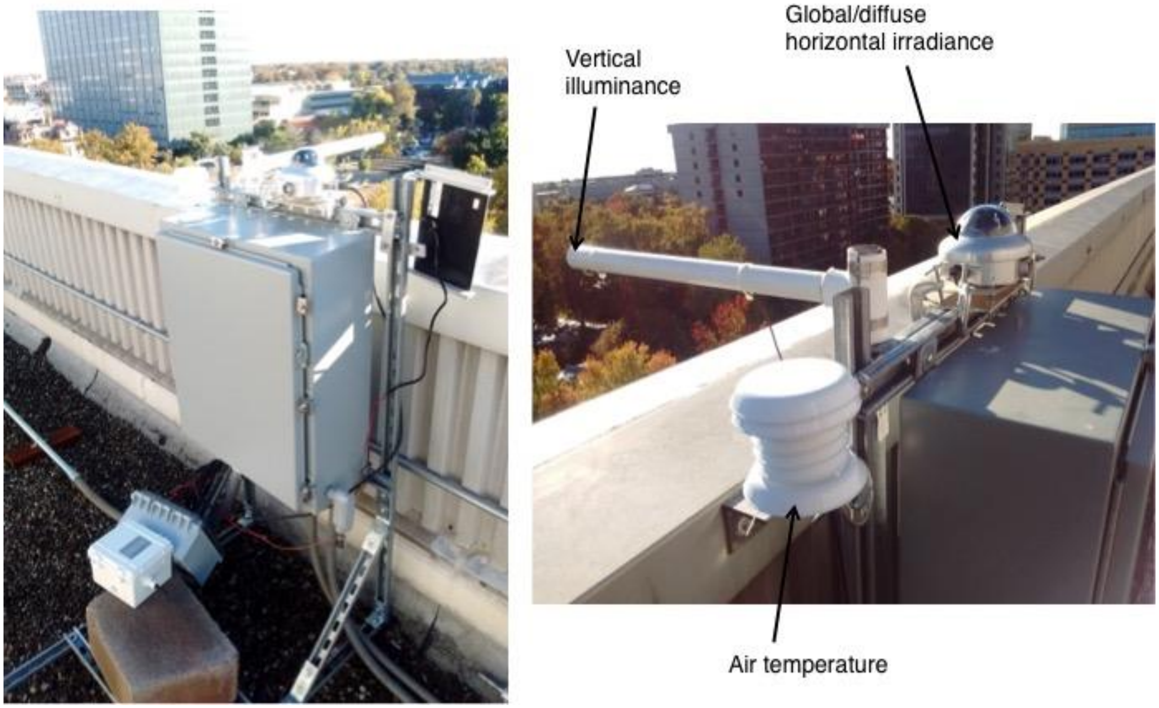
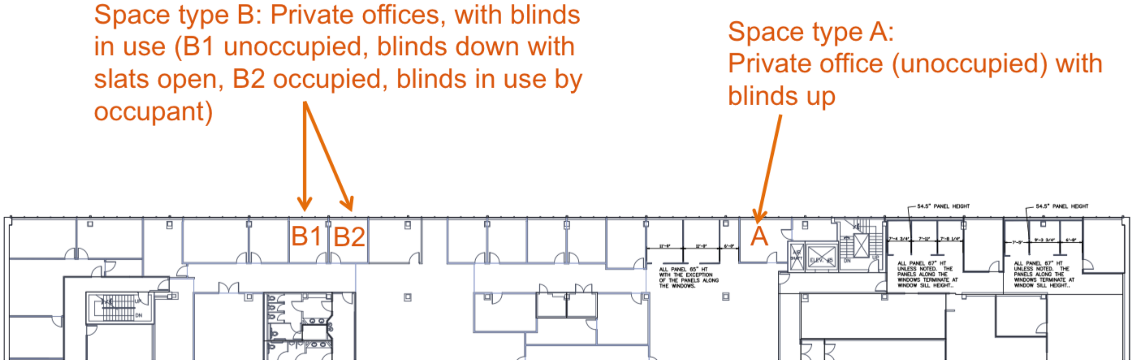


Figure IV-13. Instruments installed on the roof.

b Sixth floor

Instruments were installed at three locations on the sixth floor (Figure IV-14), in two configurations: Space Type A and Space Type B. Data in these two spaces was logged continuously at 1-minute intervals by a combination of several types of data loggers (Onset HOBO RX3000, Onset HOBO U30 and Onset HOBO U12).

Figure IV-14. Location of sixth floor spaces where instruments were installed.



Space Type A (Figures IV-15 and IV-16) comprised the following:

- Three photometers (Li-cor LI-210) with EME Systems UTA amplifiers mounted at the center of each of the three subpanes of one window

- Two thermistors (HOBO TMC20-HD) mounted on the frame of the window, at the height of the center of the top and bottom subpanes (approx. 11 inches below the top/above the bottom of the glass for the upper/lower sensors, respectively)
- Three thermistors (U.S. Sensor, Digi-Key 615-1069-ND) mounted on the glass, approx. 2 inches eastwards from the photometers and 15.5 inches from the frame on the east side
- An air velocity sensor (Degree Controls F900-O-5-1-9-2), mounted on a tripod approx. 4 ft from the window and 4 ft above the floor
- A mean radiant temperature sensor comprising a thermistor (US Sensor, Digi-Key 615-1069-ND) inside a gray sphere (44 mm diameter; estimated reflectance 18%), approximately 4 ft from the window and 4 ft above the floor
- A data logger (HOBO U-12 Temp/RH) measuring room air temperature and relative humidity, placed under one of the desks
- Two photometers (Li-cor LI-210) with EME Systems UTA amps mounted on stands placed on the desktop surfaces, 2 ft and 8 ft from the window

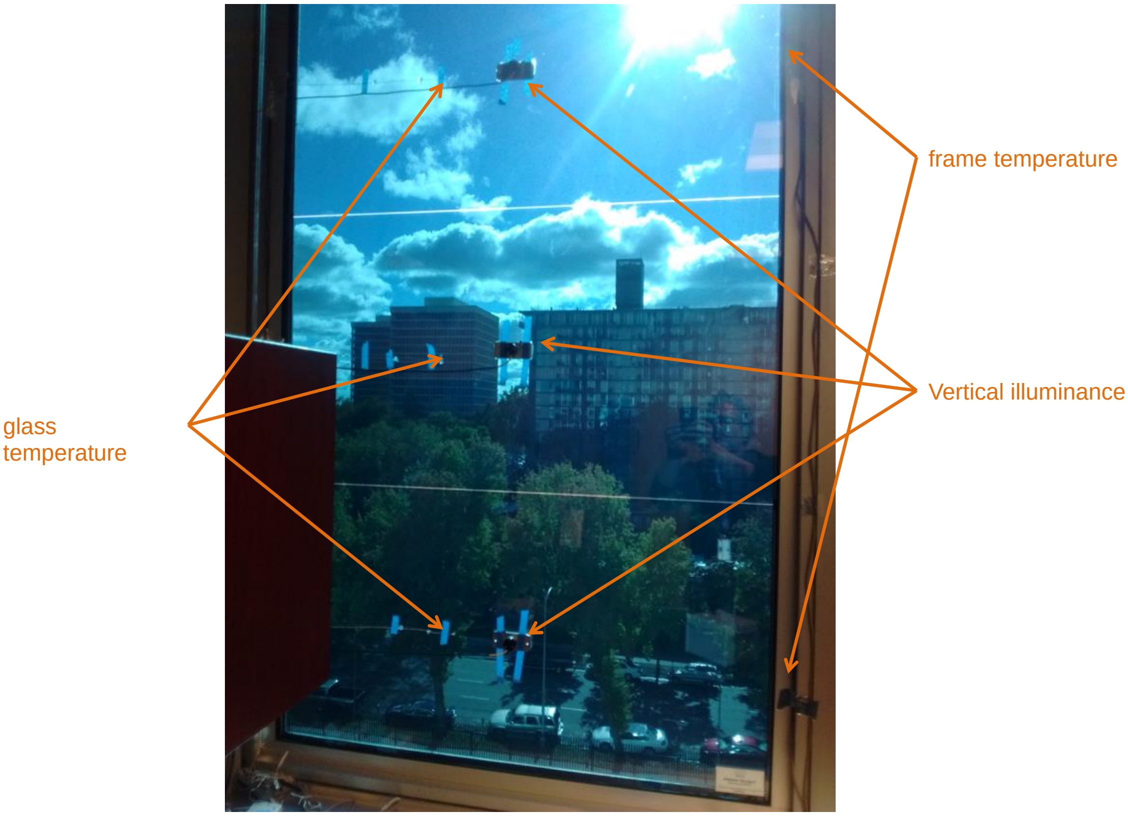


Figure IV-15. Window instrumentation in Space Type A. Blue tape shown was temporary and removed after instrument installation was complete.

Figure IV-16. Instrumentation in Space Type A. Also shown are cameras in position for HDR imaging.

Space Type B (Figure IV-17) comprised:

- Two photometers (Li-cor LI-210) mounted on custom-built stands placed on the desktop surfaces, 2 ft and 8 ft from the window. Stands were 6 inches high, resulting in sensors being placed 36 inches above the floor.

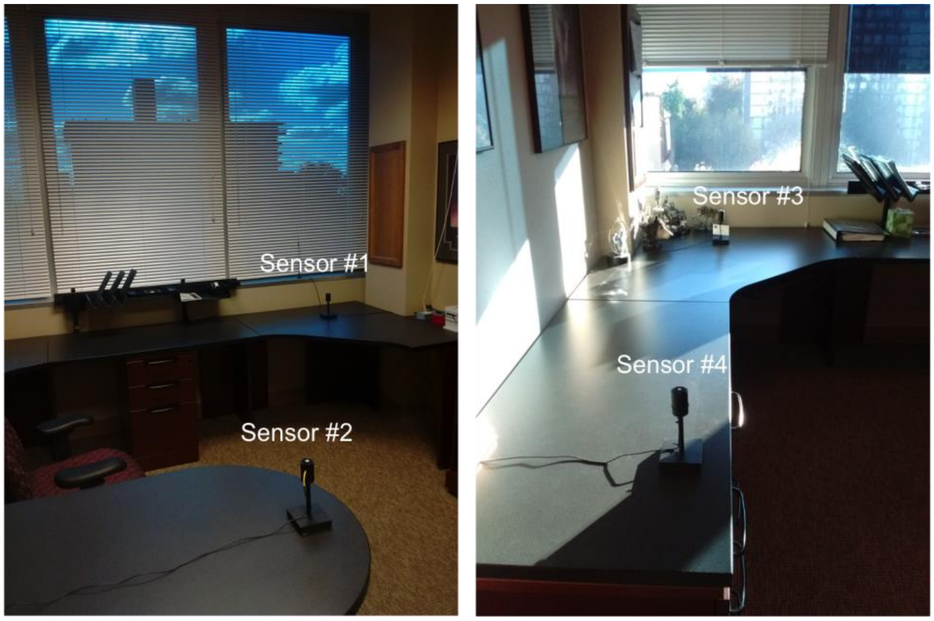


Figure IV-17. Space Type B instrumentation. The image on the left shows an unoccupied office where the blinds were kept fully lowered with the slats open. The image on the right shows an occupied office where the occupant lowered the blinds to over approximately 50% of the surface of the windows, with slats closed.

PERIODIC SITE VISITS

During site visits near the winter solstice, spring equinox and summer solstice, two types of equipment were put in place for the duration of the visit:

- Two digital cameras (Canon 60D) customized for high-dynamic-range imaging, mounted on lightweight tripods. The center of the lens was placed 47 inches above floor, 2 ft and 8 ft from window (Figure IV-16)
- Infrared camera (FLIR SC660), 8 ft from window, 5 ft 8 in above the floor (Figure IV-18).

Figure IV-18. Infrared camera deployed during site visit. One of the HDR cameras is visible at the right of the image.

E. LABORATORY TESTS

In parallel with the field activities described so far, tests at a laboratory facility were conducted to understand the performance of EC windows in aspects that were difficult to evaluate in the field: HVAC performance and visual comfort. Due to the zoning of the HVAC system in the Moss Building, it was not possible to isolate accurate performance in the perimeter zones, where the effect of the EC might be observed more prominently, from the rest of the floor. In terms of visual comfort, the lab setting allows for the continuous use of

HDR techniques, thereby complementing the three site visits that this study was limited to in the field.

FACILITY TESTBED

a Geometry

The 952 ft^2 Advanced Windows Testbed (Figure IV-19) is located LBNL in Berkeley, California (37°4' N, 122°1' W). It consists of three identical side-by-side office test rooms, designated A, B and C, from east to west, respectively. Each room was built with nearly identical building materials to imitate a commercial office environment, is 10 ft wide by 15 ft deep and 11 ft high and has a 10 ft wide and 11 ft tall reconfigurable window wall facing due south. The window is divided by a vertical frame at the middle into left and right portions and by a horizontal frame at 8.8 ft from floor into clearstory and view portions. For the tests performed in this study, Room A had an conventional (i.e., non-dynamic) insulating glass unit (IGU) with 62% transmittance (Tvis). Rooms B and C had EC windows with 60% maximum visible transmittance. The north wall contained a door and the other two walls were blank. The room contained desks along the east and west walls. A computer display was placed on the west wall desk and not turned on.

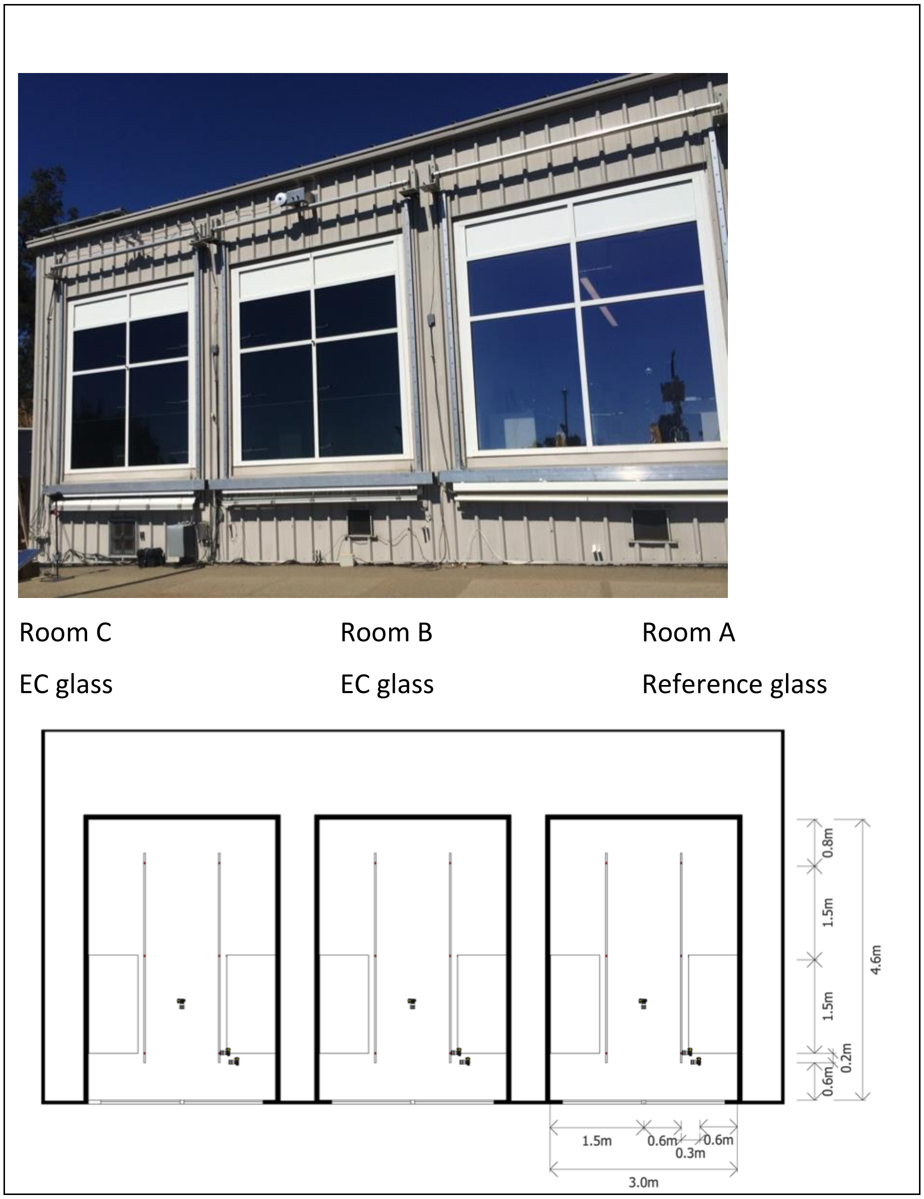


Figure IV-19. South façade of three test rooms at Advanced Windows Testbed, Lawrence Berkeley National Laboratory; (left) Room C with EC window, (middle) Room B with EC window and (right) Room A with reference window.

b HVAC

Each test room is equipped with a dedicated fan coil unit (FCU), which consists of independent cooling and heating fans to achieve constant room temperature control (Figure IV-20). Heating is provided by a modulated electric heater with a fixed fan speed. Cooling is provided by a modulated fan with a constant chilled water flow through the cooling coil, while chilled water is provided by a central chiller for all test rooms. In the case of cooling, the heating fan is modulated down to compensate the increasing flow through the cooling fan, which allows constant air change rates of 8–10 ACH in the room. The room air temperature is controlled by an independent proportional-integral-derivative controller

(PID controller) to a setpoint of 24°C for each room. The FCUs are located outside the test rooms and are lightly insulated to reduce thermal loss to the conditioned surrounding guard zone.

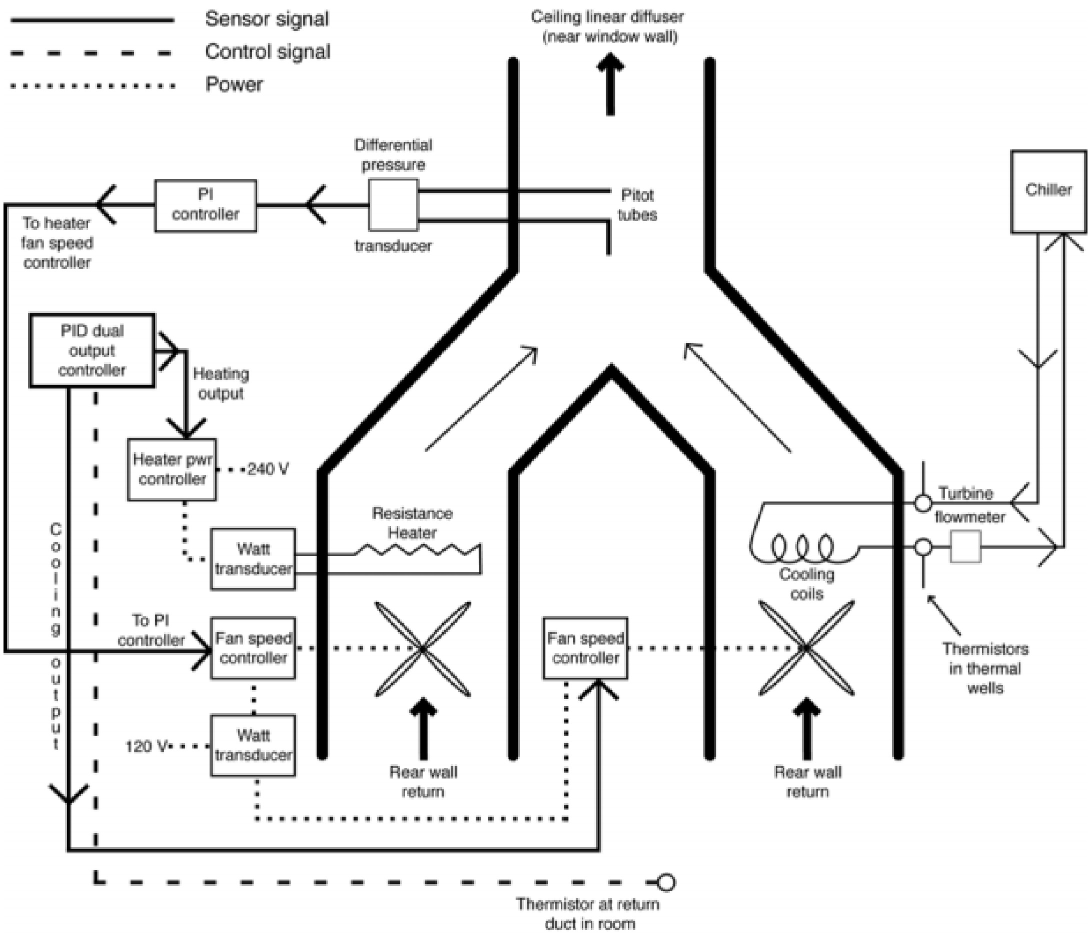


Figure IV-20. Schematic of fan coil unit.

MEASUREMENT SETTINGS

a Weather data

Outdoor weather and sky condition data were continuously collected at 1-minute intervals. Direct normal, global horizontal and diffuse irradiance were recorded using Hukseflux DR01 and SR12, SolarTrak pyranometers, with an accuracy of ±3%.

b Illuminance

Similar to weather data, illuminance was collected continuously at 1-minute intervals. Workplane illuminance was recorded at distances of 2.5 ft, 7.5 ft and 12.5 ft (window, center and rear zones, respectively) from the façade and 2.5 ft above the floor using photometric sensors (Li-Cor LI-210SA, ±1.5% to 150 klux) (Figure IV-21). Six sensors were laid out on a 2 x 3 grid (Figure IV-22). Workplane illuminance for each zone was averaged using two illuminance sensors installed at the same distance from window. Exterior vertical illuminance also was measured at the south façade.

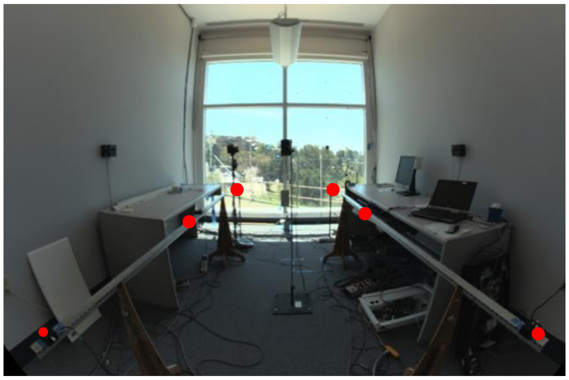


Figure IV-21. Illuminance sensor positions in a test room (red dots).

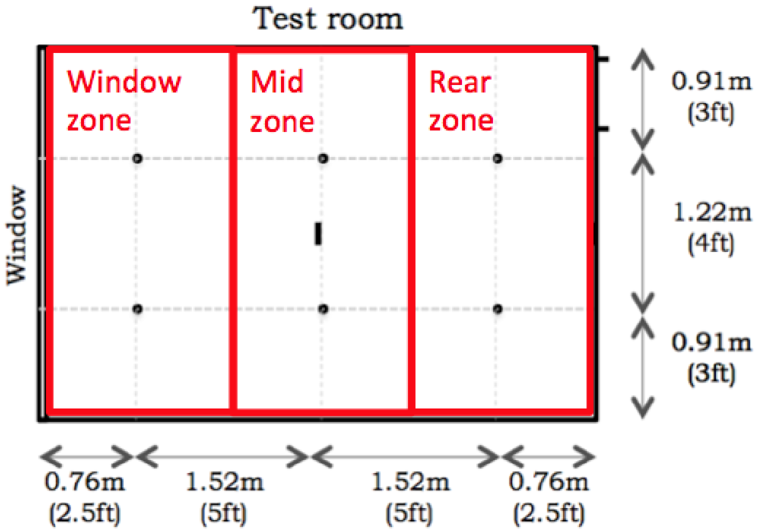


Figure IV-22. Six illuminance sensor positions in a test room (black dots).

c Transmittance sensors

The transmittance of the EC windows was measured continuously at 1-minute intervals. Transmittance was recorded at each window using photometric sensors. Figure IV-23 illustrates the six transmittance sensors in one of the test rooms.

Figure IV-23. (left) Six transmittance sensor positions in a test room. (right) Close-up view of transmittance sensor.

d Luminance mapping for glare analysis

Hemispherical luminance measurements were made with commercial-grade digital cameras equipped with an equidistant fisheye lens (Figure IV-24). Bracketed images (f-stop=5.6, between 4–7 images, depending on the brightness of the scene) were taken automatically (using the HDRcapOSX software [Mardaljevic, 2010; Ward, 2009]) at 5-min intervals from sunrise to sunset at two locations within the room interior assuming a seated occupant (4 ft eye height) (Figure IV-25). These low dynamic range (LDR) images were compiled into a single high dynamic range (HDR) image using the hdrgen tool [Ward, 2009a], where the camera response function was determined by the software and the vignetting function of the fisheye lens was determined from prior laboratory tests at LBNL. A vertical illuminance measurement was taken adjacent to each camera's lens, immediately before and after the bracketed set of images, and used in the hdrgen compositing process to convert pixel data to photometric data. To prevent damage to the camera's imaging sensor, image capture was canceled if the vertical illuminance was greater than 4000 lux for cameras facing the side wall and 14,000 lux for cameras facing the window. A lesser number of bracketed images were taken at low light levels to avoid excessively long exposures. Analysis of discomfort glare focused on two group of sky conditions: (a) clear and dynamic skies and (b) overcast and cloudy skies. LDR images captured under variable sky conditions were less accurate, but were retained for illustrative purposes. Luminance measurements of the six Canon cameras were accurate to within ±4.7% on average under stable daylight conditions up to 11,400 cd/m^2, using a Minolta LS100 spot luminance meter and reference gray card as benchmark.

Figure IV-24. Canon 5D Mk II and equidistant 180˚ angular fish eye lens used for HDR image capturing.

e Daylight Glare Probability (DGP)

Similarly to field measurements, glare analysis was done using the method developed by Wienold and Christoffersen [Wienold, 2006]. During tests, images were captured every 5 minutes from 8 a.m. to 6 p.m. standard time. Because glare is highly dependent on position, DGP measurements were performed at different locations. One of the cameras was facing the window, and a second camera was placed near the window, facing the side wall. Altogether, three camera positions were considered and used for glare measurements (Figure IV-25, Table IV-7):

1. Camera 1–2 ft from the east wall and 2 ft from the window, facing the west wall;
2. Camera 2–2.5 ft from the east wall and 3 ft from the window, facing the west wall; and
3. Camera 3–5 ft from the east wall and 5 ft from the window, facing the window.

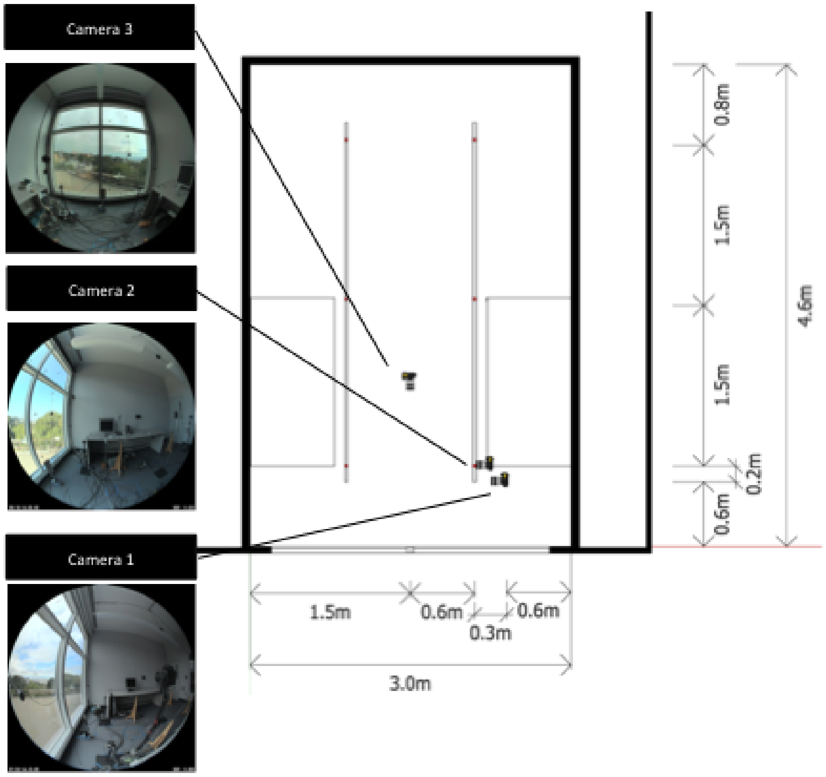


Figure IV-25. Camera positions during tests.

Table IV-7. Camera positions during tests.

	High solar altitude	**High solar altitude**	**Mid solar altitude**	**Low solar altitude**	**Low solar altitude**
Period of analysis	Jul 12–21	September 27 –August 5	September 20 –October 9	October 25–November 13	December 2–8
Max solar altitude (degree)	74.22–72.76	701.52–69.31	53.53–46.17	40.29–34.35	30.27–29.48
Light	Off	Off	Fix at 300 lux	Fix at 300 lux	Fix at 300 lux
Position 1	Camera 1	Camera 1	Camera 1	Camera 1	Camera 1
Position 2	Camera 2	Camera 2	Camera 3	Camera 3	Camera 3

f Thermal comfort

Thermal comfort was evaluated using the Predicted Mean Vote (PMV) method, as described earlier in this report. Mean radiant temperature and radiation shielded air temperature were monitored at desk level position in the test rooms (Figure IV-26) near the window. The air velocity was assumed to be 0.1 m/s, since there was no forced air flow (e.g., ceiling and fan in the space, as suggested by CBE at UC Berkeley [Hoyt, 2013], Relative humidity (RH) was assumed to be 30%, based on tests that indicated that the air was recirculated all the time without mixing any fresh outdoor air and that, therefore, relative humidity was constant. For the comfort calculations, we assumed a seated person typing (met=1.1), dressed in typical clothes (clo=0.5) and winter clothes (clo=1.0).

Figure IV-26. Thermal comfort station in test room.

g HVAC load

The heating and cooling loads are measured by precision instruments to enable accurate comparisons between the rooms. On the heating side, the electric heater is monitored by a power meter (Ohio Semitronics GW5, accuracy: 0.2 %). The cooling side is monitored by a precision water flow meter (Hoffer HO1/2X3/8A-.75- 7.5-BP- 1M-MS- X, accuracy: <1.0 %) with attached transducer and precision temperature measurements of supply and return by resistance temperature detectors (YSI 46016, accuracy: 0.5 %). The two fans are monitored by a single electric power meter (Ohio Semitronics GW5, accuracy: 0.2 %). All data is centrally collected at 1-minute intervals by a building management system, which is implemented in National Instruments LabView.

The total HVAC load, which is the thermal load for the whole room, is calculated as shown as below:

$$\mathrm{P}_{\mathrm{HVAC}} = \mathrm{P}_{\mathrm{Heat}} + \mathrm{P}_{\mathrm{Fan}} + \mathrm{P}_{\mathrm{Light}} - \mathrm{P}_{\mathrm{Cool}} + \mathrm{P}_{\mathrm{Offset}}.$$

The total HVAC load also includes the losses through the near adiabatic walls and floor. To compensate for this error, pre-determined UA values (U-value * Area) and their respective temperature differences are used to calculate these parasitic heat flows:

$$P_{\text{Window}} = P_{\text{HVAC}} - UA_{\text{Wall}} * (T_{\text{Guard}} - T_{\text{Room}}) - UA_{\text{Floor}} * (T_{\text{Underfloor}} - T_{\text{Room}}).$$

The resulting window load is the thermal and solar introduced load in the room by the whole south façade element, which includes window and frame.

ELECTROCHROMIC GLASS AND CONTROLS

a Electrochromic glass

Two EC windows manufactured by SageGlass were installed in rooms B and C. The visible transmittance (Tvis) of the EC windows could be set to one of four levels: 1%, 6%, 18%, and 60% (Figure IV-27, Table IV-8), in response to the signal from a sensor mounted on an exterior façade that monitored vertical illuminance (Figure IV-28), according to illuminance setpoints and solar position.

Figure IV-27. EC window in Room B when it was tinted, upper window transmittance = 1%, middle window transmittance = 60% and lower window transmittance = 18%.

Table IV-8. EC glass specification

SageGlass	%Tvis	%Rf Ext.	%Rb Int.	%Tsol	SHGC	U-factor	%Tuv	%Tdw-K
Clear State	60	16	14	33	0.41	0.28	0.4	15
Intermediate state 2	18	10	9	7	0.15	0.28	0.2	5
Intermediate state 1	6	10	9	2	0.10	0.28	0.1	2
Fully Tinted	1	11	9	0.4	0.09	0.28	0	0.6

Figure IV-28. Exterior illuminance sensor was attached on the window frame of south façade.

b Control settings

Similar to the field site, EC windows could operate in one of three modes: daylight mode, glare mode and manual override mode. Table IV-9 shows the setpoints for EC window operation when in daylight mode. Table IV-10 shows the parameters for glare mode.

Table IV-9. EC daylight mode setpoints.

	High solar altitude	**High solar altitude**	**Mid solar altitude**		**Low solar altitude**		**Low solar altitude**
Period of analysis	Jul 12–21	September 27–August 5	September 20–October 9		October 25–November 13		December 2–8
Set points			September 20–30	October 1–9	October 25–29	October 30–November 13	
Room B							
Top	6000 lux	6000 lux	6000 lux	4000 lux	4000 lux	4000 lux	4000 lux
Mid	6000 lux	6000 lux	6000 lux	8000 lux	8000 lux	4000 lux	4000 lux
Bottom	6000 lux	6000 lux	6000 lux	12000 lux	12000 lux	8000 lux	8000 lux
Room C							
Top	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux
Mid	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux
Bottom	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux	6000 lux

Table IV-10. Glare mode algorithm settings.

Room	**Zone**	**Morning**						**Afternoon**					
		Start		**Stop**		**Lux Value (K)**		**Start**		**Stop**		**Lux Value (K)**	
		Azimuth	Altitude	Azimuth	Altitude	Start	Stop	Azimuth	Altitude	Azimuth	Altitude	Start	Stop
B	Top	125	20	235	55	18	11	125	55	235	20	18	11
	Middle	125	10	235	45	18	11	125	45	235	10	18	11
	Bottom	125	0	235	35	18	11	125	35	235	0	18	11
C	Top	125	20	235	55	18	11	125	55	235	20	18	11
	Middle	125	10	235	45	18	11	125	45	235	10	18	11
	Bottom	125	0	235	35	18	11	125	35	235	0	18	11

V. Results

A. ELECTROCHROMIC WINDOW OPERATION

Using data from the window control system provided to LBNL by the window manufacturer, the window operation reported by the control system was compared with the control algorithm as described by the manufacturer. Throughout the study period, inspection of the data shows the control system operating according to that description. On April 13, 2016, the glare algorithm settings were changed based on input from the tenants and GSA that the windows were causing the space to appear too dark. An example of automatic operation on a typical sunny day (March 17, 2016) before the glare algorithm change on April 13, 2016, is shown in Figure V-1. Windows start the day going to light tint right before 10 a.m., then going into glare mode at around 12:15 p.m. At about 6 p.m., the upper pane is released from glare mode and goes to light tint, being joined by the two remaining panes about half an hour later. After the April 13, 2016, glare algorithm changes (Figure V-2), on April 16 the windows remain in daylight mode all day, going to light tint between after 10 a.m. and approximately before 5:45 p.m. Figure V-3 shows middle subpane tint throughout the study period for a window that was never in manual override. One can observe the prevalence of full tint until the glare algorithm is changed on April 13, with the window otherwise spending most of the time at light tint.

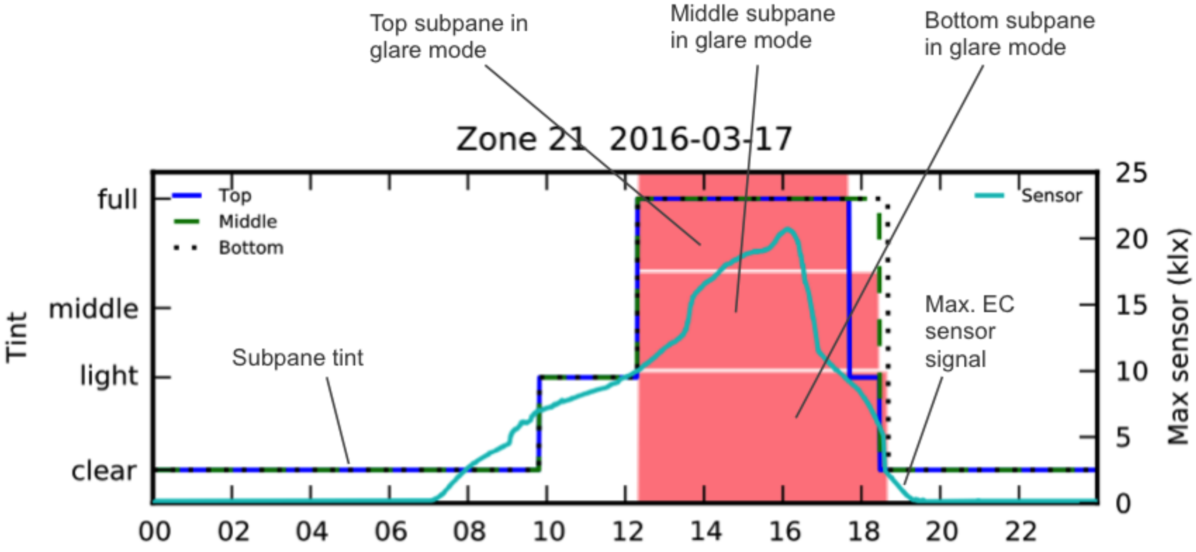


Figure V-1. Window operation on sunny day without manual overrides before April 13, 2016, glare mode algorithm changes. Subpane tint (left vertical axis) is shown by the dark blue line, dark green dash and black dotted line for the top, middle and bottom subpanes, respectively. The maximum exterior vertical illuminance measured by the EC system's three sensors (Figure IV-2) is shown by the light blue line. The red rectangles indicates the periods during which each subpane was in glare mode.

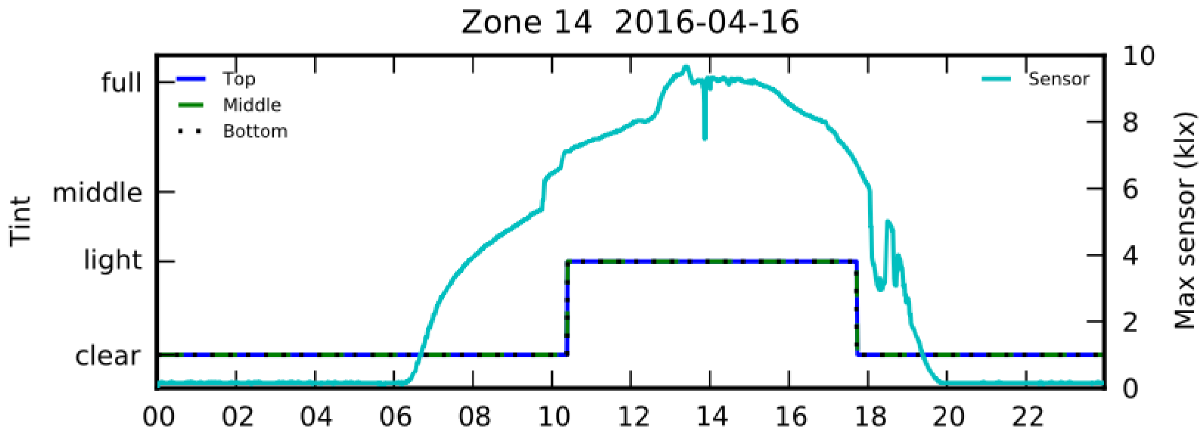


Figure V-2. Window operation on sunny day with no manual overrides after April 13, 2016, glare mode algorithm changes. Subpane tint (left vertical axis) is shown by the dark blue line, dark green dash and black dotted line for the top, middle and bottom subpanes, respectively. The maximum exterior vertical illuminance measured by the EC system's three sensors (Figure IV-2) is shown by the light blue line. All three EC subpanes were set to the same tint level and were in daylight control mode all day.

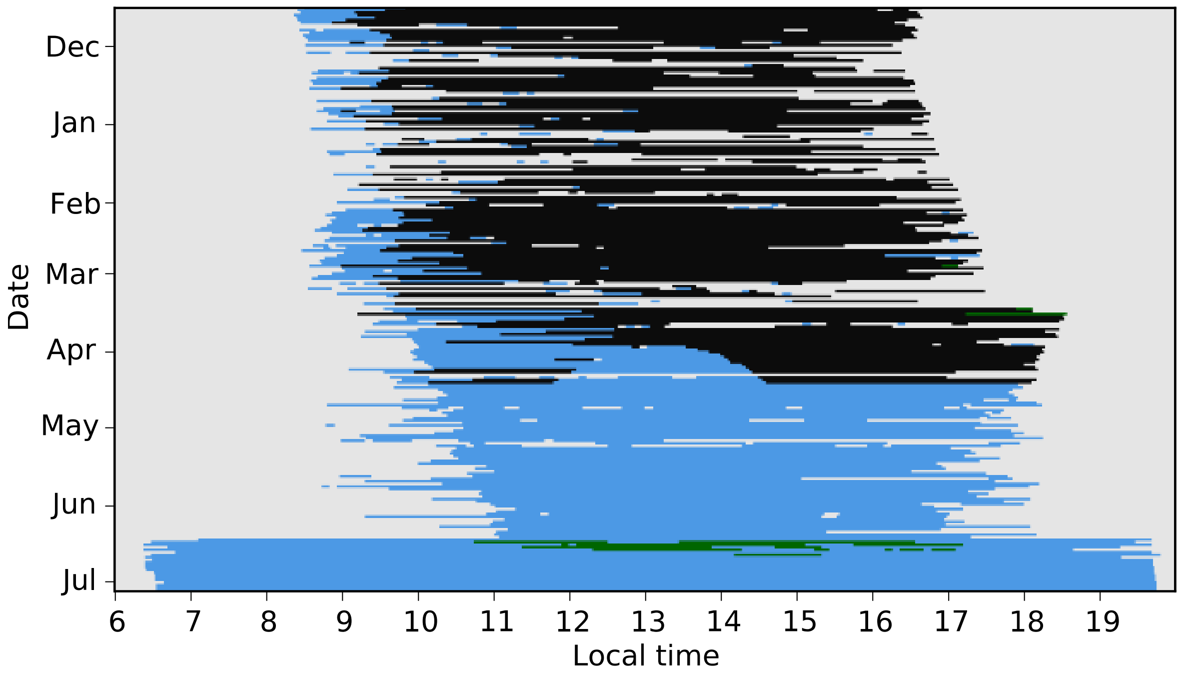


Figure V-3. Window tint when in automatic operation from November 2015 to July 2016. Data shown is for middle pane. Full tint is shown in black, medium tint in green, light tint in blue, and clear tint in light gray.

GLARE MODE

The time windows spend in glare mode depends on solar conditions (e.g., windows will not go into glare mode on a dark, overcast day) and manual overrides, which supersede glare mode, no matter how bright outside. When analyzing the time windows spent in glare mode, we chose a zone that had no manual overrides for the duration of the study and, therefore, where the windows were operating automatically for that period. Figure V-4 shows the amount of time (in minutes) that the windows in this zone spent in glare mode.

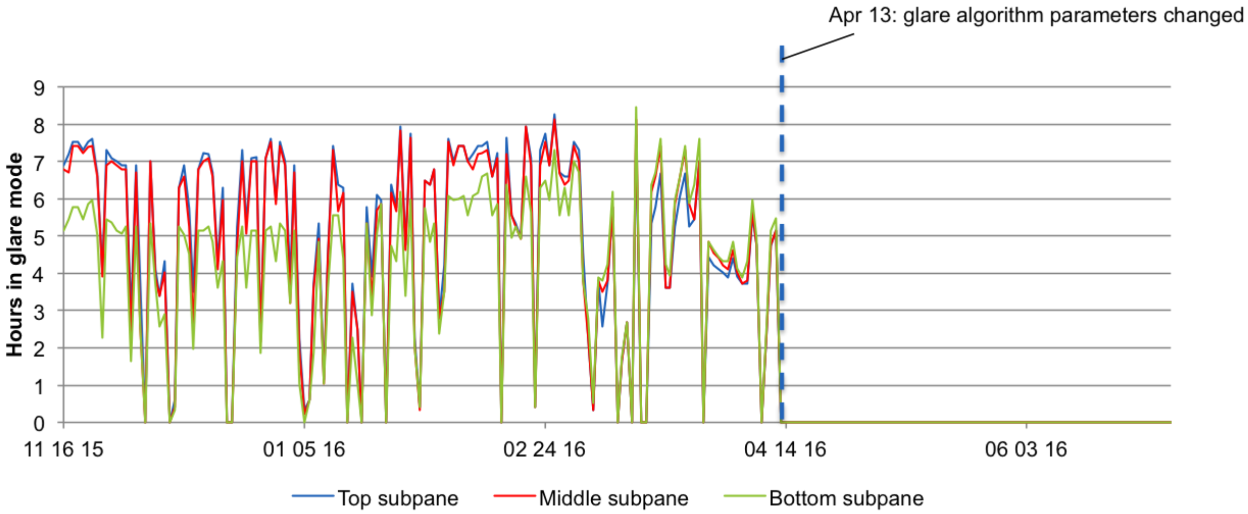


Figure V-4. Time per day at full tint due to glare mode for windows in automatic operation in an auxiliary space (zone 17) with no recorded manual overrides.

It is clear from the figure that, before the changes in the glare mode algorithm, the windows, if left under automatic control, would spend a significant part of the day in glare mode — 400–500 minutes (6.67–8.33 h) for the middle and lower subpanes, 300–500 minutes (5–8.33 h) for the upper subpanes, depending on time of year, exterior light levels and solar position. After the changes in the glare mode algorithm, however, windows spent no time whatsoever in glare mode.

MANUAL OVERRIDES

To analyze the prevalence of manual override mode throughout the study, the time each zone spent in manual override was calculated for each week during the study. The weekly average of time in manual override was, when taken throughout all zones,[1] about one hour or less per day and per zone (Figure V-5). However, manual override use varies significantly from zone to zone, with between 36% and 82% of zones registering zero minutes in manual override during any given week (Figure V-6). For each week, the zone with maximum time in override was recorded as being overridden between 2 and 9 h/day (Figure V-5). If we order the zones by time spent in manual override throughout the whole study (Figure V-7), we can see that overall manual override use falls off rapidly: 4.65 h/day for the zone with highest use, followed by 2.53, 1.98, 1.63 and 1.09 h/day for the next four zones in terms of manual

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[1] Excluding four zones that were unoccupied throughout the study: three spaces used for research (zones 6, 18 and 19) and a stairwell (zone 20).

override use. The three zones with highest manual override use account for 52% of all time spent in manual override; the eight zones with highest use account for 83% of time in manual override. Figure V-8 shows cumulative time in override (calculated by adding the amount of time each individual zone was in manual override) for every week (Monday to Friday only) from November 2015 to June 2016. Using this metric, windows spent 55%, 23%, 13%, and 9% of the time at clear, light, medium, and full tints, respectively.

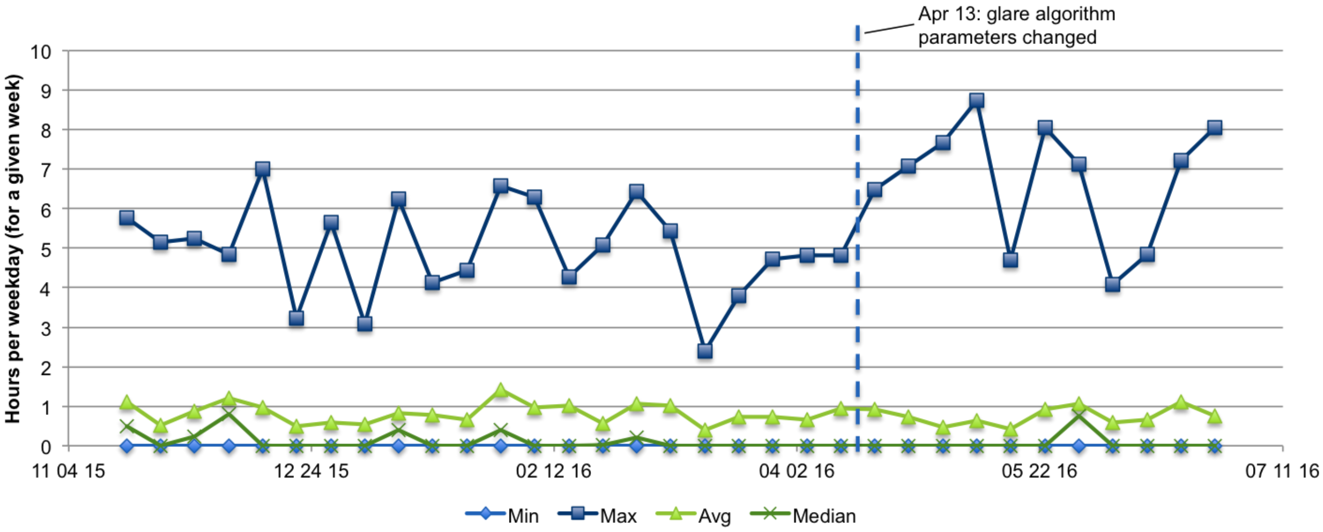

Figure V-5. Weekly minimum, maximum, average, and median hours in manual override per weekday and per zone. For each week, minimum, maximum, average, and median are calculated across all zones (excluding zones 6, 18, 19, and 20, which were considered unoccupied for the purposes of this research), for Monday to Friday.

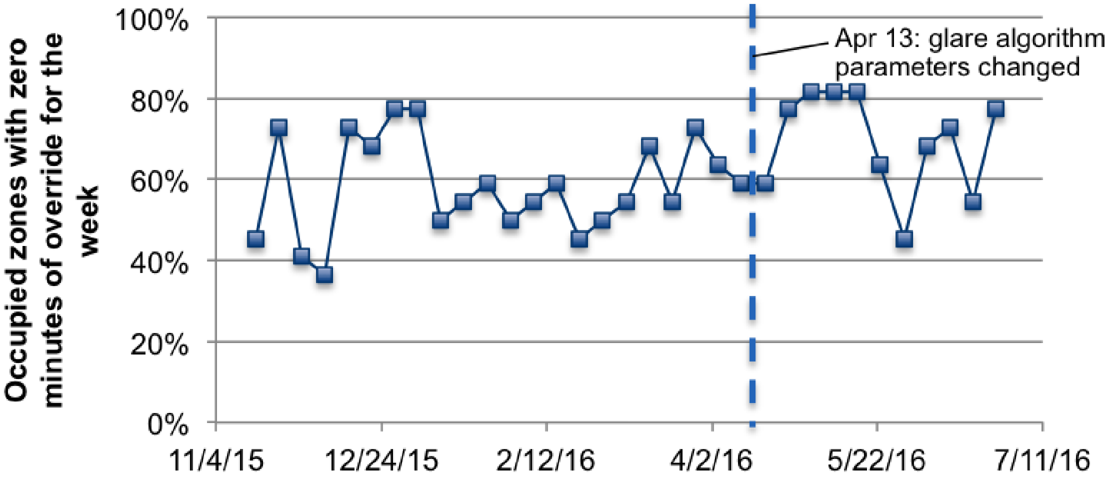

Figure V-6. Percentage of zones with zero minutes per week (Monday to Friday only) in manual override.

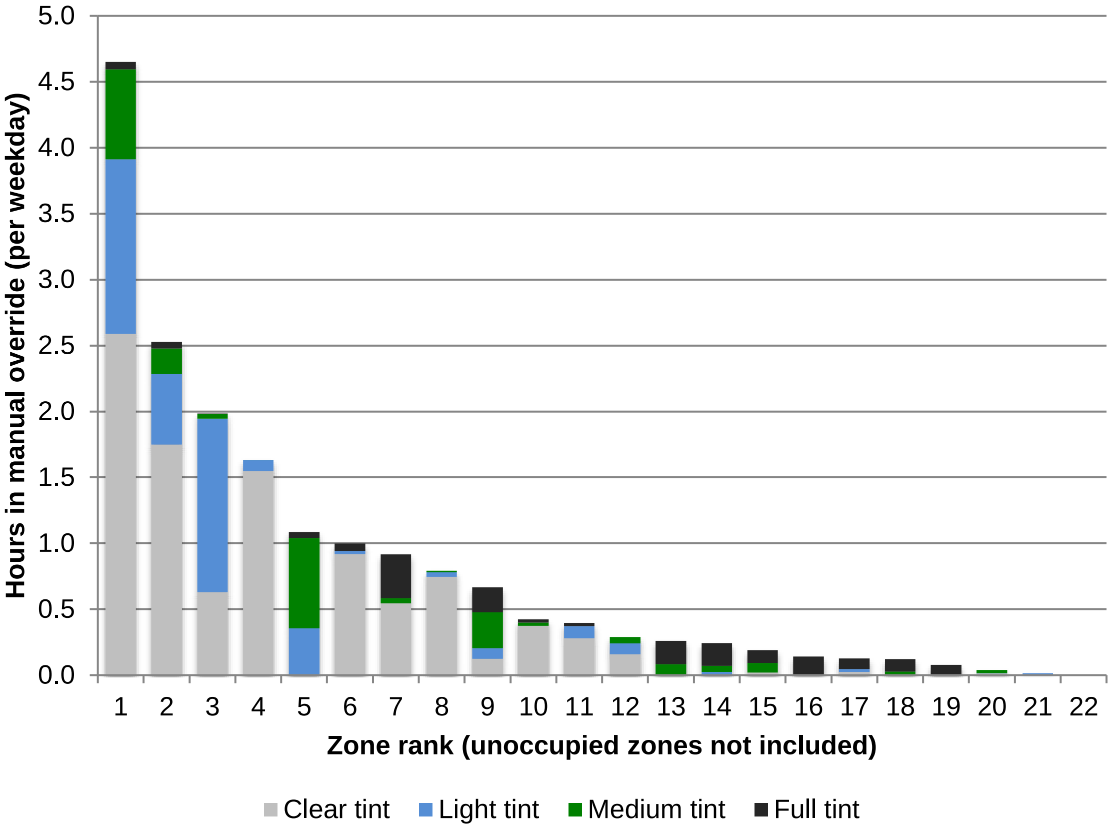

Figure V-7. Average hours per weekday in manual override for each tint level and for each zone (excluding zones 6, 18, 19, and 20, which were considered unoccupied for the purposes of this research), ranked in descending order, from November 2015 to the end of June 2016. Note that the indices on the horizontal axis denote rank and do not correspond to the zoning shown in Figure IV-3.

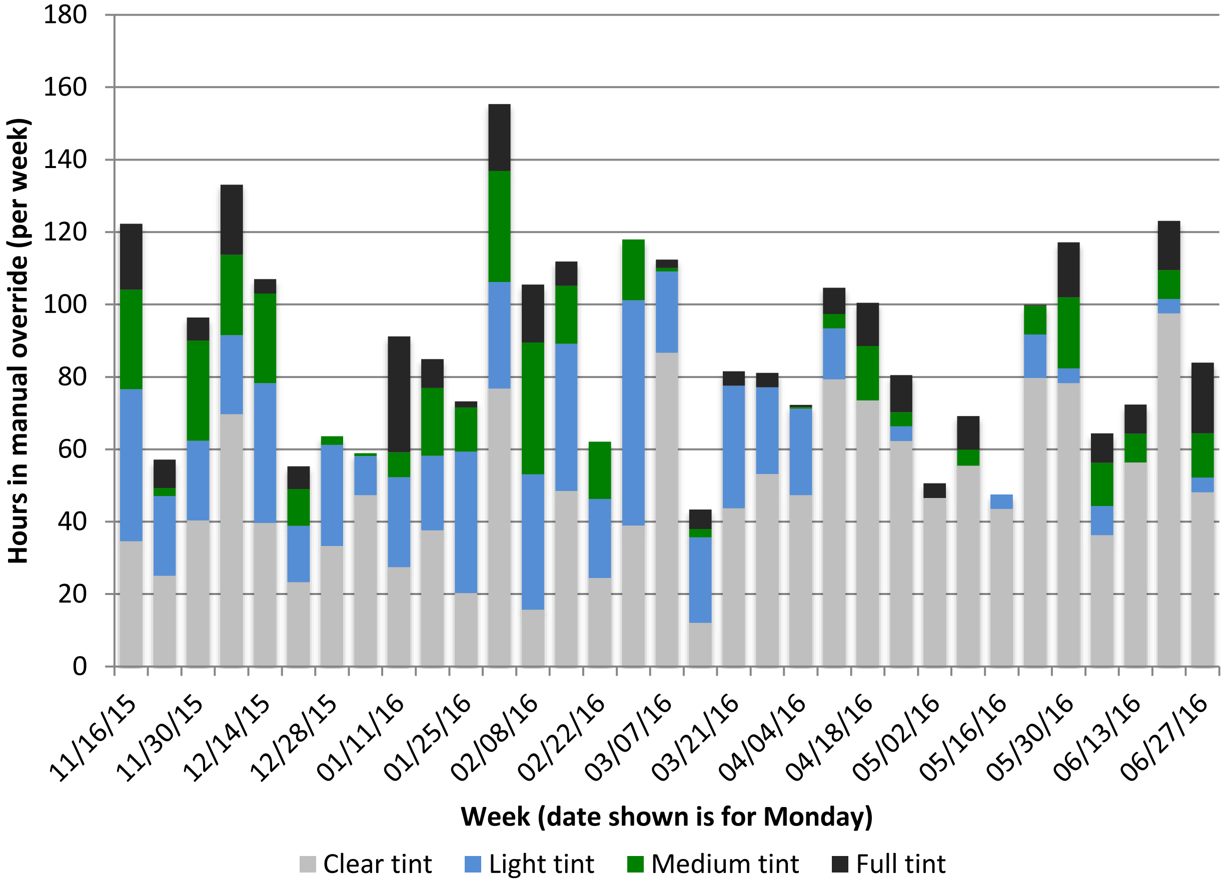

Figure V-8. Weekly (Monday to Friday only) cumulative hours in manual override for each tint level in all zones (excluding zones 6, 18, 19, and 20, which were considered unoccupied for the purposes of this research).

B. INDOOR VENETIAN BLIND USE

Figure V-9 shows the percentage of individual blinds that were observed at other than their fully raised position over the span of the study. Blinds in zones 6, 18, 19 (spaces used for research), and 20 (stairwell) were excluded from this calculation. The percentages observed are high, starting at 90% in November 2015, and then decreases gradually, but consistently (no observation was higher than the ones prior), until reaching 79% by mid-June. Also shown in the figure is the percentage of blinds that were lowered over 50% or more of the window surface. This percentage also is high, taking values in the 67%–77% range throughout the study period, with no discernible trend (sometimes increasing, other times decreasing, between consecutive observations).

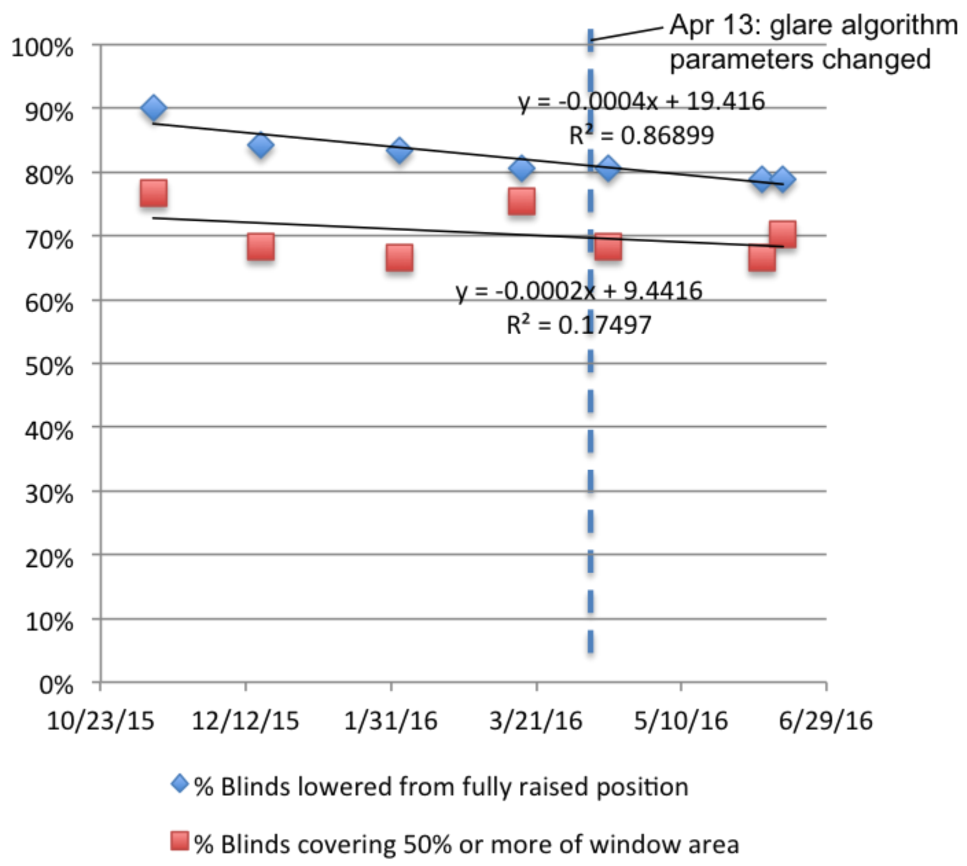

Figure V-9. Percentage of blinds observed to be in use. Zones 6, 18, 19, and 20 are excluded from this calculation.

These results need to be taken in the context of the prior, unsuccessful installation of EC windows on this floor. By the time the faulty windows were replaced with fully functional units, negative expectations of the capability of EC windows to control glare could have caused occupants to use blinds at higher rates than if they not been exposed to faulty windows beforehand.

C. OCCUPANT SURVEY

The occupants of the sixth floor were surveyed in the first half of June 2016 on several aspects of their experience with the EC windows, including visual and thermal comfort. To serve as a control group, occupants on the eighth floor were surveyed simultaneously. Twenty surveys were returned from the sixth floor and seven from the eighth floor.

Survey responses to key questions (denoted by "Q#," see Appendix A for full survey text) are summarized in Figures V-10 to V-12. Statistically significant[2] results are indicated in the

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[2] For comparisons between the two floors, statistical significance was assessed, at the 95% level (i.e., p-value < 0.05), by an equal variance two-tailed t-test. For before-after comparisons on the EC floor, 95%

figure and marked with an “**S**” in the text below. Average occupant response is indicated in the text in parenthesis. Summary results are shown in Tables V-1 and V-2.

In general, occupants performed tasks that involved mainly computer work (reported average of 76% and 62% of the time on the EC and reference floors, respectively); occupants also reported working on paper-based tasks, as well as using the phone, with the smallest amount of time (less than 6% on either floor) spent on face-to-face interactions.

In interpreting these results, it should be kept in mind that, with regards to indoor environment preferences, there is a considerable variability of preferences within the human population, and a single occupant’s experience may or may not be representative of the average occupant response.

DAYLIGHT LEVELS

Light levels reported by the occupants (Q9c) were just under “just right” (average response of 4.8) on the EC floor and slightly bright (6.0) on the reference floor. In terms of perceived sufficiency of daylight (Q10c), occupants on both floors were slightly positive on the EC floor and markedly positive on the reference floor (5.7 and 7.5 for EC and reference floors, respectively). Results do not indicate any significant difference in light levels or, more specifically, daylight levels between the two floors due to the introduction of EC windows. Lower reported light levels — and especially daylight levels — on the EC floor (versus the reference floor) would be consistent with the facts that (a) the windows, when automatically controlled, spent a significant amount of time at full tint prior to April 13, 2016 and that (b) there was a high prevalence of occupant use of blinds throughout the study.

VISUAL DISCOMFORT/GLARE

The reported level of glare (Q9d) was acceptable (5.0) on the EC floor and slightly closer to uncomfortable than to acceptable (6.1) on the reference floor. Occupants disagreed slightly with the statement that bright light on their task made it difficult to read or see (Q10a), more so on the reference floor (3.9) than on the EC floor (4.4). On the EC floor, occupants agreed slightly (5.5) with the statement that they experienced less glare with the EC windows than with the original windows (Q11a). Although the observed between-floor differences in average occupant response are not statistically significant, lower reported glare on the EC floor versus the reference floor would be consistent with lower reported between-floor levels of daylight.

THERMAL COMFORT

The reported temperature during warm/hot weather (Q9a) was just warmer than “just right” (5.3) on the EC floor, and just cooler than “just right” (4.6) on the reference floor. During cool/cold weather (Q9b), reported temperatures were slightly to moderately colder than “just right,” but virtually the same on both floors (3.6 and 3.4 on EC and reference

confidence intervals were used. For the two-alternative choice between EC and conventional windows, the Clopper-Pearson interval technique for binomial statistics was used.

floors, respectively). EC floor occupants moderately agreed with the statement that they feel less heat from the sun with the electrochromics (Q11b, **S**, 6.85), while their response was just more negative than neutral (4.75) regarding whether they felt more thermally comfortable overall with the EC windows (Q11c).

Results indicate that, on average, occupants clearly feel, although moderately, that the EC windows provide better solar control than the original windows. Other EC impacts on thermal comfort are not discernible from these results.

VIEW/USE OF SHADES

On the reference floor, occupants were neutral regarding whether the shades blocked the view (Q10b, 5.0). On the EC floor, occupants disagreed moderately (3.4). When asked whether the outside was sufficiently visible through the window (Q10f, **S** – statistically significant result), occupants on both floors agreed, strongly on the reference floor (8.7) and moderately on the EC floor (6.7).

Respondents also were asked about their use of the blinds. The majority of EC floor respondents reported lowering the blinds from their raised position since the start of the study in December 2015 (14 out of 19 responses). When asked about the reasons for doing so, 11 out of the 14 respondents who had reported using the blinds reported glare as one of the reasons (11 responses to “reducing glare when the sun is directly visible;” 8 responses to “reducing glare from daylight/sunlight”). Other reasons reported were reducing heat from the sun or controlling reflections on computer monitor (5 responses each), reducing overall brightness of the space or increasing privacy (4 responses each), reducing the cold draft from the window (3 responses), and decreasing the level of visual stimulus from the outside and hiding the tinting patterns (horizontal bands) on the window (2 responses each). Ten of these 14 occupants reported adjusting the blinds to the same height and slat angle employed before the beginning of the study. Of the other four occupants, three reported setting the blinds higher than originally and one lower. These four occupants also reported adjusting the blinds less often than before the study. These results suggest that occupants of the EC floor mostly set the blinds to their original height and that their main concern was protection from glare.

The fact that occupants on the EC floor report less access to view than those on the reference floor is surprising — one would expect blinds to be less in use on the EC floor and, therefore, access to view to be greater. At the same time, while not statistically significant, the between-floor difference in agreement with the statement “the shades blocked the view” (3.4 and 5.0 for EC and reference floors, respectively) is rather large and suggests that the lower reported access to view on the EC floor is due to a factor other than the blinds. The fact that the EC windows spent a significant amount of time at full tint until April 13, 2015, comes to mind as a probable cause.

The fact that the majority of occupants who used the blinds report doing so to the same height and slat angle that they used prior to the study is in accordance with the high prevalence of blind use recorded throughout the study on the EC floor.

EC WINDOW TECHNOLOGY

If given the option, 63% of the occupants of the EC floor responded that they would prefer EC windows (12 responses) to non-switchable windows (7 responses) in their space (Q13). However, occupants on the EC floor were, on average, only just more satisfied than neutral (5.2) with the EC windows than with the original windows (Q11d).

Occupants on the EC floor found their windows less aesthetically pleasing than those on the reference floor (Q10d, **S**, 6.0 and 8.0 for EC and reference floors, respectively). Occupants were neutral (4.95) with regard to whether the tinting/untinting of the windows did not disturb them in their work (Q10e). Occupants agreed slightly (6.0) with the statement that the wall switches allowed the windows to be manually controlled in a satisfactory way (Q10g). Occupant response was just above neutral (5.4) regarding whether they agreed that the speed at which the windows tinted/untinted was satisfactory (Q10h). Occupant response was just below neutral (4.6) regarding whether they agreed with the statement that the windows looked aesthetically pleasing when they had horizontal bands of different tints (Q10i). Occupants disagreed slightly (3.8) with the statement that those tinting patterns made sense to them (Q10j).

Almost all respondents used the wall switches to tint/untint the EC windows (17 out of 19 responses). As for the reasons for tinting/untinting windows using the wall switches, the most frequently mentioned were reducing glare when the sun was directly visible and increasing the brightness of the space (7 responses each), followed by reducing glare from daylight/sunlight (6 responses), reducing the overall brightness of the space (5 responses), decreasing the brightness of reflections on their computer monitor (4 responses), getting a better view (3 responses), and to reduce heat from the sun, reducing the cold draft from the window and increasing the level of visual stimulus from the outside (2 responses each). When asked about the frequency of wall switch use, 12 of the 17 occupants who reported using the switches reported at least daily use (6 two or more times a day, 6 once a day), with 3 reporting use less often than once a week and 2 at least once a week (but not daily). Regarding whether the windows tinted/untinted as expected when occupants used the switch, 15 out of 16 respondents agreed, and 12 out of 14 respondents reported that the windows achieved the effects that they intended when they decided to use the switch. Overall, results show: (a) a sizeable proportion of occupants report being active users of the wall switches, (b) they do so primarily for glare and light level control and (c) the windows generally respond according to occupants' expectations.

When comparing the frequency of manual overrides reported by the occupants to the duration of manual overrides reported by the control system, a discrepancy arises — it would be reasonable to expect that if 12 zones were being overridden daily, then the average time in override would be higher than what is shown in Figure V-7, given that the default duration for manual override is set to 4 hours. Several factors could contribute to this discrepancy. First, occupants may be overestimating their actual frequency of wall switch use or recalling only the days on which they were present in the office during a significant part of the day (results shown in Figure V-7 are for every weekday during the study period, including holiday periods). Second, regardless of the four-hour default period for manual override, all windows are reset to clear at around sunset, which means that the duration of overrides that happen within four hours before sunset is less than the default period. Finally, it is possible that some occupants used the switches to set the system back to automatic operation before the four-hour default override period had passed.

Overall, survey results indicate that occupants of this space prefer EC windows to conventional windows. A statistically significant improvement in thermal comfort in warm or hot weather was observed. No statistically significant negative impacts on work performance or dissatisfaction with the technology were found.

COMMENTS

The survey asked occupants for their overall comments on the windows in their space (Q26: "Please provide any comments on your experience of the switchable windows in your workplace"). Comments provided spanned a wide range of opinions, roughly categorized below, starting from the most positive to the least positive. Comments are reproduced verbatim and were not edited for grammar or spelling.

- Overall satisfied:
    - *Great product! I would love to have them @ home.*
    - *Good window system. Thank you.*
- EC helps with glare control when used with blinds:
    - *I like using them in conjunction with the blinds. The sun shines through because the windows are tall, so we need the shades to block the direct sun & brightness. I like the switchable windows. I use the blinds less (they are lifted higher than before).*
    - *Nice in conjunction with blinds. Otherwise too much direct light, glare, reflection of surface.*
- Too dark:
    - *At times it was frustrating because they would get too dark several times a day.*
    - *They are on a programmed timeline to tint - I don't like having to untint them repeatedly every day in order to try to warm up my office.*
    - *Made it look gloomy outside*
- Slow to respond:
    - *Took too much time to make adjustments, and several adjustments per day.*
- Need personalized adjustments to control algorithm:
    - *I don't like the automatic darkening of the windows but if I must have it, then it needs to over-ride able. [In other comments written down on the survey this person self-described as "very nearsighted and need lots of light"; "tired of constantly having to hit the cancel button for window darkening"]*
- Issues with subpane tinting patterns/glare control:
    - *It appears that the tint works fine except the darkening pattern sometimes does not make sense for the angle of the sun. As far as reducing heat from sun - I only feel a minimal reduction. Glare still is an issue with my CPU screen. In my*

    opinion, just tint the windows permanently or place louvers on outside of building.
  - *They need to be darker, longer adjusted for seasons to adjust of position of the sun*
- Issues with the lighting:
  - *What about survey for lights; they are not that great either.*
- Waste of money:
  - *I think the whole window tinging was a sate of money [sic]. The windows are still drafty and unsatisfactory.*
  - *It seems like a waste of federal funds.*

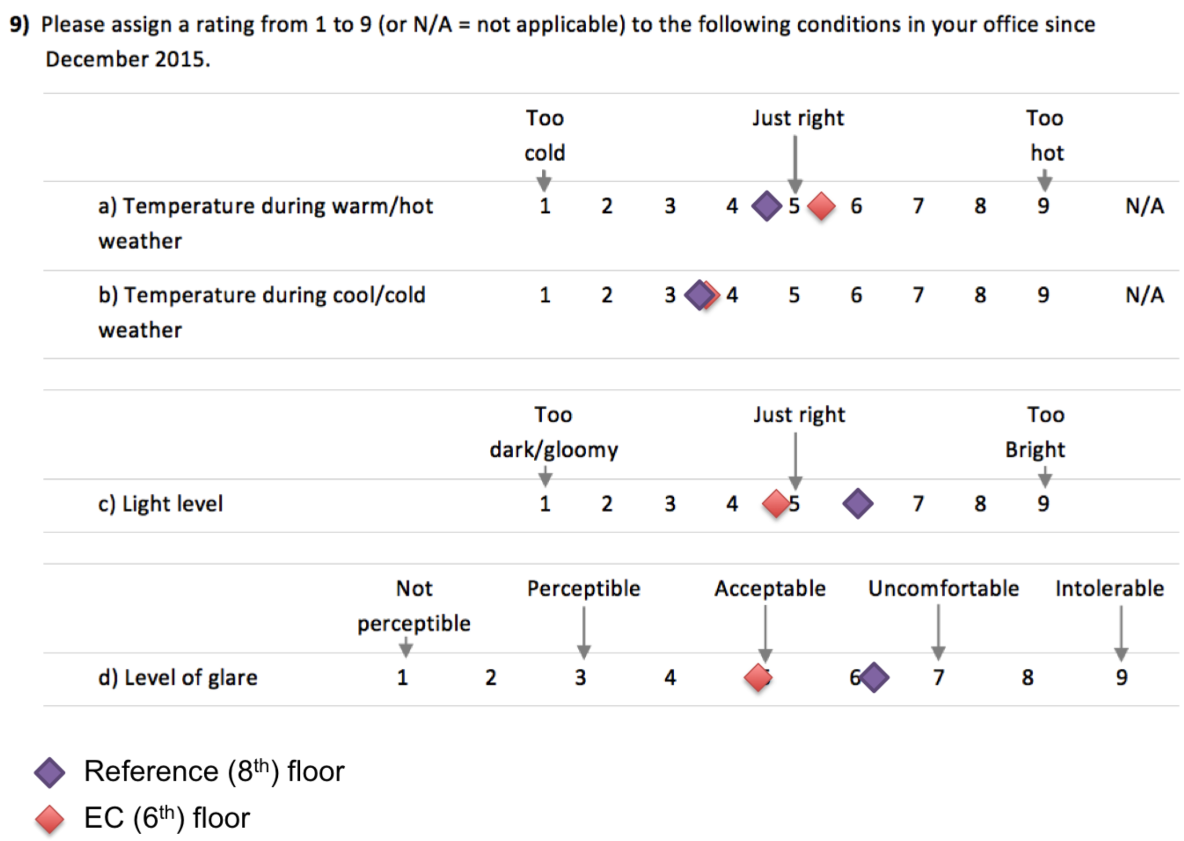

Figure V-10. Average occupant ratings of environmental conditions on reference and EC floors.

10) Indicate your level of agreement/disagreement (disagree = 1, agree = 9) with the following statements about your office since December 2015:

a) Bright light on my task made it difficult to read or see

b) The shades blocked the view

c) There was enough daylight in the space

d) The windows looked aesthetically pleasing

e) The tinting/untinting of the windows did not disturb me in my work

f) The outside was sufficiently visible through the window

g) The wall switches allowed the window to be manually controlled in a satisfactory way

h) The speed at which the windows tinted/untinted was satisfactory

i) When the windows had horizontal bands of different tints, they looked aesthetically pleasing

j) When the windows had horizontal bands of different tints, the tinting patterns made sense

Figure V-11. Average occupant agreement with statements regarding environmental conditions on reference and EC floors.

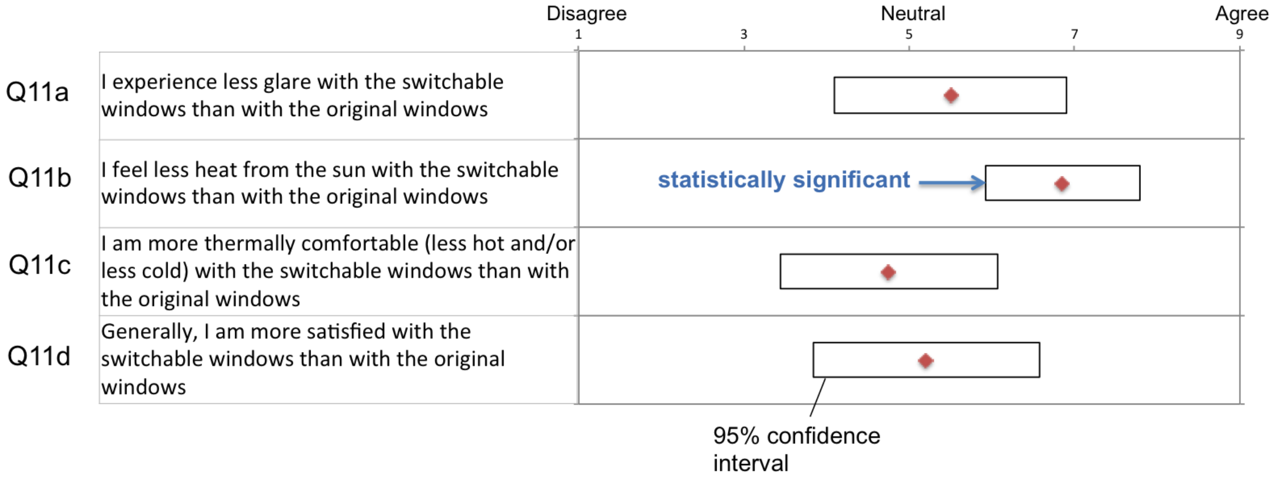

Figure V-12. Average occupant agreement with statements comparing EC windows with original windows on EC floor.

Table V-1. Summary data on key survey questions issued on both EC and reference floor.

		EC floor			Reference floor			
Question no.	Question	Number of responses	Average response	Standard deviation	Number of responses	Average response	Standard deviation	p-value
9 a)	Temperature during warm/hot weather	20	5.30	1.92	7	4.57	2.76	0.45
9 b)	Temperature during cool/cold weather	19	3.63	1.89	7	3.43	2.64	0.83
9 c)	Light level	20	4.80	1.82	7	6.00	1.15	0.12
9 d)	Level of glare	20	4.95	1.67	7	6.14	1.21	0.10
10 a)	Bright light on my task made it difficult to read or see	19	4.37	2.48	7	3.86	3.13	0.67
10 b)	The shades blocked the view	16	3.38	2.85	6	5.00	2.61	0.24
10 c)	There was enough daylight in the space	20	5.70	3.21	7	7.43	1.81	0.19
10 d)	The windows looked aesthetically pleasing	20	6.00	2.32	7	8.00	1.53	**0.04**
10 f)	The outside was sufficiently visible through the window	20	6.70	2.58	7	8.71	0.76	0.05

Table V-2. Summary data on key survey questions issued on EC floor only.

Question no.	Question	Number of responses	Average response	Standard deviation	95% confidence interval Lower bound	Upper bound
10 e)	The tinting/untinting of the windows did not disturb me in my work	20	4.95	3.50	3.42	6.48
10 g)	The wall switches allowed the window to be manually controlled in a satisfactory way	20	6.00	3.09	4.64	7.36
10 h)	The speed at which the windows tinted/untinted was satisfactory	20	5.40	2.91	4.13	6.67
10 i)	When the windows had horizontal bands of different tints, they looked aesthetically pleasing	19	4.63	2.71	3.41	5.85
10 j)	When the windows had horizontal bands of different tints, the tinting patterns made sense	19	3.79	2.74	2.56	5.02
11 a)	I experience less glare with the *switchable* windows than with the *original* windows	20	5.50	3.20	4.10	6.90
11 b)	I feel less heat from the sun with the *switchable* windows than with the *original* windows	20	6.85	2.13	**5.91**	**7.79**
11 c)	I am more thermally comfortable (less hot and/or less cold) with the *switchable* windows than with the *original* windows	20	4.75	2.99	3.44	6.06
11 d)	Generally, I am more satisfied with the *switchable* windows than with the *original* windows	20	5.20	3.12	3.83	6.57

D. VISUAL COMFORT

WINTER SOLSTICE, PARTLY CLOUDY DAY (DECEMBER 17, 2015)

On this partly cloudy day, windows spent a significant amount of time at full tint due to glare mode, starting around 10 a.m. until after 2 p.m. for the bottom subpanes and after 4 p.m. for the top and middle subpanes (Figure V-13). DGP values occasionally peak above the threshold for perceptible glare of 0.35, but without reaching 0.40, the threshold for disturbing glare (Figure V-14). This was the case for both positions measured. With respect to discomfort glare, partly cloudy days can be even more problematic than clear, sunny days due to the brightness of clouds illuminated by the sun. In this case, however, and despite the low winter sun, the EC windows were able to control glare throughout the day. Figures V-15 and V-16 show the view from both HDR cameras at noon.

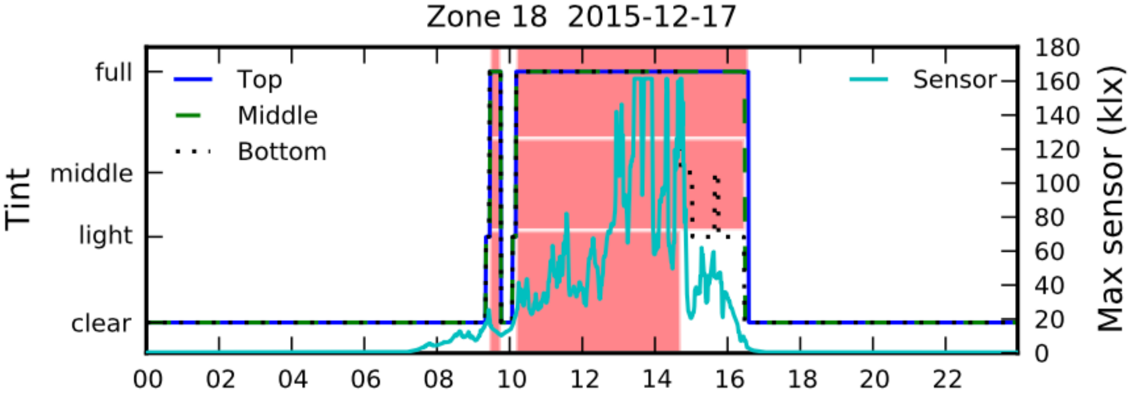

Figure V-13. Window behavior in zone 18 on December 17, 2015.

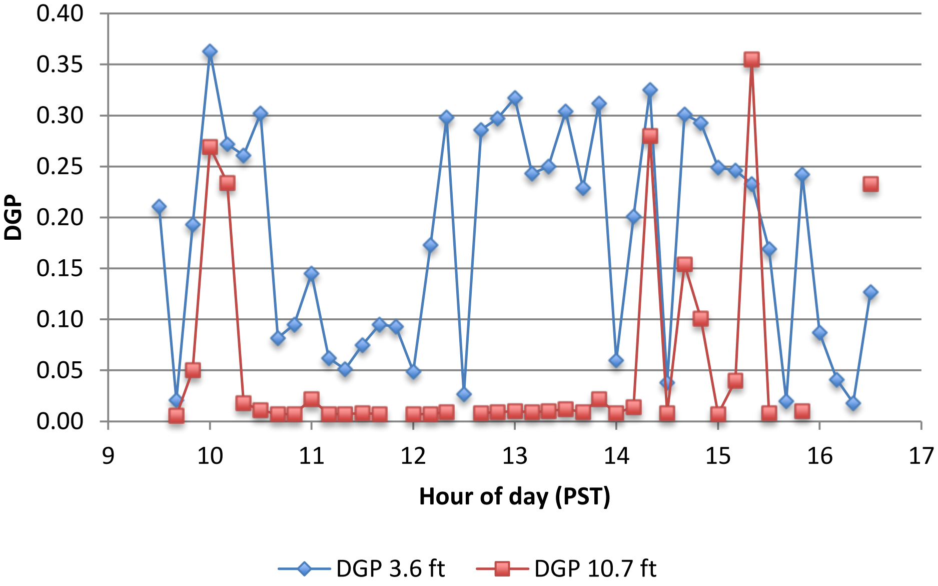

Figure V-14. Daylight glare probability (DGP) measured in zone 18 on December 17, 2015, facing towards window.

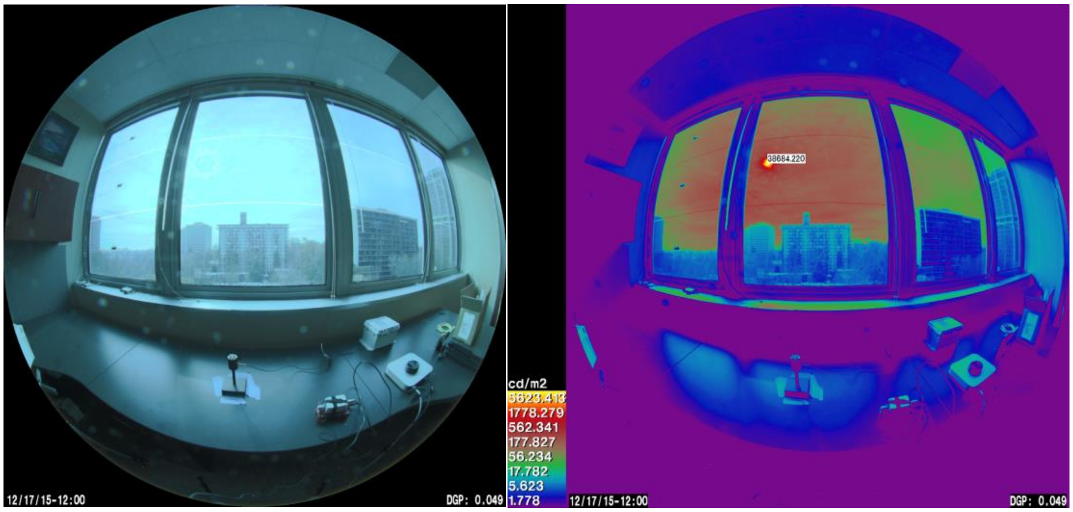

Figure V-15. Fisheye image (left) and false color luminance map (right) obtained at noon on December 17, 2015, with the HDR camera placed 3.6 ft from the window. Windows are at full tint due to glare mode.

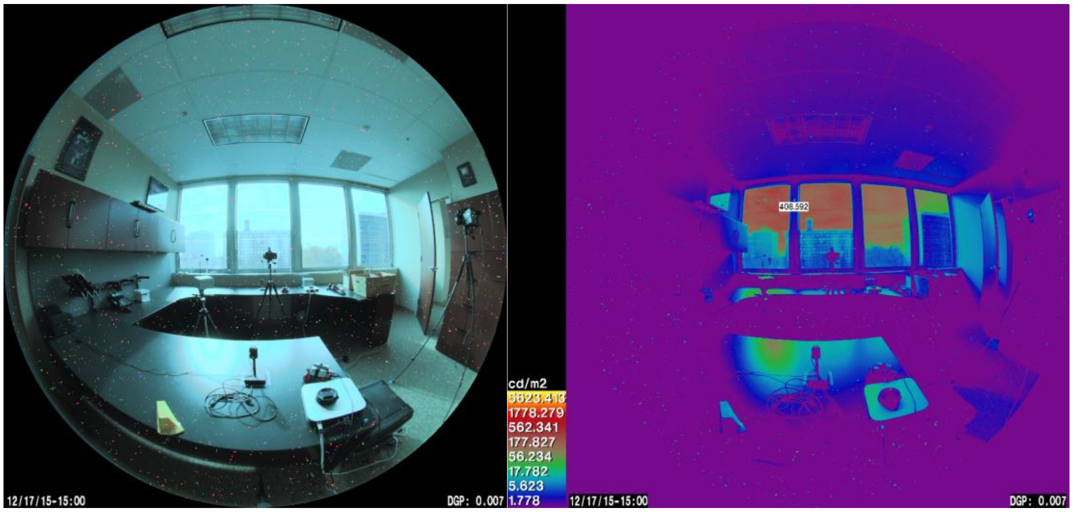

Figure V-16. Fisheye image (left) and false color luminance map (right) obtained at noon on December 17, 2015, with the HDR camera placed 10.7 ft from the window. Windows are at full tint due to glare mode.

EQUINOX, SUNNY DAY (APRIL 16, 2016)

This was a clear, sunny day. Windows were in daylight mode all day, going to light tint from approximately 10 a.m. to 6 p.m. (Figure V-17). For most of the day, the orb of the sun was not visible from any of the measured positions (Figures V-19 and V-20), with DGP staying under 0.30, denoting no perceptible glare (Figure V-18). Towards the end of the day, however, the sun was visible for a few minutes from the camera closest to the window (Figure V-21), resulting in DGP reaching 0.42, which is above 0.40, the threshold for disturbing glare, but does not reach the threshold for intolerable glare (0.45).

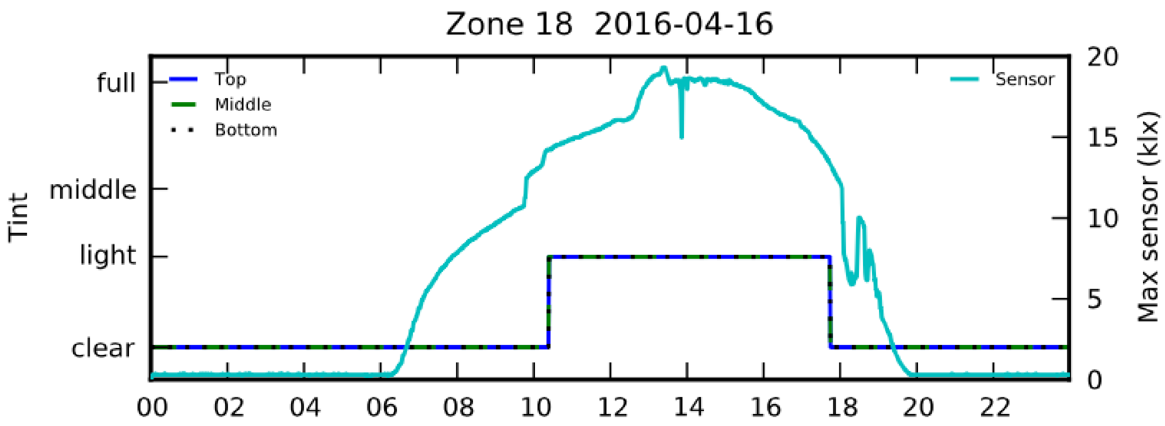

Figure V-17. Window behavior in zone 18 on April 16, 2016.

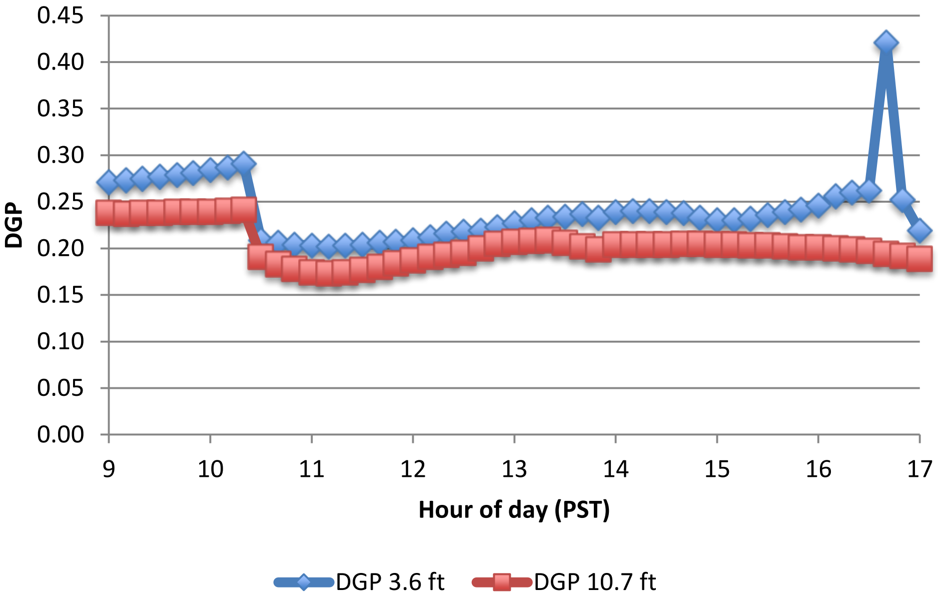

Figure V-18. Daylight glare probability (DGP) measured in zone 18 on April 16, 2016, facing towards window.

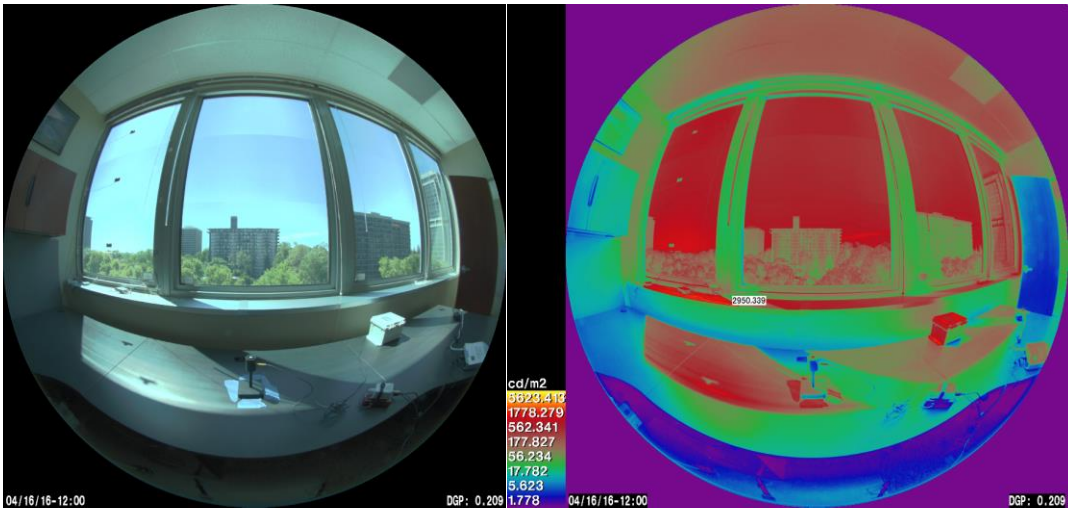

Figure V-19. Fisheye image (left) and false color luminance map (right) obtained at noon on April 16, 2016, with the HDR camera placed 3.6 ft from the window. Windows are at light tint.

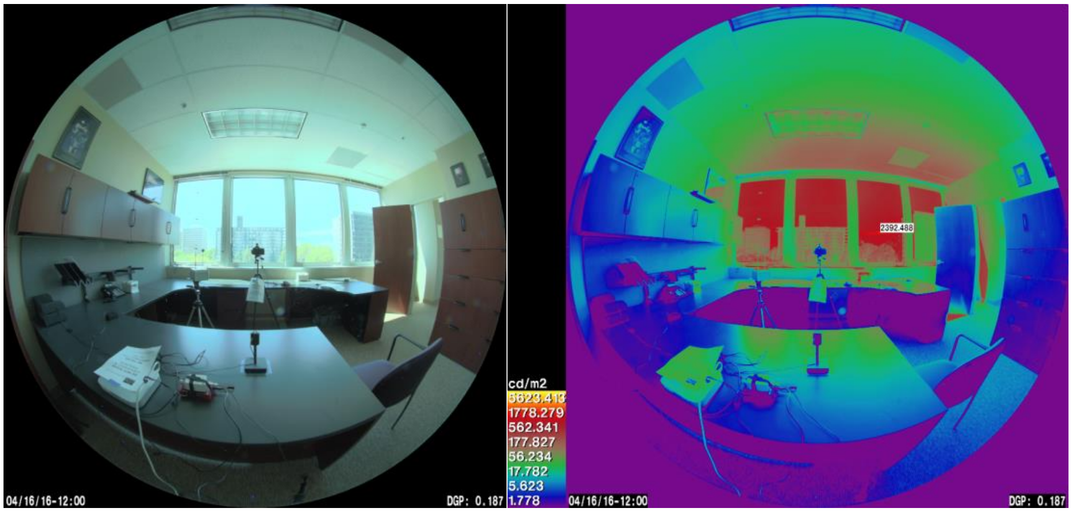

Figure V-20. Fisheye image (left) and false color luminance map (right) obtained at noon on April 16, 2016, with the HDR camera placed 10.7 ft from the window. Windows are at light tint.

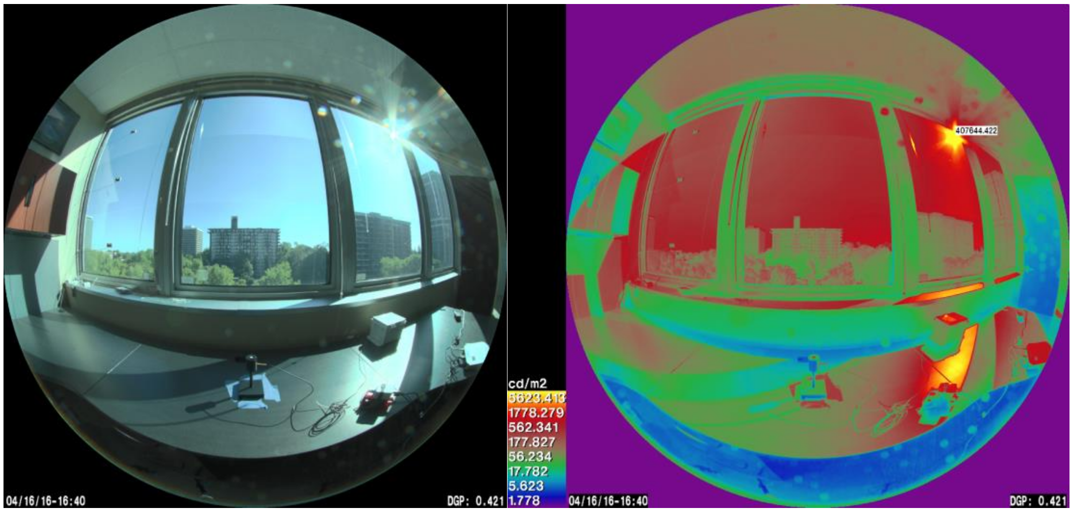

Figure V-21. Fisheye image (left) and false color luminance map (right) obtained at 4:40 p.m. on April 16, 2016, with the HDR camera placed 3.6 ft from the window. Windows are at light tint.

SUMMER SOLSTICE (JUNE 14, 2016)

This was a sunny day with some clouds. Windows were in daylight mode the whole day (Figure V-22), reaching medium tint during bright periods in the morning and afternoon. DGP was well under 0.35 the whole day (Figure V-23), with the sun not being visible from the two measurement positions throughout the day (figures V-24 and V-25).

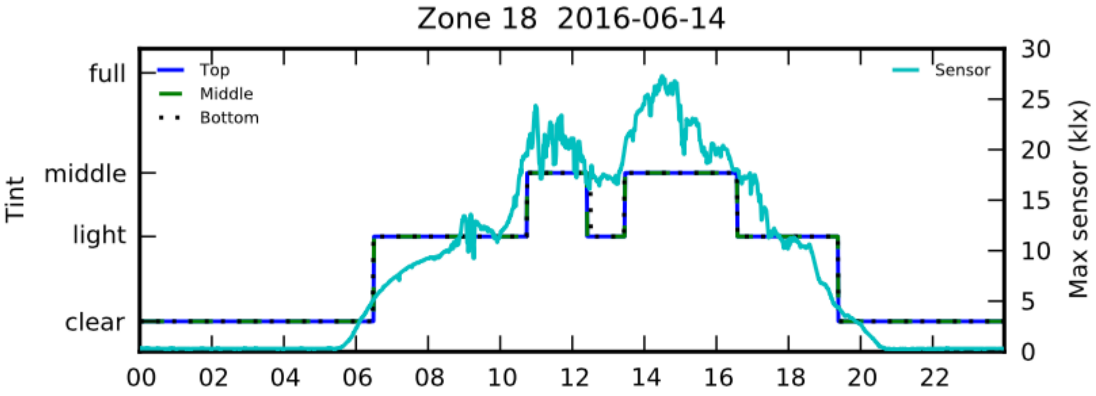

Figure V-22. Window behavior in zone 18 on April 16, 2016.

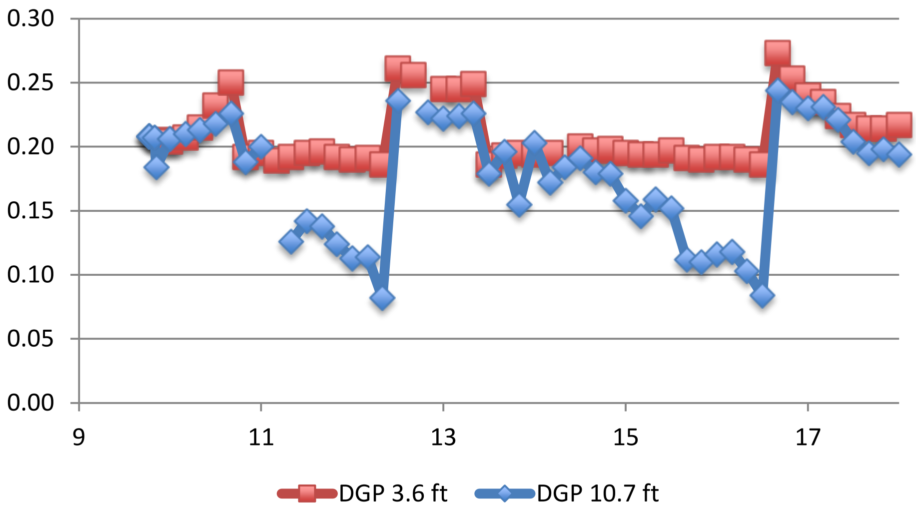

Figure V-23. Daylight glare probability (DGP) measured in zone 18 on April 16, 2016.

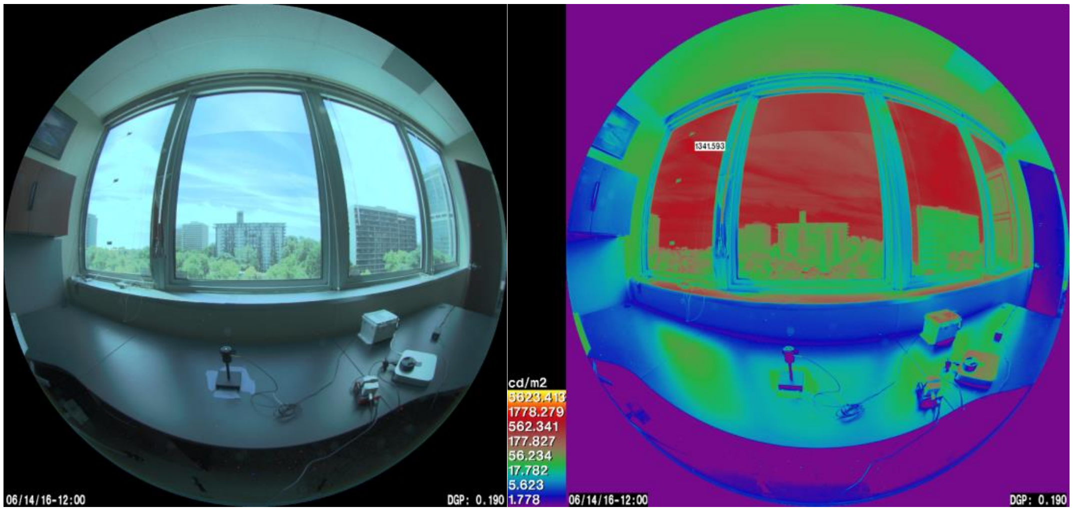

Figure V-24. Fisheye image (left) and false color luminance map (right) obtained at noon on June 14, 2016, with the HDR camera placed 3.6 ft from the window. Windows are at light tint.

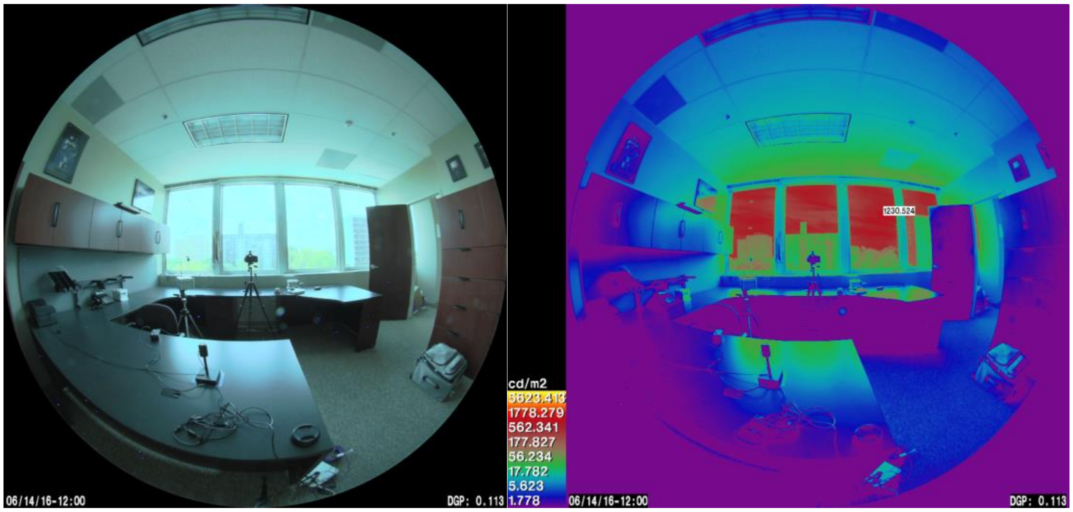

Figure V-25. Fisheye image (left) and false color luminance map (right) obtained at noon on June 14, 2016, with the HDR camera placed 10.7 ft from the window. Windows are at light tint.

E. THERMAL COMFORT

INFRARED THERMOGRAPHY

For each of the site visits during which infrared images were captured, we selected the time of day with the highest indoor glass surface temperature based on data derived from infrared images.

a Winter solstice (December 17, 2015)

Figure V-26 shows results for the winter solstice site visit (December 17, 2015); Figure V-27 shows EC window status at the time the image was taken. Window glass temperature near the center of the window is in the vicinity of 31°C (87.8°F) at 1:52 p.m. Room air temperature measured at the same time was 21.0°C (69.8°F).

b Equinox (April 16, 2016)

Results for the equinox site visit are shown in Figure V-28 (EC window status shown in Figure V-29). Window glass temperature is close to 37°C (98.6°F) at 3:50 p.m. Room air temperature measured at the same time was 26.1°C (79.0°F).

c Summer solstice (June 14, 2016)

Figures V-30 and V-31 show the same data for the summer solstice site visit. The temperature of the window glass was near 30°C (86.0°F) at 3:02 p.m., with the room air temperature taking a value of 22.3°C (72.1°F) at 1:52 p.m.

For all these three cases, the difference between the temperature of the window and the room air temperature was always well within the 23°C (41.4°F) limit prescribed by the ASHRAE 55 thermal comfort standard: 10.3°C, 10.9°C and 7.9°C (18.5°F, 19.6°F and 14.2°F) for the winter solstice, equinox and summer solstice site visits, respectively.

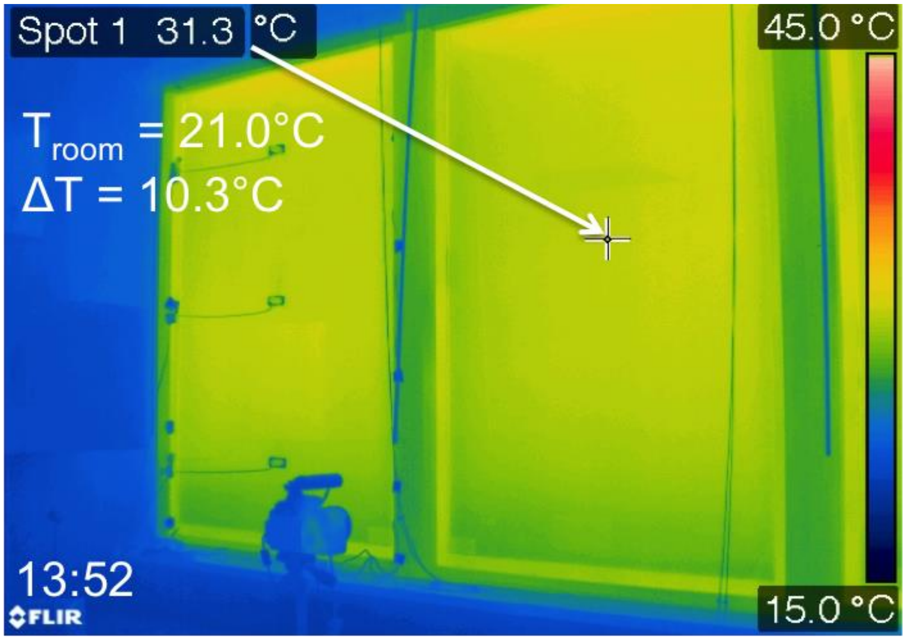

Figure V-26. Infrared false color image taken on December 17, 2015, at 1:52 p.m., when EC window glass temperature was at its peak.

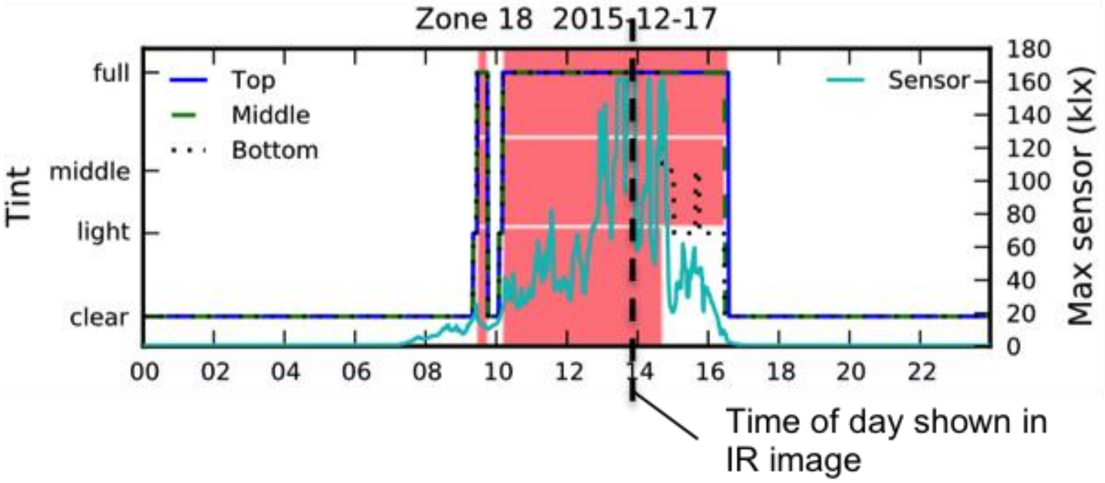

Figure V-27. Window behavior on December 17, 2015. Time at which image shown in Figure V-26 was taken is shown.

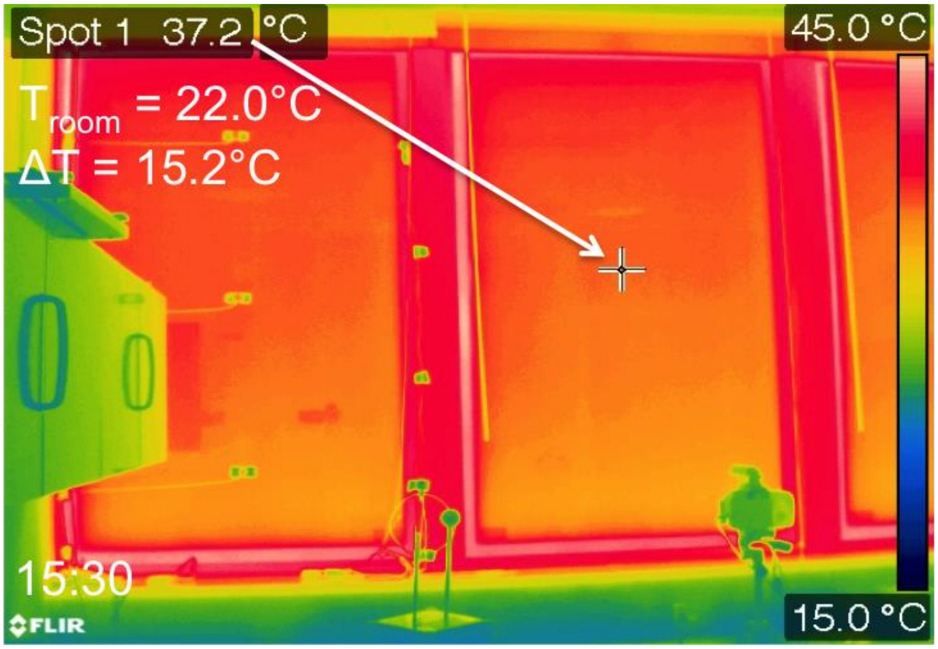

Figure V-28. Infrared false color image taken on April 16, 2016, at 3:30 p.m., when EC window glass temperature was at its peak.

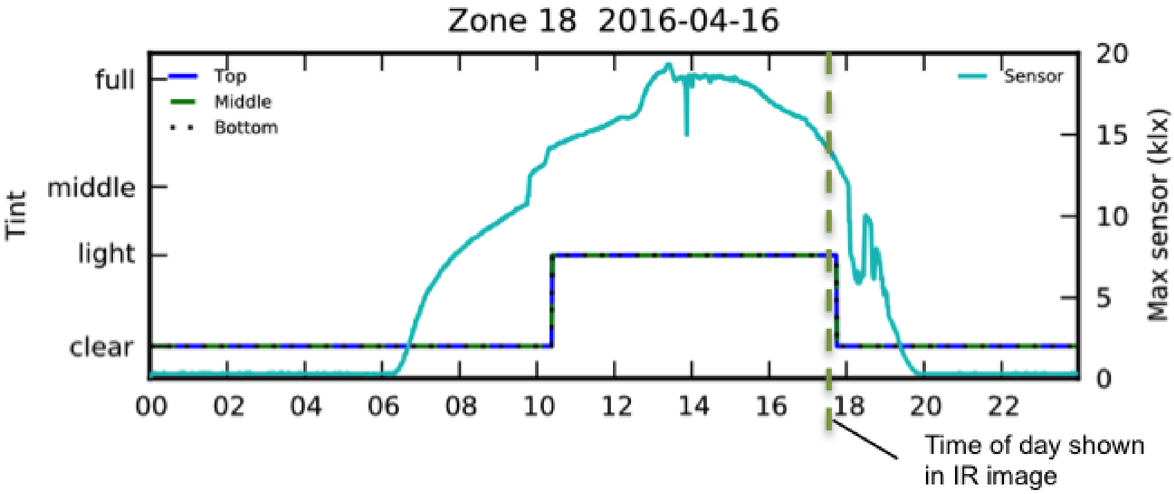

Figure V-29. Window behavior on April 16, 2016. Time at which the image shown in Figure V-28 was taken is shown.

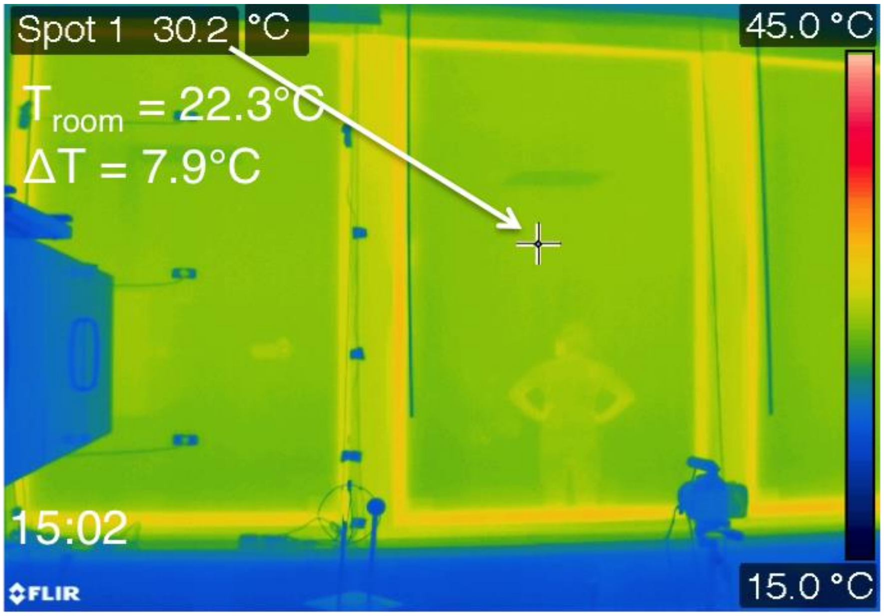

Figure V-30. Infrared false color image taken on June 14, 2016, at 3:02 p.m., when EC window glass temperature was at its peak.

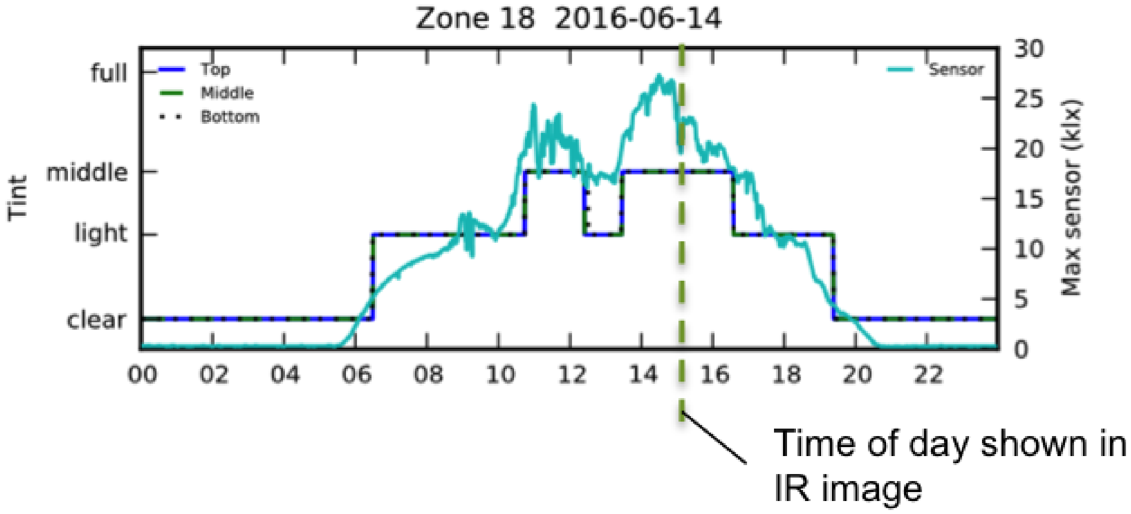

Figure V-31. Window behavior on June 14, 2016. Time at which image shown in Figure V-30 was taken is shown.

Using data from the thermistors mounted on the glass of one window (with the Venetian blinds fully raised) in zone 18 for the duration of the study, we calculated the difference between window glass temperature and room air temperature for the day on which the highest outdoor air temperature was recorded by the instruments on the roof: on June 3, 2016, the outside air temperature reached 43.16°C (109.69°F) at 1:50 p.m. Outside air, room air and glass (middle subpane) temperatures are shown for that day in Figure V-32. The behavior of the windows on that day is shown in Figure V-33. The difference between window glass temperature and room air temperature reaches a maximum of approximately 12°C (21.6°F), comfortably within the 23°C (41.4°F) limit prescribed by the ASHRAE 55 (Figure V-34).

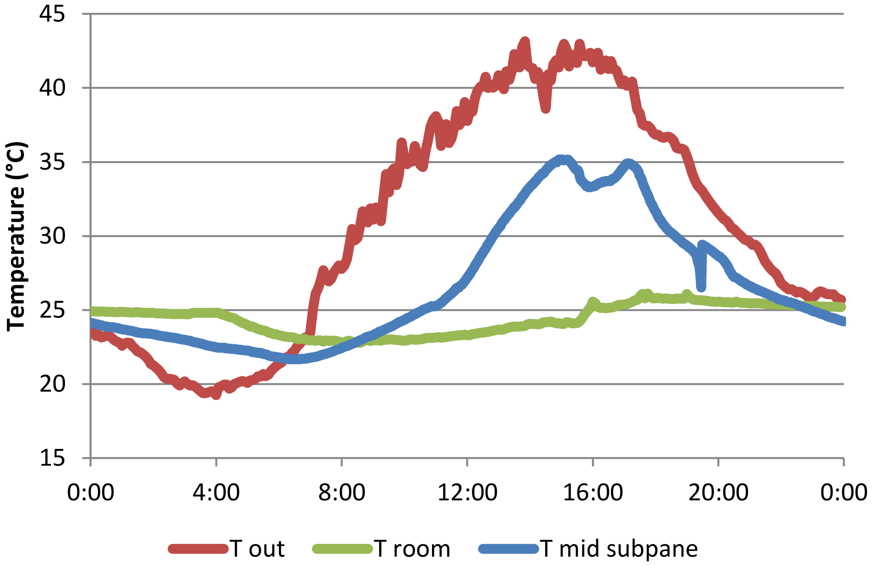

Figure V-32. Outside air, room air and glass (middle subpane) temperatures for June 3, 2016, the day on which the highest outside air temperature was recorded by the instruments on the roof during the study period.

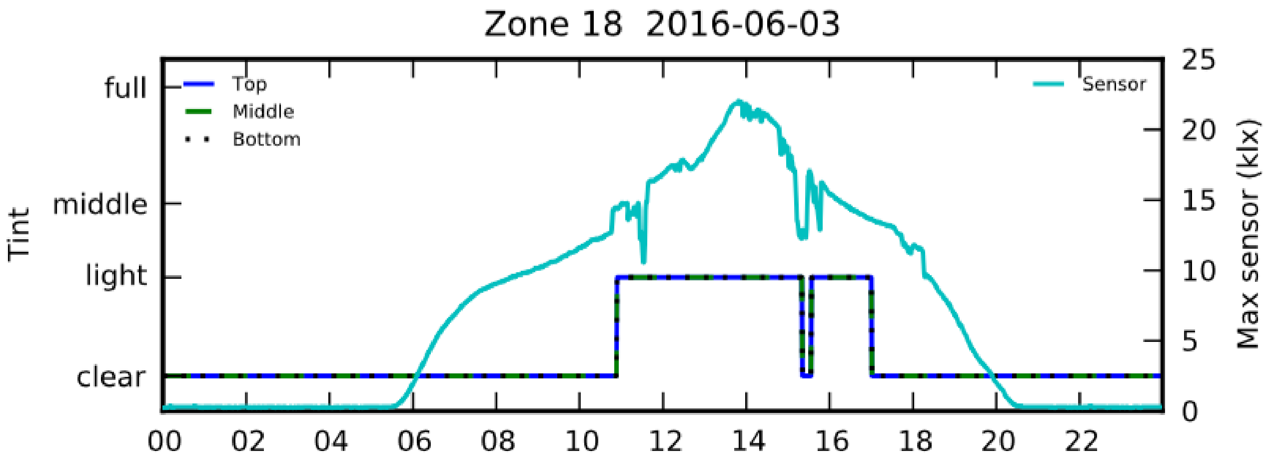

Figure V-33. EC window behavior in zone 18 on June 3, 2016.

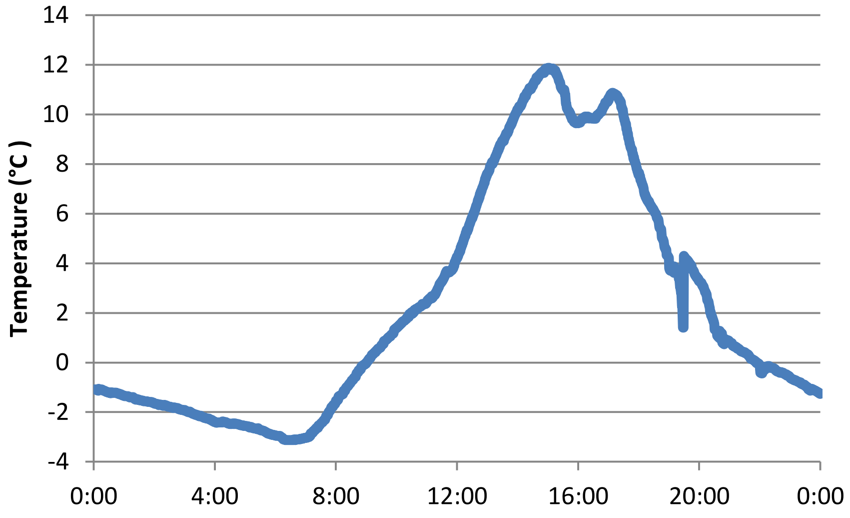

Figure V-34. Difference between window glass temperature (middle subpane) and room air temperature on June 3, 2016.

PREDICTED MEAN VALUE/PERCENTAGE OF PEOPLE DISSATISFIED

The calculation of the PMV/PPD metrics requires assumptions regarding the level of clothing worn by the occupant and the level of physical activity. The calculations shown here were done for two different levels of clothing: pants and long sleeve shirt (0.61 clo[3]) and pants, long sleeve shirt and single-breasted coat (1.01 clo). The activity level was 1.1 met ("typing").

Due to malfunction with the air velocity sensor, a sensitivity analysis was performed by calculating PMV/PPD throughout a range of typical indoor air velocities (0.01, 0.5 and 0.1 m/s). This was found to have an observable effect, but negligible within the context of this analysis; the results shown here assume an air velocity of 0.1 m/s. Similar issues affected the measurement of relative humidity, with significant data gaps. An average value (38%) derived from the available data was used in the calculation. The measurement of mean radiant temperature had two gaps in data collection: one in Jan/Feb and early April. No calculation was performed for those periods.

PMV is shown in Figure V-35 for 0.61 clo insulation level and Figure V-36 for 1.01 clo. When considering weekdays between 9 a.m. and 5 p.m., PMV is below the -0.5 lower limit recommended by the ASHRAE 55 standard 74% and 27% of the time for 0.61 and 1.01 clo, respectively. PMV is above 0.5 for 3.2% and 11% of the time for 0.61 and 1.01 clo, respectively.

Figures V-37 and V-38 show PPD for clothing insulation levels of 0.61 clo and 1.01 clo, respectively. With the lower level of insulation, PPD rises above the recommended limit

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[3] *clo* is a unit for the thermal insulation provided by clothing.

(20%) for 63% of the time on weekdays between 9 a.m. and 5 p.m. This happens especially in the morning, with afternoons being mostly comfortable after the New Year. With the higher level of clothing insulation, PPD rises above 20% for only 9% of the time.

These results indicate that, while the space appears to tend towards lower temperatures, it is possible, with reasonable clothing adjustments, to maintain thermal comfort in the space. Previous occupants of this space had described it as a “cold office,” which suggests that the thermal environment was not negatively impacted by the installation of EC windows.

One question that arises when analyzing these results is whether the changes in the control algorithm that occurred around April 13 had any significant impact on thermal comfort, in particular whether the zero occurrence of full tint (when in automatic control) after that date resulted in any noticeable decrease in heat re-radiated towards the interior by the EC glass. Figures V-39 and V-40 show interior mean radiant temperature and glass temperature (middle subpane shown). No abrupt change in either MRT or glass temperature is apparent at the time the change in the control algorithm took place, indicating that it is not likely that this change had a significant impact on thermal comfort.

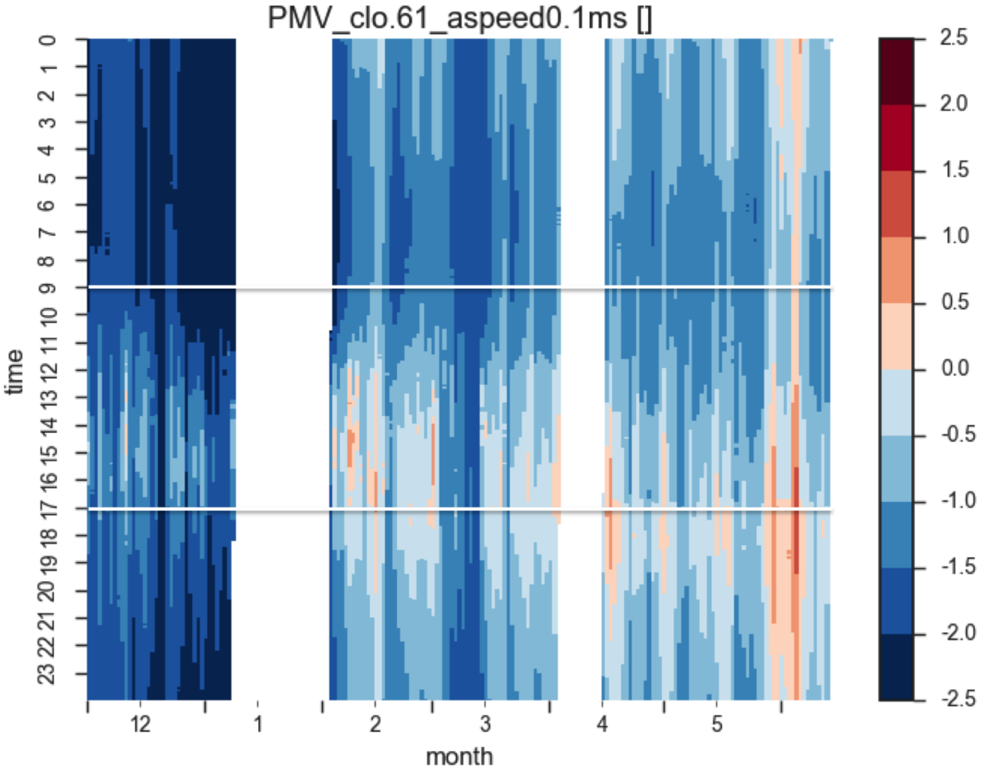


Figure V-35. Predicted mean value with 0.61 clo clothing insulation level.

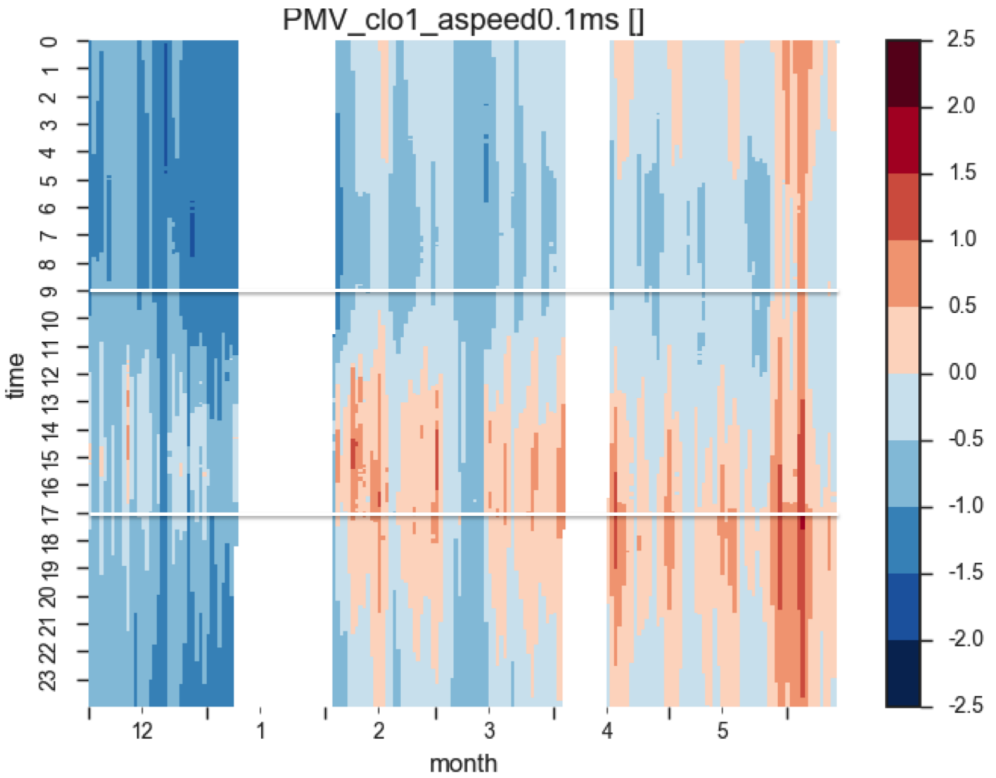


Figure V-36. Predicted mean value with 1.01 clo clothing insulation level.

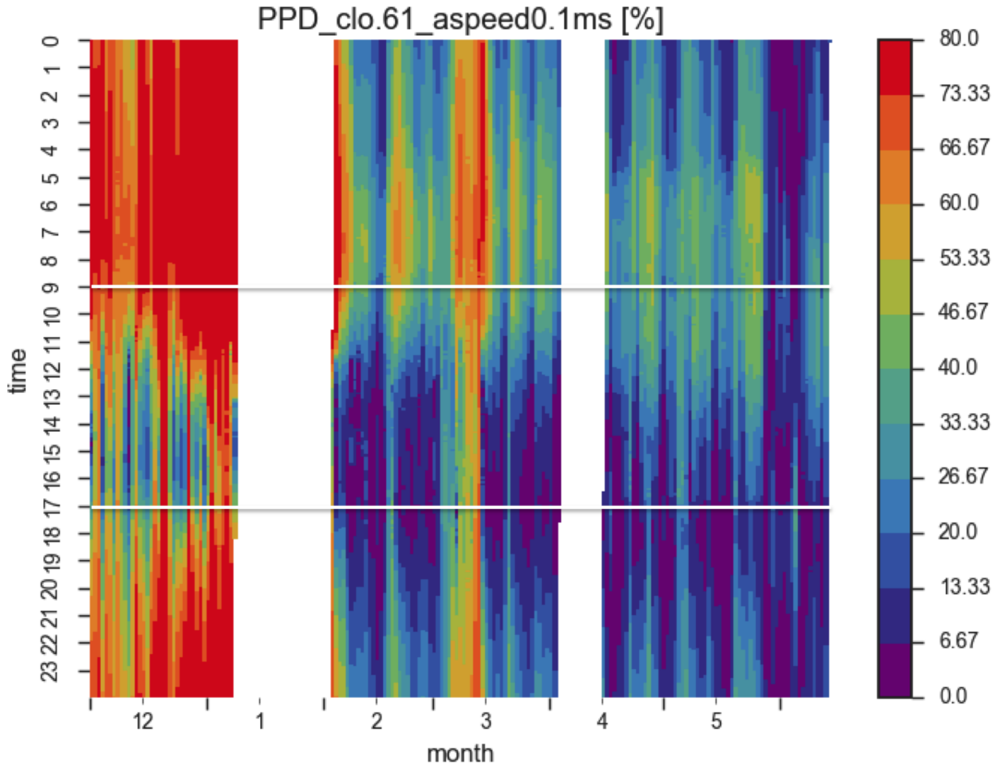


Figure V-37. Percentage of people dissatisfied with 0.61 clo clothing insulation level.

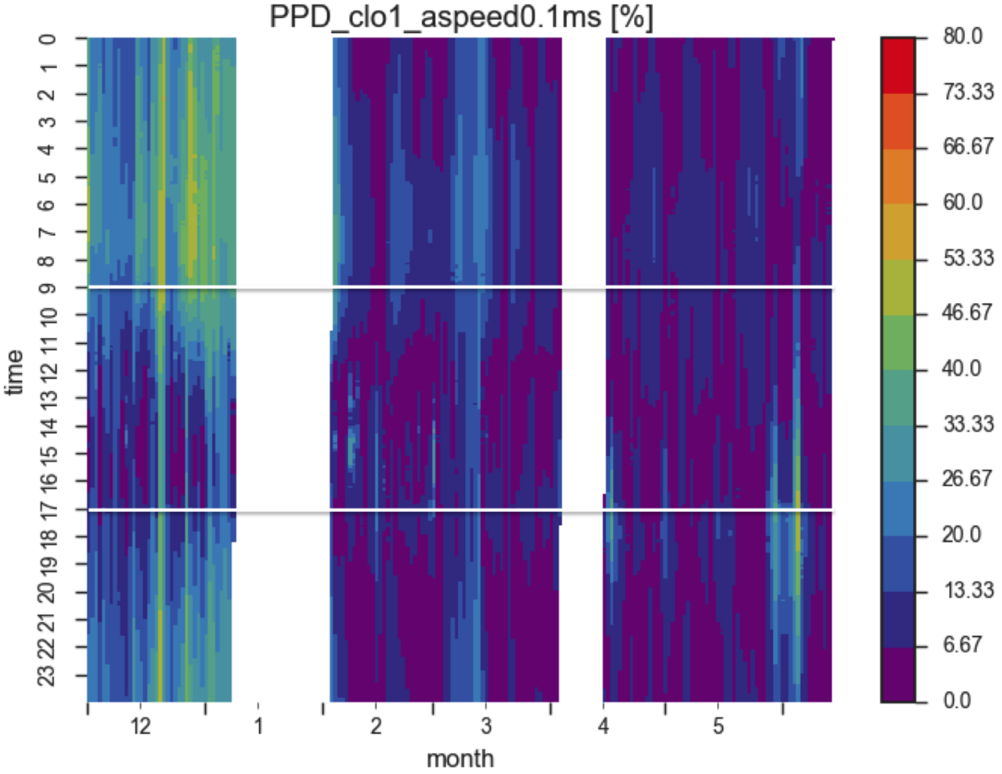


Figure V-38. Percentage of people dissatisfied with 1.01 clo clothing insulation level.

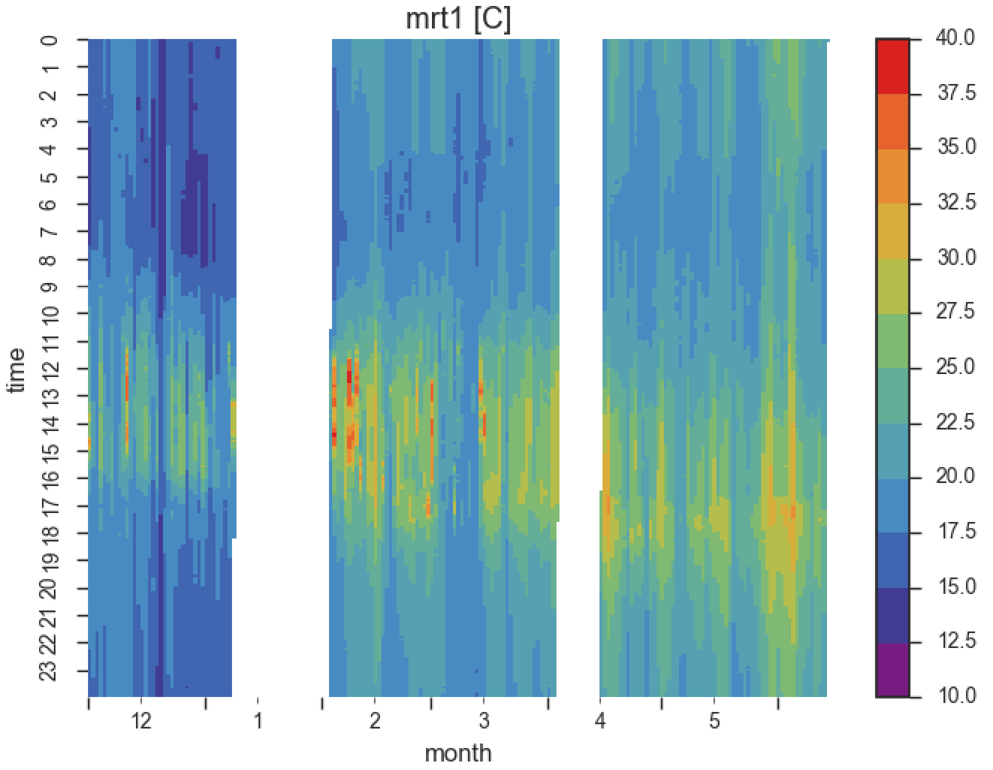


Figure V-39. Mean radiant temperature.

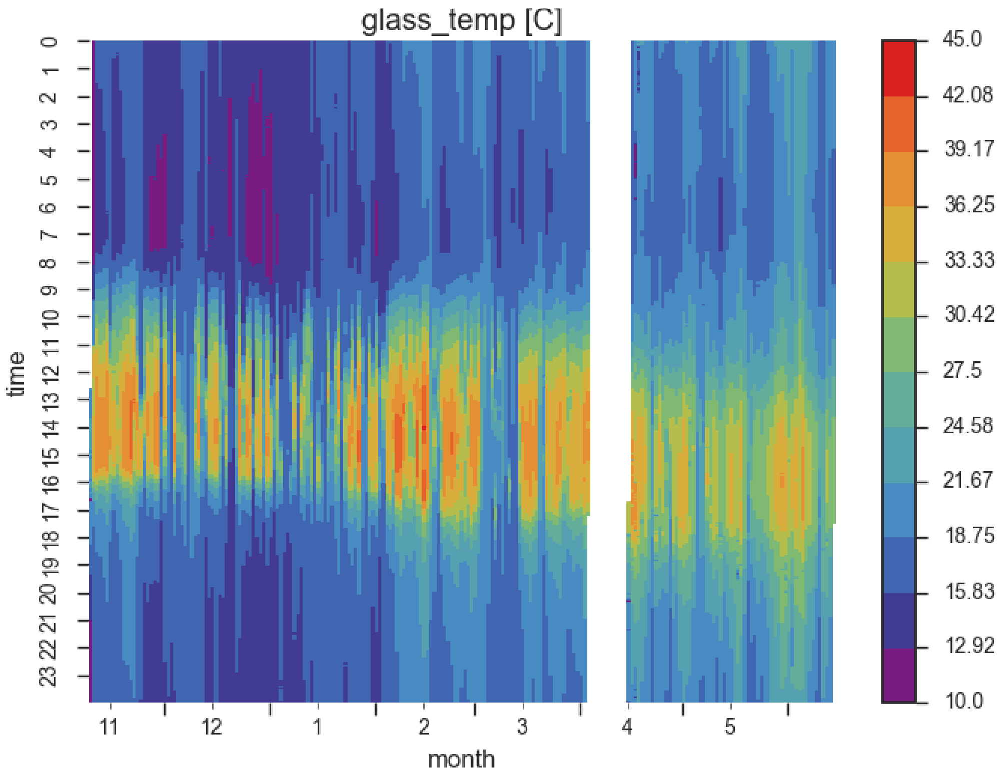


Figure V-40. Glass temperature (middle subpane).

F. LIGHTING ENERGY USE

For this calculation, we used the period from November 2015 to April 2016 as the test period, and November 2013 to April 2014 as the baseline. During Phase I of this study, EC windows started operation at the end of April 2014; for this reason, it was not possible to have a baseline comparison for the May–June 2016 period. Figure V-41 shows the spaces for which there was sufficient data to perform the lighting energy use calculation. Spaces that had more than two two-week periods with insufficient data to generate a typical two-week lighting profile were excluded from the calculation (criteria for data sufficiency were: (a) data missing for less than 10% of the working day and (b) longest continuous gap shorter than 30 minutes). In addition, daylight harvesting was not enabled in one of the open-plan areas — this area also was excluded.

Results show that, throughout the period for which there is a valid baseline, estimated lighting energy use is significantly higher with the EC windows than with the original windows (Figure V-42), equivalent to a projected 62% increase in annual lighting energy consumption, from an average weekday LPD of 0.42 W/ft^2 with clear windows (original windows or EC set to their clear state) to 0.67 W/ft^2 with EC windows in operation. Even allowing for the fact that the process used to derive this estimate could be subject to errors and for variability in weather between the reference and test periods, the fact that the differences are consistent throughout the study strongly suggests that there is an actual effect.

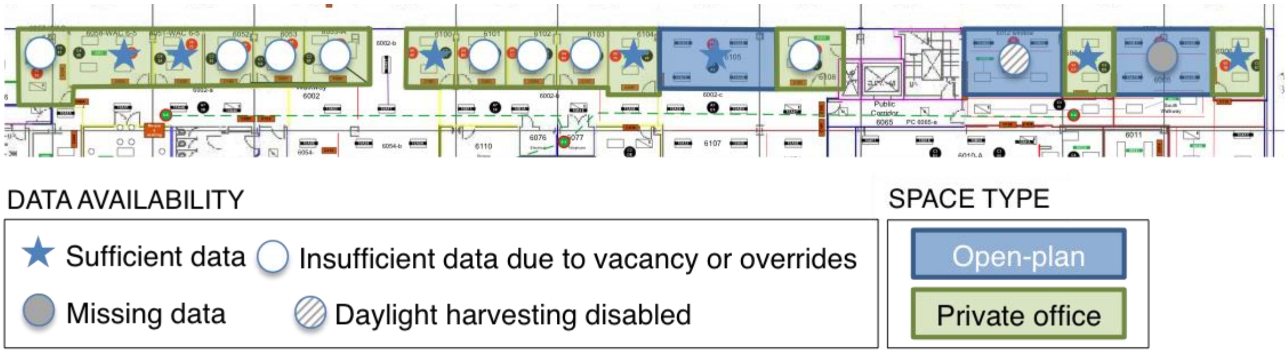


Figure V-41. Areas used in lighting energy calculation.

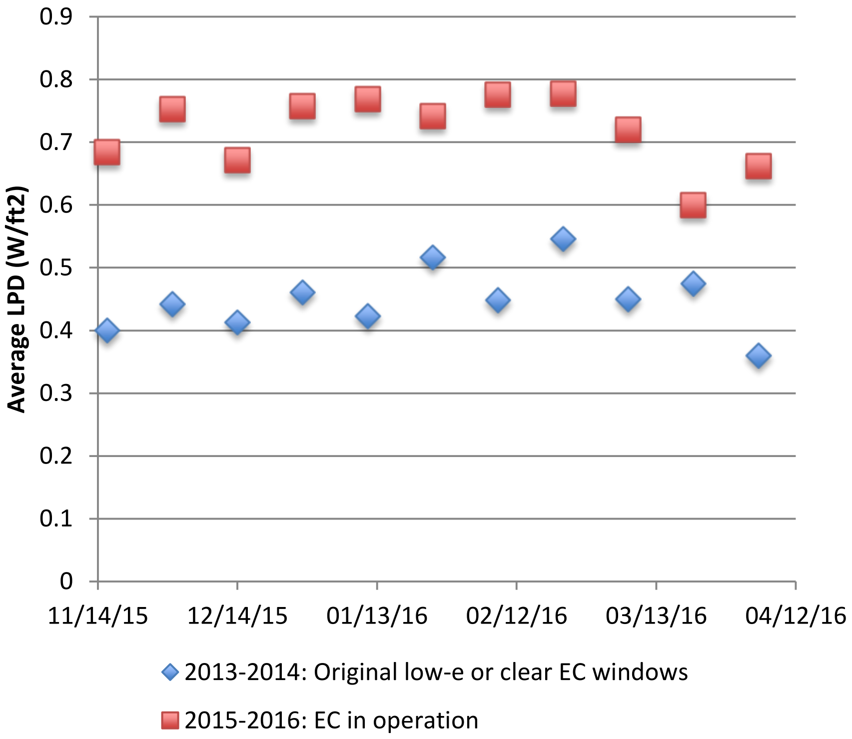


Figure V-42. Average power level for luminaires in spaces that had daylight harvesting enabled. EC windows were initially installed between February and April 2014 and kept in their clear state until the end of April 2014.

G. LIGHT AVAILABILITY

Figures V-43–48 show results from light availability calculations for the six workplane illuminance sensors. As would be expected, in all three spaces significantly more light is available two feet from the window than at eight feet. In the unoccupied office with blinds raised, light levels at two feet surpass 2000 lx for a significant (15%–41%) part of the 9 a.m. — 5 p.m. working day. This is much less prevalent in the other two offices where blinds were lowered (1%–19%). At eight feet from the window, light levels almost never surpass 2000 lx in the two offices with blinds; in the office with the blinds raised, they reach that level between 2% and 13% of the working day in December–March and then 0% for the rest of the study period. Conversely, light levels below 100 lx occur more frequently at 8 ft from the window than at 2 ft. In all three offices, a significant drop (35%–73% for December–March versus 0%–46% for April–June) in the frequency of light levels lower than 100 lx can be observed between March and April; this is likely related to the adjustments to the EC control system that eliminated the occurrence of glare mode after April 13. 35%–73% vs. 0%–46%.

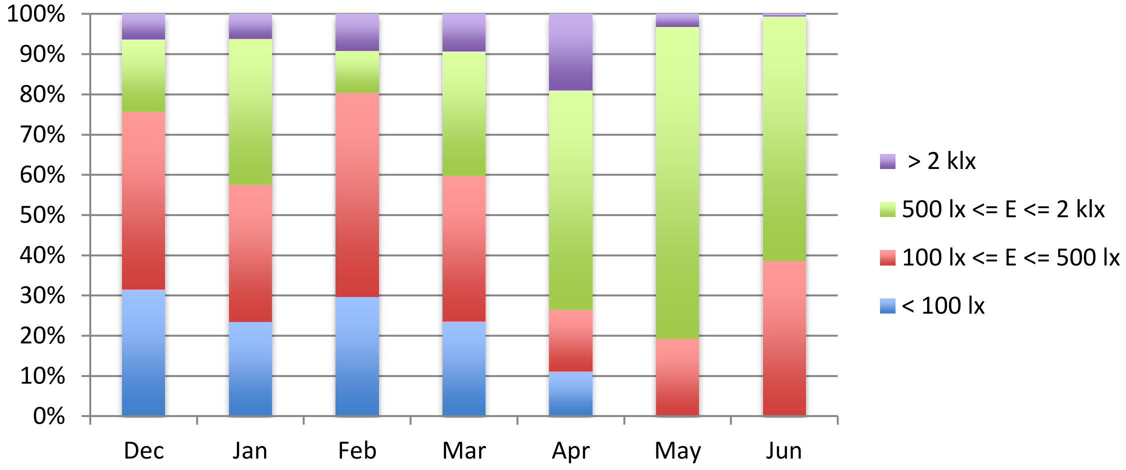


Figure V-43. Light availability approximately 2 ft from window in an unoccupied office with blinds fully lowered (slats open).

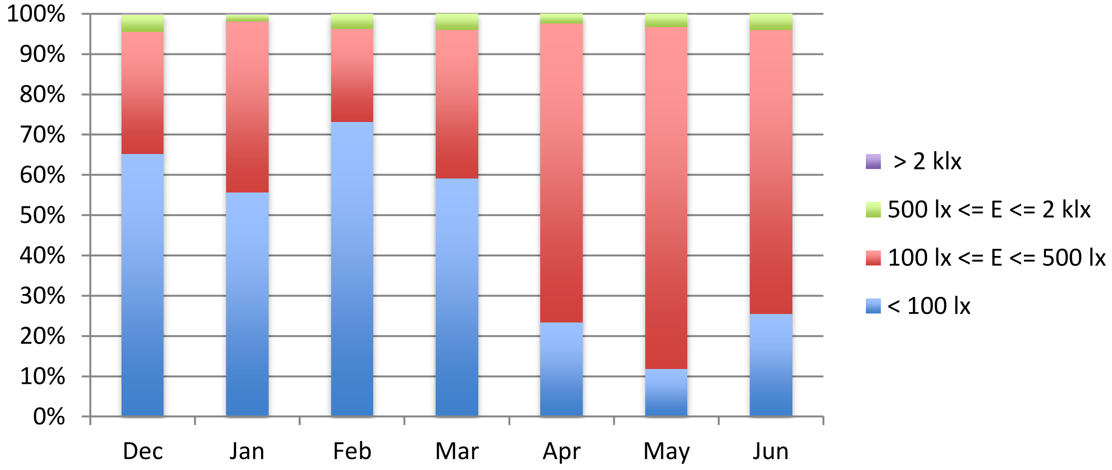


Figure V-44. Light availability approximately 8 ft from window in an unoccupied office with blinds fully lowered (slats open).

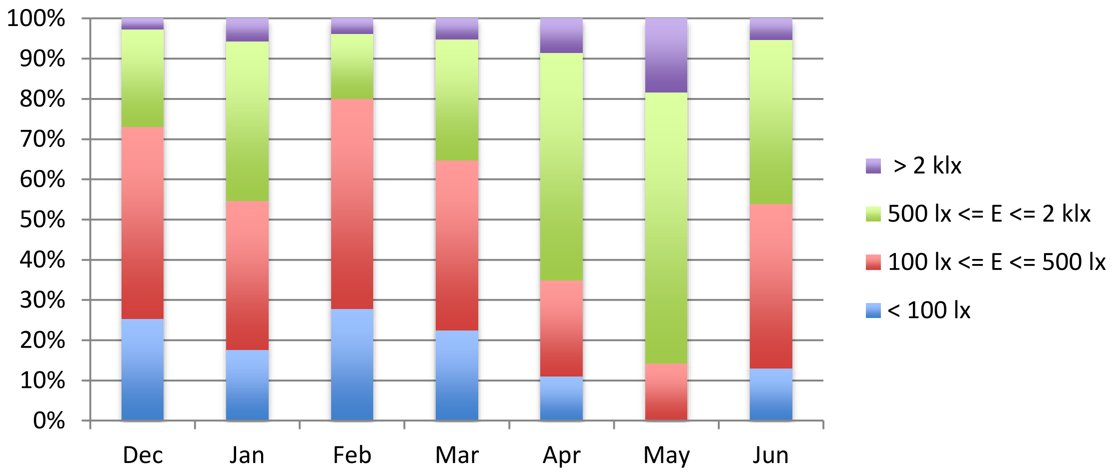


Figure V-45. Light availability approximately 2 ft from window in an occupied office with blinds approximately 50% lowered (slats closed).

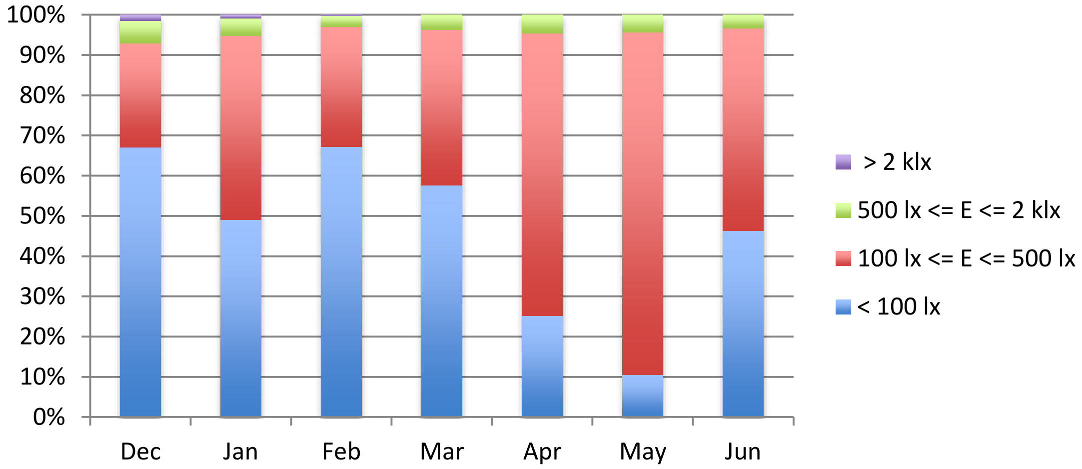


Figure V-46. Light availability approximately 8 ft from window in an occupied office with blinds approximately 50% lowered (slats closed).

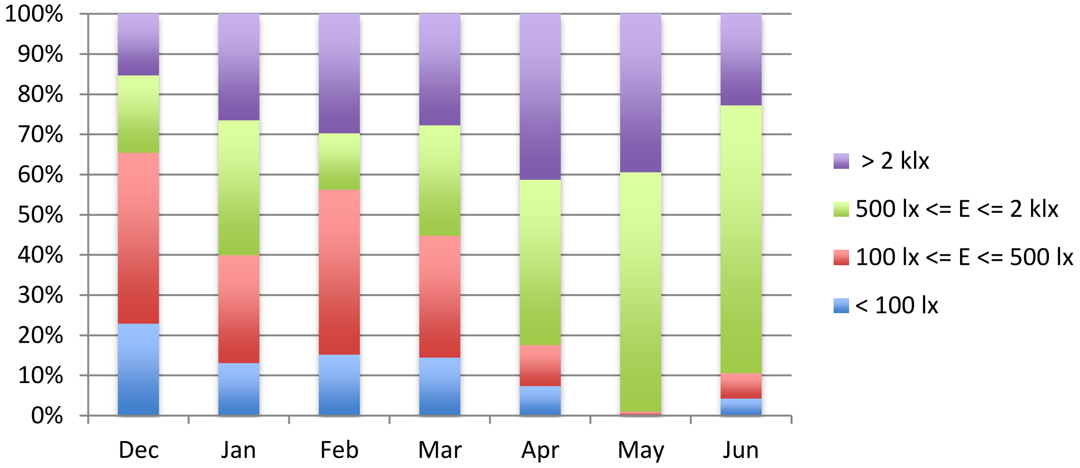


Figure V-47. Light availability approximately 2 ft from window in an unoccupied office with blinds fully raised.

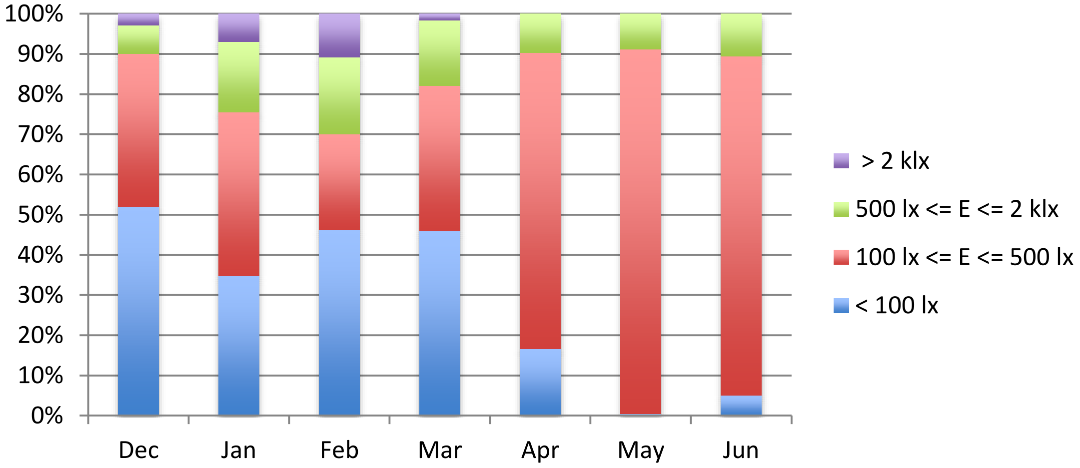


Figure V-48. Light availability approximately 8 ft from window in an unoccupied office with blinds fully raised.

H. LABORATORY TESTS

GLARE LEVELS ON SUNNY DAYS

When the study began in July 2014, test rooms B and C were set to the same settings until August 5, 2014. Results in room B and C in this period were very similar — slight differences were found due to slight variations in the exterior surroundings of these two rooms. From August 6, 2014, setpoints in Room B were seasonally changed, with the objective of optimizing the visual comfort in the test rooms and comparing it to the results obtained with the constant settings in Room C.

a July 12 to August 5, 2014 – high solar angle

Significant glare was observed in the reference room (Room A) during this period (see Figure V-49 for a typical day), with DGP above 0.4 consistently throughout the day. In contrast, visual comfort (DGP < 0.35) is maintained in the EC rooms (rooms B and C) throughout the day, with the windows at light tint most of the day, after a short period in glare mode in the morning (Figures V-50 and V-51). Figure V-52 shows a side-by-side comparison of DGP facing the window at a time when DGP in the reference room was 0.44, indicating disturbing glare. In both EC rooms, DGP is well under 0.35, indicating visually comfortable conditions.

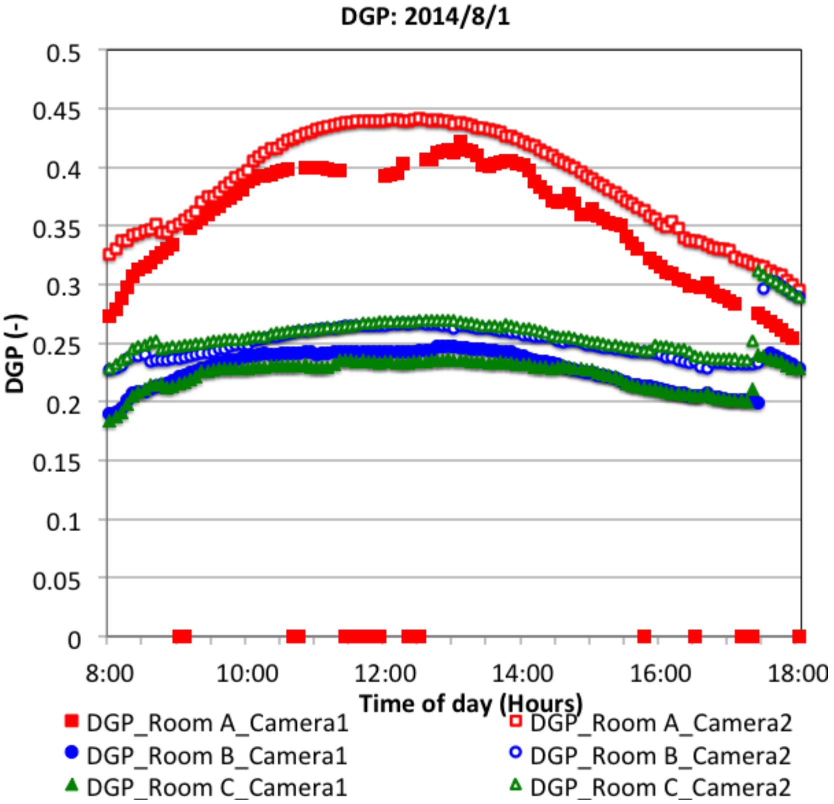


Figure V-49. DGP on a clear sky day with high-altitude sun (August 1, 2014).

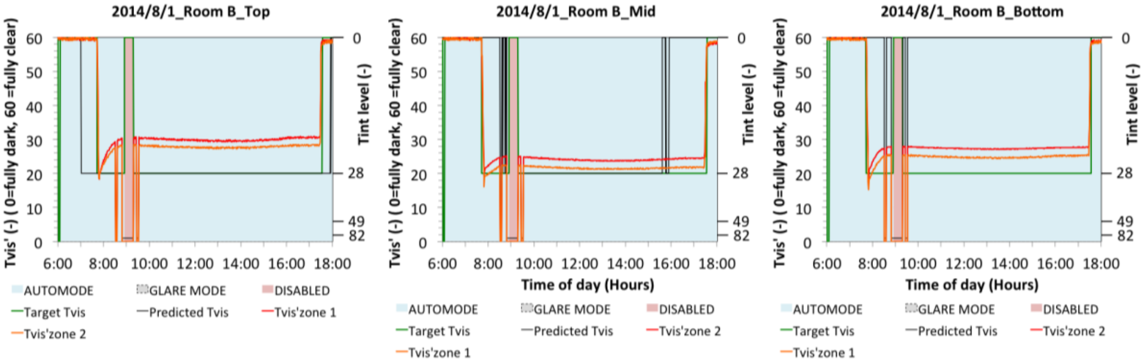


Figure V-50. Operation mode, target tint level, predicted tint level, measured Tvis of the EC window in Room B on August 1, 2014, for (left) Top (center) Mid (right) Bottom zones.

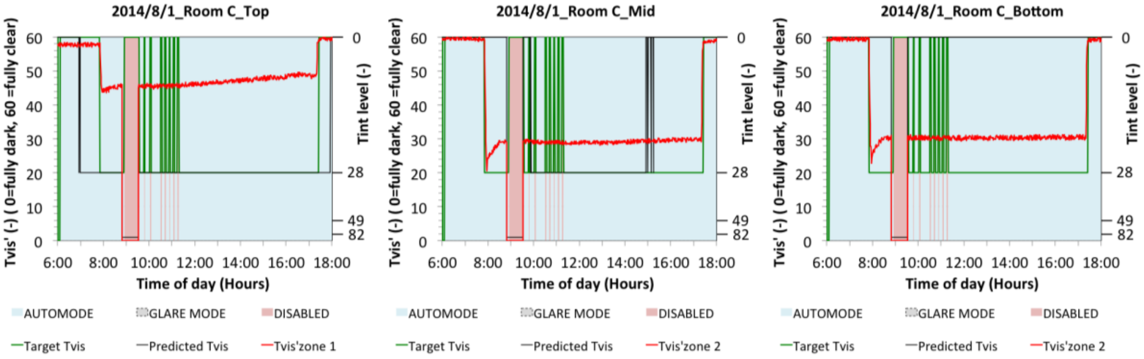


Figure V-51. Operation mode, target tint level, predicted tint level, measured Tvis of the EC window in room C on August 1, 2014, for (left) Top (center) Mid (right) Bottom zones.

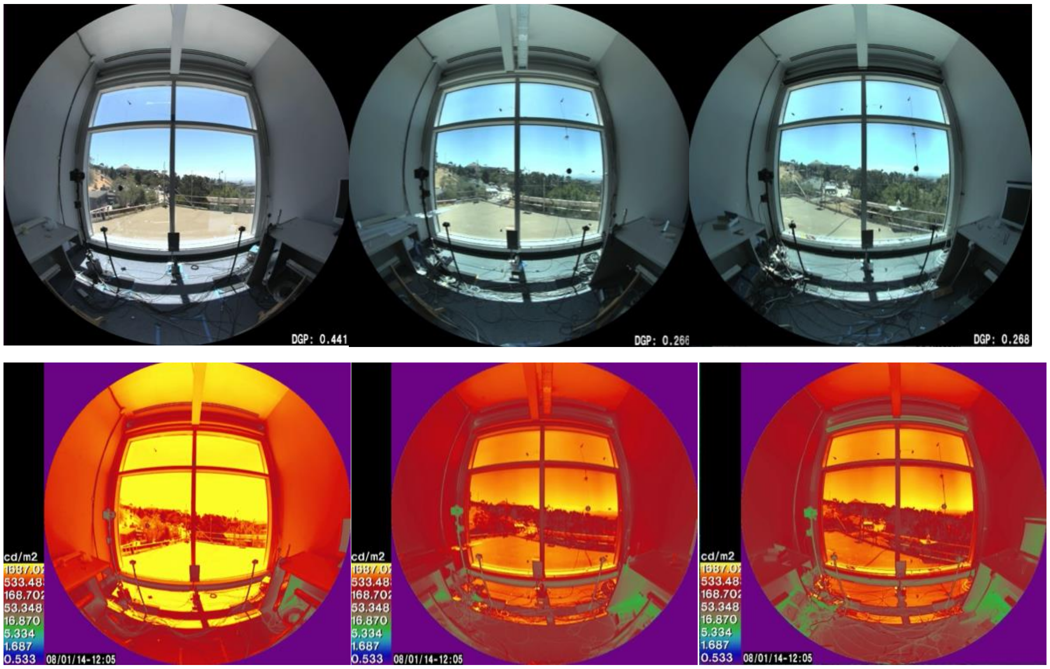


Figure V-52. August 1, 2014, 12:05 ST (left) Disturbing glare (0.441) was found in the reference Room A without EC window, (middle, right) glare reduced to 0.266 and 0.268 in the test rooms B and C with EC windows.

b September 20 to October 9, 2014 – mid solar angle

Similar to the previous period, glare levels were much higher with the reference window than with the EC windows, regardless of how the EC windows were controlled — see Figure V-53 for DGP on a typical day (October 1, 2014). However, with these lower solar angles, in the early morning and late afternoon, DGP levels above 0.35 (the threshold for noticeable glare) were observed. The top and middle pane of the windows in Room B spent a significant part of the day at full tint due to glare mode, whereas in Room C the control algorithm kept the windows mostly at light tint (Figures V-54 and V-55), with surprisingly small differences in DGP versus room B. Figure V-56 shows HDR images and DGP values for noon, with a direction of view parallel to the window.

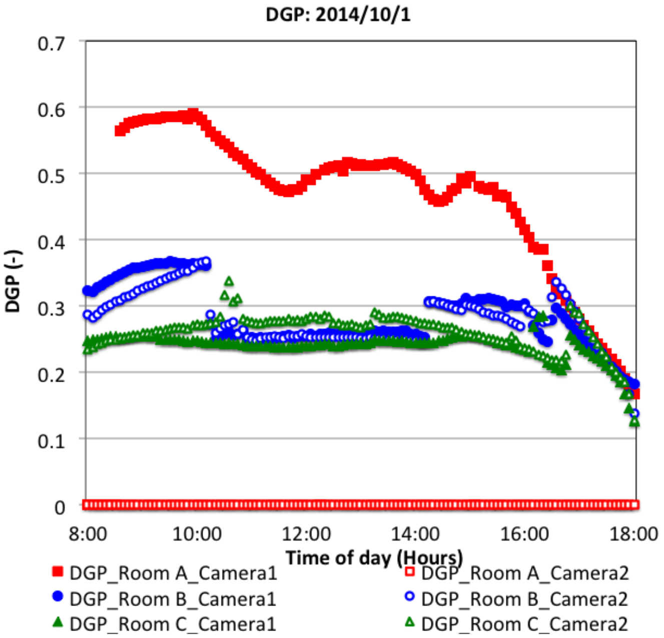


Figure V-53. DGP on a clear day with mid-altitude sun (October 1, 2014).

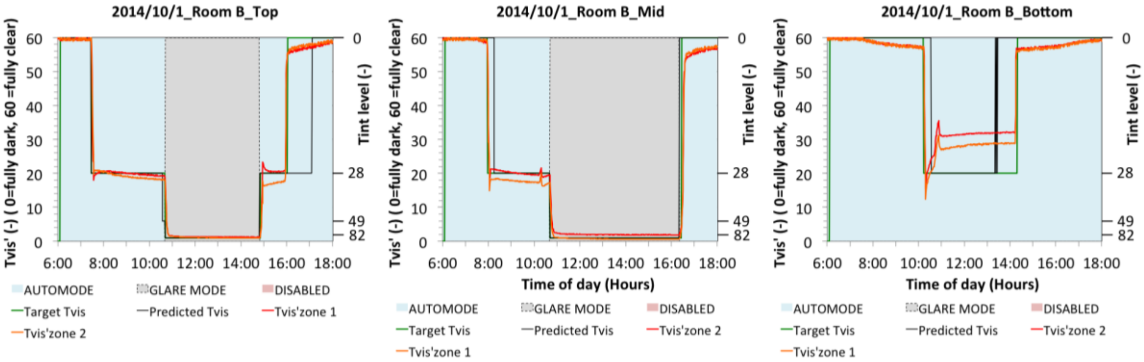


Figure V-54. Operation mode, target tint level, predicted tint level, measured Tvis of the EC window in Room B on October 1, 2014, for (left) Top (center) Mid (right) Bottom zones.

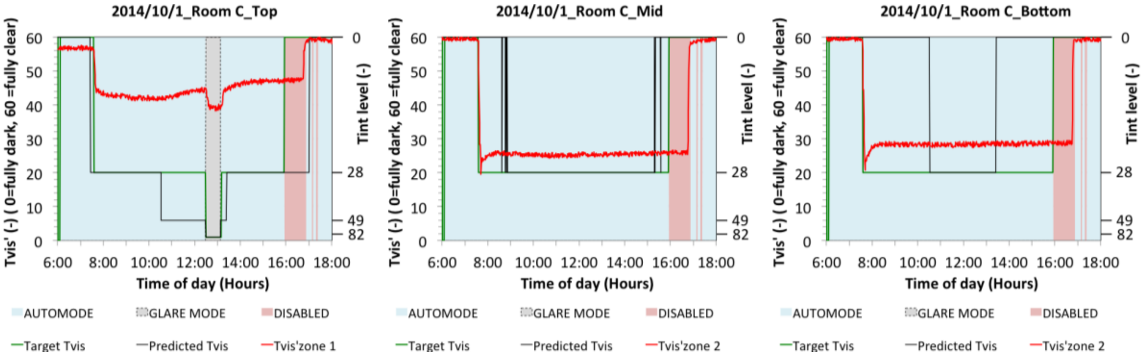


Figure V-55. Operation mode, target tint level, predicted tint level, measured Tvis of the EC window in Room C on October 1, 2014, for (left) Top (center) Mid (right) Bottom zones.

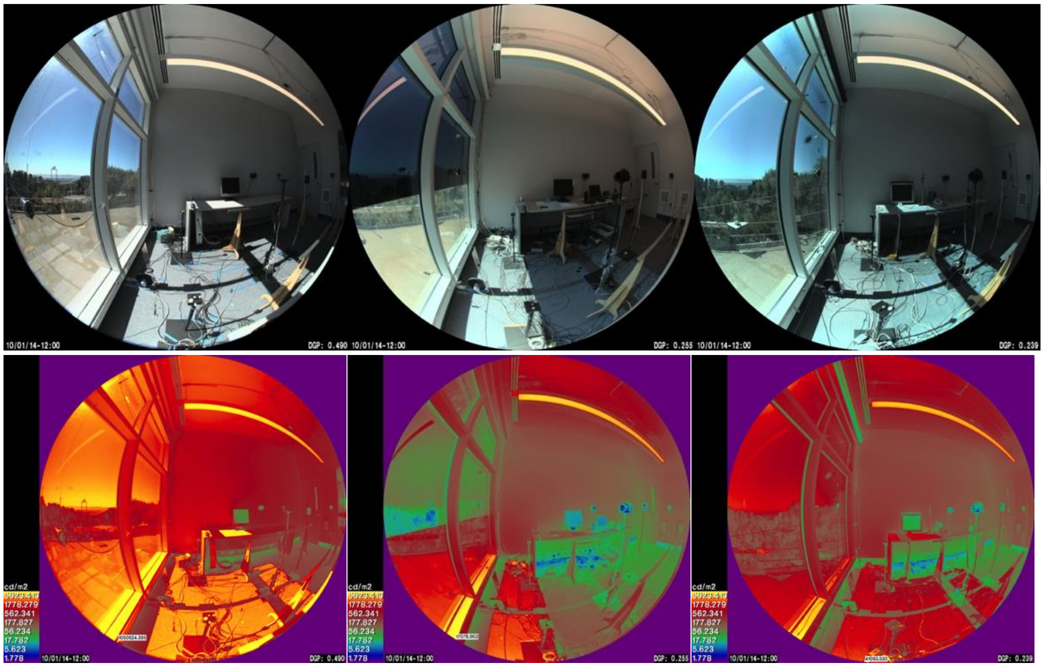


Figure V-56. October 1, 2014, 12:00 ST (left) Discomfort glare (0.490) was found in the reference room without EC window, (middle, right) glare reduced to 0.255 and 0.239 in the test rooms with EC windows.

c October 25 to December 8, 2014 – low solar angle

At low solar angles, while the electrochromics are able to control glare for part of the day, there are periods of the day, depending on the control algorithm, with perceptible (DGP > 0.35) and even disturbing (DGP > 0.40) glare. When analyzing DGP data (Figure V-57) and EC window status (Figures V-58 and V-59), several features are noticeable:

In the reference room (Room A), glare is intolerable (DGP > 0.45) from the early morning to the late afternoon (there is no Camera 3 data for most of the day because these cameras are configured to not take a measurement if vertical illuminance is high enough that it might damage the camera sensor; camera 1 data is not shown due to malfunction).

In Room B, glare is not perceptible most of the day. However, there are several times during which there is perceptible glare (DGP > 0.35). This happens when the sun enters the field of view before windows have completed their transition into glare mode or when the windows start transitioning out of glare mode before the sun has left the field of view.

In Room C, the use of glare mode is more sparse throughout the day, resulting in significant periods of intolerable glare (DGP > 0.45) when glare mode is not engaged. When glare mode is engaged, performance is similar to that observed in Room B.

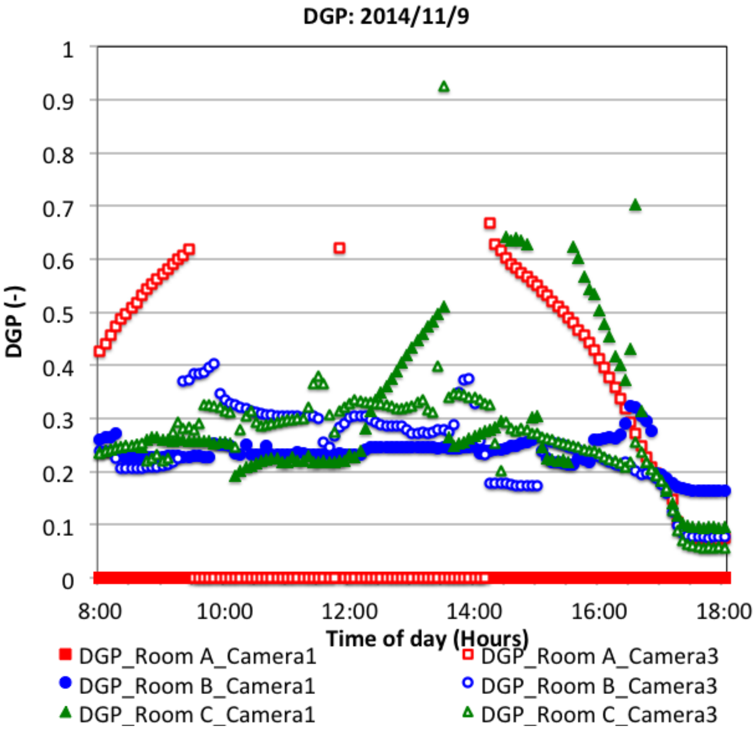


Figure V-57. DGP on a clear day with low sun (November 9, 2014).

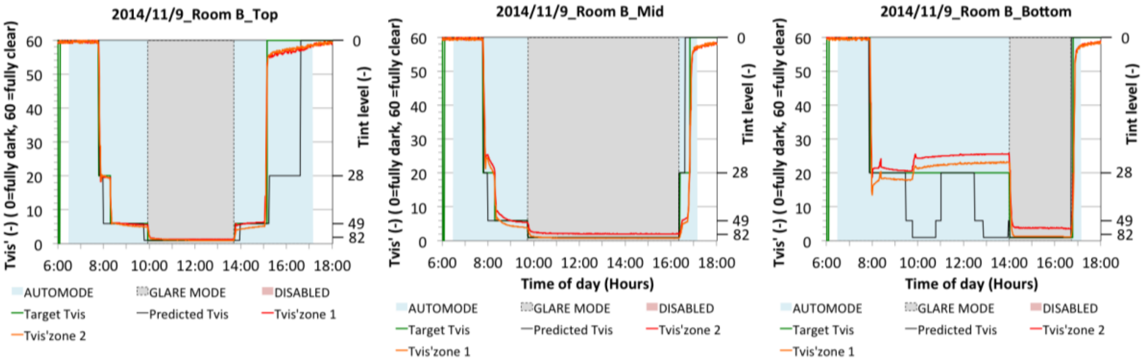


Figure V-58. Operation mode, target tint level, predicted tint level, measured Tvis of the EC window in Room B on November 9, 2014, for (left) Top (center) Mid (right) Bottom zones.

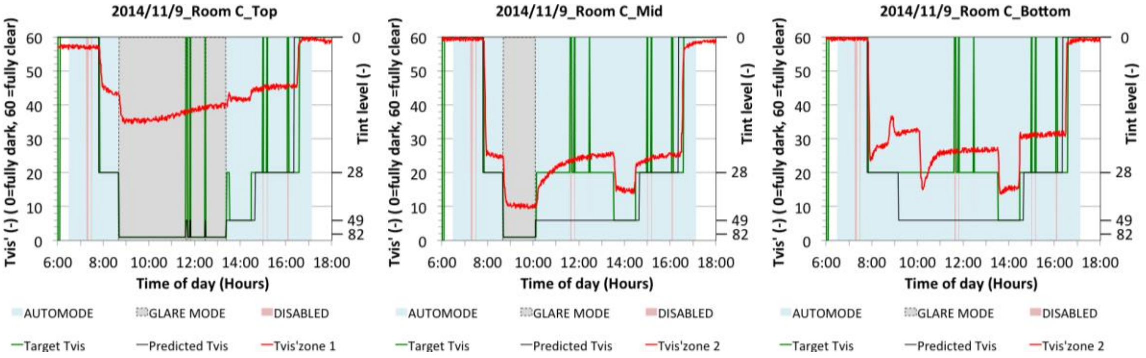
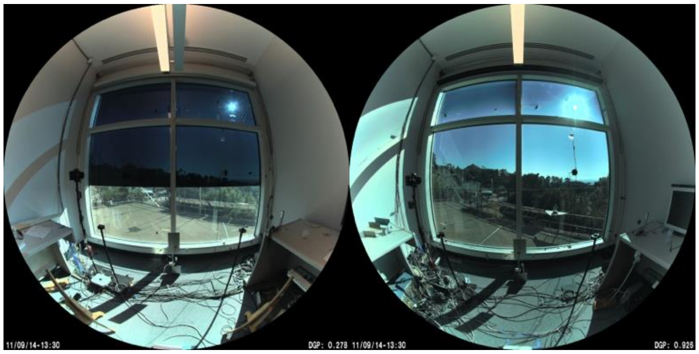
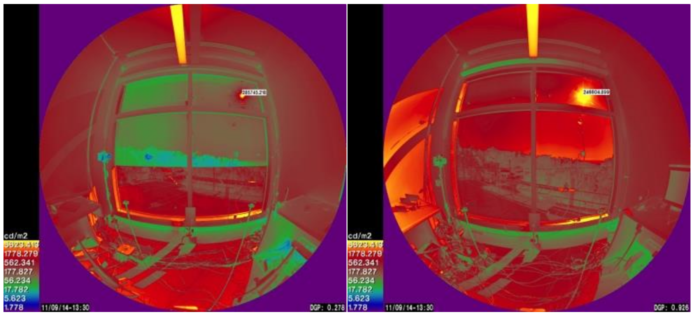


Figure V-59. Operation mode, target tint level, predicted tint level, measured Tvis of the EC window in Room C on November 9, 2014, for (left) Top (center) Mid (right) Bottom zones.



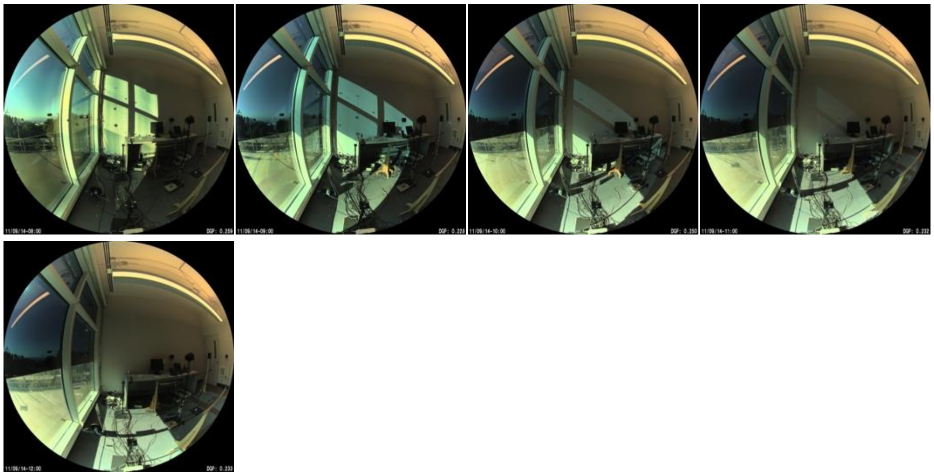
DGP = 0.278 0.926



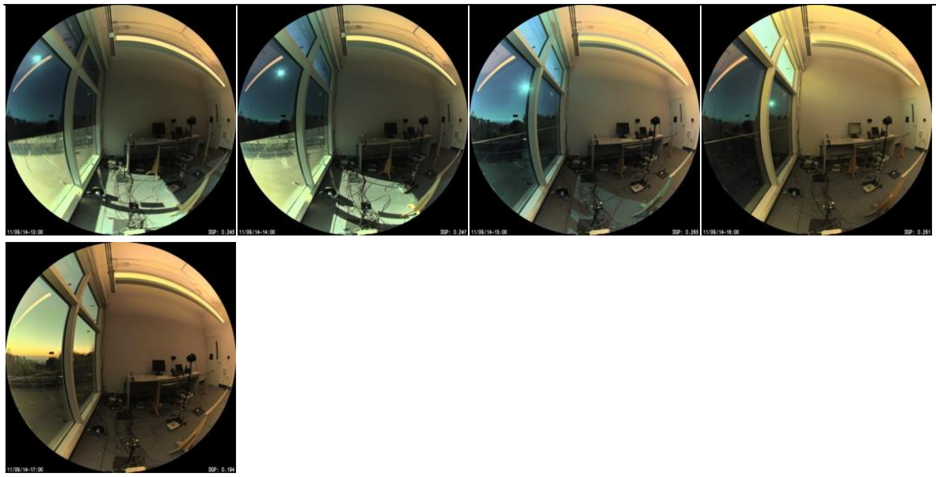
Max luminance = 285745 cd/m^2 246604 cd/m^2

B2 C2

Figure V-60. At the time when DGP reached its peak (0.93) in Room C. the electrochromics in Room B were in glare mode, effectively reducing DGP to imperceptible glare levels (DGP < 0.35). Data for Room A is not shown due to camera malfunction.



Time	8:00	9:00	10:00	11:00	12:00



Time	13:00	14:00	15:00	16:00	17:00

Figure V-61. View parallel to the window throughout November 9, 2014, in room B.

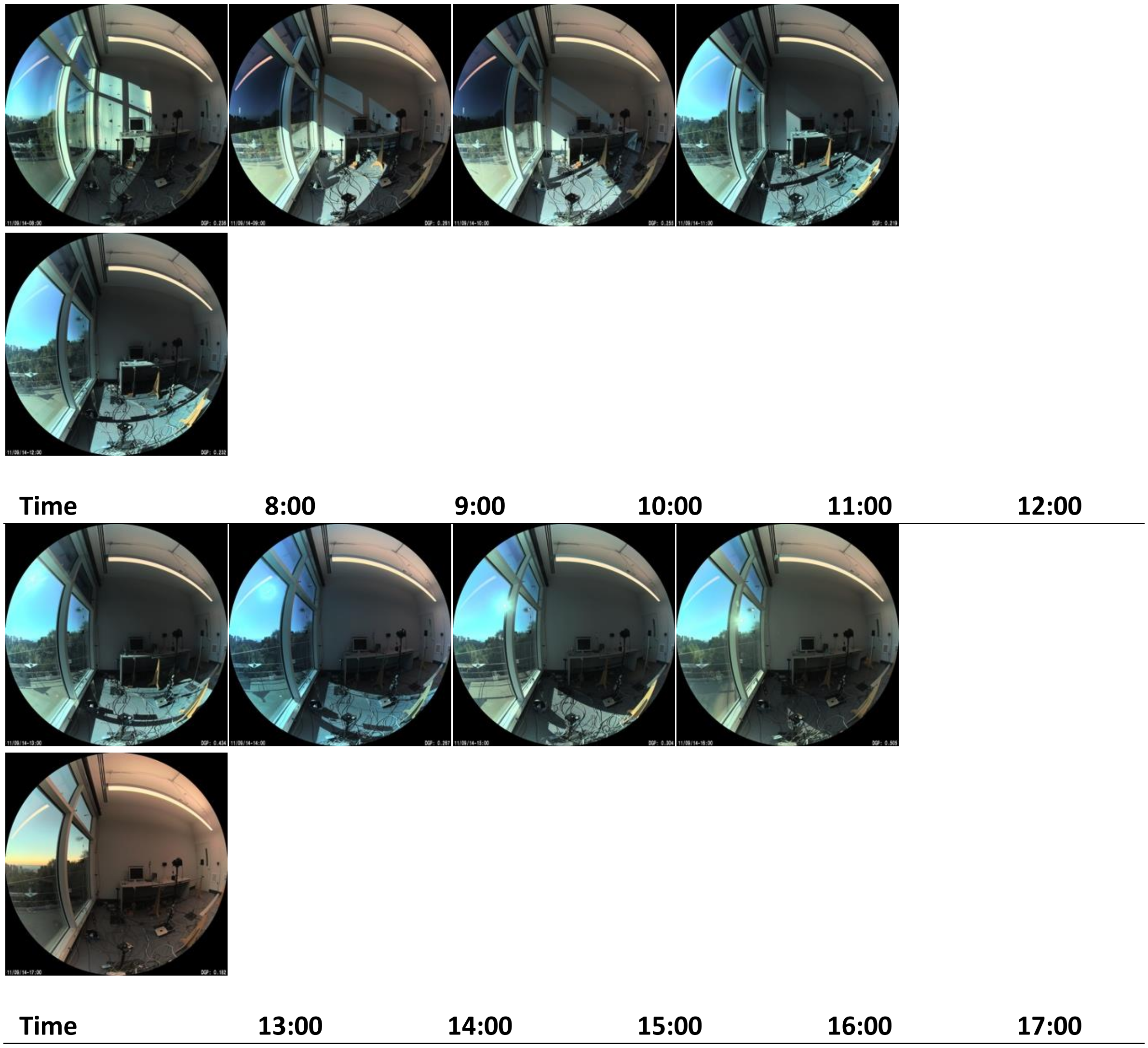


Figure V-62. View parallel to the window throughout November 9, 2014, in Room C.

HVAC LOAD

The field test started on July 12, 2014, and ended on December 9, 2014. This period of 151 days included 63 relevant test days. Within these test days, seven days were excluded due to low load condition (daily energy from 6 a.m. to 6 p.m. less than 250 Wh), one day was excluded due to insufficient temperature settling and another day was excluded due to unexpected occupancy. The resulting test data set includes 54 valid test days with 16 days being representative for summer solstice, 34 days for autumnal equinox and 4 days for winter solstice. The data set is available in 1-minute time steps, labeled in Pacific Standard Time, and was aggregated to 1-hour averages for analytical purposes.

For each of the 54 test days, daily load from the EC rooms (rooms B and C) is plotted against daily load from the reference room (Room A) in Figures V-63 and V-64. Table V-3 shows results aggregated by season. HVAC load is consistently and significantly lower in the rooms with the EC windows than in the room with the reference windows. In Room B, relative to the reference windows, EC windows result in 29%, 41% and 60% (0.43, 0.89 and 3.48 Wh/ft^2 per day) load reduction, respectively, for the summer solstice, autumnal equinox and winter solstice periods. In Room C, relative to the reference windows, EC windows result in 33%, 42% and 65% (0.48, 0.92 and 3.73 Wh/ft^2 per day) load reduction, respectively, for the summer solstice, autumnal equinox and winter solstice periods.

Peak HVAC load is shown in Tables V-4 and V-5 for test rooms with reference (Room A) and EC windows (rooms B and C) for the 54 test days, for both coincident and non-coincident peaks. By "coincident peaks" it is meant that the peak for Room A is found and the HVAC load in the EC rooms for the same timestep is used. By "non-coincident peaks" it is meant that the highest load for each of the rooms is used, even if the peaks are not simultaneous. Figures V-65, V-66, V-67 and V-68 show Room A peak HVAC load plotted against EC room peak HVAC load for coincident and non-coincident peaks, respectively. Tables V-4 and V-5 show these results aggregated by season. In Room B, relative to the reference windows, EC windows result in 26%, 44% and 51% (1.15, 5.57 and 3.56 W/ft^2) non-coincident peak reduction, respectively, for the summer solstice, autumnal equinox and winter solstice periods; the equivalent figures for coincident peaks are, respectively, 27%, 44% and 56%. In Room C, reductions are 28%, 43% and 52% (1.27, 5.51 and 3.66 W/ft^2) for non-coincident peak and 28%, 44% and 58% for coincident peaks, respectively, for the summer solstice, autumnal equinox and winter solstice periods.

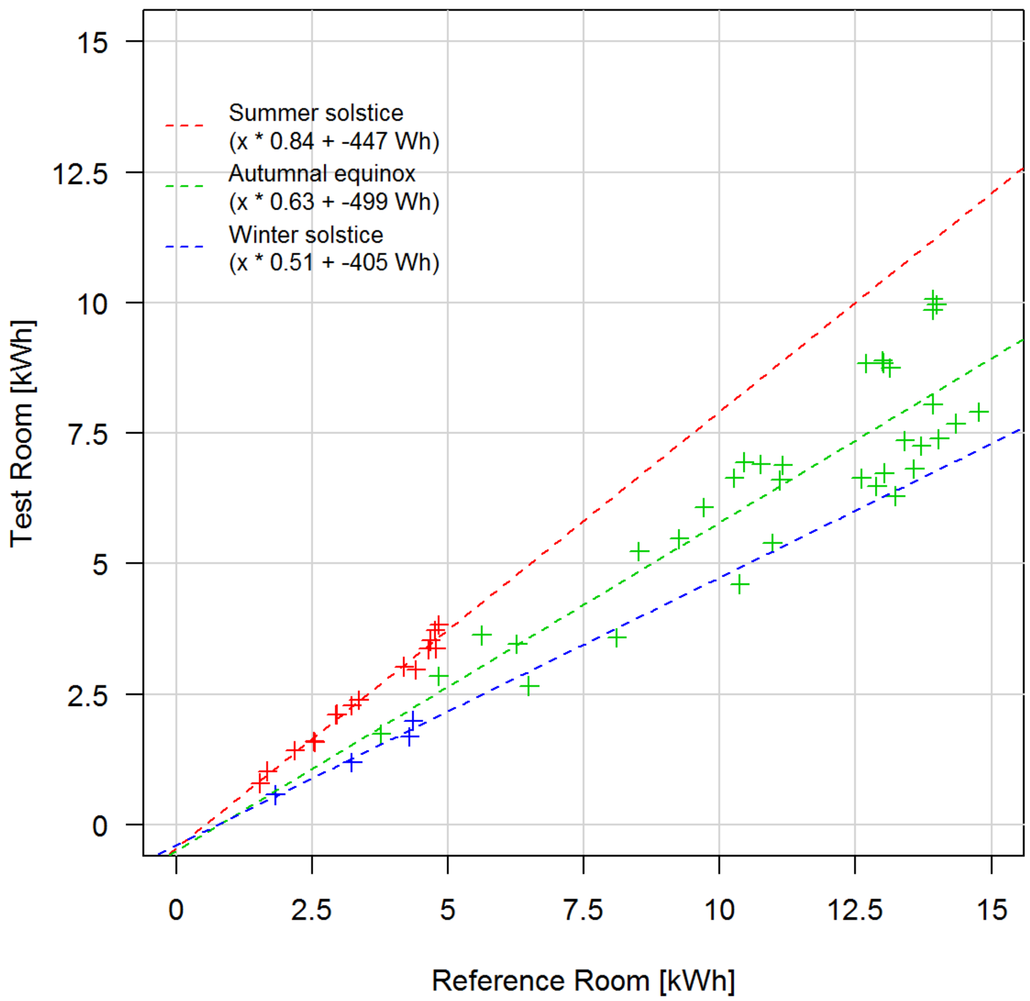


Figure V-63. Daily load with EC windows in Room B (vertical axis) plotted versus daily load with reference windows (horizontal axis).

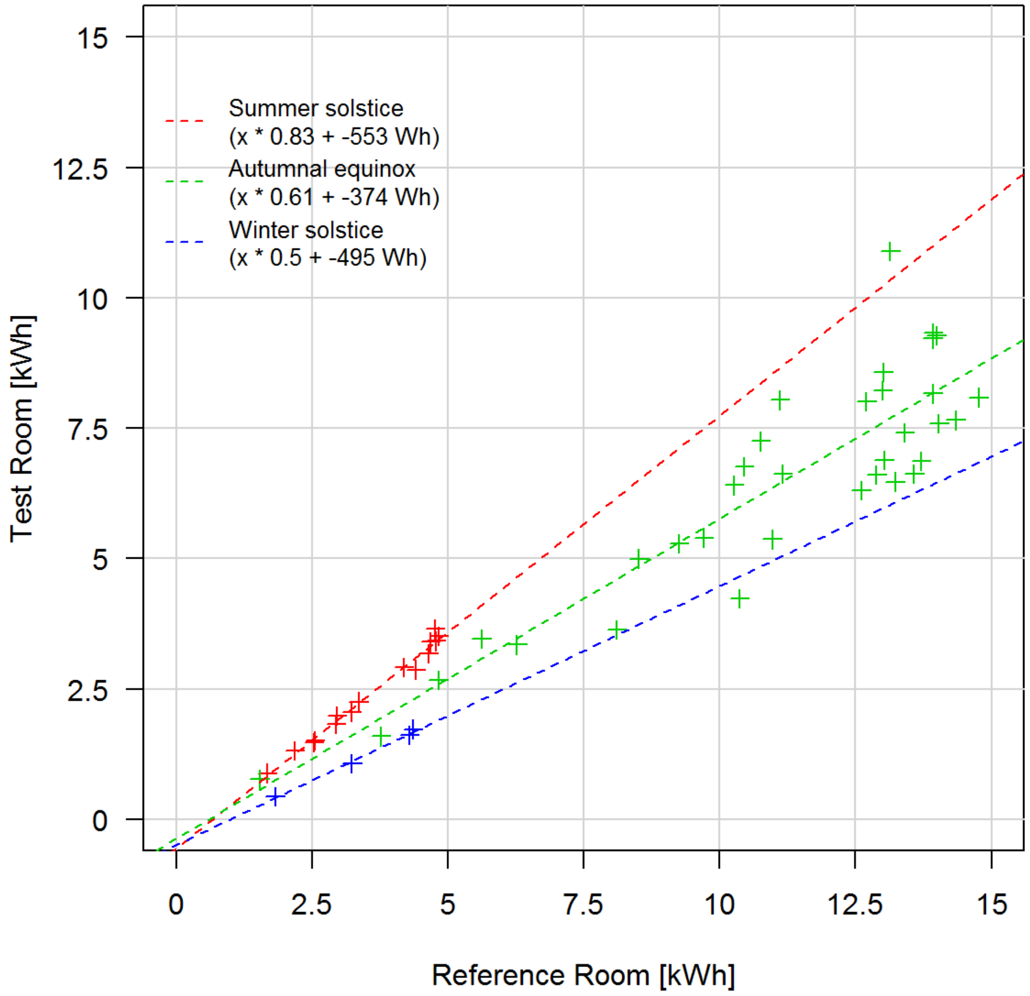


Figure V-64. Daily load with EC windows in Room C (vertical axis) plotted versus daily load with reference windows (horizontal axis).

Table V-3. Daily load with reference and EC windows aggregated by season.

Period	Daily load (Wh, 6 a.m. to 6 p.m.)			Savings (%)		Savings (Wh/ft^2-day)	
	Reference windows	EC windows (room B)	EC windows (room C)	Room B	Room C	Room B	Room C
Summer solstice	3454.9	2443.3	2312.8	29.3	33.1	0.43	0.48
Autumnal equinox	11055.3	6542.7	6412.2	40.8	42.0	0.89	0.92
Winter solstice	3426.9	1357.3	1209.6	60.4	64.7	3.48	3.73

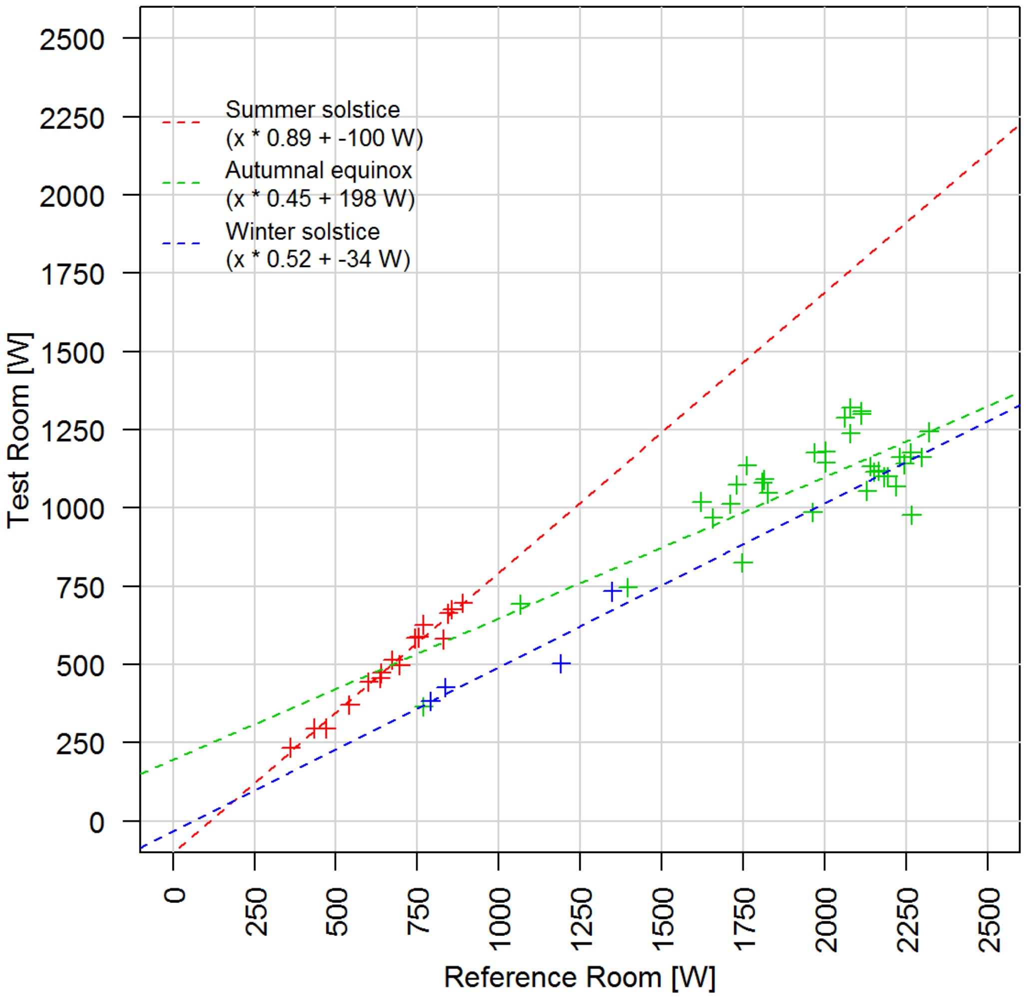


Figure V-65. Non-coincident peak HVAC load with EC windows in Room B (vertical axis) plotted versus load with reference windows (horizontal axis).

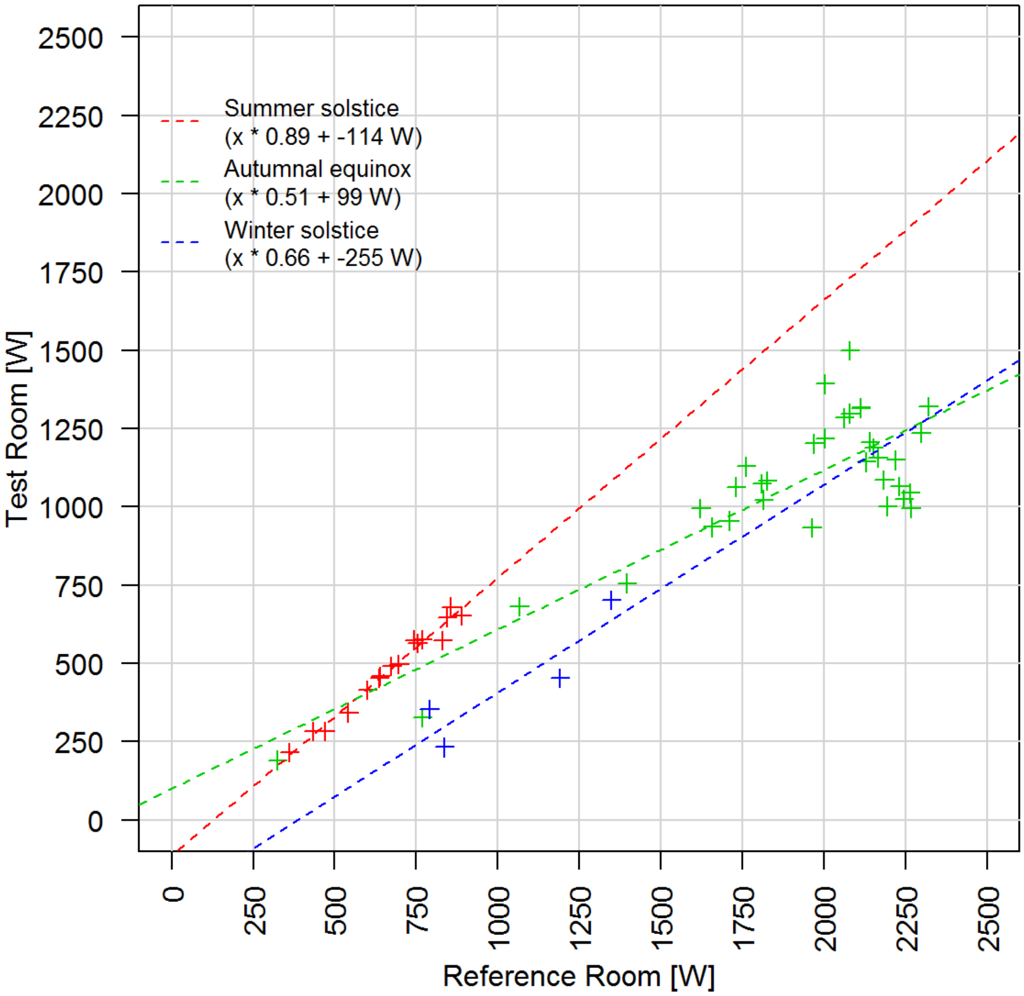


Figure V-66. Non-coincident peak HVAC load with EC windows in Room C (vertical axis) plotted versus load with reference windows (horizontal axis).

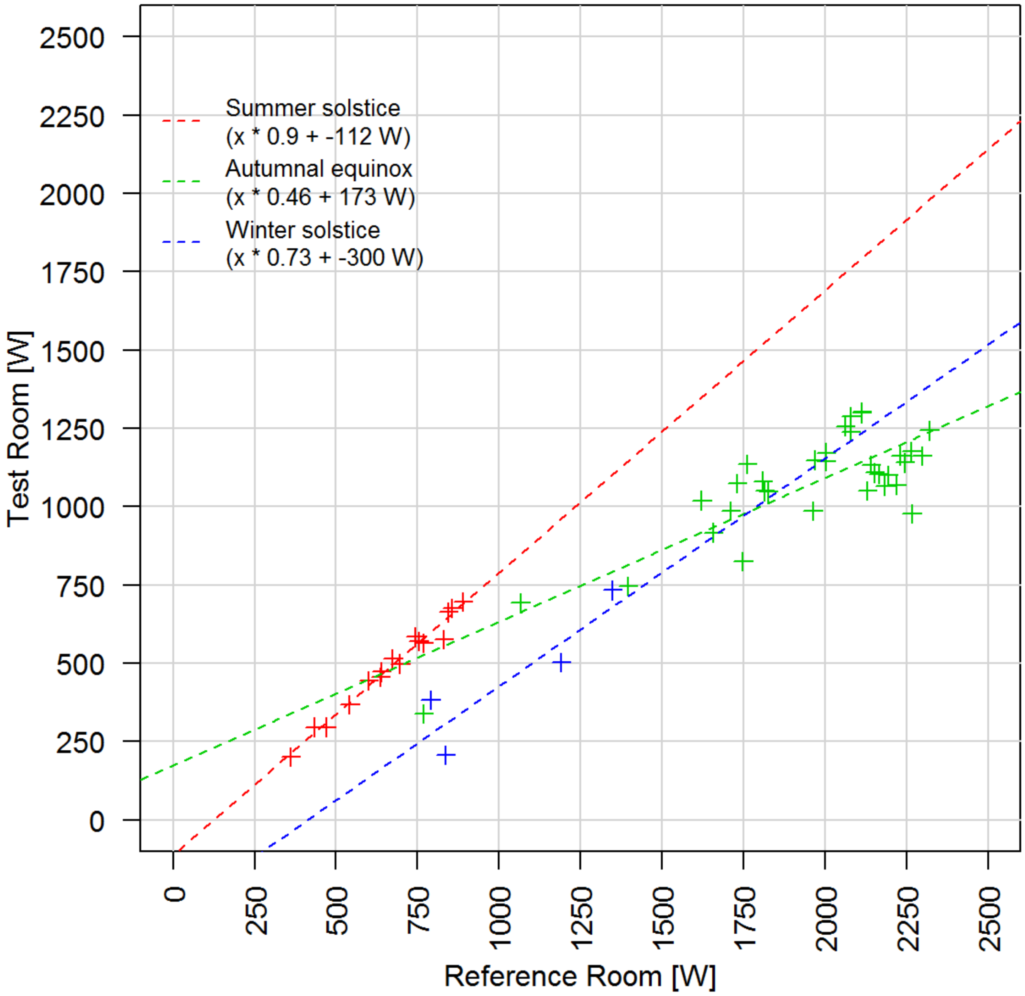


Figure V-67. Coincident peak HVAC load with EC windows in Room B (vertical axis) plotted versus load with reference windows (horizontal axis).

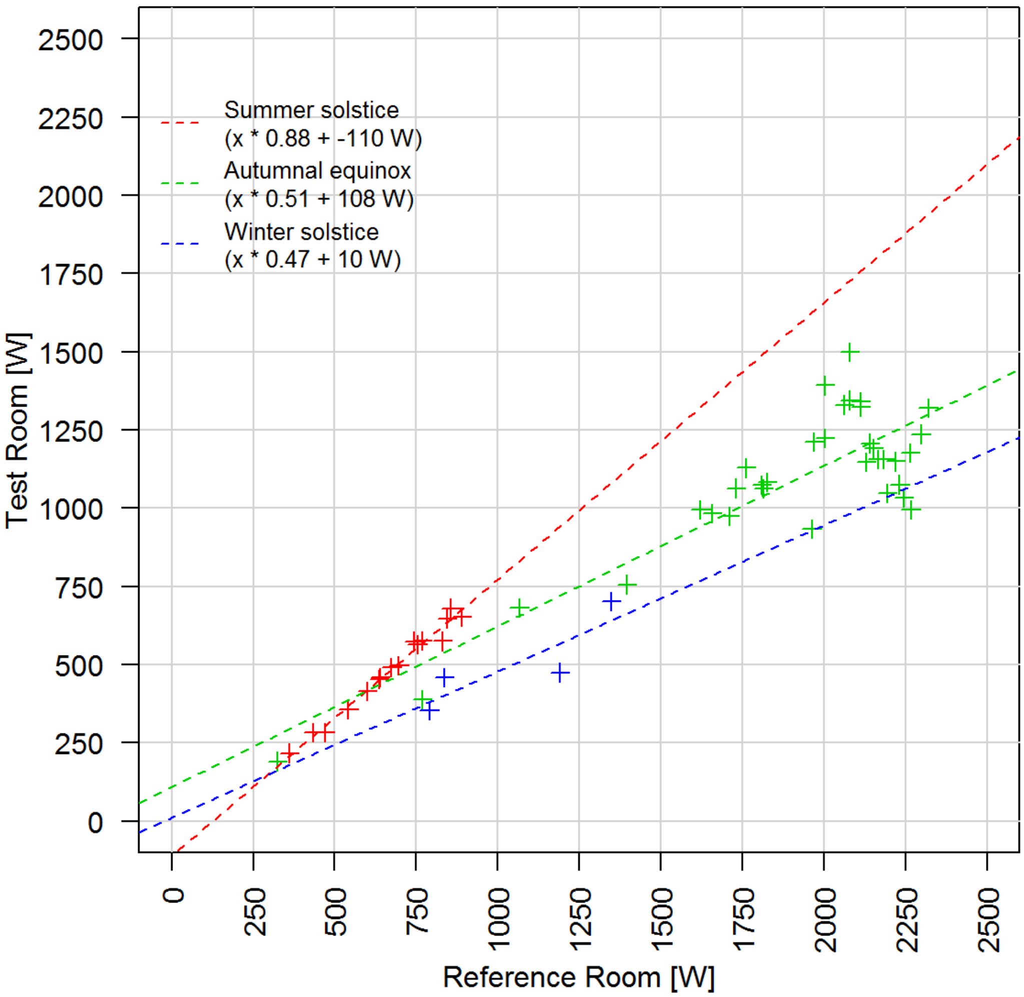


Figure V-68. Coincident peak HVAC load with EC windows in Room C (vertical axis) plotted versus load with reference windows (horizontal axis).

Table V-4. Peak HVAC load with reference and EC windows in Room B, aggregated by season.

Period	Peak HVAC load (W, non-coincident)		Peak reduction (%)	Peak reduction (W/ft^2)	Peak HVAC load (W, coincident)		Peak reduction (%)	Peak reduction (W/ft^2)
	Reference windows	EC windows (room B)			Reference windows	EC windows (room B)		
Summer solstice	671.2	500.2	25.5	1.15	671.2	492.6	26.6	1.20
Autumnal equinox	1902.8	1075.3	43.5	5.57	1902.8	1066.4	44.0	5.63
Winter solstice	1041.4	511.9	50.8	3.56	1041.4	457.0	56.1	3.93

Table V-5. Peak HVAC load with reference and EC windows in Room C, aggregated by season.

Period	Peak HVAC load (W, non-coincident)		Peak reduction (%)	Peak reduction (W/ft^2)	Peak HVAC load (W, coincident)		Peak reduction (%)	Peak reduction (W/ft^2)
	Reference windows	EC windows (room C)			Reference windows	EC windows (room C)		
Summer solstice	671.2	482.9	28.1	1.27	671.2	481.9	28.2	1.27
Autumnal equinox	1902.8	1084.8	43.0	5.51	1902.8	1067.7	43.9	5.62
Winter solstice	1041.4	497.6	52.2	3.66	1041.4	435.9	58.1	4.08

VI. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT DEMONSTRATION FACILITY

INSTALLATION AND COMMISSIONING

The installation and commissioning of electrochromic (EC) windows has additional complexities when compared to conventional windows: maintaining the physical integrity of the windows' EC properties throughout shipping and handling, controls hardware (wiring from the control system to the windows and wall switches, sensors mounted on the façade or roof), configuring the control system, and managing the occupants' initial interaction with the windows.

a Maintaining physical integrity of windows through shipping and handling

At the beginning of the project 11 windows were found to have cosmetic defects, possibly due to mishandling during shipping. Replacements were provided by the manufacturer and successfully installed. In future installations, care should be taken to anticipate this type of issue and identify which of the participants (i.e., manufacturer, shipping company or installer) bears responsibility for addressing it.

b Control hardware

1. Wiring

In most retrofit situations, façades will not have been designed explicitly to allow room for running wiring to the windows. This can pose unexpected issues. For example, in this project it was found at installation time that the façade system would not allow the wires to be routed the way it was initially anticipated. This required a custom solution to be devised and implemented. Planning for these issues beforehand will save time and effort during the installation phase.

There is more than one type of cable used to connect EC windows to the control unit and, to minimize delays and effort, care must be taken to ensure that the correct wiring is provided, preferably before any wiring is installed.

2. Wall switches

EC windows can be manually controlled using wall switches. These require additional labor and hardware that needs to be taken into account in the planning stages of the installation. In this project, the assignment of windows to switches was straightforward because most spaces were private offices and the open-plan workstations lined up well with the windows, but this might not necessarily be the case in other buildings.

3. Exterior sensors

The EC window control system relies on sensors mounted on the building exterior (façade or roof). It is important to be aware, during the planning stages, of possible issues in finding suitable locations for these sensors and also that they will need to be connected with the control system via wire. Sensors need to be facing in the same direction as that of the façade that they are controlling, and, ideally, facing a similar view (e.g., surrounding buildings, trees or other obstructions should affect the sensor in similar ways as they affect the façade being controlled).

c Control system configuration

When in automatic operation (i.e., not controlled manually via wall switch) the tint of the windows is determined by a central unit. Although there is, depending on location and façade orientation, one (or perhaps a few) standard operating modes to which the manufacturer might default based on its prior experience, there is actually a high degree of flexibility in how the control system is able to control windows and it is important to specify early on the expectations for operation, both from the facility management and the occupant standpoints. Parameters to have in mind include:

- Depth of maximum solar penetration allowable before windows go to full tint (glare mode);
- Maximum allowable tint when in glare mode, if other than full tint;
- When not in glare mode, how much windows should tint in response to exterior light levels;
- Weekday vs. weekend/holiday operation; and
- For installations, such as the one shown in this project, with windows split into subpanes: the specifics of how subpanes will be controlled independently of each other when in automatic or manual operation.

d Managing occupant transition to EC windows

In replacing conventional windows with EC windows, particular attention needs to be paid to supporting occupants throughout the transition. This may involve:

- Providing information about how the windows operate, (where applicable) how to use the wall switches to control them and what they may and may not expect from the windows in terms of behavior and/or performance;
- Informing occupants of the ability to make modifications to the automated controls according to their needs and/or preferences (it is important for this to be available on a continuous basis, particularly in the first year of operation); and
- Proactively seeking out occupants who may require special accommodations due to vision or other health issues and working with them to ensure the automatic and manual controls are configured according to their needs.

EC OPERATION AND OCCUPANT IMPACTS

a EC operation

Throughout the study, the EC windows were observed operating as configured by the manufacturer. The original configuration of the controls resulted in the windows spending most of the day at full tint, unless they were manually overridden using the wall switches. In April 2016, after five months of operation, the manufacturer readjusted the control algorithm at the request of GSA, based on feedback from the occupants that the space was too dark. After this, the windows spent most of the day at light tint (one step darker than clear).

b Use of wall switches

When looking at the whole period from November 2015 to June 2016, occupants used the wall switches fairly evenly, although with wide variations from week to week. Throughout the study, on any given week, the wall switches were used to override automatic EC window control in between 18% and 64% of the window zones (windows were grouped into zones and each zone had one assigned wall switch). The use of the wall switches was higher in a relatively small number of zones, although the data does not allow a straightforward classification of zones into “high use” and “low use” categories. Three zones accounted for 52% of the amount of time windows spent in manual override; eight zones account for 83% of time in manual override.

c Use of operable shading

Use of Venetian blinds by the occupants was highly prevalent throughout the study, with at least 79% of the blinds lowered from their fully raised position and at least 67% of blinds lowered over 50% or more of the height of the window. This is a surprising finding, when considering that the EC windows spent, until April 2016, a substantial amount of time at full tint, which, at a visible transmittance of approximately 1%, is a very dark tint. This is probably due to a combination of two factors: (1) field measurements showed that EC windows were able to control glare most of the time, but not 100% of the time, so it is possible that the occupants in this building are adjusting the blinds according to worst-case conditions, and (2) occupants’ experience with the windows in Phase I of this project, during which windows were not able to tint all the way down to 1% visible transmittance, could have reduced the occupants’ expectations of the ability of EC windows to control glare.

d Occupant experience

The survey of the occupants that was performed during this study indicates that, overall, the occupants on the sixth floor prefer the EC windows to conventional windows. Responses also indicate an improvement in thermal comfort during warm/hot weather on the EC floor (sixth floor). Occupants on the EC floor found their windows less aesthetically pleasing than occupants of another floor with conventional windows used for reference (eighth floor). Possible causes for this are (1) the EC windows spending a significant amount of time at full tint, (2) the fact that a light-colored line is visible between the subpanes when the EC windows are tinted or (3) the fact that subpanes were not all set to the same tint when the system was in glare mode. Occupants on the EC floor found that the outside was less visible through the window than on the reference floor. A probable cause for this result is the EC windows spending a significant time at full tint. In other aspects of the occupants' indoor environment experience, such as visual comfort, light levels and general satisfaction, no statistically significant differences were found between pre- and post-installation conditions on the sixth floor or post-installation conditions on the sixth floor and conditions on the eighth floor.

Occupants' comments on the survey varied from the very satisfied ("Great product! I would love to have them @ home") to the clearly not satisfied ("The windows are (…) unsatisfactory"). Two occupants pointed out that they use the EC windows in conjunction with the blinds to control glare. Issues mentioned by the occupants in comments included: the windows made the space seem too dark (three occupants), issues with the subpane tinting patterns (two occupants), need for personalized adjustments to the control algorithm (one occupant), and windows were slow to respond (one occupant).

e Visual comfort

Field and laboratory measurements showed EC windows as very capable in reducing glare to tolerable levels when at full tint, except in the most extreme conditions, such as low angle sun. However, it should be added that (1) windows at full tint are very dark and, while able to control glare in most situations, may be unappealing to the occupants — comments on the occupant suggests this could be the case and (2) when entering and exiting glare mode, if the tinting of the windows is not exactly timed with the appearance/disappearance of the sun from the field of view, occupants can experience extreme glare until the windows reach full tint — this was observed consistently in the laboratory tests.

f Thermal comfort

Measurements and occupant surveys did not suggest any significant negative impacts from the installation of EC windows. In fact, occupants of the EC floor reported an improvement in conditions during warm/hot weather.

ENERGY PERFORMANCE

a HVAC

Laboratory measurements performed during this study show significant reductions in HVAC cooling loads due to the installation of EC windows. Daily HVAC load was reduced by 29%–65% or 0.43–3.48 Wh/ft^2 per day, depending on time of year. Peak HVAC load was reduced by 25%–58% or 1.15–5.63 W/ft^2, also depending on time of year. Changing the control algorithm settings seemed to have only a minor effect on HVAC loads.

b Lighting

Estimates using data from the lighting control system on the EC floor show a 62% projected increase in annual lighting energy consumption. This significant negative impact is probably related to two factors: (1) the significant amount of time windows spent at full tint from November 2015 to April 2016 and (2) the high prevalence of occupants using the venetian blinds. Altogether, this suggests that EC windows can, but do not necessarily have a negative impact on lighting energy consumption. When installing EC windows in a space, special attention needs to be paid to the balance between glare control and lighting energy consumption.

COSTS

Manufacturer estimates of the cost of EC windows are $61/ft^2, for large volumes in a mature market, and including high-quality framing, controls, installation, equipment, project management and a 25% markup. It was not possible to calculate the payback time for this study for two reasons: (1) it was not possible to determine total energy savings because of the infeasibility of measuring HVAC energy consumption along the façade and (2) calculated lighting energy savings were negative.

B. BARRIERS AND ENABLERS TO ADOPTION

The main barrier to widespread adoption of EC technology is cost. This will be mitigated in situations where the replacement of the windows is already being considered for other reasons, or where protection of the occupants from glare, while maintaining views of the outside, can be factored into cost-benefit calculations. Also, if upgrades to HVAC systems are being considered, EC windows can be a cost-effective option for reducing peak cooling loads and, therefore, also reducing the needed investment in HVAC capacity.

For EC installations such as the one studied here, in which tint is controllable at the subpane level, the complexity of controlling the subpanes in a way that is effective at glare control, providing sufficient daylight and that is also satisfying and logical to the occupants poses an additional potential market barrier.

In retrofit situations, the installation of a non-conventional window — i.e., a window that is associated with cabling that must be run out of the window frame, along the façade and all the way to a central controller somewhere inside the building — in façades that were designed without electric connectivity in mind can be a challenge and potential source of complexities that deter market dissemination. The availability of accurate, up to date drawings of the façade is critical in anticipating any physical obstacles to wire routing.

In terms of enabling the market for EC windows, large office buildings with inefficient windows situated in warm, sunny climates in latitudes closer to the equator, and also where occupants are positioned relatively far from the windows (very roughly, not in the first 4 ft, measuring from the window glass), appear to have the greatest potential.

When considered in its totality, what the results from this study suggest is that, while the EC hardware itself is generally mature and able to perform well in controlling glare and thermal discomfort, and in the reduction of HVAC cooling loads, the algorithms that control that hardware may require improvement in terms of achieving an adequate balance between occupant satisfaction, glare control and lighting and cooling energy savings.

VII. References

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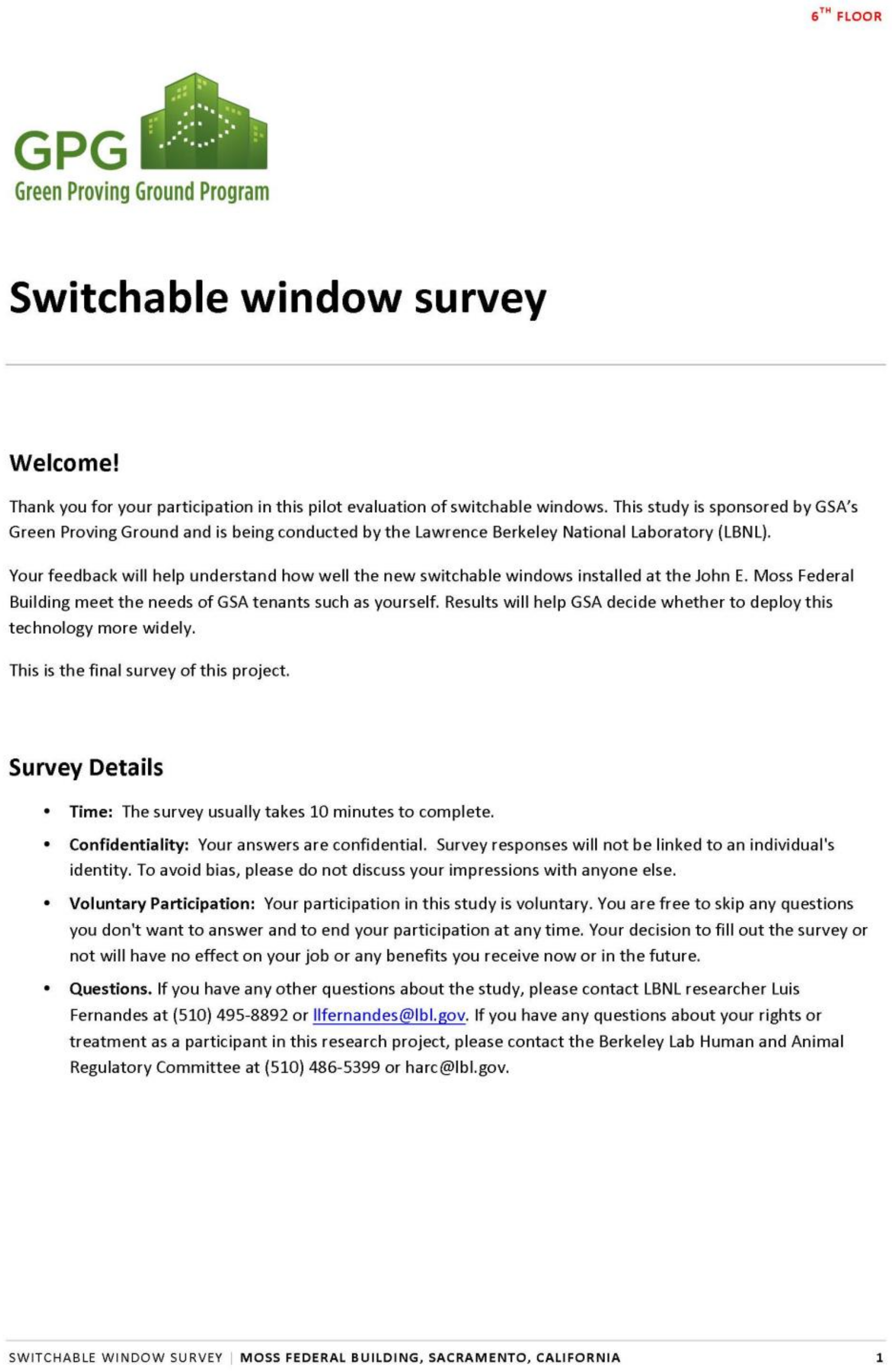
VIII. Appendix A: Full Text of Occupant Survey

A. SIXTH FLOOR (EC)



6TH FLOOR

Green Proving Ground Program

Switchable window survey

Welcome!

Thank you for your participation in this pilot evaluation of switchable windows. This study is sponsored by GSA's Green Proving Ground and is being conducted by the Lawrence Berkeley National Laboratory (LBNL).

Your feedback will help understand how well the new switchable windows installed at the John E. Moss Federal Building meet the needs of GSA tenants such as yourself. Results will help GSA decide whether to deploy this technology more widely.

This is the final survey of this project.

Survey Details

- **Time:** The survey usually takes 10 minutes to complete.
- **Confidentiality:** Your answers are confidential. Survey responses will not be linked to an individual's identity. To avoid bias, please do not discuss your impressions with anyone else.
- **Voluntary Participation:** Your participation in this study is voluntary. You are free to skip any questions you don't want to answer and to end your participation at any time. Your decision to fill out the survey or not will have no effect on your job or any benefits you receive now or in the future.
- **Questions.** If you have any other questions about the study, please contact LBNL researcher Luis Fernandes at (510) 495-8892 or llfernandes@lbl.gov. If you have any questions about your rights or treatment as a participant in this research project, please contact the Berkeley Lab Human and Animal Regulatory Committee at (510) 486-5399 or harc@lbl.gov.

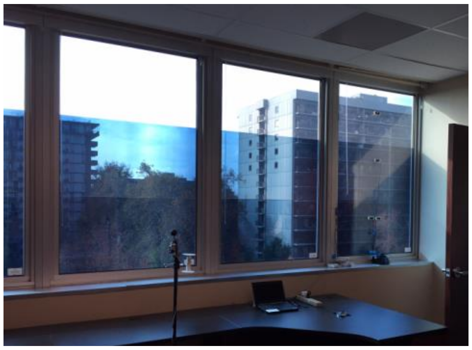
Instructions

Please fill out this questionnaire as completely as possible, skipping any question you are unable to answer or do not want to answer. Please respond to all of the items as openly and honestly as possible. There are no right or wrong answers; it is only your opinions that are important.

When you are done with the questionnaire, please place it in the provided envelope and seal the envelope before returning it.

Switchable Windows

Switchable windows are windows that can tint and untint automatically or at the press of a switch – see images below:



Switchable windows

Window switch

Original windows

In February 2014, switchable windows were installed on the 6th floor of the Moss Federal Building. Several issues required several window replacements and changes to the way windows were operated. This study focuses on a period of time after these issues were resolved: December 2015 to present.

In this survey, the term *"original windows"* refer to the non-switchable windows in your space prior to February 2014, NOT the switchable windows that were replaced in late 2015.

When answering this survey, please have in mind the operation of the switchable windows from December 2015 to present.

BACKGROUND

1) Sometimes men and women have different physiological responses to their environments. Are you:

- a) Female
- b) Male
- c) Decline to state

2) Are you…

- a) Under 40 years old?
- b) 40 or over?
- c) Decline to state

3) Do you wear glasses at work?

- a) Yes
- b) No
- c) Decline to state

4) What is your usual work location?

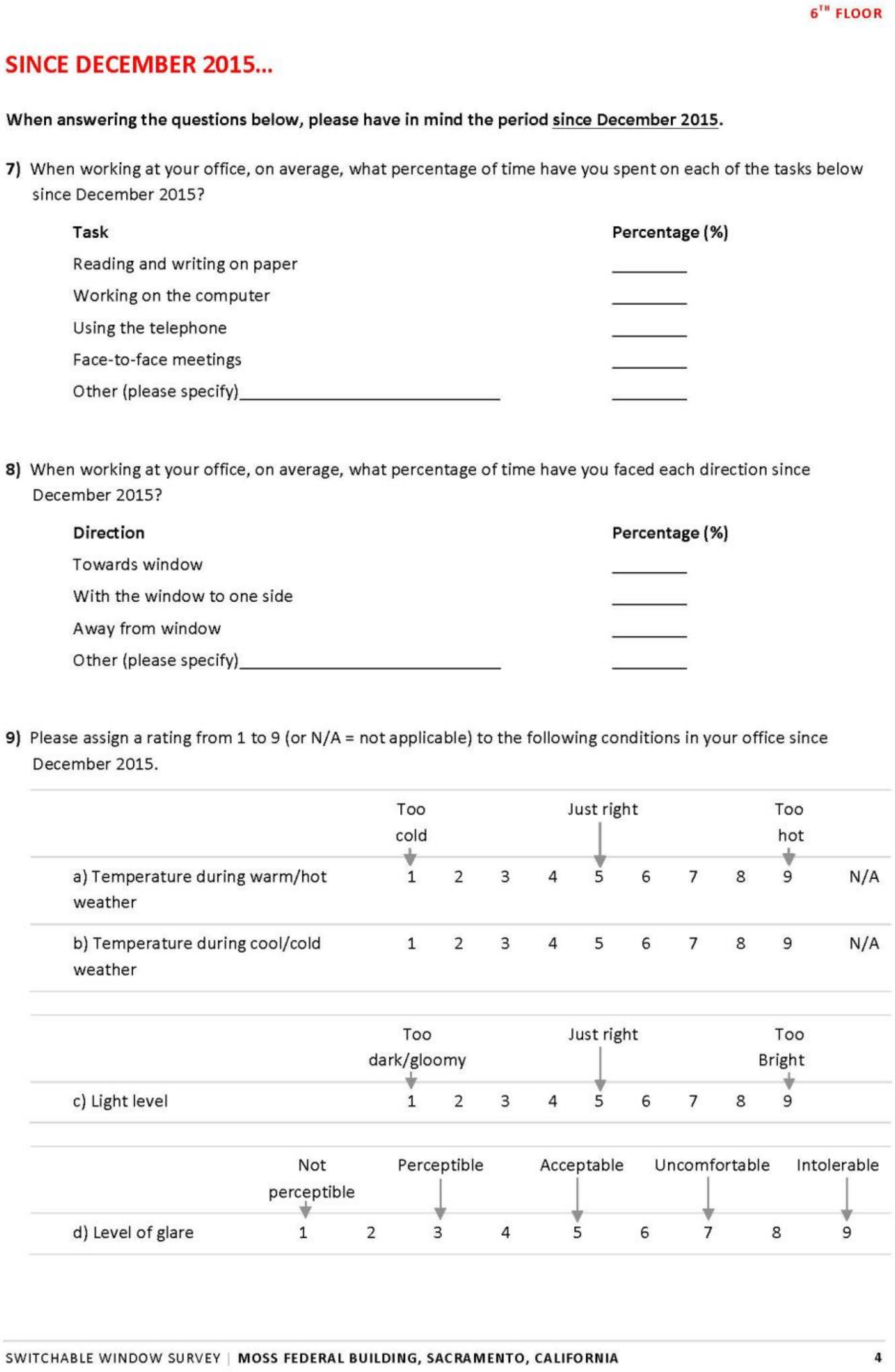
- d) Cubicle next to a window
- e) Cubicle not next to a window
- f) Private office next to a window
- g) Other (please specify) ______________________________

5) Please assign a rating from 1 to 9 for your sensitivity to the following items, with 1 being not sensitive, 5 being moderately sensitive, and 9 being very sensitive.

	Not sensitive ↓				Moderately sensitive ↓				Very sensitive ↓
a) Glare	1	2	3	4	5	6	7	8	9
b) Cold	1	2	3	4	5	6	7	8	9
c) Heat	1	2	3	4	5	6	7	8	9
d) Gloominess	1	2	3	4	5	6	7	8	9

6) When you perform your usual work tasks, what is your preferred light level in your workspace?

	Very low ↓		Low ↓		Moderate ↓		Bright ↓		Very Bright ↓
Light level	1	2	3	4	5	6	7	8	9



6TH FLOOR

SINCE DECEMBER 2015…

When answering the questions below, please have in mind the period since December 2015.

7) When working at your office, on average, what percentage of time have you spent on each of the tasks below since December 2015?

Task	**Percentage (%)**
Reading and writing on paper	________
Working on the computer	________
Using the telephone	________
Face-to-face meetings	________
Other (please specify)___________________________	________

8) When working at your office, on average, what percentage of time have you faced each direction since December 2015?

Direction	**Percentage (%)**
Towards window	________
With the window to one side	________
Away from window	________
Other (please specify)___________________________	________

9) Please assign a rating from 1 to 9 (or N/A = not applicable) to the following conditions in your office since December 2015.

	Too cold				Just right				Too hot	
a) Temperature during warm/hot weather	1	2	3	4	5	6	7	8	9	N/A
b) Temperature during cool/cold weather	1	2	3	4	5	6	7	8	9	N/A

	Too dark/gloomy				Just right				Too Bright
c) Light level	1	2	3	4	5	6	7	8	9

	Not perceptible		Perceptible		Acceptable		Uncomfortable		Intolerable
d) Level of glare	1	2	3	4	5	6	7	8	9

SWITCHABLE WINDOW SURVEY | **MOSS FEDERAL BUILDING, SACRAMENTO, CALIFORNIA** 4

SINCE DECEMBER 2015…

When answering the questions below, please have in mind the period since December 2015.

10) Indicate your level of agreement/disagreement (disagree = 1, agree = 9) with the following statements about your office since December 2015:

	Disagree				Neutral				Agree	
a) Bright light on my task made it difficult to read or see	1	2	3	4	5	6	7	8	9	
b) The shades blocked the view	1	2	3	4	5	6	7	8	9	N/A
c) There was enough daylight in the space	1	2	3	4	5	6	7	8	9	
d) The windows looked aesthetically pleasing	1	2	3	4	5	6	7	8	9	
e) The tinting/untinting of the windows did not disturb me in my work	1	2	3	4	5	6	7	8	9	
f) The outside was sufficiently visible through the window	1	2	3	4	5	6	7	8	9	
g) The wall switches allowed the window to be manually controlled in a satisfactory way	1	2	3	4	5	6	7	8	9	
h) The speed at which the windows tinted/untinted was satisfactory	1	2	3	4	5	6	7	8	9	
i) When the windows had horizontal bands of different tints, they looked aesthetically pleasing	1	2	3	4	5	6	7	8	9	
j) When the windows had horizontal bands of different tints, the tinting patterns made sense	1	2	3	4	5	6	7	8	9	

SINCE DECEMBER 2015…

When answering the questions below, please have in mind the period since December 2015.

11) Indicate your level of agreement/disagreement (disagree = 1, agree = 9) with the following statements about your office since December 2015:

	Disagree				Neutral				Agree
a) I experience less glare with the *switchable* windows than with the *original* windows	1	2	3	4	5	6	7	8	9
b) I feel less heat from the sun with the *switchable* windows than with the *original* windows	1	2	3	4	5	6	7	8	9
c) I am more thermally comfortable (less hot and/or less cold) with the *switchable* windows than with the *original* windows	1	2	3	4	5	6	7	8	9
d) Generally, I am more satisfied with the *switchable* windows than with the *original* windows	1	2	3	4	5	6	7	8	9

12) If you are more thermally comfortable (less hot and/or less cold) with the *switchable* windows than with the *original* windows, please indicate reasons why (please check all that apply):

a) When it is cold outside, I feel warmer with the *switchable* windows than with the *original* windows
b) When it is hot outside, I feel cooler with the *switchable* windows than with the *original* windows
c) There are less drafts through the window
d) Other(s) (please specify)____________________________________

13) Overall, if given the option, would you prefer switchable or conventional (i.e. non-switchable) windows in your office?

h) Switchable windows
i) Conventional (i.e., non-switchable) windows

14) Since December 2015, have you lowered the window blinds from their fully raised position?

j) Yes ---> Continue to **Question 15**
k) No ---> Skip to **Question 19**

15) When you lowered the blinds, what were the primary reasons? (please check all that apply)

- ☐ To reduce glare from daylight/sunlight
- ☐ To reduce glare when the sun is directly visible
- ☐ To reduce the overall brightness of the space
- ☐ To increase privacy
- ☐ To reduce the heat from the sun
- ☐ To reduce the cold draft from the window
- ☐ To decrease the level of visual stimulus from the outside
- ☐ To decrease the brightness of reflections on my computer monitor
- ☐ To hide the tinting patterns (horizontal bands) on the window
- ☐ Other (please specify) ____________________

16) With the *switchable* windows, did you set the blinds to the same height and slat angle as with the *original* windows?

a) Yes ---> Skip to **Question 19**
b) No ---> Continue to **Question 17**

17) With the *switchable* windows, did you set the blinds higher, lower, or at the same height as with the *original* windows?

a) Higher
b) Same height
c) Lower

18) With the *switchable* windows, did you adjust the blinds more or less often than with the *original* windows?

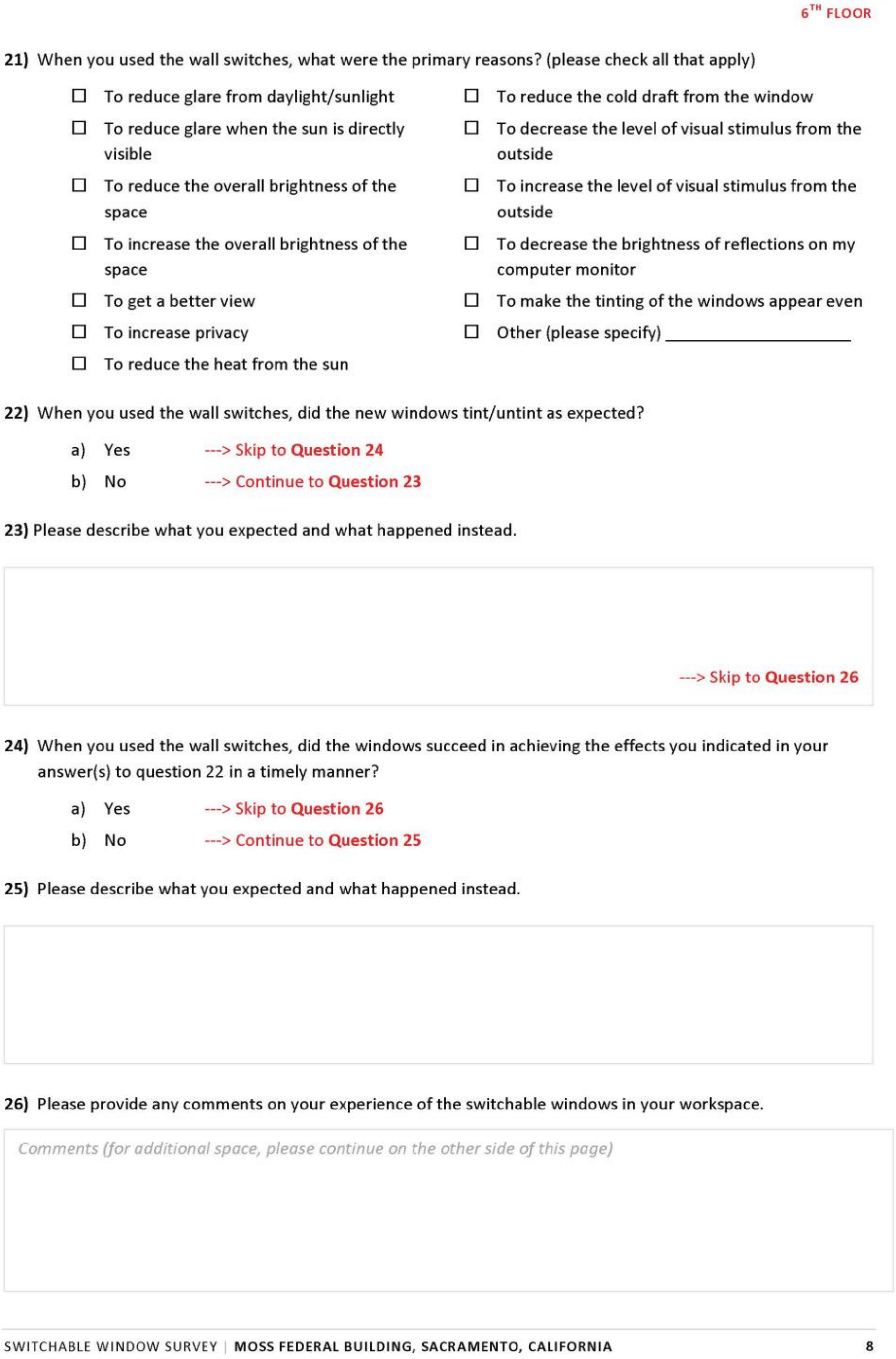
a) More often
b) Neither more nor less often
c) Less often

19) Have you used the wall switches to tint or untint the switchable windows?

a) Yes ---> Continue to **Question 20**
b) No ---> Skip to **Question 26**

20) How often did you use the wall switches?

a) Two or more times a day
b) Once a day
c) Not every day, but at least once a week
d) Less often than once a week
e) Never



21) When you used the wall switches, what were the primary reasons? (please check all that apply)

☐ To reduce glare from daylight/sunlight
☐ To reduce glare when the sun is directly visible
☐ To reduce the overall brightness of the space
☐ To increase the overall brightness of the space
☐ To get a better view
☐ To increase privacy
☐ To reduce the heat from the sun
☐ To reduce the cold draft from the window
☐ To decrease the level of visual stimulus from the outside
☐ To increase the level of visual stimulus from the outside
☐ To decrease the brightness of reflections on my computer monitor
☐ To make the tinting of the windows appear even
☐ Other (please specify) ____________________

22) When you used the wall switches, did the new windows tint/untint as expected?

a) Yes ---> Skip to **Question 24**
b) No ---> Continue to **Question 23**

23) Please describe what you expected and what happened instead.

---> Skip to **Question 26**

24) When you used the wall switches, did the windows succeed in achieving the effects you indicated in your answer(s) to question 22 in a timely manner?

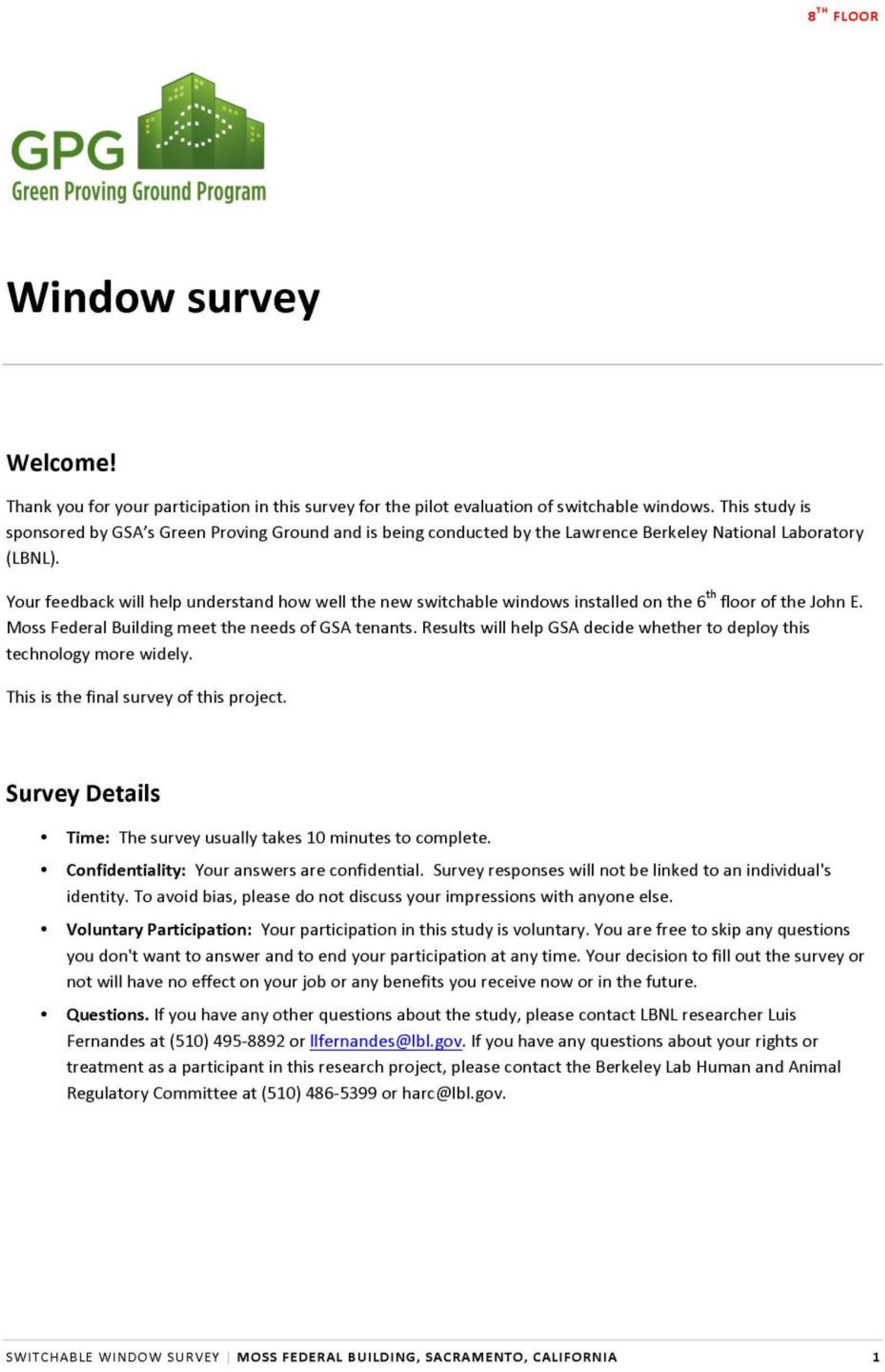
a) Yes ---> Skip to **Question 26**
b) No ---> Continue to **Question 25**

25) Please describe what you expected and what happened instead.

26) Please provide any comments on your experience of the switchable windows in your workspace.

Comments (for additional space, please continue on the other side of this page)

B. EIGHTH FLOOR (REFERENCE)



8TH FLOOR

GPG
Green Proving Ground Program

Window survey

Welcome!

Thank you for your participation in this survey for the pilot evaluation of switchable windows. This study is sponsored by GSA's Green Proving Ground and is being conducted by the Lawrence Berkeley National Laboratory (LBNL).

Your feedback will help understand how well the new switchable windows installed on the 6th floor of the John E. Moss Federal Building meet the needs of GSA tenants. Results will help GSA decide whether to deploy this technology more widely.

This is the final survey of this project.

Survey Details

- **Time:** The survey usually takes 10 minutes to complete.
- **Confidentiality:** Your answers are confidential. Survey responses will not be linked to an individual's identity. To avoid bias, please do not discuss your impressions with anyone else.
- **Voluntary Participation:** Your participation in this study is voluntary. You are free to skip any questions you don't want to answer and to end your participation at any time. Your decision to fill out the survey or not will have no effect on your job or any benefits you receive now or in the future.
- **Questions.** If you have any other questions about the study, please contact LBNL researcher Luis Fernandes at (510) 495-8892 or llfernandes@lbl.gov. If you have any questions about your rights or treatment as a participant in this research project, please contact the Berkeley Lab Human and Animal Regulatory Committee at (510) 486-5399 or harc@lbl.gov.

SWITCHABLE WINDOW SURVEY | **MOSS FEDERAL BUILDING, SACRAMENTO, CALIFORNIA** 1

Instructions

Please fill out this questionnaire as completely as possible, skipping any question you are unable to answer or do not want to answer. Please respond to all of the items as openly and honestly as possible. There are no right or wrong answers; it is only your opinions that are important.

When you are done with the questionnaire, please place it in the provided envelope and seal the envelope before returning it.

In February 2014, switchable windows were installed on the 6th floor of the Moss Federal Building. This study focuses on the period from December 2015 to present. Your responses to this survey will serve as the baseline for LBNL's analysis of user acceptance of switchable windows.

When answering this survey, please have in mind the period from December 2015 to present.

BACKGROUND

1) Sometimes men and women have different physiological responses to their environments. Are you:

- a) Female
- b) Male
- c) Decline to state

2) Are you...

- a) Under 40 years old?
- b) 40 or over?
- c) Decline to state

3) Do you wear glasses at work?

- a) Yes
- b) No
- c) Decline to state

4) What is your usual work location?

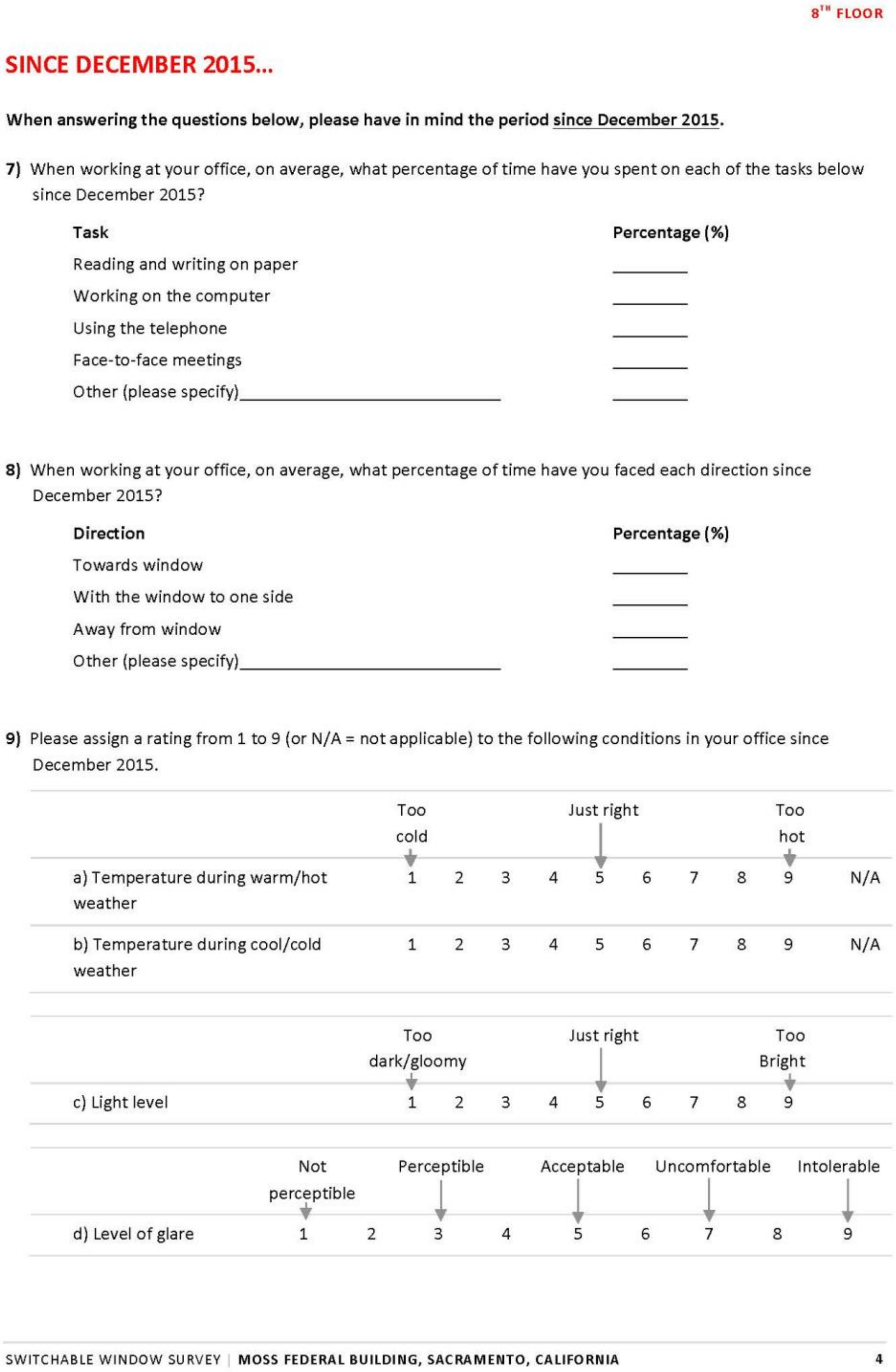
- d) Cubicle next to a window
- e) Cubicle not next to a window
- f) Private office next to a window
- g) Other (please specify) ______________________________

5) Please assign a rating from 1 to 9 for your sensitivity to the following items, with 1 being not sensitive, 5 being moderately sensitive, and 9 being very sensitive.

	Not sensitive ↓				Moderately sensitive ↓				Very sensitive ↓
a) Glare	1	2	3	4	5	6	7	8	9
b) Cold	1	2	3	4	5	6	7	8	9
c) Heat	1	2	3	4	5	6	7	8	9
d) Gloominess	1	2	3	4	5	6	7	8	9

6) When you perform your usual work tasks, what is your preferred light level in your workspace?

	Very low ↓		Low ↓		Moderate ↓		Bright ↓		Very Bright ↓
Light level	1	2	3	4	5	6	7	8	9



SINCE DECEMBER 2015…

When answering the questions below, please have in mind the period since December 2015.

7) When working at your office, on average, what percentage of time have you spent on each of the tasks below since December 2015?

Task	**Percentage (%)**
Reading and writing on paper	________
Working on the computer	________
Using the telephone	________
Face-to-face meetings	________
Other (please specify)____________________________	________

8) When working at your office, on average, what percentage of time have you faced each direction since December 2015?

Direction	**Percentage (%)**
Towards window	________
With the window to one side	________
Away from window	________
Other (please specify)____________________________	________

9) Please assign a rating from 1 to 9 (or N/A = not applicable) to the following conditions in your office since December 2015.

	Too cold				Just right				Too hot	
a) Temperature during warm/hot weather	1	2	3	4	5	6	7	8	9	N/A
b) Temperature during cool/cold weather	1	2	3	4	5	6	7	8	9	N/A

	Too dark/gloomy				Just right				Too Bright
c) Light level	1	2	3	4	5	6	7	8	9

	Not perceptible		Perceptible		Acceptable		Uncomfortable		Intolerable
d) Level of glare	1	2	3	4	5	6	7	8	9

SINCE DECEMBER 2015...

When answering the questions below, please have in mind the period since December 2015.

10) Indicate your level of agreement/disagreement (disagree = 1, agree = 9) with the following statements about your office since December 2015:

	Disagree				Neutral				Agree	
a) Bright light on my task made it difficult to read or see	1	2	3	4	5	6	7	8	9	
b) The shades blocked the view	1	2	3	4	5	6	7	8	9	N/A
c) There was enough daylight in the space	1	2	3	4	5	6	7	8	9	
d) The windows looked aesthetically pleasing	1	2	3	4	5	6	7	8	9	
e) The outside was sufficiently visible through the window	1	2	3	4	5	6	7	8	9	

11) Since December 2015, how often have you adjusted the height (by raising or lowering) of the blinds in your office?

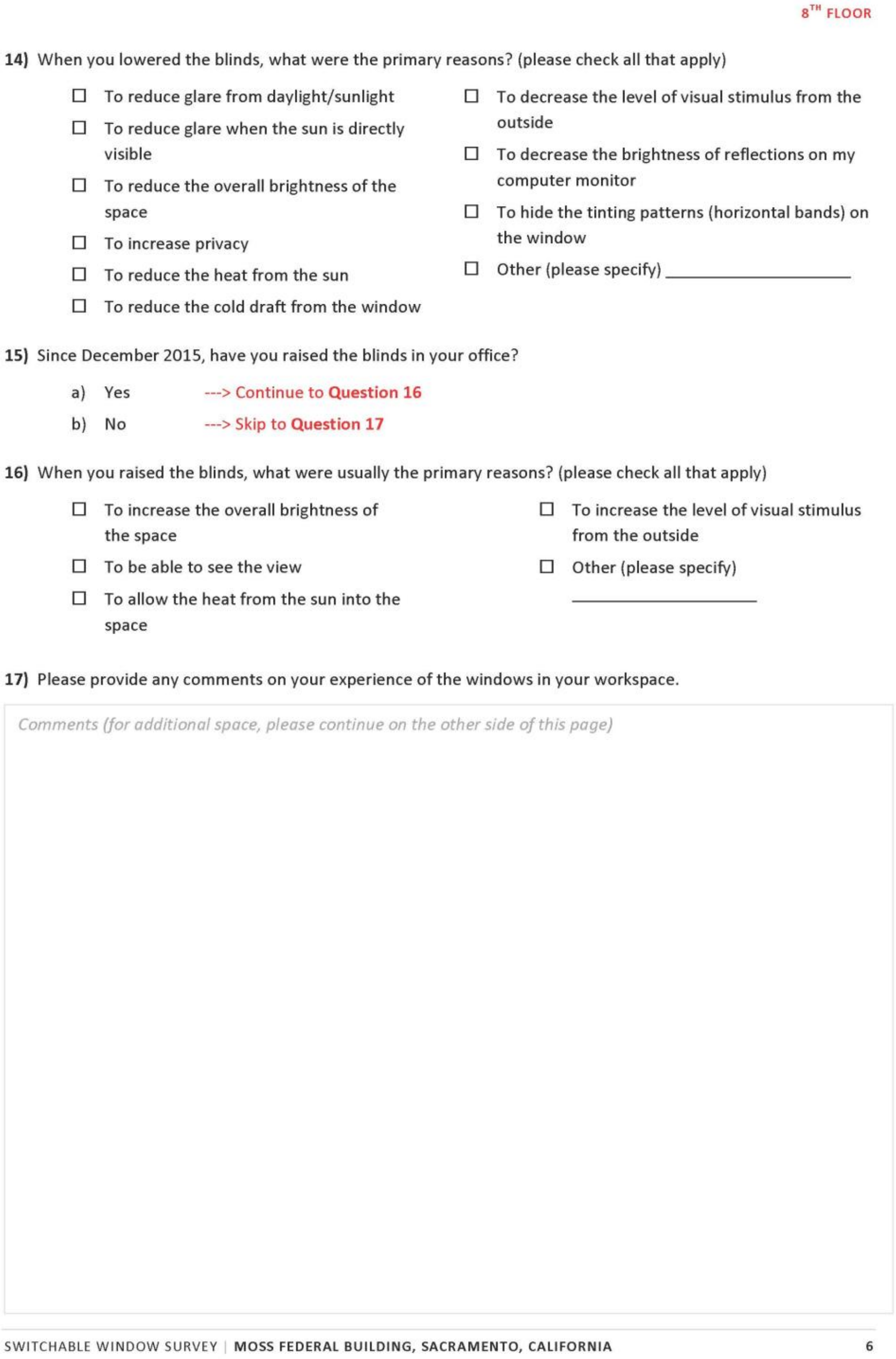
a) Two or more times a day
b) Once a day
c) Not every day, but at least once a week
d) Less often than once a week
e) Never

12) Since December 2015, in what position have usually been the blinds in your office?

a) Fully raised
b) Fully lowered
c) Somewhere in between

13) Since December 2015, have you lowered the window blinds in your office?

a) Yes ---> Continue to **Question 14**
b) No ---> Skip to **Question 15**



14) When you lowered the blinds, what were the primary reasons? (please check all that apply)

- ☐ To reduce glare from daylight/sunlight
- ☐ To reduce glare when the sun is directly visible
- ☐ To reduce the overall brightness of the space
- ☐ To increase privacy
- ☐ To reduce the heat from the sun
- ☐ To reduce the cold draft from the window
- ☐ To decrease the level of visual stimulus from the outside
- ☐ To decrease the brightness of reflections on my computer monitor
- ☐ To hide the tinting patterns (horizontal bands) on the window
- ☐ Other (please specify) ____________________

15) Since December 2015, have you raised the blinds in your office?

a) Yes ---> Continue to **Question 16**

b) No ---> Skip to **Question 17**

16) When you raised the blinds, what were usually the primary reasons? (please check all that apply)

- ☐ To increase the overall brightness of the space
- ☐ To be able to see the view
- ☐ To allow the heat from the sun into the space
- ☐ To increase the level of visual stimulus from the outside
- ☐ Other (please specify) ____________________

17) Please provide any comments on your experience of the windows in your workspace.

Comments (for additional space, please continue on the other side of this page)