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Electrochromic Window Demonstration at the 911 Federal Building, 911 Northeast 11th Avenue, Portland, Oregon, General Services Administration, Green Proving Ground Report

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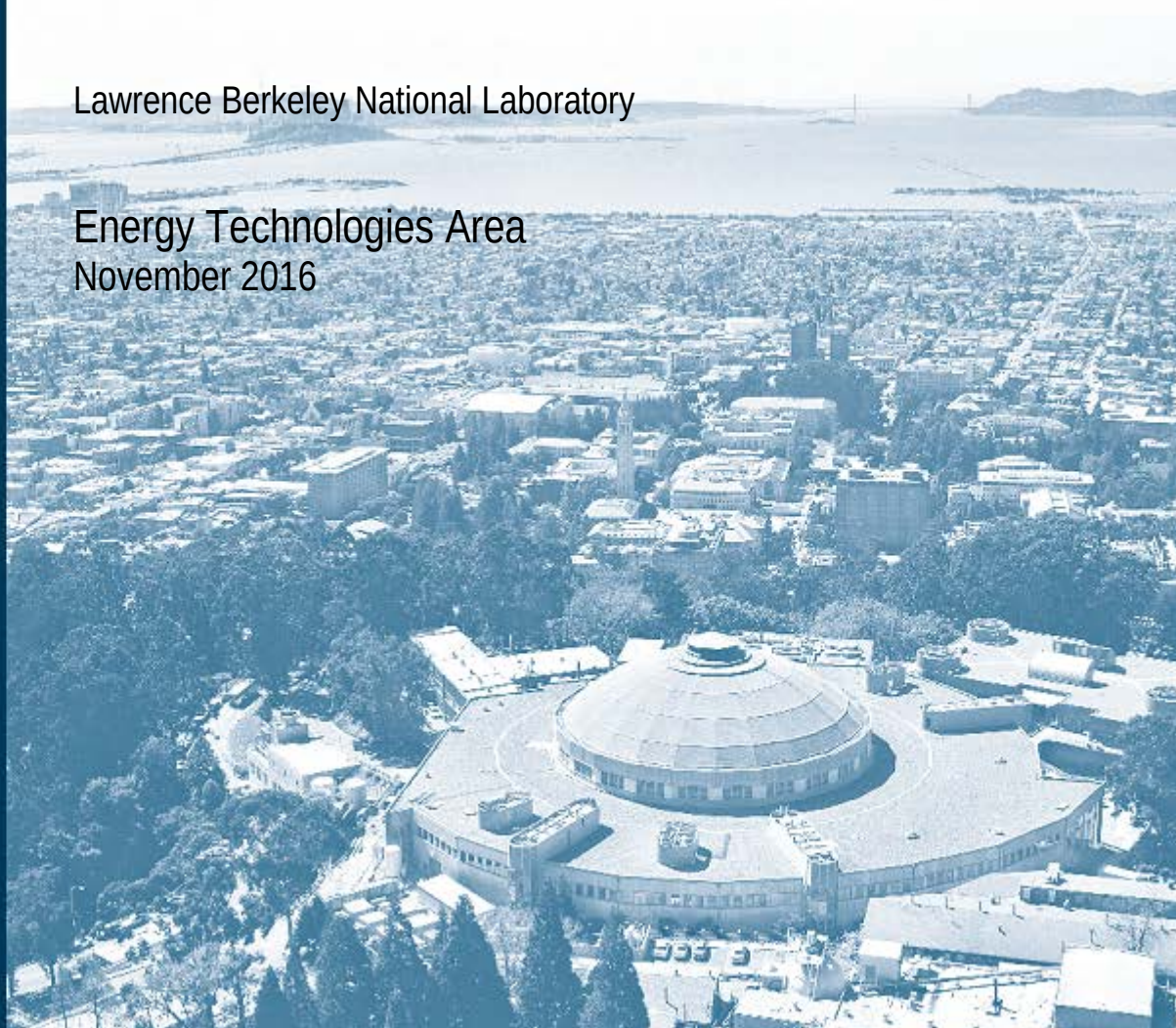

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By the Lawrence Berkeley National Laboratory

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GSA's GPG program and DOE's High Impact Technology (HIT) Catalyst program enable federal and commercial building owners and operators to make sound investment decisions in next generation building technologies based on their real-world performance.

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I. Executive Summary

A. BACKGROUND

Switchable electrochromic (EC) windows are part of a new class of dynamic, energy-efficient technologies that enable real-time, active load management in response to weather conditions and the unique operating conditions of individual buildings. Owners can now specify a solid-state technology that reacts to various stimuli like the skin of a living entity. The technology can be controlled to address multiple criteria to achieve a more optimal energy-efficient and comfortable indoor environment than one with static or manually operated technologies. Inputs can include data on outdoor solar conditions, utility rates, occupancy status, heating, ventilation, and air conditioning (HVAC), or operating emergency or security mode. The outputs then dictate how the EC window is controlled, whether as a self-contained autonomous unit that achieves specific zonal objectives or as a part of an integrated system designed to address whole building, campus and grid-related goals. Since windows typically have a 30-year life, these dynamic qualities enable the building to be adaptable and more resilient as the environmental, operating and economic context evolves.

B. OVERVIEW OF THE TECHNOLOGY

EC windows consist of an insulating glass unit with a thin, multilayer EC coating on the inboard surface of the outside pane of glass. The EC coating has broadband switching capabilities, meaning that it switches in the visible and near infrared portions of the solar spectrum, absorbing solar radiation then relying on the low-emittance (low-e) properties of the coating to keep the solar heat from coming into the building. Tinting also enables modulation of daylight levels within the building.

The coating is switched by applying a small direct current voltage that then holds the EC window at a switched tinted state. When unpowered, the window goes to its bleached, near colorless state. The window is always transparent, whether bleached or tinted, and the outdoor view is clear without haze or distortion. The thermal and optical properties of the window and its appearance are dependent on what the EC coating is combined with; the window composition is specified by the owner. When combined with clear glass, the EC window is near colorless when untinted and exhibits a blue color when tinted.

Automated control of the EC windows is key to this technology meeting its performance objectives. While the tint can be modulated, the speed of tinting is dependent on the size of the window, and for some types of EC coatings, on temperature, as well. Commercial products provide autonomous control at the zonal level, with manual override as an option. The products can be integrated with other building systems, but these solutions are currently not turnkey.

C. STUDY DESIGN AND OBJECTIVES

There have been several prior monitored demonstrations of EC windows, but the outcomes related to occupant comfort and satisfaction have been limited due to confounding factors or lack of a sufficiently large population from which to derive conclusive results. As such, there are several key questions this demonstration was designed to address related to comfort, indoor environmental quality and cost-effectiveness that are critical to widespread market adoption of the EC technology:

- Are indoor shades needed in addition to the EC window at the more northern latitudes where the sun path is low and within the occupant's field of view throughout the day and year (for a south façade)? Reducing or eliminating the need for indoor shades can make the EC technology more cost-effective.
- Can occupant requirements be met adequately under partly cloudy sky conditions, given the relatively long time it takes for EC windows to tint fully (i.e., 10–30 minutes)? There can be considerable variability in daylight levels under partly cloudy sky conditions. The sun can come out from behind a cloud and cast bright sunlight throughout the interior. This dynamic connection to the outdoors is what occupants like best about a windowed environment, but if the windows are unshaded, are occupants willing to accept the occasional prolonged discomfort while waiting for the EC windows to switch?
- Multiple EC windows can be grouped and controlled as a single zone in an office to reduce complexity and create a more uniform appearance for the exterior of the façade. However, when controlled for glare, the EC windows are switched to a dark tint level that can create a low daylit environment. Did occupants find the indoor environment produced by EC windows acceptable?

This study also addressed energy efficiency, comfort, cost-effectiveness, and other aspects of end-user satisfaction. Table ES1 shows the quantitative and qualitative performance objectives.

Table ES1: Performance Objectives

Quantitative Objectives	Metrics and Data Requirements	Success Criteria	M&V Results
Energy Savings	Metered daylight workplane illuminance and variable air volume (VAV) cooling load	>20% lighting energy savings; >10% cooling load reduction (per 15 ft. deep south-facing perimeter zone)	36% annual lighting energy savings due to daylight; 2% reduction in south zone VAV summer cooling load in normal operating mode; 57% reduction in weekend VAV summer cooling load when in setback mode with fully tinted EC window (Tint 4)
Cost effectiveness	Simple payback; Savings to Investment ratio (SIR)	Payback < 10 years; SIR> 1.	Payback = 29 years; SIR =1.04 with an installed cost of $61/ft^2. If installed cost < $21/ft^2, then payback = 10 years.
Qualitative Objectives			
Easy Installation	GSA observations when working with the installer	No change orders or time delays due to problems associated with installing the technology	No change orders, installation completed ahead of schedule.
Indoor shades	Survey of shade position	No or reduced need for indoor shades	40% more blinds were fully raised in EC area compared to original windows in private offices; mixed results in open plan offices
Reduce Maintenance	GSA effort over monitored period	<$1/ft^2-floor-yr added cost	$0.85/ft^2-floor-yr added cost of EC maintenance; cost offset by reduced maintenance of indoor shades
Increase Occupant Comfort	Survey and limited measured data	Statistically significant (SS) results that indicate greater comfort with EC windows compared to conventional windows	Less glare in open plan offices with EC windows; less glare with EC windows compared to original windows (SS); no

			difference in thermal[1] comfort.
Increase Occupant Satisfaction	Survey data	SS results that indicate greater satisfaction with the indoor environment with EC windows compared to conventional windows	More accessible view (SS) in both private offices (Phase I) and open plan offices (Phase II); light levels were slightly too dark/ gloomy with EC (SS); generally more satisfied with EC windows than original windows.
Occupant Acceptance of New Technology	Survey data	SS results that indicate greater preference for EC windows compared to conventional windows	85% and 92% of occupants preferred EC windows over existing windows in Phases I&II, respectively.

D. PROJECT RESULTS/FINDINGS

This study was conducted on four floors of an eight-story office building (1953 vintage, 312,447 ft^2 gross floor area) in Portland, Oregon. The building had south-facing, large area (window-to-exterior-wall-area ratio (WWR) of 0.46), dark tinted, dual-pane low-e windows with a solar (Tsol) and visible transmittance (Tvis) of approximately 0.06 and 0.15, respectively. The windows had manually operated, indoor venetian blinds. The existing HVAC system was a conventional VAV system with air handler units (AHU) serving both the north and south sides of the building, which tended to cause thermal discomfort due to overcooling in north and core zones. The existing lighting consisted of 2x4 troffers with T8 fluorescent lamps operated with a manual switch and occupancy sensor. Portland has partly cloudy to overcast sky conditions from about November to June, then sunny and partly cloudy conditions from June to October. Annual solar irradiance levels are amongst the lowest in the nation.

The study consisted of two phases:

- Phase I involved 40 private offices with EC windows on Floors 6–7 and 20 private offices with the existing windows. The installed 3.14 ft. by 6.14 ft. EC windows were designed to match the appearance of the existing windows (when initially there was only one floor planned to be retrofit with the windows) and, thus had a narrow switching range due to the use of the EC glass with a second dark tinted glass layer (SHGC = 0.43–0.09 and Tvis = 0.36–0.02). All EC windows in each private office were grouped as a single control zone and automatically controlled to tint between its clearest state (Tint 1, Tvis = 0.36) to an intermediate tinted state (Tint 3, Tvis = 0.13) in proportion to incident vertical solar radiation. In the initial stages of commissioning the EC

[1] Temperature during cool/ cold weather was rated as slightly "too cold" with the reference windows in Phase I and moderately "too cold" with the EC windows in Phase II. Both questions yielded statistically significant results, but the facility managers attributed these differences to the operation of the HVAC system rather than the EC windows.

windows, occupant feedback ("too dark") led to a restriction of automatic control to Tints 1–3. The occupants could override the automatic controls using a manually operated switch located in each private office to any of four tints (Tints 1–4; Tint 4 Tvis = 0.02). This would override the automatic controls for four hours. The indoor venetian blinds were zip-tied up to prevent use but were untied when requested by the occupant.

- Phase II involved a comparison between half of one floor (Floor 5) with automatically controlled EC windows and the other half of the floor with the EC windows fixed to its clearest state (Tint 1). In both the test and reference areas, there were new open plan workstations (4 ft. high partitions, plus an additional 1 ft. high glass partition on top) and new light emitting diode (LED) lighting dimmed on a fixture-by-fixture basis[2]. The indoor venetian blinds were available in both areas for use by the occupants. The EC windows were controlled for the first three months with the same control algorithm as Phase I (Tints 1–3). In the second three months of the study, control logic for glare was added to the algorithm (i.e., if glare, then switch to Tint 3). Manual override switches operated the same way as in Phase I.

The study involved continuous measurements of indoor and outdoor environmental conditions, logging of EC window tint levels and position of indoor venetian blinds, weekend measurements to assess visual and thermal comfort during the equinox and solstices, and occupant surveys. The study was conducted over two consecutive, six-month, solstice-to-solstice periods corresponding to each phase of testing.

Findings from Phase I: Private Offices

- Over the course of the six-month study, 30% of the venetian blinds were untied and made available for use. Surveys conducted approximately every month of actual venetian blind use indicated that there were more fully raised blinds in the EC offices compared to the reference offices: 80% versus 25%–50% of the blinds, respectively. After the conclusion of the study and all blinds were untied, a survey conducted several months later showed that blind use increased in both areas, but there was still 40% less blinds lowered in the EC area compared to the reference area.
- For the majority of the EC private offices with the blinds tied up, occupants relied solely on the EC windows with automatic controls and infrequently used the manual override (weekly average of 10–60 min/day/ office of all 40 offices) to satisfy their personal requirements for solar control, daylight, glare, and view. During the summer, the EC window was automatically tinted no higher than Tint 2 (visible transmittance, Tvis = 0.25) and, during the winter, the EC window was infrequently switched to Tint 3 (Tvis = 0.13). When the automatic controls were manually overridden, the majority of overrides were to Tints 3 and 4 (Tvis = 0.13 and 0.02, respectively) during the summer and Tints 1 and 4 during the winter. (Note: Using the vendor's convention, an increase in "Tint" from Tint 1 to Tint 4 corresponds to a *decrease* in tint level (Tvis = 0.36 to Tvis = 0.02, respectively).
- In the surveys, occupants indicated that glare was less with the EC windows compared to the existing reference windows (this finding was statistically significant), even though the venetian blind use was less in the EC offices. Measured data taken under cloudy and partly sunny

[2] A separate study investigating the LED lighting controls on Floors 3-4 with EC windows was conducted in parallel and is documented in another GPG report.

conditions indicated occasional periods of discomfort glare with the EC windows constrained to Tints 1–3 in the automatic mode and without blinds.

- Survey responses regarding thermal comfort were mixed and were likely due to improper VAV operations: the facility manager indicated that there were prior complaints about thermal discomfort due to unbalance loads. Measured data 4–6 inches from the window indicated that thermal discomfort was significantly greater (percentage of people dissatisfied (PPD) > 20% for six hours) with the EC windows compared to the reference windows on a hot summer day, but this may have been due to the EC window not being automatically controlled to a tint darker than Tint 2 (Tvis = 0.25). The occupant could also have used the venetian blinds or manually overridden the EC automatic controls to a darker tint level improve comfort.
- Occupants agreed (slightly above neutral) that daylight levels were sufficient in both the reference and EC offices, but found light levels in the EC offices to be slightly dark/ gloomy (just below neutral) even with the manual override option.
- With respect to view, occupants agreed strongly that the shades did not block their view, given that the blinds were used significantly less frequently with the EC windows. Occupants also agreed strongly that the outside view was sufficiently visible with EC windows.
- Overall, 85% of the occupants preferred the EC windows over the conventional windows.
- In terms of energy-efficiency, the EC windows admitted more daylight, and, therefore reduced daytime lighting energy use in the 15-ft. deep, south-facing perimeter zone by 36% compared to the reference windows (both cases with manually operated venetian blinds).
- During the summer period, HVAC cooling energy use was increased by 2% due to the way the EC windows were controlled. If controlled to minimize solar loads (fully colored, Tint 4 all day) on summer weekends, however, the VAV AHU cooling load operating in setback mode (82°F setpoint) was 57% less than with the reference windows. (Controlling the EC windows to Tint 4 during occupied hours was not acceptable to the occupants, therefore HVAC energy use measurements at the darkest Tint 4 level could not be conducted under occupied-hour setpoint temperatures.)
- Occupants indicated slightly below neutral dissatisfaction with switching speed. There were a few negative survey comments about the slow switching speed. Measured data indicated that, on a warm sunny summer day, it took about 20 minutes to transition from Tint 1 to Tint 2 and about 10 minutes to switch back from Tint 2 to Tint 1. Based on how long the indicator light blinked on the manual override switch, it appeared to take about 30 minutes to switch from Tint 1 to Tint 4. The manufacturer claimed that the switching speed of its EC window was not temperature dependent. For example, the speed is expected to be about the same when the glass is cold or hot.
- An analysis of cost-effectiveness was based on a prior simulation study of a prototypical commercial office building. If the EC windows were controlled to meet the daylight workplane illuminance setpoint (which minimizes both HVAC and lighting energy use), then the EC windows would yield a simple payback of 29 years and a savings-to-investment ratio (SIR) of 1.04. A spectrally selective, tinted low-e window would yield a simple payback of 15.7 years compared to the existing tinted low-e windows. If the installed cost of the EC windows dropped from today's estimate of \$61/ft^2 to below \$21/ft^2, the simple payback would be 10 years. If a blended electricity rate of \$0.20/kWh reflecting time-of-use demand charges

were used instead of the average Federal rate of $0.109 and the installed cost was lower than $39/ft^2, then the simple payback also would be 10 years (**Figure** I.A.1). Additional benefits, such as increased thermal comfort due to balancing of loads throughout the building, more daylight and greater access to an unobstructed view could be incorporated into the analysis from the human resources point of view. There also may be reduced costs for maintenance and replacement of the indoor blinds.

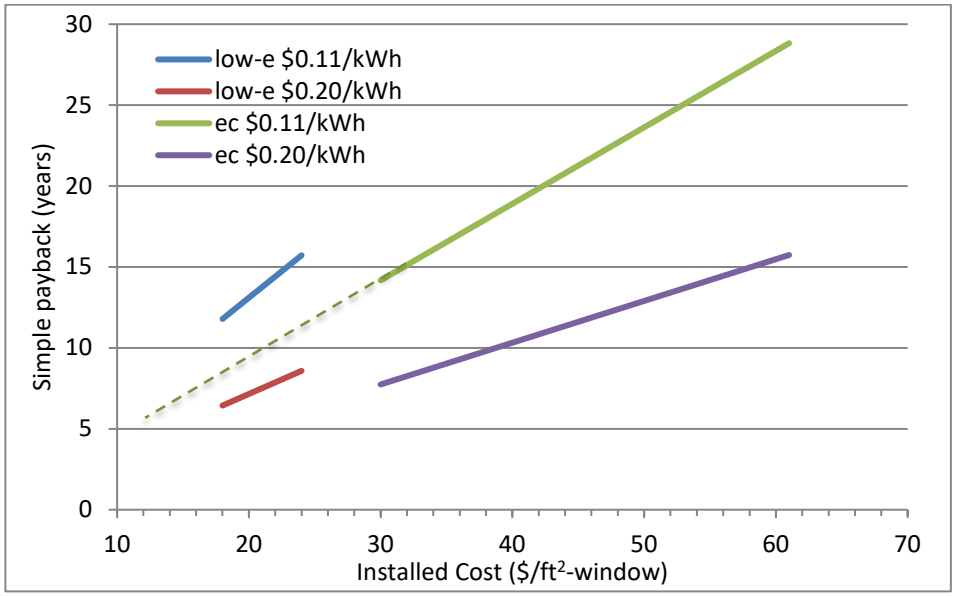


Figure I.A.1. Simple payback (years) of a conventional low-e window and EC window as a function of installed total cost ($/ft^2-window) and flat utility rate for electricity ($/kWh). Annual utility cost savings are due to the use of the two windows with daylighting controls compared to a conventional dual-pane bronze window without daylighting controls in a south-facing 15-ft. deep perimeter zone in Portland. WWR = 0.45. (See Section V-I.)

Findings from Phase II: Open Plan Workstations

- Phase II involved an evaluation in an open plan office environment where control of the EC windows was zoned to coincide with the workstations adjacent to the windows. The automatic mode of control was similar to Phase I (limited to Tints 1–3; actual tint levels were to Tints 1 and 3). With the glare mode (Tint 3) implemented halfway into the study (spring-summer period), automatic control to Tint 3 increased significantly and, with this increase, manual overrides of the automatic controls also significantly increased.
- Unlike Phase I with zip-tied blinds, occupants near the windows had the option to select their preferred tint level (of Tint 1–4 levels) and adjust interior venetian blinds, but their actions were taken with some consideration for others in neighboring workstations along the window wall and towards the core of the building. Manual override occurred for less than 25 minutes per day per zone on average and, when manually overridden, Tints 1 and 4 were selected most frequently during both the winter and summer periods.
- If the EC window was not shaded by the venetian blind, measurements indicated that discomfort glare levels were imperceptible during the winter and summer when the EC was controlled automatically within the Tint 1–3 range. Measurements were taken over three cloudy/ partly cloudy weekends over the six-month period and so did not capture critical conditions; i.e., sunny winter days when the sun was low and within the field of view

throughout the day. However, survey data showed that occupants found that the level of glare was acceptable with EC windows (and use of blinds) and that there was enough daylight in the space, although they found the light levels to be slightly darker than "just right."

- Survey data also showed that occupants did not agree that the shades blocked their view in the EC test area, while occupants in the reference area indicated slight agreement.
- If given the option, 92% of the occupants preferred switchable EC windows over conventional windows, particularly if their workstation was adjacent to the window.
- Like Phase I, occupants in Phase II strongly objected to automatic control to the darkest tint level (Tint 4). This was evidenced by complaints filed through the service ticket log and an upsurge in manual overrides when a special mode of control (switch to Tint 4 all day) was inadvertently not returned to the normal mode of operation in April 2016. This curtailed the possibility of automatically controlling the EC windows to reduce solar loads and improve HVAC operations.
- The adjustment of the automatic control settings seemed to imply a preference for daylight in this overcast climate. The facility managers agreed that daylight was an important consideration, however, they identified other factors related to the EC technology itself that influenced how the automatic controls were configured. In informal discussions with occupants, facility managers said that occupants would have preferred to switch the EC windows to a darker tint to control glare instead of using the blinds so as to preserve view to the outdoors. However, the EC windows took a long time to switch, so occupants used the blinds to reduce discomfort. In addition to the slow switching speed, the manual override option frustrated some occupants, causing them to use the blinds instead of the EC windows. If the EC windows were already in the process of switching because of automatic or prior manual control, the manual switch was locked out and occupants were not permitted to select a different tint level. The manual control logic could be modified. Improvements to the control logic or adjustments of the control settings at the site or control zone(s) in each space could enable a better balance between competing daylight, view and solar control performance objectives.

Key Findings

Looking back at the original study objectives stated in Section I.C, data and observations from this study suggest:

- Even in a predominantly cloudy climate, some occupants will need indoor shades with the EC windows to meet comfort and other requirements (e.g., sense of privacy and security). Use of the shades will be less than that with conventional static windows, in part because occupants like an unobstructed view to the outdoors.
- In a cloudy climate like Portland, Phase I results suggest that when there are no indoor shades, most occupants in private offices agreed slightly that they experienced less glare and less heat from the sun with the EC windows than the reference windows. However, survey results indicated that glare was just slightly uncomfortable in both the EC and reference offices. Occupants expressed moderate dissatisfaction with the speed of tinting and untinting. In informal discussions with the facility managers, occupants in Phase II indicated that switching speed was a consideration in how they used the venetian blinds. Due to length of time it took

the windows to switch, occupants used the blinds to control discomfort even though they would have preferred to tint the windows to preserve view.

- In Phase I, all windows in a private office were switched to the same tint level. When switched automatically to Tint 4 (Tvis = 0.02) to control glare, occupants clearly found the daylit environment to be too dark. Occupants, however, did use Tint 4 when manually overriding the automatic controls, indicating that under certain circumstances and for some end users, Tint 4 is acceptable. This has implications on the degree of solar control and cooling energy savings that can be achieved with EC windows in northern climates. With Tint 3 being the maximum tint in this study for automatic control, the minimum solar heat gain coefficient (SHGC) was 0.16. As in previous studies, more complex cooling load minimization control algorithms could be implemented to minimize the impact of Tint 4 (SHGC = 0.09) on occupants. For example, Tint 4 could be used when occupants are not in their office. The window wall could be zoned so that when in Tint 4, a small area of the window wall could be switched automatically to a lighter tint (Tint 3?) to admit daylight. The location of this section could be determined by the occupant(s) based on direction of view, location of tasks, and other considerations identified by the occupant. This mode of control was found in prior studies to increase significantly end user satisfaction with the indoor environment [7]. The windows also could be tinted only when the HVAC system is in cooling mode. For swing periods of the year when "free" cooling is provided by the economizer, for example, the automatic controls could be switched to favor minimization of lighting energy use rather than cooling. To capture both lighting and HVAC energy savings benefits, the control system will need to be defined carefully to address end user satisfaction and persistence of savings over the lifetime of the installation.
- The total annual energy savings in this particular application were modest. Lighting energy savings were achieved largely because the EC window at Tints 1–2 provided more daylight to the interior compared to the dark tinted existing windows. There were no cooling energy savings because of the way the windows were automated. Data suggests that if the controls were tuned and improved, it is likely that cooling energy savings could increase and, more importantly, the thermal discomfort due to improper AHU operations given load imbalances between the north and south zones of this building would be reduced. Access to view and daylight in a predominately cloudy overcast climate should not be underrated. Because the switching range of the EC window was lowered significantly to match the aesthetics of the existing windows, increased daylight was not a strong outcome of this study. However, greater access to view was a statistically significant outcome of this study and this is likely to have a positive impact on occupant satisfaction with the workplace environment.

E. DEPLOYMENT RECOMMENDATIONS

Results from this study indicate that EC windows can provide a comfortable, energy efficient and acceptable daylit environment in commercial office buildings in northern climates with dynamic sky conditions. Prior simulation analysis indicated that EC windows were most appropriate for commercial buildings with large-area south, east and west facing windows in hot climates. This study demonstrates that the EC technology also is applicable to less sunny climates due to the benefits associated with daylighting and access to outdoor views. The EC technology also can improve occupant comfort in buildings where cooling load imbalances between north and south perimeter zones cause thermal discomfort due to improper VAV operations.

The dynamic qualities of the EC technology enable daylighting during overcast periods and glare and cooling load control during sunny, hotter periods of the year. This demonstration showed that while the EC window technology itself operated as intended and was acceptable to occupants, the automatic controls were not yet turn key. Facility managers should expect to spend some time commissioning the automatic controls to suit occupant preferences and performance goals. Because of the significant variation among individuals in the perception of glare, the EC windows should be provided with the option for manual override of the automatic controls to increase occupant comfort and satisfaction.

Careful selection of the EC window properties also can improve occupant satisfaction and acceptance of the technology. In the long term, the performance of the building is likely to be more optimal if the EC window is designed with a broad switching range (i.e., use clear glass substrates in the insulating glass unit), particularly in overcast climates. Indoor shades will be needed with EC windows, but their use will likely be less than with conventional windows. The value proposition for EC windows should be made on the basis of increased occupant comfort, satisfaction and amenity (e.g., view) and increased energy efficiency. The active load management capabilities of this class of technology (switchable windows) also will ultimately enable buildings to achieve net zero energy in concert with other building systems.

II. Introduction

A. PROBLEM STATEMENT

The U.S. General Services Administration (GSA) is a leader among federal agencies in aggressively pursuing energy efficiency opportunities for its facilities and installing renewable energy systems to provide heating, cooling and power to these facilities. GSA's 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. This includes approximately 400 buildings listed in or eligible for listing in the National Register of Historic Places, and more than 800 buildings that are over 50 years old.

GSA has an abiding interest in examining the technical performance and cost-effectiveness of different energy-efficient technologies in its building portfolio, as well as those currently proposed for construction. Given that the large majority of GSA's buildings include office spaces, identifying appropriate energy-efficient solutions has been a high priority for GSA, as well as for other United States federal agencies. Based on the sheer size of the building portfolio, there exists a huge opportunity for potential energy savings.

Inefficient windows represent a significant liability in GSA's building portfolio. 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 [1,2]. 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. Efficient windows in Federal facilities would benefit the United States buildings industry as a whole.

In standard practice, windows are selected based on solar heat gain and thermal properties dictated by prescriptive energy efficiency codes. These mandatory requirements were formulated to minimize HVAC energy use at lowest cost. In occupied buildings, however, the benefit of daylighting is often lost, since interior shades are installed to control direct sun and window heat gains. Once lowered, interior shades are rarely raised, often for many days on end.

Integrated dynamic window systems minimize both HVAC and lighting energy use through a proactive recognition of energy- and comfort-related tradeoffs to:

- reduce window heat gains, direct sun, HVAC energy use, and glare (e.g., by lowering the shade) and
- increase daylighting, reduce lighting energy use and its associated heat gains and increase access to views (e.g., by raising the shade).

With dynamic controllable façade systems, these tradeoffs are managed automatically in real time, enabling more optimal performance over the life of the building. 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 [1].

B. OPPORTUNITY

Electrochromic coatings (EC) are an innovative, switchable thin-film coating applied to glass that can be actively controlled to change appearance reversibly from a bleached to a dark blue tint when a small direct current (dc) voltage is applied using a manually operated switch or an automated control system.

EC windows hold several distinct advantages over both manually operated and automated motorized shading systems: (a) the windows tint, but remain transparent to preserve views out, (b) the switchable glazing layer rejects solar heat gains on the outboard layer of an insulating glass unit, thereby achieving more efficient solar control than indoor shading systems, and (c) switchable glass requires less maintenance than a motorized system and cannot be damaged by the occupants or outdoor elements (e.g., ice, snow, wind, or birds).

Building energy simulations indicate that actively controlled, EC windows can reduce annual HVAC and lighting energy use in south, east and west-facing perimeter zones of commercial office buildings by
10%–20% and reduce peak electricity demand by 20%–30%, achieving energy use levels that are lower than an opaque insulated wall [3]. New material science developments and improvements in manufacturing continue to push the forefront of innovation, enabling even greater savings at lower cost.

Over the past 10 years, the technology has been used in both residential and commercial applications across the U.S. There have been several prior third-party monitored demonstrations of automated EC windows, as these technologies have been introduced to the commercial market:

- A three-year, full-scale field test in an office mockup in Berkeley, California evaluated the window heat gain and lighting impacts of an EC window integrated with a dimmable electric lighting system. Occupant comfort and satisfaction were evaluated over a short period (four- to six-hour exposure per subject) [4–5].
- A two-year monitored installation of EC windows in a large office building in Golden, Colorado demonstrated end user acceptance of this technology, but the windows were shaded by a 10-foot deep overhang and conventional skylights, confounding the analysis of energy use and occupant impacts [6].
- An 18-month installation of EC windows and dimmable lighting in a conference room in Washington DC also demonstrated feasibility of the technology. End-user acceptance was inferred by manual override switch activity, not direct subjective survey data [7].
- EC windows were evaluated for a year in a small, west-facing open plan office area in the Denver Federal Center [8]. The control system, which was focused on minimizing HVAC energy use, was adjusted in the second half of the study to better address occupants' desire for more daylight during the winter period.
- EC windows were used to retrofit part of an office building of the Department of Defense (DoD) in Miramar, California, via the DoD Environmental Security Technology Certification Program [9].
- A small demonstration of EC windows was conducted in a land port of entry in Donna, Texas [10]. End users indicated that mission critical monitoring and surveillance tasks were conducted with greater comfort and visibility compared to conventional venetian blinds.

- EC windows were installed on the south side of one floor in a large office building in Sacramento, California. Each window was subdivided into three rows that could be independently switched to meet both daylight and solar control requirements. This parallel GSA GPG program study evaluated EC windows in a sunny, temperate climate.

With respect to daylighting, the Portland climate for this study provided some unique challenges that had not yet been evaluated conclusively at other demonstration sites. The relatively high latitude (45.60°N) and dynamic skies during cold winters presented a challenging optimization problem for the automatic control system: how to balance the desire for daylight and need for glare control from low-angle sun and bright cloudy conditions given the relatively slow response time of the EC window (it can take a large-area EC window 10–30 minutes to switch from a bleached to dark tinted state).

This study, therefore, focused on how the EC window and its control system impacted occupant comfort, satisfaction and acceptance of the technology. EC windows were installed on the south side of several floors of the 911 Federal Building in Portland, Oregon. The Portland site provided an opportunity to obtain statistically significant, long-term occupant response data from tenants seated in private and open plan offices near the window.

III. Methodology

A. TECHNOLOGY DESCRIPTION

This study evaluated the performance of large-area windows with an inorganic, tungsten oxide EC coating. An EC coating is a thin, multi-layer film or stack deposited on a glass substrate. 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 (**Figure** III.A.1). 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 blue appearance. Reversing the potential causes the ions to migrate back, causing a bleached, near colorless appearance. A small amount of power is used to both switch and maintain the tinted state of the window coating. EC coatings have been tested using standardized accelerated aging techniques (defined by the ASTM E2141 standard) to verify that the coating can switch tens of thousands of cycles without degradation to its properties.

The EC technology evaluated in this study (View, Inc.) has several distinguishing qualities that the manufacturer claims will differentiate its technology from that of other competitors:

- The counter-electrode is active, not passive. One effect of this is that the EC window switches to a more neutral blue-gray color due to color changes in both the active EC and active counter electrode layers.
- A glass area of 2000 ft^2 requires an average of approximately 60 W to switch (0.03 W/ft^2-glass) and maintain the window in its tinted state. No power is required to hold the EC in its clear state. (This claim was not evaluated in this study.)
- The switching speed of this EC technology is not highly temperature dependent. It takes the same (to within about 1%–3%) amount of time to switch an EC window from fully bleached

to fully colored at room temperature as it does at -10°C. (This claim, nor its potential impact on the long-term durability of the EC coating, was not evaluated in this study.)

- Switching speed varies (fairly linearly) with the width between the bus bars; e.g., a 2 ft-wide window will tint in approximately one-third the time of a 6 ft-wide window.

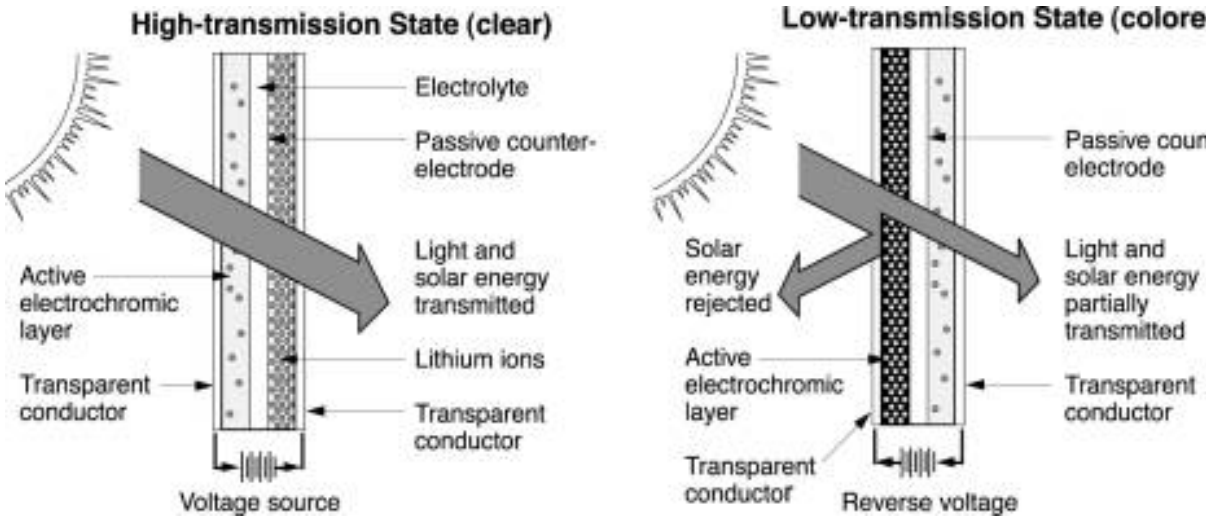


Figure III.A.1. Component layers of an EC window coating in bleached (left) and colored (right) states. For the EC technology evaluated in this study, the counter-electrode is active, not passive.

An EC window consists of two layers of glass separated by an air gap, where the EC coating is located on the surface #2 of the window (surface #1 is the exterior, outdoor surface) along with a low-emittance (low-e) coating. The inboard layer of glass is typically clear. The gap between the glazing layers can be filled with air, argon or krypton gas to improve thermal performance. When tinted, the EC window modulates solar heat gains by absorbing radiation on the outboard glazing layer. Some of this heat is re-radiated to the outdoors. The low-e coating minimizes radiative heat transfer to the indoors. Incoming daylight is modulated, as well, by the tint level of the window.

The properties of the EC window vary depending on the properties of the glass substrate on which the EC coating is deposited, the properties of the additional layers of glazing that form the insulating glass unit, the type of gas used between the layers, the thermal properties of the spacer between the glass layers, and the size and framing details of the window. Together, the window composition determines the final switching range for the visible transmittance and solar heat gain properties of the window and its color.

Low-voltage power to the EC window occurs through the connection of a pigtail that comes out of the side or top of the insulating glass unit to a power source. A connection is made to this pigtail within the framing channel and then to the local controller in the ceiling plenum. The controller, which modulates the power to the EC window when switching, is connected to the networking and communications bus that transmits and receives data from a local wall-mounted switch, mobile phone or tablet, the vendor's server, or the building management control system. The windows can be self-powered with built-in solar photovoltaic cells, but this option was not used for this project. A more detailed description of the EC windows used in this installation is given in Section IV-B.

B. TECHNICAL OBJECTIVES

The technical objectives of the study were to determine, based on measured data and occupant surveys, whether the use of EC windows in commercial buildings resulted in:

- Increased end-user comfort and satisfaction with the indoor environment, particularly in areas near the window;
- Reduction or elimination of the need for operable shading to control sunlight and glare near the window;
- Decreased lighting energy use; and
- Reduction of cooling loads on the south façade, allowing for more balanced loads between the north and south façades and reduced HVAC energy use.

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

C. DEMONSTRATION PROJECT LOCATION

Potential demonstration sites were evaluated based on size and orientation of the façade, climate and scale of the installation. The 911 Federal Building in Portland, Oregon was selected because it had large-area, south-facing windows and several floors on the building with a similar layout, enabling inclusion of a large number of occupants in the study and a direct, simultaneous comparison between the existing reference and new test condition with EC windows. Both the tenants and the local facilities management team were willing to participate and be supportive of the study.

IV. M&V Evaluation Plan

A. FACILITY DESCRIPTION

The 911 Federal Building is a Class B large office building built in 1953 and located at 911 Northeast 11th Avenue, Portland, Oregon (**Figure** IV.A.1). The building is 11 stories tall with a gross floor area of 312,447 ft^2. In 2013, the building received a Platinum-level certification for LEED-EB:OM v 2009. The façade was oriented due south. Portland's weather is relatively mild[3] with mostly sunny summers and partly cloudy, rainy winters. Compared to the rest of the United States, solar availability in Portland is among the lowest in the nation.

[3] 45.60°N, 122.60°W, 6 m elevation, 1% DBT 30°C and 1% WBT 19°C cooling and -6°C 99.6% heating, 2513 HDD18, 1398 CDD10.

Figure IV.A.1. Exterior of the south façade (left) and site layout (right).

The existing conditions within the building were typical of commercial office buildings. The study occurred on Floors 5–8 along the 350 ft. long south façade with windows. Floors 6–8 consisted of private offices along the south façade. Floor 5 was upgraded with new open plan workstations with 4 ft. high solid partitions with an additional 1 ft. high translucent glass partition on top of the opaque portion.

On Floors 6–8, the existing lighting system consisted of recessed 2x4 troffers with two T8 fluorescent lamps per luminaire. Private office lighting could be switched on or off manually with a wall-mounted switch near the door. The switch had a built-in occupancy sensor that turned the lights off after about 10 minutes of vacancy. All lights were swept to off automatically at night and on weekends through the central building management control system. On Floor 5, each LED lighting fixture was individually dimmable and each had autonomous controls (Philips Spacewise) that enabled scheduling, setpoint tuning, occupancy, and daylighting dimming. Emergency fixtures remained ON over 24-hour period, irrespective of schedule and occupancy.

The existing HVAC system was a variable air volume (VAV) overhead system that delivered conditioned air using linear ceiling diffusers located about 8–10 ft. from the window. Temperature sensors located approximately eight inches below the ceiling were used to control the VAV boxes. Each box was zoned to serve about six perimeter or core offices. There were 24 VAV boxes total on each floor. A two-pipe convector unit under all the windows provided heat during the winter.

Each of the four air handler units (AHU) for the building were designed to serve both the north and south sides of the building, including core and perimeter zones, and all floors of the building. The facility managers indicated that in the summer when the AHU responded to the high cooling load on the south side of the building (with existing windows), the same AHU tended to overcool the north side of the building, causing occupant complaints.

Conventional office tasks were conducted in all the spaces, including a mix of computer-, paper-, and phone-based tasks, as well as face-to-face occupant interactions.

B. TECHNOLOGY SPECIFICATION

1. REFERENCE WINDOWS

In Phase I, the "reference" windows were the existing windows in the building, as described below.

In Phase II, the "reference" windows were EC windows as described in Section IV.B.2 and IV.D.2.

Existing windows

The existing façade was a 1953 vintage, non-thermally broken aluminum framed curtainwall with flush mounted windows and an opaque spandrel panel between floors. The original glass was single pane clear glazing, but this was later replaced around 1987 with a double-pane, tinted low-e window.

The properties of the replacement window were unknown so in-situ measurements were made using a hand-held instrument to determine glass and gap thickness, as well as coating position. These measurements indicated that the dual-pane unit had 6 mm panes of glass, a 17 mm air gap and a low-e coating on the interior-facing surface #2 of the outboard glass pane (**Table** IV.B.1).

Table IV.B.1. Estimated composition of the existing windows

Framing	Layers (inboard to outboard)
Aluminum frame (original frame; limited information available)	6 mm glass
	17 mm gap
	6 mm glass, with low-e on surface #2 (interior-facing)

Estimated existing window solar-optical properties

The precise solar-optical and thermal properties of the existing window could not be determined without destructive testing. Measurements were made to determine the approximate solar-optical properties of the windows.

Vertical illuminance and irradiance data were collected at the center of the indoor face of the reference and EC windows. Outdoor vertical illuminance and irradiance levels also were measured on the roof. The ratio of indoor-to-outdoor illuminance or irradiance was used to approximate nominal visible (Tvis') and solar (Tsol') transmittance values.[4]

Figure IV.B.1 shows the Tvis' values for the existing and EC windows on a sunny day (August 12, 2015, incidence angle θ = 60° at noon).

[4] Note: The nominal visible transmittance (Tvis') is typically lower than the visible transmittance value measured at normal incidence (from **Table** IV.B.3) because it is measured at an off-normal, oblique angle of incidence. Nominal values also were lower because the roof sensors had a less impeded view of the sky than the sensors on the window.

- On the eighth floor, Tvis' of the existing window (double low-e, dark tinted window) was between 0.10–0.15 at noon. Tsol' was around 0.05–0.06. These estimated values place the existing window somewhere between the Tint 2 and Tint 3 states of the EC window.
- On the seventh floor, the EC window was set to Tint 2 at the noon hour and the plot shows that the Tvis' was around 0.22. This value is consistent with the Tvis value of 0.25 at normal incidence reported in **Table** IV.B.2. Tsol' was 0.10. The solar transmittance (Tsol) at normal incidence for this tint level was 0.13.
- These data for the reference windows are summarized in **Table** IV.B.3.

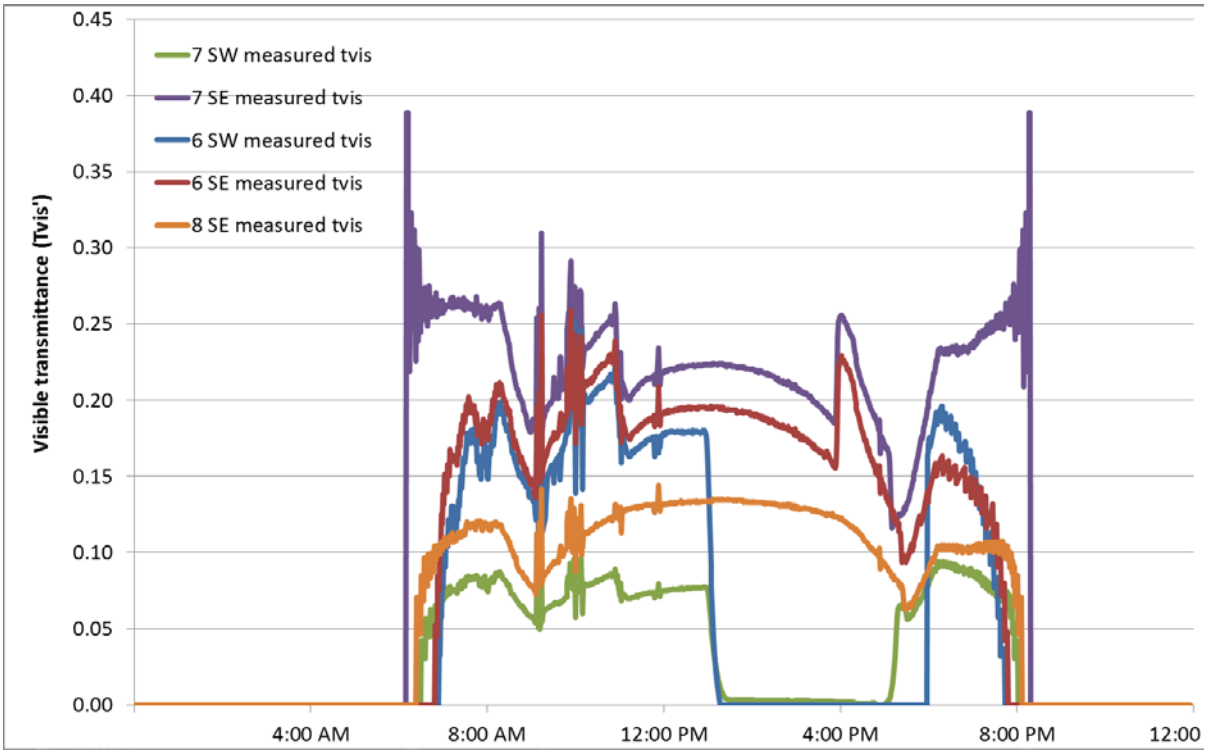


Figure IV.B.1. Ratio of transmitted to exterior vertical illuminance (approximate visible transmittance, Tvis') for the EC and existing windows. The EC window was at Tint 2 at noon on the seventh floor, August 12, 2015. Reference case (existing windows) – Floor 8; EC case – Floors 6–7.

2. ELECTROCHROMIC WINDOWS

At the beginning of the project, the building manager requested that the EC windows match the appearance of the existing windows for aesthetic reasons. The EC insulating glass unit (IGU) was, therefore, specified with an outboard EC glazing layer (with a clear glass substrate) and an inboard tinted glazing layer that closely matched the color and tint of the existing windows. This resulted in an EC IGU with a more limited switching range that was less optimal for daylight in a cloudy climate. An EC window with an inboard clear glazing layer, for example, has a visible transmittance (Tvis) range of Tvis = 0.60–0.03, admitting more daylight under overcast conditions. The Portland EC windows had a more limited switching range of Tvis = 0.36–0.02.

In Phase I, EC windows were to be installed across the entire south façade on Floors 6–7 of the building. In Phase II, EC windows with the same configuration were installed across the entire south façade on Floor 5. See Section IV.D.2 for a description of the monitoring phases of this project.

The EC window configuration consisted of:

- An outboard layer of 6 mm clear glass with the EC coating on surface #2 and an inboard layer of 6 mm spectrally selective tinted glazing (called "SolarBlue").
- Between the two layers, the 12.7 mm gap had a 90% argon gas fill.
- A warm edge spacer was used to reduce thermal heat transfer.
- The EC window could be switched to four different tint levels: Tints 1 through 4 corresponding to the fully bleached to fully colored states, respectively.

Solar-optical and thermal properties of the EC insulating glass unit were provided by the vendor and were computed using measured spectral properties, which can be found in the International Glazing Database (IGDB version 24) and WINDOW software (version 6.3) [11]. The window composition and properties are given in **Table**s IV.B.2 and IV.B.3, respectively. **Figure** IV.B.2 shows the properties of the Portland EC IGU, an EC window with an inboard layer of 6 mm clear glass, and four static IGUs for comparison. The properties of the Portland reference window IGU is likely somewhere between that of the bronze and reflective IGU.

Table IV.B.2. Physical composition of the EC window

Framing	Layers (inboard to outboard)
Aluminum frame (original frame; limited information available)	6 mm spectrally selective tinted glass (PPG SolarBlue)
	12.7 mm gap, 90% argon fill
	6 mm clear, with electrochromic coating on surface #2 (interior-facing)

Table IV.B.3. Center-of-glass properties of the electrochromic window and estimated properties of the existing window

Tint level	Transmittance		Solar Heat Gain Coefficient (SHGC)	U-Value (Btu/h-ft^2-°F)
	Visible	Solar		
EC window				
Tint 1	0.36	0.22	0.43	0.29
Tint 2	0.25	0.13	0.28	0.29
Tint 3	0.13	0.05	0.16	0.29
Tint 4	0.02	0.01	0.09	0.29
Existing window*				
	0.15	0.06		

* Estimated nominal Tvis' and Tsol' values based on data measured at the site at a 60° angle of incidence.

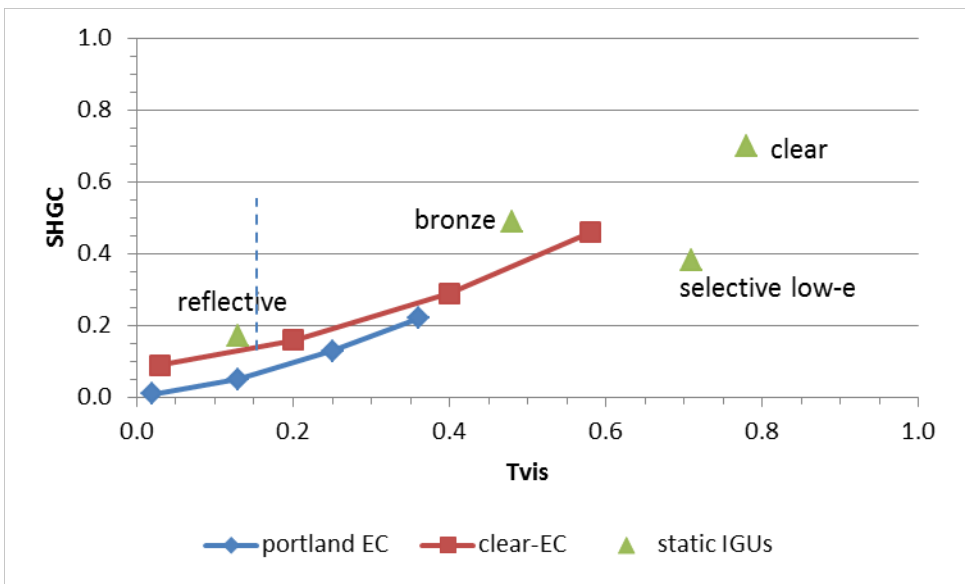


Figure IV.B.2. Visible transmittance (Tvis) and solar heat gain coefficient (SHGC) of the Portland EC insulating glass unit (IGU), a clear EC IGU, and four conventional static IGUs. The properties of the Portland existing window IGU is likely somewhere between that of the bronze and reflective IGU, as indicated by the dashed line.

All EC windows installed in the building were the same size as the existing windows: 3.14 ft. wide by 6.14 ft. tall with a 4-inch wide, 1.25-inch deep vertical mullion between panes and a sill height of 2.5 ft. The window-to-wall ratio (WWR) was 0.46, assuming a floor-to-floor height of 12 ft. The existing aluminum framing was used for the installation, without the need for modification. The insulating glass units were dry glazed, so the exterior window gasket served as a thermal break to some degree. The framing was painted a matte off-white on the interior.

The ASHRAE 90.1-2010 prescriptive requirements for this climate zone (CZ 4C) mandate an assembly maximum solar heat gain coefficient (SHGC) of 0.40 and U-value of 0.50 Btu/h-ft^2-°F for vertical glazing up to a 40% window-to-wall-area ratio. The EC windows were able to meet the SHGC requirements when switched to Tints 2–4.

The code also requires multi-level daylighting controls to be installed within the primary sidelighted area defined by the width of the private office and a depth of 9 ft. from the window wall (i.e., depth is defined by the head height of the window, or 9 ft. in this installation). Automatic bi-level or multi-level switching in primary sidelighted areas is required for effective apertures greater than 0.15. The EC windows were able to meet the effective aperture requirement when switched to Tint 1 (Tvis = 0.36, Tvis x WWR = 0.17).

Sensors

The EC control system relied on a single exterior sensor designed to measure vertical solar irradiance ("Sv"). This sensor was installed on the roof, facing the south (**Figure** IV.B.3). The signal from this sensor was used as one of the inputs to control the EC windows.

Figure IV.B.3. Rooftop sensor (circled).

Control algorithm

The tint of the EC windows was automatically controlled by the vendor's control system, unless occupants used the manual switches (located in each room or area, **Figure** IV.B.4) to override the automatic controls. Regardless of control mode (automatic or manual), windows in a single private office were zoned together; i.e., all the windows in a particular room were always controlled to the same tint.

In general, there were three control modes: "Intelligence®," manual and scheduled modes.

a) The "Intelligence" mode of the control system was designed to minimize discomfort glare from the windows and window heat gains, but admit daylight when discomfort and cooling requirements were minimal. Every five minutes, the controlled system was designed to check the exterior vertical irradiance level, Sv, and determine, based on solar geometry and time of day, the depth of direct sunlight penetration into the space as measured from the face of the window at floor level. The system also calculated the amount of direct solar radiation transmitted into the space.

   The general sequence of operations was as follows:

   - "Weather" sub mode: If the outdoor sensor value, Sv, was lower than 150 W/m^2, the EC windows were switched to Tint 1 to admit daylight (lightest tint level).
   - "Glare" sub mode: If the depth of sun penetration was greater than a specified value (e.g., 2 ft.) and the outdoor sensor value, Sv, was greater than 150 W/m^2, then the window was set to Tint 4 (darkest tint level).
   - "Radiation" sub mode: If the calculated indoor transmitted solar radiation level was greater than the design limit of 179 W/m^2, the windows were tinted until the radiation level fell below this limit.
   - Both the sensor threshold and design limit values were determined by the vendor, the latter values of which were derived through computer simulations for the climate, time of day and day of year.

b) If the occupant overrode the automatic control system with the wall mounted switch (**Figure** IV.B.4), then the control system moved into "Manual" mode where the windows were switched to the selected tint level (Tints 1–4) for four hours, after which the system reverted back to automatic control.

c) The windows also were controlled by two "Schedule" modes.

   - At night between 9:00 PM and 5:00 AM local time (LT)[5], all EC windows were set to Tint 1 (fully bleached) every day of the week.
   - As of July 1, 2015, an additional schedule was put into effect for an indefinite period, such that on weekends during the day between 6:00 AM and 8:00 PM, all EC windows were set to Tint 4 (fully colored) to reduce solar heat gains and proactively reduce cooling loads prior to occupancy in the following week.
   - Combined, the windows were in these two schedule modes for 33% of the seven-day week.

[5] Time is given in Local Time throughout this report.

Control settings

Phase I

- The Intelligence "weather" and "radiation" sub modes, "manual" mode, and "schedule" mode were configured as described in the section above.
- During the initial commissioning and start-up period for Phase I (starting April 10, 2015), occupants indicated that the "glare" sub mode produced daytime conditions that were perceived as too dark (all EC windows in a private office were being switched to Tint 4: fully tinted, Tvis = 0.02). The "glare" sub mode was, therefore, disabled and the switching range of the EC windows was limited to Tints 1–3 when in intelligence mode.
- This final mode of control was made operational as of April 23, 2015 (before the start of Phase I) and remained unchanged (except for the schedule change) throughout the solstice-to-solstice monitored period for Phase I (June to December 2015).
- After the conclusion of Phase I, the control settings were changed. Between March 25, 2016, and the end of the Phase II study in June 2016, the manufacturer enabled the "glare" sub mode with a depth of sun penetration limit of 2 ft. from the window. EC windows were switched to Tint 3 when the glare mode was in effect. The switching range of the EC windows was limited to Tints 1–3 when in the other Intelligence modes.

Phase II[6]

- The Intelligence "weather" and "radiation" sub modes and "manual" mode were configured the same way as Phase I.
- The nighttime "schedule" mode was implemented in the same way as Phase I. The daytime weekend schedule also was implemented.
- Between April and December 2015 before the start of the Phase II test, all EC windows were controlled with the same control settings as the Phase I windows.
- Between the start of the Phase II test in December 2015 and March 24, 2016, the "glare" sub mode was disabled and the switching range of the EC windows (west zone) was limited to Tints 1–3 when in the intelligence mode (same no-glare sub mode as Phase I).
- Between March 25, 2016, and the end of the study in June 2016, the manufacturer enabled the "glare" sub mode with a depth of sun penetration limit of 2 ft. from the window. The windows were switched to Tint 3 when the glare mode was in effect. The switching range of the EC windows was limited to Tints 1–3 when in the other intelligence modes.

Zoning

In Phase I, all windows in individual private offices were grouped and controlled automatically (to the same tint level) as a single zone. Each of these "zones" had its own switch for manual control.

In Phase II, EC windows on the west wing were controlled automatically as described above. Two or three windows were controlled together as a zone, with zones corresponding roughly to each open plan workstation at the window wall. There were a total of 12 control zones, each with its own

[6] EC test case, west wing only. See Section IV.D.2 for EC reference case.

manual switch. On the east wing, EC windows served as the "reference" condition and were set to the Tint 1 fully bleached state throughout the entire monitored period.

Manual switch

The tint level of the EC windows could be selected by the occupant(s) using the wall mounted keypad (**Figure** IV.B.4). The keypad had four buttons arranged vertically with a white or blue symbol above and below the buttons to indicate how the buttons were ordered (Tint 1 was the highest button, Tint 4 was on the lowest bottom). The existing state of the EC windows was indicated by a green light on one of the tint level buttons.

When selected, the tint level button blinked until switching was completed. The manual switch locked out changes to the tint level if the EC was already in the process of switching due to automatic control or a previously issued manual override.

The tint level button light blinked for about 25 minutes when switched from Tint 1 to Tint 4 and about the same amount of time when switched from Tint 4 to Tint 1 (observed while on site in April 2016). There also was an indicator light in the lower left to indicate proper communication with the main control panel.

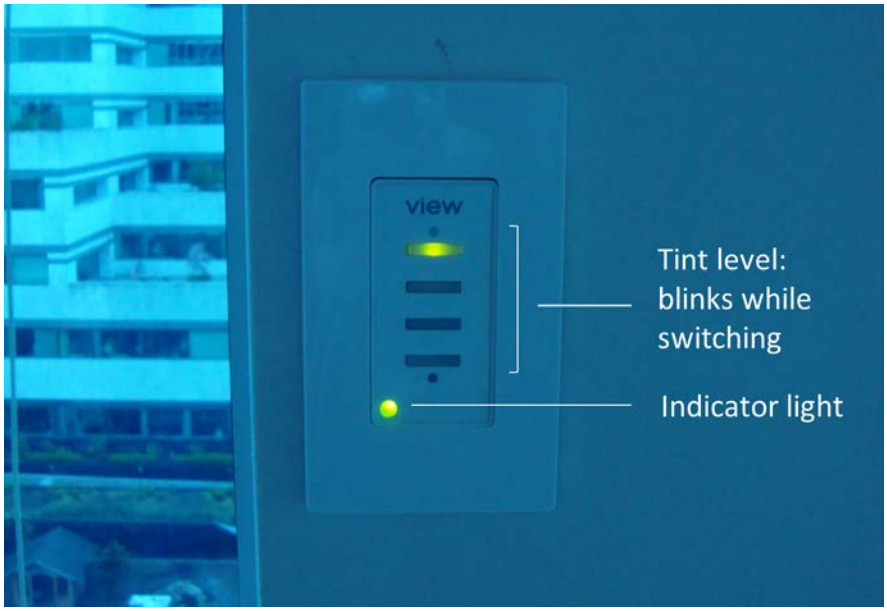


Figure IV.B.4. The EC window tint could be controlled manually using a wall-mounted switch. Switches were placed on the mullions between windows.

Control system server

The EC vendor had remote access to their main control system server and could make adjustments to their system at any time in response to suggestions by the facility managers, complaints by the occupants or for other reasons. The vendor indicated that they would provide technical support for at least a year following the installation of the windows, so as to guarantee satisfaction with the EC control system. This support was provided as a basic service to all customers.

LBNL did not have direct access to the control system server. Data related to the operational modes of the EC windows were emailed to LBNL by the vendor on a weekly basis.

C. TECHNOLOGY DEPLOYMENT

The job of installing the EC windows was put out for competitive bid. During construction, GSA observed that the installation of EC windows was comparable to conventional windows in all respects, except that the EC windows required installation of sensors and controls. The thickness of the IGU was matched to the existing condition so no modifications to the existing window frame were required. Several implementation details to pay attention to include:

- The glazier must make sure that the exterior face of the EC window is installed facing outwards, as intended.
- The pigtail coming out of the edge of the window requires careful handling so that it is located properly either in the jamb or header of the window, as defined by the vendor.
- Curtainwalls are designed to allow water to drain through the framing channels so installation of wires within these channels must be done properly to avoid shorting out the components.
- The pigtail connects to an extension cable within the framing channel. This extension cable is threaded through the framing channel and then out the top of the window to the ceiling plenum above, where it is connected to the window controller. Care must be taken to prevent pinching or crimping the cables.
- The extension cable provides the dc power needed to switch the EC windows so the standard 15-ft. maximum cable length (for this particular vendor) must be considered prior to installation; additional engineering is required for longer cables to avoid the voltage drop between the window and the EC window controller. The cable is connected to a transformer that is then connected to alternating current (AC) power provided by the building.

The power, networking and communications were unique to the EC vendor. In this case, all wiring was low-voltage and connections were made by hand (without the need for tools) using a male-female plug; none of the connections required connecting individual wires within a cable to another wire. Two window controllers were connected to the main trunk cable line which then connected to the vendor's control panel. The vendor's panel controlled up to 128 window controllers. Outdoor sensors were routed down from the roof and connected to this panel. An ethernet cable from the local area network allowed the control panel to be accessed remotely by the GSA facility management team and the vendor.

The installation of the EC windows went smoothly and was completed ahead of schedule in mid-March 2015. GSA did not encounter any trade overlap issues (e.g., curtainwall and electrical). The general contractor coordinated between the subcontractors and was monitoring the installation the entire time. There was no cost escalation due to unfamiliarity with the technology or the building.

Initial commissioning was completed before mid-April 2015, including inspections by the vendor's quality control personnel. The initial start-up of operations was complicated by the vendor having trouble gaining remote access to its system. GSA had allowed remote access via a dedicated connection that was separate from the GSA network. This issue was rapidly resolved. Adjustments to the control thresholds were made during the first weeks of operation, given occupant feedback. Other minor problems occurred during the project: a few windows did not respond to the manual switch in one zone. These issues were resolved by the vendor within a few days.

D. TEST PLAN

1. PHASES OF MONITORING AND VERIFICATION

This demonstration site had three phases of evaluation:

1. Phase I (June to December 2015) involved the evaluation of EC windows on the entire south façade of the sixth and seventh floors. On the eighth floor, the existing windows remained as is, serving as the reference floor against which the EC windows were compared. Solar access on these three upper floors was largely unobstructed by neighboring buildings. Phase I was focused on evaluating the performance of EC windows in private offices, which was the predominant space use on these floors. Results from this phase were included in this report.
2. Phase II (December 2015 to June 2016) involved an evaluation on the fifth floor, where a complete renovation had occurred, including the installation of EC windows on the entire south facade, advanced lighting controls and open plan workstations. Phase II focused on evaluating occupant comfort and satisfaction with the EC windows in an open plan office environment. Results from this phase were included in this report.
3. Phase III (December 2015 to July 2016) also involved an evaluation on the third and fourth floors, where a complete renovation had occurred, including the installation of EC windows on the entire south façade on these floors, advanced lighting controls, and open plan workstations. Installation of EC windows on these floors was made by request from the building management and regional GSA staff, based on a favorable initial experience with Phases I and II. Results from this phase were given in a separate report on advanced lighting controls.

2. REFERENCE AND TEST CONDITIONS

Phase I

The Phase I study involved simultaneous comparisons between the reference and test floors to assess impacts on energy use, comfort and indoor environmental quality (IEQ):

- **Reference condition (Floor 8)**:
  - Private offices
  - Windows: existing south-facing, double-pane low-e windows
  - Shades: Conventional, manually operated indoor venetian blinds. The horizontal slats were 1-inch wide and curved with a brushed silver aluminum finish on both sides. When lowered, the blind covered the full height of the window from the ceiling to the top of the window sill.
  - Lighting: existing lighting with manual switch and occupancy sensor in private offices.
- **Test condition – Phase I (Floors 6–7)**:
  - Private offices
  - Windows: new, south-facing, EC windows that were automatically controlled to Tint 1–3 (details given in Section IV-B.2); all EC windows in each private office were

controlled as a single zone; manual selection of the EC tint level using a wall switch permitted at any time (held for four hours then returned to automatic control).

- Shades: No interior venetian blinds, unless requested by the occupant*; if present, then same type of manually operated venetian blind as the reference case.
- Lighting: same as the reference condition.

* Note: To test for the necessity of shades, the existing indoor venetian blinds on the EC test floors were fully raised and tied to prevent occupants from lowering the blinds. Occupants were encouraged not to untie the blinds, but if requested by the occupant, the building managers untied the blinds and enabled their use. In 30% of the offices on the test floors, the blinds were not tied up at the beginning of the Phase I test due to expressed concerns by the occupant.

Phase II

The Phase II study involved simultaneous comparisons between the east and west wings of the fifth floor, where the space adjacent to the south façade was furnished with open plan workstations. Analysis focused on occupant comfort, satisfaction and acceptance of the resultant indoor environment. Monitored data were used to characterize the environmental conditions to which occupants were responding.

- **Reference condition (Floor 5, east)**:
  - Open plan workstations
  - Windows:
    - EC windows operated automatically with the Phase I control settings from August 2015, when the occupants first moved into the renovated space, until the start of the Phase II evaluation in December 2015.
    - EC windows were then set to a fixed Tint 1 level (fully bleached) starting in December 2015 until June 2016 when the Phase II test was concluded.
    - Manual override was enabled from December 2015 to February 2016 after the start of the evaluation, but used only once (for four hours). Manual override was subsequently disabled in early March 2016 until the end of the Phase II test.
  - Shades: Manually operated venetian blinds (replaced with new blinds; same type as Phase I reference blinds); blinds were operated solely by the occupants.
  - Lighting: new lighting system where each recessed luminaire was dimmed independently based on schedule, occupancy, setpoint tuning, and daylighting controls; data indicating the dimming status of the luminaires were not available.

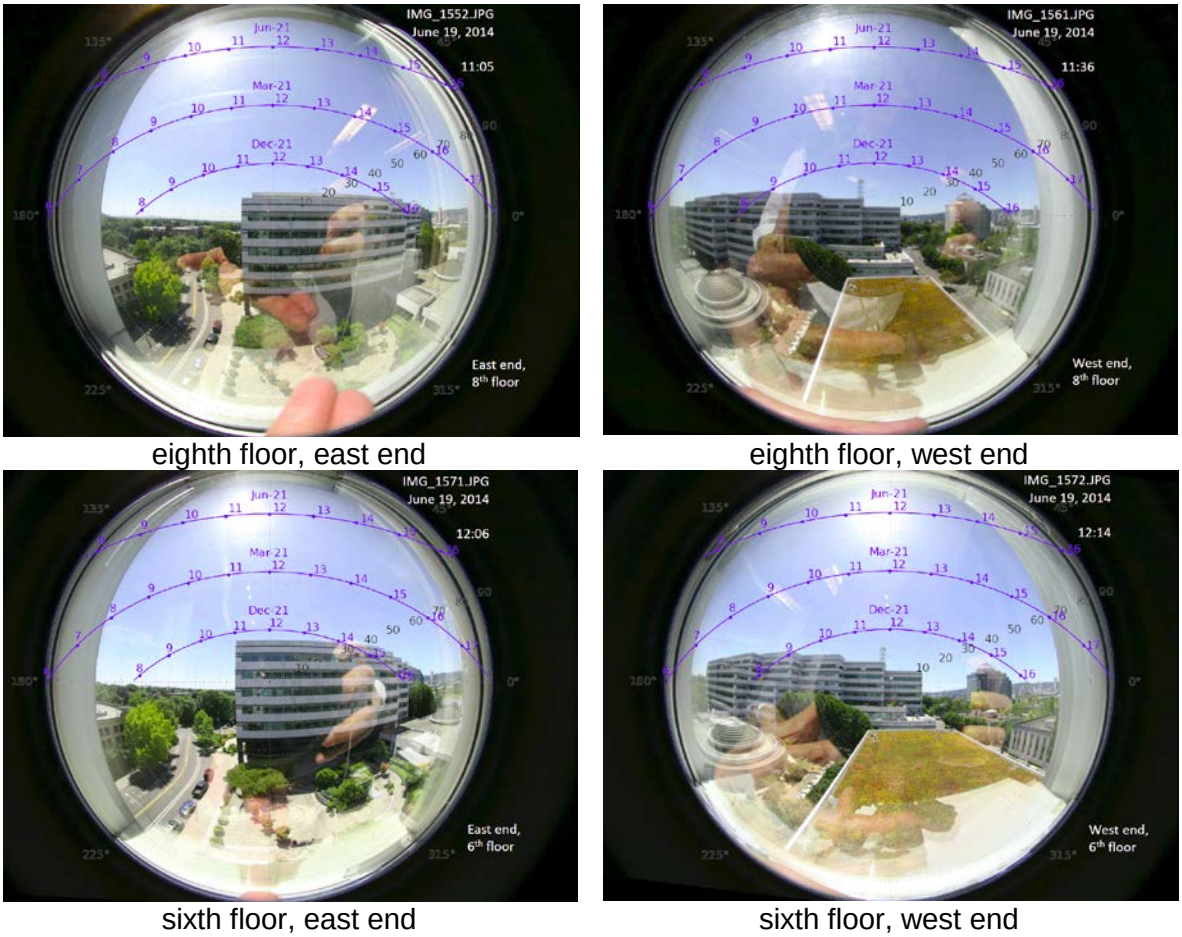
- **Test condition (Floor 5, west)**:
    - Open plan workstations
    - Windows: new, south-facing, EC windows that were automatically controlled to Tints
      1–3 (details given in Section IV-B.2); EC windows zoned to correspond to adjacent individual workstations (to the degree possible); manual selection of the EC tint level using a wall switch permitted at any time (held for four hours then returned to automatic control).
    - Shades: same type of blinds as the Phase II reference case.
    - Lighting: same as the Phase II reference condition.

Solar access

In studies involving comparisons between two conditions, it is important to minimize bias in the analysis due to other independent variables, such as differences in occupancy patterns, furniture layout, surface reflectances, and type of task being performed between the reference and test conditions that would significantly confound the outcome. Upon selection of the Portland site, the project team reviewed the spaces, tenant work hours and tasks (computer use, writing, reading, phone use), and concluded that the reference and test conditions were comparable within reasonable limits.

Dissimilar exposure of the reference and test areas to outdoor solar radiation was a potential concern due to the close proximity of neighboring buildings. Directly south was a six-story office building with a curved floor plate that stepped back away from the Federal building, such that the building was closer to the east end of the Federal building and farther on the west. In the plaza between the two buildings, there were several low, one- to two-story buildings attached to the Federal building.

The path of the sun as viewed from the south façade is shown in **Figure** IV.D.1.



eighth floor, east end | eighth floor, west end

sixth floor, east end | sixth floor, west end

Figure IV.D.1. Sun path diagrams showing when the sun was obstructed by neighboring buildings to the south. The sun path (purple line) shows the path of the sun during the summer solstice (top arc), equinox (middle arc), and the winter solstice (bottom arc). The hours are marked on each arc and are depicted in Standard Time. The photographs were taken at the indoor face of the window.

For Phase I, the reference condition on the eighth floor had the greatest exposure to the sun and sky, whereas the test conditions, which were located on the lower sixth and seventh floors, had diminished direct solar exposure due to shading from neighboring buildings during the winter solstice for several hours. On the east end of the building, differences in shading between the sixth and eighth floor occurred between 2:00–3:30 PM for about two weeks around December 21. On the west end of the building, differences in shading occurred between 7–8 AM in November and December. These differences in solar access were estimated to have minimal impact on the outcome of the study.

For Phase II, the sun path diagrams for the sixth floor were determined to be applicable to the fifth floor where the Phase II tests were being conducted. Differences in solar access occurred between 7–8 AM in November and December (no sunlight on the west end, sunlight on the east end) and for about two weeks around December 21 between 2:00–4:30 PM (no sunlight on the east end, sunlight on the west end). Due to the low occupancy that occurred at these hours, we estimated that these differences in solar access would have minimal impact on the outcome of the study.

There were potential differences in sky luminance due to differences in obstruction of the sky from the nearby buildings. There also were differences in reflected glare from the opposing building, but

since the opposing building façade had a northern exposure, these differences would have occurred only on sunny days around sunrise/ sunset (early morning and late afternoon hours) during the summer solstice period. These impacts also were estimated to have a minimal impact on the outcome of the study.

3. TEST SCHEDULE

A timeline of major events is given in **Table** IV.D.1. The Phase I study on Floors 6–8 was conducted over a six-month, solstice-to-solstice period (June to December 2015) to capture the range in solar angles that occur over a year. The Phase II study on Floor 5 was conducted over the subsequent six-month, solstice-to-solstice period (December to June 2016).

Table IV.D.1. Project timeline

Activity	Completed
Installation of EC windows on Floors 5–7, EC windows set to Tint 1	Mar 17, 2015
Pre-installation survey, Phase I Floors 6–8	Mar 31–Apr 10, 2015
Commissioning and quality inspection	Apr 10, 2015
Phase I EC final controls made operational	Apr 23, 2015
Phase I start: Venetian blinds are tied up, Floors 6–7	Jun 12, 2015
Summer solstice measurements, Floors 6–8	Jun 24–25, 2015
Schedule mode to Tint 4 on weekends initiated, Floors 5–7	Jul 1, 2015
Phase II occupants move in to Floor 5, all EC windows in automatic mode	August 2015
Fall equinox measurements, Floors 6–8	Oct 8, 2015
Phase II start: Floor 5, East wing EC windows set to fixed Tint 1	Dec 18, 2015
Winter solstice measurements, Floors 5–8	Dec 21–22, 2015
Phase I Post-installation survey, Floors 6–8	Jan 18–29, 2016
Glare sub mode enabled, 2 ft. depth, Tint 1–3 limit, Floors 5–7	Mar 25, 2016
Spring equinox measurements, Floor 5	Apr 9–10,2016
Summer solstice site measurements, Floor 5	Jun 18–19, 2016
Post-installation survey, Floor 5	Jun 20–Jul 1, 2016

4. ELECTROCHROMIC WINDOW OPERATION

The operational modes of the EC window system were evaluated in Phases I and II to determine whether the windows were operating as intended. The data also were used to explain how the EC windows were actually switched at the demonstration site when in automatic or manual modes. This assessment was conducted using: (a) reported control systems data for all installed windows from the vendor, (b) independent measurements of a small number of EC windows and (c) an occupant complaint log, maintained by the facility managers.

EC window control system data

The vendor's control system data was available at a 1-min interval on a zonal basis (i.e., group of windows in a single office) over the entire monitored period. No data were available for individual windows. Data included tint level, "Intelligence" control mode (Weather, Radiation, Glare, or manual) and the vendor's outdoor sensor value. "Tint level" indicated what the automatic control or manual switch had set the windows to, not the actual tint of the EC windows. Data files were emailed to LBNL by the vendor on a weekly basis.

The control system logic was replicated with a computer software script to the degree possible in consultation with the vendor. Differences between the reported tint level by the vendor and the LBNL calculated "proxy" value were determined on a weekly basis. Any significant discrepancies in the operations were discussed immediately with the vendor. The vendor's data also were used to study the switching patterns of the EC windows as a function of the vendor's sensor data and LBNL's independent measurements.

The number of hours that the windows were manually overridden was tallied for each day. The four-hour period of the override was included in the total number of hours (e.g., if four-hour delay, then if the windows were manually switched at 9 AM and manually switched again at 11 AM, then the total period of the override was from 9 AM to 3 PM, or six hours).

Window transmittance measurements

Independent measurements were taken by LBNL to determine the switching status of the EC windows. Pyranometer (irradiance) and photometer (illuminance) sensors were placed on the inboard surface of a limited number of EC windows and monitored at a 1-min interval on a continuous basis. An exterior vertical pyranometer and photometer (separate from the vendor's sensor) also were mounted in front of the south façade at the roof level and logged over the monitored period.

The ratio of the indoor-to-outdoor sensors provided an independent, but approximate, means of evaluating the switching status of the window. This ratio is not equivalent to the vendor's reported visible transmittance, which is measured in a lab using a standard spectrophotometer at normal incidence (perpendicular to the glass surface). This field-measured ratio, which we have identified as a nominal solar and visible transmittance (Tsol' and Tvis'), reflects an off-normal value with additional noise, due to positional differences between the exterior sensor on the roof and the indoor sensors on the various lower floors. These nominal values were not expected to match the normal incidence reported values – instead they were used as a check against the control system data.

The accuracy of the indoor solar irradiance measurements were affected by the spectral response of the switchable windows. Since the EC windows switch predominantly in the visible range of the solar spectrum, this effect is expected to be small. For both indoor irradiance and illuminance measurements, the full 180° field of view of the sensor was blocked by the edges of the window. The sensors were placed as far away from the edge of the window to minimize this effect, while adhering to the request by GSA that the sensors be minimally intrusive. The sensors were cosine corrected up to a ±80° angle of incidence. For the interior readings, the sensors were positioned 11 inches away from the edge of the window.

Occupant complaint log

A log of occupant complaints was maintained by the facility managers and shared with the project team. GSA labelled each window with a reference number. Occupants were instructed to use the existing GSA electronic system to lodge a complaint and to provide the window's reference number(s) with their complaint. GSA entered these complaints into a separate log that was accessible to the project team at any time so that the complaints could be addressed immediately. As described earlier, the EC vendor had remote access to its server and could make adjustments to its control system at any time. The vendor indicated that no adjustments were made for individual offices over the course of the project.

5. INDOOR VENETIAN BLIND USE

It was important to determine whether conventional indoor shades were necessary when EC windows were used in a building. EC windows have the potential to meet all occupant requirements without the need for additional indoor shades. Without shades, outdoor view would be unobstructed year round.

The height and slat angle of the manually operated Venetian blinds were periodically recorded by GSA and LBNL staff over the monitored period on both the reference and test floors. This was done through visual inspection of the south façades. During each walkthrough, the approximate height (25% increments of the full height, from fully raised at 0% to fully lowered at 100%) and slat angle (open/closed) of each individual blind was manually recorded on a form. The position was recorded for all but a few blinds that were located in inaccessible spaces (e.g., locked). The form used to record this information is given in Appendix A. Six walkthroughs were conducted over a six-month period in Phase I. Seven similar walkthroughs were conducted over six months in Phase II.

For each survey date, a tally was made of the number of fully raised blinds on the reference and test floors. If LBNL researchers were not permitted in the office at the time of the survey, the blinds in that office were not included in the total count of observed blinds.

6. VISUAL COMFORT

Visual comfort resulting from the use of EC windows was evaluated using three methods:
(a) continuous measurement of vertical illuminance at the eye, (b) periodic measurements of field-of-view luminance and (c) occupant surveys.

Vertical illuminance at the eye

Vertical illuminance at the eye has been shown to have some potential as an approximate predictor of discomfort glare and can easily be measured using a conventional photometer. These data were used to provide a continuous evaluation of the visual environment over the six-month monitored period in Phase I.

Vertical illuminance was measured in several occupied offices on both the reference and test floors. The sensors were placed on work surfaces that were out of the way of the occupants, but near the window. Sensors were mounted at seated eye height 4 ft. above the floor and were placed to face the center of the nearest window (and shade if lowered). Most sensors were located between 1.25 and 2.3 ft. from the face of the window, representing a worst case, conservative view position. Data were collected at a 1-min interval.

The average daily vertical illuminance was computed for weekdays between 8 AM and 6 PM, then related to glare subjective rating (SR) thresholds. The percentage of day that the SR exceeded the

"just intolerable" level of discomfort also was computed. SR is a measure of discomfort glare caused by viewing high or non-uniform luminance for computer based tasks [12]:

$SR = 0.1909*E_v^{0.31}$

where, Ev is vertical illuminance measured at the eye, and a value of:

- 0.5 defines the borderline between "just imperceptible" and "just noticeable,"
- 1.5 defines the borderline between "just noticeable" and "just disturbing," and
- 2.5 the borderline between "just disturbing" and "just intolerable."

Field-of-view luminance measurements

More detailed and accurate measurements of discomfort glare were gathered periodically using hemispherical field-of-view luminance sensors. In Phase I, time-lapsed measurements were taken over a weekend in unoccupied[7] office areas on the sixth (EC windows) and eighth (reference windows) floors during the summer and winter solstices and the equinox. Measurements were taken at seated eye height 4 ft. above the floor and 1.4 ft. and 6.6 ft. (during the winter) from the window with the venetian blinds raised (**Figure** IV.D.2). This location represented a conservative, worst case evaluation of discomfort glare. Similar measurements were made in Phase II at a distance of four ft. from the window.

Measurements were made using commercial-grade digital cameras (Canon 60D) equipped with an equidistant fisheye lens (Sigma Ex 4.5 mm f/2.8). Bracketed low dynamic range (LDR) images were taken automatically at 10-min intervals with a fixed f-stop of 5.6 using in-house modified software (hdrcaposx). Four to seven images were taken per time interval depending on the brightness of the scene. A lesser number of bracketed images were taken at low light levels to avoid excessively long exposures.

The LDR images were compiled into a single high dynamic range (HDR) image using the *hdrgen* tool. The camera response function was determined by the software. 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.

[7] The electric lights were not turned on in the area where the measurements were being taken (due to occupancy sensing). This is unlikely to affect measurements taken close to the window. For the measurements taken further from the window, adaptation levels are likely to be affected during early morning and late afternoon hours when outdoor light levels are low. This is estimated to have a minor effect on the overall daytime analysis.

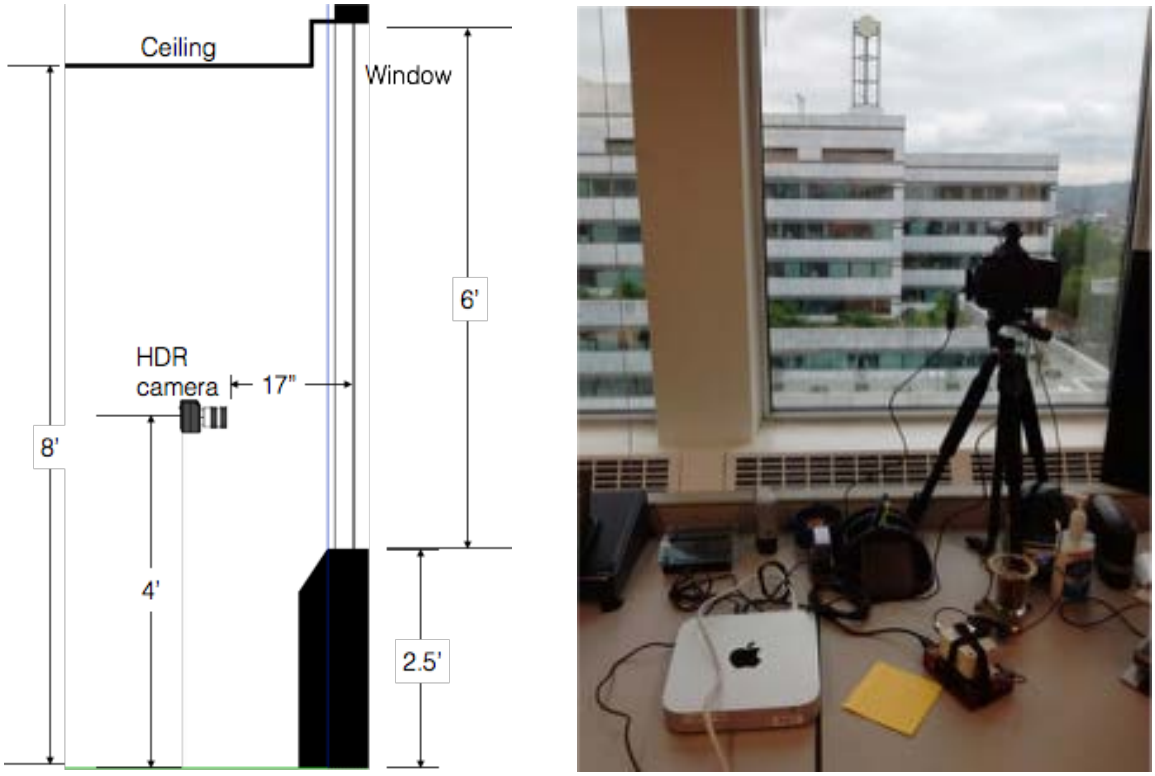


Figure IV.D.2. Section of the room showing the location of the HDR imaging system relative to the window in Phase I (left); photograph of the setup of the HDR imaging system (right). In Phase II, the lens was located 4 ft. from the window.

These HDR images were used to assess discomfort glare from daylight and identify glare sources within the field of view. The Daylight Glare Probability (DGP) index relies on high resolution, field-of-view HDR luminance images to assess glare. The index was derived through a comprehensive statistical analysis of HDR data and subjective response in a full-scale private office testbed that was retrofit with a variety of daylighting measures [13]:

$$DGP = c_1 \cdot E_v + c_2 \cdot \log(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{a_1} \cdot P_i^2}) + c_3$$

where:

E_v is the vertical illuminance at the eye;

L_s is the luminance of the source(s) within the field of view;

ω_s is the solid angle of the source; and

P is the position index of the source.

The DGP does not reflect the magnitude of glare perceived by the observer. Instead, it gets around the problem of person-to-person variability in response to perceived glare by estimating the probability that a person is "disturbed" by glare (the DGP formulation defined "disturbed" based on the subject rating the daylight glare source to be "disturbing" or "intolerable"). Wienold [13] derived a method to account for the frequency of glare over a time period, where within a defined category of comfort, 3%–5% exceedance of a threshold limit is allowed. DGP was calculated using the *evalglare* software [14] and default software settings.

Glare ratings ranging from "imperceptible" to "intolerable" were related to DGP values in a descriptive one-way analysis of the study's user assessment data (**Table** IV.D.2). In this analysis, the DGP 95% threshold value of 0.35 was used as a means of determining when discomfort glare was occurring in the space.

Table IV.D.2. Suggested definition of daylight glare comfort classes [13].

Max DGP of 95% of period		Avg DGP of 5% of period	Class	Meaning
≤ 0.35 imperceptible		≤ 0.38 perceptible	A	Best
		> 0.38	B	Good
≤ 0.40 perceptible		≤ 0.42 disturbing	B	Good
	and	> 0.42	C	Reasonable
≤ 0.45 disturbing		≤ 0.53 intolerable	C	Reasonable
		> 0.53	Discomfort	Discomfort
> 0.45 disturbing		> 0.53	Discomfort	Discomfort

Total workplane illuminance

In Phase II, workplane illuminance due to both electric lighting and daylight was monitored continuously at 1-min intervals using desktop-mounted light sensors from December 2015 to June 2016 at the locations shown in **Figure** IV.E.3.[8] The light levels reflected total illuminance, whether the individual light fixtures were turned on, dimmed for daylight or turned off due to lack of occupancy.

These data were used to characterize the general lighting environment in the open plan space to which occupants were responding when polled by the survey (See Section IV.D.10). Data were grouped into three ranges based on a daylight metric developed to assess the quality of daylight in indoor spaces [15]:

- Less than 100 lux: because individual lights may have been turned off when the space was unoccupied, this data represented daylight-only or total illuminance levels;
- between 100 and 2000 lux: daylight-only or total light levels considered to be useful for general office tasks; and
- greater than 2000 lux: daylight-only or total light levels that are likely to cause discomfort glare.
- Data are given as a percentage of weekdays between 9:00 AM and 5:00 PM for each month over the monitored period when illuminance levels were in these three ranges of illuminance levels.

The above metric is typically used to characterize the daylit environment, but it was not possible to obtain data from the lighting system that reported the status of every luminaire (on this floor, every

[8] On April 10, 2016, amplifiers for the sensors adjacent to the window were adjusted to enable a broader range of illuminance. Prior to this adjustment, data were clipped so the maximum reading was 5000 lux. After the adjustment, the maximum reading was 7500 lux.

luminaire is independently controlled from the others) and, therefore, also not possible to (a) back out the daylight contribution to workplane illuminance from the available light sensor data nor (b) determine when available light appeared insufficient because lights were off due to vacancy.

Occupant surveys

Visual comfort also was assessed using survey data. The survey contained questions about glare sensitivity, degree of visual comfort and how and why the occupant used the venetian blinds. Survey data that indicated a statistically significant difference in levels of comfort between the reference and test cases were deemed to be conclusive (i.e., $p>0.05$) for this evaluation.

7. THERMAL COMFORT

Thermal comfort was evaluated in Phase I using three methods: (a) continuous measurements of the indoor environment (e.g., air temperature and relative humidity), (b) periodic measurements of window and room surface temperatures using infrared imaging and (c) occupant surveys.

Continuous measurements

Data relevant for assessing thermal comfort were gathered at several locations near the windows in occupied offices on the reference and test floors. Sensors were located 0.5 to 3 ft. from the window. For sensors located on top of the convector, an insulating board was placed below the sensors to avoid thermal influence from the convector unit when the heating system was on (see Appendix C, **Figure** C-1).

Measurements consisted of room air temperature, air temperature in the HVAC supply diffuser, air temperature in the window wall convector, window frame temperature, window glass temperature, asymmetric mean radiant temperature (MRT), relative humidity, and air velocity. The MRT measurement was split between two hemispheres, one facing the south window and the other facing the room. When located on the convector, the MRT sensor was located on the room side of the venetian blind (if lowered) and the window. All measurements were taken at a 1-min interval over the entire six-month monitored period.

The monitored data were used to compute several indices related to thermal comfort: Fanger's predicted mean vote (PMV), predicted percentage of dissatisfied (PPD) and the temperature difference between the glass surface temperature and room air temperature [16]. A medium level of office clothing (long pants, long-sleeve shirt) was assumed (clo = 0.61). A sedentary activity level (typing) also was assumed (met = 1.1). The air velocity sensor provided erroneous data due to a limited power supply and so was assumed to be 0.15 m/s, which is within the typical operating conditions for air-based systems. PMV and PPD values were defined as:

- PMV value, which provides information on how occupants will perceive the space's thermal conditions (values range from -3 to 3; values of -3, -2, -1, 0, 1, 2, 3 imply the space being perceived as "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot" respectively), and
- PPD value, which represents the percentage of people who would be dissatisfied with the thermal conditions in the space.
- Target values between -0.5 and 0.5 for PMV and below 20% for PPD meet the ASHRAE 55 Standard for thermal comfort [17].

Infrared imaging

Infrared (IR) surface temperature measurements of the window wall were used to evaluate radiative impacts of the EC window on thermal comfort. The measurements were taken with a FLIR SC660 infrared camera using a microbolometer focal plane array sensor with 640x480 pixels [18]. The sensitivity of the sensor was less than 0.03°C. The infrared camera was fitted with a 45° opening angle lens allowing it to measure a relatively wide subject area from a limited distance. Numerous IR and visible images were collected together at 10-minute intervals during the periodic site visits around the summer and winter solstices and the equinox.

The measurements were calibrated using additional measurements of glass surface temperature, which were made in a nearby room using thermistors attached to the inboard surface of the EC windows. The calibrated infrared measurements were within 1–2°C of the surface temperature measurements made with the contact thermistors.

Occupant surveys

Thermal comfort also was assessed using survey data. The survey contained questions about temperature sensitivity, degree of thermal comfort and how and why the occupant used the venetian blinds. Survey data that indicated a statistically significant difference in levels of comfort between the reference and test cases were deemed to be conclusive (i.e., $p>0.05$) for this evaluation.

8. LIGHTING ENERGY USE

Daylight through windows can be used to offset use of the electric lights, thereby saving energy. In Phase I, we assessed lighting energy use savings in 15-ft. deep perimeter zone private offices, assuming automatic lighting controls were in place to switch or dim the lights in proportion to available daylight.

Measurements of daylight illuminance and lighting energy use could not be accomplished directly at this site. In Phase I, the existing lighting system was controlled with manual on-off switches and automated occupancy-based control. There was no switching status data available from the lighting control system. Sensors were installed that measured total workplane illuminance (electric and daylight illuminance) at a height of three ft. above the floor (approximately desk height). Custom-made light sensors also were installed inside the luminaires adjacent to the lamp, and the sensor signal was used to determine whether the grouped luminaires in the room were turned on or off.

These data were used to disaggregate the electric lighting contribution from the total measured illuminance based on the monitored on-off status of the lights, so that lighting energy use due to daylighting could be computed. Eleven test offices and seven reference offices were monitored over the six-month period. Two values were calculated:

1. Lighting energy use based on ON-OFF status: The luminaire sensor signal was used to determine the percentage of day the lights were ON in each office. The difference in the use of lights on the reference and test floors was then compared. This comparison included, however, both the difference in switching due to occupancy and any potential manual switching due to sufficient illuminance from daylight.

2. Lighting energy use based on daylight availability: When the luminaire sensor signal indicated that the lights were on, the electric lighting contribution to the workplane illuminance sensor was subtracted from the total illuminance. The remaining daylight illuminance level was then used to determine the amount of lighting energy needed to top

up the lighting level to meet the setpoint illuminance level (e.g., 300, 500 and 1000 lux). The required electric lighting illuminance was converted to lighting energy use using a linear relationship between energy consumption and light output and assuming an installed lighting power density of 1 W/ft^2 and zero energy use when light levels were zero. This calculation was performed for the occupied daytime period between 8 AM and 6 PM and ignores the added savings that could have occurred due to occupancy-based controls.

Results were indicative of potential savings because not all offices could be metered and the location of the workplane illuminance sensors was not ideal. Daylight dimming is typically determined by a ceiling-mounted photosensor located toward the rear of the room. In this study, the sensors were located very near the window due to location of the furniture and to avoid inconveniencing the occupant. With a low setpoint of 300 lux, the lights would likely be turned off for the majority of the day in both the reference and test areas because there is typically more than enough daylight close to the window. The 1000 lux setpoint was an adjusted value that compensated for the close proximity of the sensor to the window.

In Phase II, lighting energy use was not metered or calculated because a new lighting system was installed with autonomous, stand-alone controls in each fixture. No data were available from this system. Determining savings based on measurements on a fixture-by-fixture basis was beyond the resources of this project.

9. HVAC LOAD

The building has a history of unbalanced cooling loads between the north and south sides of the building, causing complaints of thermal discomfort because the same AHU serves both sides of the building. If the cooling loads on the south side were reduced using the EC windows, then the loads could be more balanced, potentially solving this problem. The goal of the HVAC analysis, therefore, was to determine whether the loads on the north and south sides of the building were more balanced, and if they were, whether complaints of thermal discomfort were reduced.

Historical data on HVAC operations were not available, so the reference condition on the top eighth floor was used to represent the pre-retrofit conditions of the lower test floors.

In Phase I, the cooling load was determined at the VAV box level, where the supply air temperature, supply air flow and room air temperature were trended at a 10-minute interval off of the existing building automation system. All VAV boxes were calibrated to within 10% by a GSA test and balancing contractor prior to this evaluation. LBNL checked the calibrations using a "Duct Blaster" connected to a flow capture hood where the fan in the "Duct Blaster" was used to overcome the increase in flow resistance (which happens when the duct blaster is connected). The duct blaster has a flowmeter in it with an accuracy of ±3% of reading. The methods used for the calibration are described in [19]. The resulting VAV calibration was estimated to be accurate to within ±4%–5%.

With these measured data, the cooling loads on the north and south sides of the building were calculated. The south-to-north cooling load ratios were calculated for each floor and compared between the EC and reference floors to determine the cooling load reduction.

In Phase II, HVAC loads were not evaluated.

10. OCCUPANT SURVEYS

Surveys were issued to the occupants in the reference and test areas to assess visual comfort, thermal comfort and satisfaction with the reference windows, EC windows and resultant indoor environment. Several aspects of how and why occupants interacted with the EC windows and

operable shading were also surveyed. In Phase I, a pre-retrofit survey was issued in March–April 2015 to ask occupants about their impressions with the existing reference windows. The post-retrofit survey was issued in January 2016 after the occupants had experienced the EC windows during both summer and winter solstice conditions. Occupants on the reference floor were also asked to fill out another survey. The schedule for the pre- and post-installation surveys is given in **Table** IV.D.1.

In Phase I, the pre-retrofit survey was the same on both floors, whereas the post-retrofit survey had some differences: (1) for the reference floor, post-retrofit questions were the same as in the pre-retrofit survey, but referred to the period after the pre-retrofit survey; (2) for the test floor, there were additional post-installation questions about their impressions of the EC windows and controls. The complete text of the surveys is given in Appendix B.

In order to be able to collect anonymous responses but then match up pre- and post-retrofit responses from a single individual, the individual was asked to select a random card from a deck of cards when issued the pre-retrofit paper-based survey and to note which card they had received on the survey. The individual was then asked again to note which card they had received when filling out the post-retrofit survey. Surveys were collected by the GSA management team, then mailed to LBNL. Analysis focused on identifying statistically significant differences in performance between the reference and test conditions.

In Phase II, a single, post-retrofit survey was issued in both the EC and reference areas at the conclusion of the monitored period in early June 2016. The survey was similar to the Phase I survey, with some changes to allow for the diversity in workstation types (open-plan workstations by a window, interior open-plan workstations, window private offices, interior private offices) and for the fact that the occupants in the reference area had already experienced the EC windows in automatic control mode for four months prior to changing the operations to a fixed tint level with no manual override. See Appendix B.

E. INSTRUMENTATION PLAN

In support of the test plan and assessment of performance as described in Section D, Phase I data were collected as follows (see summary **Table** IV.E.1, **Figure** IV.E.1). Data were recorded then transmitted remotely every day to an LBNL server. Photographs of the instrumentation are given in Appendix C.

- **Location A**: Sensors measuring workplane illuminance, thermal comfort, lighting on/off status, and EC window transmission, and EC glass surface temperatures. These sensors were metered continuously at a 1-min interval for the six-month duration of the study. Sensors were placed in south facing offices, two offices per floor on the east and west ends of the building on Floors
6–8.
- **Location B**: Sensors measuring thermal comfort and the reference window transmission and glass surface temperatures. These sensors were metered continuously at a 1-min interval for the six-month duration of the study. Sensors placed in three north facing offices, one office per floor on Floors 6–8.

- **Location C**: Sensors measuring workplane illuminance and lighting on/off status. These sensors were metered continuously at a 1-min interval for the six-month duration of the study. Sensors placed in south facing offices, two offices per floor on Floors 6–8.
- **Location D**: Sensors measuring lighting on/off status. These sensors were metered continuously at a 1-min interval for the six-month duration of the study. Sensors placed in south facing offices, three to four offices per floor on Floors 6 and 8.
- **Weather**: Sensors placed on the roof to measure outdoor weather conditions, including global and diffuse irradiance, outdoor air temperature and relative humidity, wind speed and direction, vertical irradiance, and illuminance at the south façade. These sensors were metered continuously at a 1-min interval for the six-month duration of the study.
- **EC window control** data provided by the vendor, including outdoor sensor reading, control mode and tint level of the EC window zones on Floors 5–7. Data were reported at a 1-min interval for the six-month duration of the study. LBNL did not have independent access to this data. The vendor had remote access to its EC control system throughout the project.
- **Site visits**: Periodic time-lapsed measurements of room luminance and room surface temperatures in one south-facing office on the seventh and eighth floors (**Figure** IV.E.2). These measurements were taken at a 10-min interval on 1 or 2 days around the summer and winter solstice and the equinox.

Figure IV.E.1. Locations of continuously monitored sensors on Floors 6–8.

Figure IV.E.2. Locations of sensors on Floors 6 and 8 for the periodic site visits during the summer and winter solstices and the equinox.

Table IV.E.1. Instrumentation for Phase I

Location, # sensors A	B	C	D	Monitored variable	Sensor	Range, accuracy all sensors sampled and recorded 1 /min
6		5		Workplane illuminance	Li-cor LI-210SA photometer	13,000 lux, ± 3 lux
6	3	5	8	Low-res light sensor	photoresistor	on/off status
6				Vertical illuminance at the eye	Li-cor LI-210SA photometer	13,000 lux, ± 3 lux
6				Transmitted vertical illuminance at glass	Li-cor LI-210SA photometer	134,000 lux, ± 33 lux
6	3			Transmitted vertical irradiance at glass	Li-cor LI-200SA pyranometer	1200 W/m^2, ± 0.3 W/m^2
6	3			Interior glass surface temperature	US Sensor, Digi-Key 615-1003-ND thermistor	-40° to 100°C, ± 0.2°C
6	3			Window frame surface temperature	US Sensor, Digi-Key 615-1003-ND thermistor	-40° to 100°C, ± 0.2°C
6	3			Indoor air temperature, shielded	HOBO TMC20-HD thermistor	-40° to 100°C, ± 0.2°C
6	3			Mean radiant temperature	US Sensor, Digi-Key 615-1003-ND thermistor	-40° to 100°C, ± 0.2°C
6	3			Relative humidity	HOBO ZW-003	10 to 90% RH, ± 2.5%
6	3			Air velocity	F900-O-5-1-9-2 Omnidirectional	0.015 to 6 m/s
6	3			Ceiling supply diffuser air temp	HOBO TMC20-HD thermistor	-40° to 100°C, ± 0.2°C
6	3			Convector air temp	HOBO TMC20-HD thermistor	-40° to 100°C, ± 0.2°C
Roof				Global and diffuse horizontal irradiance	Delta T SPN1	0-5000 W/m^2, ± 1.2 W/m^2
Roof				Incident vertical irradiance	Li-cor LI-200SA pyranometer	0-2470 W/m^2, ± 0.6 W/m^2
Roof				Incident vertical illuminance	Li-cor LI-210SA photometer	0–256 klux, ± 0.062 klux
Roof				Outdoor dry-bulb temperature, shielded	Onset S-THB-M002	-40°C to 75°C, ±0.21 (normal temperature range)
Roof				Relative humidity	Onset S-THB-M002	10 to 90% RH, ± 2.5%
Roof				Wind speed at façade	Onset S-WSET-A	0–45 m/s, ± 1.1 m/s
Roof				Wind direction at façade	Onset S-WSET-A	0–355°, ± 5°
Select offices				HDR imaging for room luminance	Canon EOS 60D camera	
Select offices				Infrared imaging for room surface temperature	IR imaging system	

Phase II instrumentation consisted solely of workplane illuminance sensors (same type as Phase I) placed in various occupied, open-plan workstations in each wing on Floor 5 (**Figure** IV.E.3). Sensors were placed on unobstructed desk surfaces at three ft. above the floor. Distances from the window varied from 4 to 26 ft. from the window. Data were collected over the six-month period at a 1-min interval. Remote access to these data was not enabled. Data were collected by LBNL staff when site visits were conducted every three months.

Additional site visits were made during solstice and equinox periods to assess visual comfort using the same methods as Phase I. The location of these measurements (four ft. from the window) also is indicated in **Figure** IV.E.3.

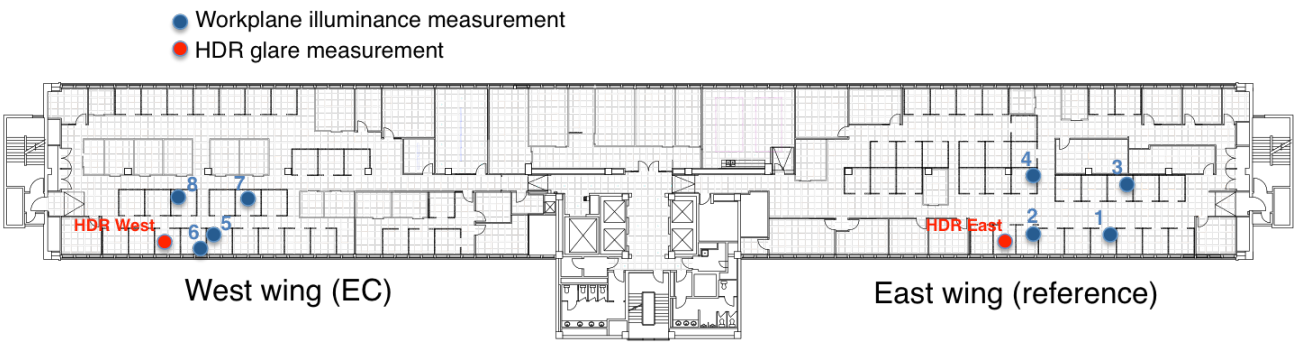


Figure IV.E.3. Location of Phase II workplane illuminance measurements on Floor 5. Sensors 1 to 8 were mounted approximately 4, 8, 23, 26, 8, 2, 20, and 20 ft. from the window, respectively. The red points indicate location of high dynamic range (HDR) sensors used to measure visual comfort.

V. Results

A. ELECTROCHROMIC WINDOW OPERATION

1. AUTOMATED CONTROL AND CONTROL SYSTEM RELIABILITY

Control patterns

The EC windows were controlled automatically according to the algorithms described in Section IV.B.2. The following Figures V.A.1–3 illustrate how the EC windows were controlled over the two monitored periods, Phases I and II.

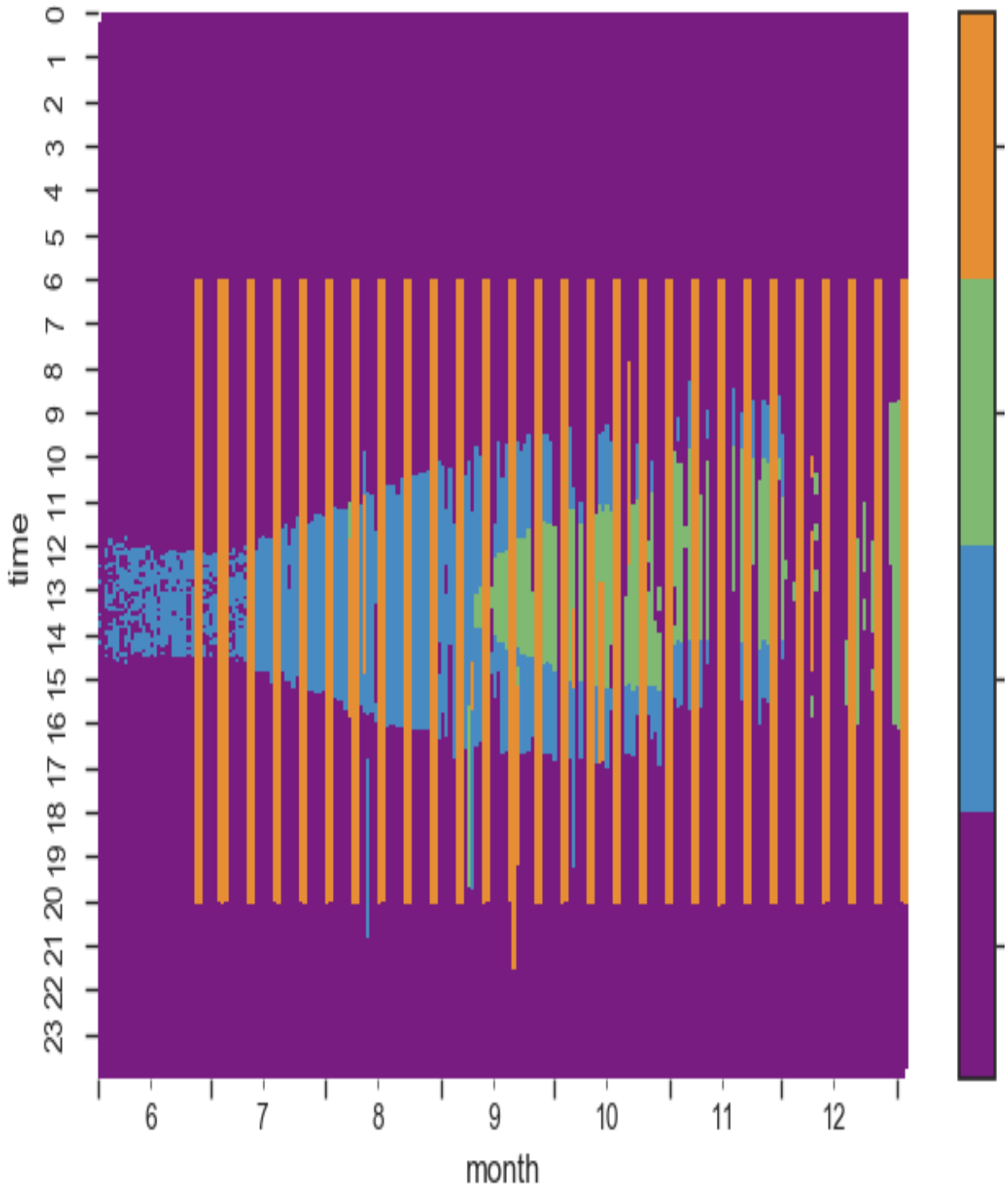


Figure V.A.1. Phase I, Floor 6. Tint level (Tint 1–4) of the EC windows in a south-facing zone (6W10) versus month of year and hour of day. Data are given from June 1, 2015, to January 3, 2016. The x-axis value of "6" is for June 15, 2015. EC windows were scheduled to Tint 4 on weekends (orange stripe) from 8AM–6PM. Random vertical lines on the graph indicate manual overrides that occurred at minimum four hours.

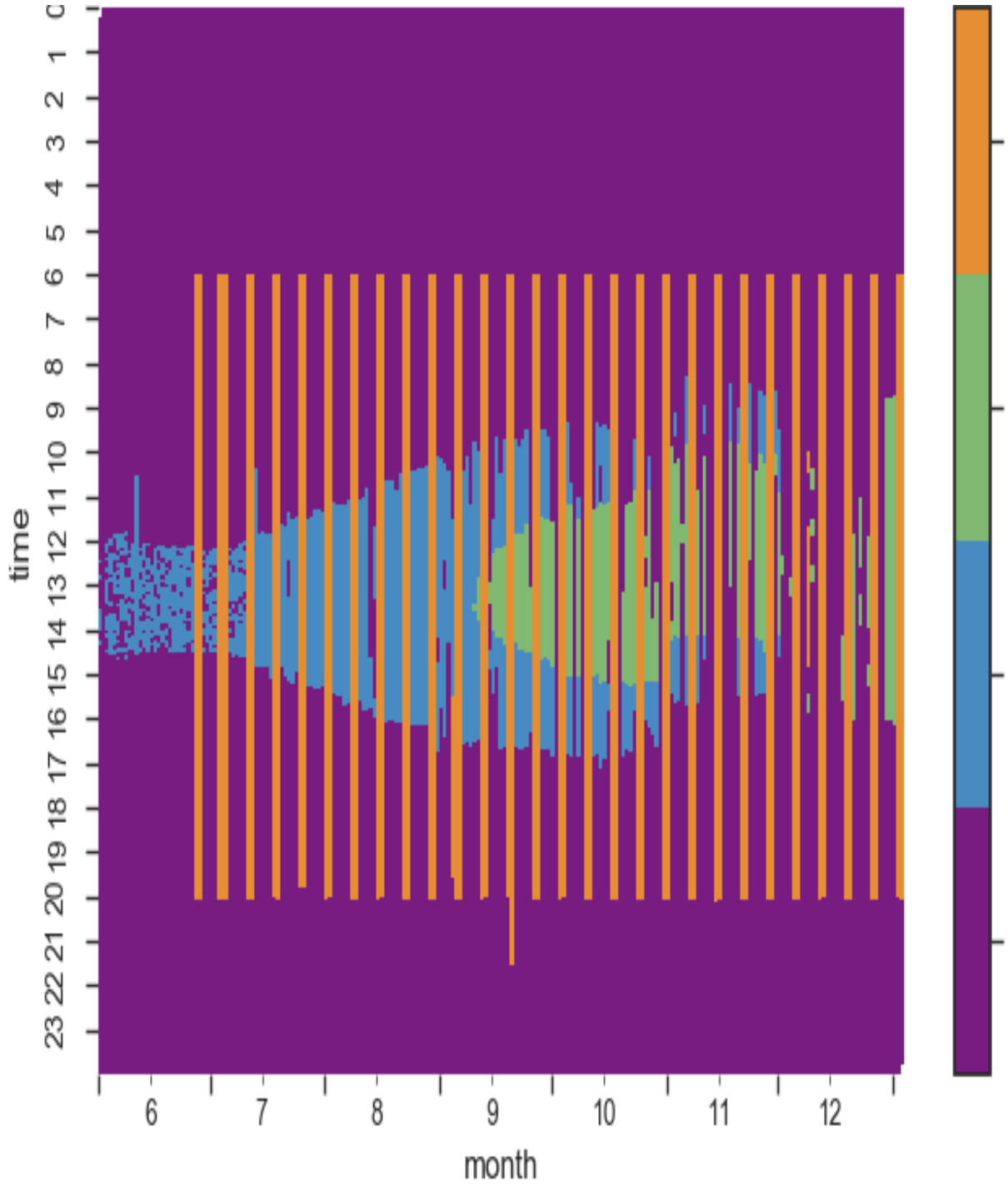


Figure V.A.2. Phase I, Floor 7. Tint level (Tint 1–4) of the EC windows in a south-facing zone (7W8) versus month of year and hour of day. Data are given from June 1, 2015, to January 3, 2016. The x-axis value of "6" is for June 15, 2015. EC windows were scheduled to Tint 4 on weekends (orange stripe) from 8AM–6PM. Random vertical lines on the graph indicate manual overrides that occurred at minimum four hours.

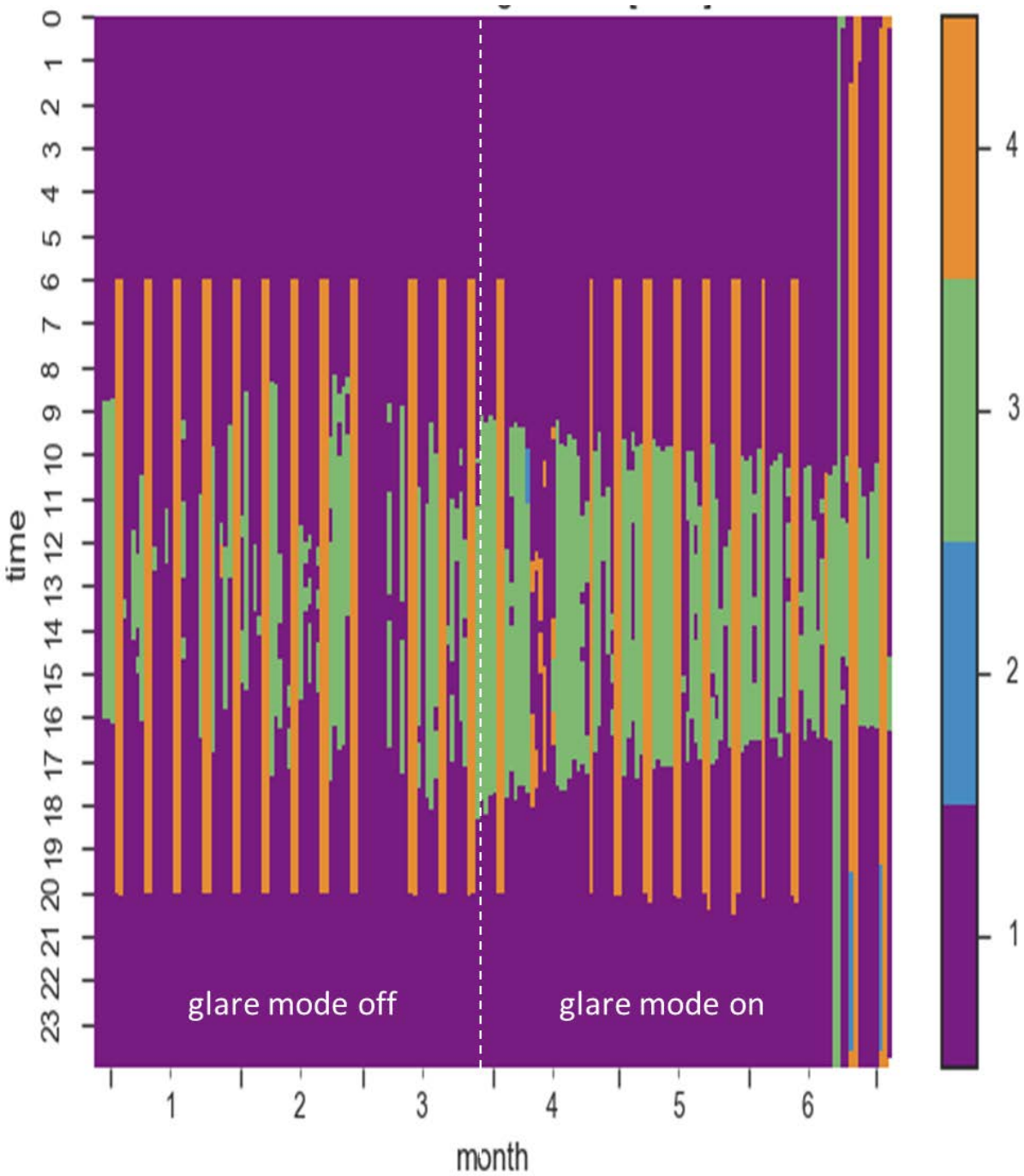


Figure V.A.3. Phase II, Floor 5. Tint level (Tint 1–4) of the EC windows in a south-facing zone (5W5) versus month of year and hour of day. Data are given from December 28, 2015, to July 3, 2016. The x-axis value of "1" is for January 15, 2016. EC windows were scheduled to Tint 4 on weekends (orange stripe) from 8AM–6PM. Random vertical lines on the graph indicate manual overrides that occurred at minimum four hours. The glare control mode was added March 25, 2016 (white dashed line).

Reliability

LBNL replicated the vendor's EC control logic, then evaluated every EC window zone on the sixth and seventh floors to determine whether the computed "proxy" control status matched that reported by the vendor. This independent analysis of the EC window control system showed that the vendor's control system was operating as specified when in either automatic or manual override mode. The

percentage of time when the proxy and actual tint levels did not exactly match was less than 2.5% of the time and likely due to small time step differences between the control event and logged data.

An example of EC operation in a private office is shown in **Figure** V.A.4 for a typical sunny summer day. Windows were tinted in response to increased readings from the vendor's outdoor sensor and untinted when sensor readings decreased. Discrepancies between the computed proxy control status and reported status by the vendor is shown in the lower graph with a lime green vertical line.

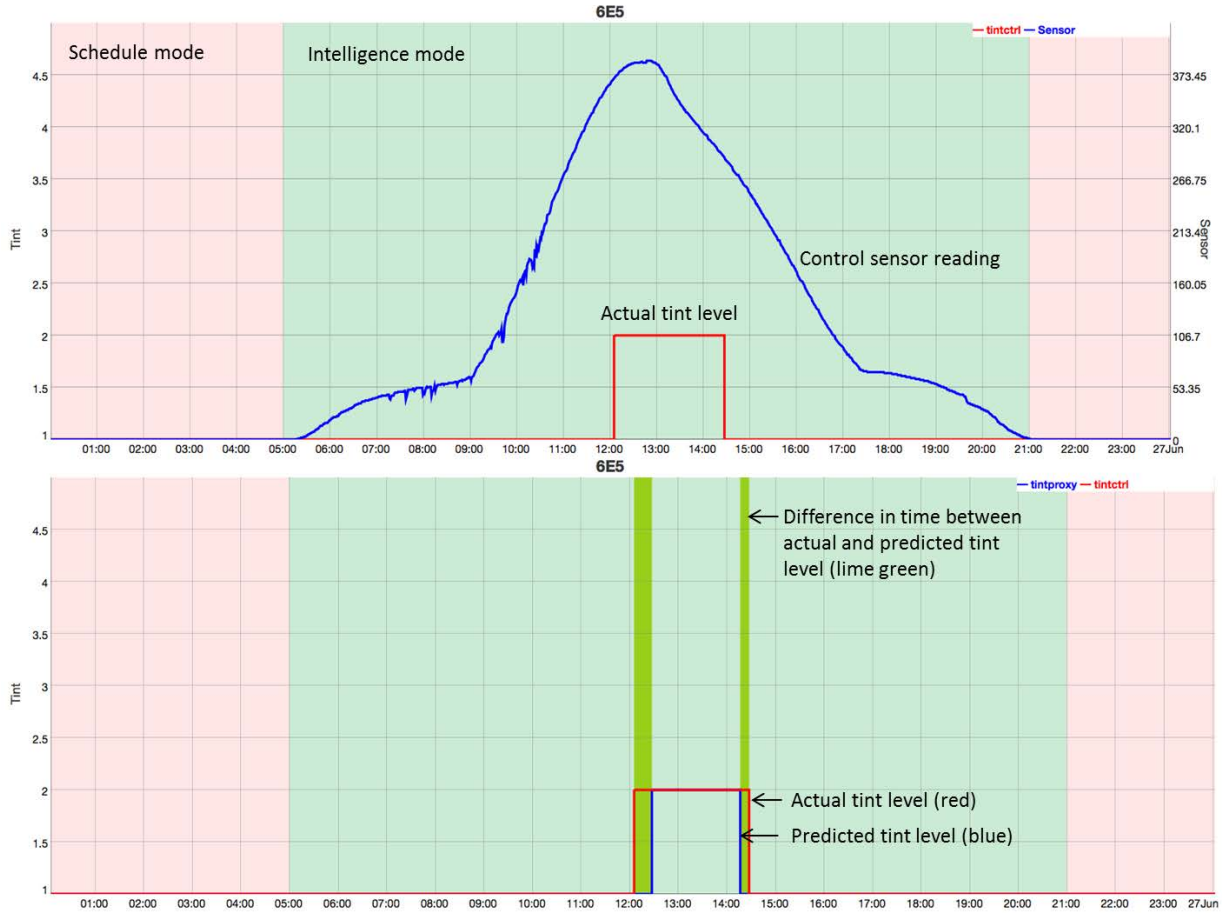


Figure V.A.4. EC operation in a private office for a typical sunny summer day (Jun 26, 2015). <u>Upper plot:</u> shows the actual tint level to which the EC windows were controlled to (red line) and exterior vertical irradiance (blue curve, W/m^2). <u>Lower plot:</u> shows the tint level to which the EC windows were controlled (red curve) and tint to which we think they should have been controlled (blue line) based on the algorithm information provided by the manufacturer. Discrepancies between the two lines are highlighted with lime green background shading. In both plots, the green and pink background shading show the time windows were in Intelligence and Schedule Modes, respectively.

2. MANUAL OVERRIDES – PRIVATE OFFICES (PHASE I)

Occupants were provided with a wall switch in every private office enabling them to override the automatic control system and set the EC windows to their preferred level of tint. The override remained in effect for four hours then reverted back to automatic control. The vendor's logged data were analyzed to determine frequency, duration and tint level selected by the occupants. These data were assumed to be an indicator of the level of satisfaction with the automatic controls.

Frequency and duration of manual overrides

The frequency of the manual overrides was analyzed for the monitored period spanning from May 25 to December 27, 2015. During the "summer" period from June 1 to August 23, 738 manual overrides occurred among a total of 40 offices (about 11 overrides per weekday). During the "winter" period from October 19 to December 27, 185 manual overrides occurred (about 3 overrides per weekday).

For each weekday, the number of minutes that the EC windows were manually overridden was computed for each of the 40 south-facing offices on the sixth and seventh floors. The average and median number of minutes for all 40 offices were then computed from this data for each week. As shown by the white dot on each of the vertical lines representing data for one week, the average duration of manual overrides ranged from about 10 minutes to about one hour per day, with no discernable trend in use over the six-month period (**Figure** V.A.5).

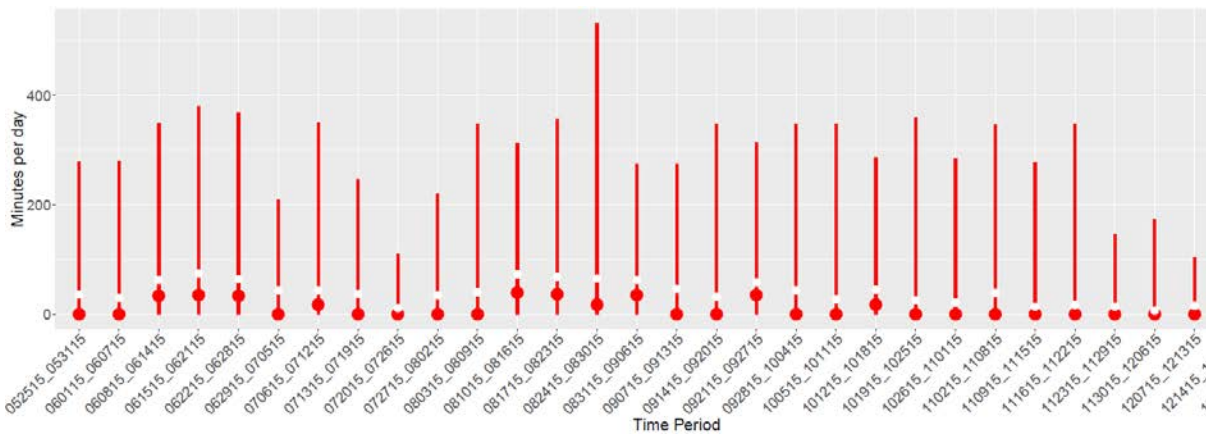


Figure V.A.5. Duration of manual overrides for each week between May 25 to December 27, 2015. The top and bottom of each vertical red line represent the maximum and minimum manual override duration in minutes per day among all the sixth and seventh floor zones. The red circle represents the median and the white dot represents the average value (per day and per zone), respectively.

Number of manual overrides and selected tint level per office

Figures V.A.6 and V.A.7 provides more detail on manual override usage for each office of the sixth and seventh floors.

Figure V.A.6 (b) displays the total count or number of manual overrides that occurred over the summer period. This total count per office was subdivided by the count per selected tint level. Note that the usage of the manual override was more frequent on the seventh floor than on the sixth floor. In addition, the majority of the overrides were to switch the windows' tint darker to Tint 3 or 4. (With the automatic controls, the windows were never switched to Tint 4.) Indeed, the frequency of usage of Tint 1 and 2 was relatively small. Offices 7E6 and 7W12 had the highest number of manual overrides. In the office 7E6, the occupant used only Tint 4 when overriding the automatic control system.

Figure V.A.6 (a) shows the vendor's measured exterior vertical irradiance, Sv, when the occupant of the corresponding office manually overrode the automatic controls. In most cases, the windows were manually overridden when the median sensor signal exceeded the 179 W/m^2 threshold defined by the vendor. Note that the vendor's vertical irradiance sensor was located on the roof,

not at each floor, so the automatic controls were operating in an open-loop mode to an exterior sensor signal that was a distant approximation to the actual incident irradiance on the facade.

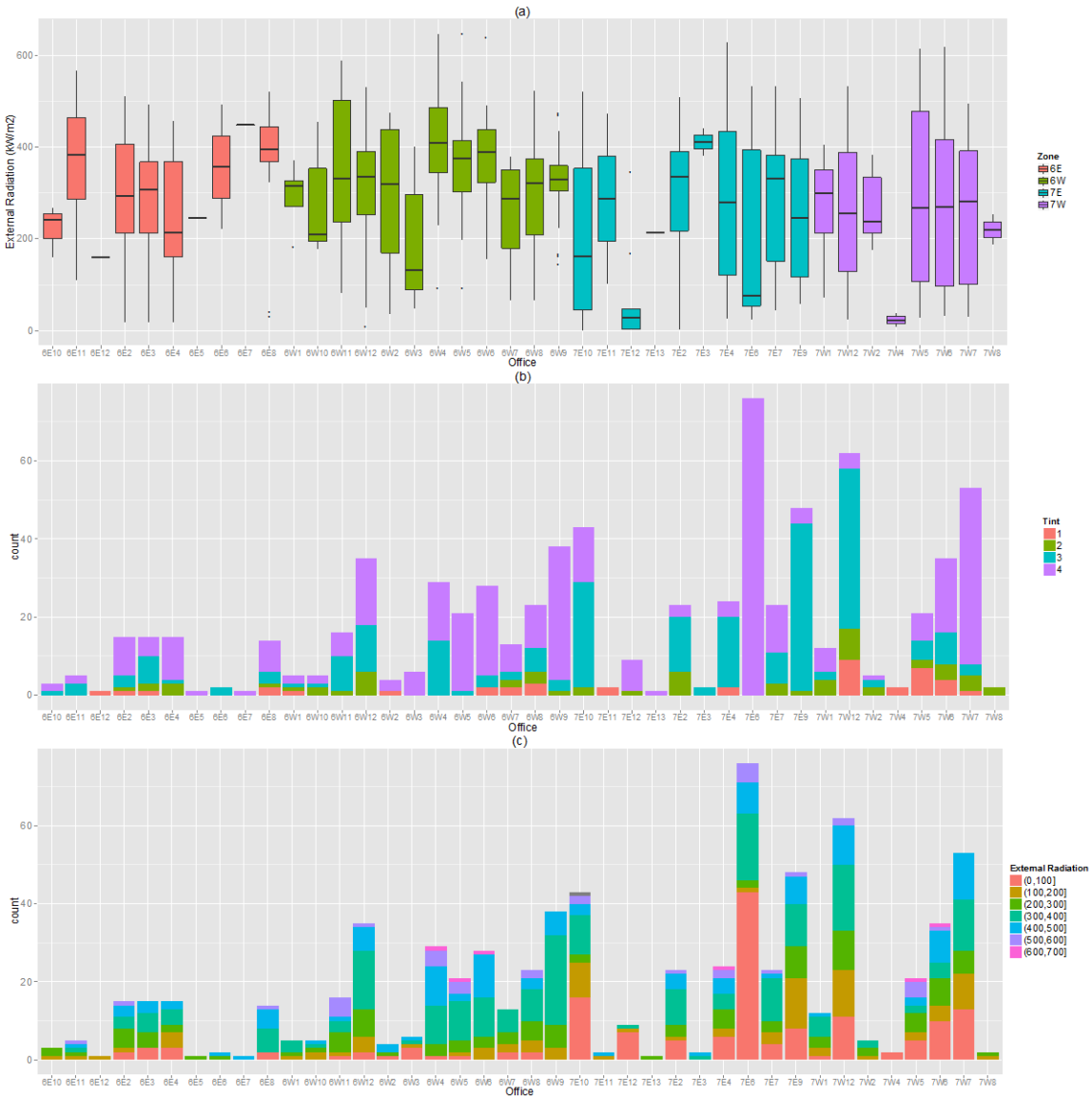


Figure V.A.6. Summer. Number of manual overrides (total count/three-month period) for each office on the sixth and seventh floors between May 25 and August 23, 2015: (a) box plots* of the vendor's measured exterior vertical irradiance (W/m^2) when the manual override occurred, where the different colors represent different areas of the floors; (b) frequency of tint level selected with manual override; and (c) frequency of the vendor's measured exterior vertical irradiance (presented as intervals) when the manual override occurred.

(* Note: box plots show the minimum and maximum as whiskers, and the first quartile, median, and third quartile as the lower, mid, and top edges of the box.)

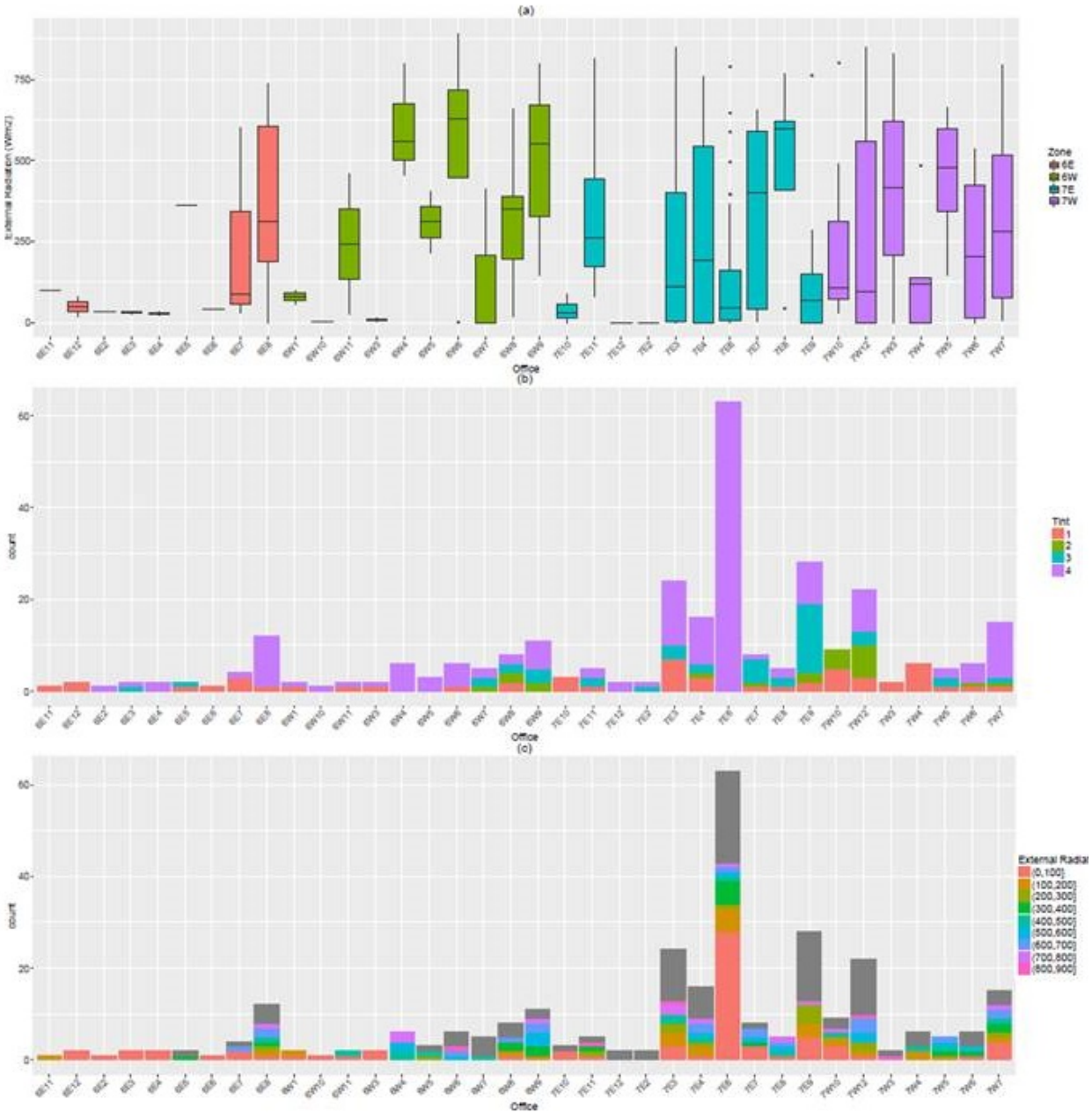


Figure V.A.7. Winter. Number of manual overrides (total count/two-month period) for each office on the sixth and seventh floors October 19 and December 27, 2015: (a) box plots* of the vendor's measured exterior vertical irradiance (W/m^2) when the manual override occurred, where the different colors represent different areas of the floors; (b) frequency of tint level selected with manual override and (c) frequency of the vendor's measured exterior vertical irradiance (presented as intervals) when the manual override occurred.

(* Note: box plots show the minimum and maximum as whiskers, and the first quartile, median and third quartile as the lower, mid and top edges of the box.)

Figure V.A.7 for the winter period shows that the number of manual overrides decreased significantly and the tint level to which the EC windows were overridden were now in some offices mixed between Tint 1 (bleached) and Tint 4 (dark tint). The number of overrides on Floor 7 was again greater than that of Floor 6. When overridden, the sensor signal was mixed between being lower than the thresholds defined by the automatic control system and greater than the thresholds.

Figure V.A.8 summarizes the override data for all 40 offices on a per week basis over the entire six-month monitored period. Here it becomes more evident that the majority of the manual overrides were largely to Tints 3 and 4 and the median exterior irradiance level when switched was greater than the 179 W/m^2 threshold. From **Figure** V.A.8 (a), notice that the median value of the vertical external irradiance increased over time from a value of lower than 200 W/m^2 to almost 600 W/m^2. Also note that vertical irradiance levels on the south façade increased (on sunny days) as the sun angle decreased with the transition toward the winter period, so these irradiance levels reflect both occupant preferences and the change in irradiance levels due to the solar incident angle on the facade.

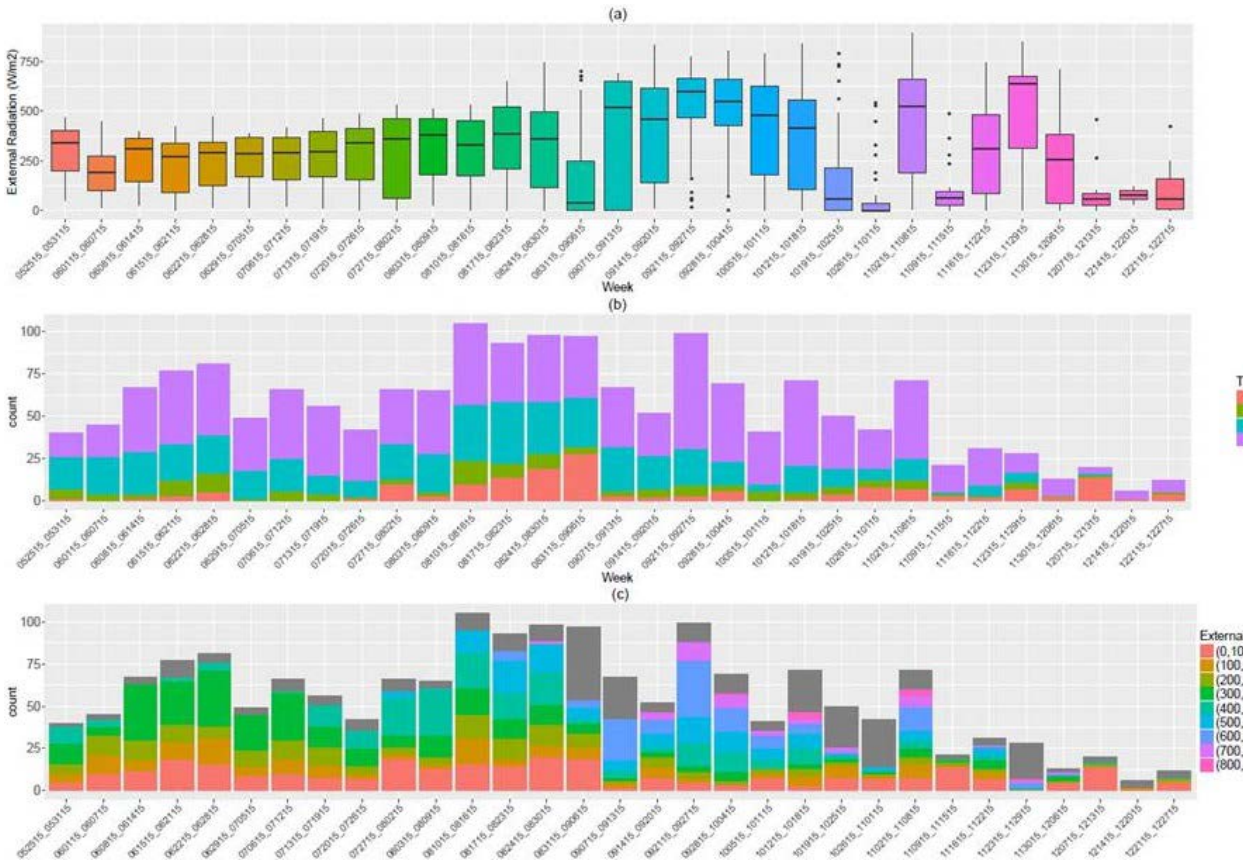


Figure V.A.8. All offices. Number of manual overrides (count/week, 40 offices) between June 1 and December 27, 2015: (a) box plots of the vendor's measured exterior vertical irradiance (W/m^2) when the manual override occurred; (b) tint frequency (count/week) used during the manual override and (c) frequency of vertical irradiance (presented as intervals) when the manual override occurred.

3. MANUAL OVERRIDES – OPEN PLAN OFFICES (PHASE II)

Frequency and duration of manual overrides

Similar to Phase I, the average duration of manual overrides in the EC wing was low: less than 25 minutes per zone per day for almost all weeks over the six-month period (**Figure** V.A.9). During the week of April 11, 2016, the average reached 100 minutes per day per zone. This was due to the control system having been mistakenly left operating in a test glare mode (after a site visit) that set the windows to Tint 4 all day instead of the usual automatic mode. Occupants used the wall switches to set the windows to Tint 1 (fully bleached). The normal control settings were restored by the end of the week on April 15, 2016.

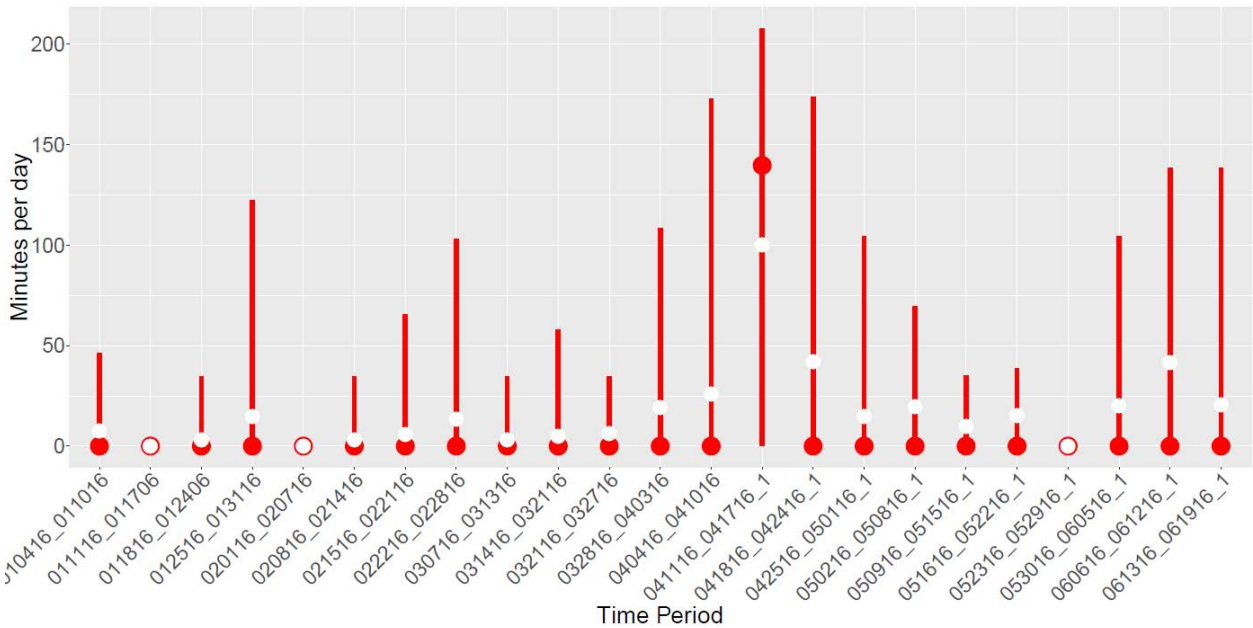


Figure V.A.9. Duration of manual overrides for each week between January 4 and June 19, 2016. The top and bottom of each vertical red line represent the maximum and minimum manual override duration in minutes per day among all the zones in the west wing of Floor 5. The red circle represents the median and the white dot represents the average value (per day and per zone), respectively. Note that results between April 11 and May 29 were based on 7 zones only (versus all 11 zones), due to limited available data.

Use of the manual override mode was less frequent in Phase II than in Phase I. This may be due to several factors:

- The zoning of the EC windows and switches did not exactly correspond to the workstation layout adjacent to the windows, so one individual's override was likely to affect the adjacent neighboring workstation(s).
- Unlike occupants in private offices on Floors 6–7, occupants in the open plan workstations adjacent to the EC windows may have considered the impact of switching the EC windows (or lowering the venetian blind) on occupants that sat further away from the windows.

Number of manual overrides and selected tint level

When manually overridden, Tint 1 (fully bleached) or Tint 4 (fully colored) were selected by the occupants most frequently. Prior to the change to glare mode on March 25, 2016 (denoted by the dashed vertical line in **Figure** V.A.10), there were less overrides during the winter to equinox period. Between the equinox to summer period (after the dashed line), the number of overrides increased, with Tint 4 being most prevalent. The median sensor signal, when overrides occurred, appeared to have a downward trend between winter and summer solstices.

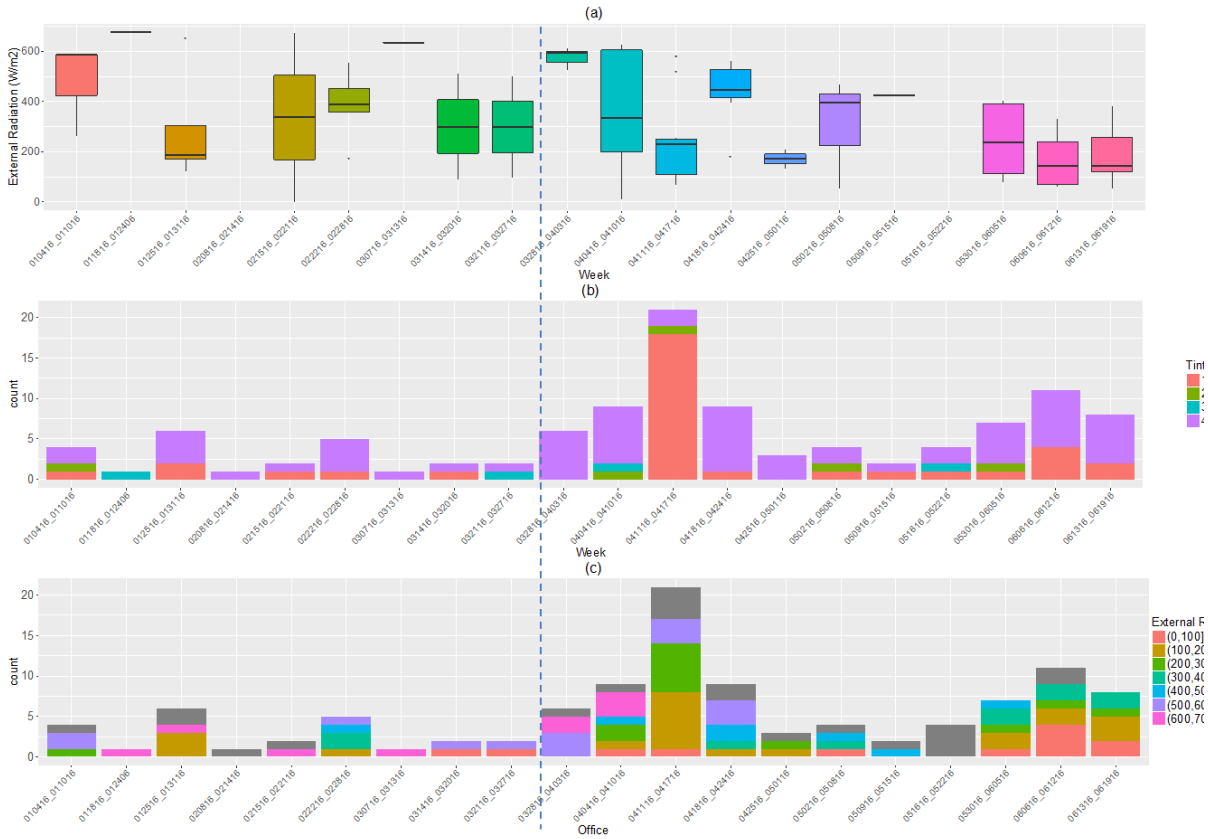


Figure V.A.10. Number of manual overrides (count/week, 12 zones) between January 4 to June 19, 2016: (a) box plots of the vendor's measured exterior vertical irradiance (W/m^2) when the manual override occurred; (b) frequency of tint level used during the manual override and (c) frequency of vertical irradiance (presented as intervals) when the manual override occurred.

4. SWITCHING SPEED AND WINDOW APPEARANCE

Switching speed

The switching speed of the 3.14 ft. wide by 6.14 ft. tall EC windows was evaluated with limited on-site measurements in this study. A fast switching speed can help minimize discomfort; occupants are unlikely to accept discomfort if the time that it takes for EC windows to switch from fully bleached or clear to fully tinted is too long.

To assess switching speed, the tint level (i.e., nominal visible transmittance) of the EC window was estimated by computing the ratio of indoor transmitted vertical illuminance at the face of and center of the EC window to the outdoor vertical illuminance measured by LBNL on the roof.

Figure V.A.11 shows this nominal visible transmittance (Tv') for one of the EC windows on the seventh floor on a warm sunny summer day with clear sky conditions (August 7, 2015). The red line shows the center-of-glass visible transmittance (at normal incidence) corresponding to the tint level to which the vendor's control system switched the EC window during this period. The blue line shows the nominal visible transmittance measured on site. The sharp transitions in the blue line at 9 AM and 5 PM indicate when direct sun was in the plane of the window.

- Around 11 AM, the transition from Tint 1 (fully bleached, Tvis = 0.36) to Tint 2 (Tvis = 0.25) took about 20 minutes.
- Around 3 PM, the transition from Tint 2 to Tint 1 took about 10 minutes.

- Switching from Tint 1 to Tint 4 (fully colored, Tvis = 0.02) is likely to take significantly longer than 20 minutes. Unfortunately, there were no data under the equivalent temperature and solar conditions to compare with this example.

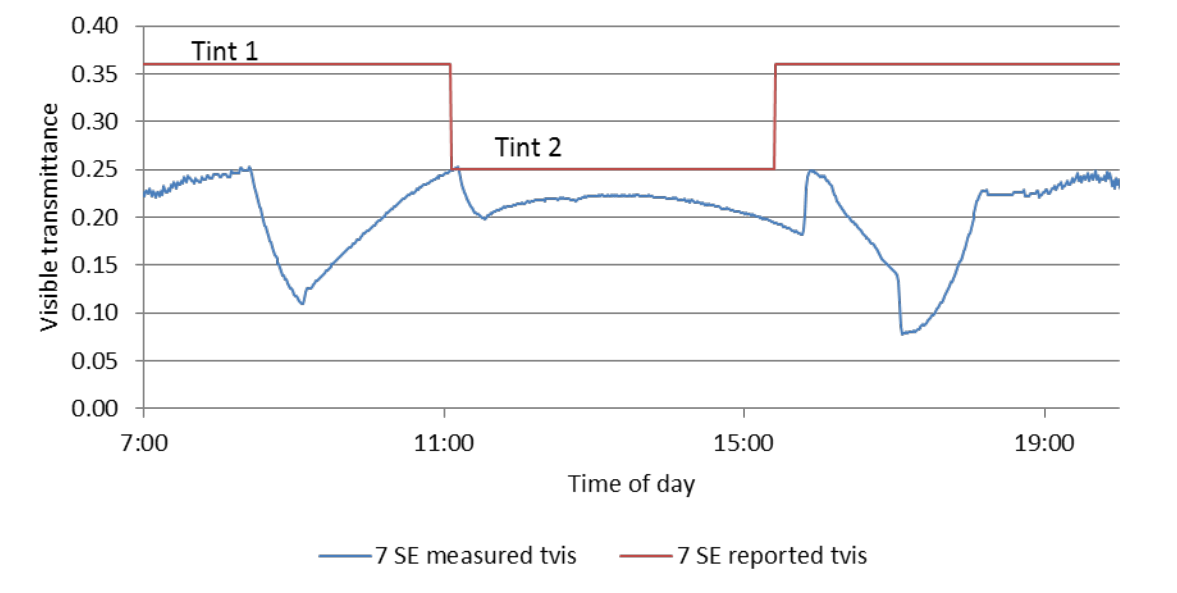


Figure V.A.11. Nominal visible transmittance ("measured") and visible transmittance of the EC window corresponding to the tint commands ("reported") on August 7, 2015.

Appearance of the EC window while switching

The following photographs (**Figure** V.A.12) show what the EC window looked like while switching. The bus bars were located on the two opposing vertical sides of the IGU. Within the first six minutes, notice how the switch to the darker tint occurred faster at the vertical sides near the bus bars, while the center of the window was less tinted. The uniformity of the tint was difficult to assess given that the photographs were taken at dusk (to avoid interference with other measurements that were being taken during the day).

Note that reflections off of the indoor surface of the EC window can obscure views out during low light or nighttime conditions. Specifying a window with a low visible reflectance can improve views to the outdoors, particularly in overcast climates like Portland.

6:25 PM (0 min)

6:31 PM (6 min elapsed)

6:43 PM (18 min elapsed)

6:53 PM (28 min elapsed)

Figure V.A.12. Indoor photographs of the EC windows on Floor 5 when switched from Tint 1 to Tint 4 starting at 6:25 PM on April 10, 2016. (These photos depict both the change to a darker tint level, as well as a gradual decline in outdoor daylight levels over the 30 min. period. Sunset was at 7:50 PM.)

5. APPEARANCE OF THE EXTERIOR FACADE

Photographs of the exterior façade (**Figures** V.A.13 and V.A.14) were taken in April 2016 to illustrate the appearance of the EC windows from the outside of the building.

Figure V.A.13. Photograph of the east wing of the south façade on Friday, April 8, 2016, at 2:15 PM. The Phase I EC windows on Floors 6–7 were operating in automatic mode (Tints 1–3). Some windows may have been set manually to Tint 4. The Phase II EC windows on Floor 5 were set to Tint 1 (reference condition). Floor 8 shows the appearance of the original ("o") existing reference low-e windows.

Figure V.A.14. Photograph of the west wing of the south façade on Saturday, April 9, 2016, at 8:30 AM. The Phase I EC windows on Floors 6–7 were operating in the Schedule mode and set to Tint 4. The Phase II EC windows on Floor 5 were operating in the automatic mode (Tints 1–3). Floor 8 shows the appearance of the original ("o") existing reference low-e windows.

B. INDOOR VENETIAN BLIND USE

1. PHASE I

As described in Section IV.D.2, the indoor venetian blinds were tied up in most offices on the EC test floors (Floors 6–7) at the beginning of the test period (June 12, 2015) and occupants were encouraged not to untie their blinds unless all other options had been exhausted. For example, the EC automatic control system switched the windows to Tint 1-3, so if occupants were experiencing glare, they had the option to tint the windows further to Tint 4 using the manual override switch. If they were aware of this option and still requested that the blinds be untied (for glare or any other reason), the facility managers complied.

Figure V.B.1. shows the percentage of all indoor venetian blinds (across the entire south façade) that were fully raised between May and December 2015. Offices were surveyed six times over the course of the six-month period. On the day of the second survey (June 12, 2015), 90% of the blinds were zip-tied on the EC test floors. The percentage of fully raised blinds decreased slightly between summer and winter from 83% to 77%. Overall, the percentage of blinds that were fully raised was about 80% with the south-facing EC windows. The majority of the blinds remained zip tied throughout the six-month study. On the reference floor (Floor 8), 50% of the blinds were fully raised in the early summer, but by winter, only 26% of the blinds were fully raised.

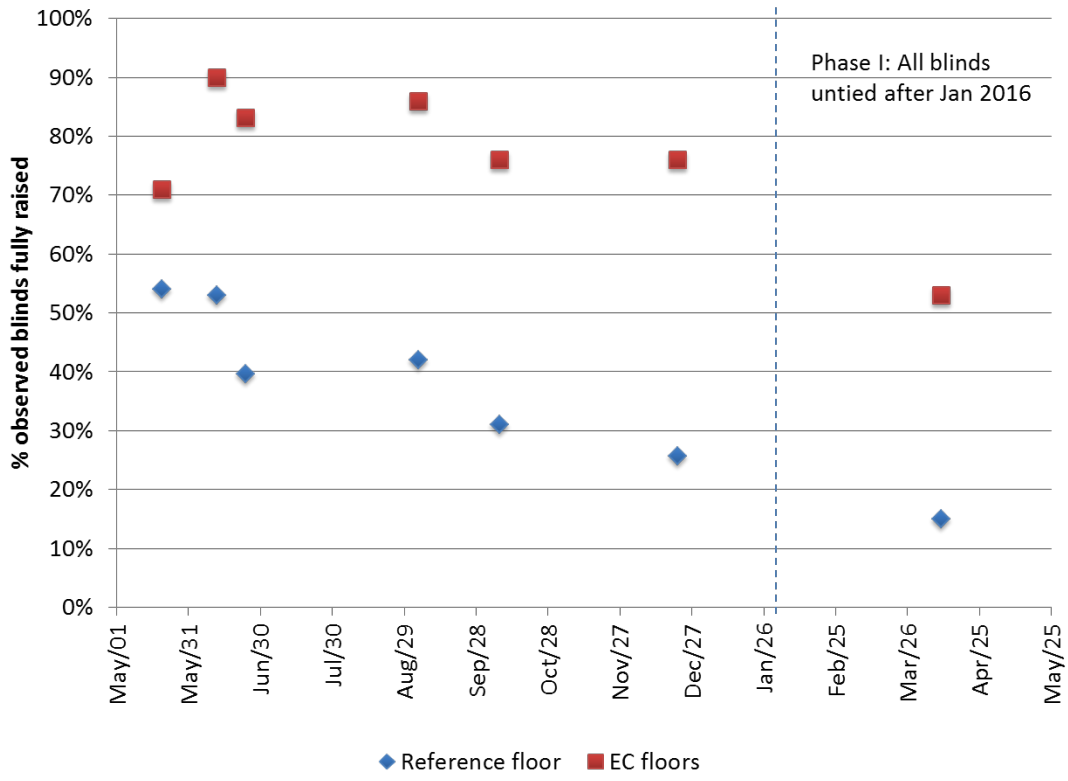


Figure V.B.1. Phase I: Percentage of observed blinds in fully raised position on reference and EC floors between May and December 2015. After January 2016, all blinds on the EC test floors were untied. Data for a survey conducted April 9, 2016, are shown for EC Floor 7 (EC Floor 6 was not occupied). The reference condition was the existing window (Tvis' = 0.15).

After the conclusion of Phase I in January 2016, the blinds were untied in the private offices on the EC test floors. A survey was performed on April 9, 2016 to determine if blind use had changed after the blinds were untied. On the sixth floor, the original occupants had moved out and the spaces were unoccupied. Results for blind use for the seventh floor with EC windows are shown in **Figure** V.B.1. Note that while use of the blinds increased in both the reference and test areas, the use of blinds was significantly less in the EC test areas compared to that in the reference area.

2. PHASE II

Like Phase I, surveys were conducted on a monthly basis to evaluate the necessity of indoor shades with automated EC windows. In this phase, however, none of the venetian blinds along the south façade were tied to prevent their use. Occupants in the open plan area were free to position the height and slat angle of the venetian blinds as they wished.

A survey of blind position was conducted at the beginning of the Phase II study on December 20, 2015. Prior to December 18, both the east and west wings of the fifth floor had the EC windows operating in automatic mode (control mode described in Section IV.B.2). The survey showed that there were slightly more fully raised blinds in the east wing than the west: 54% versus 45% of the 11 blinds per wing, respectively, were fully raised (a difference of 1 blind).

On December 18, 2015, the east wing EC windows were set to the reference condition (static Tint 1 (fully clear)) and the west wing EC windows were set to the test condition (automatic mode). Surveys were conducted by LBNL during site visits and by GSA facility managers. After the December 20, 2015, survey, all blinds along the entire south façade were fully raised. After the March 19, 2016 survey, all the blinds in the EC test wing (west) were fully raised. This action was taken to counter the typical end user pattern of lowering then leaving the shades for weeks on end.

Surveys showed that over time there were more fully raised blinds in the west wing with automated EC windows compared to the east wing reference case. After March, 70%–80% of the blinds were fully raised in the test area compared to 30%–58% of the blinds in the reference area. See **Figure** V.B.2

This survey data shows that, for some occupants, shades are required with EC windows even when automatically controlled (with or without a glare mode to Tints 1–3) and with the option to override the windows manually to full tint (Tint 4). The survey data also seems to suggest that shades may be used slightly less with an EC window than with a conventional window, although this may due to other factors, such as small differences between individuals in their sensitivity to thermal or visual discomfort or preference for view and privacy. Note that, unlike Phase I with the original windows (Tvis' = 0.15), the Phase II reference window (EC at Tint 1, Tvis = 0.36) had a higher visible transmittance than the Phase I.

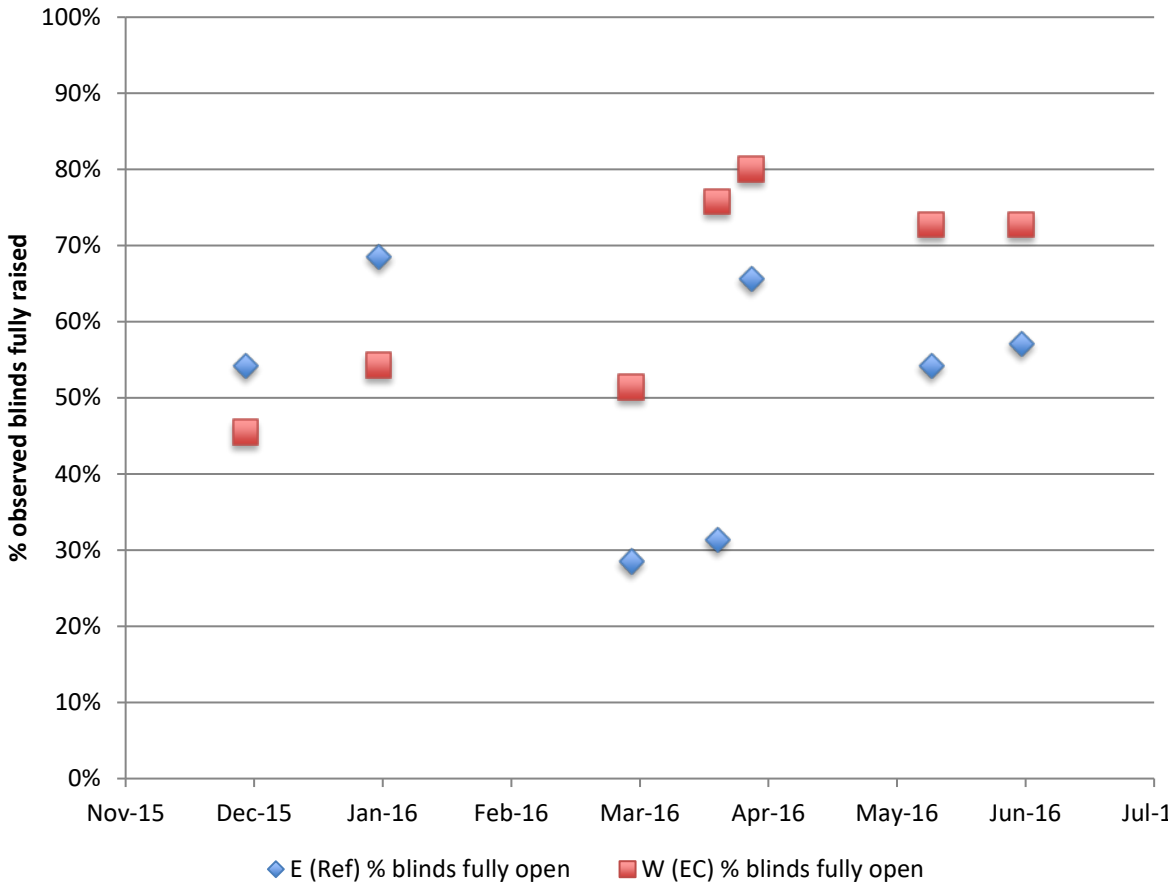


Figure V.B.2. Phase II: Percentage of observed blinds in fully raised position on reference (E = east) and EC (W = west) test areas on the fifth floor between December 2015 and June 2016. The reference condition was the EC window at Tint 1 (Tvis = 0.36).

C. VISUAL COMFORT

1. VERTICAL ILLUMINANCE AT THE EYE

In Phase I, vertical illuminance was measured in two occupied south-facing private offices on the reference and four offices on the test floors. These measurements were omitted in the more limited Phase II study. The data reflected the effects of both the operation of the EC windows, the difference in visible transmittance between the reference and EC windows (see Section V HVAC Load for an analysis of the existing window properties) and the impact of the venetian blind if sufficiently lowered.

The average daily vertical illuminance (8 AM to 6 PM) was computed for the east or west ends of each floor. These data are shown for weekdays in **Figure** V.C.1, where each line segment represents a single week of data. Vertical illuminance levels of 780 lux and 4000 lux correspond to subjective rating (SR) levels of 1.5 and 2.5, respectively. The average percentage of day SR was equal to or greater than 2.5 (threshold between "just disturbing" and "just intolerable") is given in **Figure** V.C.2.

Observations from these figures are as follows:

- During the summer period, the percentage of time glare exceeded "just intolerable" levels during the day (8 AM to 6 PM) was greater than 20% for both the reference and test case floors.

- During the equinox period (around September 21), glare levels were similarly high on both the reference and EC floors.
- In the winter, when partly cloudy conditions prevailed, glare levels were lower and were nearly the same in magnitude on both the reference and EC floors.
- Across the entire monitored period, average SR levels were greater than the 1.5 "just disturbing" threshold level on both floors. The percentage of time that SR was greater or equal to 2.5 declined from about 30% during the summer to about 10%–20% during the winter on both the reference and EC floors.

Because the sensor was placed 1.25–2.3 ft. from the window to avoid being in the way of the occupant and faced directly toward the window, these data represent conservative, worst case scenarios. The data also does not reflect necessarily what the actual occupant was experiencing in the space, so the EC window may not have been tinted to a level that would have adequately controlled glare at the sensor location.

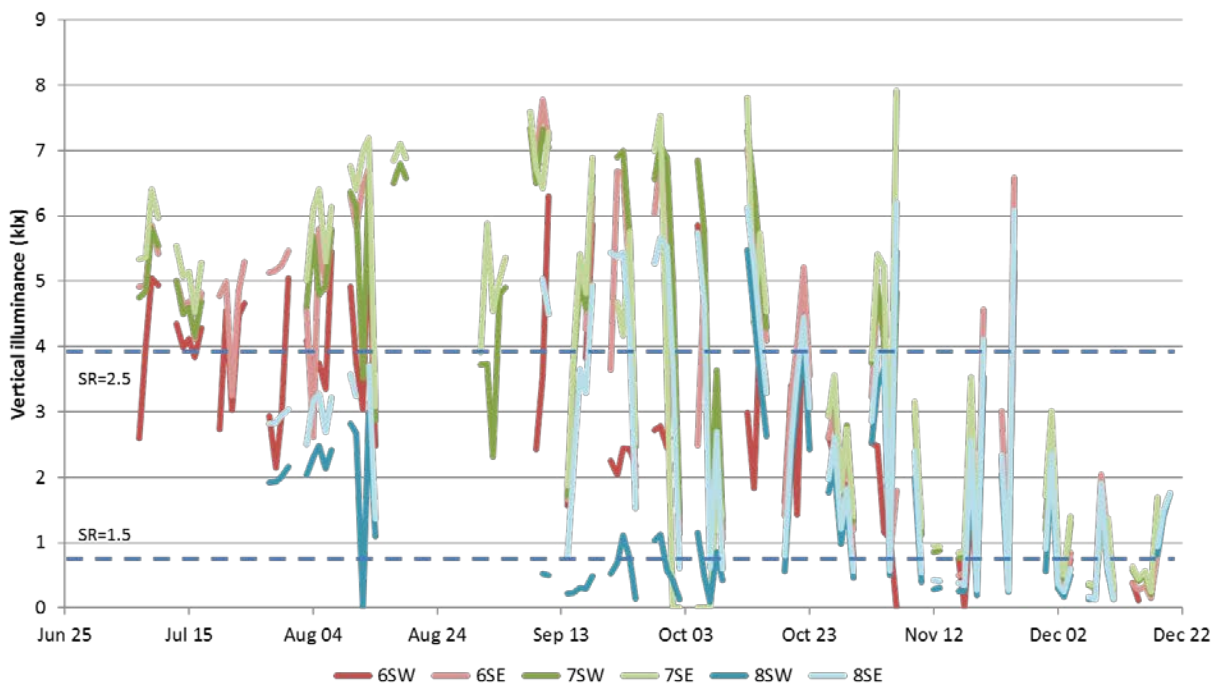


Figure V.C.1. Average daily vertical illuminance at the eye (8 AM to 6 PM). The subjective rating (SR) levels are shown as dashed lines on the graph. An SR of 1.5 defines the borderline between "just noticeable" and "just disturbing," and 2.5 the borderline between "just disturbing" and "just intolerable." Data in September for the 8SW zone should be ignored: the sensor was found turned toward the wall. Reference case – Floor 8; EC case – Floors 6–7.

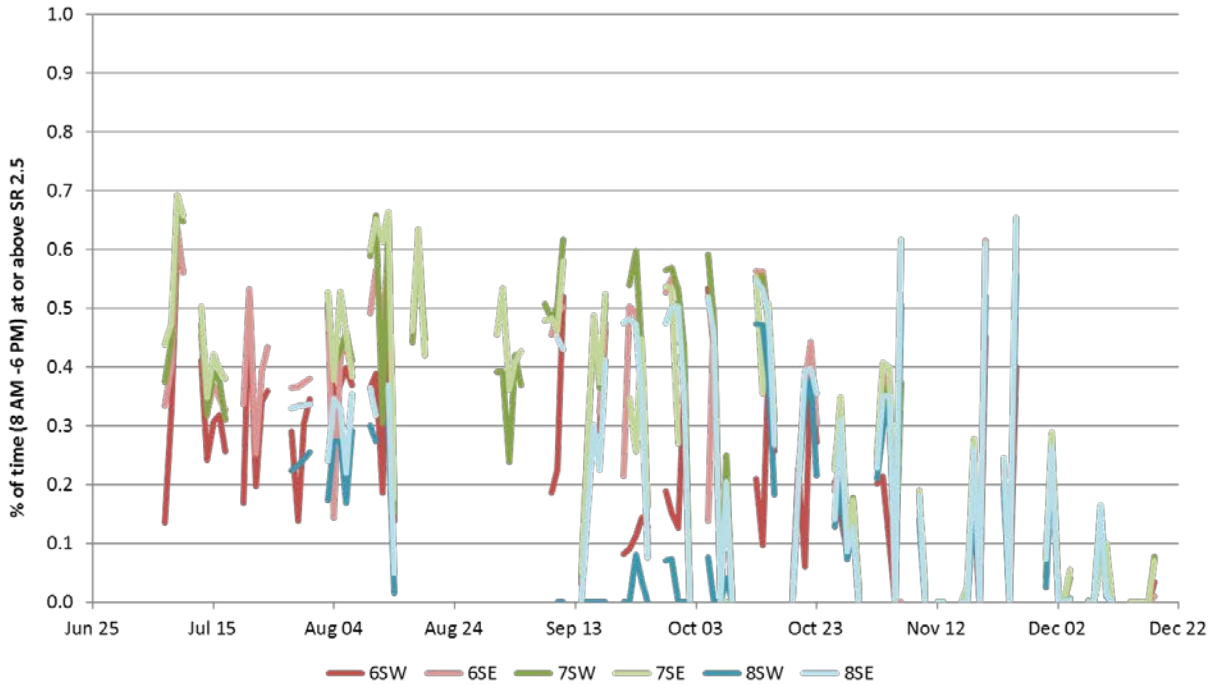


Figure V.C.2. Percentage of day that the subjective rating is greater than 2.5, which is the borderline between "just disturbing" and "just intolerable." Data in September for the 8SW zone should be ignored: the sensor was found turned toward the wall. Reference case – Floor 8; EC case – Floors 6–7.

2. DISCOMFORT GLARE – PHASE I

Detailed measurements were made over a weekend during the equinox and solstice periods using HDR imaging techniques to produce luminance maps from various viewpoints at seated height. Unlike the previous analysis of vertical illuminance, this analysis was conducted for the worst case condition where the shades were not lowered over the reference or EC windows and the viewpoint was located next to the window, facing the window. The EC windows were operated in the automatic mode defined in Section IV.B.2 (i.e., glare sub-mode was disabled and the switching range was constrained to Tints 1–3). This was the automatic control mode that was experienced by most occupants. Some occupants did choose to override the system manually (Tints 1–4) as discussed in Section V.A.2.

Time-lapsed measurements were taken for a full day during the time of visit in an unoccupied office on the sixth floor and an occupied office on the eighth floor (both on the west end of the building). Measured results were as follows:

Summer solstice, sunny day (July 24–25, 2015):

- For this clear, sunny summer "day" (composite of the afternoon of July 24 and morning of July 25), daylight glare probability (DGP) values for the reference window condition were less than "imperceptible" (DGP<0.35) (**Figure** V.C.3). Measurements for this period were made 1.4 ft. from the window. (Note: In general, DGP levels below 0.20 are invalid and should be ignored.)
- The EC window had consistently greater DGP levels than the reference condition during the early morning and late afternoon hours of the day, but glare levels were still below

"imperceptible" (**Figure** V.C.3–4). A significant increase in EC DGP levels around mid-day was due to exposure of the sensor to direct sun. In the reference case, the inset of the window frame shaded the sensor. For the period from 10:30 AM to 2:00 PM, the comparison between cases was, therefore, invalid.

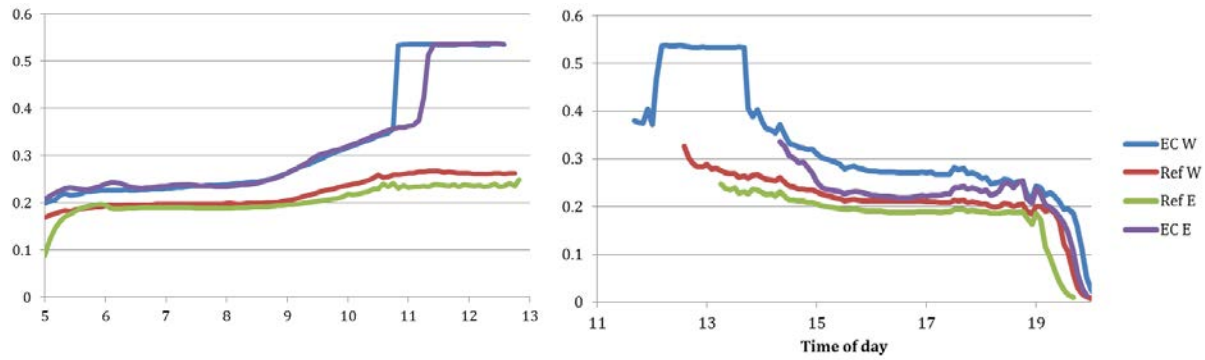
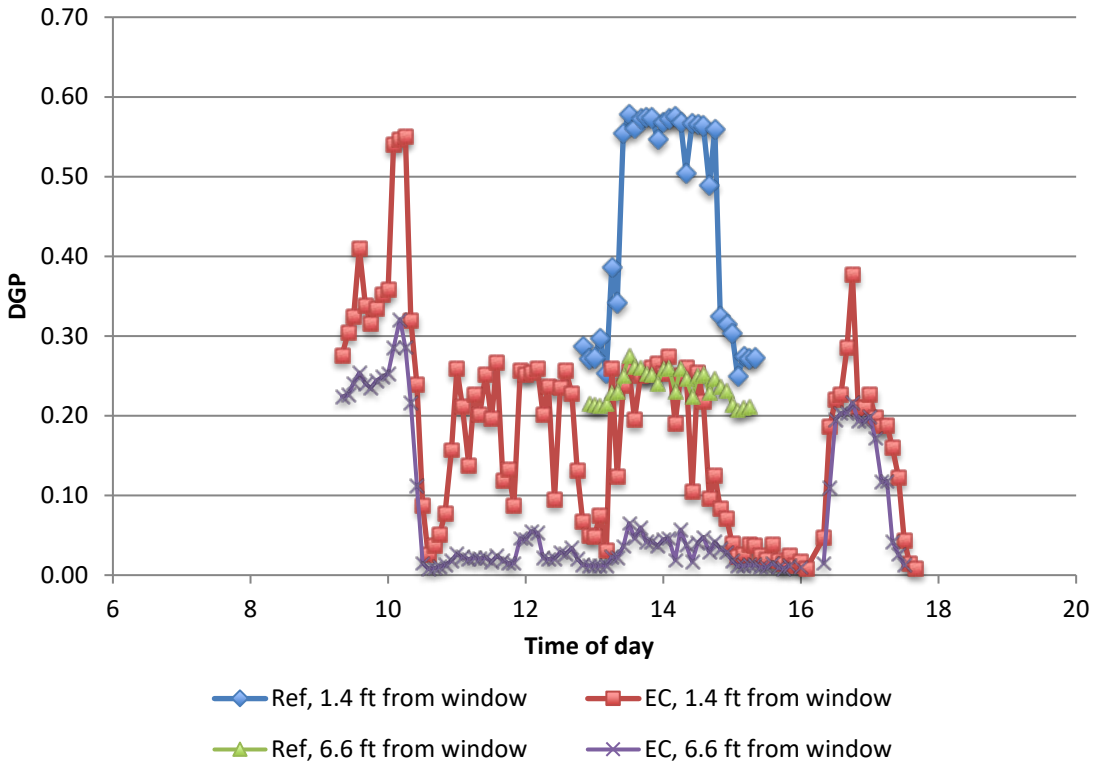


Figure V.C.3 (left) and V.C.4 (right). Daylight glare probability (DGP) for a view facing the window at seated height, 1.4 ft. from the south-facing EC or reference window. Data are given for the morning of July 25 (left) and the afternoon of July 24 (right). Results are shown for both east and west wing locations.

<u>Equinox, partly cloudy conditions</u> (October 8, 2015):

- A partial day of measurements were taken on an overcast then partly cloudy day during the equinox period. The EC windows were found to have been switching to Tint 4 instead of Tint 3 in the automatic mode and are, therefore, not indicative of conditions experienced by the occupants. This is, however, a good example of how well the EC window can control glare when switched to its darkest tint level between 11:00 AM and 5:00 PM, compared to the existing windows.
- For the unshaded reference case, discomfort glare exceeded intolerable levels for about two hours during the early afternoon for the view point 1.4 ft. from the window looking at the window. Discomfort glare was below imperceptible levels for the viewpoint further from the window (6.6 ft.), **Figure** V.C.5.
- For the EC test case, discomfort glare was below "imperceptible" levels (DGP = 0.35) both near (1.4 ft.) and further from the EC window (6.6 ft.) with the exception of a few peaks that occurred in the morning and afternoon for the view point close to the window.
- For one of these peaks in the case of the EC window, discomfort glare rose to "intolerable" levels when the cloud cover thinned and the sun backlit this cloud cover, producing a large-area glare source. Notice the progression from "imperceptible" glare (DGP = 0.35) at 10:00 AM to "intolerable" glare levels (DGP = 0.55) at 10:15 AM in **Figure** V.C.6.
- For the other peak, we see that conditions were partly cloudy in **Figure** V.C.6. Direct sun came out from behind the clouds at 4:45 PM and produced a DGP of 0.38, just above "imperceptible" glare levels.



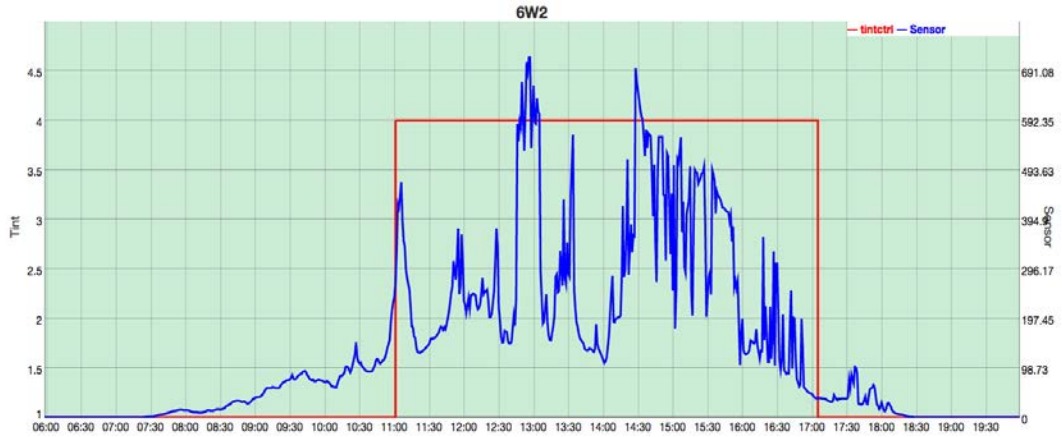


Figure V.C.5. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 1.4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for October 8, 2015.

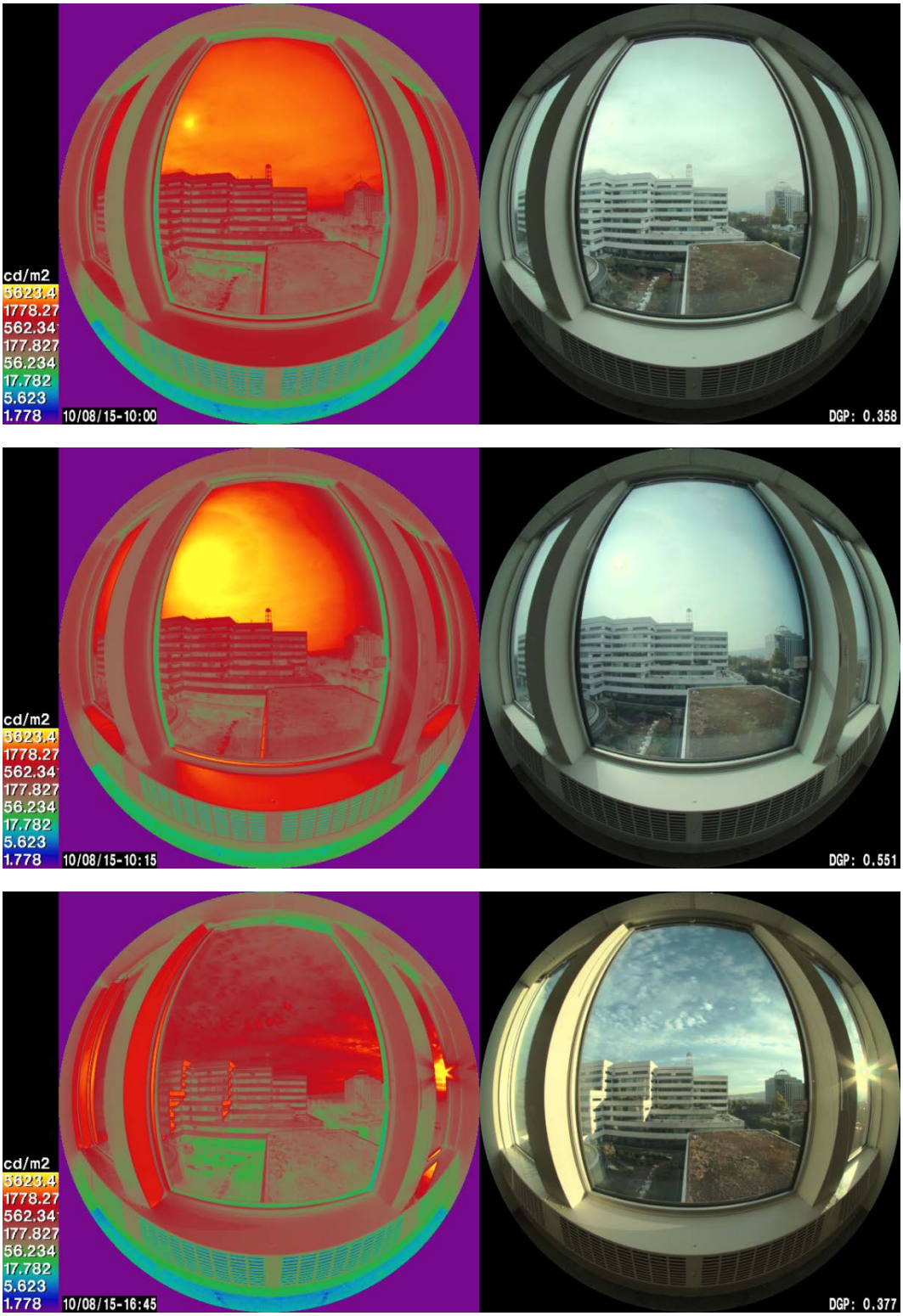


Figure V.C.6. HDR image (left) and photographic (right) views from 1.4 ft. from the south-facing EC window, October 8, 2015, at 10:00 AM, Tint 1 (top), 10:15 AM, Tint 1 (middle), and 4:45 PM Tint 4 (bottom).

Winter solstice, partly cloudy conditions (December 21, 2015)

- At the time of the site visit, the EC windows were found to have been switching to Tint 4 instead of the Tint 3 limit in the automatic mode. The vendor changed the settings back to the Tint 3 limit on December 21 around noon.
- For the unshaded reference case, discomfort glare frequently exceeded "disturbing" levels (DGP = 0.45) at 1.4 ft. from the window, but less so (three brief spikes) at a depth of 6.6 ft. from the window when facing the window (**Figure** V.C.7).
- For the unshaded EC window case, discomfort glare frequently exceeded "imperceptible" levels (DGP = 0.35) and occasionally exceeded "disturbing" and "intolerable" levels throughout the day at depths of 1.5 and 6.6 ft. from the window. The overall magnitude of glare was less than the reference window (**Figure** V.C.7).

Like the equinox condition and for both the reference and EC window cases, the partly cloudy conditions produced occasional periods when the sun orb was within the field of view. During the winter solstice, the sun angle was low on the horizon, so discomfort glare occurred at view points both near and deeper into the space. An example of intolerable glare is given in **Figure** V.C.8, where the orb of the sun is just visible behind the thin layer of clouds on the horizon.

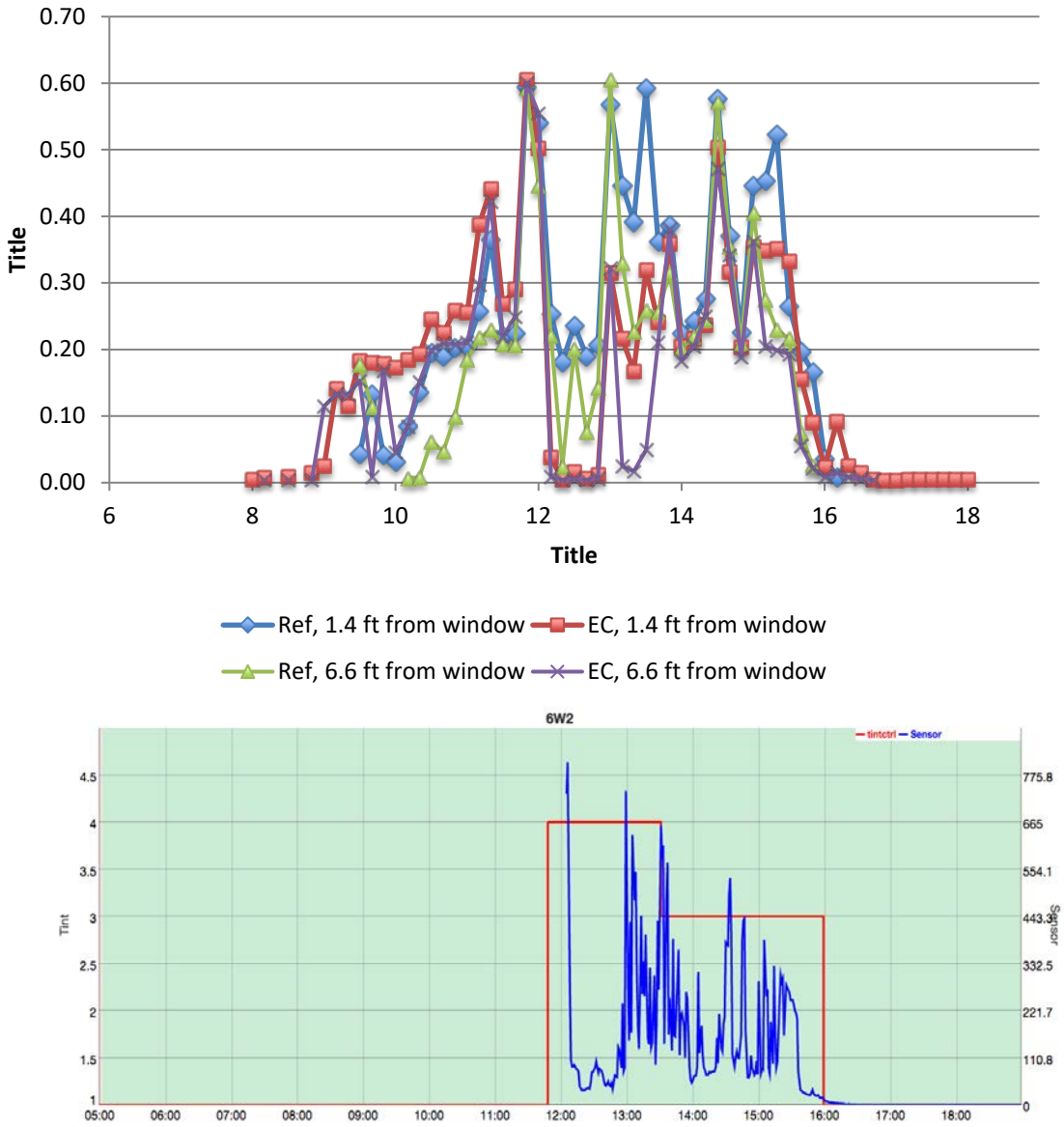


Figure V.C.7. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 1.4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for December 21, 2015.

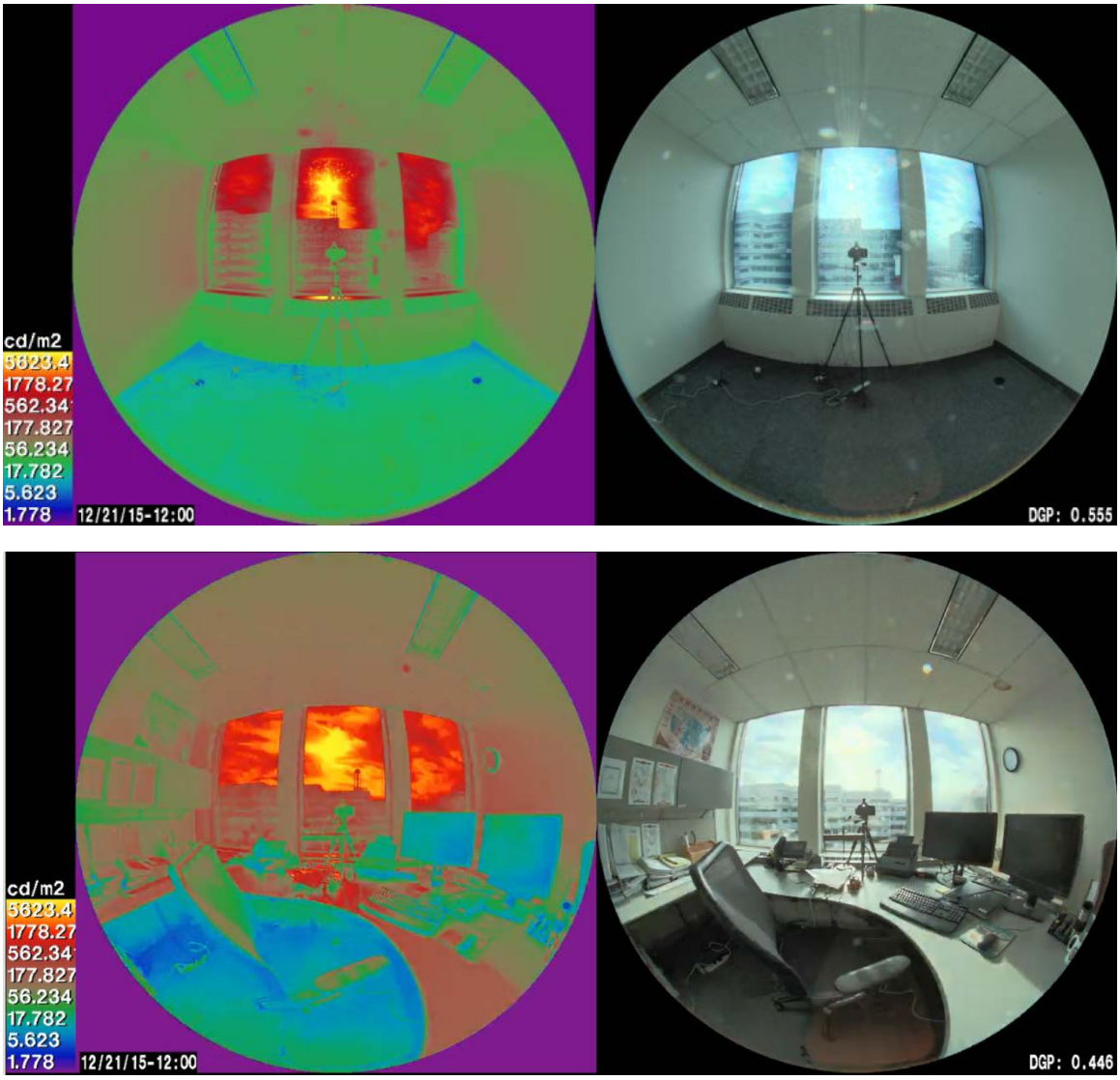


Figure V.C.8. HDR image (left) and photographic (right) views of the EC window, Tint 4 (upper row) and reference windows (lower row) from 6.6 ft. from the south-facing window, December 21, 2015, at noon.

3. DISCOMFORT GLARE – PHASE II

In Phase II, HDR measurements were taken simultaneously in the reference and test areas on the fifth floor with the venetian blinds fully raised. Time-lapsed measurements were taken at four ft. from the window, facing the window.

- For the winter measurements, the EC control was configured normally, as would be experienced by the occupants (automatic mode limited to Tints 1–3). Measurements were taken in unoccupied workstations in the EC and reference areas during a weekday with the blinds fully raised. The space was sparsely occupied due to the upcoming winter holidays, so the windows in adjacent zones were not manually switched by the occupants and the blinds remained fully raised.[9]

[9] The electric lights may or may not have been on in the area where the measurements were being taken, depending on whether the individual fixture had been triggered by passing occupants. Given the close proximity

- For the equinox and summer solstice measurements, measurements were taken in unoccupied workstations on one weekend day with the normal EC settings (no manual override). The venetian blinds were fully raised in both the EC and reference areas. Measurements were taken on a second weekend day with the glare submode switched to Tint 4 instead of Tint 3.

Winter solstice, overcast day (December 22, 2015):

- For the unshaded reference and EC window case, DGP values were below the 0.35 threshold for imperceptible glare over the day with the exception of one datapoint at around 1:30 PM (**Figure** V.C.9). There was extensive cloud cover observed on the measurement day. Images taken at noon are shown in **Figure** V.C.10.

to the window, this is expected to affect adaptation levels during early morning and late afternoon hours and have a minor effect on the analysis.

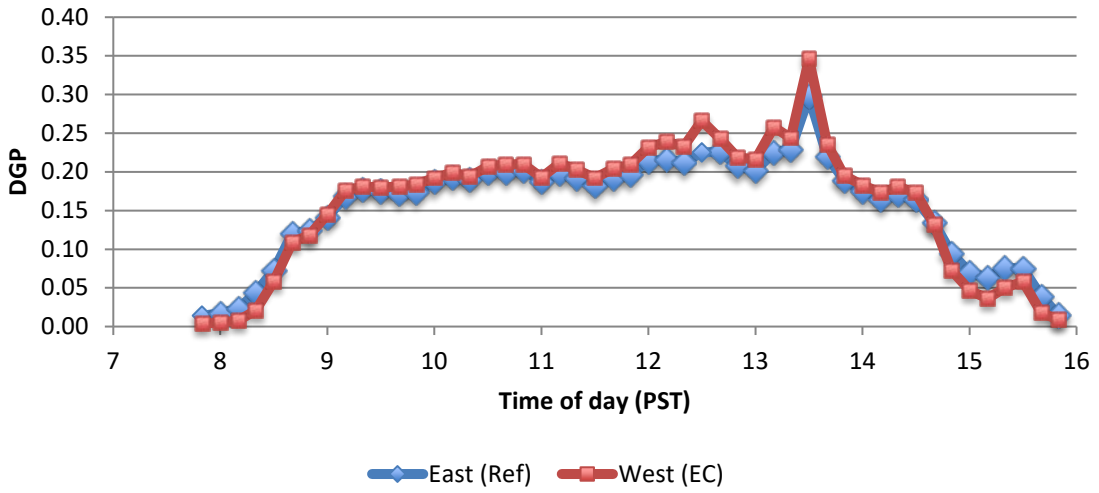


Figure V.C.9. Glare submode, Tint 3 max. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for December 22, 2015. Note: glare mode was not triggered for this day.

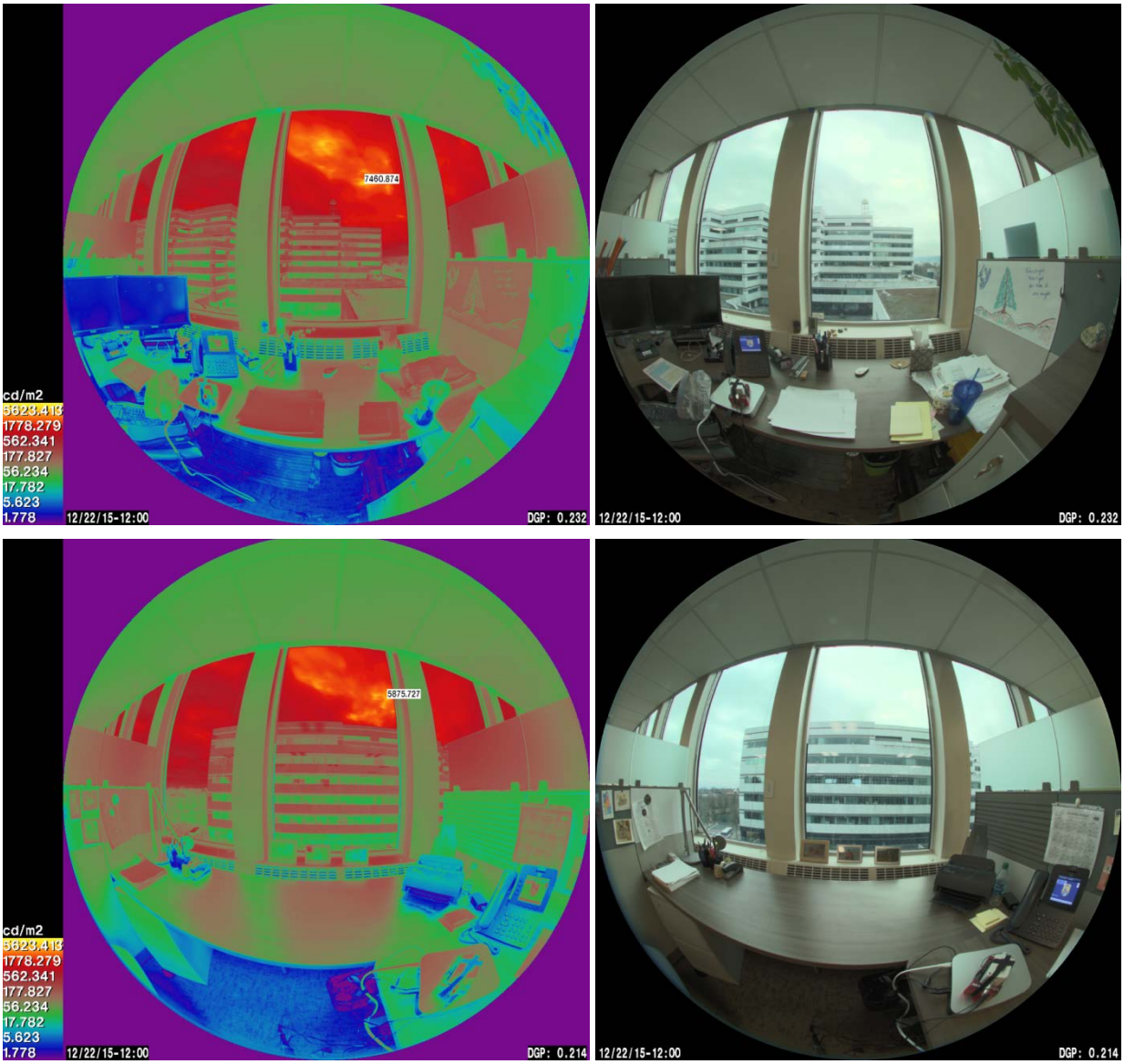
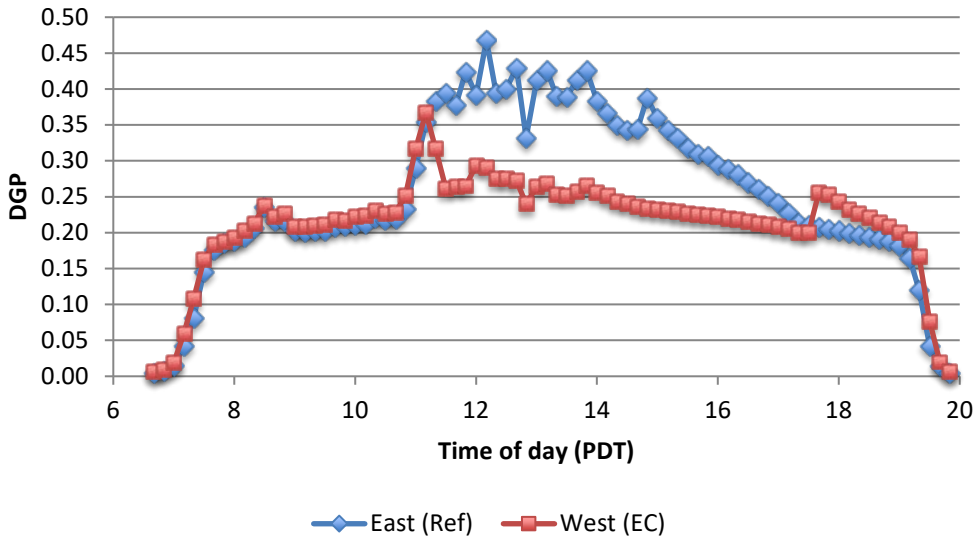


Figure V.C.10. Glare submode, Tint 3 max. HDR image (left) and photographic (right) views of the EC window at Tint 1 (upper row) and reference windows (lower row) from 4 ft. from the south-facing window, December 22, 2015, at noon.

Equinox, partly cloudy conditions, maximum tint set to Tint 3 (April 9, 2016):

- Sky conditions were overcast until about 10:30 AM, then partly cloudy until 3 PM, then clear for the rest of the day.
- For the unshaded reference case, glare was significantly greater than imperceptible levels (DGP = 0.35) from around 11:00 AM to 1:30 PM, reaching intolerable levels (DGP = 0.47) around 12:10 PM (**Figure** V.C.11). **Figure** V.C.12 shows images taken at noon.
- For the unshaded EC case, glare was below imperceptible levels throughout the day, except for a minor peak of 0.37 at approximately 11:10 AM (**Figure** V.C.11).



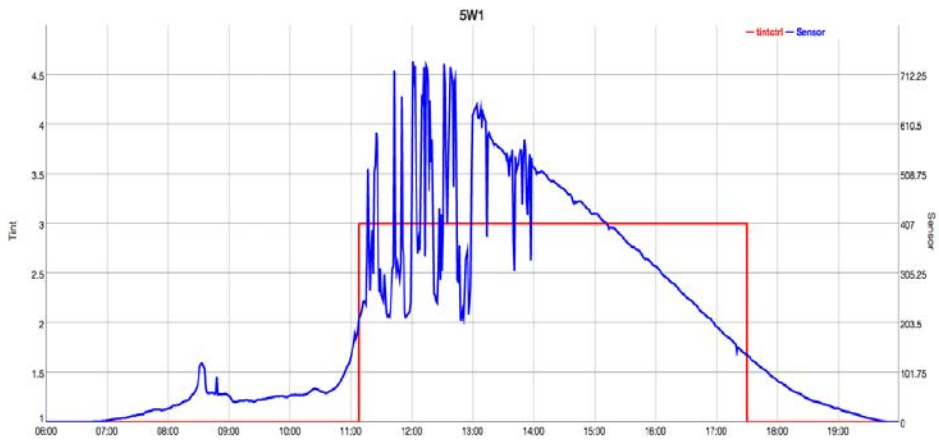


Figure V.C.11. Glare submode, Tint 3 max. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for April 9, 2016.

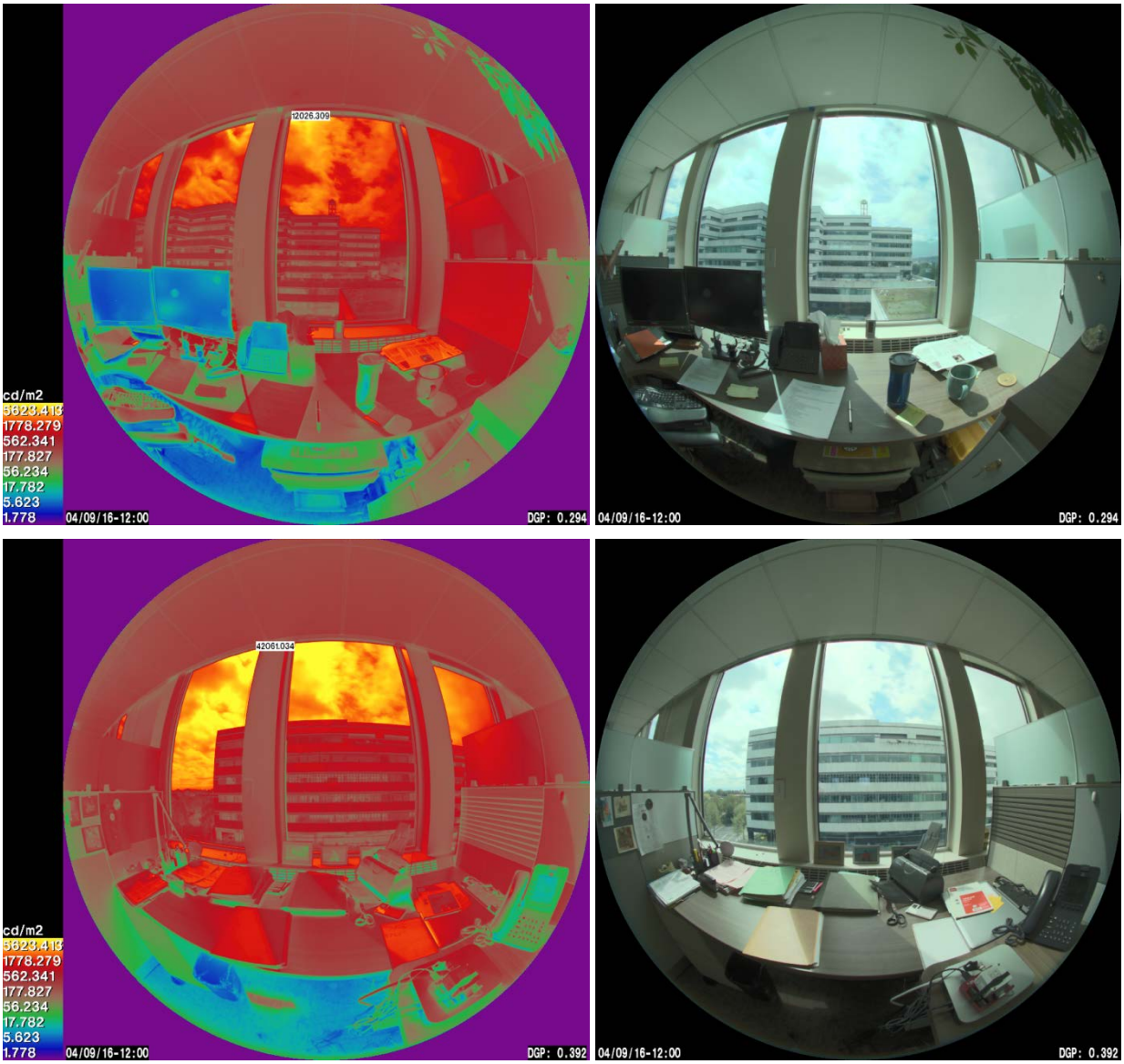


Figure V.C.12. Glare submode, Tint 3 max. HDR image (left) and photographic (right) views of the EC window, Tint 3 (upper row) and reference windows (lower row) from 4 ft. from the south-facing window, April 9, 2016, at noon.

Equinox, partly cloudy conditions, maximum tint set to Tint 4 (April 10, 2016):

- Sky conditions were overcast until approximately 3 PM, then partly cloudy for the rest of the day.
- For both cases, glare was below imperceptible levels throughout the day (**Figure** V.C.13). DGP values dropped significantly when the EC windows were switched to the alternate glare mode (Tint 4).

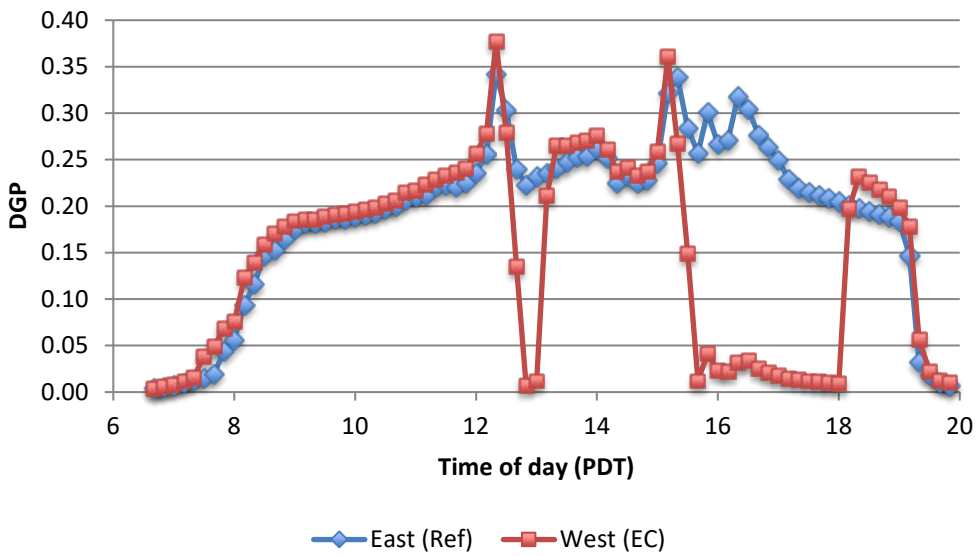


Figure V.C.13. Glare submode, Tint 4 max. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for April 10, 2016.

Summer solstice, partly cloudy conditions, maximum tint set to Tint 3 (June 18, 2016):

- On this partly cloudy day for the unshaded reference case, discomfort glare exceeded "perceptible" levels (DGP = 0.40) for one 10-min. data point over the course of the day (**Figures** V.C.14–15). For the remainder of the day, glare levels were below "imperceptible" levels (DGP<0.35).
- For the unshaded EC test case, discomfort glare was below "imperceptible" levels throughout the day.

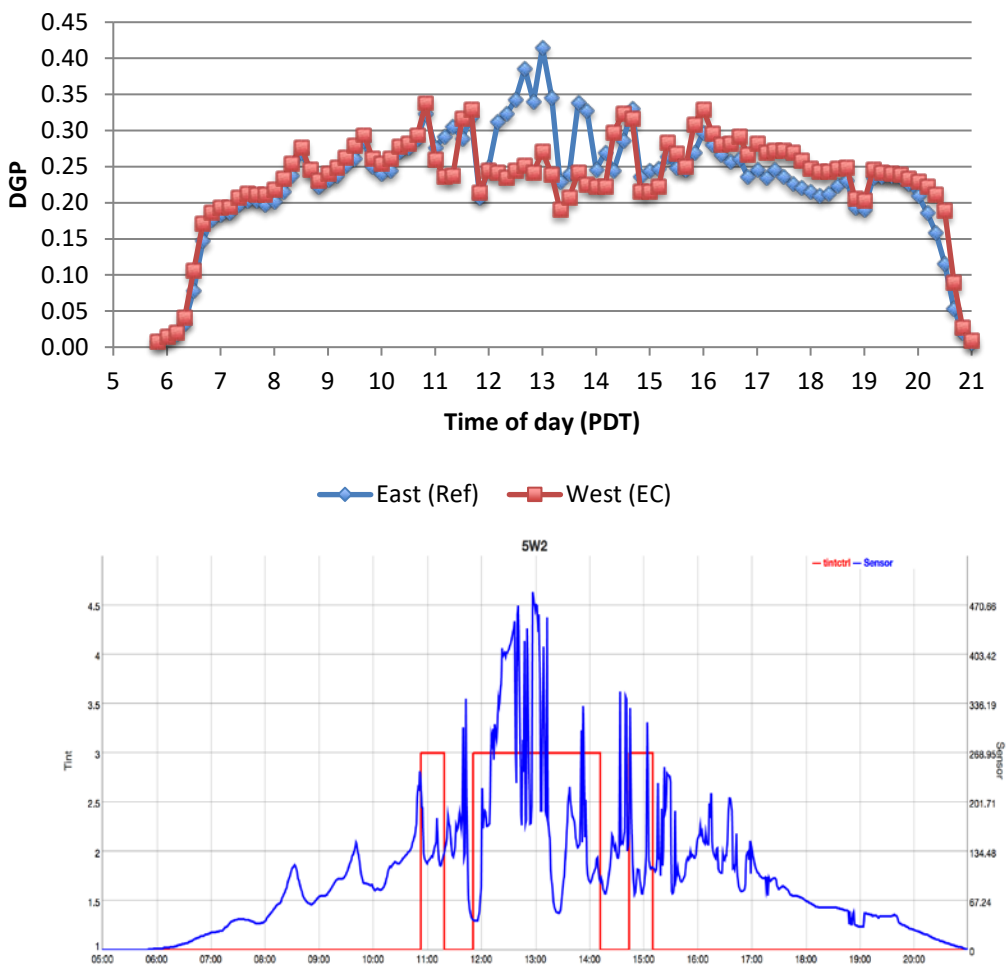


Figure V.C.14. Glare submode, Tint 3 max. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for June 18, 2016.

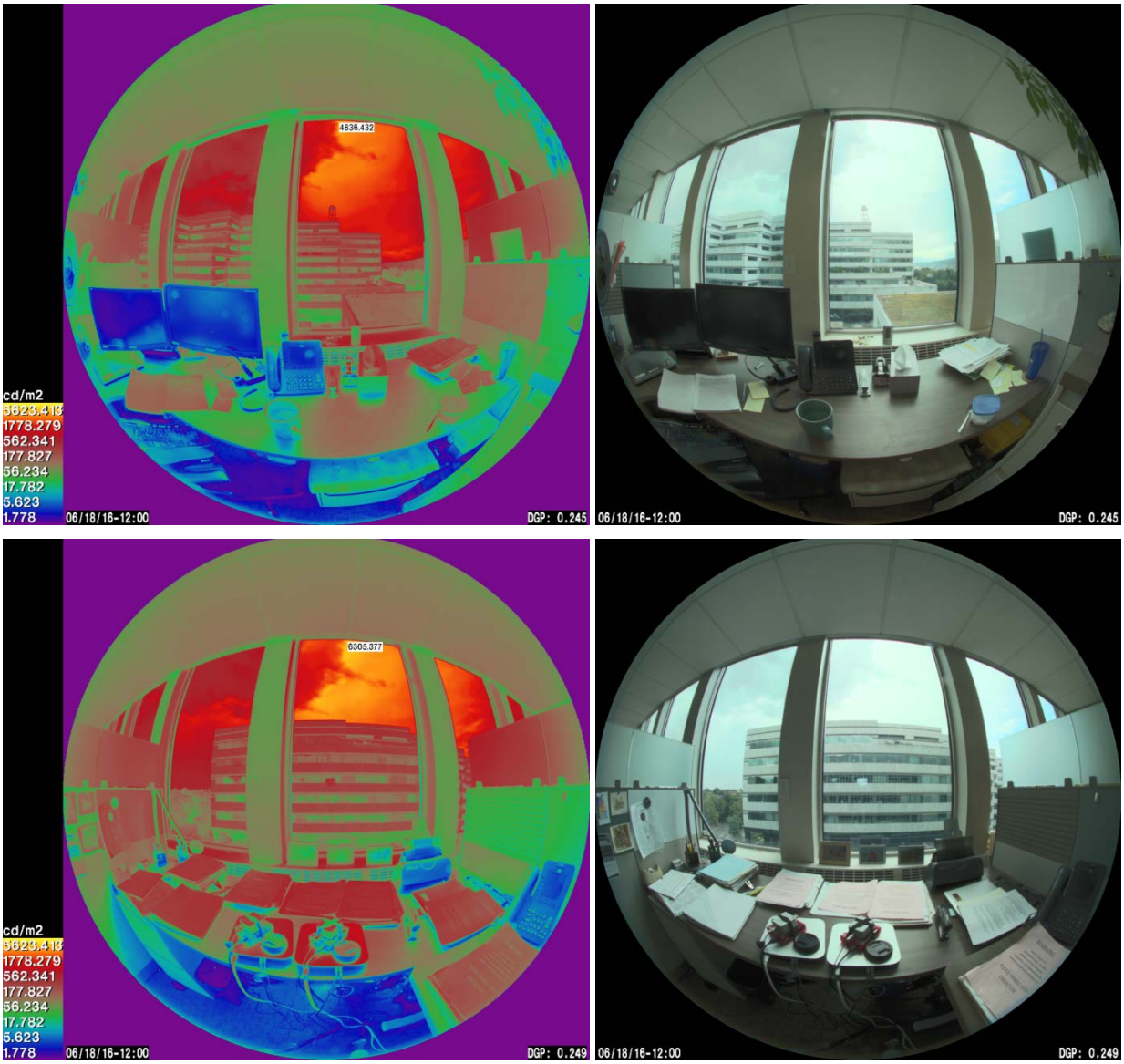
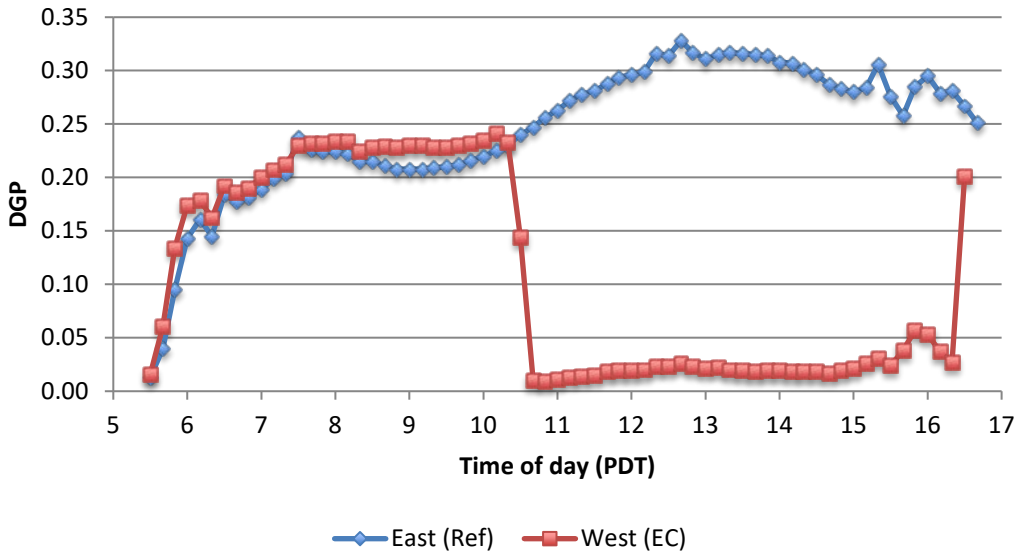


Figure V.C.15. Glare submode, Tint 3 max. HDR image (left) and photographic (right) views of the EC window at Tint 3 (upper row) and reference windows (lower row) from 4 ft. from the south-facing window, June 18, 2016, at noon.

Summer solstice, partly cloudy conditions, maximum tint set to Tint 4 (June 19, 2016):

- On this partly to overcast day and for both the unshaded EC test and reference case, discomfort glare was below "imperceptible" levels throughout the day (**Figures** V.C.16–17). DGP values dropped significantly when the EC windows were switched to the alternate glare mode (Tint 4).



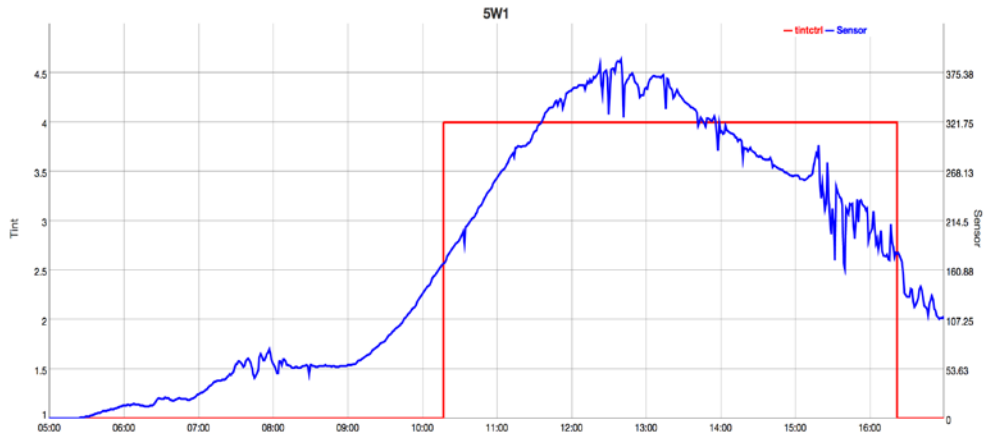


Figure V.C.16. Glare submode, Tint 4 max. Above: Daylight glare probability (DGP) for a view facing the window at seated height, 4 ft. from the south-facing EC or reference window. Below: EC tint level (red line, left y-axis) and outdoor vertical illuminance sensor (blue line, right y-axis) versus time of day. Data are given for June 19, 2016.

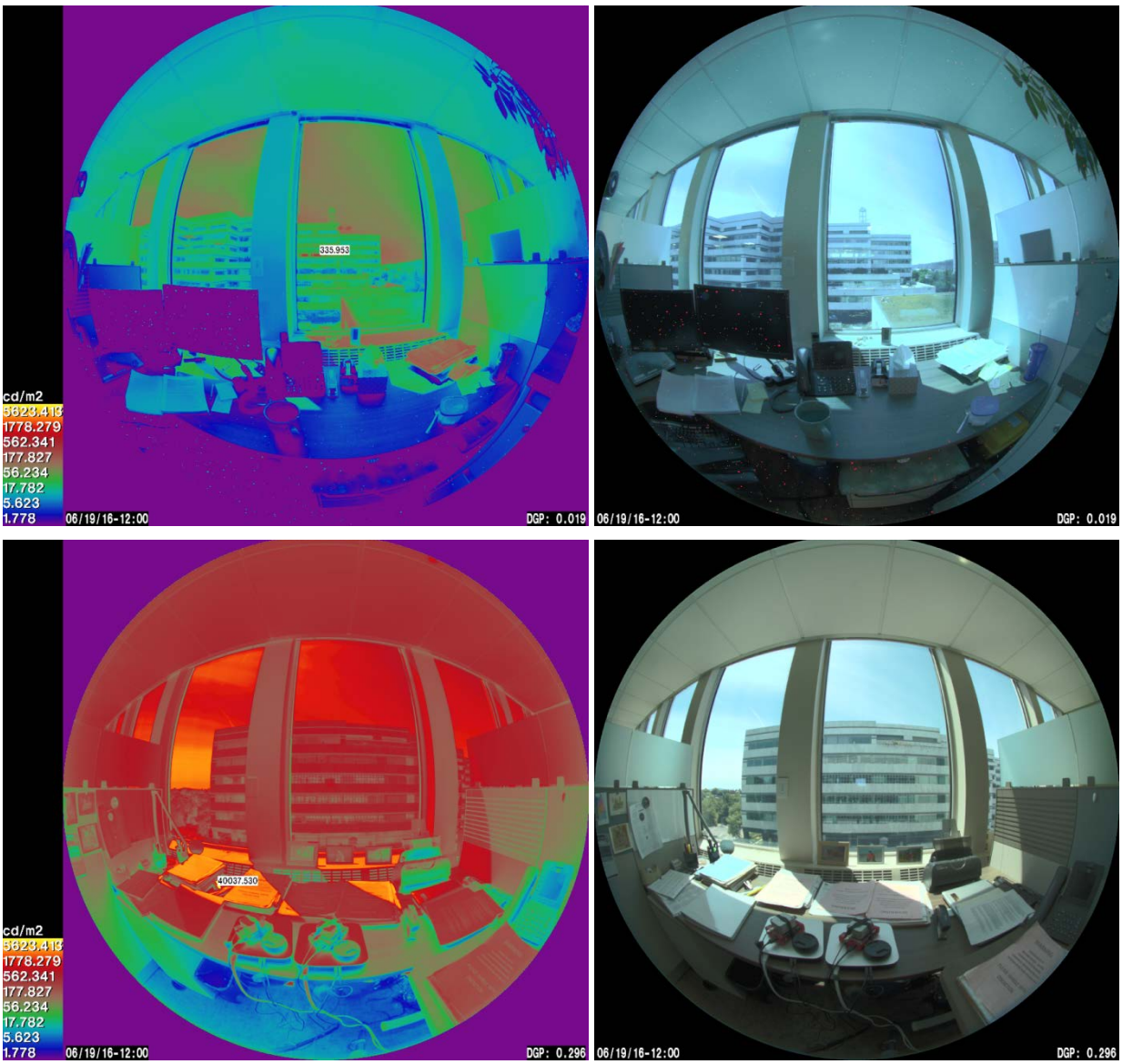


Figure V.C.17. Glare submode, Tint 4 max. HDR image (left) and photographic (right) views of the EC window at Tint 4 (upper row) and reference windows (lower row) from 4 ft. from the south-facing window, June 19, 2016, at noon.

These results show the EC windows generally being able to control glare even when limited to Tint 3. It should be noted, however, that the cloudy weather patterns that are predominant in the Portland area prevented the assessment of glare under the conditions expected to be the most severe: low angle direct sun under clear sky conditions.

For the special tests conducted in April and June, the switch to glare mode (Tint 4) was warranted in April (when DGP occasionally exceeded 0.35), but not in June (based on DGP levels that were already below "imperceptible" in June). This control resulted in reduced indoor daylight illuminance levels (**Figure** V.C.18), which may explain the occupants' preference for the lighter Tint 3 level when in glare mode. During weekdays following the special weekend test in April, when the special mode of control was mistakenly not returned to the normal control mode, the windows were manually overridden with a frequency that exceeded the entire six-month period: an average 100 minutes per day per zone (see Section V.C.3). There also were five service requests to disable the glare / Tint 4 control mode (see Section V.G.4).

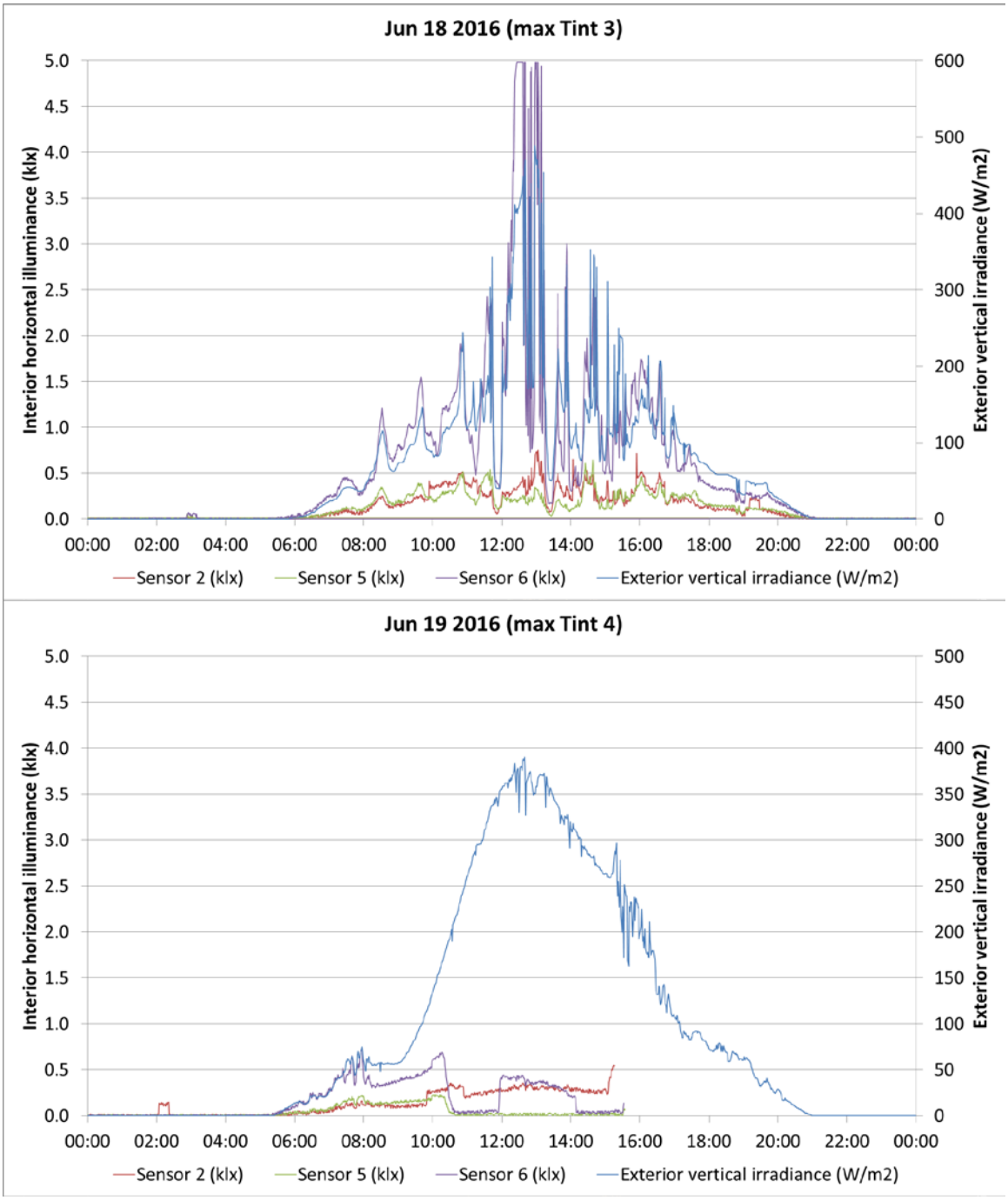


Figure V.C. 18. Total workplane illuminance (klx) and outdoor vertical solar irradiance (W/m^2) in the reference area (sensor 2) and EC area (sensors 5–6) near the window. The EC window was switched to Tint 3 at 10:50–11:19 AM, 11:51 AM–2:02 PM and 2:44–3:10 PM on June 18, 2016. The EC window was switched to Tint 4 from 10:45 AM–4:30 PM on June 19, 2016.

4. WORKPLANE ILLUMINANCE – PHASE II

Figures V.C.19–20 show the percentage of weekdays in each month when the total workplane illuminance at eight locations in the open office areas was within three specified ranges of illuminance.

In the open plan workstations about 20–26 ft. from the windows (sensors 3 and 4 on the reference area and sensors 7 and 8 on the EC area), the plots are quite similar between the two areas. The total workplane illuminance was within the acceptable range of 100–2000 lux for 89% (sensor 8, May) or more of the time. In December, the percentages are lower, most likely due to lower occupancy during the holiday period.

In the open plan workstations next to the window, a few differences between the EC and reference areas were apparent:

- In the EC area, data for sensor 6 showed a significant percentage of time when light levels were greater than 2000 lux (between 14% in June and 26% in April). This was due to the sensor's position 2 ft. away from the window (no free and unobstructed surface was available to position this sensor in the 4–8 ft. range where the other sensors were installed). For occupants seated very close to the window, total light levels may be considered to be too bright.
- In the EC area, sensor 5 showed increased percentage of time spent under 100 lx starting in April. This was due, in part, to the luminaire over this workstation having been turned off in April due to a request by the occupant (unrelated to this study).

From these data we can conclude that the general lighting environment was maintained within an acceptable range indicative of a comfortably lit office environment, both adjacent and further from the window.

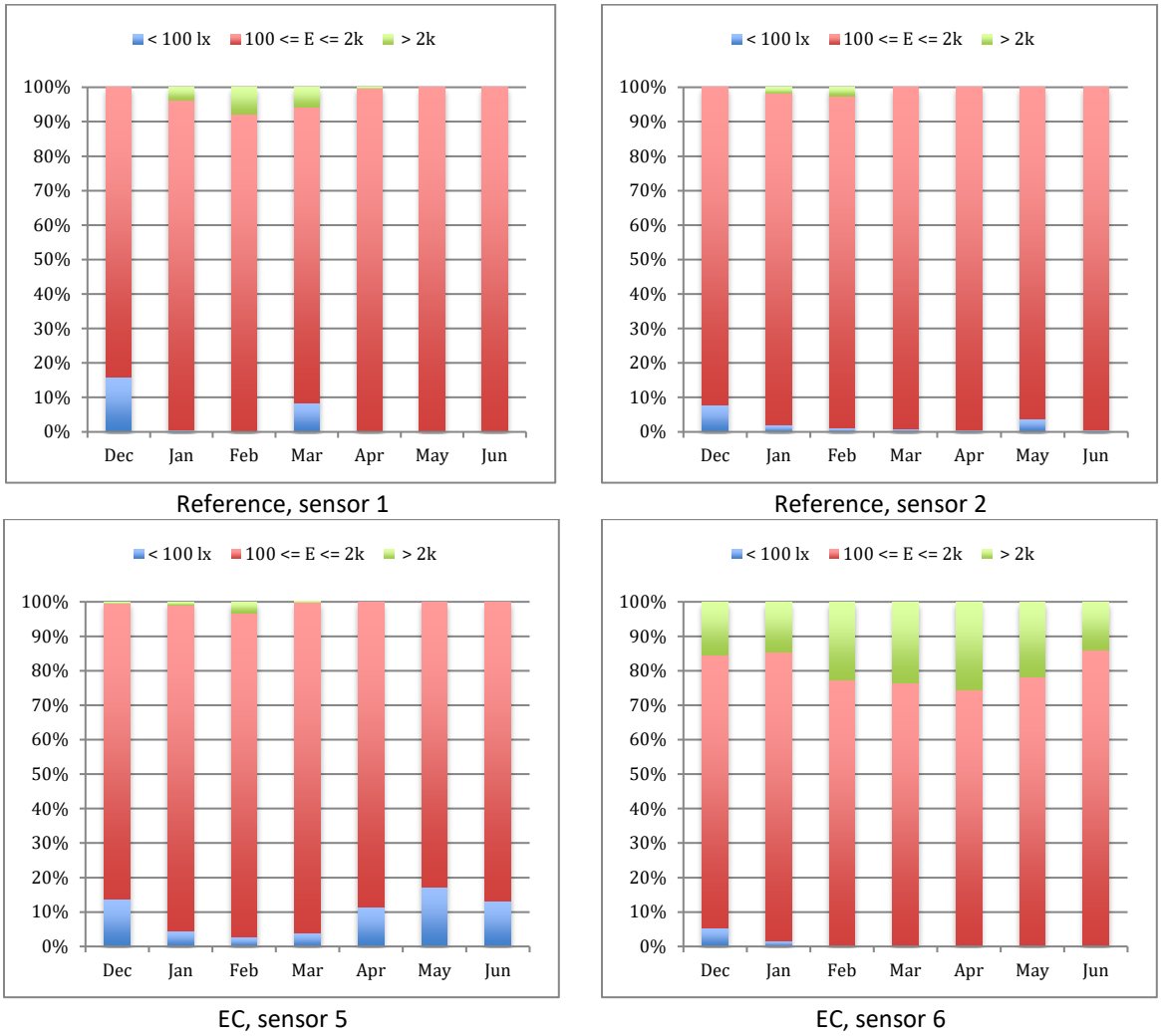


Figure V.C.19. Adjacent to the window (2–8 ft). Percentage of the period when the workplane illuminance was within the three binned levels: 0–100 lux, 100–2000 lux and greater than 2000 lux. Weekdays, 9:00 AM–5:00 PM.

Figure V.C.20. Further from the window (20–26 ft). Percentage of the period when the workplane illuminance was within the three binned levels: 0–100 lux, 100–2000 lux and greater than 2000 lux. Weekdays, 9:00 AM–5:00 PM.

D. THERMAL COMFORT

Sensors were installed in Phase I to evaluate thermal comfort. For Phase II, only subjective surveys were used to evaluate thermal comfort.

1. THERMAL COMFORT ON A SUNNY SUMMER DAY, FANGER MODEL

During the summer, thermal discomfort from windows is influenced by (a) solar radiation absorbed by the body and (b) by the long-wave radiative heat exchange between the occupant's body and the window, given differences in surface temperature. With conventional windows, occupants will usually lower the shades or adjust their position to avoid thermal discomfort from the window. In the case of EC windows, thermal discomfort could be mitigated by adjusting the tint level of the window without the use of shades.

An analysis was made of thermal discomfort near the south façade in occupied offices at a seated height of 3 ft. above the floor and a distance of 4–6 inches from the window. Data were analyzed for a clear sunny, hot summer day (August 13, 2015); outdoor temperatures were the hottest of the season. The mean radiant temperature sensors were located inboard of the EC glazing and venetian

blind, if lowered (the height and slat angle of the blinds were unknown). This measurement location represents a worst case scenario where the occupant was seated at the window wall, could be directly irradiated by sunlight (if the blinds were raised) and had maximum exposure (i.e., view factor) to the window wall as a source of radiant heat.

The EC windows were operated in the automatic mode defined in Section IV.B.2 (i.e., glare sub-mode was disabled and the switching range was constrained to Tints 1–3). This was the automatic control mode that was experienced by most occupants. Some occupants did choose to override the system manually (Tints 1–4) as discussed in Section V.A.2.

For this day, the south-facing EC windows in the west wing (7W5) were switched to Tint 1 (fully bleached) all day, except for the mid-day period from 10:50 AM to 3:40 PM when the EC window was switched to Tint 2 (Tsol = 0.13, SHGC = 0.28). The blinds were raised in this unoccupied office.

During peak solar conditions around 2 PM, the maximum difference between the mean radiant temperature facing toward and away from the EC window was 4.3°C (7.7°F). The maximum indoor glass and window frame surface temperatures were 36.1°C (97°F) and 32.8°C (91°F), respectively. The difference between the glass surface temperature and ambient air temperature was 12°C (22°F). Data also are given for the eighth floor reference window, where glass temperature and mean radiant temperatures were lower than that of the EC window. The lower temperatures for the reference condition is partly explained by the use of MRT data from the east wing instead of the west (MRT data were not available for the west wing): glass temperatures on the east were 9°C (5°F) lower than on the west. The reference window also could have had the blinds lowered.

Using the Fanger method, the predicted mean vote (PMV) and percentage of people dissatisfied (PPD) results are shown for the reference (eighth floor) and test conditions (sixth and seventh floors) in **Figure**s V.D.1 and V.D.2. The window-side MRT value was used for this calculation.

- Under the reference condition, occupants were determined to be “slightly cool” in the morning, then thermally neutral from noon until 6 PM. Occupant comfort was maintained throughout the day with PPD levels under 20% (as required by the ASHRAE Standard 55-2010; i.e., no more than 20% of people dissatisfied), except for the morning start-up period between 6:30–7:45 AM when the HVAC system turned on and conditions were too cool.
- Under the EC condition, occupants also were “slightly cool” in the morning due to morning start-up and then between 11:30 AM and 8:00 PM, were “slightly warm” to “warm” on both the sixth and seventh floors. PPD levels exceeded the 20% threshold for about two hours in the morning and then six hours in the afternoon. Note that the outdoor air temperature peaked above 31°C (88°F) at around 5 PM.
- EC discomfort levels in the afternoon were due to both incident solar irradiance (the MRT range was 90–93°F on Floor 6 and 93–96°F on Floor 7 from noon until 3:00 PM) and the elevated mean radiant temperature of the window glass (Tg = 97°F). Discomfort could be mitigated by sitting further from the glass or switching the glass to a deeper tint level (Tint 3–4) to reduce transmitted solar radiation levels. Unfortunately, there were no PPD data available at these tint levels.

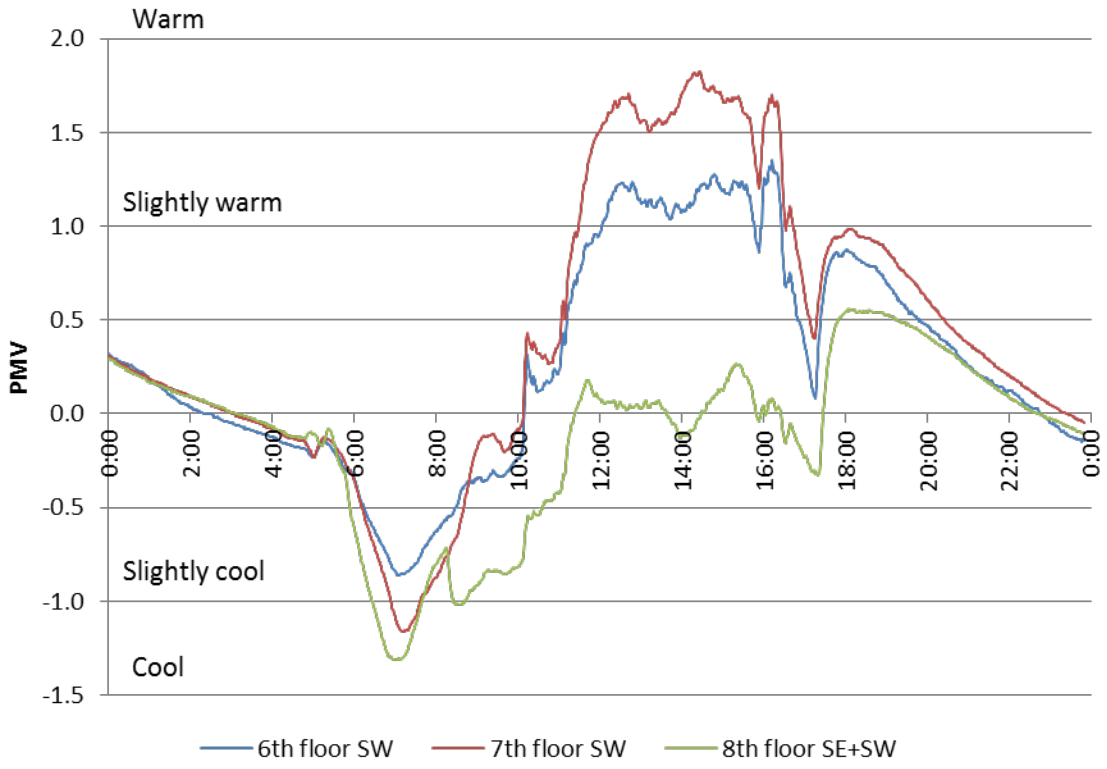


Figure V.D.1. Predicted mean vote (PMV) on a sunny, hot summer day (August 13, 2015). Data given for 3 ft. above the floor, 4.5 ft. from the window. The venetian blinds may have been lowered. Values of -3, -2, -1, 0, 1, 2, 3 mean the space would be considered by occupants to be "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot". Reference case – Floor 8; EC case – Floors 6–7.

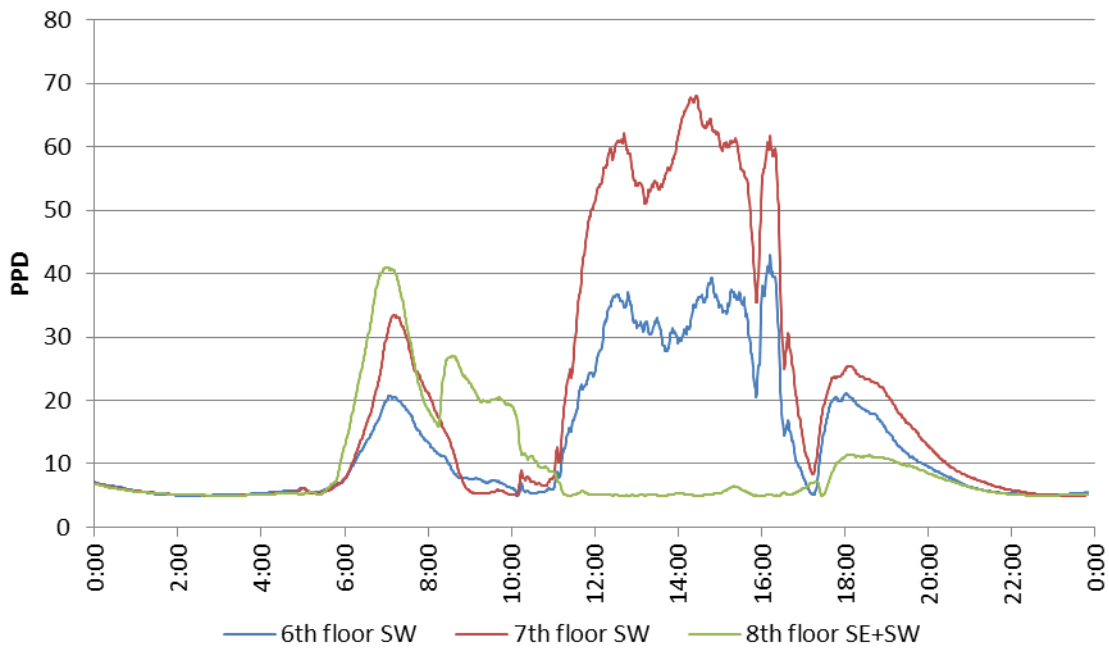


Figure V.D.2. Percentage of people dissatisfied on a sunny, hot summer day (August 13, 2015). Data given for 3 ft. above the floor, 4.5 ft. from the window. The venetian blinds may have been lowered. Reference case – Floor 8; EC case – Floors 6–7.

2. THERMAL COMFORT ON A SUNNY SUMMER DAY, UCB MODEL

The Fanger model was developed using subjective tests in a uniform thermal environment, whereas windows typically create an asymmetric thermal environment. The University of California, Berkeley (UCB) developed a more sophisticated thermal comfort model that is capable of assessing comfort under non-uniform thermal conditions caused by localized sources, such as direct sunlight. This model was used to evaluate both the effect of direct solar irradiance on the body and mean radiant temperature asymmetry due to the window on thermal comfort in a study conducted by Huizenga et al. in 2006 [20].

The UCB study determined the maximum allowable transmitted solar radiation for different types of windows that would maintain the thermal comfort of an occupant located 3 ft. away from a fully glazed façade, as was measured in Portland. Under summer conditions, solar transmittance (Tsol) and the solar heat gain coefficient (SHGC) were identified as the two predominant properties that had an effect on thermal comfort. With the EC at Tint 2, the maximum allowable transmitted solar radiation would be about 253–340 W/m^2, assuming that Tint 2 has roughly an equivalent effect on absorbed solar irradiance as the study's modeled dual- or triple-pane, spectrally selective low-e window with similar SHGC properties as the EC window.

Transmitted solar radiation levels were measured by LBNL sensors at the indoor face of the EC window. The "radiation" sub mode of control was configured to tint the EC windows until transmitted solar radiation levels fell below the 179 W/m^2 limit (see Section IV.B.2), well below the estimated UCB limit of 253-340 W/m^2. Monitored irradiance levels are shown in **Figure** V.D.3 for August 13: the peak irradiance level of 170 W/m^2 occurred at noon. A second peak of 194 W/m^2 occurred at 4 PM. In both cases, irradiance levels were significantly lower than the UCB model's 253–340 W/m^2 threshold range, indicating that thermal comfort was maintained even if the occupant was exposed to direct sunlight from the window. Discrepancies between this and the

previous analysis in Section V.D.1 are likely due to the difference in how the metric was defined. In the previous analysis, thermal discomfort was evaluated at 4–6 inches from the window. In this section, threshold values were determined for a location of 3 ft. from the window, reflecting the fact that the radiative impact of the hot window surface on comfort significantly diminishes as one moves further from the window.

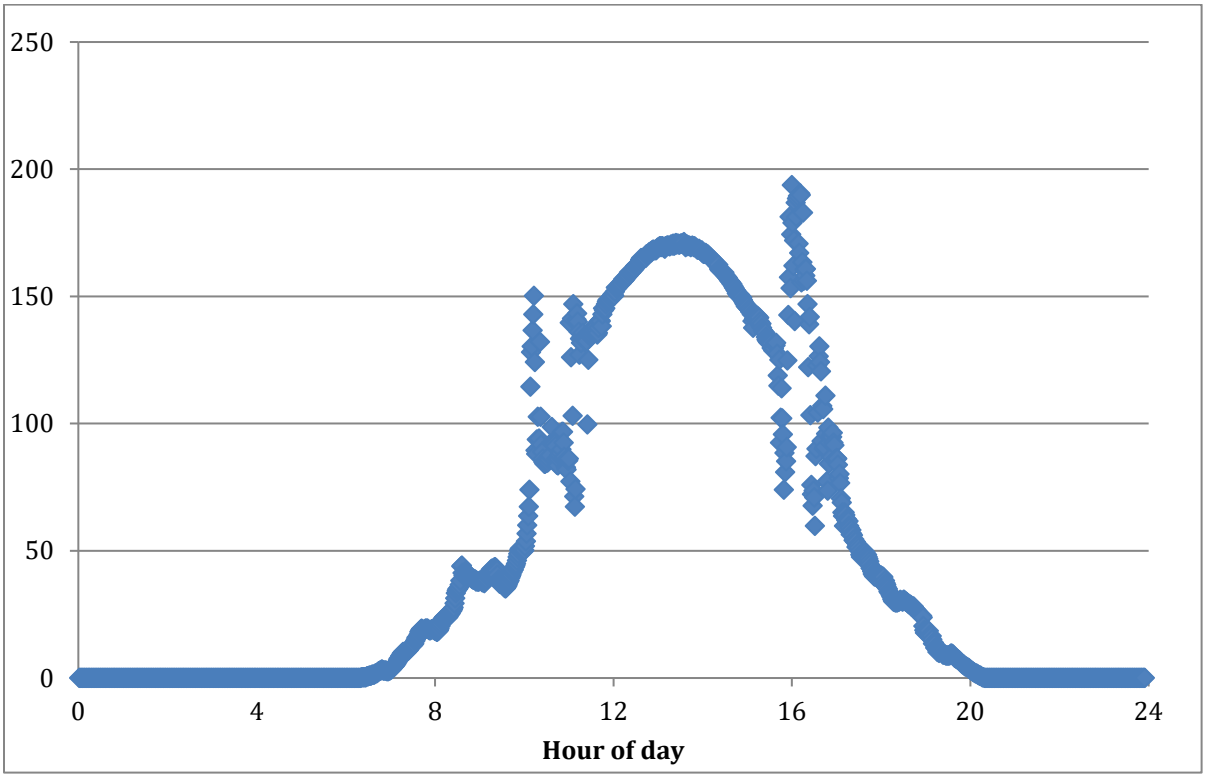


Figure V.D.3. Transmitted solar irradiation levels (W/m^2) through the south-facing EC window (7E13) on a sunny, hot summer day (August 13, 2015). The maximum allowable transmitted solar radiation was about 253-340 W/m^2 for the period when the EC was at Tint 2 (about 10:50 AM to 3:40 PM).

3. THERMAL COMFORT ON A SUNNY SUMMER DAY, ASHRAE 55-2004 GUIDELINES

Radiant temperature asymmetry

The ASHRAE 55 comfort standards limit radiant temperature asymmetry due to warm or cool walls to less than 23°C (41.4°F) and 10°C (18°F), respectively [17]. Note that this method of evaluation does not take into account direct solar irradiation on the body.

In this analysis, **we assumed that the surface temperature of the surrounding interior walls was the same as the ambient** air temperature (Troom). **Figure** V.D.4 shows the difference in surface temperature between the window and room for the same hot summer day, August 13, where each line on the graph represents data from a single, occupied, private office. For all south- and north-facing windows, the difference in temperature was within the warm (daytime) and cool (nighttime) limits for maintaining thermal comfort. During the day, the EC and reference windows produced a peak surface temperature difference of 10.5–14.4°C (19–26°F) on the south façade, while the north reference windows produced a peak temperature difference of 2.2–2.8°C (4–5°F). The temperature difference varied between floor levels and glass type due to differences in the use of the venetian blinds or differences in incident solar radiation on the façade, or both.

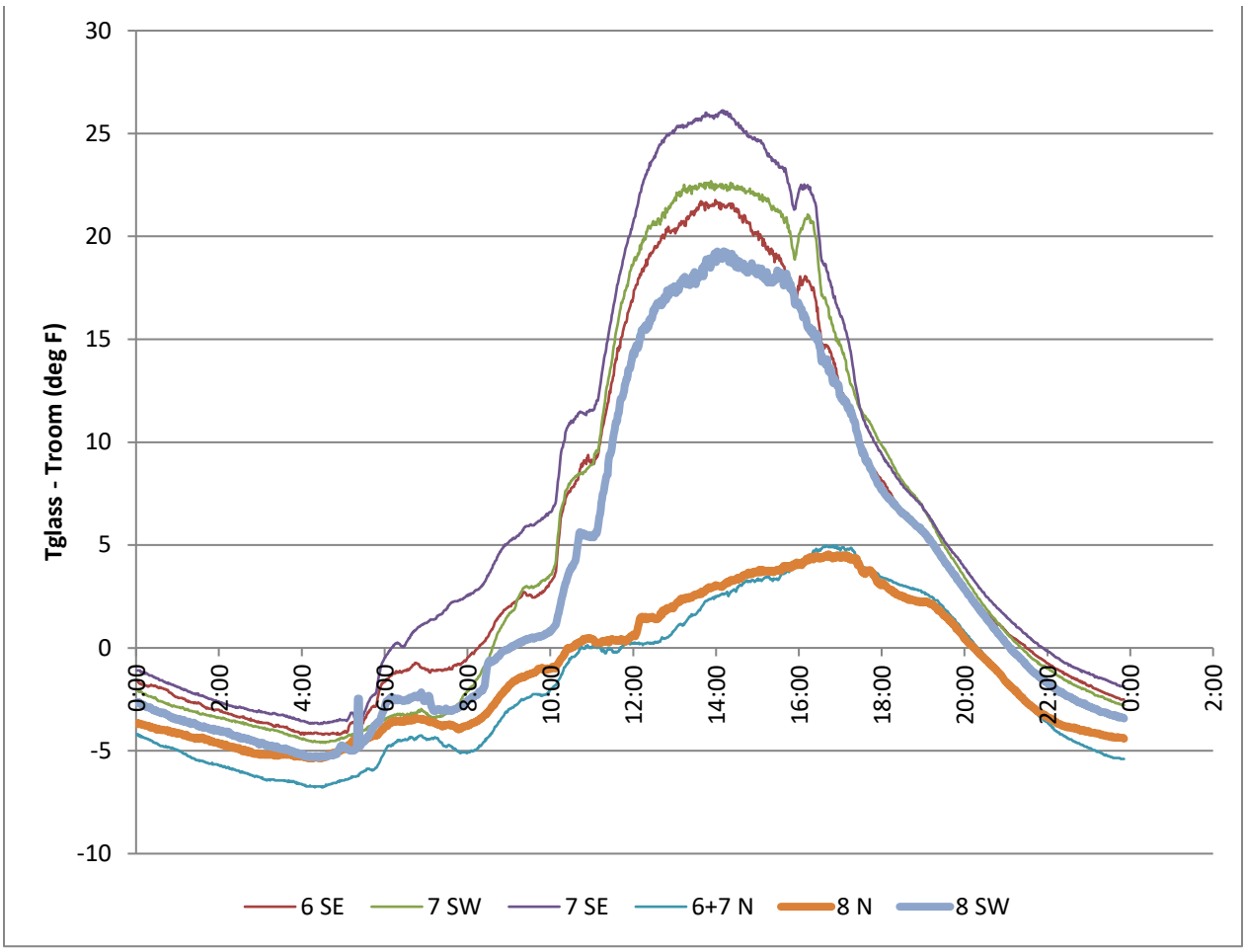
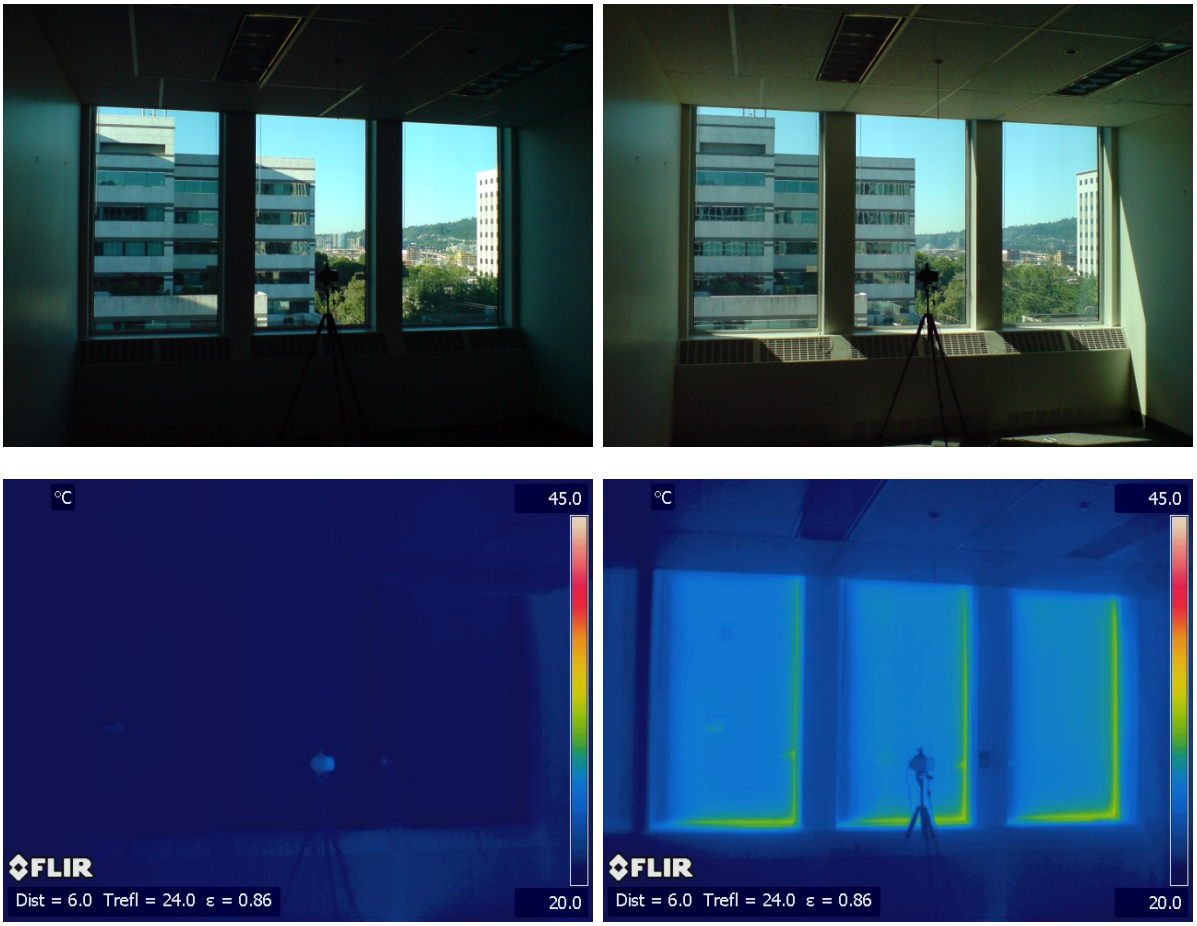


Figure V.D.4. Difference in surface temperature of the window and the ambient air temperature of the room for the north and south facades in the reference (Floor 8) and EC (Floors 6–7) offices, August 13, 2015.

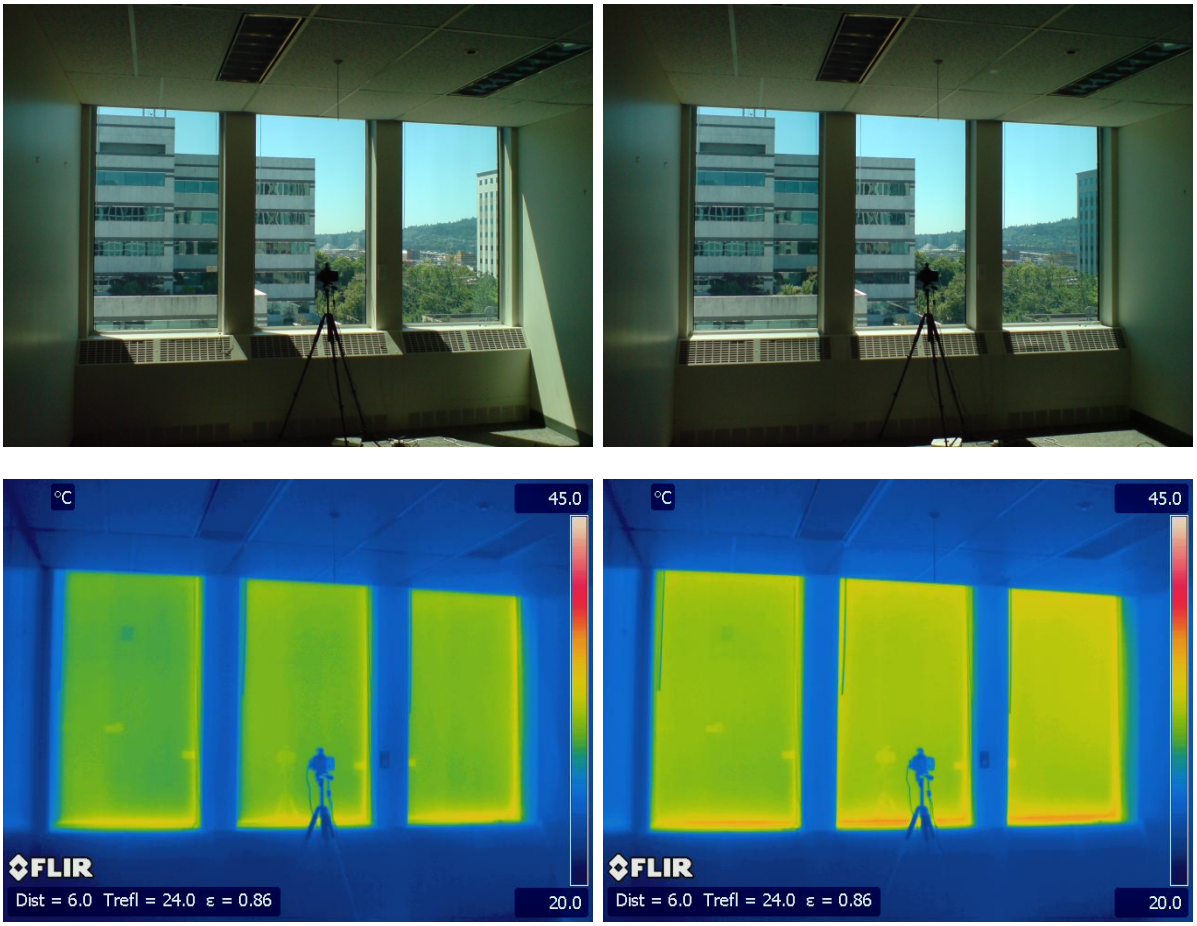
Infrared images

Figures V.D.5 (a) and (b) show the patterns of direct sunlight in the space and a falsecolor map of EC window and room surface temperatures on a sunny day, June 25, in an unoccupied office in the west wing on the sixth floor. Data were acquired using time-lapsed infrared imaging. This was the temperature distribution had the shades been raised for the entire day in the office. The glass surface temperature of about 32.5°C (90.5°F) did not reach the same levels as on August 13, since June 25 was not as hot or sunny, but the surface temperature distribution across the window and surrounding walls would be nearly comparable. Sunlight would extend deeper into the room in August.



8:24 AM 12:04 PM

Figure V.D.5.(a) Photographs (upper) and falsecolor infrared images indicating surface temperature (°C) (lower) of the south-facing office with EC windows (sixth floor, west wing) at 8:24 AM and 12:04 PM on June 25, 2015.



12:54 PM 2:14 PM

Figure V.D.5.(b) Photographs (upper) and falsecolor infrared images indicating surface temperature (°C) (lower) of the south-facing office with EC windows (sixth floor, west wing) at 12:54 PM and 2:14 PM on June 25, 2015.

4. THERMAL COMFORT ON A SUNNY WINTER DAY – FANGER MODEL

PPD and PMV

During a sunny cold winter day (November 25), monitored data indicated that occupants were likely to be "cold" to "slightly cool" in the early morning and late afternoon and "slightly warm" between 10:00 AM to 2:00 PM when transmitted solar irradiance and increased outdoor air temperatures helped to improve thermal comfort (**Figures** V.D.6 and V.D.7). Thermal conditions (PMV) on the sixth floor with EC windows were warmer than the reference windows in the morning, but cooler than the reference windows in the afternoon. During the mid-day period, EC and reference PMV levels were about the same. Unacceptable PPD levels (>20%) occurred from around 3:30 PM in the afternoon into the night. A full day of PMV and PPD data were not available on the seventh floor due to faulty instrumentation.

In winter, Huizenga's study indicated that the predominant factor influencing thermal comfort was surface temperature of the window, which is defined by the U-value of the window. The EC technology, however, in and of itself does not affect window U-value.

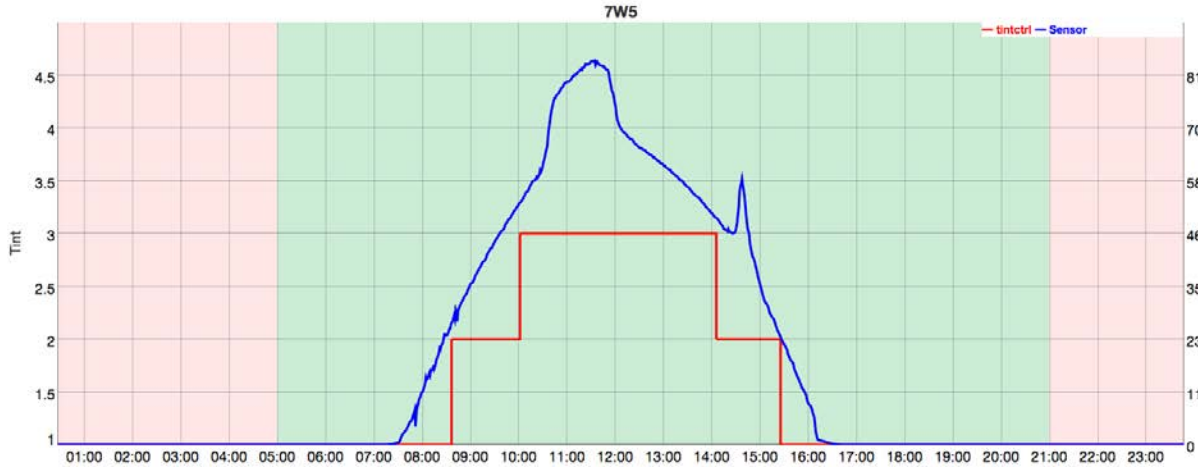


Figure V.D.6. Tint level (red line) and sensor signal (blue curve, W/m^2) for the EC windows on a sunny, cold winter day (November 25, 2015). The light green and red background shading show when the EC windows were in Intelligence and Schedule Modes, respectively.

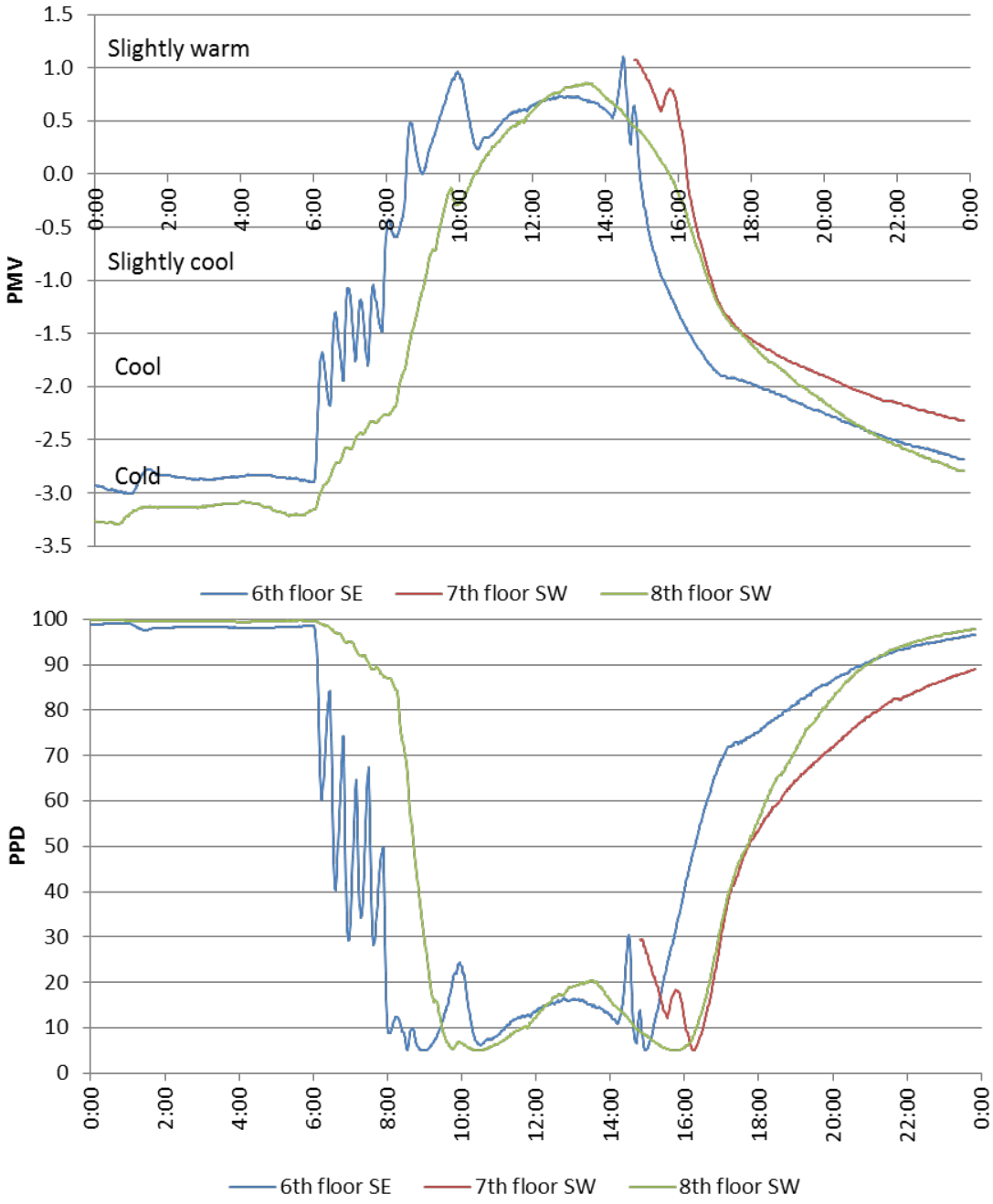


Figure V.D.7. Percentage of people dissatisfied on a sunny, cold winter day (November 25, 2015). Reference case – Floor 8; EC case – Floors 6–7.

Infrared images

Time-lapsed infrared images were taken on a partly cloudy winter day, December 21, 2015. Room and EC window surface temperatures were between 10–15°C at night then rose to 23°C in the early afternoon when irradiated by partial sun (**Figures** V.D.8 and V.D.9). The non-thermally broken window frame produced local sources of cold discomfort: frame temperatures remained low at about 12–16°C. To combat cold envelope surfaces, the convector heating unit below the window cycled on and off throughout the day.

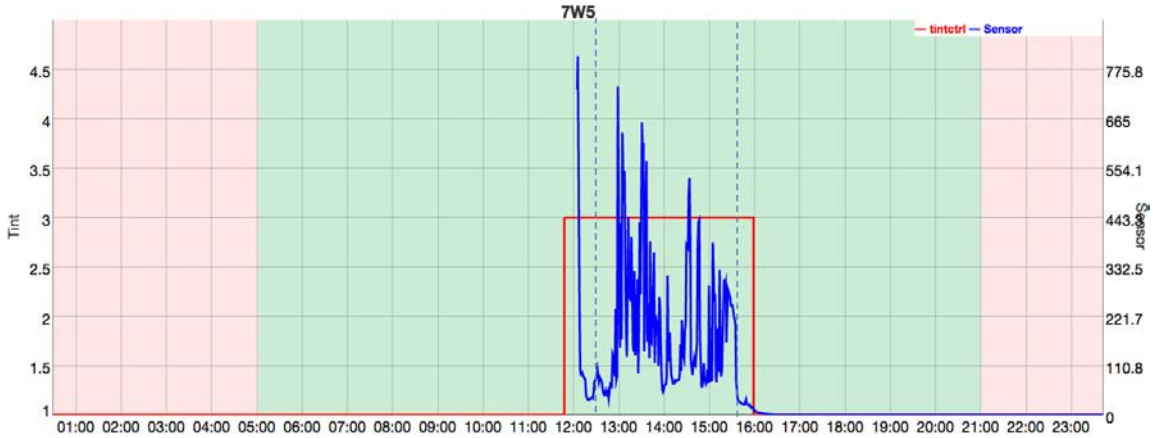
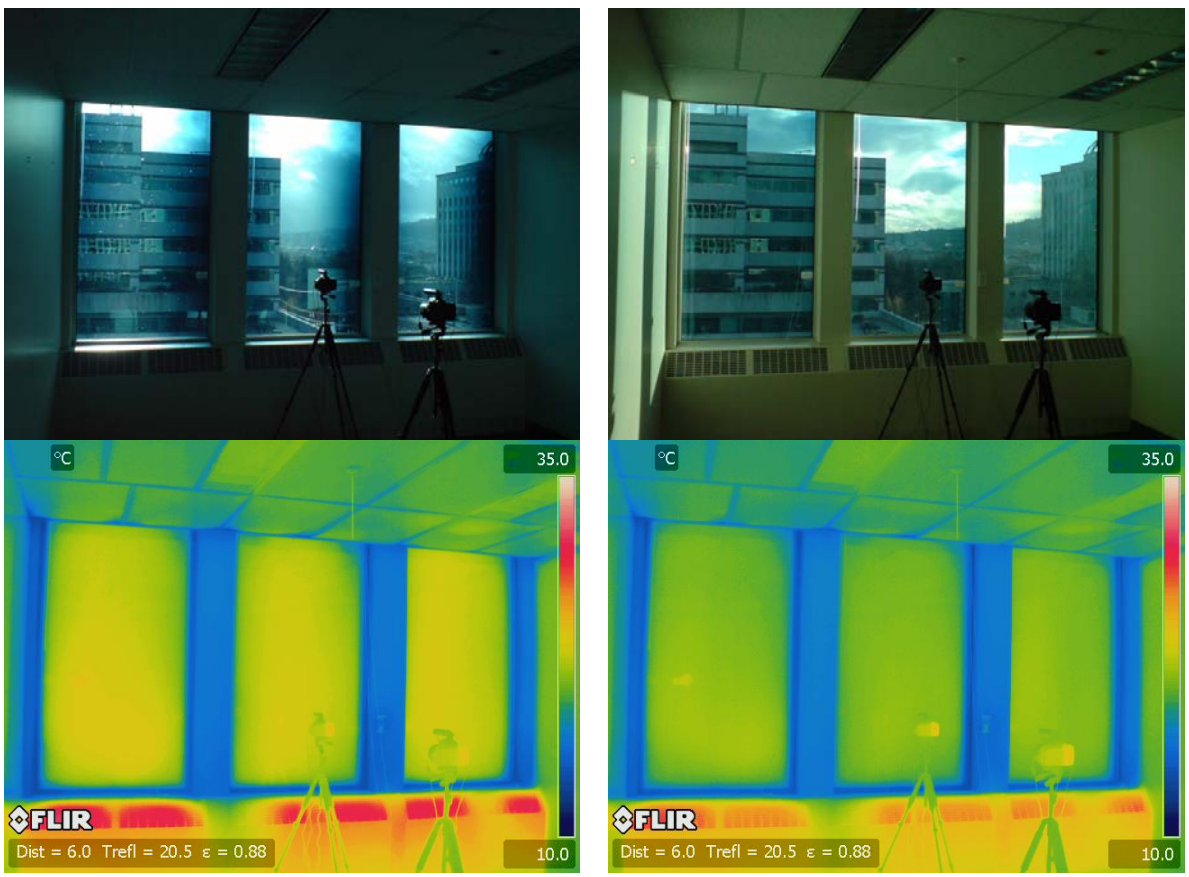


Figure V.D.8. Tint level (red line) and sensor signal (blue curve, W/m^2) for the EC windows on a partly cloudy, cold winter day (December 21, 2015). The light green and red background shading show when the EC windows were in Intelligence and Schedule Modes, respectively. Dotted vertical lines correspond to times when IR images were taken in Figure V.D.7.



12:30 PM 3:40 PM

Figure V.D.9. Photographs (upper) and falsecolor infrared images indicating surface temperature (°C) (lower) of the south-facing office with EC windows (sixth floor, west wing), December 21, 2015.

E. LIGHTING ENERGY USE

Lighting energy use was determined in Phase I. In Phase II, lighting energy use was not evaluated due to the type of lighting controls installed during the renovation of the fifth floor.

Lighting energy use savings resulted from the use of the bleached, clear EC states (Tints 1–2) during overcast periods, and periods of the day when daylight levels were low (typically morning and evenings). Since the visible transmittance of the reference windows was so low (about Tvis' = 0.15), savings also may have occurred during mid-day hours in the 15-ft. deep daylit zone. Savings also may have been due to the reduced use of venetian blinds in the EC offices.

1. LIGHTING ENERGY USE BASED ON ON-OFF STATUS

Using the monitored on-off status of the light fixtures in each private office, the percentage of day that the lights were ON between 8 AM and 6 PM was computed for each office per day then the results were averaged for the 7 offices on the 8th reference floor versus the 11 offices on the 6th and 7th test floors. A comparison is given in **Figure** V.E.1, where each line segment represents a week of data, excluding weekends. The reference floor with conventional windows and manually operated venetian blinds showed greater use of the lights than the EC floors. For the period between July 25 and December 23, the lights were ON for an average of 51% for the reference condition and 26% for the EC condition, a savings of 48%. The difference cannot be entirely attributed to the difference in manual switching due to daylight. Some or all of this difference could be due to differences in occupancy of the private offices. Notice, for example, the decline in lighting energy use during November and December for the EC offices: this difference with the reference offices was likely due to differences in occupancy during the holidays.

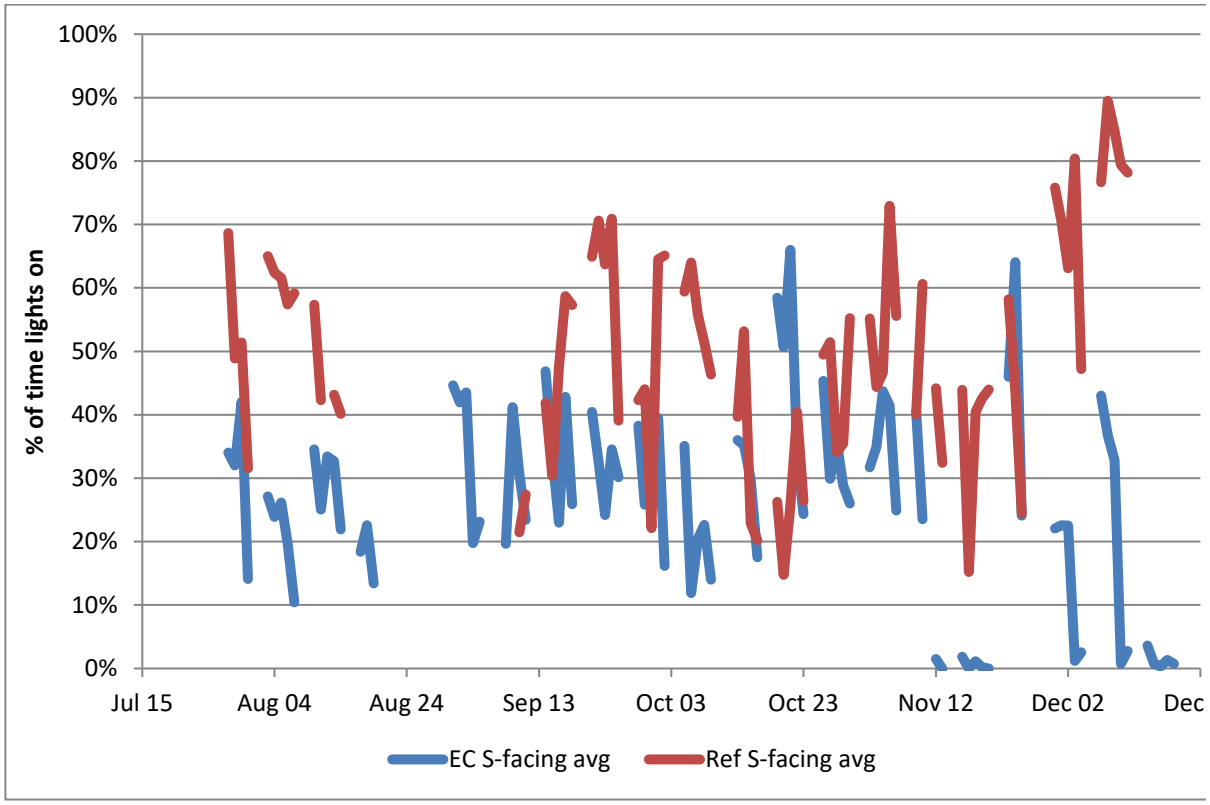


Figure V.E.1. Average percentage of time lights were on between 8 AM and 6 PM in the monitored offices with electrochromic (sixth and seventh floor) and reference (eighth floor) windows. Each line segment shows data for one work week.

2. LIGHTING ENERGY USE BASED ON DAYLIGHT LEVELS

To control for the effects of occupancy and manual operation of the lights, lighting energy consumption was determined based on available daylight measured in the private offices. As described in Section IV.D.8, the daylight contribution to horizontal illuminance was determined using continuous measurements of horizontal illuminance at desk height near the south-facing windows and sensor data indicating whether the electric lights were on or off.

Figure V.E.2 shows the results for the period between July 28 and December 22. Lighting energy consumption in the 15-ft. deep private offices was lower on the EC floors than for the reference floor, by 74%, 36% and 36% for horizontal illuminance setpoints of 300, 500 and 1000 lux, respectively (**Table** V.E.1).

While these percentage savings appear high, it should be noted that the actual annualized energy use intensities were quite low – between 0.02 to 0.87 kWh/ft^2-yr (8 AM to 6 PM weekdays only assuming 1 W/ft^2 installed lighting power density) across the range of setpoint illuminance levels. As a benchmark, if lights were on at full power all day, annual lighting energy use would have been 2.6 kWh/ft^2-yr. The large reduction in energy use was due primarily to the location of the horizontal illuminance sensors, which were placed within 1–3 ft. from the windows to allow reasonable consistency of placement between locations. The variation in setpoint levels from 300 to 1000 lux was used as a proxy to assess the sensitivity of lighting energy use to distance of the sensors from the windows (making some gross assumptions regarding the typical asymptotic fall off of daylight with distance from the window and assuming photosensor placement at 10 ft. from the window in a 15-ft. deep office). Irrespective of these limitations, results show EC windows leading to reduced need for electric lighting, in part due to a decreased need for the venetian blinds.

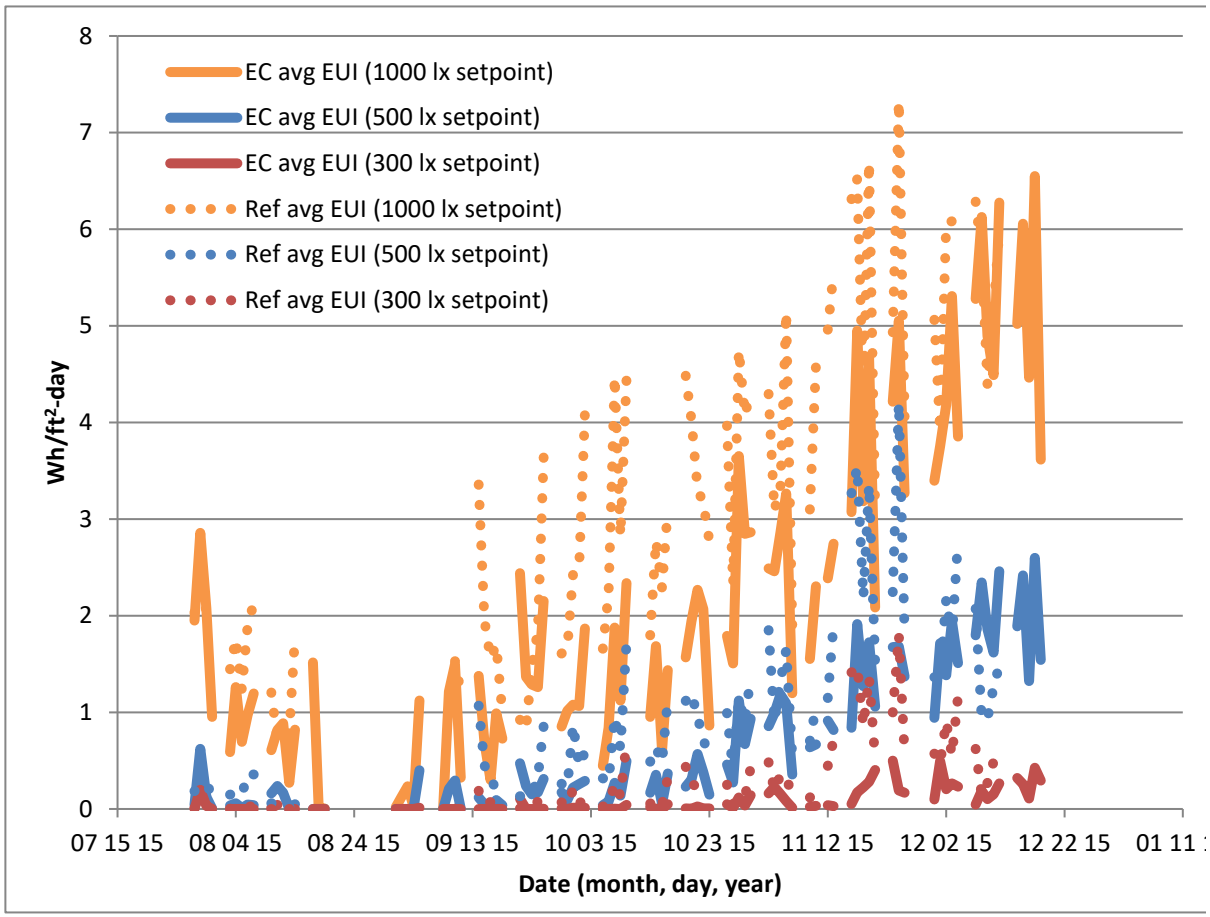


Figure V.E.2. Predicted weekday daily lighting energy use intensity (Wh/ft^2-day) for test (sixth and seventh) and reference (eighth) floors for three horizontal illuminance setpoints (300, 500 and 1000 lx). Daily lighting energy use was computed for 8 AM to 6 PM period in a 15-ft. deep south-facing, perimeter zone private office.

Table V.E.1 Predicted lighting energy use intensity (Wh/ft^2-yr) and savings

	Lighting Energy Use Intensity (Wh/ft^2-yr) for setpoints:		
	1000 lux	500 lux	300 lux
Reference	870.9	256.1	78.4
Electrochromics	554.2	164.0	20.3
Savings	36%	36%	74%

F. HVAC LOAD

The impact of EC windows on HVAC operations was evaluated for Phase I only.

A 2.5 month period (July 30 to October 19, 2015) during the summer was analyzed to evaluate (a) whether the EC windows resulted in a more balanced cooling load between the north and south sides of the building and (b) whether the EC windows significantly reduced the cooling load on the south side of the building compared to reference case.

1. BALANCING THE AHU LOAD BETWEEN NORTH AND SOUTH ZONES

Normal mode of operation (Automatic to Tints 1–3)

The transmitted vertical solar irradiance through the reference and EC south-facing windows were plotted for a week (August 9–15, 2015) in **Figure** V.F.1. The middle five days show the weekday profiles when the EC window (7SE) was at Tint 2 at noon.

- On the south façade, transmitted solar irradiance through the EC windows (7SE) at noon was about 50% greater than the reference window (8SW), which is consistent with the percentage difference in Tsol' between the EC window at Tint 2 and the reference windows.
- Therefore, between the north and south sides of the building, transmitted irradiance levels were not more equitable and, as a consequence, the cooling load also was not more balanced.
- Note how the transmitted solar irradiance on the north (8N) side of the reference floor was greater than that on the south (8SW) side of the reference floor. This may have been due to reflected solar radiation from an opposing tall building to the north of the north façade.

Note that this measured quantity reflects only part of the total heat gains through the window. In addition to direct transmitted solar radiation, which gets absorbed by interior surfaces within the room and then is released into the space as a load some time later (depending on how much thermal mass there is in the incident surface), there is also absorbed solar radiation in the window, a fraction of which is re-radiated to the interior, and conductive and convective (infiltration) heat gains and losses through the window. Because the EC and reference windows have low-e properties and the U-values are approximately the same, the majority of the change in total window load is due to the solar-optical switching properties (Tsol) of the EC window.

Scheduled mode to Tint 4

To determine whether the EC window was *capable* of leveling the load between the north and south sides of the building, the EC was scheduled to switch to Tint 4 from 6:00 AM to 8:00 PM on weekends (**Figure** V.F.1).

Here, the transmitted solar irradiance levels at noon in the south zone with EC windows (7SE) were almost nil (2–3 W/m^2) compared to the south- and north-facing reference windows (8SW, 8N; 28–30 W/m^2). These data demonstrate that the EC windows are capable of leveling transmitted solar irradiation loads on sunny days when switched to Tint level 4 (Tsol = 0.01, SHGC = 0.09) and are, therefore, capable of leveling the cooling load between the north and south sides of a building so as to improve the operational efficiency of the air handler unit.

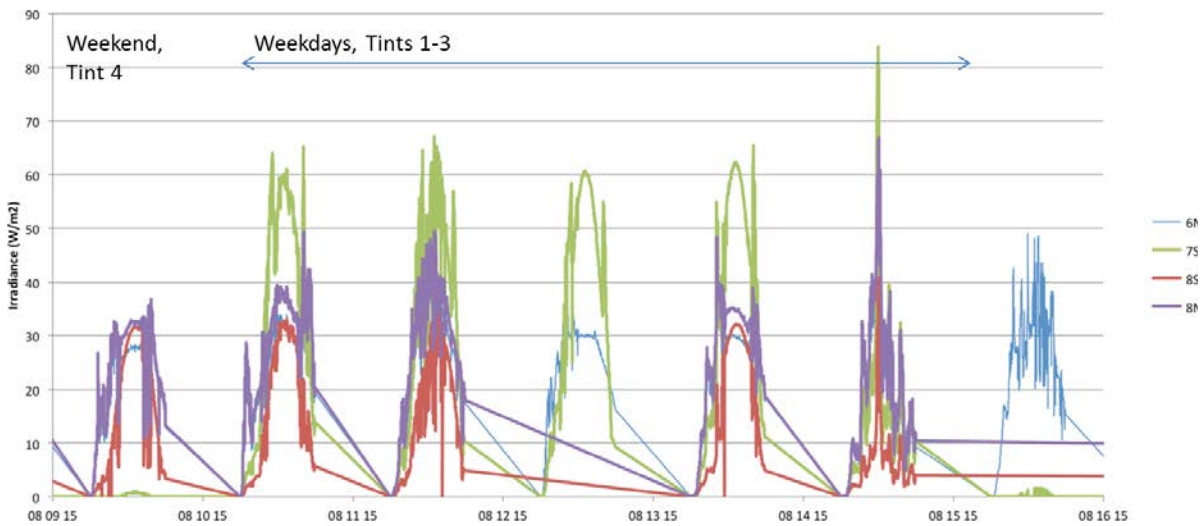


Figure V.F.1. Transmitted vertical solar irradiance (W/m^2) at the reference and EC window for the week of August 9–15, 2015. Reference case – Floor 8; EC case – Floors 6–7.

2. COOLING LOAD REDUCTIONS IN SOUTH ZONES

Normal mode of operation (Automatic to Tints 1–3)

HVAC cooling loads were determined over the 2.5 month period using VAV box level data from the building automation system and the method described in Section IV.D.9. The total cooling load from July 30 to October 19, 2015, was 19,892 and 20,315 kBtu (-2%) for the Floor 8 reference and Floor 7 EC south perimeter zones, respectively.

A more detailed analysis was conducted, focusing on the afternoon period (weekdays, noon to 5 PM). Afternoon loads were most likely driven by window heat gains and less affected by any pull-down loads that occurred during the morning start-up period (**Figure** V.F.2). The cooling load on the south side of the building with EC windows was 45% greater than the north side on the seventh floor with reference windows. Therefore, the loads on the north and south sides of the building were not balanced with the EC windows.

This was due to the light tint level of the EC windows and control algorithm, which was adjusted by the facility manager to admit more daylight (Tints 1–3) instead of minimize window cooling loads (Tint 4). The glare control sub mode also was turned off during this test, which allowed more direct

sunlight deeper into the space. With this automatic control mode, the EC windows were never tinted darker than Tint 2 (Tvis = 0.25, SHGC = 0.28) between June and mid-September.

Note that differences in internal loads due to occupancy, equipment and construction (e.g., roof load on the eighth floor) also could be a source of differences in loads between north and south zones and between floors. The supply air temperature was maintained between 22.2–22.8°C ± 3.6°C (72–73°F ± 2°F) on all floors. Large differences in HVAC load due to errors in calibration of the VAV supply air volume and temperatures were unlikely.

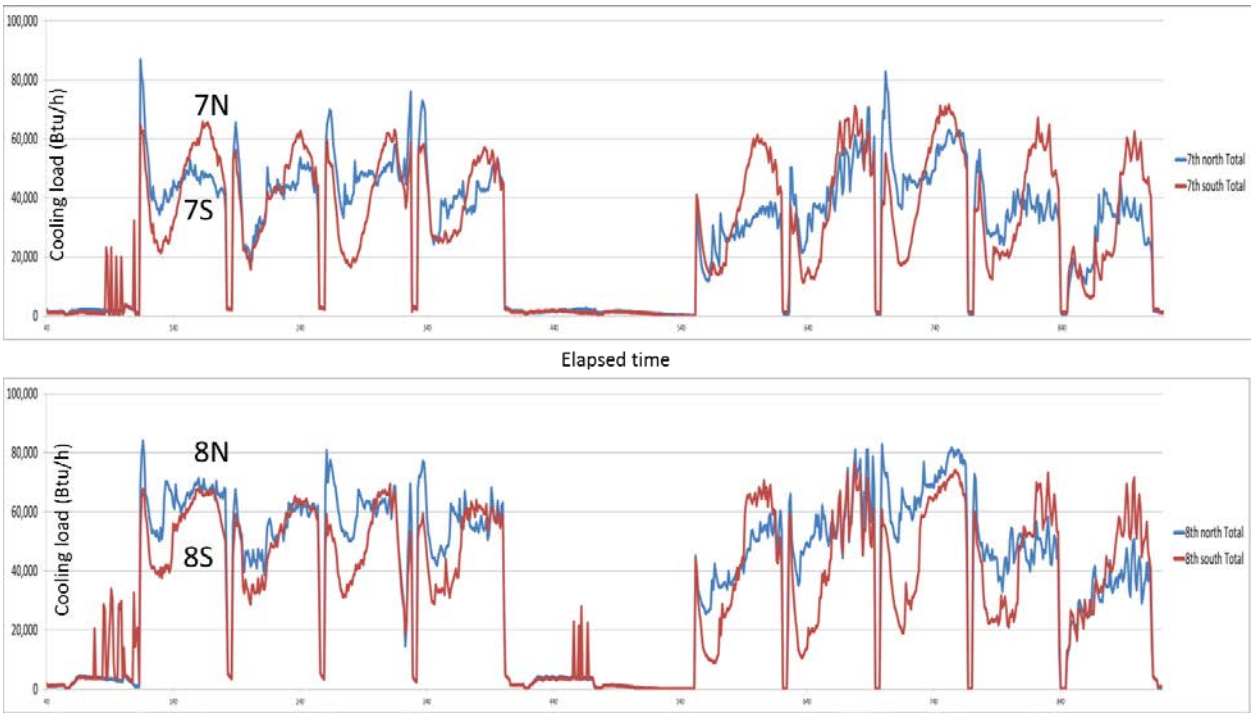


Figure V.F.2. Example of cooling load (BTU) for the entire north (blue) or south (red) sides of the building on the seventh (upper graph) and eighth (lower graph) floors. Data are given for the period August 9–21, 2015, 6 AM to 6 PM PDT per day. The period with no cooling load occurred when the HVAC system was shut down during the weekends. Reference case – Floor 8; EC case – Floors 6–7.

Scheduled mode to Tint 4

During weekday occupied hours, the automatic mode of control restricted switching of the EC windows to Tint levels 1–3, but during the weekend, the EC windows were set to Tint 4 (fully colored) between 6:00 AM and 8:00 PM using the "Schedule" mode of control.

This resulted in a significant reduction on cooling load, but because the HVAC system was operating in an energy-conservation mode on weekends, the difference in cooling load between the north/south sides of the building or the reference versus EC windows could not be measured for the typical weekday HVAC mode of operation during this period.

Figure V.F.3 shows an expanded view of the weekend and nighttime periods where the cooling load was a fraction of that during weekday occupied hours. Note, however, the cooling energy use expended on the eighth floor south zone with the reference windows. The difference between this energy use and that of the seventh floor south zone was due to use of the EC windows, demonstrating the benefit of Tint 4 in reducing window heat gains (assuming a higher cooling temperature setpoint).

A more detailed explanation of HVAC operations may be helpful: This demonstration site employed nighttime setback and morning setup controls for the HVAC system. The setback control provided temperature setback for heating at night and temperature setup for cooling in the morning so as to avoid wasting energy during unoccupied hours. During off-hours (nights and weekends), the HVAC system was allowed to restart automatically and temporarily operate to maintain the space within the setback or setup temperature setpoint. This prevented offices from becoming too hot or too cold during off-hour, avoiding potential temperature-related damage to furnishings and equipment within the building. It also enabled temperatures to be brought back to a comfortable range within a reasonable amount of time prior to occupancy.

Based on the operational data, the demonstration site used a setup temperature setpoint of 27.8°C (82°F). In **Figure** V.F.3 during the weekends, note how the AHUs serving the eighth floor south zone (with the reference windows) needed to cycle ON more often to maintain the unoccupied setpoint temperature than those serving the seventh floor south zone (with the EC windows). This resulted in energy savings and was due to reduced transmitted solar radiation when using EC windows.

For the period from 12:00 AM on August 8 (Saturday morning) to 12:00 AM on August 10 (Sunday evening), the AHU cooling load in the south zone on the seventh floor with the EC windows was 23.43 kWh, while on the eighth floor with reference windows, the cooling load was 54.27 kWh, a reduction of 30.84 kWh (56.8%) for the south side of the floor when operated at a cooling setpoint of 82°F.

Note that because of this setback for cooling, reduction of the morning pull down load on the HVAC system (from 12:00 AM to 6:00 AM) was not observed when using the EC windows.

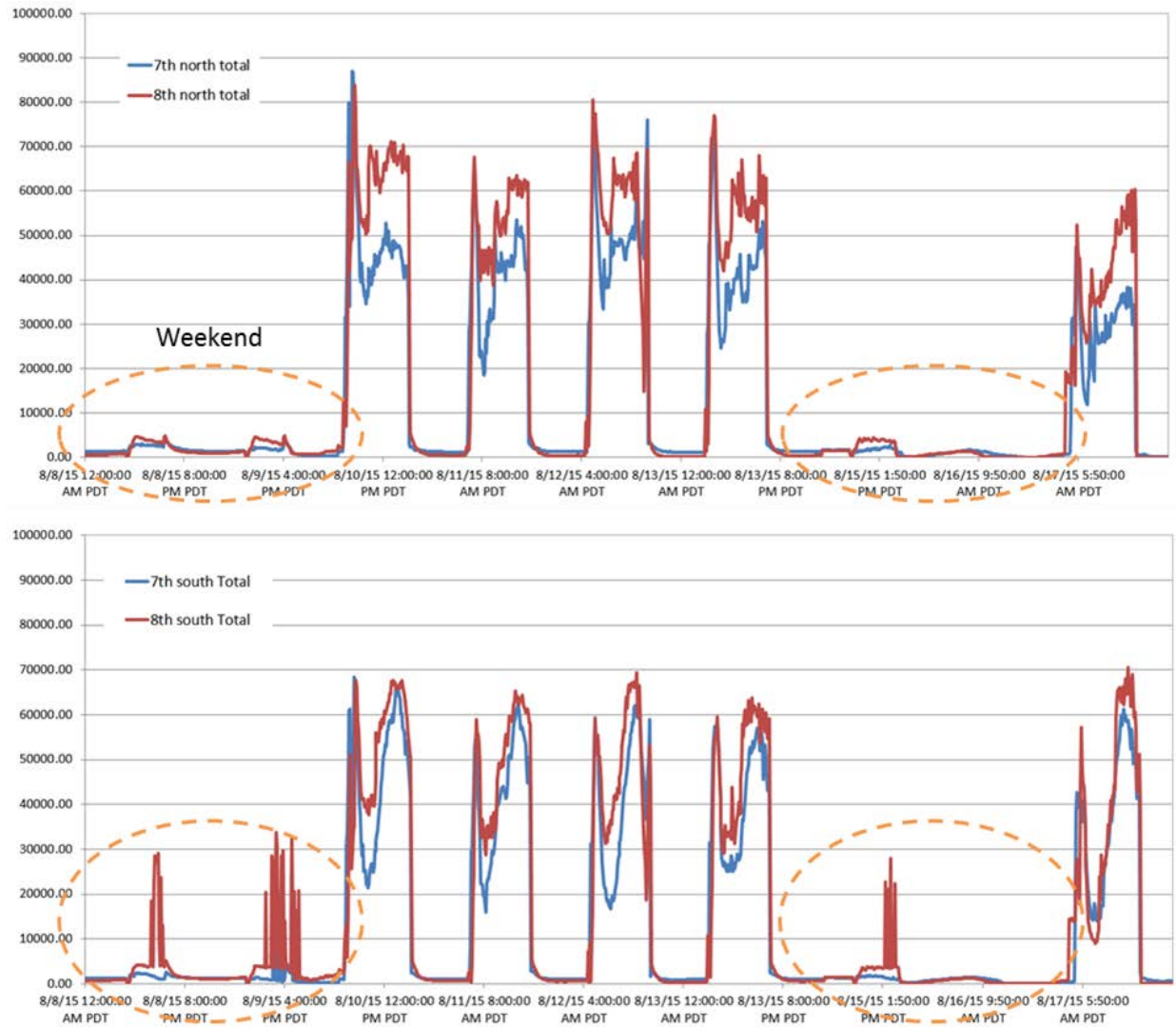


Figure V.F.3. Example of cooling load (BTU) for the eighth floor with reference windows (red) and seventh floor with EC windows (blue) for the north (upper) and south (lower graph) zones of the building. Data are given for the period August 9–21, 2015 (24 h/day). Weekend days are circled with the dotted line. Reference case – Floor 8; EC case – Floors 6–7.

3. HVAC OPERATIONS AND ENERGY USE

When discussing the load reduction potential with GSA, facility managers at Portland argued that the greatest benefit of EC windows was their ability to provide dynamic solar control; i.e., reducing the absolute cooling load from facades with moderate to significant exposure to direct solar radiation (i.e., east, west and south-facing, moderate to large-area windows) when needed, thereby improving HVAC operations and, most importantly, occupant comfort.

- EC windows with a SHGC of 0.09 when fully tinted provided facility managers with the capability to reduce cooling loads and, potentially, HVAC energy use, when needed.
- For VAV systems, in general, the impact of solar loads is offset using VAV. Zones with extended solar exposure require about 3.5 CFM/ft^2 at 55°F whereas interior office zones require a fraction of this volume: e.g., 0.5–0.6 CFM/ft^2. With the EC windows controlled to reduce solar loads actively, the difference in air side demand is reduced, resulting in more even operation of the air system and more steady operation of the cooling plant. The

facility managers suggested that this can result in increased thermal comfort among occupants as a whole.

- Whether this active load management results in HVAC energy savings depends on the configuration of the air distribution systems and chiller plant. In the case of the Portland building, there was already significant thermal discomfort because the AHU was configured to serve both sides of the building, instead of just the north or the south sides of the building, resulting in suboptimal AHU operations. Balancing the north/south load with the EC windows would likely improve operations and occupant comfort, and reduce floor level AHU energy use. Reductions in cooling load at the central plant also would likely lead to HVAC energy use reductions – the Portland central plant was capable of maintaining cooling efficiencies even at lower cooling capacities (i.e., very low turn-down ratio; Smardt chiller, Mag-Lev bearings).
- Impacts on heating energy use was not monitored in this study, but when fully bleached, EC windows with a SHGC of 0.43 can enable passive solar heating in buildings that are operating in the heating mode during the winter season.

G. OCCUPANT SURVEYS AND SERVICE CALL LOG

1. PHASE I: PRE-INSTALLATION SURVEY RESULTS

A pre- installation survey was issued to all occupants in the south-facing perimeter offices on Floors 6–8 prior to automation of the EC windows (March 31 to April 10, 2015). Occupants were asked questions regarding their experience with the indoor environment. Twenty-eight responses were received from the EC floors and ten responses were received from the reference floor (**Table** V.G.1). The average responses on a 9-point Likert scale are shown with error bars in **Figures** V.G.1 (by floor) and V.G.2 (by east and west wing). No statistically significant differences were observed between floors or wings.

Table V.G.1. Number of responses received from pre- and post-installation surveys for Phase I.

Survey	Date	Number of responses		
		Total	EC floors	Ref floor
Phase I pre-installation	Mar 31–Apr 10, 2015	38	28	10
Phase I post-installation	Jan 18–29, 2016	37	28	9

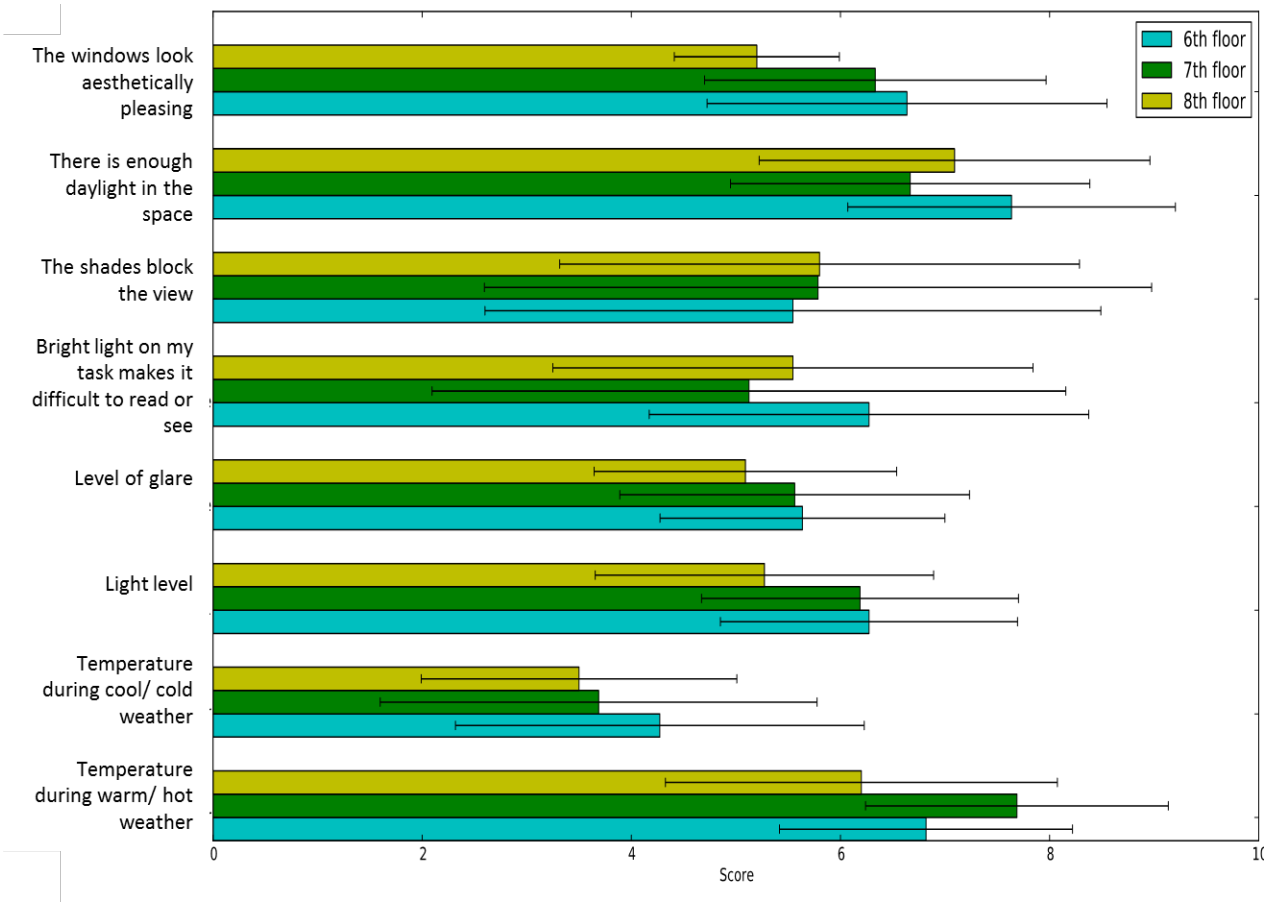


Figure V.G.1. Phase I. Occupant response regarding indoor environment prior to installation of the EC windows, grouped by floor. Error bars show standard deviation. 1 = disagree, 4 = neutral, 9 = agree or glare: 1 = not perceptible, 9 = intolerable; light level: 1 = to dark/ gloomy, 9 = too bright; temperature: 1 = too cold, 9 = too hot. Reference case – Floor 8; EC case – Floors 6–7.

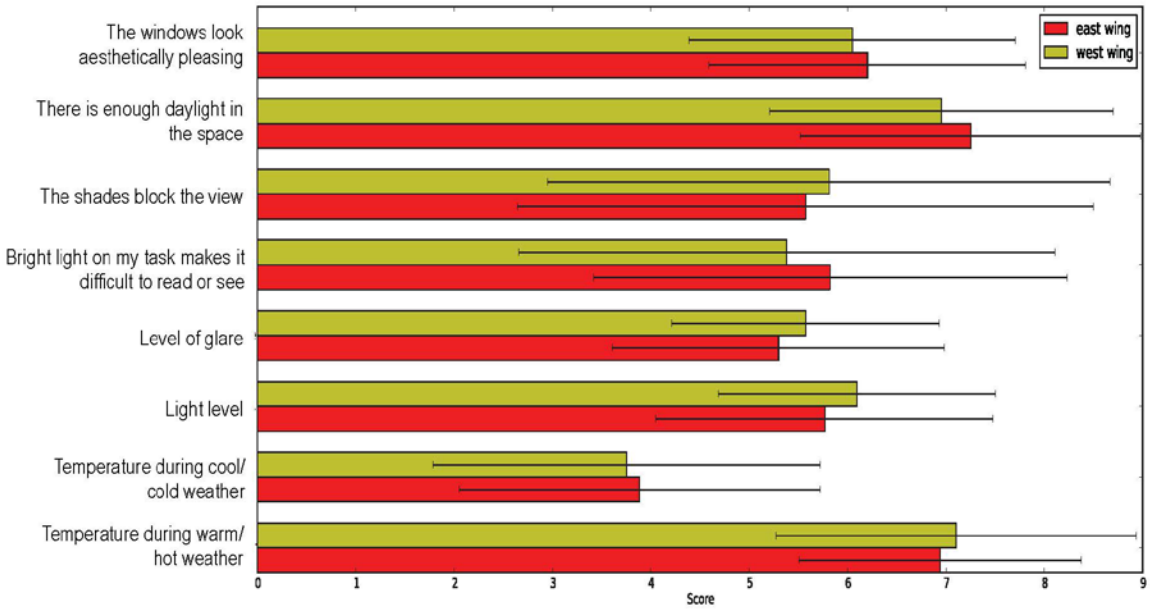


Figure V.G.2. Phase I. Occupant response regarding indoor environment prior to installation of the EC windows, grouped by wing. Error bars show standard deviation. 1 = disagree, 4 = neutral, 9 = agree or glare: 1 = not perceptible, 9 = intolerable; light level: 1 = to dark/ gloomy, 9 = too bright; temperature: 1 = too cold, 9 = too hot. Reference case – Floor 8; EC case – Floors 6–7.

2. PHASE I: POST-INSTALLATION SURVEY RESULTS

The post-installation survey was issued after the occupants had experienced both summer and winter conditions with the EC windows. Twenty-eight responses were received from the EC floors and nine responses were received from the reference floor.

In the comparison between window conditions, the analysis defined two separate groups of responses to the reference condition: the 38 total responses from the pre-installation survey and the 9 reference floor responses from the post-installation survey, where the former is likely to have greater statistical significance due to its larger sample size. The post-installation survey, however, occurred at the same time of the year.

Survey responses to specific key questions (number "Q#", see Appendix B) are summarized in **Figures** V.G.3–V.G.5 and **Tables** V.G.2–3. Those responses that were found to be statistically significant[10] between the EC and pre-installation survey responses are indicated in the figure and denoted with an "**S**" in the list below. All occupants performed tasks involving the computer, phone and paper-based reading and writing. On the reference and EC floors, 43% and 48% of the survey respondents, respectively, faced the window with the remaining facing the side or back wall.

[10] Statistical significance assessed, at the 95% level (i.e., p-value < 0.05), by an equal variance two-tailed t-test.

V.df

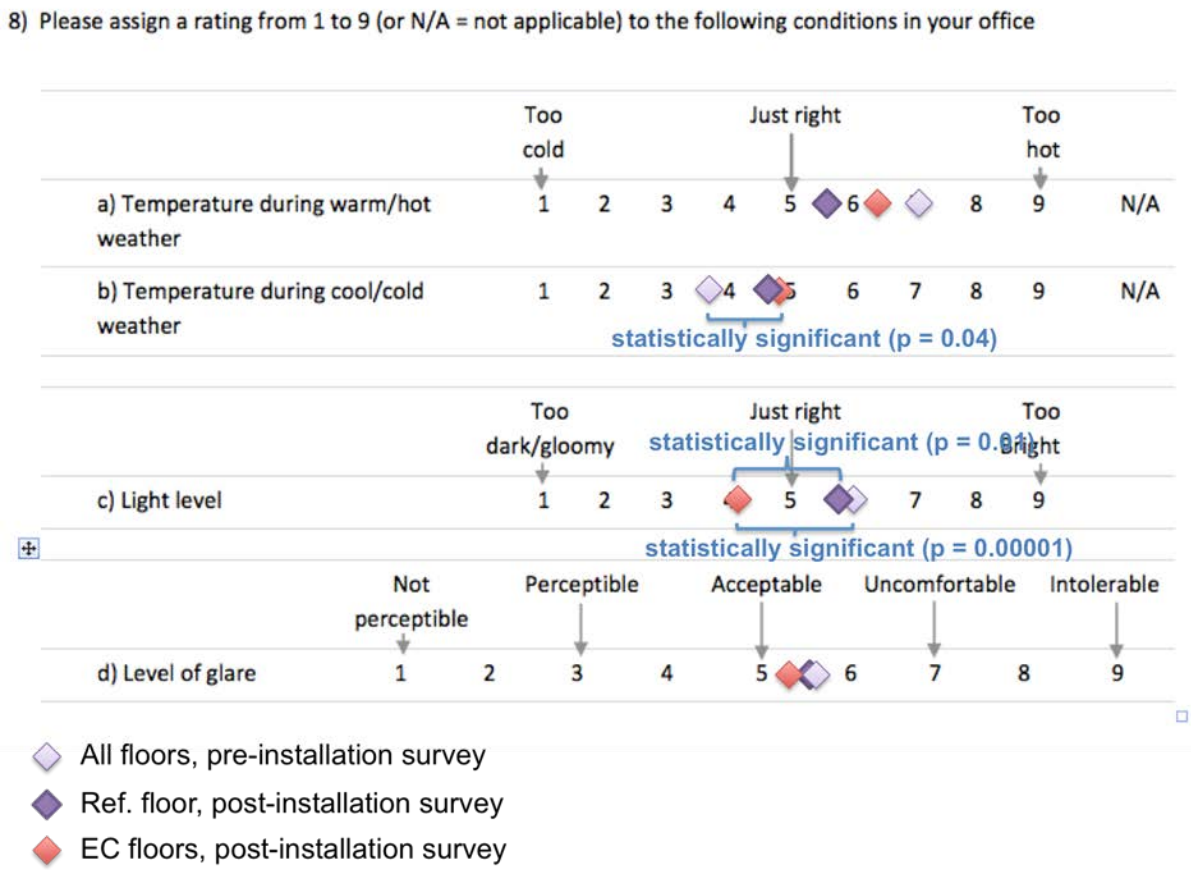
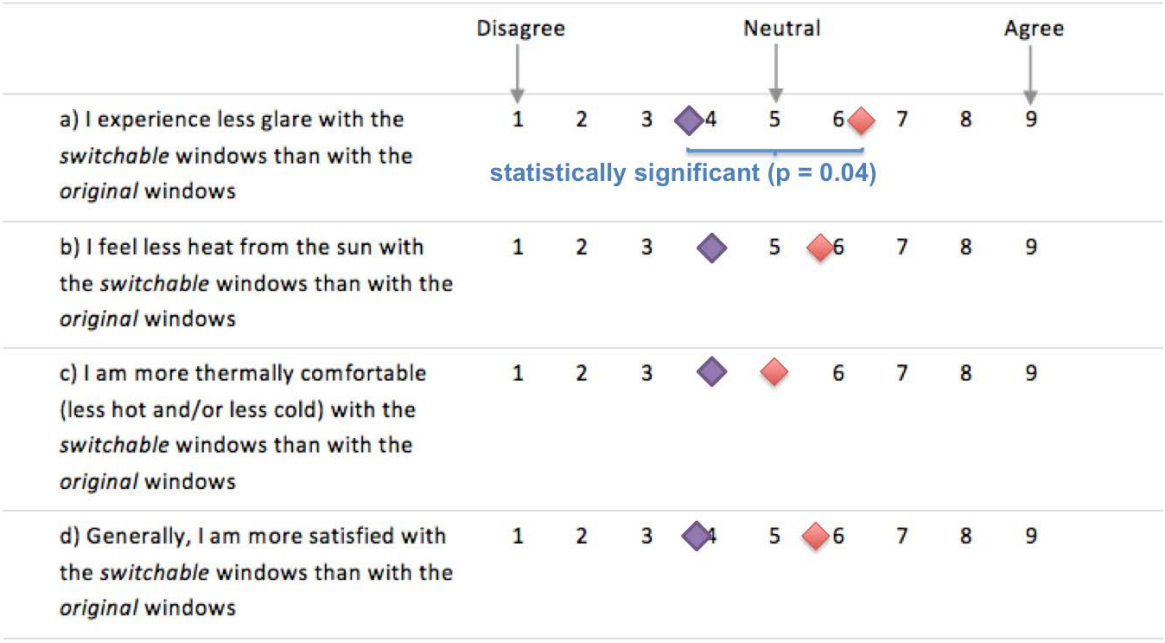


Figure V.G.3. Phase I. Average occupant response regarding indoor environment with reference or electrochromic windows.

Figure V.G.4. Phase I. Average occupant response regarding indoor environment with reference or electrochromic windows.

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



EC floors, post-installation survey
Ref. floor, post-installation survey

Figure V.G.5. Phase I. Average occupant response regarding indoor environment with and without electrochromic windows. [11]

[11] Note that, on the reference floor, the wording of these questions read: "I experience less glare since April 2015 than before," "I feel less heat from the sun since April 2015 than before," "I am more thermally comfortable (less hot and/or less cold) since April 2015 than before," and "Generally, since April 2015 I am more satisfied than before with the windows in my office."

Table V.G.2. Phase I statistics summarizing responses to survey questions comparing EC and reference conditions

Question no.	Question	Responses on EC floors			Responses on ref. floor			p-value
		N	Avg.	Stdev.	N	Avg.	Stdev.	
8 a)	Temperature during warm/hot weather	27	6.30	1.64	9	5.78	2.54	0.48
8 b)	Temperature during cool/cold weather	27	4.85	2.40	9	4.56	2.46	0.75
8 c)	Light level	27	4.15	1.59	9	5.89	1.96	**0.01**
8 d)	Level of glare	27	5.19	1.42	9	5.44	1.01	0.62
9 a)	Bright light on my task made it difficult to read or see	23	3.70	2.58	9	5.33	1.87	0.09
9 b)	The shades blocked the view	21	2.90	2.26	8	5.38	3.38	**0.03**
9 c)	There was enough daylight in the space	26	6.50	2.23	9	6.22	1.86	0.74
9 d)	The windows looked aesthetically pleasing	26	6.77	2.34	9	5.00	2.29	0.06
9 f)	The outside was sufficiently visible through the window	25	7.00	2.00	9	5.67	2.18	0.10
10 a)	I experience less glare with the *switchable* windows than with the *original* windows (EC floors) / I experience less glare since April 2015 than before (reference floor)	26	6.23	2.92	8.00	3.88	1.81	**0.04**
10 b)	I feel less heat from the sun with the *switchable* windows than with the *original* windows (EC floors) / I feel less heat from the sun since April 2015 than before (reference floor)	27	5.81	2.70	8.00	4.00	1.93	0.09
10 c)	I am more thermally comfortable (less hot and/or less cold) with the *switchable* windows than with the *original* windows (EC floors) / I am more thermally comfortable (less hot and/or less cold) since April 2015 than before (reference floor)	28	5.00	2.68	8.00	4.00	1.93	0.33
10 d)	Generally, I am more satisfied with the *switchable* windows than with the *original* windows (EC floors) / Generally, since April 2015 I am more satisfied than before with the windows in my office (reference floor)	27	5.74	2.81	8.00	3.88	1.89	0.09

bold = statistically significant; N = number of responses; Avg.= average response; Stdev. = standard deviation.

Table V.G.3. Phase I statistics summarizing responses to survey questions related to EC test conditions only

Question no.	Question	N	Avg.	Stdev.	95% confidence interval	
					Lower bound	Upper bound
9 e)	The tinting/untinting of the windows did not disturb me in my work	25	5.56	2.58	4.55	6.57
9 g)	The wall switches allowed the window to be manually controlled in a satisfactory way	26	5.31	2.60	4.31	6.31
9 h)	The speed at which the windows tinted/untinted was satisfactory	26	4.12	2.57	3.13	5.10

bold = statistically significant; N = number of responses; Avg. = average response; Stdev. = standard deviation.

Key findings include:[12]

Daylight levels

- Q8c, **S**: Occupants found the light level in the EC offices to be slightly too dark/gloomy (4.2), while occupants in the reference offices found the light level to be slightly too bright (6 pre; 5.9 post).
- Q9c: Occupants agreed in both the EC (6.5) and reference (6.2 post) offices that there was enough daylight in the space.

Visual discomfort/ glare

- Q8d: Occupants found that the level of glare was just slightly uncomfortable in both the EC (5.2) and reference (5.4 post) offices.
- Q9a, **S**: Occupants disagreed that bright light on their task made it difficult to read or see in the EC offices (3.7). Occupants agreed slightly in the reference offices (5.6 pre).
- Q10a, **S**: EC floor occupants agreed (6.2) that they experienced less glare with the EC windows than the reference windows.

Thermal comfort

- Q8a: Occupants found the temperature in their offices during warm/hot weather to be too warm in both the EC offices (6.3) and reference offices (pre-retrofit) (7.1).
- Q8b, **S**: Occupants found the temperature in their offices during cool/cold weather to be just right (4.9) in the EC offices, slightly too cool (4.6) in the reference offices (post-retrofit) and too cool (3.7) in the reference offices (pre-retrofit). Comfort may have been improved

[12] Average response level for the EC floors and reference floors (pre-installation survey only) is given in parentheses. If post-installation survey data are given, the average response is denoted with "post" after the number.

in the reference offices after the pre-retrofit survey was issued due to rebalancing of the HVAC system.

- Q10b: EC floor occupants agreed slightly (5.8) that they felt less heat from the sun with the EC windows than the reference windows.
- Q10c: EC floor occupants were neutral (5.0) regarding whether they were more thermally comfortable (less hot or less cold, or both) with the EC windows than the reference windows.

View/use of shades

- Q9b, S: Occupants in the EC offices did not agree that the shades blocked the view (2.9), while occupants in the reference offices indicated slight agreement above neutral (5.8 pre; 5.4 post) that the shades blocked the view.
- Q9f: Occupants strongly agreed that the outside was sufficiently visible through the EC window (7), while occupants of the reference offices slightly agreed (5.7 post).

About the EC window technology

- Q12: If given the option, 85% of the occupants preferred switchable windows (n = 23) over conventional windows (n = 4) in their office. Based on these responses, a statistical estimate[13] of the proportion of the general office population that will, in similar circumstances (building, orientation and climate), prefer switchable windows yields a minimum value of 66% and maximum value of 96%.
- Q10d: Occupants agreed slightly (5.6) that they were more satisfied with the EC windows than the reference windows.
- Q9e: Occupants agreed slightly (5.6) that the tinting and untinting of the windows did not disturb them in their work.
- Q9g: Occupants agreed slightly (5.3) that the wall switches allowed the EC windows to be manually controlled in a satisfactory way.
- Q9h: Occupants disagreed moderately (4.1, 5 = neutral) that the speed at which the EC windows tinted and untinted was satisfactory.
    - This finding should be qualified. During the summer, the EC window was automatically tinted no darker than Tint 2 (32% of full tint) and, during the winter, the EC window was infrequently switched to Tint 3 and 4 (68% and 100% tinted). Sky conditions may have been dynamic, but the delays needed to switch to Tint 4 were not experienced very often. There were a few negative survey comments about the slow speed and this may have occurred during manual overrides to Tint 4.

Occupants entered some detailed comments when filling out the survey. Some expressed satisfaction with the EC windows. Others expressed dissatisfaction with the switching speed and confusion over the keypad interface.

[13] Using the binomial distribution, with 95% confidence interval determined using the Clopper-Pearson method.

These results indicate that, overall, occupants preferred the EC windows to the pre-existing conventional windows, as well as experienced improvements in visual comfort and access to views of the outdoors when in a space with EC windows.

Although no significant reduction in the overall absolute level of glare was reported (Q8d), when asked about the practical consequences of glare (Q9a) and to directly compare the EC windows to the reference windows (Q10a), occupants on the EC floors indicated an improvement in visual comfort.

As observed in a prior study [8], EC windows also resulted in a space that appeared slightly darker (Q8c). However, here no difference was found between EC and reference windows in terms of whether they provided enough daylight to the space (Q9c), which suggests that there was little or no negative impact.

3. PHASE II: POST-INSTALLATION SURVEY RESULTS

The Phase II survey was issued to the occupants of the south side of the fifth floor in June 2016, after the occupants had experienced the test conditions for nearly six months. Twenty-nine responses were received in total, 14 from the west (EC) wing and 15 from the east (reference) wing (Table V.G.4). Results were analyzed using similar techniques and criteria as described for Phase I.

Table V.G.4. Number of responses received from post-installation surveys for Phase II.

Survey	Date	Number of responses		
		Total	EC floors	Ref floor
Phase II post-installation	Jun 20–Jul 1, 2016	29	14	15

Phase II survey responses to specific key questions (number "Q#", see Appendix B) are summarized in **Figures** V.G.6–7 and **Tables** V.G.5–6. Those responses that were found to be statistically significant are indicated in the figure and denoted with an "**S**" in the list below. Occupants performed tasks involving the computer, phone and paper-based reading and writing.

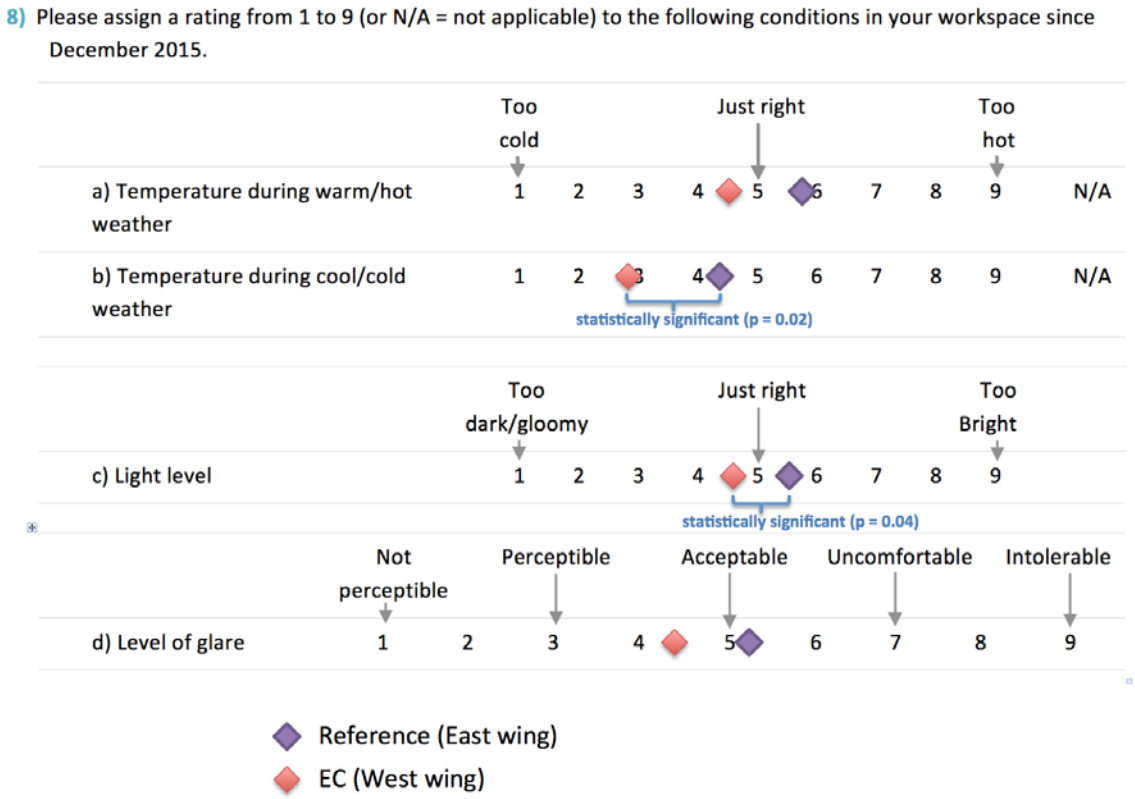


Figure V.G.6. Phase II. Average occupant response regarding indoor environment on electrochromic (west) and reference (east) wings.

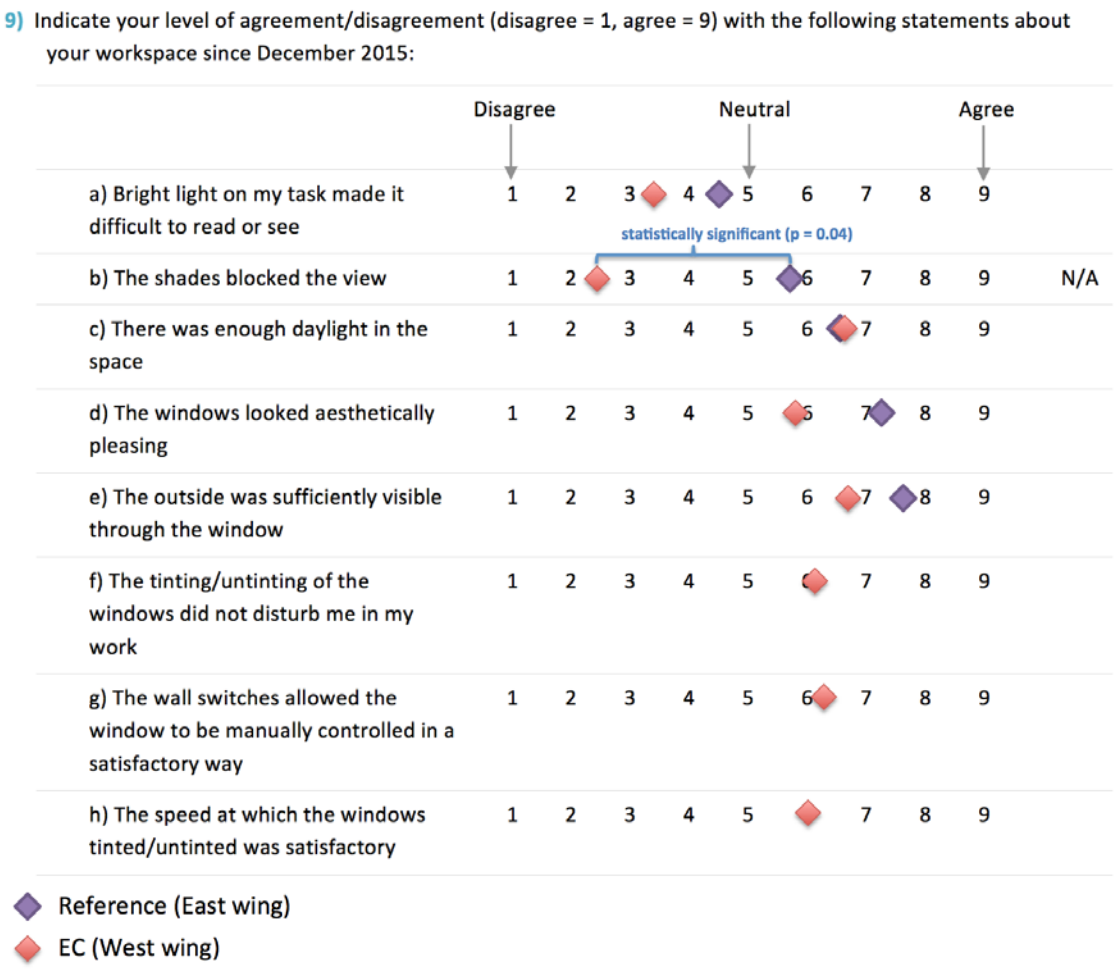


Figure V.G.7. Average occupant response regarding indoor environment on electrochromic (west) and reference (east) wings.

Table V.G.5. Phase II statistics summarizing responses to survey questions comparing EC and reference conditions

Question no.	Question	EC wing			Reference wing			p-value
		N	Avg.	Stdev.	N	Avg.	Stdev.	
8 a)	Temperature during warm/hot weather	14	4.50	2.44	15	5.80	2.46	0.16
8 b)	Temperature during cool/cold weather	14	2.93	1.21	15	4.27	1.75	**0.02**
8 c)	Light level	14	4.57	1.02	15	5.53	1.30	**0.04**
8 d)	Level of glare	14	4.36	1.86	15	5.20	1.52	0.19
9 a)	Bright light on my task made it difficult to read or see	14	3.29	2.81	15	4.47	3.04	0.29
9 b)	The shades blocked the view	13	2.38	2.90	12	5.75	2.99	**0.01**
9 c)	There was enough daylight in the space	14	6.64	3.03	15	6.53	2.29	0.91
9 d)	The windows looked aesthetically pleasing	14	5.93	2.64	15	7.13	2.10	0.18
9 f)	The outside was sufficiently visible through the window	14	6.79	2.83	15	7.67	1.91	0.33

bold = statistically significant; N = number of responses; Avg. = average response; Stdev. = standard deviation.

Table V.G.6. Phase II statistics summarizing responses to survey questions related to EC test conditions only

Question no.	Question	N	Avg.	Stdev.	95% confidence interval	
					Lower bound	Upper bound
9 e)	The tinting/untinting of the windows did not disturb me in my work	14	6.07	3.32	4.33	9.39
9 g)	The wall switches allowed the window to be manually controlled in a satisfactory way	13	6.23	2.83	4.75	9.06
9 h)	The speed at which the windows tinted/untinted was satisfactory	14	6.00	2.35	4.77	8.35

bold = statistically significant; N = number of responses; Avg. = average response; Stdev. = standard deviation.

Key findings include:

Daylight levels

- Q8c, **S**: Occupants found the light level in the EC offices to be slightly darker than "just right" (4.6), while occupants in the reference offices found the light level to be slightly brighter than "just right" (5.5).
- Q9c: Occupants agreed in both the EC (6.6) and reference (6.5) offices that there was enough daylight in the space.

Visual discomfort/ glare

- Q8d: Occupants found that the level of glare was acceptable in the EC (4.4) wing and just slightly uncomfortable in the reference (5.2) wing.
- Q9a: Occupants disagreed that bright light on their task made it difficult to read or see in the EC offices (3.3); less so in the reference offices (4.5).

Thermal comfort

- Q8a: Occupants found the temperature in their offices during warm/hot weather to be just below "just right" in the EC offices (4.5) and slightly too warm in the reference offices (5.8).
- Q8b, **S**: Occupants found the temperature in their offices during cool/cold weather to be somewhat too cold (2.9) in the EC offices and slightly too cool (4.2) in the reference offices. Information available from the facility management team did not reveal any difference in HVAC operations between the two wings that could explain this result. Also, no significant differences were observed regarding self-reported occupant sensitivity to heat or cold.

View/ use of shades

- Q9b, **S**: Occupants in the EC offices did not agree that the shades blocked the view (2.4), while occupants in the reference offices indicated slight agreement above neutral (5.8) that the shades blocked the view.
- Q9e: When asked whether they agreed that the outside was sufficiently visible through the windows, both occupants in the EC and reference wings agreed, with the latter agreeing more strongly than the former (6.8 and 7.7 for the EC and reference wings, respectively).

About the EC window technology

- Q10:
    - EC wing: If given the option, 92% of the occupants preferred switchable windows (n = 12) over conventional windows (n = 1) in their space. Based on these responses, a statistical estimate of the proportion of the general office population that will, in similar circumstances (building, orientation and climate), prefer switchable windows yields a minimum value of 64% and maximum value of 100%.
    - Reference wing: If given the option, 87% of the occupants preferred switchable windows (n = 13) over conventional windows (n = 2) in their space (this was based on their four-month experience with automated EC windows prior to the start of the Phase II test). Based on these responses, a statistical estimate of the proportion of the general office population that will, in similar circumstances (building, orientation and climate), prefer switchable windows yields a minimum value of 60% and maximum value of 98%.
    - When analyzing the responses to this question by workstation position relative to the window, we obtained the following results (includes responses to automated EC windows in the reference area prior to start of Phase II):
        - Workstations adjacent to windows: 17 respondents preferred EC windows, 1 preferred the original windows (94% preferred EC windows, confidence interval 73%–100%)
        - Workstations not adjacent to windows: 8 responses preferring EC windows, 2 preferring original windows (80% preferred EC windows, confidence interval 44%–97%)
- Q9f: Occupants of the EC wing agreed somewhat (6.1) that the tinting and untinting of the windows did not disturb them in their work.
- Q9g: Occupants agreed somewhat (6.2) that the wall switches allowed the EC windows to be manually controlled in a satisfactory way.
- Q9h: Occupants agreed somewhat (6.0) that the speed at which the EC windows tinted and untinted was satisfactory.

Occupants were given the opportunity to enter detailed comments when filling out the survey. Some expressed satisfaction with the EC windows regarding having control of glare and light levels. Occupants in the reference wing expressed the desire to have the ECs resume switchable operation. Occupants in both wings expressed dissatisfaction with the reduction in available daylight. Additionally, some comments stemmed from the fact that occupants did not have control of the windows (in the case of occupants of workstations that aren't adjacent to windows) or, if they did, comments stemmed from the border between window control zones not aligning with the workstation partition (in the case of occupants of window workstations).

4. PHASES I AND II: SERVICE CALL LOG

An electronic tracking system was set up enabling occupants and the GSA facility managers to issue requests for service on the EC windows or to request that the venetian blinds be untied. The system notified the facility managers and the EC window vendor. The log then recorded the actions taken and indicated whether the request was considered closed.

A total of 16 service calls were made over a one year period between April 8, 2015, when the log was first set up, and when the log was last checked on October 12, 2016. The last service call entry was dated April 15, 2016. Six additional entries having to do with getting the system first set up in April 2015 were excluded from this count.

Phase I

- 2 requests were made to untie the venetian blinds.
- 2 requests were made by GSA to the vendor to adjust the settings for the automatic control system (1 for a schedule change to Tint 4 on weekends, 1 for a change to Tint 4 in the server room).
- 4 requests were made by the occupants regarding the EC windows not switching at all, not tinting when using the manual switch or tinting too early.

Phase II

- 5 requests were made to disable Tint 4 because conditions were too dark (these were associated with a special control mode having been left on after a special weekend tests had been conducted during an LBNL site visit).
- 2 requests were made in the reference (east wing) area to turn the EC controls back on to reduce solar loads or to enable manual override of the EC windows.

Almost all requests were resolved within a day or two of the request.

Note that for requests indicating dissatisfaction with the indoor environment associated with Tint 4, the facility manager and occupant response to this mode of control was immediate. The “standard” intelligence defined by the vendor with the glare mode set to Tint 4 was not acceptable to the occupants (“too dark”). This was observed both at the start up of Phase I and when inadvertently switched to this mode in April 2016.

H. SUMMARY OF RESULTS

1. PHASE I INSTALLATION IN PRIVATE OFFICES

This section synthesizes and summarizes the various measured and survey results presented in Sections V.A–G.

Configuration of the EC windows and controls

- South-facing, large-area (WWR = 0.46), dual-pane EC windows were installed on Floors 6–7. Solar-optical properties of the EC windows ranged from a bleached (Tint 1) to dark tint (Tint 4): SHGC = 0.43–0.09 and Tvis = 0.36–0.02. Properties of the reference window on Floor 8 were unknown, but measured field data indicated that both the visible and solar transmittance (Tvis’ = 0.10–0.15, Tsol’ = 0.05–0.06) were lower than that of the EC window at Tint 2 (Tvis’ = 0.22).

- The EC windows were controlled using an automatic system that switched the windows to three tint levels (Tints 1–3). Occupants indicated that the "glare" sub mode produced daytime conditions that were perceived as too dark (EC windows were being switched to Tint 4: fully tinted, Tvis = 0.02). The glare mode was, therefore, disabled. All EC windows in each office were controlled to the same tint level; there were no subzones of control in a single office.
- A keypad enabled occupants to select a preferred tint level (Tints 1–4), which overrode the automatic system for four hours. Manual overrides occurred infrequently: on average 11 times per day during the summer and 3 times per day during the winter (out of 40 offices). The majority of the overrides were to a darker tint level (Tint 3 or 4).
- The existing indoor venetian blinds were tied up in the EC offices at the beginning of the test to prevent their use. Occupants were discouraged from untying their blinds, but 30% of the offices untied their blinds from the start of the monitored period. The frequency of blind use was about the same (20% of blinds lowered) between summer and winter with the EC windows. With the reference dual-pane, low-e windows (Floor 8), blind use in the summer was 50% and increased to 75% in the winter. After all the blinds were untied at the conclusion of the study, an additional survey taken about three months later indicated that the use of blinds increased in both reference and EC areas.
- Based on occupants' actions, the EC's automatic mode with a maximum tint level of 3 appeared to be acceptable for the majority of the occupants. Occupants used the venetian blinds and Tint 4 occasionally.

Visual comfort

- For a worst case viewpoint seated 1.3–2.3 ft. from the window and looking out the window, continuous measured vertical illuminance data indicated that discomfort glare in occupied offices with EC windows was greater than that with the reference window throughout the summer and comparable to the reference window throughout the winter. Local differences in sun and shade due to the height and slat angle of the blinds influenced these results.
- Detailed field of view, high dynamic range luminance measurements taken during solstice and equinox conditions indicated that, under partly cloudy sky conditions, the unshaded automated EC window (Tints 1–3 limit) reduced discomfort glare compared to the unshaded reference window. Occasionally, discomfort levels exceeded disturbing and intolerable levels both near (1.4 ft.) and far (6.7 ft.) from the EC window when the orb of the sun came out from behind the clouds.
- Occupant survey data indicated that occupants found glare from the EC windows to be less than that from the reference windows (Q10a, 6.2 out of 9, where 5 = neutral, 9 = agree), when asked to compare between the two windows. Reported glare levels were just slightly uncomfortable for both cases. These responses were in keeping with the end users' occasional use of the Tint 4 manual override and reduced use of blinds compared to the reference case.
- The difference between measured and survey results could be explained by differences between the measured and actual view points of the occupants. Visual discomfort due to direct sun may also have been infrequent and, therefore, tolerated given the typically

cloudy weather patterns in Portland. Annual solar radiation levels are among the lowest in the country.

Thermal comfort

- Measured data on a hot summer and cold winter day indicated that there was no significant difference in percentage of people dissatisfied (PPD) between the reference and EC windows during daytime occupied hours.
- On a hot summer day, direct solar irradiance transmitted through the EC windows and radiant temperature asymmetry between the EC window and room surfaces did not exceed limits defined by the UCB model or the ASHRAE 55-2004 guidelines, indicating that thermal conditions were satisfactory even if the occupant was working in attenuated direct sunlight.
- Occupants were neutral in their opinion on whether they were more comfortable (less hot or less cold, or both) with the EC windows than the reference windows.

Lighting energy use

- Measured results showed that lighting energy use based on ON/OFF manual switching patterns over the six-month period was 48% lower with the EC windows compared to the reference windows, where both cases have manually operated venetian blinds. Part of this difference could be due to differences in occupancy between the floors.
- Results indicated that daytime lighting energy use based on daylight workplane illuminance levels measured near the window was 36% lower with the EC windows compared to the reference windows, where both cases had manually operated venetian blinds. These data are indicative of potential daytime savings (8 AM to 6 PM) in a 15-ft. deep private office and do not include savings due to occupancy.

HVAC energy use

- One of the primary reasons that the GPG Portland facilities managers were initially interested in the EC technology was its ability to control solar heat gains. The facility managers were interested in determining whether discomfort complaints due to overcooling on the north side of the building could be reduced with the use of EC windows on the south side of the building. The AHUs had been zoned improperly in the original building and had subsequently caused problems that impacted comfort and building energy efficiency.
- Given its switching range, EC windows could reduce the difference in loads between the two sides of the building if switched to Tint 4 (fully colored) to minimize cooling loads. Upon commissioning the windows, however, the maximum tint level of the EC windows was set to Tint 3 instead of Tint 4 to favor admission of daylight rather than reduction of solar loads. This automatic mode resulted in the EC windows never tinting darker than Tint 2 between June and mid-September. Summer cooling loads were, therefore, not more balanced because the solar heat gain rejection properties of the EC window at Tint 2 was likely[14] greater than that of the reference windows.

[14] The exact properties of the reference windows were unknown. Nominal solar and visible transmittance (Tsol' and Tvis') were estimated using on-site measurements.

- Because daylight was preferred over solar control, HVAC cooling energy use on the EC floors was likely increased compared to the reference floor during the summer. This increase, however, could be offset by reductions in lighting energy use (and the heat gains due to the electric lighting), if the lights were controlled manually or automatically for daylight.
- When controlled to minimize window heat gains during summer weekends (i.e., Tint 4 all day during daytime hours), the EC windows reduced transmitted solar radiation levels to 10% of that measured through the reference windows during peak summer periods. This mode of operation also resulted in a 57% reduction in the south zone AHU cooling load when operated with a cooling setpoint of 82°F over the 48-hour weekend. These special tests demonstrated the load shed capability of the EC windows.
- If controlled to minimize solar heat gains (Tint 4) during weekday (occupied) cooling periods, thermal comfort is expected to be improved due to more even AHU operations between the north and south zones of the building. HVAC energy savings also are likely to occur due to reduced AHU air volume requirements at the south zone and reduced loads at the central plant. This mode of control, however, was not acceptable to the occupants – alternate control strategies are needed to satisfy both energy-efficiency and occupant requirements more optimally.

Indoor environmental quality

- Survey data indicated that occupants agreed (Q9c, 6.2 out of 9) that there was enough daylight in both the reference and EC offices. Given the large-area, south-facing windows combined with the dark tinted glass of the reference windows in a relatively cloudy climate, this mild level of agreement is consistent with expectations.
- Survey data also indicated that occupants found the light levels in the EC offices to be slightly dark/gloomy, while in the reference offices, they found the light levels to be slightly bright. These results were counterintuitive since the visible transmittance of the EC windows was greater than that estimated for the reference window: the visible transmittance, Tvis, of Tints
  1–3 were between 0.36 and 0.13 compared to the reference window's nominal Tvis' of 0.10–0.15 and greater use of venetian blinds. The perception of gloom could be attributed to the occasional use of Tint 4 (Tvis = 0.02) during periods of manual override or to automated control to Tint 3 during the equinox to winter period.
- Views to the outdoors were significantly less obstructed by shades with the EC windows compared to the reference windows. Field observations showed that about 80% of the venetian blinds were fully raised in the offices with EC windows over the summer and winter periods, whereas shades were fully raised in 50% and 26% of the reference offices in the summer and winter periods, respectively.
- Occupants strongly agreed that the outside was sufficiently visible and disagreed that the shades blocked the view in offices with EC windows. On the other hand, with the reference window, occupants agreed slightly that shades blocked their view and agreed slightly that the outside was sufficiently visible.

About the EC window technology

- Generally, 85% of the occupants (n = 28) preferred EC windows over conventional windows despite slightly above neutral agreement that they were more satisfied with the EC windows compared to the reference windows, that the tinting and untinting did not disturb them in their work and that the wall switches allowed them to control the EC windows in a satisfactory way. Occupants agreed that the windows looked aesthetically pleasing (6.8).
- Occupants disagreed slightly that the speed of EC switching was satisfactory and there were a few comments expressing dissatisfaction with switching speed under partly cloudy conditions. There also were comments expressing dissatisfaction and confusion with the operation of the wall switches. Both of these aspects of the EC technology may have influenced end user acceptance of the initial control strategy to minimize both HVAC and lighting energy use in the building.

2. PHASE II INSTALLATION IN OPEN-PLAN OFFICES

Configuration of the EC windows and controls

- EC window controls were configured with the same settings as Phase I, with the exception of an added glare submode in the second half of the six-month monitored period (tint levels were still constrained to Tints 1–3). Performance was compared to a "reference" case where the EC windows were set to a fixed Tint 1 throughout the study period.
- Venetian blinds were operated manually in both the reference and test areas without restrictions. Occupants also could manually override the automatic control system similar to Phase I (Tints 1–4).

Visual comfort

- For a window-facing seated viewpoint 4 ft. from the window (reflecting where, on average, an occupant would be sitting at a workstation adjacent to the window), high-dynamic range luminance measurements indicated that unshaded EC windows provided adequate glare control during winter solstice (overcast), equinox (partly cloudy and sunny) and summer solstice (partly cloudy) conditions, even when automatic operation was limited to no darker than Tint 3.
- It should be noted that, the overcast weather patterns pervasive in the area during the winter period prevented glare measurements under low altitude sun clear sky conditions, which are usually the worst case regarding glare.

Indoor environmental quality

- Survey data indicated that occupants in the EC test area found the space darker than in the reference area, although not by much.
- Occupants in the EC area disagreed that the shades blocked the view, while in the reference area occupants agreed slightly. Field observations show that venetian blind use was markedly more prevalent in the reference area than in the EC test area after March. Before March, blind use was at similar or somewhat higher levels in the EC area.
- When the weather was cool/cold, occupants reported being significantly colder in the EC area than in the reference area.

About the EC technology

- In both the EC and reference areas, occupants (92% and 87% of the occupants, respectively) preferred EC windows over the non-switchable windows.
- When grouping responses by workstation position (adjacent to window versus non-adjacent) rather than by area, the majority of the occupants still preferred EC windows (94% and 80% for workstations adjacent and not adjacent to windows, respectively).

Automated controls: Can an HVAC and daylight mode of control be acceptable to occupants in a cloudy climate?

- In this study, the facility managers chose to tune the automatic control system to favor daylighting. Given the cloudy climate, occupant initial complaints at the start of Phase I about the use of Tint 4 seemed to be mostly directed at the dark appearance of the space.
- Later in Phase II, when tuned deliberately to favor reduction of solar heat gains and cooling load[15], occupants again responded negatively because the windows tended to tint more frequently to Tint 3 (Tvis = 0.13) or Tint 4 (Tvis = 0.02) or to tint too long unnecessarily during partly cloudy and cloudy sky conditions or during dawn/ dusk periods.
- The cause of the Phase II negative response may also have been due to other mitigating factors, not necessarily just objections about the dark appearance of the space. Facility managers identified two other issues that contributed to dissatisfaction with the EC windows when talking to occupants informally:
    - Switching speed: Occupants indicated that they would have preferred to have used a darker tint to control glare instead of the venetian blinds so as to preserve view to the outdoors. However, the EC windows took a long time to switch, so occupants used the blinds to reduce discomfort. (Section V.4 indicated that it took 20 minutes to switch from Tint 1 to Tint 2; switching to Tints 3 or 4 is likely to take 30 or more minutes).
    - Manual override logic: In addition to the slow switching speed, the manual override option frustrated some occupants, causing them to use the blinds instead of the EC windows. If the EC windows were already in the process of switching because of automatic or prior manual control, the manual switch was locked out and occupants were not permitted to select a different tint level.
- The manufacturer has since modified the logic of the manual override. Improvements to the control logic also may enable a better balance between competing daylight, view and solar control performance objectives.

I. ENERGY AND ECONOMIC ANALYSIS

Annual energy savings were estimated by referencing a prior energy simulation study conducted on EC windows. In Lee et al. 2004 [3], a parametric analysis was conducted for a prototypical commercial office building designed to meet the ASHRAE 90.1-1999 prescriptive standards.

[15] Tint 3 was used more frequently when the glare sub mode was implemented in April 2016 (Section V.A.1). Tint 4 was used all day by accident during weekdays following a special April weekend test, resulting in an upsurge in occupant complaints and manual overrides (Section V.A.3).

Perimeter zone energy use and peak demand savings were determined by window orientation, window size and climate zones for a range of conventional windows and for EC windows. Data from this study were used to estimate annual energy savings and economic feasibility of the EC technology at the Portland site.

An assumption was made that if the windows were to be replaced at the Portland site, the GSA facility manager would weigh the economics of a conventional spectrally selective low-e replacement window against an EC window. Assumptions for calculating the economic payback were as follows:

- The Portland climate (cooling degree days (CDD), base 80°F of 71; heating degree days (HDD), base 65°F of 4492) was assumed to be comparable to that of the modeled California climate zone 3 (CDD80 108, HDD65 3042, San Francisco Airport).
- The Portland reference window was assumed to be the comparable to the modeled dual-pane, bronze low-e window (window "E"), which had a solar heat gain coefficient (SHGC) of 0.39 and visible transmittance (Tvis) of 0.36. This window matched the composition of the window that was determined using a handheld meter, as described in Section IV.B.2. This baseline reference case was assumed to have no daylighting controls.
- The Portland conventional replacement window was assumed to be the modeled dual-pane, spectrally selective tinted low-e window (window "F"), which had a SHGC of 0.27 and visible transmittance (Tvis) of 0.43. This test case was assumed to have daylighting controls.
- The replacement EC window was modeled with a continuous (not stepped) switching range of SHGC = 0.10–0.37 and Tvis = 0.02–0.45 and was controlled to meet the setpoint illuminance level with daylight. This algorithm minimized solar heat gains and maximized daylighting energy savings. This test case was assumed to have daylighting controls.
- The added energy-efficiency benefit of manually operated interior shades was not included in the simulation model for any of the three cases.
- Site energy savings in the 15 ft. deep south-facing perimeter zone with a window-to-wall-ratio of 0.45 with the low-e and EC windows were 5.57 and 7.72 kWh/ft^2-yr, respectively, assuming that the reported primary electricity savings were due to reductions in lighting and cooling electricity (heating energy use was minimally affected).
- Peak electricity demand in the south facing perimeter zone was reduced by 3.3 W/ft^2.
- The Portland facility managers estimated an incremental increase in effort to maintain the EC windows of 96 hours per year (1 day/month) at $150/ hour. This represented an added cost of $14,400/yr or $0.85/ft^2-floor-yr for the five floors of 15-ft. deep perimeter zones with EC windows. This and the added cost of a maintenance agreement with the vendor was assumed to be offset by the incremental cost of maintaining the more frequently used venetian blinds for the reference condition.

Cost data from a prior GPG study was used in this analysis [8]. RS Means provides cost data for the building industry, where the costs are given for the general Midwest. These costs represent a median value across the country. In **Table** V.I.1, the low-e materials and installation costs were derived from Means, while the EC window cost breakdown was based on costs provided by the manufacturer. The manufacturer estimated a mature market, large volume total cost of $61/ft^2 for

the EC glazing, high-quality framing, controls, installation, equipment, project management, and 25% markup. All costs are given as a final cost to the end user.

Table V.I.1 Predicted lighting energy use intensity (Wh/ft^2-yr) and savings

	Material	Labor	Total
	($/ft^2)	($/ft^2)	($/ft^2)
Low-e IGU	15	9	24
Low-e IGU + frame	19	23	42
EC IGU	49	12	61
EC IGU + frame	53	26	79

Note: Includes all markups.

An economic analysis was performed where the federal utility cost was assumed to be a flat $0.1092/kWh, 6% discount rate and technology life time of 30 years. The cost of daylighting controls was not included. The economics of this scenario were as follows:

- With a bronze low-e window as reference, the simple payback for conventional low-e windows was 15.7 years. The savings-to-investment (SIR) ratio was 1.91. The cost of conserved energy was $0.12/kWh. The internal rate of return (IRR) was 5%.
- With a bronze low-e window as reference, the simple payback for the EC windows was 28.8 years. The SIR ratio was 1.04. The cost of conserved energy was $0.23/kWh. The IRR was 0%.
- The incremental difference in installed cost was $37/ft^2-glass and the difference in simple payback between the spectrally selective, low-e and EC window was 13 years.

For non-Federal facilities, utility costs are higher if there are time-of-use demand charges. **Figure** V.I.1 shows that the simple payback of EC windows can be within 10 years if the installed total cost is lower than $39/ft^2 and the utility rate is $0.20/kWh (which is the average blended rate for metropolitan areas like New York City) or if the installed total cost comes down to below $21/ft^2 with a utility rate of $0.109/kWh. These scenarios are intended to provide one with a sense of what the installed cost would need to be to achieve a 10-year payback and are not intended to be a projection of what the installed cost for future EC windows will be.

The decision to use EC windows may involve other non-energy benefits as indicated from the results of this study:

- Greater access to outdoor view
- Greater access to daylight when solar control is not needed
- Significant solar control and, therefore, balancing of loads between zones exposed to significant solar radiation and internal and north-facing zones. This can improve thermal comfort throughout the building if the HVAC system is unable to respond properly to zones with significant differences in thermal loads.

- Potential health and productivity benefits due to increased daylight and access to outdoor views

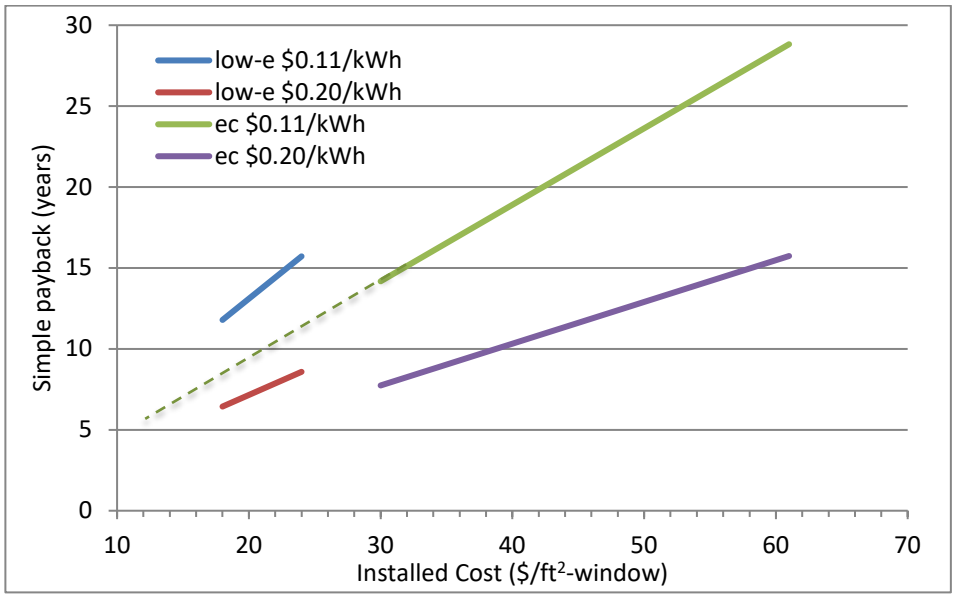


Figure V.I.1. Simple payback (years) of a conventional low-e window and EC window as a function of installed total cost ($/ft^2-window) and flat utility rate for electricity ($/kWh). Annual utility cost savings are due to the use of the two windows with daylighting controls compared to a conventional dual-pane bronze window without daylighting controls in a south-facing 15-ft. deep perimeter zone in Portland. WWR = 0.45.

VI. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT THE DEMONSTRATION FACILITY

The technical objectives of this study were to determine whether the use of EC windows as a retrofit technology in an existing commercial building resulted in decreased lighting energy use, more balanced HVAC loads between the north and south facades of the building, increased comfort and amenity, and decreased use or even elimination of indoor shading. The study also evaluated occupant acceptance and satisfaction with the EC technology. A point-by-point summary of results is given in Section V.H. This section synthesizes these results and addresses these key objectives.

Portland's weather is relatively mild with mostly sunny summers and partly cloudy, rainy winters. Compared to the rest of the United States, solar availability in Portland is among the lowest in the nation. The demonstration was conducted in an existing 1953 large office building with large-area south-facing, dark tinted, low-e windows (WWR = 0.46, Tvis of about 0.15[16]). This type of window was typical of products available in the 1980s and was used primarily to control solar heat gains and conductive losses through the window. In the mid- to late-1990s and thereafter, spectrally selective, low-e windows were introduced to the market. These windows provided more daylight

[16] The nominal visible transmittance of the existing glass was estimated to be about Tvis'=0.15 at a 60° angle of incidence.

than their older counterparts, with similar or better solar heat gain rejection properties. Outcomes from this study reflect energy performance and end-user perspectives relative to older vintage, dark tinted windows.

1. PHASE I

Phase I involved private offices on three floors. EC windows were selected by GSA to match the existing dark tinted, dual-pane, low-e windows and, as such, the switching range of the EC windows was narrowed by the use of an inboard layer of static blue tinted glass. The solar-optical properties of the installed EC window were Tvis = 0.36–0.02 and SHGC = 0.43–0.09. When the EC windows were installed, GSA decided to disable the automatic "glare" mode of control and opted to not allow the EC windows to tint to its darkest state ("Tint 4"). This allowed for improved daylighting in this fairly cloudy climate. Manually operated keypads in each private office enabled occupants to switch the windows to Tint 4 (or any of the other three tint levels) if desired.

End-user comfort and satisfaction with no indoor shades

The need for indoor shades or blinds is a key question related to the cost-effectiveness of EC windows. If EC windows obviated the need for shades, then the economic case would involve weighing the cost of conventional low-e replacement windows with shades or blinds and their associated maintenance against EC windows without shades. To address this question, the existing indoor venetian blinds were tied up to prevent the occupants from using them. If the occupant requested that the blinds be untied, GSA permitted their use. On the reference floor, the operable blinds remained as is.

Over the six-month, monitored, solstice-to-solstice period, the automated controls for the EC windows were found to operate as intended for 97.5% of the time. The remaining 2.5% difference was likely due to time differences between LBNL's calculated data and actual control. When the occupants overrode the automatic controls, the actions were logged by the control system. These data showed that manual overrides were infrequent. When the automated controls were overridden, the majority of the overrides were to Tint 3 or 4 (darker). The controls were overridden more often during the summer compared to the winter.

Use of the indoor venetian blinds was infrequent with the EC windows. Only 30% of the blinds were untied during the monitored period. Blinds were observed to be used in only 20% of the EC offices over the six-month period. Blind use in the reference offices was greater: 50%–75% of the offices used their blinds. So while blinds were used less, this study concluded that blinds will be required in combination with EC windows by some end users.

With the blinds tied up, most occupants in the private offices relied solely on the EC windows to meet their requirements and were largely satisfied with the result. The Phase I EC test configuration without blinds resulted in survey results indicating access to more view, a perception of a slightly dark environment (slightly below neutral towards "dark") and slight perception of increased glare (slightly above neutral towards "glare"). Some occupants voiced annoyance at the blinds being tied up. After the conclusion of the monitored study, observations of blind position indicated an increased use of blinds in the EC test areas, but still less use than in the reference areas.

Based on these data, we inferred that provision of the manual override option of the EC automated controls when the venetian blinds were tied up helped to increase occupants' satisfaction with the EC windows. Occupants could switch the EC windows manually based on the weather forecast, real-time sky conditions, view position in the space, task being conducted, preference for indoor

brightness, and personal tolerance for glare discomfort. The high level of preference for EC windows over conventional windows suggests that this level of personal control improved end user satisfaction with the technology.

Occupant comfort, satisfaction and acceptance of the EC technology

The most important outcome from this study was the survey data. Prior to this field study, there had been no monitored study involving long-term exposure to EC windows with modulated control and a large enough population from which to draw statistically significant results (n≥30).[17] In this case, 40 private offices with EC windows were involved and survey responses were received from 28 of the occupants. For the reference case, a pre-retrofit and post-retrofit survey was issued and a total of 38 and 10 responses were received, respectively.

Occupants overwhelmingly preferred the EC windows (85%) over the reference windows. When asked why, a primary reason may have been greater access to outdoor views: occupants strongly agreed that the view to the outdoors was sufficiently visible with the EC windows and less so with the reference windows. Satisfaction with the EC windows and the way they operated was just above neutral compared to the reference windows. Glare levels were just slightly above neutral (toward "uncomfortable") for both the EC and reference windows, even though the EC controls were not automatically controlling for glare. Thermal comfort was neutral (neither too hot nor too cold) between the EC and reference windows. While the occupants agreed that there was enough daylight for both window conditions, they also found the EC offices to be slightly too dark and gloomy and the reference windows slightly too bright. The sense of gloom could be attributed to the occasional manual override to Tint 4 or automated control to Tint 3 during the equinox to winter period.

Energy savings

The value proposition for EC windows involves increased energy efficiency over the incumbent technology, improved comfort and amenity and lower life-cycle cost. For this building, monitored illuminance and switch status data indicated that daytime lighting energy use savings (8 AM–6 PM) in a 15-ft. deep office zone based on daylight availability was 36%. These savings were achieved over the reference case with conventional windows and with both cases having manually operated venetian blinds. These daylighting savings were achieved with negligible differences in occupants' perceptions of glare or thermal discomfort and with minimal use of the indoor venetian blinds.

In terms of the HVAC energy use, savings were highly dependent on how the EC automated controls were configured by the facilities management team. In this case, daylighting was prioritized over solar control, resulting in the EC windows being automatically controlled to a maximum level of Tint 2 during the summer. The cooling loads were, therefore, not balanced between the north and south sides of the building. Total window heat gains may have been greater than that of the reference windows: the solar-optical and thermal properties of the reference windows were unknown. GSA did switch the EC windows to Tint 4 on weekends, which resulted in transmitted solar radiation levels that were 10% that of the reference windows. This demonstrated the load management potential of the EC windows. If the GSA management chose to minimize cooling demand during

[17] The Denver Federal Center study [8] involved more than 30 survey respondents but the EC windows were controlled to only the fully bleached or fully colored states and most of the respondents were seated in cubicles with 5 ft. high partitions and no direct view of the EC windows.

critical peak summer periods, EC windows could provide the opportunity to reduce HVAC energy use and improve occupant comfort.

Determining how to configure the EC automatic controls (and control zones) to balance trade-offs between HVAC and lighting energy end uses and occupant satisfaction with the indoor environment requires knowledge about the relative operating efficacy of these two systems and judgment regarding the subsequent impact on the occupants. For this application, the facility managers opted to minimize occupant complaints about the workplace being "too dark" by limiting use of the fully tinted level (Tint 4) that would have enabled reduction in HVAC cooling loads.

This preference for more daylight (no automation to Tint 4) was likely to have been due to the cloudy Portland climate where bright daylight and sunlight are highly valued for the infrequent times when conditions are sunny. But the daylight-preferred configuration of the automatic controls also may have been due to other mitigating factors, not necessarily just objections about the dark appearance of the space. Facility managers identified two other issues when talking to occupants informally that contributed to decisions on how the automatic controls were configured:

- Switching speed: Occupants indicated that they would have preferred to have used a darker tint to control glare instead of the venetian blinds so as to preserve view to the outdoors. However, the EC windows took a long time to switch, so occupants used the blinds to reduce discomfort. (Section V.4 indicated that it took 20 minutes to switch from Tint 1 to Tint 2; switching to Tints 3 or 4 was likely to have taken about 30 minutes).
- Manual override logic: In addition to the slow switching speed, the manual override option frustrated some occupants, causing them to use the blinds instead of the EC windows. If the EC windows were already in the process of switching because of automatic or prior manual control, the manual switch was locked out and occupants were not permitted to select a different tint level.

The final automatic control configuration was tuned to prefer daylight and not automate reduction of HVAC cooling loads, but use of manual controls to Tints 3 and 4 suggests that occupants may not be averse to adding a mode of control that would reduce HVAC cooling loads, if implemented when necessary. The manufacturer has since modified the logic of the manual override. Improvements to the control logic would enable a better balance between competing daylight, view and solar control performance objectives.

An analysis of the cost-effectiveness of EC windows with automated daylight and solar control indicates that the annual electricity savings could yield a simple payback of 16 to 29 years and an IRR of 0%–5%. Additional benefits, such as increased daylight and greater access to an unobstructed view should be incorporated into the analysis from the human resources point of view. There also may be reduced costs due to improved HVAC operations and for maintenance and replacement of the indoor blinds.

2. PHASE II

Phase II involved open-plan workstations on two wings of one floor. EC windows were the same as used in Phase I. On the east wing, EC windows were disabled and set to the clear state (Tint 1) for the duration of the study to serve as the reference condition. On the west wing, EC windows were automatically controlled (Tint 1–3) like Phase I without the glare mode for the first three months of the study and then with the glare mode for the last three months of the study. Manual override to

any tint (Tint 1–4) was possible at any time. And unlike Phase I, occupants were free to use blinds in both areas as they saw fit for the duration of the study.

End user satisfaction with indoor shades

In this Phase II, occupants could control their environment with the EC windows the venetian blinds, or both, and like Phase I, also were largely satisfied with the resultant environment. The difference in use of blinds between the EC west wing and reference east wing was not as clear as with Phase I — over the six-month period, sometimes blind use was greater with the EC window. With the introduction of the glare mode during the summer, the automated controls switched the EC windows to Tints 1 and 3 exclusively (Tint 2 was not used), compared to use of Tints 1 and 2 with the Phase I mode of control. Occupant use of the manual override increased significantly when the glare mode was implemented — overrides to Tint 4 still occurred, but there was also an increase in the use of Tint 1 (clear). While perceptions of light level were similar to Phase I (slightly towards "dark"), perceptions of glare were lower in Phase II compared to Phase I. The high level of preference for EC windows over conventional windows suggests that this level of personal control using both EC manual controls and blinds also was satisfactory for the occupants.

Occupant comfort, satisfaction and acceptance of the EC technology

The major distinction between Phase I and II with and without venetian blinds appeared to be occupant's perceptions of glare: Phase I had a higher perceived level of glare compared to Phase II. This may be due to the inherent qualities of the EC window (e.g., switching speed, switching range), since the occupant did not have the blinds to control discomfort. It also may be due to other factors such as use of the glare mode in Phase II or space layout (private office versus open plan office layout).

As in Phase I, occupants overwhelmingly preferred the EC windows to the reference windows. This was evident whether responses were grouped by wing or by distance from window. Survey responses also showed that occupants perceived the space to be darker in the EC area than in the reference area, and that they found that the blinds blocked the view less in the EC are than in the reference area.

In the occupants' comments to the survey, two issues specific to the use of EC windows in open plan areas came up: (1) occupants in workstations away from the windows felt that they were subject to the preferences of the occupants that worked by the window and who, therefore, had control of the window (and/or blinds), and (2) conflicts can arise between occupants of adjacent window workstations when the border between window control zones does not coincide with workstation partitions.

B. BEST PRACTICE

Dynamic EC windows provide end users with the capability to balance the competing demands of daylighting, solar control, glare control, and access to view using real time automated management of the tint level of the glass and therefore are applicable to existing buildings with either dark or light tinted windows. This demonstration illustrated that, in a northern climate like Portland with dynamic sky conditions, EC windows can provide an acceptable daylit environment with minimal use of indoor shades, and despite the slow switching speed of the windows.

Applicability

EC windows are most applicable to commercial office buildings with large-area windows with poor solar-optical properties (e.g., low visible transmittance, high solar heat gain coefficient) and significant exposure to solar radiation (i.e., south-, east- and west-facing orientations).

Facility managers at Portland argued that the best application for EC windows were buildings that required significant solar control, had complaints of thermal discomfort from solar radiation through windows or had complaints of discomfort from improper HVAC operations. They also argued that any building with excessive solar exposure, whether in Alaska or the southern regions of the U.S., could benefit from EC windows, since there is always a cooling season that limits the desire for solar exposure.

Buildings with low-energy cooling systems are likely to benefit from the dynamic control provided by EC windows. For example, buildings with radiant cooling could benefit since such systems take longer to respond to solar conditions. Proactively limiting solar exposure could improve comfort for tenants in these spaces.

EC windows also are applicable to buildings in northern US climates where sunlight, daylight and view are desirable during the winter when conditions tend to be overcast or partly cloudy and where significant solar control is necessary during hot periods of the summer.

Specification of electrochromic windows

It is important to select the proper EC window for the building site and window orientation. EC windows can be configured with different combinations of glass substrates and coatings, which then affect the long-term performance of the installation. The value of EC windows is due to its dynamic qualities. An EC window with a clear glass substrate and clear inboard glazing layer will have a broad switching range. An EC window with tinted glass substrates will have a narrow switching range (particularly for northern, cloudy climates), but may meet the aesthetic requirements of the owner. The narrow range lessens the EC's ability to respond to diverse environmental conditions, particularly daylighting during overcast periods and periods around sunrise and sunset when light levels are low. Select EC windows with a clear inboard glass layer when possible to get the best performance out of the window (e.g., Tvis = 0.58–0.03, SHGC = 0.46–0.09).

If matching existing conditions is of concern, the color of the EC window can be modified by the substrate glass on which the EC coating is deposited or the inboard glazing layer on which the EC outboard glazing layer is combined. The long-term consequences of this decision should be weighed against occupant satisfaction and energy efficiency goals. Some EC coatings have been engineered to exhibit a more neutral blue-gray color when switched. To compare products, ask for samples of the EC glass layer on a clear glass substrate and switch the glass to judge appearance.

The number of times the EC window is switched, switching speed and patterns of control for EC windows are inherently tied to the life of the window. Fast switching speeds can compromise durability for some types of coatings. Allowing the EC window to "rest" at the fully bleached level can enhance durability for some types of coatings. Check the warranty period as an indicator of the lifetime limits of the EC window. The economic analysis assumed a 30-year life for the EC window.

Check with the manufacturer on switching speed as a function of glass temperature. The speed of some types of EC windows is significantly slower when cold compared to other EC windows that do not exhibit temperature dependence. The 3.14 ft. wide EC window in this study took 20 minutes to switch from fully clear (Tint 1, Tvis = 0.36) to the next level of tint (Tint 2, Tvis = 0.25) under warm

sunny summer conditions. The manufacturer claimed that the speed would remain about the same when cold (-10°C).

Controls

The control algorithms for EC windows can be complicated to achieve an optimal balance between competing performance requirements. Discuss control options with the manufacturer and understand where sensors will need to be located and how often they will need to be maintained. It will be important that the facility management team understand that the reliability of the control system is completely dependent on the roof sensor operating properly over the life of the installation. Discuss how HVAC requirements will be addressed along with daylighting and view requirements. Because of the significant variation in glare tolerance, positions of view, tasks, and other factors that impact comfort, we strongly recommend that all projects enable manual override of the EC automatic controls.

Controlling all EC windows to the same tint level in a single space along a façade can reduce the initial capital cost of control wiring for some EC products and simplify operations. It also can create a more uniform exterior façade appearance. However, this and other studies have concluded that the fully colored state yields an environment with which occupants tend not to be satisfied — complaints of the space being too dark or unconnected with the outdoors are common. To increase end user acceptance, consider manual override or automatic control options that switch some small part of the window wall to a lighter tint than others, for example, during periods when solar control is required.

Test out the logic behind the manual control keypad. Some systems lock out the end user, preventing changes to the tint level until after the EC has completed switching. Given the long periods it takes to switch EC windows (30 minutes), lock outs can frustrate the end user and cause greater use or need for indoor shades.

Proper design of the power and communications system can facilitate installation of EC windows in buildings. Look for systems that enable electrical connections to be made with minimal on-site labor. Systems that require individual wire connections to be made on scaffolding outdoors will be inherently much more expensive to install, troubleshoot and maintain.

It may be prudent to power up and test each EC window prior to installation to check for any electrical problems with the EC window units that may have occurred while shipping or defects in the EC coating.

Consider integrating EC controls with other systems in the building. As HVAC and lighting systems are upgraded in the building and facility management goals shift toward net zero energy use, the automated controls for the EC windows can be reprogrammed to accommodate improvements in HVAC or lighting efficacy, changes in utility energy and demand rates and addition of renewable resources to the grid.

C. BARRIERS AND ENABLERS TO ADOPTION

The primary market barrier to adoption of the EC window technology is cost, particularly if non-energy benefits, such as increased comfort, satisfaction and amenity, are not factored into the economic analysis.

- The primary market sectors that benefit from EC windows are large commercial office buildings with large-area windows facing south, east or west and significant solar exposure. Simulations indicate that total energy savings are greater in hotter climates because of the active solar control, but this demonstration showed that there can be significant daylighting benefits, as well, in more moderate, cloudy climates.
- Other applications include projects where replacement of existing windows is already being considered and/or where upgrades to the chiller, cooling tower or other aspects of the HVAC system are being considered. The EC windows can significantly reduce peak cooling loads, which, in turn, can reduce the required capacity and, thus, capital cost for cooling system upgrades.

Other market barriers that may prevent adoption are aesthetic concerns, since the windows can be very dark when fully switched and because different patterns of manual switching can create a non-uniform appearance at the exterior façade.

This study also revealed the complexity of defining an EC control algorithm that achieved an optimum balance between competing performance requirements. Control systems integration with the lighting and HVAC system represents an opportunity to achieve more optimal energy-efficiency/demand responsive control, but integrated controls are not yet turnkey and require careful engineering to get the multiple systems to perform as intended.

Are there market barriers that may prevent the adoption of the new technology? Are there current GSA or industry performance standards/guidelines that need to be revised to enable/stimulate adoption of this technology? Are there incremental first costs for materials and installation that need to be accounted for? Is there risk that will be monetized? As part of the technology deployment, were any significant issues identified by GSA or tenant agency staff?

Summarize whether the technology is cost-efficient and what the assumed payback is, as well as its acceptability among tenants/occupants. Also compare its performance to competing technologies and whether this is the recommended technology for adoption or whether there might be a more effective alternative. Describe locations where it should be deployed as well as circumstance for deployment such as new construction, major renovation or small retrofits. How can the M&V results be extrapolated to other buildings in the portfolio? Provide an overall estimate of the total deployment potential across GSA's portfolio, including overall first costs, payback, and savings.

RECOMMENDATIONS FOR INSTALLATION, COMMISSIONING, TRAINING, AND CHANGE MANAGEMENT

EC windows are fairly simple and straightforward when it comes to installation, as elaborated on in Section IV-C. The wiring and controls associated with the windows are uncommon, but the glazing industry was able to accommodate the task of low-voltage wiring through the framing channel without changes to the procurement and bidding process and without involvement with the electrician's union (this, however, may vary by city).

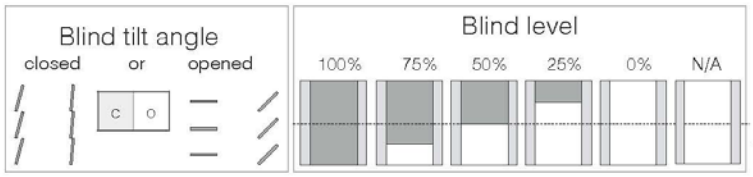
Configuring and commissioning the automatic control system for the EC windows is critical for end user acceptance and satisfaction with the technology. In this case, GSA management opted to set the automatic system to provide more daylight versus control glare in response to early user feedback when first commissioning the system. Manual override switches and indoor blinds were installed to enable personalized control. The vendor was actively involved on the project and addressed facility management concerns and occupant complaints within a few days. It will be

important for the project team to understand that there will be some adjustment period needed to fine tune the automatic controls to the preferences of the occupants and the performance objectives of the facility manager.

The facility management team may be unaccustomed to addressing questions and complaints from the occupants regarding the dynamic windows. Educating the occupant about the technology and user interface (keypad) will be critical for end user satisfaction. A hands-on demonstration or, at minimum, a brochure should be provided to all end users to explain how the technology works for both automated and manual override mode as related to switching speed, control logic, and other aspects of the system. The end user also should be informed as to who they should contact in the event of a problem with the windows.

VII. Appendices

A. SHADING SURVEY FORM



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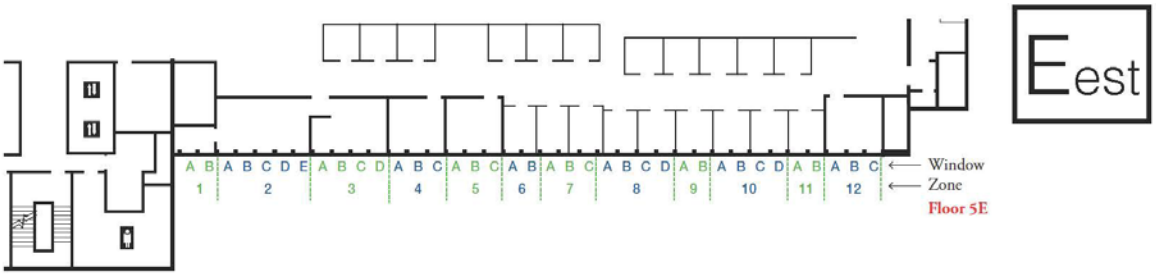

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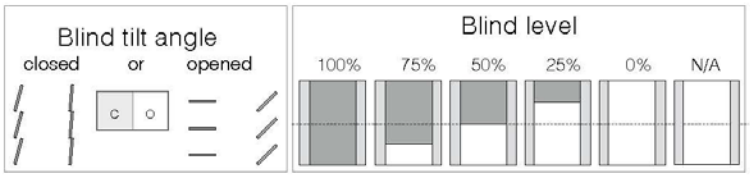

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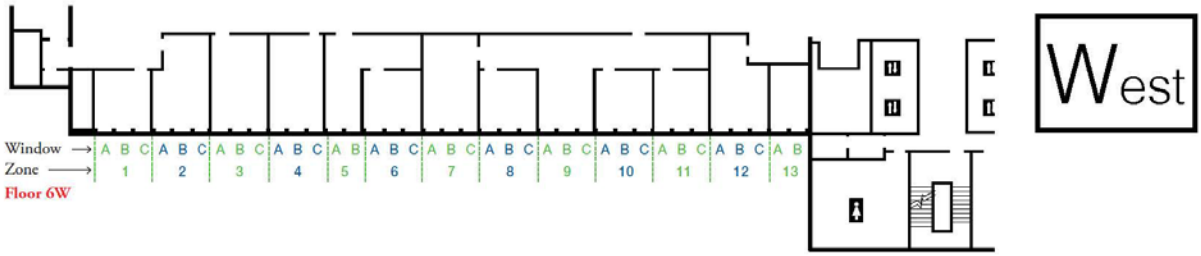

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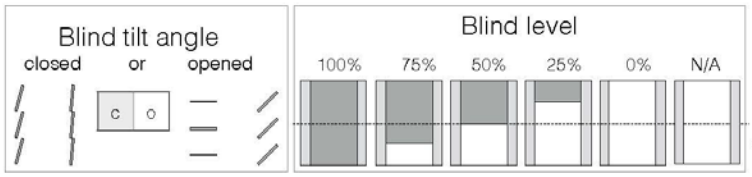

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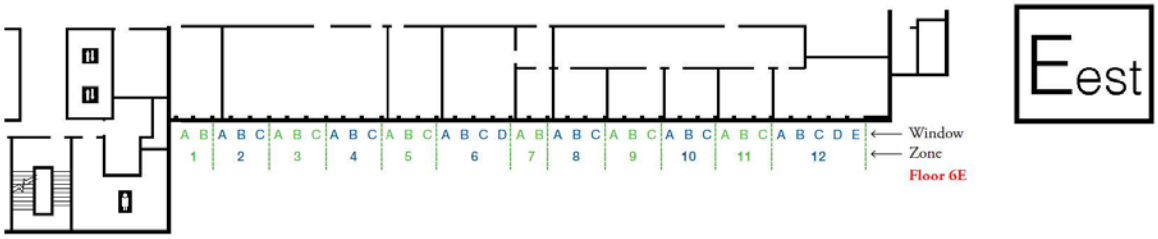

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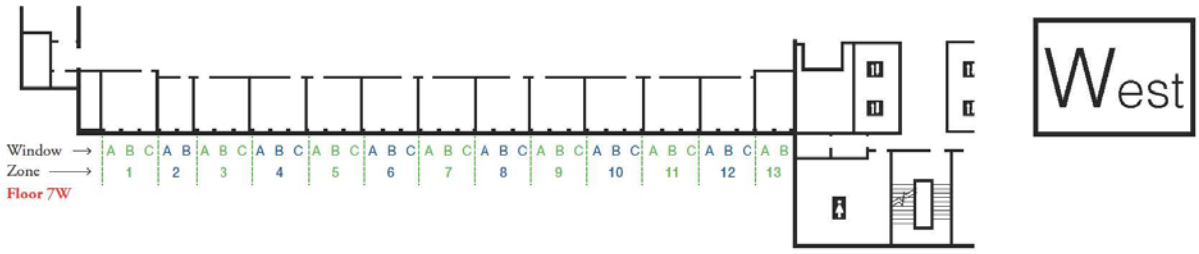

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Blind level

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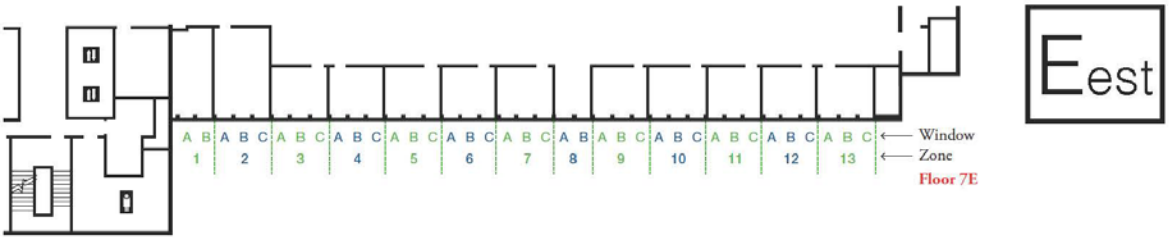

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100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O

6			7			8		9			10		
A	B	C	A	B	C	A	B	A	B	C	A	B	C
0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O	C O

11			12			13		
A	B	C	A	B	C	A	B	C
0%	0%	0%	0%	0%	0%	0%	0%	0%
25%	25%	25%	25%	25%	25%	25%	25%	25%
50%	50%	50%	50%	50%	50%	50%	50%	50%
75%	75%	75%	75%	75%	75%	75%	75%	75%
100%	100%	100%	100%	100%	100%	100%	100%	100%
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C O	C O	C O	C O	C O	C O	C O	C O	C O

B. OCCUPANT SURVEYS

1. PRE-INSTALLATION SURVEY

Switchable windows: Pre-installation 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 switchable windows that are being installed at the 911 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 first of two surveys that are planned to be issued during this project. The second survey will be issued after the switchable windows have been in place and operating for several months.

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.

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.

The envelope provided with this questionnaire also contains a playing card like the ones depicted in the image below. **Please keep it until the second questionnaire is issued in a few months.** This will allow researchers to link your responses to the two questionnaires without your identity becoming known to them.

When you are done with the questionnaire, please place it in the provided envelope and seal the envelope before returning it – and don't forget to keep the playing card!

Switchable Windows

Switchable windows are windows that can tint and untint automatically or at the press of a switch like in the image below:

In March 2015, switchable windows were installed on the 5th, 6th and 7th floors of the 911 Federal Building.

BACKGROUND INFORMATION

1) Please circle the suit, number and back of the playing card that was included with this questionnaire:

Suit: ♣ ♦ ♠ ♥

Number: A K Q J 10 9 8 7 6 5 4 3 2

Back:

2) On what floor is the office where you usually work?

a) 5th floor

b) 6th floor

c) 7th floor

d) 8th floor

3) In what wing of the building is the office where you usually work?

a) East wing

b) West wing

QUESTIONS

4) 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

5) 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

6) When working at your office, on average, what percentage of time do you spend on each of the tasks below?

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

7) When working at your office, on average, what percentage of time do you face each direction?

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

****** When answering the questions below, please refer to your experience with CLEAR, NONSWITCHABLE windows in your workspace, i.e., before any of the electrochromic windows were installed. ******

8) Please assign a rating from 1 to 9 (or N/A = not applicable) to the following conditions in the office where you usually work.

	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

9) Indicate your level of agreement/disagreement (disagree = 1, agree = 9) with the following statements about the office where you usually work.

	Disagree				Neutral				Agree	
a) Bright light on my task makes it difficult to read or see	1	2	3	4	5	6	7	8	9	
b) The shades block the view	1	2	3	4	5	6	7	8	9	N/A
c) There is enough daylight in the space	1	2	3	4	5	6	7	8	9	
d) The windows look aesthetically pleasing	1	2	3	4	5	6	7	8	9	

****** When answering the questions below, please refer to your experience with CLEAR, NONSWITCHABLE windows in your workspace, i.e., before any of the electrochromic windows were installed. ******

10) Usually, how often do you adjust 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

11) Usually, in what position are the blinds in your office?

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

12) When you **lower** the blinds, what are usually 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 brighness of reflections on my computer monitor
    - ☐ Other (please specify) _____

13) When you **raise** the blinds, what are 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) _____

14) Please provide any comments on the windows in your office.

****** If you are on the 6th or 7th floor, please refer to your experience with CLEAR, NONSWITCHABLE windows in your workspace, i.e., before any of the electrochromic windows were installed. ******

Comments

2. POST-INSTALLATION SURVEY

Electrochromic floors

Switchable windows: Post-installation 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 911 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.

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.

A playing card, like the ones depicted in the image below, was included with the first survey last April. **Please retrieve the card before filling out this questionnaire.** This will allow researchers to link your responses to the two questionnaires without your identity becoming known to them. **If you do not retrieve the card, please fill out the questionnaire anyway – your response is just as valuable.**

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 like in the image below:

In March 2015, switchable windows were installed on the 5th, 6th and 7th floors of the 911 Federal Building and have been in operation for approximately nine months.

BACKGROUND INFORMATION

1) Please circle the suit, number and back of the playing card that was provided with the first survey:

Suit: ♣ ♦ ♠ ♥

Number: A K Q J 10 9 8 7 6 5 4 3 2

Back:

2) On what floor is the office where you usually work?

a) 5th floor

b) 6th floor

c) 7th floor

d) 8th floor

3) In what wing of the building is the office where you usually work?

a) East wing

b) West wing

QUESTIONS

4) 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
e) Glare	1	2	3	4	5	6	7	8	9
f) Cold	1	2	3	4	5	6	7	8	9
g) Heat	1	2	3	4	5	6	7	8	9
h) Gloominess	1	2	3	4	5	6	7	8	9

5) 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 THE SWITCHABLE WINDOWS HAVE BEEN OPERATING…

When answering the questions below, please have in mind the period since the electrochromic windows were installed (April 2015 to present).

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

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

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

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

8) Please assign a rating from 1 to 9 (or N/A = not applicable) to the following conditions in your office since April 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 THE SWITCHABLE WINDOWS HAVE BEEN OPERATING…

When answering the questions below, please have in mind the period since the electrochromic windows were installed (April 2015 to present).

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

SINCE THE SWITCHABLE WINDOWS HAVE BEEN OPERATING…

When answering the following questions, please have in mind the period since the electrochromic windows were installed (April 2015 to present).

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

11) 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):

f) When it is cold outside, I feel warmer with the *switchable* windows than with the *original* windows
g) When it is hot outside, I feel cooler with the *switchable* windows than with the *original* windows
h) There are less drafts through the window
i) Other(s) (please specify)_____

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

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

13) Since the switchable windows have been operating, have you lowered the window blinds from their fully raised position?

c) Yes
d) No

14) (If "Yes" on 13) 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
- ☐ Other (please specify) _____

15) (If "Yes" on 13) With the *switchable* windows, did you set the blinds to the same height and slat angle as with the *original* windows?

a) Yes
b) No

16) (If "No" on 15) 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

17) (If "Yes" on 13) 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

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

a) Yes
b) No

19) (If "Yes" on 18) 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

20) (If "Yes" on 18) 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
- ☐ Other (please specify) _____

21) (If "Yes" on 18) When you used the wall switches, did the new windows tint/untint as expected?

a) Yes
b) No

22) (If "No" on 21) Please describe what you expected and what happened instead.

23) (If "Yes" on 18) When you used the wall switches, did the windows succeed in achieving the effects you indicated in your answer(s) to question 18 in a timely manner?

a) Yes
b) No

24) (If "No" on 23) Please describe what you expected and what happened instead.

25) 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)

Additional comments

Reference floor

Switchable windows: Post-installation 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 911 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.

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.

A playing card, like the ones depicted in the image below, was included with the first survey last April. **Please retrieve the card before filling out this questionnaire.** This will allow researchers to link your responses to the two questionnaires without your identity becoming known to them. **If you do not retrieve the card, please fill out the questionnaire anyway – your response is just as valuable.**

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 like in the image below:

In March 2015, switchable windows were installed on the 5th, 6th and 7th floors of the 911 Federal Building and have been in operation for approximately nine months.

BACKGROUND INFORMATION

1) Please circle the suit, number and back of the playing card that was provided with the first survey:

Suit: ♣ ♦ ♠ ♥

Number: A K Q J 10 9 8 7 6 5 4 3 2

Back:

2) On what floor is the office where you usually work?

a) 5th floor

b) 6th floor

c) 7th floor

d) 8th floor

3) In what wing of the building is the office where you usually work?

a) East wing

b) West wing

QUESTIONS

4) 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
i) Glare	1	2	3	4	5	6	7	8	9
j) Cold	1	2	3	4	5	6	7	8	9
k) Heat	1	2	3	4	5	6	7	8	9
l) Gloominess	1	2	3	4	5	6	7	8	9

5) 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 APRIL 2015…

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

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

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

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

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

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

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

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

SINCE APRIL 2015…

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

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

	Disagree				Neutral				Agree
a) I experience less glare since April 2015 than before	1	2	3	4	5	6	7	8	9
b) I feel less heat from the sun since April 2015 than before	1	2	3	4	5	6	7	8	9
c) I am more thermally comfortable (less hot and/or less cold) since April 2015 than before	1	2	3	4	5	6	7	8	9
d) Generally, since April 2015 I am more satisfied than before with the windows in my office	1	2	3	4	5	6	7	8	9

11) If you are more thermally comfortable (less hot and/or less cold) since April 2015 than before, please indicate reasons why (please check all that apply):

j) When it is cold outside, I feel warmer since April 2015 than before
k) When it is hot outside, I feel cooler since April 2015 than before
l) There are less drafts through the window
m) Other(s) (please specify)_____

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

n) Two or more times a day
o) Once a day
p) Not every day, but at least once a week
q) Less often than once a week
r) Never

13) Since April 2015, in what position have usually been the blinds in your office?

d) Fully raised
e) Fully lowered
f) Somewhere in between

14) Since April 2015, have you lowered the blinds in your office?

e) Yes
f) No

15) (If "Yes" on 14) When you lowered the blinds, what were usually 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
- ☐ Other (please specify) _____

16) Since April 2015, have you raised the blinds in your office?

a) Yes
b) No

17) (If "Yes" on 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) _____

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

Comments

Additional comments

C. INSTRUMENTATION

Below are photographs showing the various types of instrumentation installed in the building.

Figure C.1. Room with instrumentation level A. Image taken prior to completion of installation. In particular, blue masking tape was removed after silicon sealant was set.

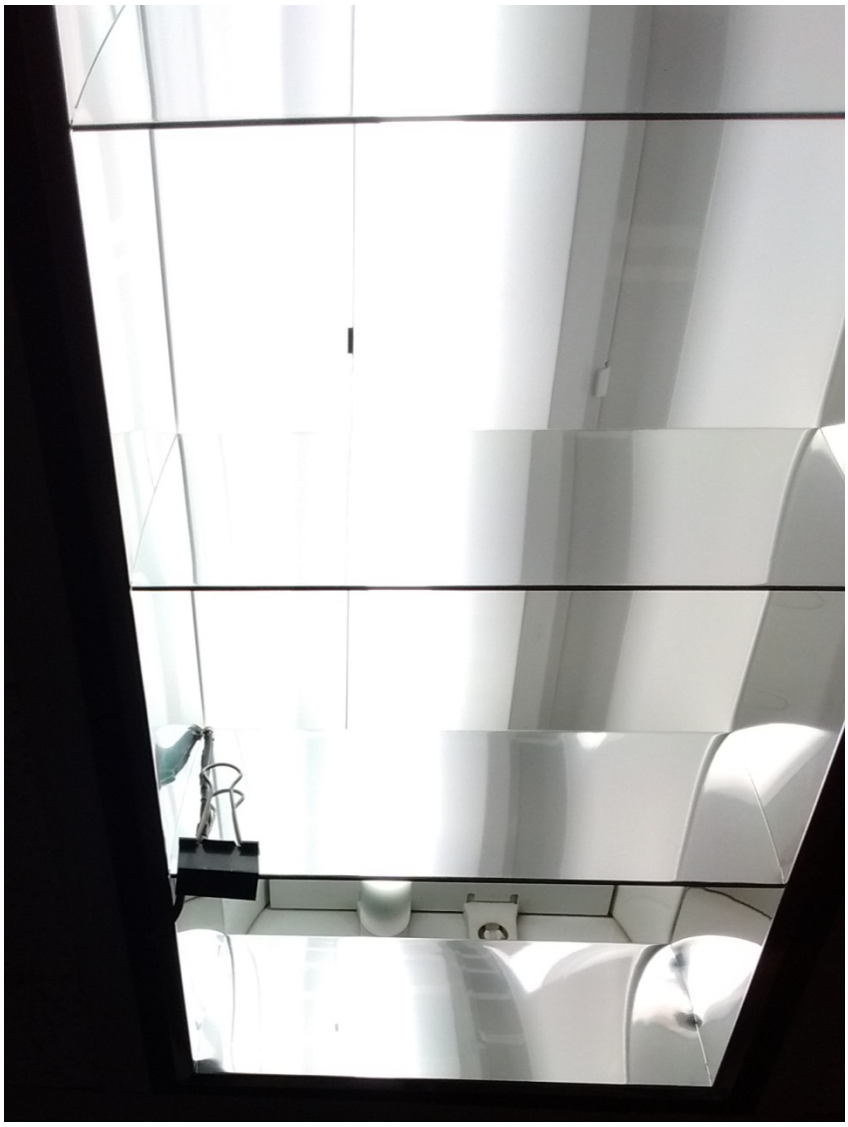

Figure C.2. Luminaire photoresistor sensor.

Figure C.3. Room with instrumentation level B.

Figure C.4. Room with instrumentation level C. Image was taken prior to completion of installation.

Figure C.5. Exterior vertical irradiance and illuminance sensors. These sensors face due south, and are mounted over the edge of the south façade of the building's service core. They are mounted on a steel tube structure, secured with steel cables and weighted down by cinder blocks. The image was taken facing approximately ESE. South is to the right of the picture, approximately.

Figure C.6. Weather instruments. To the left, the global and diffuse horizontal irradiance sensor is mounted on a pre-existing metal platform, atop a pole. Wind, temperature and relative humidity sensors are mounted on a tripod-base structure, shown at the center of the image. The structure also holds a solar panel for powering the data acquisition system (white box under tripod).

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E. GLOSSARY

Daylight Glare Probability (DGP)	A metric for visual comfort. Its values range from 0 to 1, representing the probability that a person would experience disturbing glare in a particular situation.
Illuminance	The amount of luminous flux falling on a surface. Its customary units of measurement are lux (lx) or foot-candles (fc). It can be understood as the amount of visible light falling on a surface.
Infrared radiation (IR)	Infrared electromagnetic radiation with wavelengths greater than 0.7 microns. Short-wave infrared radiation is from 770–2500 nm (0.77–2.5 microns). Long-wave infrared is defined by wavelengths greater than or equal to 2.6 microns.
Low-e (low-emittance) coating	A thin (<100 nm) metal, metal oxide or multilayer coating deposited on glass to reduce its thermal infrared emittance and radiative heat transfer.
Luminance	The amount of luminous flux leaving a surface in a particular direction. Its customary unit of measurement is the candela per square meter (cd/m^2). It can be understood as a measure of brightness of a particular point in the field of view.
Nominal solar transmittance (Tsol')	Monitored solar transmittance at the window in the field test as expressed as the ratio of the solar irradiance transmitted through the window at the indoor face of the glass divided by the incident solar irradiance at the outdoor face of the glass. It is expressed as a number between 0 and 1.
Nominal visible transmittance (Tvis')	Monitored visible transmittance at the window in the field test as expressed as the ratio of the vertical illuminance transmitted through the window at the indoor face of the glass divided by the incident vertical illuminance at the outdoor face of the glass. It is expressed as a number between 0 and 1.
Solar heat gain coefficient (SHGC)	The fraction of solar radiation admitted through a window including both directly transmitted and absorbed radiation that is released inward to the building. The SHGC has replaced the shading coefficient (SC) as the standard indicator of solar control. It is expressed as a number between 0 and 1. The lower the value, the less solar heat the window transmits.
Solar transmittance (Tsol)	The fraction of solar radiation transmitted by the glazing system between the limits of 300 to 2500 nanometers at normal incidence. It is expressed as a number between 0 and 1.
U-value	The heat transmission per unit time through a unit area of material or construction (including the boundary air films on the surface of the material) induced by a unit temperature difference between the environments on each side of the material. The

	lower the U-value, the greater the insulating value or the window's resistance to heat flow. Also known as the U-factor.
Visible transmittance (Tvis)	The fraction of solar radiation transmitted by the glazing system between the limits of 380 to 770 nanometers at normal incidence. It is weighted according to the photopic response of the human eye and is expressed as a number between 0 and 1.
Window-to-wall ratio (WWR)	The ratio of the total area of the windows (glass area plus frame) divided by the total area of the floor-to-floor exterior wall.