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Arnold Schwarzenegger
*Governor*

# ADVANCEMENT OF ELECTROCHROMIC WINDOWS

PIER FINAL PROJECT REPORT

*Prepared For:*
**California Energy Commission**
Public Interest Energy Research Program

*Prepared By:*
**Lawrence Berkeley National Laboratory**

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# Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Advancement of Electrochromic Windows is the final report for the Advancement of Electrochromic Windows project, contract number 500-01-023, conducted by the Lawrence Berkeley National Laboratory, Berkeley, CA. The information from this project contributes to the PIER Building End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Energy Commission's Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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# Abstract

Switchable variable-tint electrochromic windows preserve the view out while modulating transmitted light, glare, and solar heat gains and can reduce energy use and peak demand. To provide designers objective information on the risks and benefits of this technology, this study offers data from simulations, laboratory tests, and a 2.5-year field test of prototype large-area eletrochromic windows evaluated under outdoor sun and sky conditions. The study characterized the prototypes in terms of transmittance range, coloring uniformity, switching speed, and control accuracy. It also integrated the windows with a daylighting control system and then used sensors and algorithms to balance energy efficiency and visual comfort, demonstrating the importance of intelligent design and control strategies to provide the best performance. Compared to an efficient low-e window with the same daylighting control system, the electrochromic window showed annual peak cooling load reductions from control of solar heat gains of 19–26% and lighting energy use savings of 48–67% when controlled for visual comfort. Subjects strongly preferred the electrochomic window over the reference window, with preferences related to perceived reductions in glare, reflections on the computer monitor, and window luminance. The EC windows provide provided the benefit of greater access to view year-round. Though not definitive, findings can be of great value to building professionals.

Keywords: Electrochromic windows, switchable windows, daylighting controls, daylight, energy efficiency, peak demand, visual comfort, human factors, commercial buildings

# Executive Summary

## Introduction

Switchable variable-tint electrochromic (EC) windows preserve outside views while modulating transmitted light, glare, and solar heat gains. They also offer the potential to significantly reduce building energy use and peak demand by impacting heating, cooling, and lighting consumption. This newly commercialized technology has sparked considerable interest, and its innovative aspects are likely to capture the imagination of leading-edge architects and building owners. However, these market movers require realistic quantification of window performance, energy impacts, and user acceptance to gain the confidence needed to adopt and promote this technology.

To provide this information, this study made use of large-area EC window prototypes to conduct a 2.5-year field test in an office-building testbed located in Berkeley, California. This field test, along with other tests and simulations, allowed quantification of EC window performance under realistic commercial office conditions and enabled the research team to refine the system design to improve performance and reliability. Parallel efforts to develop solar optical characterization–enabled rating, labeling for EC products, and information products promise to help build the market for EC windows and facilitate their use.

## Purpose

This project aimed to advance EC windows as a viable marketplace solution for energy savings and load management by:

- Solving critical hardware and software design and engineering integration issues related to using EC windows within a whole building energy efficient system
- Providing accurate and objective data to validate EC window energy performance and quantify the value of EC window comfort, reliability, and performance
- Developing the information products needed to foster use of EC windows and maximize their benefits while minimizing risk and performance uncertainties

## Project Objectives

- Systems engineering: Develop integrated whole building EC solutions that address comfort concerns, maximize energy and peak demand reductions, and are reliable, practical, and cost-effective for most commercial buildings
- Performance impacts: Identify and quantify overall benefits, costs, and risks of EC technology under realistic operating conditions to stimulate market interest and enhance market success
- Information resources: Develop tools and information resources to increase awareness of EC windows and enable the use of this technology

## Project Outcomes

The outcomes discussed below apply specifically to the prototypes supplied by one manufacturer in 2003. These prototypes have since been refined, and other manufacturers may be offering products with different properties. However, the conclusions below are relevant to the broad class of dynamic glazing products.

### *Systems Engineering*

*EC window and dedicated intermediate-state controller*

The field test program evaluated the performance of 0.46-m by 0.89-m (18x35-inch) absorptive tungsten-oxide EC windows with a visible transmittance (Tv) range of 0.60–0.05 and solar heat gain coefficient (SHGC) range of 0.42–0.09. Findings included the following:

- Switching from bleached to full color took about 6–7 minutes for EC surface temperatures greater than 10ºC (50ºF). For colder temperatures with low solar irradiance, switching could take 40–85 minutes to reach full coloration.
- The EC window switched with an applied voltage of ±3-5 V dc. Average daily power consumption for switching and maintaining steady state for a 12-hour day was 0.03–0.07 W/ft$^2$-floor (4.6-m, 15 ft-deep perimeter zone).
- The prototype EC windows had minimal optical defects. For several of the 30 supplied EC prototypes, the switching range decreased over the 2.5-year installed period.
- A new closed-loop intermediate-state controller was devised by LBNL with the manufacturer, which provided significantly more accurate transmittance control over a six-month test period than did the original alpha intermediate-state controller.

*Integrated EC window and daylighting control system*

An integrated EC window and daylighting control system was engineered, tested, and refined over 20 months in a full-scale testbed facility in Berkeley, California consisting of three private office test rooms with a south-facing unshaded window wall. The optimal field solution called for dividing the EC window wall into two zones to reduce solar heat gains and glare without eliminating daylight:

- The upper EC daylighting zone, with an interior Venetian blind (~45° slat angle) to block sunlight, was controlled to admit sufficient daylight so as to minimize use of supplemental electric lighting.
- The lower EC view zone was controlled to admit daylight under diffuse sky conditions or was switched to fully colored (Tv=0.05) under direct sun conditions to reduce glare and brightness contrasts on task surfaces.

A simulation using two software tools—Radiance and Mathematica—quantified the performance of a more refined solution that involved manipulating the Venetian blind to block direct sun from the occupant’s view, constraining the tint of the upper and lower EC zones for visual comfort, and optimizing both EC zones to admit sufficient daylight. Additional studies showed that achieving maximum energy reduction required controlling the window and lighting system to minimize lighting energy use rather than to reduce solar heat gains, primarily because the coefficient of performance (COP) of conventional HVAC systems shows little daily variation.

### *Performance Impacts:*

*Energy and peak demand performance*

To understand energy and demand performance, the project team installed a 2.7x3.0-m (9x10-ft) windowwall of 15 EC windows in each of two private office rooms in the Berkeley testbed and equipped the third office with efficient spectrally selective low-e windows (Tv=0.42, SHGC=0.22) to serve as a reference room. All three rooms had identical daylight-controlled electric lighting systems and were thermally isolated with dedicated HVAC systems. More than 100 sensors installed in each room monitored control response, EC and lighting operations, thermal loads, and visual comfort on a minute-to-minute basis. Findings included the following:

Lighting energy savings

Results are representative of annual results, having been monitored over a six-month solstice-to-solstice period at minimum. The reference case assumed use of matte-white Venetian blinds, well-tuned daylighting controls (used in only 1–2% of buildings today), and Tv=0.42.

- Controlling the EC window to maximize daylight and energy efficiency yielded average daily lighting energy savings of 6±7% and 26±15%, respectively, compared to the reference case without and with fully lowered blinds.
- Controlling the EC window to meet visual comfort and daylight requirements decreased the average daily lighting energy savings of 26±15% for the reference case to 10±15%.
- Daily lighting energy savings are much greater, 44±11% on average, compared to a more typical reference case with blinds and no daylighting controls.

Cooling load reductions

- In general, visual comfort control had a far greater effect on lighting energy savings than on monitored daily cooling load reductions due to solar heat gains.
- Controlling the full EC window wall for glare (Tv=0.05, SHGC=0.09) reduced average daily cooling loads due to solar heat gains by 8±9% and 3±8%, respectively, compared to the reference window without and with a fully lowered blind.
- Use of a split-façade EC window raised average daily cooling loads due to solar heat gains by 11±12% compared to the shaded reference case.
- Including daily cooling loads due to lighting heat gains, total daily room cooling loads were unchanged (0±3%) for the split façade case.

Peak demand reductions

- The EC system provides potentially large savings in electric demand on hot days. The windows reduced peak cooling loads by 26% and 19%, respectively, compared to the unshaded and shaded reference case.
- Switching the lighting system to standby power yields savings of 97% (1.36 W/ft$^2$-floor) if the reference case has no lighting controls.
- DOE-2 simulations showed greatest energy and peak demand savings for perimeter zones facing south, east, and west in hot U.S. and California climates.

### *Occupant comfort, satisfaction, and acceptance*

To determine non-energy benefits, which are critical to market success, 43 subjects completed a questionnaire after being exposed for 40–60 minutes to three different EC window-lighting conditions:

- A reference mode of Tv=0.60 and manually operated Venetian blind and lights
- A semi-automatic mode
- A fully automated mode that switched the entire windowwall based on daylight and glare

Results confirm the promise of EC systems to improve satisfaction and comfort in work spaces. Occupants found the EC window system significantly more desirable than the reference window, where preferences were strongly related to perceived reductions in glare, reflections on the computer monitor, and window luminance.

With the EC systems, subjects chose to face the window to do computer-related tasks, presumably for view, despite minor complaints of glare and brightness. The key benefit of year-round view was confirmed by a Radiance-Mathematica simulation. For the south-facing façade, which receives direct sun, view was available for 98% of annual daylight hours with the EC case and only 38% with the reference case.

The EC windows darken by absorption, and the surface temperature of the exterior pane can reach levels of ~72.6ºC (163ºF) in direct sunlight for the Berkeley climate. Subjects did not complain about thermal discomfort due to the surface temperature of the window (radiative heat transfer was decreased with the low-emittance coating) or direct solar irradiance (which they could block with the blind).

### *Information Resources*

Public awareness of the emerging EC window technology was increased via conferences, meetings, tours of the LBNL EC test facility, and publications. In addition, groundwork, including development of dynamic window ratings with the National Fenestration Rating Council (NFRC), will enable architects and engineers to compare, rate, and compute the performance impacts of EC windows in buildings. Design guidelines and a website (http://windows.lbl.gov/comm_perf/electroSys-cec.htm) were also produced.

## Conclusions

EC windows can deliver significant energy and peak demand savings, visual comfort, and greater access to view, depending on the assumptions for the reference case and how the EC window is controlled to manage direct sun and glare. To achieve savings, comfort, and amenity routinely, an accurate intermediate-state EC window controller must be devised. Practical integrated EC window-lighting systems, which modulate glass transmittance to manage daylight, glare, and cooling load and to dim lights to capture energy savings, must also be developed to meet visual comfort requirements while maximizing daylight admission and reducing lighting power.

The first EC products that became commercially available in 2006 do not have all of these desired capabilities, offer only on-off control, and are burdened with a cost premium. Costs should decrease significantly as volume increases. At this time, EC products in isolation are not cost-effective based on energy savings alone, but their load management and non-energy benefits are likely to stimulate market interest among early adopters. As with many new energy efficiency products, feedback from the early applications of the technology should lead to enhanced performance and reduced costs.

**Recommendations**

- EC manufacturers should develop an accurate intermediate-state controller and work toward faster switching speeds, less color in the tinted state, lower minimum transmittance, and reduced manufacturing costs.
- Additional field tests are needed to quantify the performance of more mature EC windows. Further, load management and demand response capabilities need to be explicitly tested in the field.
- Work is needed to develop integrated window-lighting control algorithms that are more versatile, practical, and reliable and that accommodate different visual tasks, building occupancies, and climate/HVAC conditions.
- New designs that address the subtleties of optimizing glare and energy control will make it easier for architects to use EC windows.
- Further work is required to implement the infrastructure to support design and specification of EC windows in buildings: rating and labeling systems, codes and standards, design guides, and tools. The history of new technology adoption suggests that various forms of this support will be needed over a 5–10 year period to advance these smart glazing technologies into the marketplace.

**Benefits to California**

Thanks to their cooling and daylighting benefits, EC windows will help California decrease energy use and demand by providing building owners with a technology to respond to future time-dependent price structures for electricity or an emerging demand response requirement. Technologies of this sort will also help California achieve the aggressive energy savings goals set by the Governor. Furthermore, within next five years, EC windows could provide a cost-effective option for the utility-administered energy savings programs initiated by the California Public Utilities Commission (CPUC).

This project has already increased public awareness of the technology and will provide objective third-party information about the characteristics of EC windows and their likely performance impacts in commercial buildings. The information in this report clearly delineates the risks and benefits of using the EC window technology in a typical commercial office application today and the future promise of the technology.

# Introduction

## 1.1. Background and Overview

Electrochromic coatings (EC) are switchable thin-film coatings applied to glass or plastic that reversibly change optical transmission with a small applied voltage. EC windows can preserve view out while modulating transmitted light, glare and solar heat gains (Figure 1). Prior building energy simulation studies indicated that electrochromic windows have the technical potential to significantly reduce energy use and peak demand in residential and nonresidential buildings. Some of these studies (primarily conducted in the 1980s to early 1990s) have estimated that electrochromic windows can reduce annual energy use by 20-30% and reduce electric demand in commercial office buildings situated in moderate to hot climates if combined with daylighting controls that dim the electric lighting in response to daylight (e.g., Sullivan et al. 1994, Lee and Selkowitz 1995). Given the importance of cooling and lighting energy use in most California commercial buildings and the role of cooling in residences, particularly in the rapidly growing hot inland climate regions, and the critical role that cooling and lighting play in electric demand and thus in any load management or demand response program, these technologies may play a crucial enabling role in emerging efforts to reduce energy use and electric loads. These simulation studies helped to spur early public and private R&D investment in this new emerging technology with the hopes that development and deployment of such a technology would significantly improve the energy efficiency of future building stock in California.

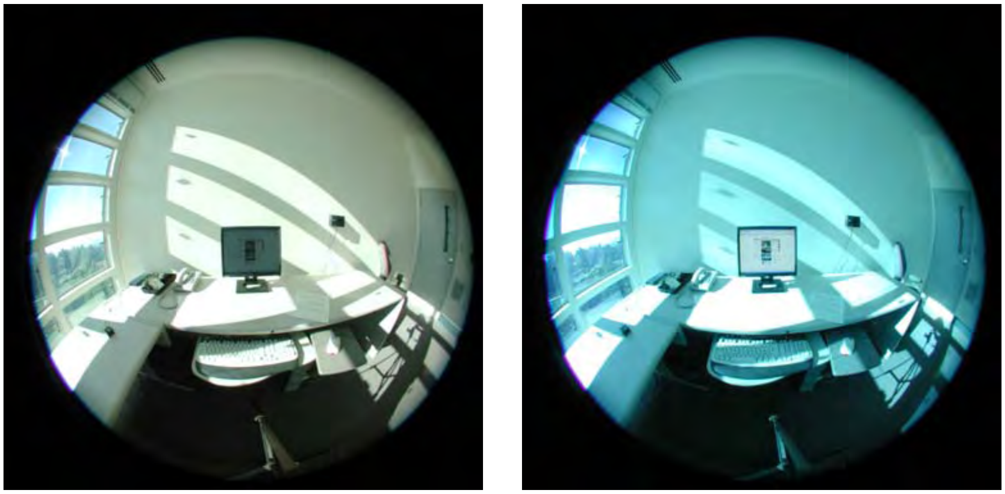

**Figure 1. EC window at a visible transmittance (Tv) of Tv=0.60 (left) and Tv=0.05 (right) on a clear sunny winter day.**

Making a thin-film coating with a wide dynamic switching range that will operate over tens of thousands of switching cycles is a major technological challenge for material scientists. As the material science R&D on chromogenic coatings matured, coating properties and durability improved and progressed from small laboratory-sized test samples (0.075 m, 3-inch square) to pilot production facilities producing large-area (1-2 $m^2$, 11-21 $ft^2$) windows in the late 1990s. In parallel with these advances, the focus of the applications side of R&D shifted from simulations to full-scale testing of pre-market EC devices in real-world applications in order to identify and address unforeseen engineering issues, gauge user acceptance, and measure actual energy and demand savings under realistic weather conditions. As with any new technology, there are significant technical, engineering, architectural, and general public interest questions that remain unanswered. Answering these questions enable major stakeholders to adopt this technology without undue risk and can accelerate broader acceptance and implementation of this technology within emerging building markets. Objective information about the performance and impacts of this technology in buildings provides architects, engineers, and building owners with the necessary information needed to make sound business decisions. Products will fail in the marketplace if these impacts are not well understood. This applications R&D activity has been particularly important for the electrochromic technology because accurate solar-optical characterization of this glazing material is challenging and simulation tools do not yet adequately describe the various control systems and response characteristics of the technologies involved. Furthermore, the implementation of automated control of switchable windows and integration with other building control systems to achieve satisfactory and acceptable control are yet unproven and present relevant challenges that must be addressed and resolved before the market will accept and adopt these technologies on the widespread scale needed to impact societal energy use and demand.

To date, several field studies have been conducted over the past few years on large-area electrochromic prototype windows that were deemed sufficiently mature for market introduction. "Maturity" was defined by devices that had acceptable appearance (e.g., uniformity of tint), reasonable switching range, good potential durability, and the potential to be manufactured at low cost. In 1999, a four-month field study was conducted by the Lawrence Berkeley National Laboratory (LBNL) in two private offices involving continuously modulated large-area EC windows (a then commercially available German product) integrated with daylighting controls (see Appendix A, citation 6). The study mapped basic characteristics of EC windows (switching range, switching speed) to monitored performance variables and presented lighting energy use savings and visual comfort data for daylight- and glare-controlled EC windows. Within the three-year European Union (EU) Switchable Facade Technology (SWIFT) program (completed in 2003), several field studies were undertaken: one for a residential application and several for typical private offices that are common to commercial buildings. These studies were undertaken to gain real-world experience with electrochromic (the same type used for the LBNL study) and gasochromic[1] facades, to evaluate user reactions to switchable facades, and to monitor various environmental variables (interior air and operative temperature, illuminance, luminance distributions over a two-week period) resulting from the use of such technologies as compared to conventional technologies. The EU approach for use of EC windows in buildings differs from the U.S. due to its milder climate and more restrictive building regulations. Limited results from this study became publicly available in 2004 (Platzer 2003). While continued materials development has progressed largely with industry funding, there has been no such investment in the critical field performance area. Field tests conducted under real sun and sky conditions subject these products to a thorough "road" test enabling stakeholders to directly experience and judge performance. Such studies provide manufacturers

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[1] Gasochromics have a similar basic composition but the active electrochromic layer switches with the insertion and removal of hydrogen gas into the between-pane gap of an insulating glass unit (IGU).

with useful feedback to improve their products. But even more important, information is generated for utilities and public entities such as the California Energy Commission (Energy Commission) that are required to make estimates of future generation needs and develop new building standards. For technologies of this complexity, which require building systems integration to achieve their potentials, it is impossible to accurately assess performance with simulation alone. Accordingly, following the limited 1999 LBNL field study, a three-year field test program was initiated in 2002 and supported jointly by the U.S. Department of Energy (DOE), the Energy Commission, and the U.S. Department of Housing and Urban Development. This program focused on conducting field trials of emerging qualified EC window prototypes for residential and commercial building applications. LBNL was tasked to conduct the commercial field tests, while the National Association of Home Builders (NAHB) Research Center and the National Renewable Energy Laboratory (NREL) conducted the residential field tests. This field test program was complemented by other R&D work supported by DOE to develop novel electrochromic material concepts (e.g., reflective hydrides), establish durability test procedures and verify EC prototype long-term durability, and to assist industry with the development of new EC coating manufacturing processes that would improve yield and quality and reduce production cost. This final report documents the commercial field tests. The complementary projects are documented to varying limited degrees in other publications.

This commercial field test program has met its initial critical goals of clarifying and quantifying the performance potentials of the emerging generation of EC glazings in a timely manner. In the last half of this program, one U.S. manufacturer, SAGE Electrochromics, Inc., began supplying small sized (0.46x0.89 m, 18x35 inches) glazed units with “on-off” switching to a skylight manufacturer (Velux) for test markets in the U.S. SAGE Electrochromics says that they have begun shipping large-area EC windows and skylights (up to 1.1x1.5 m, 42.5x60 inches) with on-off switching in early 2006. This project has provided objective information to technology developers, potential users, and public interest entities with an interest in promoting these efficiency technologies. At the same time, the project has identified additional crucial engineering data and solutions that will need to be implemented by manufacturers and architects and engineers if the technology is to succeed in the marketplace.

Engineering solutions that integrate EC windows in a whole building context with lighting and HVAC systems were tested, monitored, and assessed in an iterative test-redesign-test cycle, pointing toward the importance of implementing new features, such as continuous switching controls, and new designs that separately modulate glare and daylight. Lessons learned are applicable to other developers of EC windows and competing “Smart Window” technologies, thus stimulating a competitive market amongst manufacturers. With this approach, emerging EC windows can be introduced into the market with fewer setbacks and failures in an industry that does not readily provide integrated building solutions and is risk averse. The work completed to date and documented in this report will facilitate introduction of the first wave of commercial products in 2006. The suggested extensions to the work outlined in Section 5.3 are designed to solve problems and challenges identified in this report from the completed phase of these field tests.

## 1.2. Report Organization

The three main objectives of this research were to advance EC windows as viable marketplace solutions for energy savings and load management by:

1) Solving critical hardware and software design and engineering issues related to the use of the EC window as an integral component within a whole building energy-efficient system
2) Providing accurate and objective scientific and engineering data that validate smart window energy performance and quantifies the "added value" potential for building owners and occupants (e.g., comfort, reliability, performance)
3) Providing information products needed to support the effective use of this technology in buildings with minimal risk and performance uncertainties

This final report is structured to track these three main research objectives from approach to project outcomes:

**Section 2 Systems Engineering** explains how well the EC window and controller prototype provided by the manufacturer met our specifications and how well it worked as determined through a series of laboratory and field tests. The evaluation reviews glazing appearance, size, switching speed, switching range, power consumption characteristics, control accuracy, and reliability. This section also explains how reliably the integrated EC window-daylighting control system developed by the project team that met control objectives over a 2.5-year test period in the field and its general applicability to commercial buildings.

**Section 3 Performance Impacts** presents energy, peak demand, visual comfort, and occupant response data gathered from a variety of sources: field studies, human factors tests, DOE-2 simulations, and Radiance-Mathematica simulations. The data illustrates the magnitude of energy-efficiency trade-offs one must make to meet visual comfort requirements and demonstrates how savings estimates are dependent on reference case assumptions.

**Section 4 Information Resources** describes the numerous activities conducted throughout the project to disseminate information about this emerging technology, increase public awareness and future use of this emerging technology, and establish the groundwork for evaluating, rating, designing and specifying EC windows for buildings.

**Section 5 Conclusions** provides a broad interpretation of the potential of emerging electrochromic windows to save energy, reduce peak demand, and deliver increased comfort and amenity to building occupants based on the results of this study. It summarizes the performance of an EC window product that is now commercially available. It explains the basic assumptions and features of an integrated EC window-daylighting control system needed to meet visual comfort requirements and optimize energy efficiency. A summary of the performance benefits resulting from this integrated system is given. These benefits are weighed against the increased costs and market barriers of implementing widespread use of this technology in commercial buildings. Recommendations are given for the next stages of R&D and commercialization of this technology.

## 2.0 Systems Engineering

### 2.1. Objectives

The specific objectives for this task were to:

- Develop integrated whole building EC solutions that address comfort requirements, maximize energy efficiency, and are acceptable to occupants.
- Develop integrated whole-building control algorithms that enable EC windows to achieve 15-25% energy use and peak demand reductions in the perimeter zones of commercial buildings.
- Develop hardware and software EC solutions that are reliable, practical, and cost effective for typical commercial buildings.

This task addresses the problem resulting from a fragmented building industry. EC window systems are more energy-efficient compared to static conventional window solutions because they can actively manage daylight and solar heat gains in real time, thus impacting electric lighting and HVAC system energy use. Industry rarely offers integrated cross-disciplinary building products, although this trend is changing slowly. Because integrated building systems require knowledge of traditionally disparate areas of expertise, engineering of such solutions is unlikely to occur given the limited capabilities and resources of individual manufacturers. Architects who refer to future "intelligent" buildings often conjure up images of a living and breathing entity whose skin senses and responds to external stimuli. Such visionary systems require a degree of engineering that is well beyond standard practice in the industry today.

Engineering of such integrated solutions involves the design of the hardware (sensors, actuators, networking, etc.) and software "smarts" to achieve reliable and optimized control of automated window-lighting-HVAC components which then results in greater energy efficiency, comfort, and amenity. A technical solution that can be judged as successful should work reliably under variable sun and sky conditions, be judged as acceptable and satisfactory by typical building occupants, and produce significant performance benefits. The solution must also be cost-effective when all appropriate costs and benefits are considered at mature market status. The challenge of successfully achieving this project objective has been in overcoming or compensating for the fact that emerging EC prototype window products are still relatively immature considering the type of use envisioned for switchable windows. Prototype EC products also have unique, not generic, characteristics and capabilities depending on the manufacturer's stage of development. To create and test successful EC solutions in this field study, developers need to create the desired integrated systems functionality that buyers expect of a mature market EC product.

### 2.2. Approach

Before starting on the design and engineering of integrated EC window solutions, a qualified EC product was first selected for the field test program. The program was opened in early 2003 to any EC manufacturer who could meet specified requirements for durability and functionality and were entering the market in the near-term. A single manufacturer was selected in a competitive process to participate in the field test program. This manufacturer's product was then tested over the course of the three-year program. Long-term durability was assessed by NREL. Basic functionality of sample EC windows was evaluated by LBNL prior to purchasing the windows. Because of the competitive nature of the industry and to establish a candid and collaborative relationship, the manufacturer was assured that specific proprietary aspects of their technology would be held throughout the project as confidential information.

For the LBNL tests, the EC window product was evaluated using both laboratory and field tests. These tests were conducted to assess and characterize the properties and performance of the manufacturer's EC window and control system.

- Bench-scale tests were conducted on large-area EC prototypes to characterize the functional aspects of the EC window and controller. The range and variation in transmittance across the face of sample insulating glass units (IGUs) were evaluated. Tests were also conducted to measure the reliability and accuracy of the manufacturer's alpha intermediate-state window controller (similar to dimming control of electric lighting).
- Switching speed of the EC windows was characterized as a function of temperature using a modified setup in the LBNL Infrared Thermography Lab. A large-area EC IGU was exposed to isothermal conditions varying between –10ºC to +65ºC (14–149ºF). The EC IGU was cycled between the two end states. Direct normal visible transmittance was measured at several locations across the face of the IGU.
- Outdoor field tests were conducted in the LBNL Window Testbed Facility (Figure 2) to further characterize the reliability and accuracy of window function over a two and half year period. EC window transmittance was measured for each of the 30 installed EC windows at a 1-minute sampling rate every 24-hour day. Input control commands and outputs to the EC window controller were also monitored and analyzed.
- Solar-optical properties of various EC devices were measured over the course of this project in the LBNL Glazing Optics Laboratory. Measurements of spectral transmittance and front and back reflectance were made at normal incidence (250–1700 nm) using a Lambda 19 automated spectrometer. Spectral data were measured with the EC device in the fully bleached and colored states. These data were processed and used with Optics and WINDOW5 to compute solar-optical properties and thermal data of whole window assemblies and then used in DOE-2 and Radiance simulation studies. Data were also provided to the manufacturer as they progressed in their development and refinement of EC coatings.

Practical integrated systems were engineered for full-scale private office applications, including software and sensors to control the EC windows and electric lighting components.

- Design, engineering, and installation of an EC curtainwall was conducted in collaboration with a curtainwall manufacturer and the EC manufacturer. Practical issues such as how to run the low-voltage wiring through the framing system, weatherproofing, and IGU replacement were discussed and resolved. A solution was installed in the LBNL Window Testbed Facility.
- Engineering of an automated integrated EC window and daylighting control system was accomplished in collaboration with industry by first characterizing the EC controller function (as described above) then building the hardware and software to interface with it. The software interface was constructed on the National Instruments LabView platform. New sensors and algorithms were devised as needed to improve function,

reliability, and accuracy of control. Practical solutions using off-the-shelf readily available components were devised to the extent possible. The number of sensors required for control was minimized to keep the cost of the control solution low. Graphical user interfaces were developed to enable user adjustment of the automated control setpoints and manual control of individual EC windows.

- The initial solutions were refined and tuned in response to subjective surveys, field observations, and analysis of monitored data. This iterative cycle occurred throughout the duration of the project.

**Figure 2. LBNL Window Testbed Facility (upper photo). South elevation of EC facades (middle and left) and spectrally selective low-e façade (right) on August 20, 2004 (lower photo).**

Computer-based simulations were conducted to determine how best to use and control EC windows in the context of whole building applications.

- DOE-2 building energy simulations were used to quantify the energy and peak demand savings potential of EC control algorithms and various architectural strategies in typical commercial office buildings throughout the U.S. and in the 16 climate zones in California. Demand-response strategies were also derived from these simulations.

- A focused DOE-2 building energy simulation study was conducted to explore the energy and peak demand savings potential of alternate architectural solutions for EC windows. The EC window performance was studied with and without overhangs and controlled to minimize visual discomfort. This study modeled a zoned window system where the upper and lower EC apertures were controlled using various combinations of control algorithms. Performance data were computed for Houston and Chicago climates.
- The Radiance ray-tracing visualization program was combined with Mathematica optimization routines to determine the lighting energy impacts of EC windows controlled to meet various visual comfort criteria then to optimize daylight illuminance. A new Radiance daylight coefficient method was created to accelerate the generation of accurate annual performance data.

### 2.3. Description of the EC Window Prototypes and Controller

This section describes the actual EC window product that was used in the field tests and modeled in the simulation studies. It is important to understand the key attributes of the EC window product so that one can understand how to interpret the results. EC windows modulate tint and therefore the solar-optical (solar heat gain and visible transmittance) properties of the window. Current EC windows cannot modulate thermal properties (U-value). The range of modulation dictates the ability of the EC window to optimize building performance across a wide range of interior and exterior conditions. Switching speed is proportional to the size of the EC window and temperature. Faster switching speeds enable greater responsiveness and reduce control oscillations.

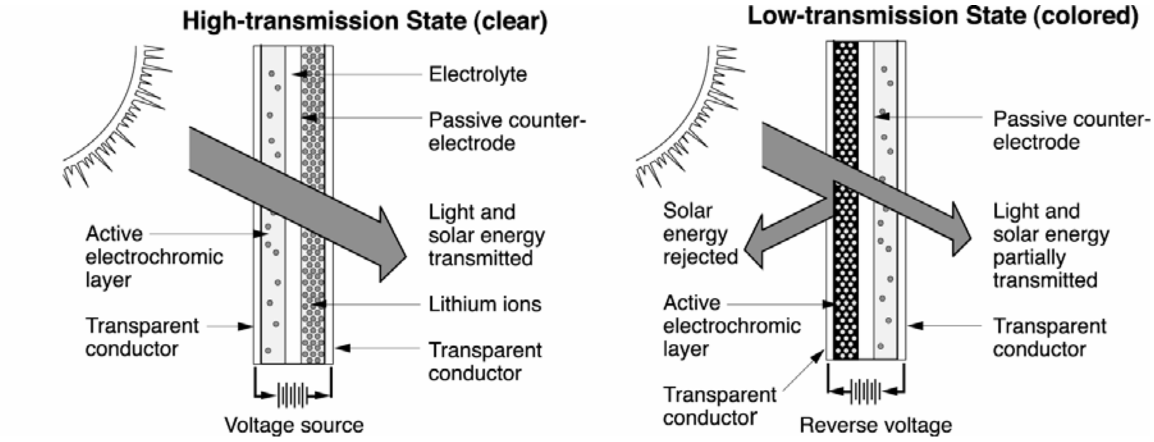


**Figure 3. Diagram of a typical tungsten-oxide electrochromic coating.**

EC coatings are composed of a thin film, multi-layer stack deposited on a glass or plastic transparent substrate. Transparent conductors form the outer layers of the stack, an active electrochromic and passive counter-electrode layer form the middle layers, and an ion-conducting electrolyte layer forms the center portion of the stack (Figure 3). 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 electrochromic layer. A reversible electrochemical reaction takes place causing a tinted Prussian blue appearance. Reversing the potential causes the ions to migrate back, causing a bleached clear appearance. The reaction that takes place can be grossly simplified (Granqvist 2000) as follows:

$$WO_3 + xM^+ + xe^- \leftrightarrow M_xWO_3$$

With $M^+ = H^+$, $Li^+$, $Na^+$ or $K^+$, and e- denoting electrons.

The material composition of the EC coating and manufacturing process can vary considerably and are held as intellectual property by the manufacturer. The composition dictates the unique properties of the EC window: its switching range, speed versus temperature characteristics, power consumption when being switched, color, and even its physical makeup. For example, in the prior field tests in the Oakland Federal Building, the EC window was a polymer-based EC coating manufactured by a German company. The product tested in this project was a thin-film ceramic coating that has the potential to be manufactured at higher speeds and lower cost. The physical appearance of the two types of EC windows were similar since both were based on a tungsten oxide EC coloring layer.

For the EC products that are now being considered for the market, the solar-optical (Tv and SHGC) range is of utmost importance when considering the likely performance benefits of this technology and market acceptance. Various static thermal properties are dictated by the substrate on which the EC coating is deposited and the make up of the insulating glass unit. A "super-insulating" EC window can be created by combining an EC coating, multiple layers of glass, argon gas fill, and low-conductance spacers. These aspects were not considered in this project. The focus was to isolate the performance benefits to the EC coating itself so all aspects of the reference case (size, thermal properties, composition) were matched as closely as possible to the EC window with the exception of the EC coating itself.

The solar-optical switching range of the EC product tested was broad: Tv=0.60–0.05 and solar heat gain coefficient range of 0.42–0.09. Generally, performance benefits will increase as switching range increases (e.g., the German prototype had a more limited switching range of Tv=0.50–0.15). The size of the windows was also relatively small—0.46-m by 0.89 m (18x35 inches)—and the climate in which they were tested was mild, so switching speeds will be optimal (typically 1–4 minutes). Generally, acceptability of large-area windows that take longer to respond (i.e., 20–40 minutes) will be less. In cold climates where the outdoor air temperature is low (<0ºC, <32ºF) and incident irradiation levels are also low, EC windows may take even longer to respond (+40 minutes).

The following EC characteristics were specified by the selected manufacturer (differences in attributes are discussed in Section 2.5.1). The entire EC product consisted of an EC insulating glass unit with low-voltage wiring, an "alpha" intermediate-state EC window controller with dc power source (enabling continuous modulation between bleached and colored states), and a RS485 serial connection to the LBNL supervisory controller. All EC windows tested were created using pilot production facilities in early 2003 and therefore represent the manufacturer's emerging manufacturing processes.

### 2.3.1. Manufacturer-specified EC window product characteristics

- The EC is a thin-film WO3-based ceramic multilayer device, which requires a small trickle charge to hold it in a tinted state. If no potential is supplied, the EC rests in a bleached mode. Power required to hold the window in any given state was less than 0.14 W per window unit.
- The insulating glass unit was composed of a 4-mm tempered EC glazing outboard layer (EC coating on number 2 surface), 6-mm tempered clear glazing inboard layer, 14-mm aluminum spacer, 15-mm air gap, and polyisobutylene (PIB)/silicone dual-seal construction.
- The center-of-glass visible transmittance range for the IGU was specified by the manufacturer as Tv=0.05–0.60 with an error of ±10% of value. LBNL computed the solar heat gain coefficient range to be SHGC=0.09–0.42 and the center-of-glass U-value to be 1.87 W/m2-ºC (0.33 Btu/h-ft2-ºF) using spectral data measured on samples provided in 2000 and LBNL Optics and WINDOW5 software. For these calculations, the emittance of the EC layer was assumed to be 0.84 on the exterior uncoated surface and 0.15 on the interior coated surface. The photopic transmittance ratio (PTR, ratio of maximum to minimum Tv) was greater than 5. The manufacturer noted that the samples provided for this field test program matched those measured in 2000.
- The EC switching time was designated as less than 30 minutes to achieve a PTR of 5:1 within an operating temperature range of –30˚C to 90˚C (–22ºF to 194ºF).
- At the time of delivery, durability was assessed at 4000 cycles at 90˚C (194ºF) under 1.5 Air Mass Unit (AMU) irradiation without reducing the PTR below 4 (ASTM E2141).
- Visible optical defects were designated as minimal.
- The alpha intermediate state EC controller supplied a low bipolar potential (referred to as the current-to-voltage (I-V) waveform) to the transparent conductor layers in order to switch the EC device. A unique integrated circuit (IC) control board was assigned to each EC window and up to six IC boards were housed in a single ganged controller box. An RS485 serial communication port on each IC board allowed communication and control of each individual EC IGU. A transmittance command between 0.05–0.60 was accepted as input by the EC controller. The EC was not adjusted if the command Tv was within ±0.02 of current Tv. If the command was between Tv=0.51–0.60, then the EC was switched to Tv=0.60. The EC controller output a Tv estimate of each EC window.
- The EC transmittance was to be matched to within ±10% of value at any state between fully bleached and fully colored over the stated operating temperatures.

The objective of this technical evaluation was to assess the performance of a projected mature-market product given the existing capabilities of early market prototypes. The manufacturer delivered an EC product manufactured on a pilot production line with projected levels of functionality and accuracy given their expectations for product usage. The LBNL field test program pushed the products to expected levels of real world usage (e.g., frequency of switching)—this enabled us to evaluate the energy-savings potential of the technology in the context of its intended use, not current state of development. The manufacturer's product and manufacturing processes improved over the course of the field test program but the EC windows were not replaced due to resource constraints. The solar-optical properties of the improved EC devices did not change significantly from those tested in this field study.

## 2.4. Description of the EC Window-Daylighting System

Over the course of this study, an integrated EC window-daylighting system was engineered through an iterative design-build-test cycle as described above. The system was engineered for a specific application: perimeter zone private offices in a typical commercial building. The control algorithms were first derived from earlier DOE-2 simulations, then refined based on analysis of the field monitored data, field observations, and subjective appraisals.

The characteristics of the DOE-2 prototypical three-story commercial office building module were derived from energy standards, survey data, and engineering judgment. These building characteristics have significant bearing on the design of the integrated control algorithm and resultant energy and peak demand savings. The EC window effectively “trades-off” space conditioning load requirements (increase tint, decrease SHGC and solar heat gains, decrease cooling) and lighting energy use requirements (decrease tint, increase Tv and interior daylight levels, decrease lighting energy use). The efficacy of the space conditioning HVAC system and electric lighting system therefore dictates in part the relative importance of these two loads for control optimization (Figure 4). For example, German building energy standards do not allow air-conditioning systems to be installed in new buildings unless there are extenuating circumstances. This northern climate is generally mild during the summer. Therefore, researchers have determined that an appropriate control algorithm would be to switch the EC to fully colored during the summer to prevent solar heat gains and keep air temperatures to within acceptable limits and to switch the EC to fully bleached during the winter to enable passive solar heating.

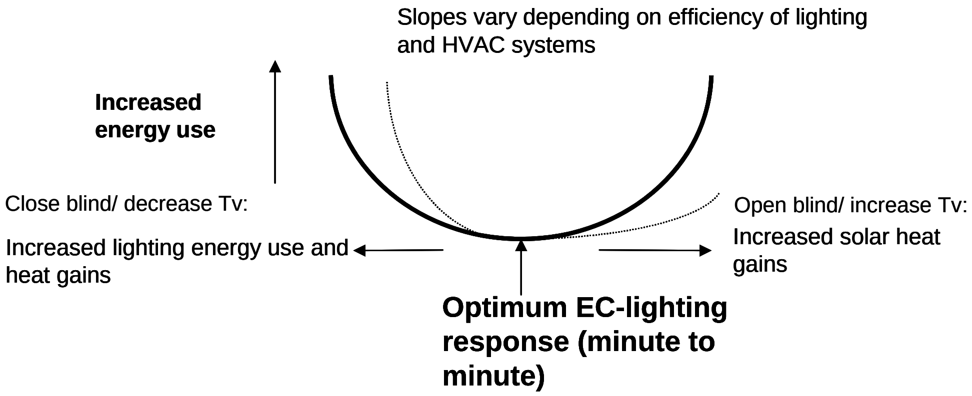


**Figure 4. Real-time trade-offs between cooling and lighting energy use.**

These European approaches would not be the preferred approach in California. With a variable-air-volume (VAV) system and daylight-controlled ambient lighting, the optimal energy-efficient control algorithm for typical U.S. commercial buildings is to optimize daylight in the perimeter zone. This “daylight” algorithm admits just enough daylight to enable the electric lights to be dimmed or even shut off while controlling solar heat gains. This strategy also enables one to target the two largest end-uses in commercial buildings—cooling and lighting—during peak summer conditions.

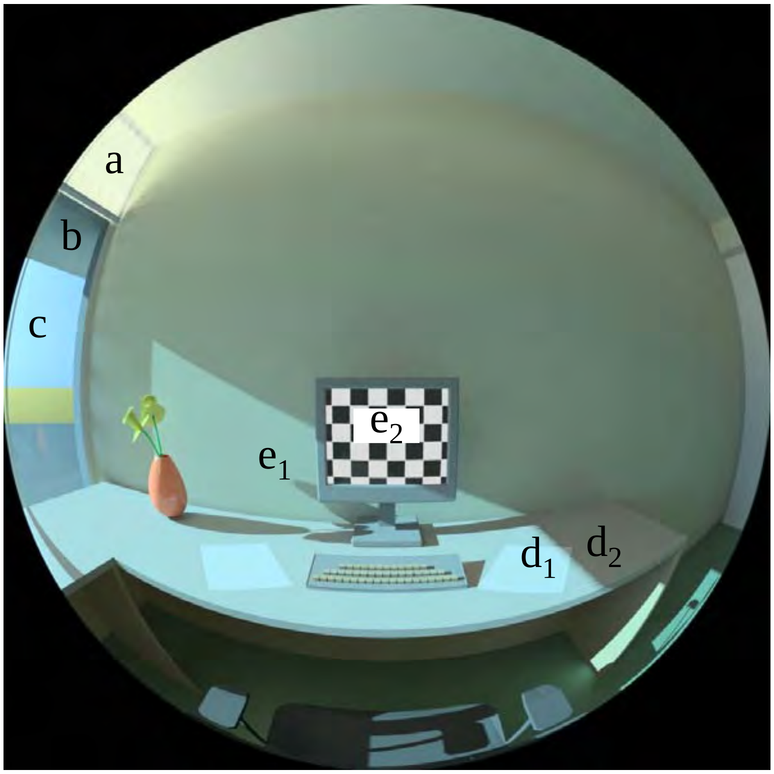


**Figure 5. Radiance simulation of a south-facing private office at 11:30 on a clear winter solstice day. This image illustrates the EC control algorithm for visual comfort. Direct sun is blocked from the occupant's field of view by the upper zone's Venetian blind (a) or by an overhang (b). This upper EC zone (b) is controlled to admit daylight. The lower EC zone (c) is switched to Tv=0.05 to minimize luminance contrasts between the VDT (e2) and sunlit (e1, d1) surfaces and between paper-based tasks that are sunlit (d1) and shadowed (d2). The luminance of the lower window is controlled (c). View out is preserved (c). See Figure 23 for images for other times of the year.**

In sunny climates like California, visual discomfort due to direct sun is a significant problem. Inland and coastal California climates both have the potential glare problem but the inland climates have more challenging cooling conditions. Sky glare can also be a problem in climates dominated by sunny or hazy sky conditions. The challenge is to control sunlight and glare without compromising interior daylight in all climates. The avoidance of visual discomfort was addressed in several ways with the design of the EC control system (Figure 5):

1. We assumed that the orb of the sun must be blocked from one's field of view by an opaque Venetian blind for the majority of the year to prevent disability glare.
2. We assumed that any direct sunlight penetrating the room must be attenuated by an EC window at Tv=0.05 to limit luminance contrasts between sunlit and shadowed areas and between tasks (paper or computer monitor) and surrounding surfaces.
3. We assumed that daylight (Tv=0.05–0.60) or glare (Tv=0.05) control of the EC window was sufficient to control bright sky luminance that can cause discomfort glare.

In addition to these algorithms, the project team tested two window configurations: a one-zone EC window wall, where the entire window is controlled to the same transmittance level, and a two-zone EC window wall, where an upper daylight aperture with Venetian blinds is controlled to admit daylight while the lower vision aperture without Venetian blinds allows view out at all times and is controlled for daylight and glare.

For item (1) with the two-zone EC window wall, direct sun is blocked from view by the blinds in the upper aperture except for a few hours in the early afternoon between the equinox and winter solstice on clear sunny days, assuming a seated position 1.5 m (5 ft) from the window facing the west sidewall. For the one-zone EC window wall with fully lowered blind, direct sun is blocked for all hours. For item (2), the EC "glare" control mode switches the EC to its minimum transmittance (Tv=0.05) when the solar profile angle is lower than 75° and incident vertical illuminance (Ev) is greater than 30,000 lux. For this façade design, all incoming direct sunlight is attenuated by the EC switched to Tv=0.05, no matter what the depth of sunlight penetration is into the space. The Ev threshold value was derived from both human subject studies and field experience. A value of 20,000 lux was found to correlate to a near 100% probability that the occupants would draw the blinds over the EC windows in a companion user assessment field study (see Appendix  A , citation 11). A less conservative threshold value of 30,000 lux was used in combination with partially lowered Venetian blinds. For item (3), window luminance of the lower aperture was controlled adequately for most EC configurations as confirmed by monitored data of the average window luminance.

The final integrated engineered solution implements both the energy-efficient EC "daylight" control mode and the EC "glare" control mode. Test and comparative cases are described in the Section 3.3. The EC window-daylighting control system hardware and software is summarized below.

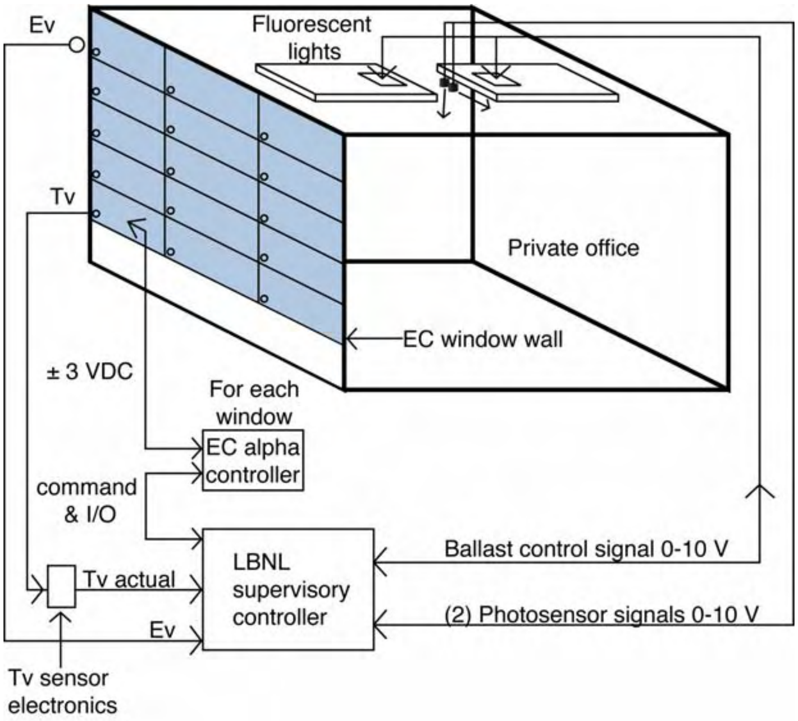


**Figure 6. Diagram of an integrated EC window and daylighting system.**

An EC window and fluorescent lighting system was installed in each of two fully glazed private office test rooms. The final engineered solution had the following attributes (Figure 6):

- Each EC window was powered via low-voltage wiring between the window's terminal block connector and the manufacturer's EC controller box located in the interior of the building. A 12 V dc switching power supply delivered power for up to 18 windows. The EC controller box contained individual controllers (IC circuitry) calibrated to each unique window.
- Initially, the alpha intermediate-state EC controller regulated the transmittance of the window continuously between the fully bleached and fully colored states with no sensor feedback. Later, an LBNL-transmittance sensor mounted on each EC window was used to improve accuracy and reliability of transmittance control. This was not a mature market solution. Further engineering will be required to make this solution robust for commercial applications.
- From the EC controller box, an RS485 communications link was run to the supervisory controller (National Instruments LabView). The LabView software platform enables one to develop control systems without the inconvenience of having to breadboard the solution in hardware. Some aspects of control can be breadboarded later. Other functions can remain in software in the final commercial solution.
- The electric lighting system is a fairly standard set-up consisting of ceiling-mounted lighting fixtures, T8 lamps, and 0–10 V electronic dimming ballasts. The system received dimming voltage input via the LabView system. The ballasts had a power dimming

range of 28–100% with a light output range of 10–100%. The lights could have been switched off (to standby mode) for greater energy efficiency.

- Two ceiling-mounted shielded photosensors were used for control of both the EC window and electric lighting system. Each photosensor consisted of a color-corrected photodiode mounted in a simple black-matte metal tube so that its cone of view was approximately 60º. The photosensors were located in the same location but one was positioned to look downward while the other was positioned to look toward the rear wall of the test room. For some cases, the EC window was allowed to admit direct sunlight deep into the space. This tended to skew the photosensor reading and cause the work plane illuminance to be less than the setpoint. To address this issue, the signal between the two sensors were compared and if the signal differed by greater than 5%, the reading from the rear wall sensor was used to control the lights. This resulted in very reliable illuminance control.
- An exterior-mounted vertical illuminance sensor was also used to control the EC window. This sensor was placed so that it had an unobstructed view of the sky and ground as seen by the EC windows. This illuminance sensor was used to determine when exterior sun and sky conditions warranted glare control of the EC windows. Illuminance levels greater than 30,000 lux instigated glare control (EC switched to minimum Tv=0.05). See algorithm description below.
- Several correlations were made between the sensors, lighting equipment, and interior environmental conditions: a) interior photosensor signal to interior fluorescent illuminance level, b) fluorescent ballast control signal (0–10 V) to fluorescent illuminance level, and c) interior photosensor signal to interior daylight illuminance level. These were used to determine how to control the EC and lighting systems in real time. For the first two correlations, a test must be conducted at night, where each fluorescent lighting dimming zone is stepped across its full dimming range and the fluorescent ballast control voltage, photosensor signal, and work plane illuminance levels are recorded. For the third correlation, a test must be conducted to determine the photosensor response to daylight work plane illuminance under representative sun and sky conditions. This correlation may also be established using Radiance annual simulations.
- A real-time clock was used to determine solar altitude relative to the façade (i.e., solar profile angle). Solar position was used to determine the depth of direct sun penetration into the room.
- For some cases, the window wall was divided into two separate control zones where the upper aperture was controlled separately from the lower aperture. See algorithm description below.
- A LabView graphical user interface (GUI) consisting of buttons and slider switches was created as a separate module from the supervisory control system using LabView. This executable module was mounted on the computer located in the test rooms and operated by occupants during the subjective survey of the EC windows. The module was interfaced to the supervisory system via a couple of bytes of digital I/O to the main control PC. It enabled control of the EC windows and lighting system in an automated, semi-automated and manual mode. Manual control of individual EC windows via slider switches was implemented as a separate GUI module.

- Three side-by-side, top-down interior Venetian blinds were installed to cover the full window wall. The blinds had a typical 2.5-cm (1-inch) curved slat (concave downward) with a matte white finish. The slat angle was set by hand to approximately 45°, which blocked direct sun over the entire year. When used, the height of all three blinds was set to either the bottom of the top row of EC windows (2.25 m, 7.4 ft above the floor) or the bottom of the second top row of EC windows (1.77 m, 5.8 ft above the floor). Both the height and slat angle were kept the same throughout the day.

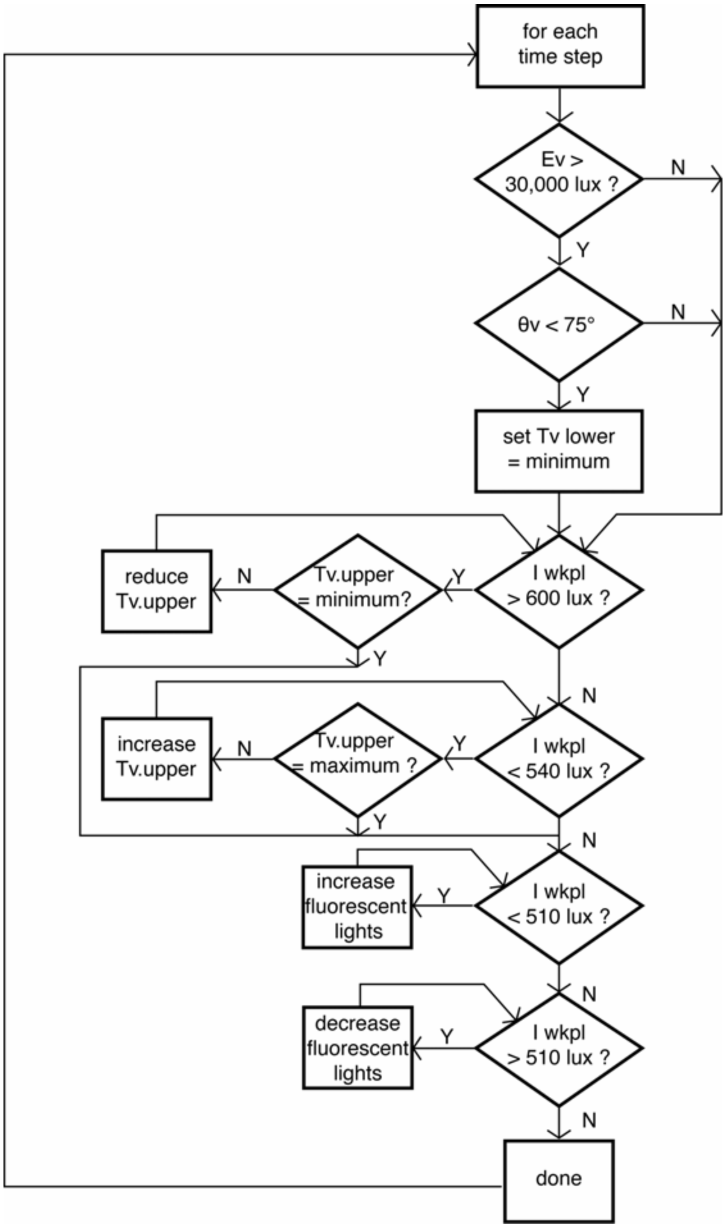


**Figure 7. Sequence of operations for the two-zone EC window wall controlled for daylight and glare (e.g., Test conditions EC-F and EC-G given in Table 1, Section 3.3)**

For each minute time step, the supervisory controller's sequence of operations was as follows (Figure 7):

Step 1. Determine the exterior vertical illuminance incident on the façade, Ev. If Ev is greater than 30,000 lux, then determine solar profile angle, θv.

- If θv is greater than 75°, then switch both upper and lower EC zones (same transmittance) by the daylight mode (go to step 2).
- If θv is less than 75°, then switch the lower zone EC windows by the glare mode to minimum transmittance (Tv=0.05). Go to step 2 to switch the upper window by the daylight mode.

Step 2. If Ev is less than 30,000 lux, then determine whether the interior daylight illuminance at the work plane, Iwkpl, is within the daylight setpoint range (540–600 lux). Determine daylight illuminance using the ceiling-mounted photosensors.

- If it is, then control the fluorescent lighting (step 3).
- If Iwkpl is greater than 600 lux, then decrease the EC transmittance (color the EC) until Iwkpl is reduced to the daylight setpoint level of 600 lux. Then go to step 3.
- If Iwkpl is less than 540 lux, then increase the EC transmittance (bleach the EC) until Iwkpl is increased to the daylight setpoint level of 540 lux. Then go to step 3.

Step 3. Determine the interior daylight illuminance at the work plane, Iwkpl, using the ceiling-mounted photosensors.

- If Iwkpl is less than the fluorescent setpoint level (510 lux), then raise the fluorescent light output.
- If Iwkpl is greater than the fluorescent setpoint level (510 lux), then lower the fluorescent light output.

## 2.5. Outcomes

### 2.5.1. EC Prototype Window

**Outcome:** The foundation for the development of integrated EC systems is an EC window product that meets basic specifications and is well characterized. The qualified EC windows that were procured in 2003 and tested extensively met most of the basic specifications. Newer products would probably perform better, given the continuous improvements being made by the manufacturer. Judging based on functional performance, there were no fundamental aspects of the EC window that would suggest that its market introduction is premature.

The following EC window performance requirements were dictated by the procurement specifications. The foundation for these requirements was established by the EC window R&D community given the material/physical limitations of the switchable material and its likely use in building applications. The manufacturer's product specifications are given in Section 2.3 above.

#### 2.5.1.1. Procurement specifications for the EC window:

1. Provide a photopic transmittance ratio (ratio of maximum to minimum Tv) of at least 5:1 in the bleached and colored states (e.g., 60–70%: 12–14%, respectively of a single-pane electrochromic glazing layer)
2. Operating glass surface temperatures from –30˚C to 90˚C (–22ºF–194ºF)
3. Coloring and bleaching times (across full switching range) of less than 30 minutes over an EC surface temperature range from 0˚C to 50˚C (32–122ºF) with a 2-m2 (21.5-ft2) glass area
4. Switching over the full optical range with applied dc low-voltages as designated by the manufacturer
5. Open-circuit memory of several hours with minimal power support (<1–2% drift in photopic transmittance within 2 hours)
6. Minimal visible optical defects (e.g., spots or discoloration) in the colored or bleached states.
7. Ability to switch through 4000 bleach and coloration cycles at a sample (colored state) temperature of 90ºC (194ºF) with AMU 1.5 solar radiation produced using appropriately filtered xenon-arc lamps to simulate 1.1 sun equivalent irradiance from 250 to 1100 nm without degradation of the PTR to less than 4 or significant degradation in optical, visual, and switching performance

The ability of the EC window prototypes to meet the performance criteria is discussed on a point-by-point basis as follows:

1. Photopic transmittance ratio. In the field, the EC prototype window was operated over an estimated photopic transmittance range of Tv=0.60–0.05, which provides a PTR of 12:1 for a double-pane unit with a clear glass inboard layer. Solar-optical data were measured for more recent samples from the same company. These data are now included in the International Glazing database (version 14.4, http://windows.lbl.gov/materials/IGDB/default.htm). The center-of-glass transmittance range is Tv=0.039–0.696 (PTR of 18:1) for an EC coating on a single-pane 4-mm clear glass substrate (the EC must be sold as a double-pane unit).

2. Operating temperature. The EC prototype window was demonstrated to cycle between bleached and colored states (Tv=0.60–0.05) within a surface temperature range of –10˚C to 65˚C (14–149ºF) in a limited laboratory test. During the 2.5-year field test, the EC window operated within a surface temperature range of 4–73ºC (39–163ºF). NREL durability tests cycled the EC window between Tv=0.60–0.05 under stable ambient temperatures and irradiated conditions where the EC reached a maximum temperature of 95ºC (203ºF).

3. Switching speed. Coloring and bleaching times differed from the above specification because the EC window size was smaller (0.41 m2 in area, not 2 m2). To assess switching time, one EC sample was measured under controlled isothermal conditions in the LBNL Infrared Thermography Laboratory, where the air temperature was increased gradually by 5ºC (9ºF) every three hours over a range from –10ºC to 65ºC (14–149ºF). The air and surface temperature of the EC were nominally the same. The EC window was cycled

fully every 37 minutes. Generic EC devices exhibit several well-known characteristics with decreased temperature: 1) switching speed decreases and 2) the EC contrast ratio decreases. Switching speed exhibits an exponential function (Figure 8). For this size sample, the EC took 37 minutes to switch from Tv=0.56 to 0.13 and 36 minutes to switch from Tv=0.13 to 0.56 at EC surface temperatures of –1°C to –3°C (30–37°F). The cycle period of 37 minutes turned out to be too short for the EC to reach its fully colored state under cold conditions. Switching speeds were faster (<6–7 minutes) for temperatures greater than ~10°C (50°F).

This test was conducted without irradiation on the glass. Switching speed should be characterized as a function of ambient air temperature and incident solar radiation to gauge whether such speeds will be problematic for typical building applications. This was not done systematically within the scope of this project. An example of switching under cold air irradiated conditions is given in Figure 9. The relationship of speed to transmittance from bleached to clear is exponential. The EC took 40 minutes to switch from Tv=0.60 to Tv=0.08 (PTR=7.5:1) with an outdoor dry-bulb air temperature of Tdbt=3–6°C (37–43°F) and vertical irradiance range of Iv=24–540 W/m2. It then took 83 minutes to switch from Tv=0.08 to Tv=0.05 with Tdbt=6–8°C (43–46°F) and Iv=540–770 W/m2. With these speeds and for other reasons, it is impractical to use the EC to block direct sun, particularly if the occupant faces the window.

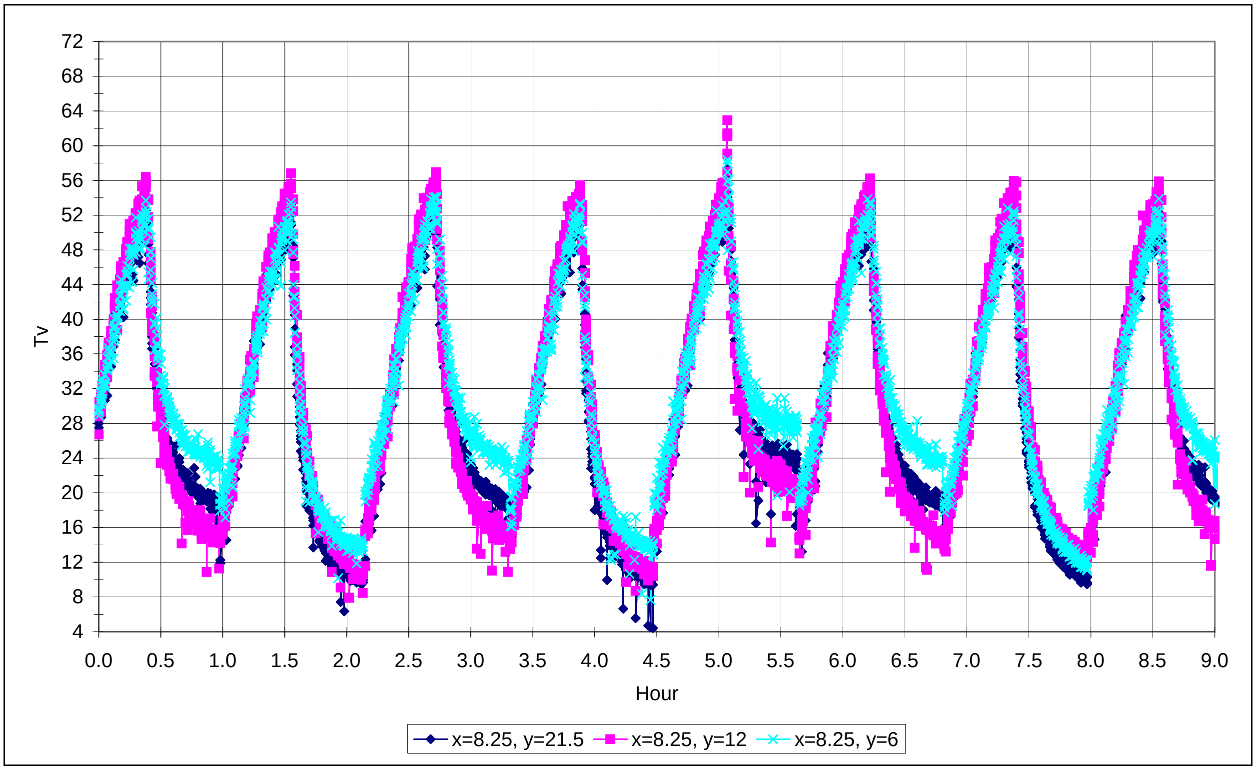


**Figure 8. EC transmittance versus time, or switching speed of an 0.46x0.89-m (18x35-inch) device with an average EC surface temperature of –3°C (27°F). Each transmittance sensor was 0.21 m (x=8.25 inches) from the bus bar edge but at various distances from the non-bus-bar edge (y dimension in legend (inches)). Transmittance levels are not expected to match when in the process of switching.**

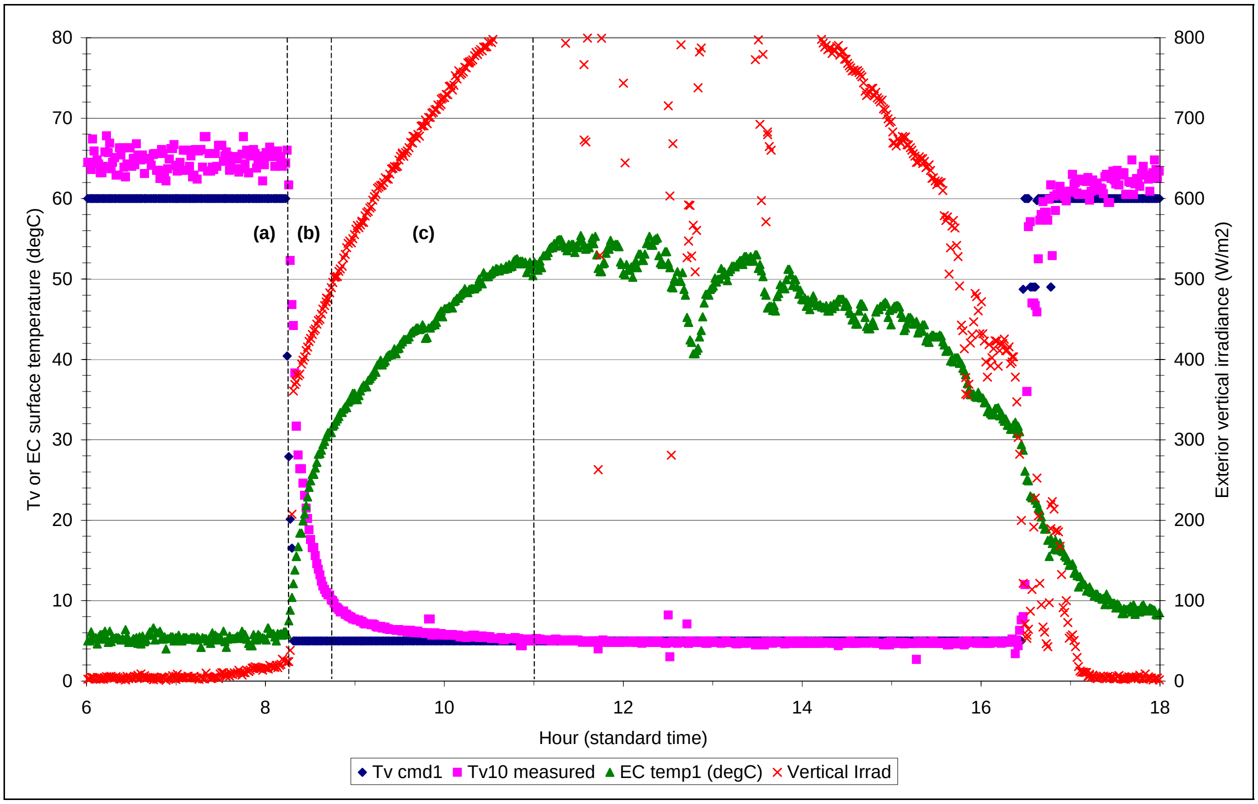


**Figure 9. Switching speed when the 0.41 m² (4.4 ft²) EC window is irradiated. On January 14, 2005, Room C's EC window is given a command (Tv cmd1) to switch to Tv=0.05 at 8:15 (a). The EC switches rapidly to Tv≈0.10 by 8:45 (b) with EC at 30°C (86°F) then reaches Tv=0.06 by 10:00 and Tv=0.05 by 10:30 (c). Irradiation is blocked by low hills between 6:50–8:15, but this measurement was taken at Room B's facade immediately to the east so solar radiation levels on Room C's façade were higher between 8:00–8:20 than that depicted here.**

4. Switching voltages. Switching occurred over the full optical range with an applied bipolar dc voltage between ±3 V. The applied current-to-voltage waveform is dictated by the EC manufacturer's EC window controller and is designed to prevent degradation of the EC window over its expected long-term life.

5. Memory. This type of EC device requires a small trickle charge to hold it in a tinted steady state (no change in transmittance). If no potential is applied, the EC "rests" at a bleached state with a higher or lower transmittance level that differs from the operating bleached state. When the EC windows are operating at a steady state, fifteen 0.46x0.89 m (18x35 inch) EC devices consume 0.07–0.15 W/ft$^2$-glazing or 0.03–0.067 W/ft$^2$-floor (4.6-m, 15 ft-deep perimeter zone). When the EC windows are being switched fully or partially between end states (e.g., Tv=0.60–0.20 or Tv=0.05–0.60), peak power consumption is 0.26–0.32 W/ft$^2$-glazing or 0.11–0.14 W/ft$^2$-floor. These values differed from that provided by the manufacturer (Section 2.3). Our values were the ac power consumption as an end use load. Average daily (12-hour) power consumption of the EC system (window + controller + power supply) with the EC windows operated for daylight and glare control was 0.03–0.07 W/ft$^2$-floor. The dc power consumption at the window unit will most likely vary linearly with window area. Each individual EC

window controller requires a small constant residual power of 3 W dc. The switching power supply consumes 2–3 W dc. These consumption levels can be reduced to 25–30% of current levels, if the control circuitry and power source are designed more efficiently. For larger-scale installations, the power supply consumption will become a smaller percentage of the total load and the number of EC controllers will decrease with larger-area windows, lowering the above values. Other types of EC devices require power only to adjust the EC window to a different state.

6. Appearance. A bench-scale test was conducted in 2003 on two EC samples to evaluate within-pane uniformity at ten arbitrary locations across the face of the EC window. The samples were switched to intermediate and end states and monitored under stable ambient conditions. The monitored transmittance was found to vary slightly by Tv=0.03–0.05. The differences in transmittance between areas tended to be constant across the full switching range. With visual inspection from inside the field test facility, the EC windows had good within-pane uniformity in the bleached and colored states given the mixed content of the outside view. The coloration across each window was uniform when switching was completed. The EC devices had tiny pinholes (no more then 5 in a set of 30 prototype windows), which did not enlarge over the 2.5-year long test. The view out was not fuzzy or distorted. No discoloration or spots were noted on any of the windows. The EC windows had a noticeable non-uniform pinkish surface reflectance, which was visible under low daylight and nighttime conditions (Figure 10). These various faults were attributed to the pilot manufacturing process.

**Figure 10. Exterior view of the EC windows on September 10, 2003 (left) and interior view of EC windows on July 5, 2005 (right).**

7. Durability. Long-term durability was not evaluated by LBNL. NREL conducted an assessment of durability but the results are not publicly available. In the field test, about 25% of the installed EC windows operated less accurately and reliably after 1–2 years of operation. This poor performance could be attributed to the alpha intermediate-state controller. LBNL operated the EC constantly within a PTR of 12:1 (Tv=0.60–0.05) under

non-steady state environmental conditions while the NREL tests evaluated EC durability under steady state environmental conditions defined by the ASTM Standard E2141. The LBNL test may have pushed the EC product beyond the manufacturer's expected levels of usage. When the manufacturer's controller was replaced with an LBNL controller, reliability and accuracy were brought back to near acceptable levels.

### 2.5.2. Intermediate-State EC Window Controller

**Outcome:** The manufacturer must produce an accurate and reliable intermediate-state EC window controller in order to capture the full benefits of EC windows. The alpha controller provided by the manufacturer proved to be inadequate. A closed-loop prototype solution devised by LBNL in collaboration with the manufacturer shows promise as a viable technical solution, assuming that small local areas of an EC window are and will remain representative of the tint across the entire window surface. Simple electrical characterization of the EC appears to be inadequate if accurate control is to be maintained over the long term—a trimming function should be provided to the user or facility manager as the EC coating characteristics change. A product that provides only on-off (full bleached or full colored) control will be of limited benefit if a primary goal is to minimize energy use and peak demand. Stepped transmittance control (e.g., 5–10 incremental states between fully bleached and fully colored) would provide more benefit. Continuous transmittance control (as was implemented in this field test) would be ideal. If inaccurate intermediate-state control is provided (difference in between-pane Tv is greater than ±10% of value), the color matching between adjacent EC window panes will be poor. Architects and building owners will not accept the appearance of a random checkerboard façade. Fine-tuning the EC window wall to meet specific control criteria (e.g., energy-efficiency and visual comfort) will also be difficult.

The EC window controller modulates the current-to-voltage waveform so as to switch the EC window to various levels of tint. The fully clear or bleached state and the fully tinted or colored state are the two end states of the switching range. A modulated tint between these two end states is termed an intermediate state. The following basic performance specifications for the EC window controller were delineated by LBNL to satisfy energy-efficiency and other energy-related control objectives for commercial building applications:

#### 2.5.2.1. LBNL procurement specifications for the EC intermediate-state window controller:

- Ability to switch individual EC window to any specified transmittance level over the switching range to within 5% of true value after reaching the requested value. The accuracy level defines the EC controller's ability to achieve visual uniformity between multiple side-by-side windows (also referred to as between-pane uniformity or multipane synchronization). Ideally, uniformity should be achieved at all times irrespective of whether the devices are in transition or at rest so as to avoid a visually detracting checkerboard façade appearance.
- Ability to report accurate Tv data. For window systems that take a long time to switch, knowing the current state of the EC window can help to avoid control oscillations under variable sky conditions.
- Each EC window should have individual control electronics with a group control interface for networking/multiplexing multiple windows. The group controller should

be capable of providing data and status information on individual EC devices (e.g., ready, busy, error). The EC controller should accept several basic commands: request device status data; set the EC transmittance; stop switching and stabilize at the current state; and clear if there is an error or reset/reinitialize if necessary. The user must have the ability to control and monitor I/O to each EC window. Communication via RS485 is preferred (e.g., RS232 severely limits cable lengths).

- If there is a reduction in the EC switching range over extended cycling, the EC controller should be able to maintain the above performance characteristics.

The manufacturer's initial specifications for their alpha intermediate-state EC window controller estimated control accuracy to be within ±10% of Tv value at any state, which was greater than LBNL's desired ±5% specification. This was the manufacturer's first attempt to design an intermediate state controller for the specific purpose of use in this field test program. With visual inspection from the interior of the field test facility, the entire EC window wall of 15 individual EC window units initially had a uniformly colored appearance when the EC windows were at any resting intermediate state (Figure 11). The controller also demonstrated reliable control (see Appendix A, citation 7). Later, the appearance degraded as the EC intermediate controller lost accuracy over the 2.5-year test period—possibly due to unanticipated control exerted by the LBNL supervisory control system or to other unknown factors. The gradual degradation in performance suggests that a simple electrical characterization of the EC window is unlikely to be sufficient to achieve long-term accuracy.

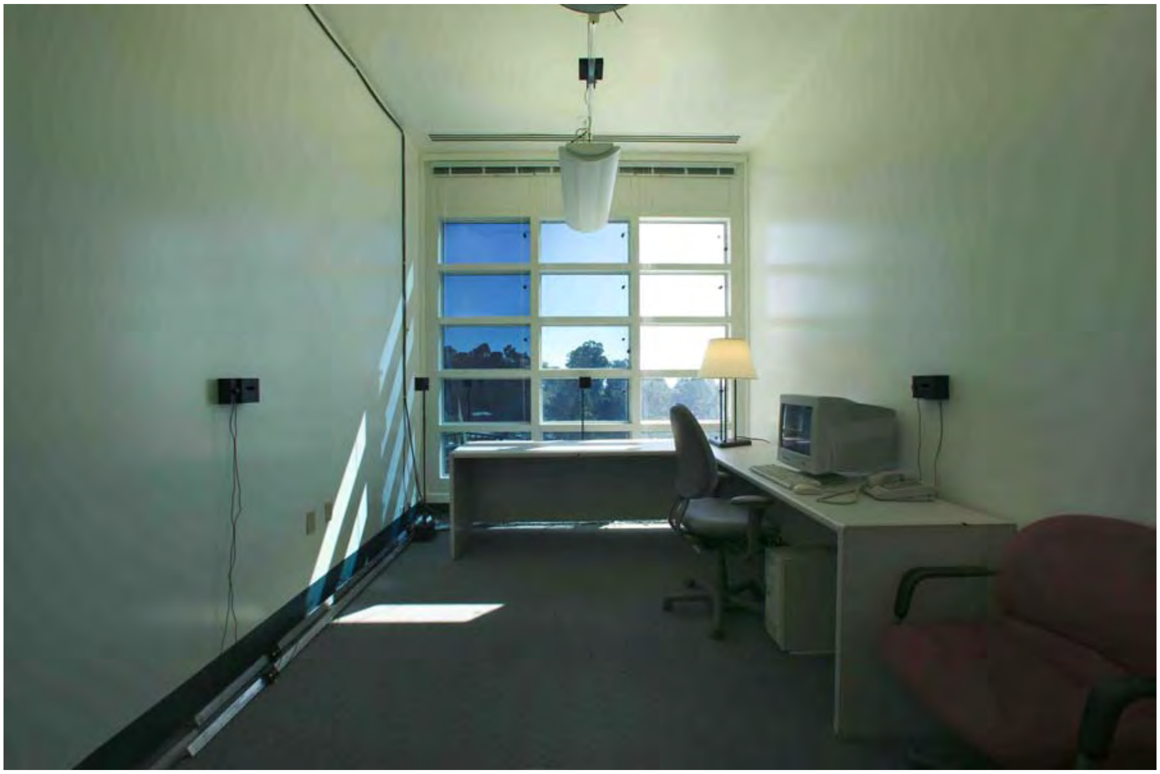


**Figure 11. Interior view of EC window wall shortly after EC windows were first installed, September 10, 2003.**

To improve control reliability, transmittance sensors were used to implement closed-loop feedback control during the last four months of the field test. These sensors were initially designed and installed by LBNL at the start of the field test program to monitor EC function and assess between-pane color matching. The sensors were designed and engineered for research purposes, not practical real-world applications: the housing of the sensor was large (2.54-cm (1-inch) diameter cylindrical housing with a 0.48-cm (~3/16-inch) diameter sighting tube) and was mounted on the interior and exterior face of the EC window. The photodiode/LED sensor measured a small area on the device (<5 mm diameter) and its accuracy will be dependent on the uniformity of the EC coating. Further work will be required to develop practical solutions. For example, minute transmittance sensors could be mounted near the edge of the EC IGU and be covered by the window frame (assuming EC coating uniformity to the edge). Multiple sensors would be required on each EC IGU since a single sensor failure would otherwise compromise the long-term life of the EC window.

While sensors add cost, accuracy and operational reliability were significantly improved with this form of closed-loop control. The façade appearance maintained a nearly uniform colored appearance over the four-month test period. An example of before and after performance is given in Figures 12 and 17, respectively.

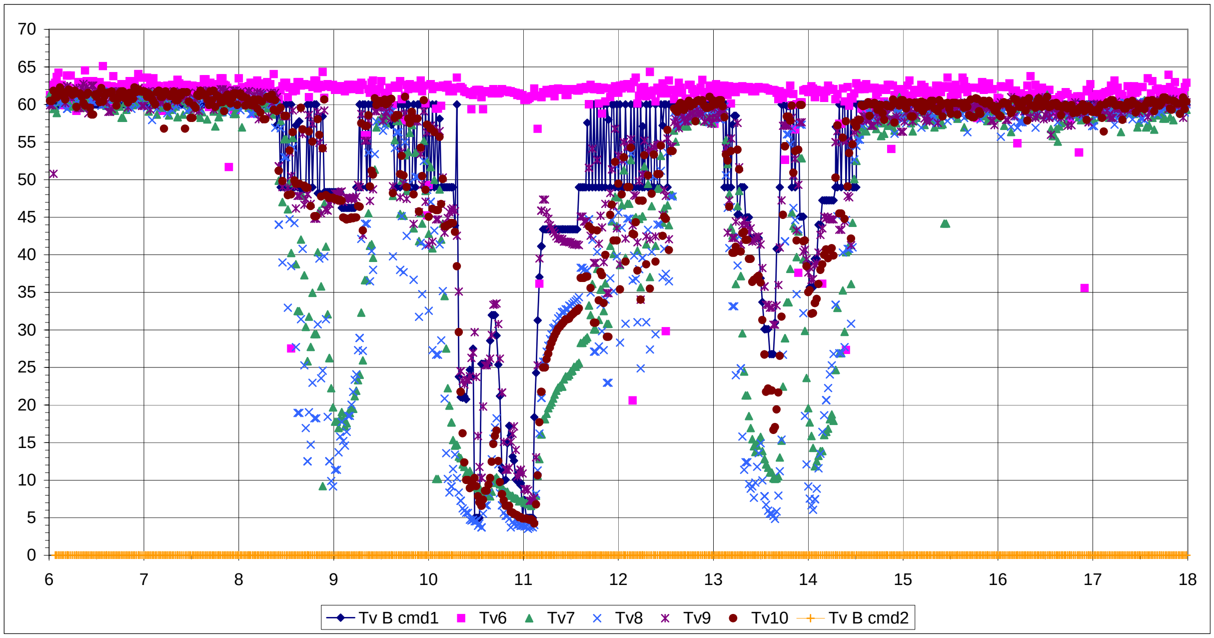


**Figure 12. Example of inaccurate control exerted by the EC alpha intermediate-state controller on a partly cloudy day, February 8, 2005. The "cmd1" line controlled the lower EC zone windows (Tv7 to Tv10) and exhibits the control oscillations that occurred in the deadband range of Tv=0.49–0.60. The "cmd2" line controlled the upper EC zone window, Tv6.**

Although EC windows do not produce mechanical noise that could annoy the occupant, color matching between side-by-side windows can be poor if frequent and significant adjustments to the transmittance are made because of control oscillations or unstable sky conditions. There were a number of factors that contributed to control errors in the field: 1) inaccurate transmittance data provided by the manufacturer's EC controller, 2) the deadband range of the

EC controller, and 3) indirectly, the nonuniformity of coloration as the EC window switches. Accurate transmittance data from either closed-loop sensors or the manufacturer's EC controller are required to implement proper control of the EC windows without error. The LBNL supervisory controller relied on knowing the status of the EC windows at all times (during switching and when the EC devices were at rest) to implement the control algorithm. Control status was checked once every minute and if a change to the EC and/or lighting system was required, then the components were actuated. If the intermediate-state controller's reported transmittance was inaccurate, the EC window received new erroneous commands that prevented the system from achieving control objectives.

The EC alpha controller placed several limits on control. If the command was within the deadband control range of Tv=0.50–0.60, the EC was fully bleached to Tv=0.60. In addition, the EC controller did not adjust the window if the Tv command was within ±0.02 of the current Tv. To prevent oscillations at the top end when the supervisory control system was fine-tuning control, commands between Tv=0.50–0.57 were adjusted to Tv=0.49. Still, oscillations occurred when daylight conditions varied such that command values oscillated between the Tv=0.49 and Tv=0.60 states. To avoid this hysteresis, the simplest solution would be to control the EC within the narrower Tv=0.05–0.50 range or implement time delays based on historical trending of exterior sky conditions.

Each EC prototype window had a slight to noticeable non-uniform coloration when in the process of switching—the regions closest to the edge bus bars colored first while the center colored later (Figure 13).

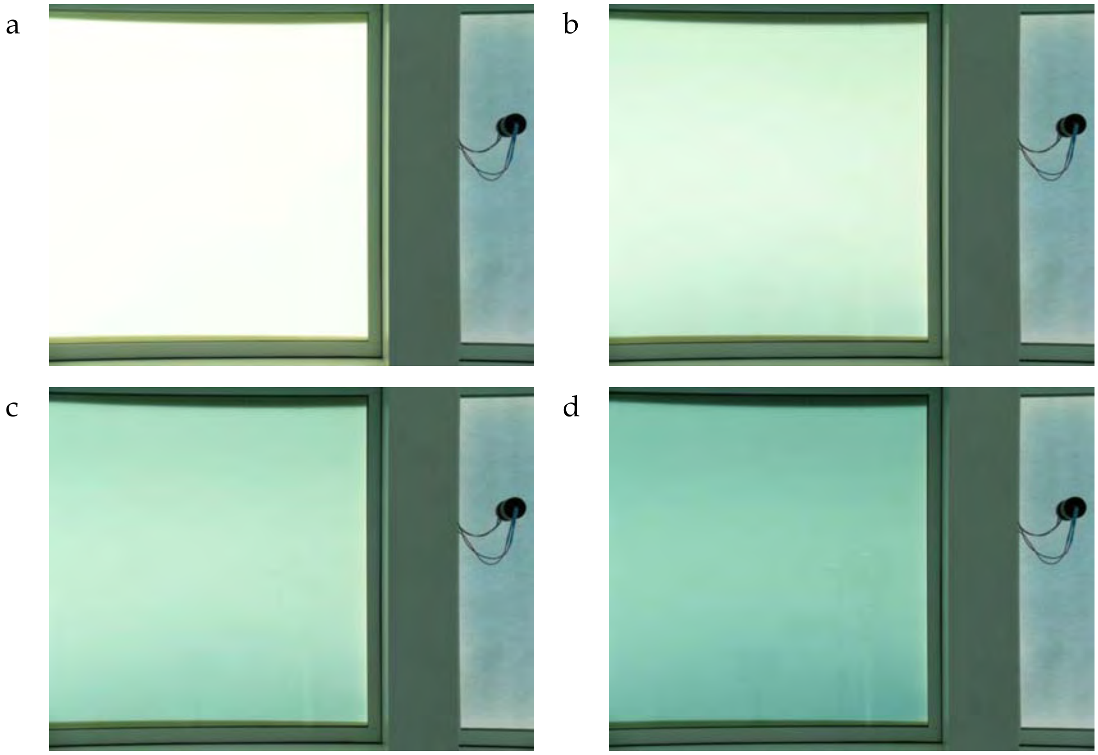


**Figure 13. Appearance of the EC window when switching (1-minute time-lapsed images from a to d). The bus bars are located on the top and bottom edges so the tinting occurs faster at these edges while the middle portion switches slower.**

This non-uniformity will affect the accuracy of the closed-loop transmittance sensors—control algorithms should also account for this effect. On partly cloudy days when the EC windows were switched frequently between the bleached and colored end states, the multi-pane façade exhibited a slight checkerboard appearance. Time delays should be implemented to dampen the response of the EC windows under rapidly changing sky conditions. Under cold conditions, when the switching speed decreases significantly, this effect could be more pronounced particularly if individual EC windows have different response characteristics, if there are different levels of incident radiation on the EC windows due to shadowing from overhangs or other local obstructions, or if adjacent panes are of different sizes.

The alpha EC intermediate-state controller reported moderately accurate Tv data for each EC window to the LBNL supervisory control system. It provided no device status information given its preliminary stage of development. Initial bench-scale tests in 2003 demonstrated that the EC controller communicated via RS485 with an electrically sound interface.

### 2.5.3. Integrated EC Window-Daylighting Systems

**Outcome:** A prototype integrated EC window-daylighting system was engineered for a private office application. The final technological solution includes EC windows, a dimmable electric lighting system, practical low-cost sensors, and the necessary control software to optimize daylight and cooling while addressing visual comfort requirements. A graphical user interface was made available to the occupant via their local desktop PC. The solution has been tested in a private office application but the solution developed is generic (aside from the unique interface to the EC window product) and applicable to other smart window technologies and most building space types where there are vertical windows and overhead lighting.

The basis for the design of the integrated EC window system and technical details for its implementation are given in Section 2.4. This basic design is practical and generic enough to be used in most building applications. The EC window, dimmable 0–10 V electronic ballasts, and 0–10 V photodiode sensors were all networked via the supervisory control system using conventional and reliable methods now common to the industry. The placement of sensors followed common practice established by commercially available products: at the ceiling or on the exterior face of the building. The solution was demonstrated to be reliable under variable sun and sky conditions across a range of seasons (see the next Outcome in this section).

The method of implementation is likely to change given the rapid movement toward wireless high-speed networking and controls and the industry trend toward individually controlled digital ballasts (e.g., digital addressable lighting interface (DALI)). T8 lamps are now being replaced by more efficient T5 lamps. Efficient light-emitting diodes (LED) are unlikely to be used in overhead lighting in the near term, but as task lighting, they are an efficient alternative to overhead lighting. The details of hardware and software interface will need to evolve given these technological advances.

The technical solution was implemented in a private office and is applicable regardless of window orientation or window size. Open plan offices will require alternate commissioning approaches. To implement the “daylight” control algorithm, the current closed-loop control solution requires that the EC window manufacturer work with the lighting controls manufacturer to obtain the ballast control voltage signal and photosensor signal for each daylit zone. To commission the system, daytime and nighttime correlations between the voltage signal, photosensor signal, and work plane illuminance must be made for each daylit zone. These relationships are used to determine how to switch the EC windows and electric lighting. For private offices, this commissioning requirement is challenging given standard practices of today. For open plan offices with multiple dimming zones (and likely to head toward individually dimmed DALI ballasts) and frequent space reconfigurations, this solution becomes impractical with current technologies and practices unless the process is automated. The reliability of open-loop control solutions should be investigated.

For other spaces serving similar purposes as private offices, this solution is applicable; e.g., school classrooms, libraries, conference rooms, patient rooms, and some retail and manufacturing spaces. For spaces with multiple occupants, it would be best to use automated blinds to block direct sun if needed; if manually operated blinds are specified, the EC control algorithm should be designed to optimize daylight, leaving the glare and direct sun control function to the occupant-controlled blind.

For conventional skylighting applications, the solution can be simplified dramatically if the EC layer is combined with a diffusing layer to control direct sun. For properly sized skylights, the EC will most likely not need to be controlled for energy efficiency—the fully bleached state will offset lighting energy use requirements and thermal loads will be controlled by the correct sizing of the skylight. EC switching can be used to control interior illuminance levels, if so desired, and skylight glare, particularly for low-ceiling applications. EC skylights would allow current skylight area restrictions to be relaxed; with increased area, energy savings could be extended on overcast days, or winter morning and afternoon conditions. Under bright sky or summer cooling conditions, the EC devices would restrict glare and cooling. For large-area skylights used for atria or indoor courts, further study is required to develop control algorithms that optimize daylight and space-conditioning load tradeoffs.

**Outcome:** The integrated EC window-daylighting system for a private office application was developed and tested iteratively under real sun and sky conditions over a period of 2.5 years. To maximize energy efficiency and address visual comfort requirements, the EC window wall was divided into two separately controlled apertures: an upper "daylighting" aperture and a lower "view" aperture. A manually operated interior Venetian blind was assumed to be part of the solution, with seasonal adjustments to the height of the blind, ideally, so that the orb of the sun was blocked from the occupant's field of view for the majority of the day. Reliability was good but dependent on the accuracy and reliability of the EC intermediate-state controller. The spectral shift produced by the EC window did not significantly affect photosensor response. Direct sun had more of an effect, so a dual-headed photosensor was devised to improve lighting control reliability. More sophisticated sensors and algorithms are needed to better address visual comfort requirements.

The core control objectives of the integrated system were to maintain interior illuminance levels to within a specified range, to eliminate visual discomfort arising from direct sun and high window luminance, and to operate in a reliable manner under representative sun and sky conditions. The first objective yields optimal energy savings, the second and third objectives helps to avoid occupant discomfort and complaints. This section reviews issues related to reliability of the integrated EC window and daylighting control system. Reliability of the EC window controller alone was discussed in Section 2.5.2.

For the daylight control algorithm, a common problem with conventional daylighting control systems is that the target work plane illuminance is not maintained reliably under variable sun and sky conditions. To address this issue, a single ceiling-mounted color-corrected photosensor was used initially to control both the EC window and electric lighting system. The photosensor signal was correlated to interior daylight illuminance levels and this correlation was used in part to control the two components. The correlation was found to be insignificantly influenced by the spectral shift in daylight caused by the EC window as it switched from a clear to a blue tinted state (Tv=0.05). Sky and direct sun conditions were found to cause greater variability in the correlation (see Appendix A, citation 7 and Figure 14).

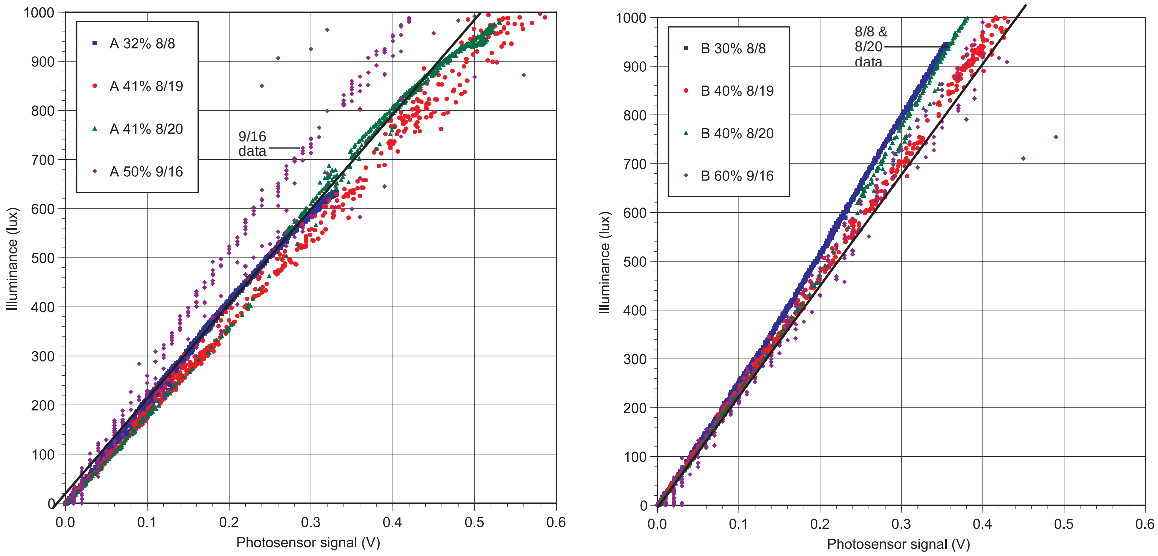


**Figure 14. Correlation between the downward looking ceiling-mounted photosensor signal and daylight illuminance at the work plane with the EC window at different transmittance levels (legend shows Tv values of 32%, 41%, etc.). Data are given for sunny and partly cloudy days in August and September.**

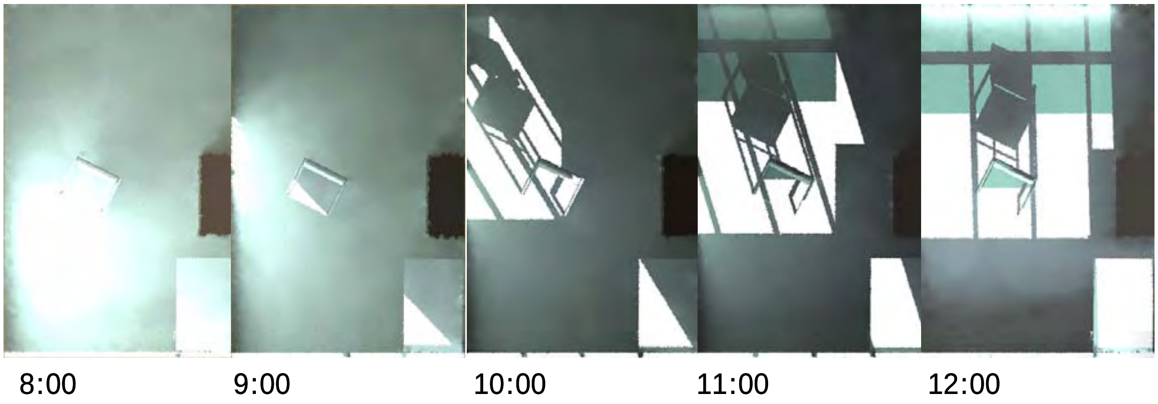


**Figure 15. Radiance-generated image of what a ceiling-mounted photosensor would see in a private office (with a 0.9-m-, 3-ft-deep exterior overhang) at different hours on a sunny winter day. The south-facing window is at the bottom of the image.**

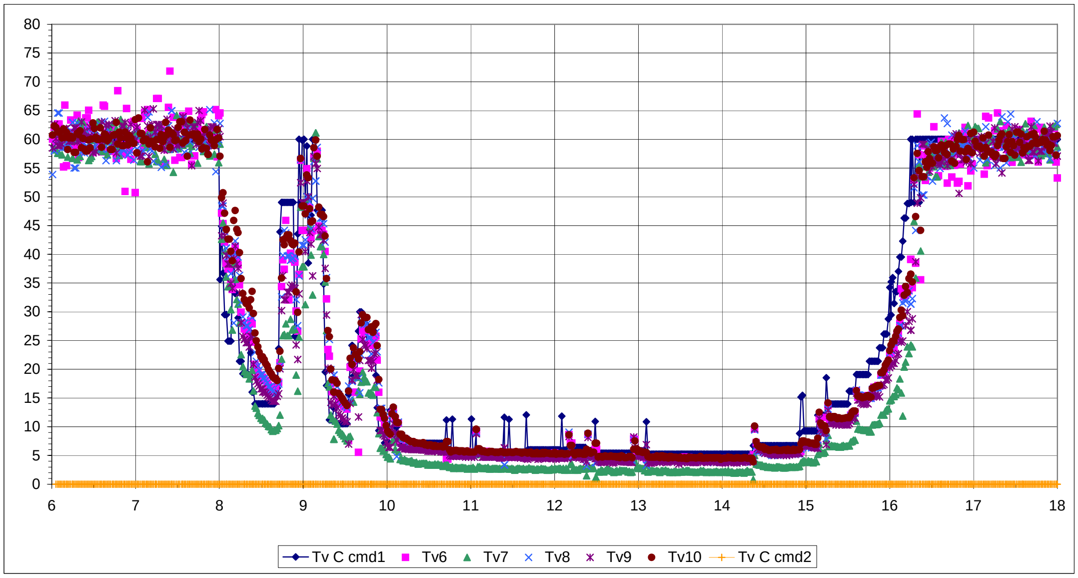
Direct sun significantly influenced the reliability of the daylighting control system. EC windows tint—they do not diffuse or redirect sunlight (Figure 15). Therefore, if direct sun is not blocked (using interior or exterior shading systems), the luminance pattern within the interior will be non-uniform and special considerations must be made to place the control photosensor so that it will not be unduly influenced by the patches of direct sun. To address this problem, a second photosensor aimed at the rear wall of the private office was used in combination with the first downward-looking sensor to achieve more reliable control of the electric lighting system.

The integrated EC-daylighting control system maintained the work plane illuminance above 90% of the setpoint illuminance level for greater than 96% of the day on average for the various EC test conditions tested. An example is given in Figure 16.

The glare control mode operated reliably because it was simple: if the exterior vertical illuminance exceeded some threshold value, the EC window was switched to its maximum colored state or a user-selected intermediate state (subjects selected Tv=0.11 on average in our human factors tests as opposed to the device minimum, Tv=0.05). An assessment of its comfort and energy performance is given Section 3.4. To implement the visual comfort control solution described in the Radiance-Mathematica optimization study (Section 3.4.3.4), more sophisticated sensors and algorithms will be needed.

The final engineered solution assumes the use of an interior Venetian blind based on the human subjects/subjective survey results from this project. For cost-effectiveness, a manually operated blind is assumed (an automated motorized blinds would improve performance but the automated EC window-blind combination would not be cost justified based on energy savings alone). Seasonal adjustments to the blind height would be ideal (see Section 2.4 for blind use description). To ensure high performance, the occupant should be made aware in some non-intrusive fashion of how seasonal adjustments to the blind height should be made. An EC with a broader switching range and a very low transmittance (1% or less) when fully colored would reduce or eliminate the dependence on interior sun-blocking shades for some applications.

The final engineered solution assumes that the EC window wall is zoned into an upper and lower EC aperture with separate control algorithms for each aperture. See Figure 17 for an example of control operations. No special sensing hardware was needed to implement this solution—the EC window controller already enabled control of individual EC windows so the control logic for the EC windows was simply modified to address separate zones. The number of rows of EC windows included in the top zone was adjusted using a manual toggle; e.g., single top row for the late summer to equinox condition, two top rows (or more) for equinox to the winter condition. A zoning schedule will be required to adjust the height of the EC zones automatically by season.



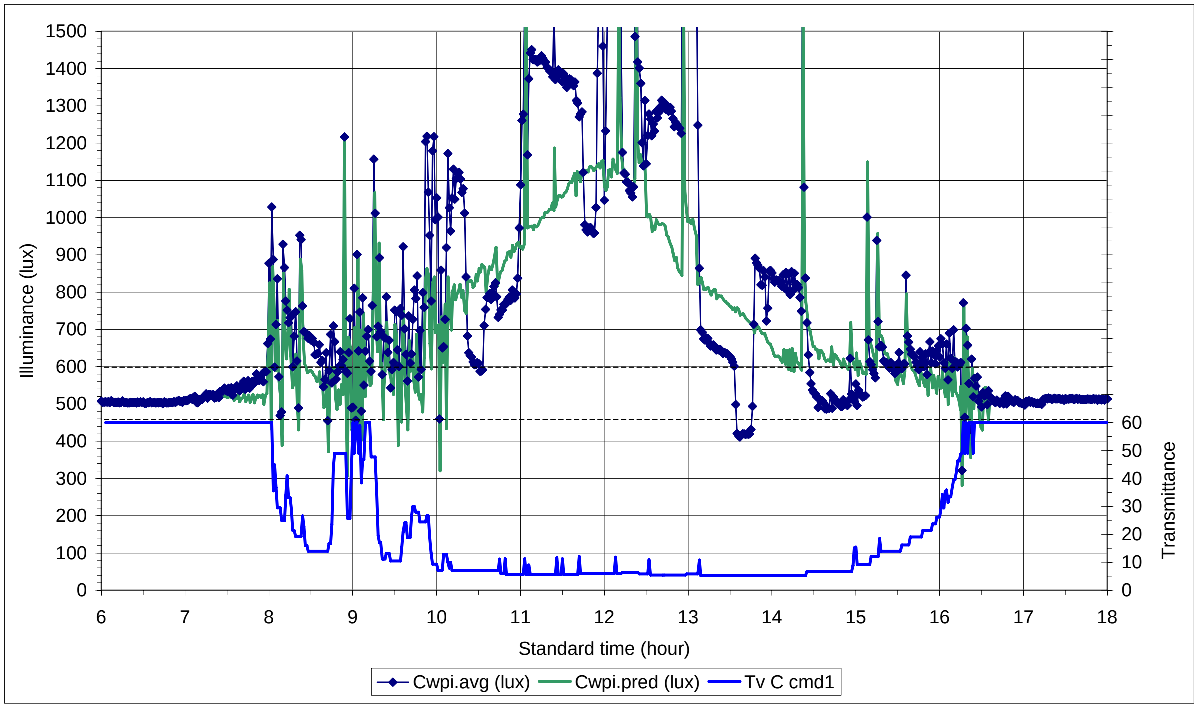


**Figure 16. Example of the daylight-controlled EC window and daylighting control system on December 11, 2004. Unshaded EC windows are tinted in proportion to available daylight (5 of the 15 EC windows are shown in the upper plot; Tv C cmd1 in lower plot). Total work plane illuminance levels (lower plot, Cwpi.avg) exceed the upper limit of the setpoint range (510–600 lux) because of direct sun. Note that with the dual-photosensor control solution, the work plane illuminance was less than 90% of the minimum setpoint (459 lux) for only 2% of the day. The EC alpha intermediate-state controller was used.**

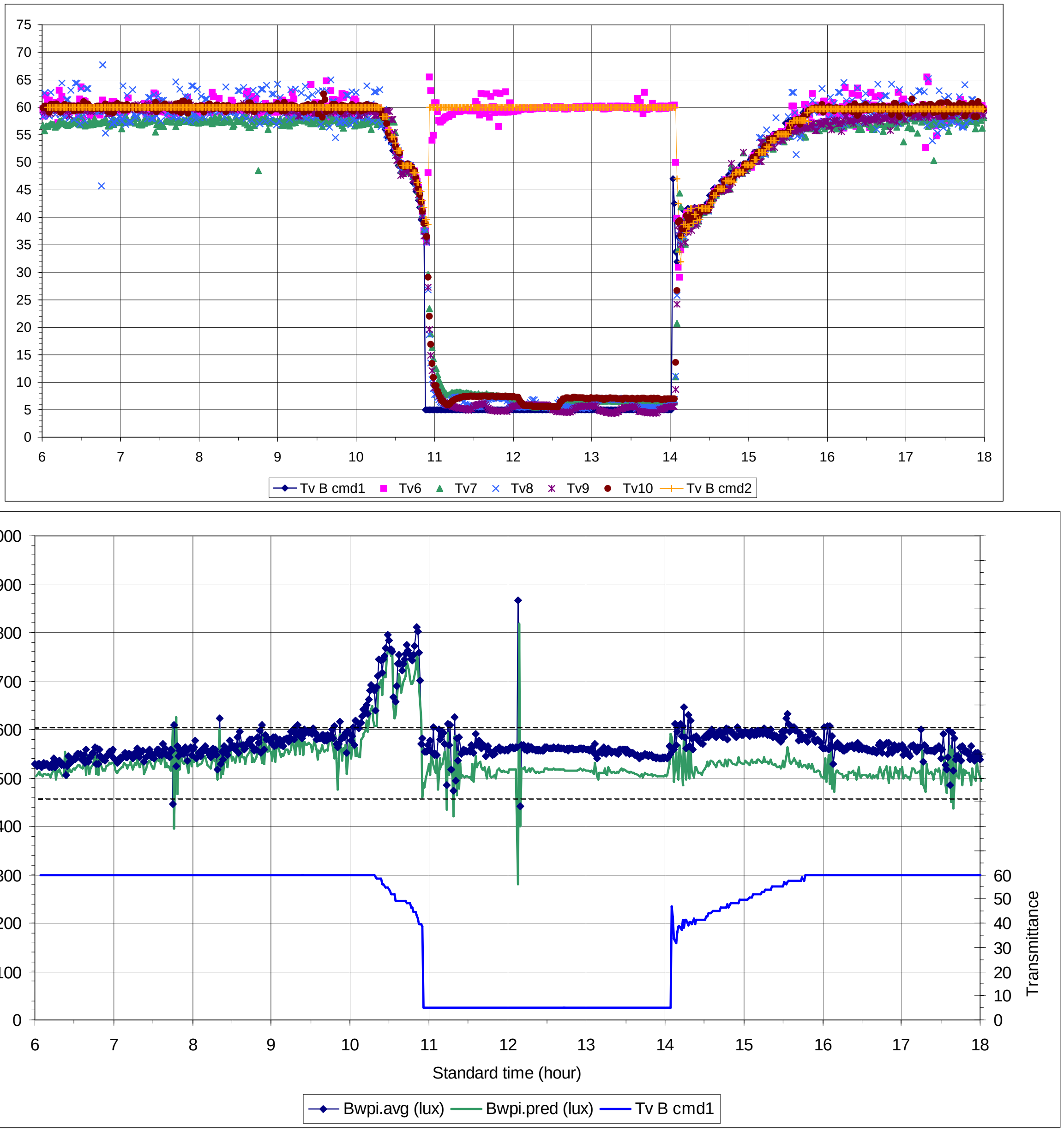


**Figure 17. Example of the 2-zone EC window and daylighting control system on July 19, 2005. The upper EC window (Tv6) is in the daylight mode (and shaded by a Venetian blind) while the lower EC windows (Tv7 through Tv10) are in the daylight-glare control mode (upper plot). The total work plane illuminance level is maintained within the 510–600 lux setpoint range for the majority of the day (lower plot). The LBNL EC intermediate-state controller provided more accurate EC control.**

In the same manner, a user control interface was developed for the human factors/subjective survey task. Additional work is required to make this interface more user friendly and intuitive. Individual pane control appears to have some value—when given the opportunity, occupants tuned their façade to additional criteria not addressed in our solution: view, privacy, EC reflectance (see Section 3.4.3 below).

Variations in switching speed were not accommodated in the final control solution. For cold climates or for larger-area windows, algorithms should be devised that account for long switching speeds (e.g., >10 minutes). The feedback transmittance sensors can provide one method of determining speed (the supervisory system would need to trend EC response over time, however) but does not allow one to separate diagnosis of EC failures from temperature effects. Temperature sensors on the EC devices would provide a more reliable feedback mechanism for determining switching speed, but this would increase the cost of the EC unit.

**Outcome:** The EC window (and dimmable ballasts) was networked and controlled via a low-cost building-wide networking-control scheme in a limited bench-scale proof-of-concept test. The integrated system can also be integrated with the building management control system (BMCS) via a networked gateway, as is done typically today. Such solutions enable whole-building integration of EC windows, paving the way for implementation of building-wide control based on demand response, real-time pricing, occupancy, life-safety, façade-as-advertising or signage, and other building-wide schemes. A simplified engineering study concluded that EC control on a short time step (minutes or hours) based on HVAC status did not create any added energy-savings benefit to that provided by the local perimeter zone control algorithms evaluated in this study. More study is warranted. The control algorithm will need to be modified if the HVAC or lighting system's efficacy diverges significantly from typical VAV or lighting systems used in current commercial buildings. Occupancy- or schedule-based control would further improve the performance of EC systems.

To implement building-wide control, a low-cost building communications network scheme was evaluated to determine applicability to EC windows (see Appendix A, citation 2). This network would allow individual window and lighting loads to be controlled from an existing enterprise local area network (LAN) at a significant cost reduction in per point networking costs. A prototype interface was created using 1-Wire Dallas Semiconductor/Maxim network components then evaluated using bench-scale tests. The interface successfully delivered a transmittance command to the dedicated EC controller and monitored EC window status. The solution, while of practical use, was not of immediate relevance to EC manufacturers because the costs of the network and controller were considered to be minor compared to the cost of the entire system.

The relative efficacy of the lighting and HVAC systems has significant bearing on the energy-efficiency control algorithm. While variable-air-volume space conditioning systems are common in today's commercial office buildings, there is a slow trend toward low-energy and other alternate cooling systems. Overhead lighting may also have significant improvements in efficiency due to ballast or lamp improvements (e.g., LEDs). With these changes, the tradeoffs between cooling load and daylighting must be reexamined. With very efficient lighting systems of the future and conventional HVAC systems, greater energy efficiency may be obtained if the EC control algorithm is designed to minimize space-conditioning loads. For very efficient HVAC systems, the daylighting aspect of EC control should be optimized. A generic supervisory control system interface should have setpoints and other features that enable finetuning of the software to specific building applications, schedules of operation, etc. for different types of lighting and HVAC systems. For the same reasons, the user interface should have options to finetune or override the control system.

Other control components should be integrated with this system: e.g., occupancy sensors to reduce energy use when the occupant is not present; integration with the energy management control system (EMCS) to implement demand-responsive whole building strategies. For occupancy-mode control, the lights should be dimmed to minimum or standby power or shut off while the EC should be set to a mode that minimizes space-conditioning loads. The response time of the EC window should be taken into account when developing these algorithms. For demand response, the most energy-efficient mode would be to switch to the non-occupied control mode. Alternatively, the daylight mode could be implemented, ignoring visual comfort requirements. Using simplified calculation methods, the team found no additional energy-savings benefit with EC-daylighting-HVAC integration (assuming a conventional VAV system with a COP that varies seasonally, not daily). However, further study is warranted.

## 3.0 Performance Impacts

### 3.1. Objectives

The objective of this task was to:

- Identify and quantify overall benefits, costs, and risks of the EC technology under realistic building operating conditions so as to stimulate market interest and enhance market success of this emerging technology.

This task addresses the need for objective third-party data to verify a manufacturer's claims for product performance and to quantify the net worth of integrated EC solutions. Performance data also provide timely feedback to developers, identifying critical path market barriers that will need to be addressed by industry well before product introduction to the market. For the architect, engineer and building owner, the key question that needs to be answered prior to adoption is: can the bottom-line incremental cost for the technology be justified by lower energy and demand operating costs, decreased capital costs due to possible HVAC downsizing, increased occupant comfort and performance, and increased amenity for a given building application? Other major stakeholders such as utilities and public agencies vested in managing and meeting the statewide demands for increased energy supply in forthcoming years focus on determining whether such emerging technologies can ultimately provide persistent and reliable energy efficiency gains and demand reductions across a broad range of building types or in regions where significant growth in population is anticipated. Factors such as ease of use, magnitude of impact, and likelihood of user acceptance determine whether such technologies are promoted by public entities in the marketplace.

### 3.2. Approach

Full-scale integrated EC window and daylighting systems engineered in the first task were monitored in the LBNL Windows Testbed Facility to quantify energy and peak demand performance for a typical commercial private office application. Subjective response and visual comfort were also evaluated. Computer simulations also provided relevant energy and visual comfort performance data. The data resulting from these various methods were used in combination to formulate answers to the questions that architects, engineers, building owners, utilities, and other major stakeholders are likely to ask.

A full-scale 88.4 $m^2$ (953 $ft^2$) LBNL Windows Testbed Facility was built, instrumented, calibrated, and used to evaluate the function and reliability of the EC window product and the performance of the EC window-daylighting system, to measure energy use and demand, and to evaluate the quality of the interior environment under representative sun and sky conditions (see Appendix A, citation 8 for a more detailed description of this facility). Over 100 sensors were installed in three south-facing test rooms designed and furnished as private offices. The EC system's performance was compared to a spectrally selective low-emittance window with the same daylighting control system to isolate performance benefits to the EC technology alone as compared to the state-of-the-art static window technology now on the market (window U-value was factored out of the comparison). Both the EC and reference cases were tested with and without an interior Venetian blind.

Measurements were made over a two and a half year period where various reference and test case combinations were evaluated. In order to obtain statistically significant results that can be generalized to annual performance, the team attempted to monitor each test condition for at least 30 representative days over a six-month solstice-to-solstice period. The performance impacts of seven different test conditions were monitored, of which six had statistically representative data. The remaining case yielded data that were suggestive of performance trends. To obtain accurate data, all aspects of the prototype integrated control system, measurement equipment (e.g., chiller, fan coil units, pumps, PID controllers), and instrumentation (e.g., turbine flowmeters, thermistors, watt transducers, illuminance sensors, etc.), must operate within specification. This was particularly challenging since the integrated system was being developed as the measurements were being performed. The EC window controllers were also not reliable; after a one to two year period, they no longer consistently met the manufacturer's stated levels of accuracy. Various data filters were used to obtain test data that met specific quality control and measurement criteria.

**Figure 18. Thermal calibration tests in the LBNL Window Testbed Facility**

Monitoring thermal loads accurately is particularly difficult in a multi-purpose test facility. A single-purpose calorimeter facility employs heat flow sensors on all interior room surfaces to monitor thermal loads accurately at a small time step. The LBNL Mobile Window Thermal Test Facility, for example, can monitor window loads to within ±10 W at a 10-minute time step. Such facilities can be used to derive or validate basic mathematical models for thermal performance. The multi-purpose test facility used for this project was designed to monitor cooling or heating demand due to the windows for each test room and enable daylighting technology development and human subject tests as well. Measurements were corrected for temperature and room-to-room variations using a static thermal model (Figure 18; see Appendix A, citation 10). The resulting "dynamic net heat flow" or standardized cooling demand, is expected to represent, on average, only the effects of solar gain (including internal solar storage) on a standardized room. Daily thermal loads were monitored to within an average overall error estimate of ±3% or ±14–32 W. Lighting electric loads were monitored to within 0.2% of reading. These energy-savings data were correlated to exterior environmental conditions.

Shielded photometric sensors monitored illuminance and luminance of various room surfaces. These data were used to compute luminance ratios, the daylight glare index, average window luminance, and other performance metrics for judging visual comfort. The reference case and various modes of EC control were correlated to computed performance parameters (e.g., average window DGI or percentage of day that the window luminance exceeded 3000 cd/m$^2$) to determine whether EC windows yield more comfortable conditions than the unshaded or shaded reference window condition.

Bracketed digital photographic images of the same scene were combined to create a high-dynamic range (HDR) luminance image. These images of the test room interior were captured every 12 minutes over the course of the day during the last four months of the field test. Automated image analysis tools were created to extract detailed luminance ratio data, glare source data, and illuminance data. These and additional webcam images taken every 6 minutes were used to document and diagnose EC operations in the test rooms.

A subjective survey was issued to 54 subjects exposed to three separate conditions in the EC test rooms: a) automatic mode, b) semi-automatic mode, and c) reference mode (EC at Tv of 0.60, manually dimmed electric lights). The surveys were issued during the worst-case solar condition with low solar altitude: from the winter solstice to the vernal equinox (although subjects were exposed to both clear and sky conditions, depending on the weather during this period). Sessions for each of the three modes ranged from 40 minutes to an hour. Filling out a questionnaire for each session, subjects were asked to judge the work environment, the EC modes of operation, and select reasons for why they were satisfied or dissatisfied with the technology or environment. Subjective appraisals were related to independent environmental variables. Probabilistic functions for shade deployment were derived from these occupant studies.

### 3.3. Summary of Test Conditions and Comparative Cases

Table 1 lists the reference and test case conditions for the field tests, human factors/subjective survey, and Radiance-Mathematica optimization study. All of these studies were conducted with approximately the same office setup, large-area window, and south-facing perimeter zone in the Berkeley or Oakland, California climate.

## Table 1. Field Test Reference (R) and Test (EC) Conditions

| Code | Tv cog | SHGC cog | U-factor W/m2-C | WWR | Window zones | Window control mode | Blind control mode | Lighting | control freq |
|---|---|---|---|---|---|---|---|---|---|
| **Field Test: Energy, Peak Demand, Visual Comfort** | | | | | | | | | |
| R-1-F | 0.42 | 0.219 | 1.408 | 0.66* | 1 zone | none | 1 blind, fully raised all day | daylight controls | na |
| R-2-F | 0.42 | 0.219 | 1.408 | 0.66* | 1 zone | none | 1 blind, fully lowered all day, 45deg slat angle fixed | daylight controls | na |
| EC-A | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 1 zone | daylight*** | none | daylight controls | 1-min |
| EC-B | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 1 zone | daylight | 1 blind, fully lowered all day, 45deg fixed slat angle | daylight controls | 1-min |
| EC-C | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 1 zone | daylight + glare**** | none | daylight controls | 1-min |
| EC-D | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 2 zones, 1 upper row, 4 lower rows | upper: daylight; lower: glare | none | daylight controls | 1-min |
| EC-E | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 2 zones, 1 upper row, 4 lower rows | upper: daylight; lower: glare | 1 blind lowered over upper zone all day, 45deg fixed slat angle | daylight controls | 1-min |
| EC-F | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 2 zones, 1 upper row, 4 lower rows | upper: daylight; lower: glare; glare mode if solar profile angle < 75deg | 1 blind lowered over upper zone all day, 45deg fixed slat angle | daylight controls | 1-min |
| EC-G | 0.05-0.60 | 0.09-0.42 | 1.87** | 0.66* | 2 zones, 2 upper rows, 3 lower rows | upper: daylight; lower: glare; glare mode if solar profile angle < 75deg | 1 blind lowered over upper zone all day, 45deg fixed slat angle | daylight controls | 1-min |
| **Field Test: Subjective Survey** | | | | | | | | | |
| R-1-HF | 0.6 | 0.42 | 1.87** | 0.66* | 1 zone | none | three side by side blinds, individually controlled by occupant to any height or slat angle | manual dimming switch (0-100% light) | 1-min |
| EC-auto | 0.02-0.60 | 0.09-0.42 | 1.87** | 0.66* | 1 zone | daylight^ + glare^^ | three blinds, individually controlled by occupant to any height or slat angle | daylight controlled* | 1-min |
| EC-semi-auto | 0.02-0.60 | 0.09-0.42 | 1.87** | 0.66* | 1 zone | daylight^ + glare^^ | three blinds, individually controlled by occupant to any height or slat angle | daylight controlled* | 1-min |

R=Reference mode condition; EC=Test mode condition for electrochromic; Tv=visible transmittance; cog=center-of-glass; SHGC=solar heat gain coefficient; WWR=window-to-wall-ratio; freq=frequency; na=not applicable

Field test notes:

| | |
|---|---|
| * | For thermal loads, WWR=0.66. For daylighting, WWR=0.54–0.66 since desk blocked lower windows. |
| ** | Cooling loads due to solar heat gains were monitored. Conductive loads were factored out. |
| *** | Daylight mode: maintain daylight illuminance within 540–600 lux setpoint range. |
| **** | Glare mode: Tv=0.05 when Ev>30,000 lux. |
| ^ | Total illuminance setpoint determined by occupant using slider switch |
| ^^ | glare mode: minimum Tv=0.02–0.03 |

## Table 1. Field Test Reference and Test Conditions (continued)

| Code | Tv cog | SHGC cog | U-factor W/m2-C | WWR | Window zones | Window control mode | Blind control mode | Lighting | control freq |
|---|---|---|---|---|---|---|---|---|---|
| **Radiance-Mathematica (RM) Simulations** | | | | | | | | | |
| R-1-RM | 0.6 | na | na | 0.6 | 2 zones, each with fixed height | none | 1 blind, 2 heights, height and slat angle controlled hourly for visual comfort for side wall VDT task | daylight controlled | hourly (TMY) |
| R-2-RM | 0.6 | na | na | 0.6 | 2 zones, each with fixed height | none | 1 blind, 2 heights, slat adjusted 1/day for worst case for side wall VDT task | daylight controlled | 1/day |
| EC-RM | 0.05-0.60 | na | na | 0.6 | 2 zones, each with fixed height | Upper and lower zones controlled hourly to meet visual comfort needs and optimize for daylight (600 or 800 lux) | 1 blind, 2 heights, height and slat angle controlled hourly to block direct sun at eye then for visual comfort | daylight controlled | hourly (TMY) |

## Table 2. Comparative Cases for Energy and Peak Demand Field Measurements

| Case | Reference condition* | Blind position ** | Mode*** | Test condition* | Window zones | EC control upper/lower | Blind position ** | Mode*** | Used when^ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | R-1-F | no blind | T-24, HVAC | EC-A | 1-zone | daylight | no blind | EE | |
| 2 | R-1-F | no blind | T-24, HVAC | EC-C | 1-zone | glare | no blind | VC+EE | |
| 3 | R-2-F | 100% blind, 45deg | Manual | EC-A | 1-zone | daylight | no blind | EE | |
| 4 | R-2-F | 100% blind, 45deg | Manual | EC-B | 1-zone | daylight | 100% blind, 45deg | VC+EE | Winter solstice |
| 5 | R-2-F | 100% blind, 45deg | Manual | EC-C | 1-zone | glare | no blind | VC+EE | |
| 6a | R-2-F | 100% blind, 45deg | Manual | EC-D | 2-zone, 1 upper row | daylight/ glare | no blind | VC+EE | Summer solstice |
| 6b | R-2-F | 100% blind, 45deg | Manual | EC-E | 2-zone, 1 upper row | daylight/ glare | 20% blind, 45deg | VC+EE | Equinox |
| 6c | R-2-F | 100% blind, 45deg | Manual | EC-F | 2-zone, 1 upper row | daylight/ glare, 75deg profile angle | 20% blind, 45deg | VC+EE | Equinox |
| 7 | R-2-F | 100% blind, 45deg | Manual | EC-G | 2-zone, 2 upper rows | daylight/ glare, 75deg profile angle | 40% blind, 45deg | VC+EE | Equinox |

* See "code" field in Table 1.

** 100%=fully lowered, 0%=fully raised, 45° slat angle

*** Modes:

T-24: Title-24 code 2005 (Table 143-A) would have required a SHGC=0.41 for this climate (ctz03), no interior shades, and no daylighting controls.
HVAC: HVAC designers would size their cooling plant based on this condition.
Manual: Likely blind position if the blinds were manually operated.
EE=Energy-efficient mode
VC=Visual comfort mode

^ Used when: In terms of visual comfort, this comparative case is most applicable if used during this period of the year.

Table 2 lists the comparative cases that were measured in the field test facility. These comparisons were made to quantify the potential energy and peak demand savings that would result from the use of EC windows. The first two cases assume a Title-24 compliant condition as the reference case:

- Case 1 compares the performance of a perimeter zone office designed roughly to meet the requirements of the CEC Title-24 (2005) prescriptive code to that of the EC window-lighting system. For this climate zone (ctz03) and large window size (WWR≅0.60) used in the field tests, DOE-2 simulations (see Appendix A, citation 9) indicate that the total primary annual energy use budget should be 43.8 kWh/ft$^2$-floor-year (149.5 kBtu/ft$^2$-floor-year; assuming prescribed SHGC and U-value shown in Table 143-A for WWR=0.40 with no interior shades). Specific windows were modeled in DOE-2. A modeled reflective window (center-of-glass (COG) Tv=0.13, SHGC=0.17, U-value=2.27 W/m$^2$-°K (0.40 Btu/h-ft$^2$-°F)) was found to meet the energy budget requirement to within 5%. A modeled tinted spectrally selective low-e window (Tv=0.53, SHGC=0.29, U-value=1.65 W/m$^2$-°K (0.29 Btu/h-ft$^2$-°F)) with daylighting controls was also found to meet this budget. Since spectrally selective low-e windows represent the state-of-the-art in window coating technology, a commercial product (COG, Tv=0.42, SHGC=0.22, U-value=1.42 W/m$^2$-°K (0.25 Btu/h-ft$^2$-°F)) that best matched the properties of the modeled windows was selected and installed in the field test facility. There are no blinds for both the reference and test cases.
- Case 2 makes nearly the same performance comparison as Case 1 (Title-24 compliant case) but controls the entire EC window wall for glare and daylight. There are no blinds for both the reference and test cases.

The remaining cases assume “occupied” reference conditions, which assumes that occupants will lower their blinds to control interior brightness or to create comfortable thermal conditions, then rarely operate their blinds thereafter.

- Case 3 is analogous to Case 1 but the reference case has manually operated blinds that are fully lowered all day. The EC window is controlled for daylight but has no interior blind.
- Case 5 is analogous to Case 2 but the reference case has manually operated blinds that are fully lowered all day. The EC window is controlled for daylight and glare but has no interior blind.
- Cases 4, 6, and 7 directly address the issues of visual comfort in both the reference and test cases. The reference case has the blinds down all day. The EC window either has a fully lowered blind (Case 4) or a partially lowered blind over the upper portion of the EC window wall (Cases 6 and 7).
- Note that seasonal adjustment of the blinds and EC zoning configuration could yield better performance. The monitored data, however, reflects annual performance using the same control scheme throughout the year. Case 1 would be appropriate for the period between summer solstice and early equinox when solar altitudes are high and the Venetian blind is not required to block direct sun for the majority of the daytime hours. Cases 6 and 7 are most appropriate for the late summer solstice to early winter solstice period where the partially lowered blinds provide direct sun protection for the majority

of the day. Case 4 is most appropriate for the winter solstice period when sun angles are low and direct sun protection is needed on the south façade throughout the day.

The four relevant energy performance values that were computed in this field test were:

- Daily cooling energy use. Cooling load savings were isolated to those resulting from reduced solar gains through the window, Qw[2]. Total cooling load savings resulting from both the EC window and the daylighting control system, Qw+l, were computed assuming 100% conversion of lighting energy to heat (pendant light fixtures were used).
- Peak cooling load savings. The peak cooling load due to the window was defined as the measured load that occurred two hours after the hour when the vertical solar irradiance level was at its peak. The peak *daily* cooling load did occur at different times in each room, but the mechanism driving peak loads was solar irradiance and this analysis focuses on the difference in coincident peak solar loads produced by the EC window (EC windows modulate only solar heat gains, not U-value). Differences in maximum daily peak load and coincident peak load were small, with the latter method producing less scatter.
- Daily lighting energy use. Lighting energy use was sampled every 6 s then averaged and recorded every 1 minute. The data were summed over the day between 6:00–18:00 Standard Time.
- Peak lighting demand. The peak hour was the same as that used for the peak cooling load computation.

## 3.4. Outcomes

### 3.4.1. Energy Performance

**Outcome:** For the earlier energy savings estimates based on DOE-2 simulations, the EC window was controlled to optimize daylight admission. The EC system must also address visual comfort requirements. A number of control options that addressed direct sun and window glare were evaluated. For some of these options, lighting energy use was increased significantly, eroding the energy savings derived from reduced cooling load due to solar heat gains. If the EC window is zoned and controlled carefully, however, monitored field data and Radiance-Mathematica simulations suggest that lighting energy use savings can return to significant levels with comparable or improved levels of visual comfort and significantly greater access to outdoor views. Since the same daylighting control system was used in the reference case, these savings can be fully attributed to the EC window system. The efficacy of the lighting control system will affect the magnitude of savings. Assumptions for blind usage in the reference case can also significantly affect estimates of energy-savings potential.

Definition of the reference case condition has a significant effect on projected energy use and peak demand savings. If the baseline is defined by ASHRAE 90.1-2005 with prescribed SHGC and U-value window properties, no interior shades and no daylighting controls, then DOE-2

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[2] The heat flow does include differences in dynamic conductive loads through the window (e.g., due to absorbed solar radiation in the glass layers), but the difference in steady-state conductance due to differences in IGU U-value were subtracted off.

simulations indicate that an EC window with daylighting controls can reduce a typical commercial office building's perimeter zone annual primary energy use by 15–23% for moderate-area windows (WWR=0.30) and 10–24% for large-area windows (WWR=0.60). These savings ranges are given for all four cardinal window orientations in six representative U.S. climates assuming that the EC is controlled to optimize work plane illuminance (see Appendix A, citation 9). Peak demand reductions are of similar magnitude.

If one is trying to isolate the energy benefit to the EC window technology alone, separate from those gained through the use of daylighting controls, then a comparison should be made where both the reference and EC cases have the same daylighting control system. The results can vary widely depending on the base case window type and behavioral model for how the interior shades are operated by the occupant. If the reference window is a state-of-the-art commercially available spectrally selective low-e window with interior shades that are operated "ideally" every hour to control direct sun and window discomfort glare, then the energy benefit derived from EC windows is small or even negative for moderate-area windows. The maximum savings are derived if the window is large: primary annual energy use savings are 8–12% on the south façade across the six U.S. climates. Greater savings were projected for some California climates: e.g., 16% for south-facing perimeter zones in climate zone 3 (Oakland/Berkeley). These savings are due to the EC window's active management of solar heat gains and daylight admission over and above that achieved by the conventional static window and actively managed interior shade (see Appendix A, citation 9).

The flaws in these projections for energy-savings are two-fold. First, the reference case interior shade model is certainly far from what is actually practiced in the real world. Manually operated shades are lowered typically when visual or thermal discomfort becomes significant and then are rarely adjusted thereafter—often for days or weeks on end (Inkarojrit 2005 provides a good literature review). Second, the EC window control algorithm used in these DOE-2 simulations do not directly address visual comfort requirements, only the work plane task illuminance requirement (i.e., "daylight" control mode).

The field test program was designed to address these concerns (see Appendix A, citation 8). The monitored savings are given for a specific case—a mild climate, a large-area south facing window—but the lessons learned from this field study can be applied to future simulation studies to quantify annual energy use savings for other building applications and climates.

To address the first concern above, two basic reference cases were defined in the monitored field study: a state-of-the-art spectrally selective low-e window with an interior Venetian blind in either the fully raised or fully lowered position all day. These two cases form the boundaries of performance for a realistic reference case. Energy standards and mechanical system sizing assume no thermal benefit from interior shades, so the no-shades case also provides relevant data for design purposes. The blind slat angle was set at a fixed angle all day to just block direct sun (daylight admittance and lighting energy use savings were greater with this slat angle compared to a more closed angle, but under some solar conditions, visual discomfort may result). The impact of blind use on lighting energy use and solar heat gains are shown in Figure 19.

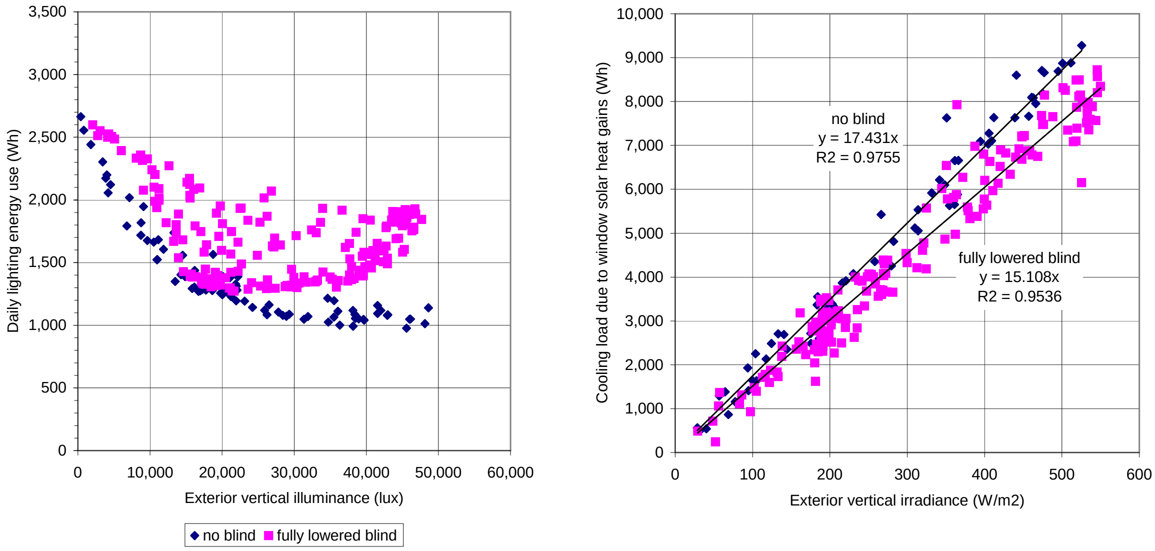


**Figure 19. Effect of interior Venetian blind on the reference case window performance. Daily lighting energy use (left) and cooling load due to solar heat gains, Qw, (right) for the reference spectrally selective window (SHGC=0.22) with and without a fully lowered matte-white Venetian blind with 2.54-cm (1-inch) slats tilted to 45° (view of ground from inside). Data were computed for 6:00–18:00 and are given for the full 20-month monitored period. On average over the year, the blind reduced daily Qw by ~13%. Minimum daily lighting energy use is 720 Wh.**

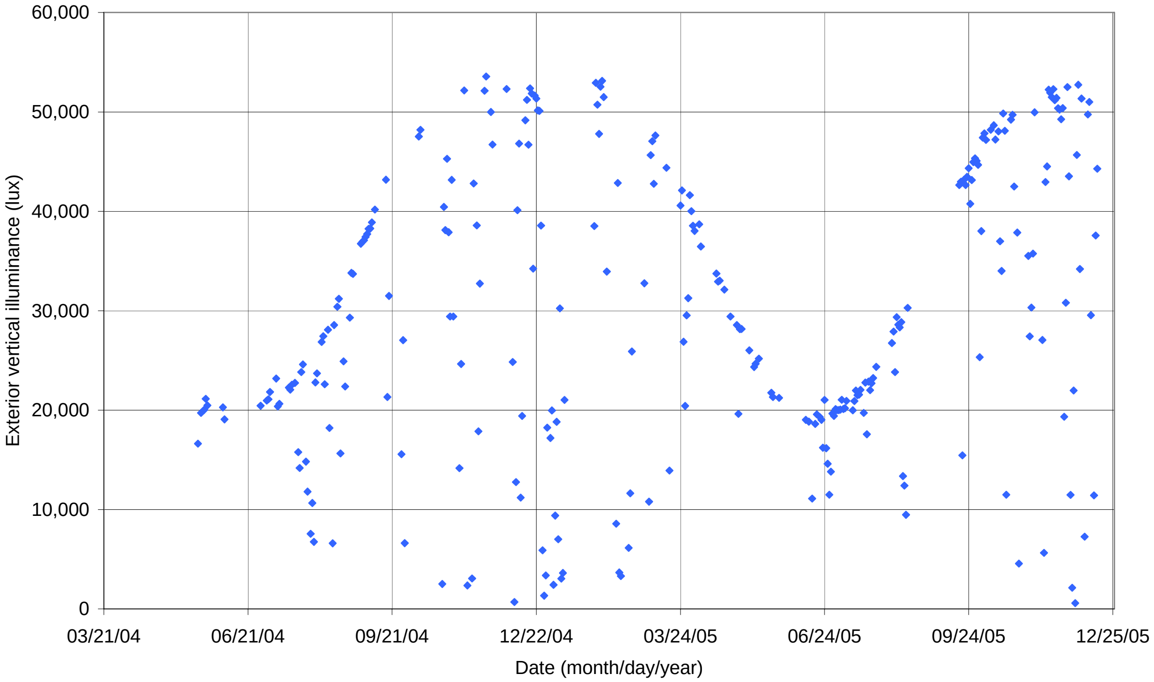


**Figure 20. Average daily exterior vertical illuminance levels monitored on a south-facing façade at the LBNL Window Testbed Facility. The upper points forming the sinusoidal shape are the clear sunny days with lowest levels (~20,000 lux) occurring around the summer solstice and highest levels occurring around the winter solstice (54,000 lux).**

To address the second concern above, the EC "daylight" control mode modeled in the DOE-2 simulations was first implemented in the field study. Other control modes were then developed to address visual comfort requirements. The daylighting control systems were the same between the reference and test cases to isolate energy benefits to the EC window alone.

For a large-area EC window controlled solely by the daylight control mode (no visual comfort control, no blinds), savings varied considerably depending on the reference case condition:

- Average daily Ev levels monitored throughout the test period are given in Figure 20.
- For each comparative case, Figure 21 shows the daily lighting energy savings (left-hand column) and cooling load savings (middle column) as a function of average daily incident vertical illuminance level. Daily lighting energy use savings were combined with cooling load savings (assuming a HVAC system/plant coefficient of performance (COP) of 3) to estimate total net energy savings (right-hand column).
- For Case 3 (Figure 21 row 3) where the reference case has Venetian blinds, the daily net energy savings range from 600–800 Wh or 0.33–0.44 W/ft$^2$-floor on days when the Ev level was less than 30,000 lux (cloudy days year-round to clear sunny summer days) and range from 200–500 Wh or 0.11–0.28 W/ft$^2$-floor on days when the Ev level was greater than 30,000 lux (partly cloudy to clear equinox to winter solstice days).
- For Case 1 (Figure 21 row 1) where the reference case is unshaded, total net energy savings are positive only when Ev levels exceed 30,000 lux, due to EC reductions in solar heat gains.
- ▪ Also note that the daily power consumption used to switch and maintain the EC windows at a steady state was not included in these net savings. Average daily power consumption of the EC system (window+controller+power supply) was 0.03–0.07 W/ft$^2$-floor (4.6-m, 15 ft-deep perimeter zone). These consumption levels can be reduced to 25–30% of current levels, if the control circuitry and power source are designed more efficiently. Other types of EC devices require power only to adjust the EC window to a different state.

If the EC is controlled for visual comfort, there are significant variations in lighting energy use depending on how well the control solution balances daylight admission against glare reduction (see Cases 2, 5, 6, and 7 in Figures 21–22):

- If the entire unshaded EC window wall is controlled to a minimum transmittance (Tv=0.05, Cases 2 and 5) to reduce window glare and luminance contrasts between sunlit and shadowed areas when Ev levels exceed 30,000 lux, then useful daylight is sacrificed and electric lighting energy use increases for all but the cloudiest conditions.
- Dividing the EC window wall into separately controlled upper and lower apertures with blinds on the upper aperture to control direct sun significantly improves lighting energy use performance compared to the shaded reference case for average daily Ev levels less than 30,000 lux (Cases 6 and 7, Figure 22 rows 2 and 3). However, lighting energy use savings decrease when the EC glare control mode kicked in on sunnier days. Lighting energy use savings are negative for Ev levels greater than 30,000 lux. Case 6 with one upper row of EC windows (WWR=0.10) does not provide sufficient daylight when the lower windows switch to fully colored to control glare. Case 7 with a WWR of 0.20 sizes

the upper aperture more adequately: the net energy savings is only slightly negative to neutral (depending on whether it is Room B or C) for Ev levels greater than 30,000 lux.

Data from all cases are summarized in Table 3. See Table 2 in Section 3.3 for a detailed description of the comparative cases.

The one obvious drawback of the EC window system is that since this transparent glazing material cannot fully block direct sun, it must be combined with either fixed or moveable secondary shading elements for most façade orientations. With a minimum EC transmittance of Tv=0.02–0.05, the EC tested was unable to sufficiently control the brightness of direct sunlight in the human factors subjective study: a Venetian blind was required. There are alternate views on this subject. Different office layouts, partitions, etc. could position occupants and tasks so that direct view of the sun would be minimized or eliminated. Fabric roller shades, coated plastic shades and perforated blinds are used in commercial buildings today and these systems do not fully block direct sun. It is unknown whether occupants find the visual environment comfortable with these solutions. More research is required to fully understand the degree to which direct sun blockage is critical with EC windows. EC manufacturers are striving to achieve a lower Tv (e.g., Tv<0.01) while maintaining the high end Tv (e.g., Tv>0.60), but given the switching speeds discussed earlier, this may not be the best solution.

**Table 3. Percentage Savings in Daily Lighting Energy Use, Cooling due to Window (Qw), Cooling due to Window and Lighting (Qw+l), and Peak Cooling Load due to Windows (Qw peak)**

| | Daylight control | | Daylight+glare, 1 zone | | | Daylight+glare, 2 zones | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case No. | 1 | 3 | 4 | 2 | 5 | 6 | 6 | 7 | 7 |
| Reference | no blind | VB1.45 | VB1.45 | no blind | VB1.45 | VB1.45 | VB1.45 | VB1.45 | VB1.45 |
| EC algorithm | d | d | d | dg5 | dg5 | 1d.4dg5:75 | 1d.4dg5:75 | 2d.3dg5:75 | 2d.3dg5:75 |
| Shade? | no blind | no blind | VB1.45 | Shade0 | Shade0 | VB020.45 | VB020.45 | VB040.45 | VB040.45 |
| Test room data: | B,C | B,C | B,C | B,C | B,C | B | C | B | C |
| Daily lighting energy use | | | | | | | | | |
| ndays | 37 | 48 | 73 | 46 | 40 | 30 | 30 | 44 | 23 |
| avg | 6% | 26% | 5% | -22% | -6% | 7% | 12% | 10% | 10% |
| stdev | 7% | 15% | 5% | 22% | 20% | 30% | 22% | 15% | 15% |
| Daily cooling load due to window (Qw) | | | | | | | | | |
| ndays | 26 | 21 | 45 | 25 | 22 | 19 | 23 | 38 | 20 |
| avg | 2% | -9% | -12% | 8% | 3% | -8% | -6% | -11% | -6% |
| stdev | 11% | 10% | 10% | 9% | 8% | 12% | 10% | 12% | 18% |
| Daily cooling load due to window and lighting (Qw+l) | | | | | | | | | |
| ndays | 26 | 21 | 45 | 25 | 22 | 19 | 23 | 38 | 20 |
| avg | 3% | 7% | -6% | -3% | 4% | -5% | 0% | -4% | 0% |
| stdev | 8% | 4% | 5% | 10% | 4% | 6% | 3% | 3% | 3% |
| Peak cooling load due to window (Qw peak) | | | | | | | | | |
| ndays | 13 | 12 | 31 | 8 | 10 | 13 | 12 | 23 | 16 |
| max | 22% | 14% | 8% | 26% | 19% | 5% | 8% | 7% | 15% |
| avg | 11% | -1% | -2% | 17% | 10% | 1% | 4% | -3% | 6% |
| stdev | 9% | 9% | 7% | 7% | 6% | 2% | 2% | 8% | 4% |

Lighting energy savings (Wh)    Qw+l savings (Wh)    Lighting + Qw+l/COP savings (Wh)

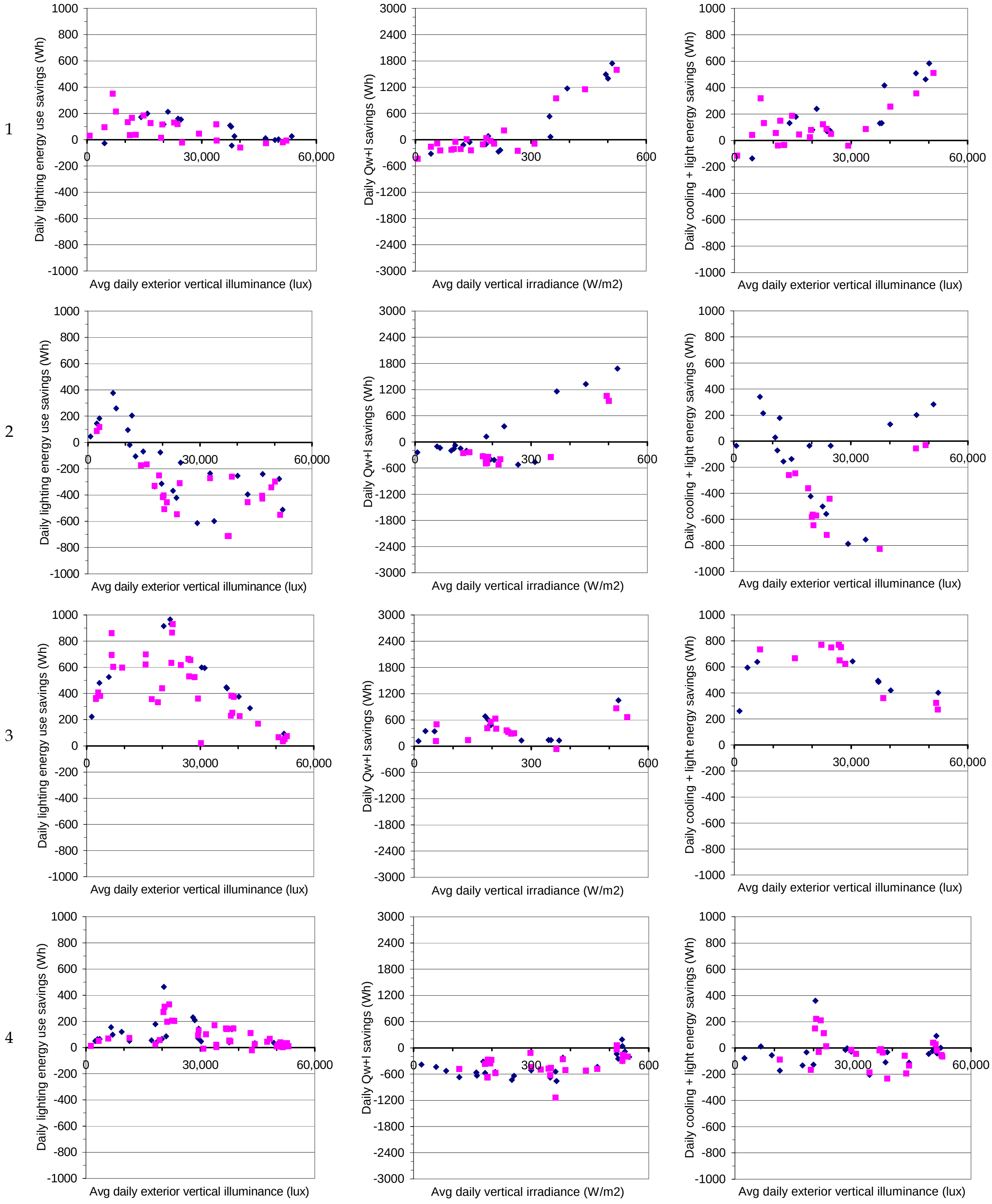


**Figure 21. Average daily vertical illuminance or irradiance versus daily lighting energy savings (left), daily cooling load savings due to solar heat gains and lighting (middle), and net daily energy savings (right) for Cases 1 (top) through 4 (bottom). diamonds: Room B; pink squares: Room C.**

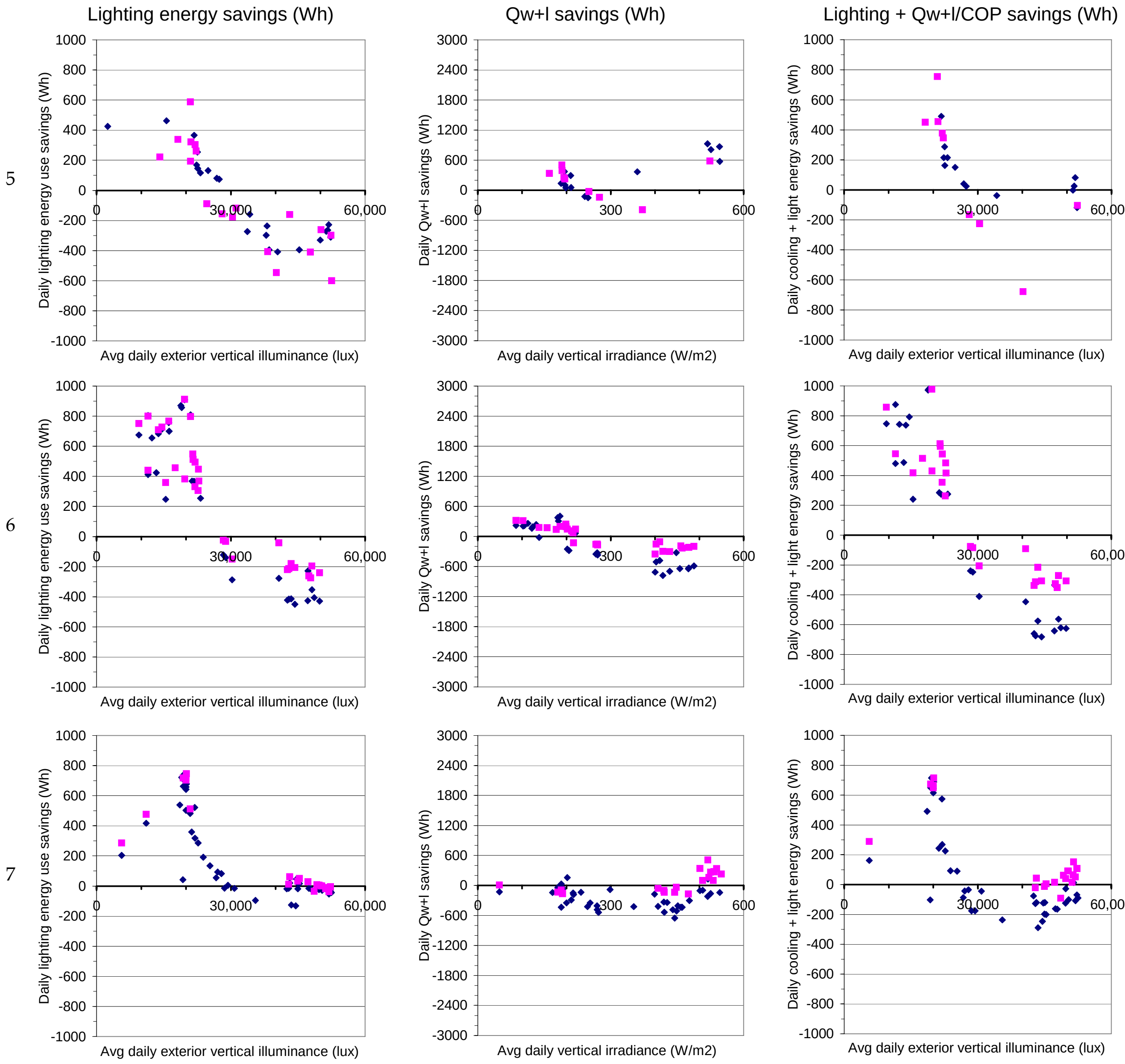


**Figure 22. Average daily vertical illuminance or irradiance versus daily lighting energy saving (left), daily cooling load savings due to solar heat gains and lighting (middle), and net daily energy savings (right) for Cases 5 (top) through 7 (bottom). Blue diamonds: Room B; pink squares: Room C**

The problem with combining the EC window with an interior shade is that the shade must be automated to capture the full energy-savings benefit of EC windows. Otherwise, human inertia will likely erode the benefit of using EC windows—the blinds will likely be lowered most of the day. Best case solutions (e.g., Case 7) require minimal manual control of the Venetian blind (cover the upper aperture only then leave it for a season) and presume that the occupants are seated far enough from the window (1.5 m, 5 ft or more) or has a view orientation that allows them to avoid most incidences of low-angle direct sun coming through the lower EC aperture in the late afternoon or early morning. The severity of this problem is dependent on the frequency of direct sun striking the occupant's eyes (this can be determined through sun angle calculations) and the likelihood that the weather will be clear (e.g., TMY weather data). The

Radiance-Mathematica simulations discussed below (Section 3.4.3.4) show that manual blind use with EC windows is very infrequent for a typical occupant position in a private office.

With exterior shading devices like an overhang, the EC dependence on well-managed, manually operated interior shades to block direct sun can be lessened but the cooling load benefits derived from dynamic solar heat gain control will be lessened. An overhang is static and therefore provides a non-optimal solution over the course of the entire year. A DOE-2 simulation study was conducted where the window wall was defined by an EC upper aperture controlled for daylight and a lower EC aperture shaded by a 0.9-m (3-ft) deep overhang and controlled for many different control algorithms including glare (see Appendices I.3 and I.4, and Figure 23). The EC apertures were not modeled with interior shades. The reference case had the same divided window wall, window size, and overhang as the EC configuration—its spectrally selective low-e lower and upper apertures each had interior shades operated hourly to control direct sun and glare. The daylighting controls were the same between the reference and test cases. The EC case reduced the average annual daylight glare index significantly (sidewall view). Unlike the field tests, the lower EC transmittance was modulated based on incident solar radiation levels (63–315 W/m$^2$), instead of a threshold value of 30,000 lux—daylight admission was more optimized but luminance contrasts were not as controlled. Total primary annual energy use savings were 10% in Chicago and 4% in Houston for a perimeter zone with a large-area south-facing window. Solar heat gains in Houston due to direct sun through the lower aperture eroded savings. Since hourly control of the reference case's manually operated blinds is unlikely, these energy savings are likely to be conservative.

Neither the engineered solution tested in the field study nor the systems modeled in the DOE-2 simulations satisfied visual comfort requirements optimally: both could have used more refined methods to control glare and direct sun and increase daylight. For example, the transmittance of the window when in the glare mode could have been greater (e.g., Tv=0.15 versus Tv=0.05) if sky glare was the source of discomfort. This would increase daylight savings while still addressing glare concerns. A separate Radiance-Mathematica simulation study was run where EC window control was optimized to satisfy various visual comfort criteria first, then the work plane illuminance criterion was satisfied. Lighting energy use savings and other benefits derived from this study were significant as discussed in Section 3.4.3.4 below. With or without overhangs, EC windows have the potential to meet comfort requirements and save energy, if controlled carefully.

Further savings could be extracted from the EC system if occupancy-based controls are added. When the room is unoccupied, the EC could be switched to the bleached mode during the heating season or switched to the colored mode during the cooling season and the electric lights could be turned off.

The assumptions for the reference case lighting system significantly affect end use energy savings. Well-commissioned daylighting control systems have penetrated less than 1–2% of the market. If the reference case is assume to have no lighting controls, then average daily lighting energy use savings would be 44±11% for Case 7.

The efficacy of the lighting control system will also affect the magnitude of savings. The older 0–10 V ballast technology is inefficient at the low end of the dimming range—some systems consume ~35% of full power while providing ~10% of full light output. This is due to the power consumption of the electronic circuitry, which is fixed irrespective of dimming level. With the newer DALI digital ballasts, the low end can be reduced to 17% of full power while providing ~1–9% of full light output. Lighting energy savings will increase with these and other more efficient lighting technologies.

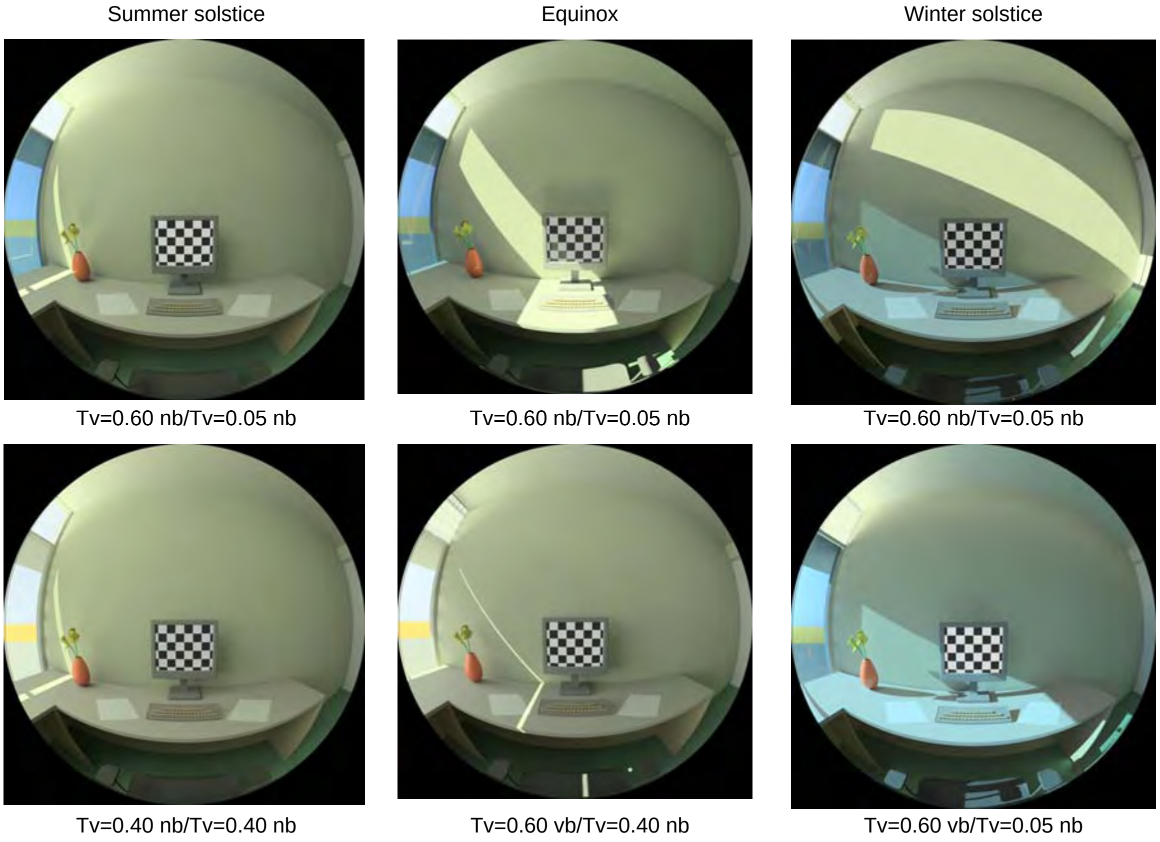


**Figure 23. Radiance simulation of a private office space with overhang under clear sunny skies at 11:30 on the summer solstice (left), equinox (middle), and winter solstice (right) in Chicago. The top row shows the upper aperture EC at Tv=0.60 without Venetian blinds ("nb") and the lower aperture EC at Tv=0.05. The bottom row shows the upper aperture EC at Tv=0.60 with Venetian blinds ("vb") for the equinox and winter solstice conditions (no blind needed for the summer solstice condition) and the lower aperture EC at Tv=0.40 to reduce sky glare on the equinox and summer solstice condition and at Tv=0.05 for direct sun control on the winter solstice condition.**

### 3.4.2. Peak Demand Performance

The reference window was large and had a sufficiently high visible transmittance (Tv=0.42, WWR=0.60) that interior daylight illuminance levels exceeded the design illuminance setpoint (538 lux) under clear sky conditions even with the blinds fully lowered (45° slat angle). If the reference and EC test cases have the same daylighting control system, there are no additional peak lighting demand savings derived from EC windows alone (assuming a high-transmittance reference window). For example, during the hot August to October period, the reference case lights were at minimum power or off from 10:00–14:00 in August and 9:00–15:00 in late September. But if no daylighting or other lighting controls are assumed for the reference case, as is current practice, then there are substantial peak lighting demand savings: 70% during the mid-day to late afternoon hours on clear sunny summer days if the lights are dimmed to minimum power, 97% if dimmed to standby power, and 100% if switched off. Savings were not quantified for a reference case with occupant-controlled on-off switches but existing data suggests that occupants do not reliably use manual controls.

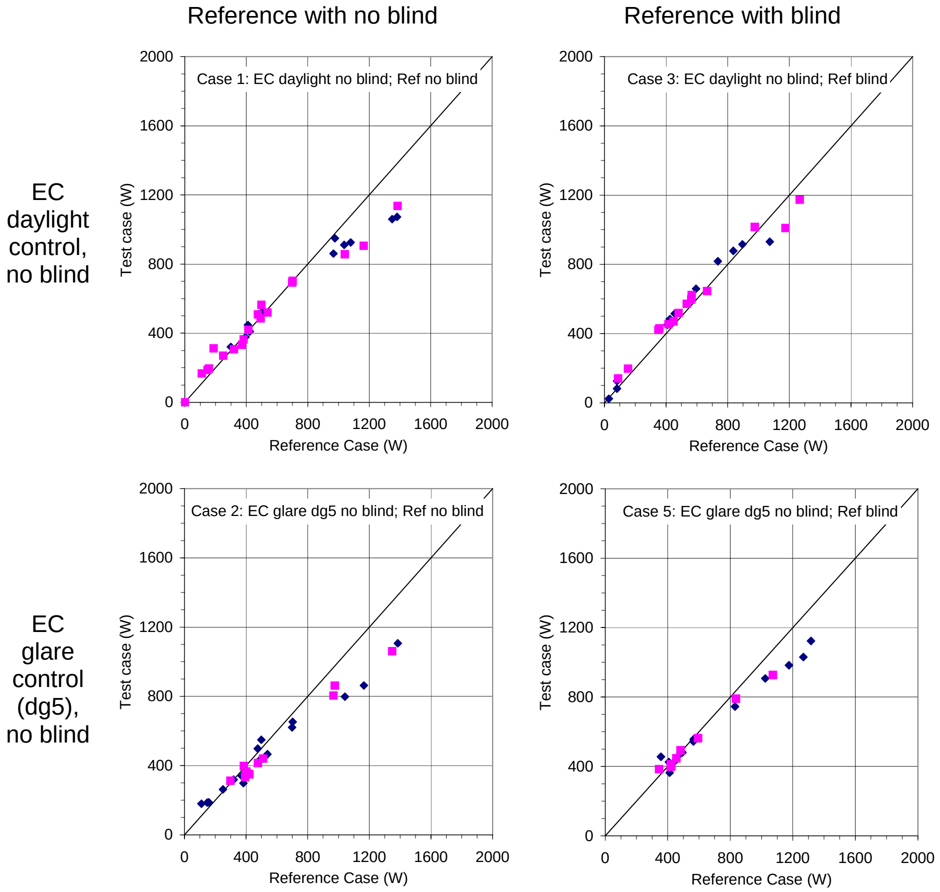


**Figure 24. Hourly peak cooling load due to heat gains from window and lights for the single-zone EC system controlled by daylight (upper row) or by glare (Tv=0.05, lower row) compared to the reference case with or without fully lowered Venetian blinds (45° slat angle).**

Peak cooling load reductions can be significant because the EC window can substantially reduce solar heat gains when switched to its maximum colored state (SHGC=0.09). Solar heat gains (and lighting energy use) constitute a large percentage of the perimeter zone peak load. For this south window orientation, the peak condition occurs on a clear winter day when solar irradiance levels are the highest of the year. Peak cooling load reductions due to solar heat gains were a maximum of 26% and 19% compared to an unshaded and shaded reference case if the EC is controlled to its lowest transmittance. Figure 24 shows that the peak load reductions for these cases and for the daylight-controlled EC windows, which has similar levels of reductions. Note that the EC window control system can be switched automatically to either of these demand response (DR) strategies.

If the building manager is able to turn off all non-emergency perimeter zone lights during a DR load shed, then the EC windows could be switched to a DR mode to minimize solar heat gain admission (SHGC=0.09; see Appendix A, citation 1). Some occupants could work by daylight alone. Occupants located further from the window could use high-efficiency LED task lights (e.g., 9 W per work station).

### 3.4.3. Occupant Comfort, Satisfaction and Acceptance

#### 3.4.3.1. Subjective Responses to EC Windows

**Outcome:** Occupant comfort is a critical condition to most building owners and may ultimately be a market driver in terms of the adoption of new energy-savings technologies. Occupants judged the EC window system as significantly more desirable than the reference window, where preferences were strongly related to perceived reductions in glare, reflections on the computer monitor, and window luminance. Blinds were fully raised during 77–79% of the automated EC-mode sessions versus only 38% of the reference sessions. The EC color and room appearance were judged satisfactory. Subjects often faced the EC window to do computer-based tasks despite complaints of glare or brightness. If the reference case had a lower transmittance window, complaints of glare and use of blinds would likely be less for these winter solar conditions, but energy savings would be lower as well.

A subjective survey was conducted to obtain appraisals of the EC technology, the desirability of different EC operating modes, and satisfaction with the resultant working environment (see Appendix A, citation 11). It is important to understand the conditions of the test in order to judge the outcomes. Forty-three subjects worked individually in a south-facing private office with EC windows, manually operated Venetian blinds, and dimmable fluorescent lights over a three-hour work session. Subjects were asked to fill out questionnaires after having spent 40–60 minutes exposed to each of three EC-daylighting control modes (described below). Forty percent of the subjects were under 40 years old. Seventy-three percent of the subjects who were 40 years and over wore glasses at work. Subjects, on average, spent 69% of the time working on the computer doing self-appointed tasks. Approximately half brought their own laptop computer. Others used the PC or Macintosh computer with a flat-panel liquid crystal display (LCD) screen provided in the test rooms. The majority of the subject's time was spent facing the sidewall (62% of the time) or the window (36% of the time). The test was conducted between the end of November and the end of March. Fifty percent of the time the skies were cloudy and for the remaining time, 25% was partly cloudy and 25% was clear skies. The solar profile angle was low: $35 \pm 9^{\circ}$. Due to the low solar angle, this subjective study presented a severe test of the ability of the EC window and Venetian blinds to control glare.

The EC window and dimmable electric lighting system were operated in three different modes: 1) automatic, 2) semi-automatic, and 3) reference modes. One mode was tested per 40–60-minute session. With the reference mode, the subject could dim or turn off the lights but the window was set to a fixed high transmittance level (Tv=0.60). The automatic and semi-automatic modes implemented the daylight-glare control mode for the entire EC window wall and dimmed the lights according to daylight availability. With the semi-automatic mode, the user could set the minimum and maximum setpoint light levels (both the EC and electric lighting were adjusted to maintain light levels within these targets) and the minimum window transmittance when in the glare-blocking mode (e.g., Tv=0.03). The EC windows were controlled within a continuous range of Tv=0.60–0.03. The lower Tv value was achieved with a special EC controller used only during the human subject tests. For all three modes, manually operated Venetian blinds were provided to the subjects and the subjects were asked to wait five minutes after the beginning of the session before drawing the Venetian blind if they felt the blinds were needed.

In general, the subjects were satisfied with the various attributes of the EC window (appearance, time to lighten/darken, and color) but some subjects had specific complaints:

- The windows had a faint yellow tint when fully bleached and a deep blue tint when fully darkened, but only two subjects had significant negative reactions to the color.
- One subject was not satisfied with the overall appearance of the window wall, reacting negatively to the color differences between window panes.
- Two subjects thought that the individual EC window panes (18x35 inches) were too small (2.5 rating, where 2=not satisfied and 3=just satisfied).
- One subject was very dissatisfied with the lack of control of individual EC window panes.
- Three subjects were not satisfied because the transmittance range was insufficient to control glare from direct sun.
- Subjects were asked specifically whether they would be more satisfied with the electrochromic windows if they could darken more than they did. The majority (58%) of the subjects responded affirmatively. It was further found that subjects who wore glasses were more likely to answer affirmatively (73% versus 19%).
- Seemingly contrary to this, occupants on average set the glare control mode transmittance to a higher transmittance than that provided in the EC's maximum colored state. The semi-automatic mode had an option to define the transmittance of the window when the EC was in the glare mode. The default setting was Tv=0.03. Fifty percent of the subjects left the setting at Tv=0.03. The average setting selected by users was Tv=0.11 in the presence of direct sun.
- On average, subject response to the switching speed of the windows was approximately midway (average=3.6) between just satisfied (=3) and satisfied (=4), but five subjects (12%) were not satisfied. There was no trend in the subjective rating of switching speed and EC window surface temperature: the average temperature was 19°C, 31°C, and 47°C (66, 88, 117°F) for the three most unsatisfied subjects with cloudy sky conditions for two of the subjects and clear sky conditions for the third.

The study was constructed to determine whether the dynamic modes of the EC window-daylighting system provided more benefit to the occupants than the reference mode, which was designed to be equivalent to a conventional static window with manually dimmed lights. The subjective responses and measured data were consistent with the hypotheses that the dynamic modes consistently provided higher satisfaction than the reference static mode and also resulted in significantly less blind use:

- The semi-automatic and automatic modes were judged significantly more desirable than the reference mode. The preferences were strongly related to perceived reductions in glare as well as measurable reductions in window luminance. Occupants were more satisfied with the following attributes of the EC window control system than the reference mode: glare control, control of reflections on the computer monitor, and ability to control windows and lighting system.

- The semi-automatic and automatic modes resulted in significantly less blind usage than the reference mode window. The blinds were not used (fully raised) 77% of the sessions in the semi-automatic mode and 79% of the sessions in the automatic mode, while the blinds were not used 38% of the sessions with the reference mode.

With respect to visual comfort and lighting quality, the EC alone was insufficient to control window glare, but the blinds were used less frequently (fully raised) with the dynamic EC modes than the reference mode:

- Subjects rated their overall level of glare sensation as barely above perceptible (2.3 on average, where 1=not perceptible, 2=perceptible, 3=acceptable, 4= uncomfortable, and 5=intolerable) for the two EC operable modes. For the reference mode, the glare sensation was 2.7 on average. This difference was not statistically significant, indicating that the subject (after having lowered the blind) was able to control glare adequately with any of the three modes. The reference mode tended to have more light available from the window even when the blinds were lowered than the other two control modes.
- 59% of the subjects listed one or more glare sources during the three sessions. The most common source of glare was the windows (59% of responses) while wall surfaces (20% of responses) and reflections on the computer screen (14% of responses) were also cited as sources of glare. The use of high-quality LCD screens is a critical factor in user satisfaction in any office with high window luminance and the possibility of direct sun. Reflections off the monitor were a problem despite the use of LCD screens.
- The Venetian blinds were used primarily to reduce glare from daylight or sunlight (57% of responses) or to reduce the overall brightness of the room (33% of responses). The blinds were used more often in the reference mode than the other modes. There was no significant difference in the way they were used, between the different modes, once they were deployed. The tilt angle averaged 70±15° (view toward the ground from interior). The average blind height for all modes was 5.5±3.3 (0=down, 10=up). This is an average height above the floor of 1.6 m, which allows a seated person a horizontal view out.
- The test room lighting level for the automatic mode was judged just right, 3.08 average (where 3=just right and 5=too bright) while the reference mode was judged 3.46 on average.
- On a scale of 1 to 5 with 1=unnatural and 5=natural, the room color rendering was judged 3.4 on average between all three modes. Only one of the 43 subjects felt that the room color rendering was unnatural. The ceiling and walls were painted white. The carpet was gray and the furniture was a warm gray with a slight purple hue.

With respect to thermal comfort, subjects did not complain about thermal discomfort due to the warm surface temperature of the window or direct solar irradiance, perhaps because it was winter:

- The mean temperature rating was “just right” with the EC and reference modes of operation. Despite the fact that subjects were told that the temperature could be changed, two subjects reported being too cold in one of the sessions. For 4% of the responses, subjects lowered the blinds to reduce the heat from the sun (in all sessions). None of the subjects reported deploying the blinds to reduce a cold draft from the windows.

- There was no correlation between the exterior window surface temperature and the subjective temperature ratings. Because of the low-emittance coating (e=0.15), the interior surface temperature of the window did not elevate to levels that would cause thermal discomfort. The average exterior surface temperatures for the automatic and semi-automatic modes were higher than for the manual mode (because the manual mode had the EC in its least absorptive, bleached state), but the difference was not statistically significant. The average exterior surface temperature of the EC window was 30±15ºC (86±59ºF). The lowest temperature was 10–12ºC (50–54ºF). The highest temperature was 72.6ºC (163ºF).

With respect to view:

- A paired comparison test was run between subject's rating of overall satisfaction with the EC window control system, considering or not considering the view (there was a spectacular west view of the San Francisco Bay from the test rooms and the furniture was oriented to enable subjects to look west comfortably). The test confirmed our suspicion that view was important in their overall satisfaction with the EC system ($P<0.01\%$), despite a fairly small difference (0.3) in the mean ratios for the two questions.
- A high fraction of subjects faced the window despite the fact that the window was the most commonly cited glare source and that for 90% of the responses, blinds were lowered to reduce glare or brightness. Approximately 50% of the subjects using a laptop computer faced the window and almost two-thirds of the subjects faced the window when not using a computer. Facing the sidewall is less glaring but the sun may fall directly on the computer monitor if the blinds are not lowered. Facing the window enables a direct view out and prevents the sun from falling on the monitor while keeping reflections off the monitor but creates contrast problems between visual display terminal (VDT) screen brightness and view brightness.
- Foot traffic near the windows was minimal and none of the subjects reported deploying the blinds for privacy. Blinds were deployed 4% to decrease the level of visual stimuli from the outside.

### 3.4.3.2. Visual Comfort Assessment Using Monitored Data

**Outcome:** An analysis of monitored data was made to assess visual comfort. EC windows provide a benefits package of energy savings and comfort that exceeds conventional "window plus blind" systems. In comparison to the reference case of windows with the blinds down, EC windows offer the possibility of higher use of daylight and lower energy consumption than normal windows, which will often have the blinds lowered, while at the same time providing better visual comfort than normal windows with the blinds raised. The EC system has the added advantage over a window blind system of being able to provide views out for a larger percentage of the day.

The energy performance results given in Section 3.4.1 above revealed that the lighting energy use savings were very sensitive to the way in which daylight admission and glare control were addressed by the EC control system. An analysis of the testbed monitored data was made to judge the relative difference in visual comfort for the various EC control options tested (see Appendix A, citation 13). Illuminance and luminance levels were measured at various points in each test room every minute on a 24-hour basis over a 2.5-year period. For some EC control algorithms, there were sufficient data to make an assessment of trends on an annualized basis. Several performance metrics were applied to assess visual comfort and lighting quality: average daily illuminance, average daily luminance ratios, weighted daily average daylight glare index, percentage of time the window luminance exceeded 3000 cd/m², and probability that the blind would be lowered based on the probabilistic fit derived from the subjective study described above (termed "blind probability").

The two reference cases were the static spectrally selective low-e window (Tv=0.42) with or without a fully lowered Venetian blind with a slat angle of approximately 45°. An analysis of the average annual and maximum values suggested that visual comfort requirements were met for most situations throughout the year for this large-area south-facing window with the blinds lowered all day. On average over the year, the window luminance exceeded 3000 cd/m² only 0.2% of the time. On the worst-case day, this threshold was exceeded only 5% of the day. With the blinds already lowered, the blind probability value indicates the percentage of day that the blind slat angle would have been more closed. On average, the blind probability was 18% of the day, suggesting that the blind position and slat angle were nearly suitable for annual conditions. On the worst-case day, the blinds would have been further "closed" 37% of the day. The weighted daily average daylight glare index (DGI) facing the window was just within acceptable levels (average=18.1, acceptable<20) but the average window luminance ratio (ratio of window luminance to surround luminance) of 6.4 exceeded the 3:1 recommended value for direct views of the window (from the back of the room).

With the blinds-down reference case established as having provided visual comfort for most situations throughout the year, an evaluation of the test EC cases was made relative to the reference cases by computing the difference in average daily values (EC test case value minus the reference window value) then using fits based on independent values (exterior vertical illuminance, solar angle, etc.) to correct the computed values to those that are representative of performance over a full year.

In general, the annual trends are what one expects. It is only a question of magnitudes of the effects that is of interest. In comparison to the reference case with blinds lowered all day, the various modes of EC control showed few statistically significant improvements in visual comfort given that the reference mode already provided comfortable conditions over most of the year. The two aspects worth remarking on were control of the window wall luminance and blind deployment probability:

1) The average difference in the weighted daily average DGI facing the window was significantly worse for EC-A (daylight mode, no blinds—see Table 1 in Section 3.3 for a description of EC test conditions) than the reference window with blinds. EC-B, which is the daylight harvesting mode with the blinds fully lowered, shows the most improvement as expected, and maintains glare in the acceptable range even on the worst days. EC-C through EC-E are intermediate in performance: they still permit unacceptable glare on the worst days but the increase in glare relative to the reference window with blinds was not statistically significant. A similar pattern was evident in the window wall to background luminance ratio results.

2) The EC windows in all modes of operation were capable of reducing the average fraction of time that the window luminance exceeded 3000 cd/m² to almost zero. For EC-A, the worst-day

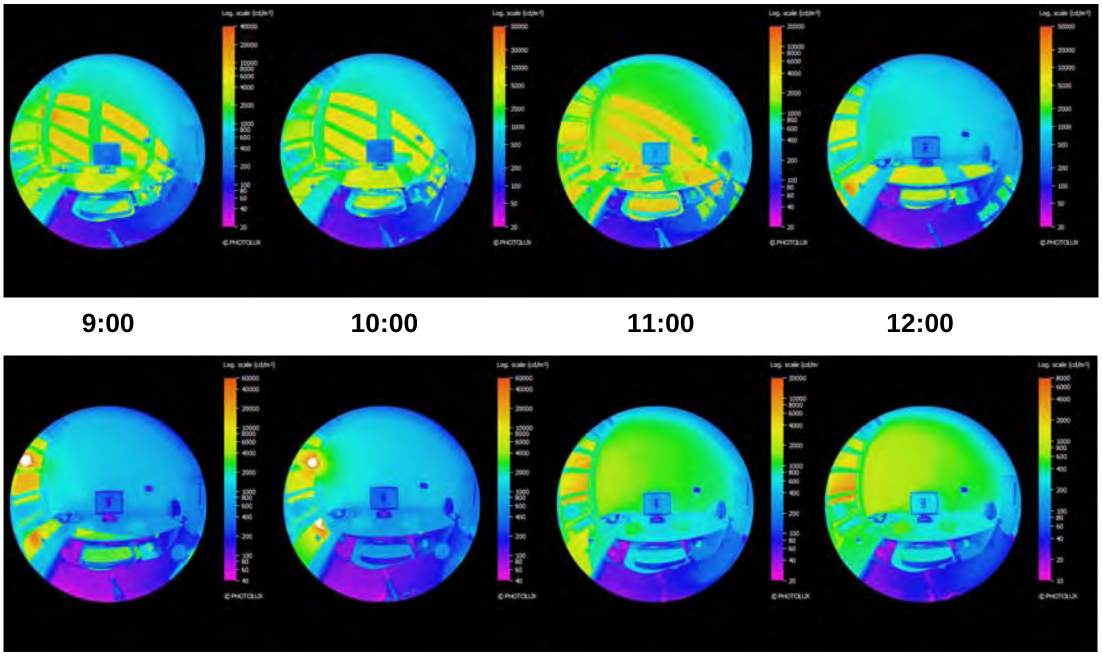
exceedance was for almost 10% of the day (day=6:00–18:00). For EC-C, the next worst case, the worst-day exceedance was 5% of the day. For the remaining EC control conditions, the maximum exceedance was under 1% (7 minutes of the day). With the logistic blind probability function, there was no significant difference in any of the EC control conditions from the reference window with blinds.

To summarize, in comparison to the reference case with the blinds down, EC windows offer the possibility of higher use of daylight than normal windows, which will often have the blinds lowered, while at the same time providing better comfort than normal window with the blinds raised. Electrochromic windows have the potential to achieve levels of optimal performance that has never been achieved with fixed or manually controlled window and shading systems. Façade designs that are optimized for energy performance alone involve tradeoffs between cooling and lighting. EC systems, when properly designed and operated, can capture significant daylight savings and additional cooling benefits, while maintaining or improving visual and thermal comfort. However achievement of these benefits will only come from careful design and optimized controls, as reported here. The mere presence of EC windows does not guarantee energy savings or visual comfort and freedom from glare. However, the results from the testbed suggest that a marketable EC system can be developed that will save energy while maintaining visual comfort. The EC system has the added advantage over a conventional window and blind system of being able to provide view for a greater percentage of the day.

### 3.4.3.3. Visual Comfort with HDR Observations

**Outcome:** The assessment of visual comfort remains challenging as the various comfort indices in use today have known limitations. The team explored new metrics and developed new approaches that may provide better techniques for assessing these important building and occupant impacts. High dynamic range luminance images taken in the field test facility provided more detailed information on the visual comfort levels resulting from the use of EC windows. This study focused on the question of whether visual comfort requirements could be met given a large-area window with the EC fully colored. Under clear sky equinox or solstice conditions, the EC window at Tv=0.05 maintained the luminance ratio between the paper and VDT task below the 3:1 recommended limit except when direct sun was on the paper task (maximum ratio of 6:1). If one's eye is poorly adapted to the brightness of the window wall (for example if one was seated at the back of the room facing the window), then the computed daylight glare index rises to almost "just uncomfortable" levels during midday winter solstice hours. If one looks directly at the sun through the darkened window, the luminance of the orb of the sun was greater than 60,000 cd/m$^2$ on the winter solstice, which is still unacceptable, but direct view of the sun is never assumed to be desirable.

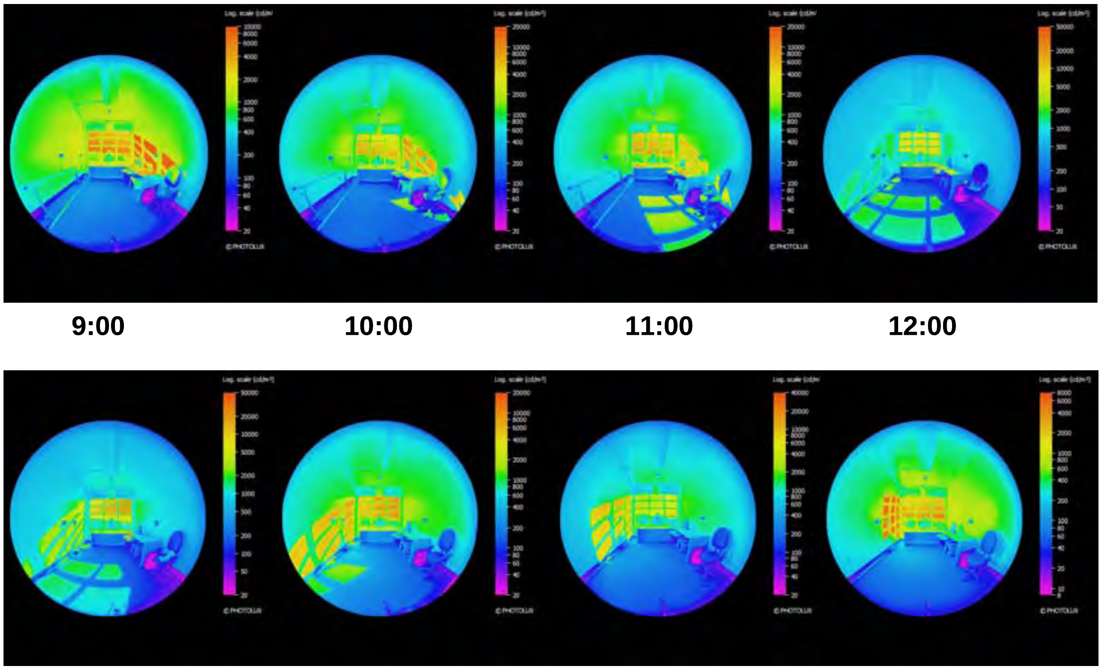
Digital photographs were taken in the LBNL windows testbed offices every hour on clear solstice and equinox days and analyzed (see Appendix A, citation 12). These images were converted to calibrated high-dynamic-range images using the Photolux software (Coutelier and Dumortier 2003), which depict the luminance of all surfaces seen in the image. The entire EC window wall was set to a fixed transmittance of approximately Tv=0.05 or Tv=0.60 to quantify the range in luminance levels experienced in the space (the manufacturer's controller was accurate to ±10% of value). No Venetian blind was used.



9:00 10:00 11:00 12:00

13:00 14:00 15:00 16:00

**Figure 25. Time lapse luminance images of the testbed on a clear sunny winter solstice day with a south-facing EC window at Tv=0.05. View of LCD VDT from the seated position of the occupant. Note that the maximum value on the false color luminance scale differs for each image. The sun orb is visible at 13:00 and 14:00.**



9:00 10:00 11:00 12:00

13:00 14:00 15:00 16:00

**Figure 26. Time lapse luminance images of the testbed for same conditions as in Figure 25. View of the EC window from a seated position in the back of the room.**

Various viewpoints were analyzed: 1) 1.5 m (5 ft) from the window at a seated position looking at a flat-screen LCD computer VDT toward the west side wall with paper tasks placed to the left and right of the VDT (Figure 25), and 2) looking from the rear of the office (~4.27 m, ~14 ft back) toward the south window wall (Figure 26).

Various performance metrics were computed for each hour: maximum luminance levels, the daylight glare index, luminance ratios, and task visibility based on the relationship between the average task luminance and adaptation level (global luminance). With direct sun, the EC window created patterns of sunlight and shadow on the room interior. Individual sunlit patches were not used to compute the performance metrics. Instead, average luminance levels were computed over specific regions or surfaces within the field of view.

When the occupant sits facing the west sidewall, the left- and right-hand paper tasks were in direct sun during some hours on the equinox and winter solstice days. Under most of these conditions, the EC window at Tv=0.05 was able to keep the luminance ratio between the paper task and the VDT task below the 3:1 recommended limit. However on the winter solstice, the luminance ratio limit was exceeded during most hours when direct sun was on the paper task (10:00–13:00) with a maximum ratio of 6:1. Since the task area is small, this is not expected to cause significant discomfort. When there was no direct sun on the task, the EC window was able to control luminances to within the 3:1 ratio limit: on the summer solstice, a transmittance of Tv=0.60 maintained the ratio within limits throughout the day and on the equinox and winter solstice, intermediate states between Tv=0.60–0.05 will be needed.

Generally, the same trends were found for the luminance ratio between the VDT task and the adjacent surround (0–30° field of view, <1:3) and the luminance ratio between the VDT and the remote surround surfaces (30–60° field of view, <1:10), but for the worst case winter solstice, Tv=0.05 was adequate: the luminance ratio limits were never exceeded.

The worst-case daylight glare index was computed from the rear of the test room facing the window. The electric lights were turned off so the room cavity luminances were significantly lower than the luminance of the EC window. The eye will be poorly adapted to the brightness of the window. The DGI value varied depending on how one computed the luminance of the window wall as a glare source. If the window luminance was defined by the entire EC window wall, the DGI was 2–4 units lower than if the window luminance was computed for each of the individual glazed portions of the EC window wall. Interpretation of the Cornell-Hopkinson glare formula is a challenge given the new HDR luminance mapping capabilities of today. If the latter method is used and the EC transmittance is Tv=0.05, then the DGI was maintained below "just acceptable" discomfort glare levels for all equinox and solstice hours with the exception of midday hours (12:00–14:00) on the winter solstice, when the DGI rises to a maximum of 22 (20=just acceptable and 24=just uncomfortable). The fully bleached state (Tv=0.60) will suffice during all hours on a clear summer solstice day. It is generally accepted in the daylight glare research field that the Cornell-Hopkinson glare formula needs to be replaced with a more robust glare formula; the HDR digital luminance mapping technique used here with an appropriate new formula may be a future replacement.

The luminance of the orb of the sun was greater than 60,000 cd/m$^2$ on the winter solstice when the EC transmittance was Tv=0.05. If direct sun is in the field of view, the EC can reduce the sun's overall brightness level but cannot effectively reduce the luminance of the solar disk to acceptable levels. The assumption has been that such EC windows will be combined with interior blinds that can block one's view of the sun orb. The frequency of blind use is dependent on window orientation, sky conditions (e.g., are winters typically cloudy?) and interior conditions (task, view direction, etc.).

### 3.4.3.4. Radiance-Mathematica Optimization

**Outcome:** With visual comfort requirements satisfied directly by the EC control system in a simulated case, annual lighting energy use savings were significant (48–67%) assuming a reference case (Tv=0.60) with a manually operated Venetian blind that is lowered once per day to address visual comfort requirements. This simulation study demonstrates that lighting energy use savings can be maintained at significant levels with a zoned EC system controlled to first address visual comfort concerns. The study results also reaffirm findings from the field test and DOE-2 simulations, where visual comfort criteria were satisfied indirectly. In addition, the percentage of year that the occupant has a view out is significantly greater: 98% for the EC case versus 38% for the reference case. These simulation data suggest that EC windows can lead to increased greater occupant satisfaction and perhaps increased productivity and a more healthful environment.

A proof-of-concept lighting simulation study (see Appendix A, citation 5) was conducted to evaluate lighting energy savings of EC window systems controlled to satisfy key visual comfort parameters directly or optimally as opposed to indirectly as was done in the testbed field studies and with prior DOE-2 simulations. Radiance was used to compute interior illuminance and luminance levels within a south-facing private office that was similar in geometry and furnishings to that of the LBNL windows testbed facility. The occupant was set close to the large-area window, so meeting the visual comfort conditions were challenging. However, the occupant's view angle was of the side wall not the window which would have been even more challenging (and not consistent with good office planning criteria).

A unique "daylight coefficient" approach was developed that enabled rapid evaluation of different sun and sky conditions for each of the different blind and window combinations which then facilitated computation of annual performance using Oakland TMY weather data. Mathematica was used in conjunction with Radiance to select the EC window transmittance and Venetian blind height and slat angle that best satisfied various comfort variables via least-squares optimization with linear inequality constraints. Post-processing scripts were also used to compute the lighting energy use given the same ceiling-mounted photosensor setup and response characteristics as in the testbed.

For the EC test case, the iterative hourly control optimization scheme was to first use the Venetian blind to block direct sun from view of the occupant, assumed to be sitting 1.5 m (5 ft) from the window with a view of the west sidewall. Then an upper and lower EC window was set to a transmittance level (Tv=0.05–0.60) that provided optimum use of daylight (600 lux at the work plane) without exceeding two visual comfort constraints: 1) luminance ratios between the computer VDT and the surround not to exceed IES recommended limits and 2) total vertical illuminance at the eye not to exceed 800 lux. The VDT was an LCD screen with an average luminance of 200 cd/m$^2$ and a low specular and diffuse reflectance of 1–2%, which is common of commercial products today. The luminance level of the surround was defined by the maximum luminance patch within cones centered about the occupant's direction of the view.

IES recommended luminance ratios were 1:3, 1:10, and 1:40 for the 30°, 60°, and 90° cones of view, respectively.

The reference case assumed the same window geometry but used a static reference window with a visible transmittance of 0.60. The Venetian blind operation was "manual" in the sense that the occupant controlled the interior shades to eliminate visual discomfort: for every hour, the blind was lowered to block direct sun to the eye then the slat angle was progressively closed to reduce the luminance ratios and vertical illuminance at the eye to within the same constraints as the test case. These schemes were evaluated for a 2-zone window with and without a 0.9-m (3-ft) overhang placed between the upper and lower window apertures for both the test and reference cases. This operating strategy is probably not likely to be implemented by average occupants so represents an optimal result for manually operated systems. Annual lighting energy use was increased by 61% for the no-overhang EC case compared to this reference case. Like the field study, lighting energy savings relies heavily on the assumptions for the reference case. For example, if the illuminance setpoint for the EC was raised from 600 lux to 800 lux while still meeting the visual comfort constraints, savings would be 4%, although cooling energy use savings may suffer slightly.

Assuming that the behavioral model for manual blind deployment is wrong and that it is likely that the occupant will draw the blind once at the first instance of visual discomfort, then leave it there for the rest of the day (e.g., Rubins et al. 1978 found that blinds were adjusted more than once per day in only 50 out of 700 windows observed), savings rise to a respectable 48% and 67% for setpoints of 600 lux and 800 lux, respectively. Since the Tv of the reference case is the same as the maximum transmittance of the EC window, the EC window is only able to obtain positive lighting energy savings when it can provide more daylight to the work plane than the reference window, while satisfying the same visual comfort constraints. Therefore, savings are obtained when the reference case window plus blinds provides less daylight than the test case after having satisfied visual comfort constraints.

The full benefit of EC windows can go largely unappreciated unless one examines the quality of the interior space. For the reference case with hourly blind deployment, the blinds were lowered over the entire window for 62% of annual daylight hours with slat angles that largely blocked the view for this large-area, high-Tv south-facing window (Figure 27). For the EC case, the Venetian blinds were lowered over the entire EC window for only 2% of annual daylight hours between the 13:00–15:00 hours on sunny days during the few winter solstice months. The blinds were lowered over the upper EC window only during the equinox to winter solstice period between ~10:30 and 15:00 (7% of annual hours). The slat angle was tilted slightly down from horizontal.

We believe that view has important if not yet quantifiable value. The value of view out (hopefully to something pleasant and relaxing) and daylight may some day be translated into productivity dollars. Then the economic justification for EC windows could be made more easily. Studies indicate that if an occupant has a view out, stress and eye fatigue can be reduced (Boyce et al. 2003).

Figure 28 shows the EC window transmittance of the lower and upper aperture. The importance of inter-dependently varying the upper daylight window and lower view window was established in this study. Glare control is achieved in the lower window: Tv is within the range of 0.05–0.20 for the majority of the daylight hours. The upper window provides more uniform daylight illuminance to the interior and is only infrequently at low transmittance levels to control glare or direct sun.

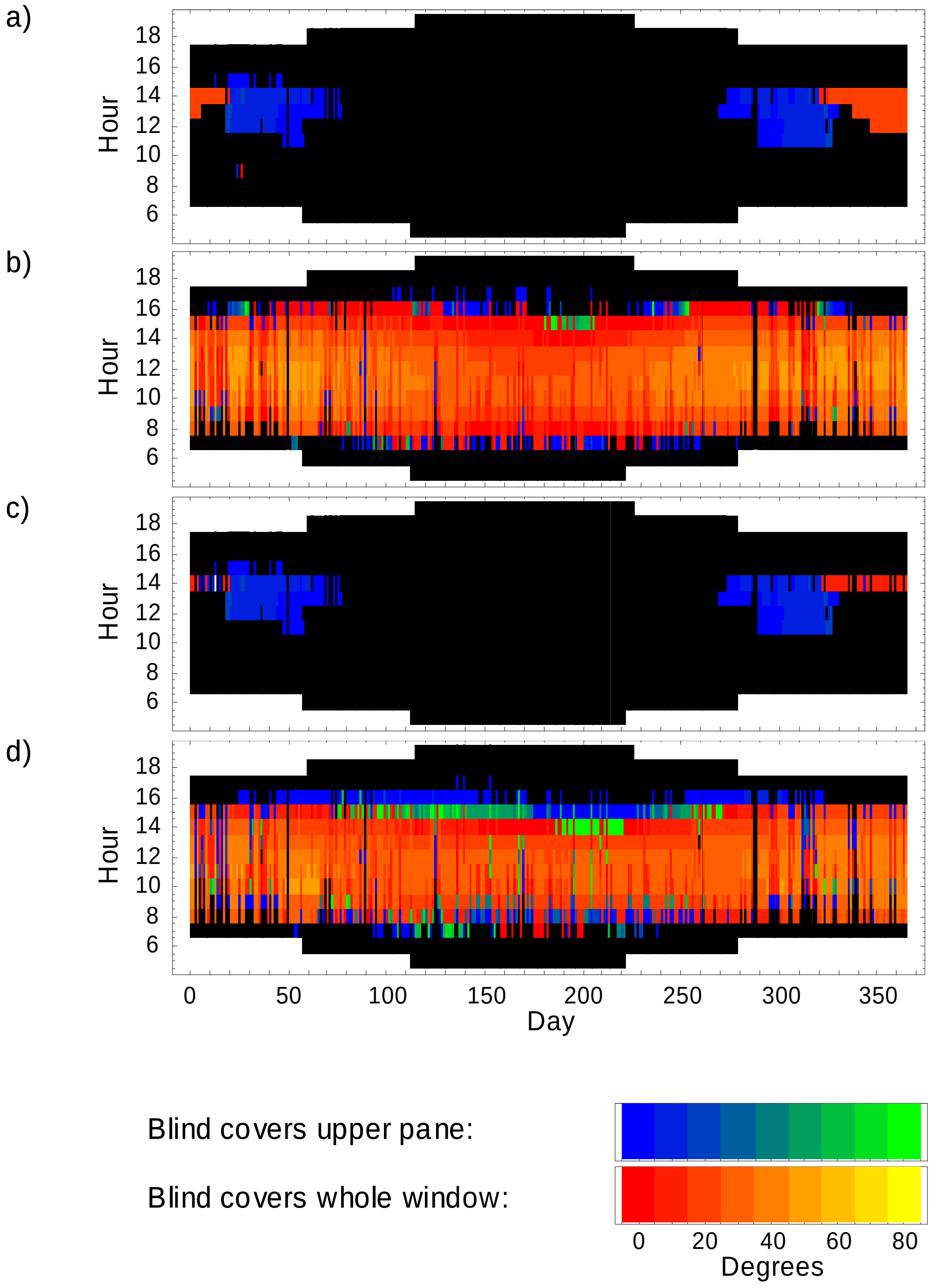


**Figure 27. Blind deployment throughout year: a) electrochromic windows without overhang, b) reference window without overhang, c) electrochromic windows with overhang, d) reference window with overhang. Black means that there is no blind required**

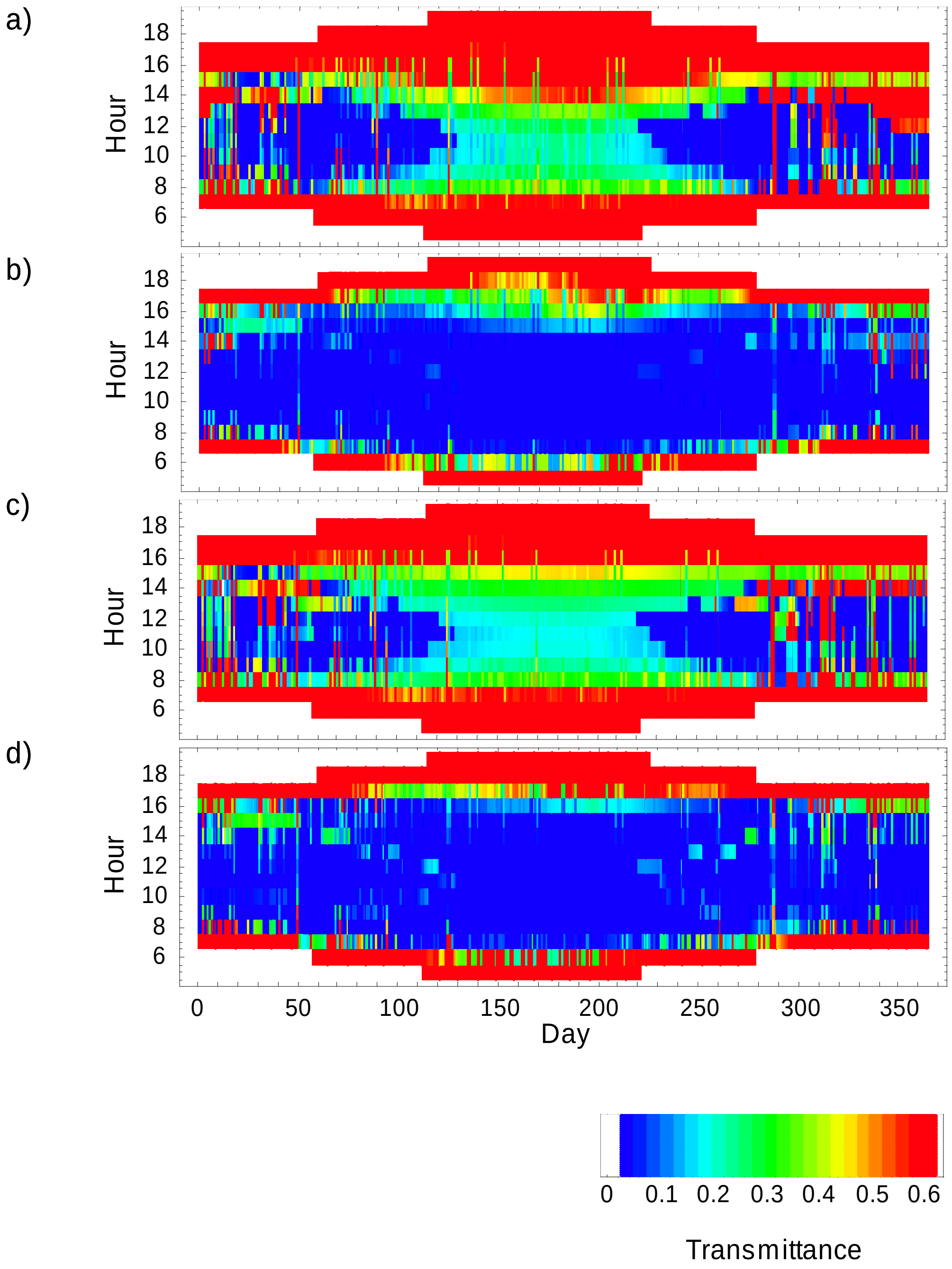


**Figure 28. Electrochromic pane transmittance throughout year: a) upper pane, no overhang; b) lower pane, no overhang; c) upper pane, overhang; d) lower pane, overhang.**

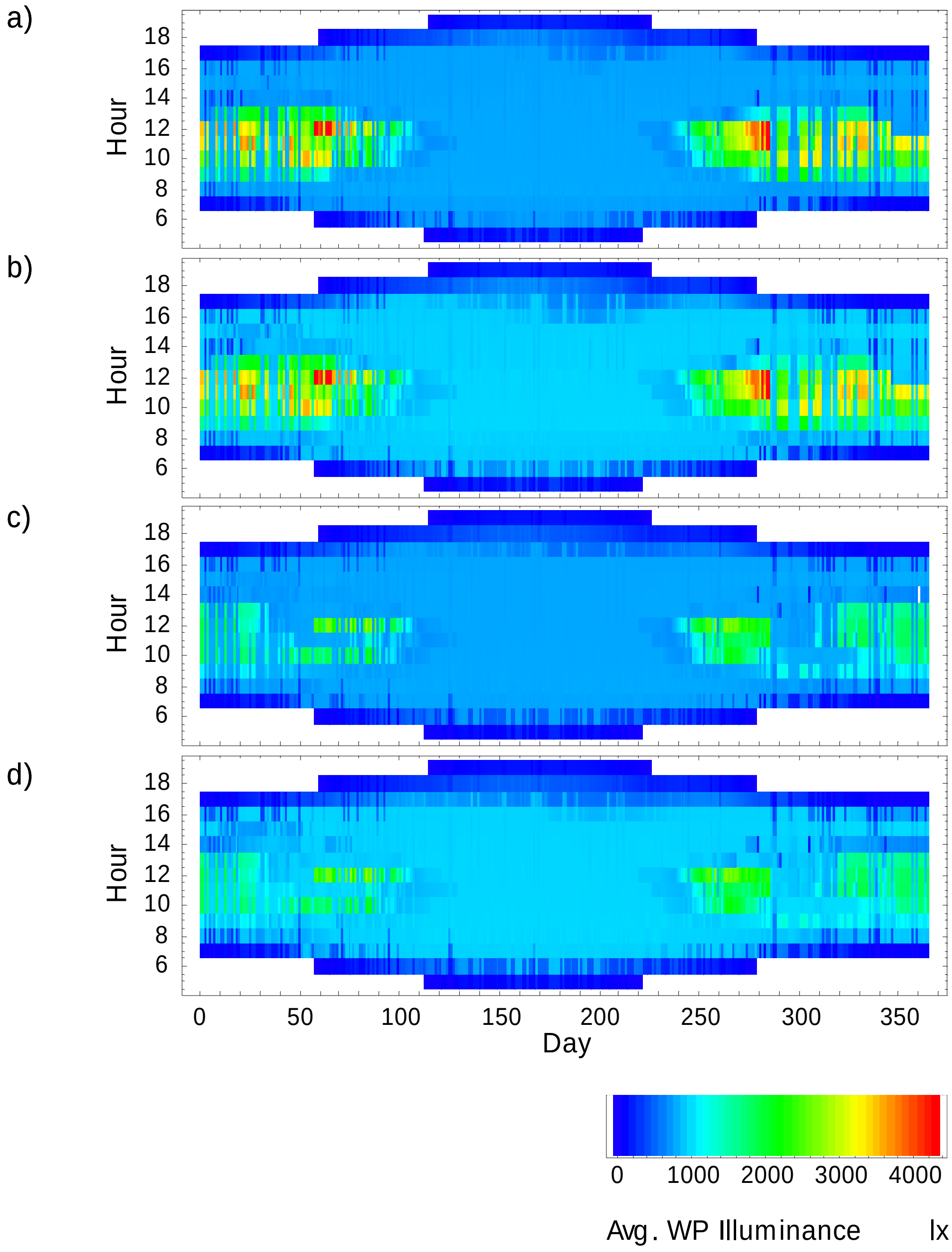


**Figure 29. Average workplane illuminance with electrochromic windows: a) without overhang, 800 lux setpoint; b) without overhang, 1000 lux setpoint; c) with overhang, 800 lux setpoint; d) with overhang, 1000 lux setpoint.**

There may also be a concern that EC windows controlled for glare will suppress all variation and high intensity levels of interior daylight that may be beneficial for satisfying one's "biophilic" or innate desire for connection with the outdoors, regulating Circadian rhythm, and combating seasonal affective disorder. Interior daylight levels can still vary considerably over the day, particularly if there is uncontrolled direct sun on some non-critical task surfaces during the winter to spring equinoxes (Figure 29). The degree of variation can also be tuned if the user interface provides such options. For example, if an occupant switches from computer tasks to a 30-minute conference call, a simple click of a user interface could raise room daylight levels by a factor of 5. Further study is needed to determine how much variation is needed and the impacts on energy efficiency.

Earlier DOE-2 studies reflected speculations on how the blind would be operated with EC window system. These simulations show that we can assume manually operated blinds set to a fixed position for the equinox-to-equinox (winter) period over the upper aperture, yet still maintain visual comfort and significant lighting and cooling load savings. Reliance on an automated blind with the EC system may be unnecessary if the occupant can be educated on “proper” blind usage. With lower-transmittance EC windows (minimum Tv=0.01–0.02) on the future horizon, the requirement for blinds may be obviated for many building applications.

### 3.4.3.5. Pilot Human Subjects Test

**Outcome:** Occupants could be provided with individual pane control to increase user satisfaction. In a limited human factors study, subjects were found to adjust individual EC panes to suit their requirements for privacy, view out, and glare. This of course leads to an ad hoc appearance of the exterior façade, which may be either condoned or exploited by the architectural community as a design feature.

The earlier subjective study did not allow the user to “play” around with the EC control and create an environment that was suitable for their needs. A user interface was created that enabled the occupant to switch each of the 15 individual EC windows to any transmittance level and to dim the overhead lighting between 0–100% light output. The five subjects were not naïve: i.e., researchers from our own group. Subjects could use their own laptop or the PC provided in the space to do their work, as in the earlier subjective study. Subjects spent 4–8 hours in the space and recorded their observations about the EC window and comfort of the interior work environment in an informal fashion.

**Figure 30. Occupants switched individual EC window panes to suit their preferences for view, glare control, and privacy.**

While the data are anecdotal, a few observations came as a surprise. Some subjects liked to have control of individual EC window panes so that they could tune each area for separate requirements: view, privacy, glare, and daylight. Some tinted the windows to enhance the view out to the San Francisco Bay while mitigating glare (Figure 30). When exterior illuminance levels were low on overcast days or during late afternoon hours, others bleached the EC glass to avoid loss of view due to reflections off the interior glass surface. The south-facing windows were in full view of a main LBNL thoroughfare (although some distance away). To avoid the fishbowl effect, some subjects tinted certain panes to achieve increased privacy. Venetian blinds were used, but since there were three blinds, some were lowered to block direct sun from falling on some surfaces or decrease reflected glare off the VDT screen, while others were kept fully raised in order to preserve view out. Lights were often turned off or dimmed substantially, reflecting the high ambient light levels and the nature of this biased subject sample.

The above observations point to the types of control users might implement given the novel ability to exert full control over their windowed environment. Certainly other considerations must be met when designing the EC control system including the increased complexity of a control and user interface that would allow control of individual glazings. Some form of manual control override must always be a component of the EC control system.

Another observation to be further addressed in future studies is what impacts such control will have on the exterior appearance of the façade. Architects and class-A building owners prefer a more ordered appearance to the façade. A randomly varying checkerboard façade may be deemed architecturally interesting by some and a visual blight on the urban landscape by others.

## 4.0 Information Resources

### 4.1. Objectives

The objective of this task was to:

- Promote EC windows and increase consumer awareness of this emerging technology.
- Build the necessary tools and information resources needed to enable the use of EC-windows in residential and commercial buildings for energy efficiency and other performance benefits.

This task addresses the typical market barriers faced by emerging energy-efficiency technologies: lack of information, lack of consumer awareness, and lack of tools and information resources needed to design and specify electrochromic window systems in buildings. Given that products are now entering the market, it would also be useful to have a suite of information resources (e.g., design and application guidelines, design tools) that help architects and engineers understand how best to use such technologies in commercial buildings and evaluate performance impacts to justify the increased costs. To support the specification and use of such products, the groundwork for characterizing, labeling, and comparing such products must be laid.

### 4.2. Approach

Since the EC technology was not commercial available during the course of the project, the team focused on information resources that helped to enhance public awareness and interest in the technology. Public awareness of this technology was increased through participation in key conferences and meetings whose attendees included stakeholders who were in the position to promote such technologies in the market (utilities, government, academics), or those who were likely to specify such technologies in future buildings (architects, engineers, building owners) or develop the infrastructure to support its use (industry). There is already considerable interest in this technology. The team addressed public inquiries into the current status and availability of the technology on a regular basis. The EC window test facility was also made available to building industry professionals who wanted to see a demonstration of the technology.

EC windows present a unique challenge to the conventional window industry as their solar-optical properties are dynamic. LBNL participated in international conferences and collaborated with other organizations (International Standards Organization (ISO) and International Energy Agency (IEA) Task 27 and Task 31) and industry to develop standard protocols for laboratory measurements and solar-optical characterization of electrochromic windows. The team also participated in the Dynamic Windows Subcommittee of the National Fenestration Rating Council to derive a rating system for electrochromic window systems. Ultimately these ratings will have to be provided for use by the Title-24 building codes.

Information products were developed over the course of this project and disseminated via published books, design guides, or websites. These products incorporated the knowledge learned over the course of this project. Results were also published in conference proceedings and journal articles.

## 4.3. Outcomes

**Outcome:** The EC window technology was promoted to the public but not to the extent previously anticipated because of the immature commercial status of the EC window system and because these windows were not commercially available for standard specification during the term of the project. A “mature” product in this study was defined as one that would enable performance benefits to be achieved on a reliable basis. Current product offerings in the U.S. enable switching to only the fully clear or tinted states. Fundamental groundwork was conducted in this project to start to establish the supporting infrastructure needed to implement EC windows in the real-world. Solar-optical properties of commercialized EC windows were included in the International Glazing Database used by window manufacturers and specifiers. Some progress was made in the Dynamic Glazings committee of the National Fenestration Rating Council towards creating a standardized label for EC windows. A new method was developed in Radiance that enables one to quickly compute annualized performance of dynamic window systems. A hands-on demonstration of a new technology is always a key approach to build confidence in an emerging product category and our testbed facility enabled many visitors to make their own observations of the technology first hand. The team provided lab tours of the EC testbed to the public, published and presented project results at major U.S. and international conferences and meetings. Design assistance was provided to Southern California Edison as they developed designs for an EC window demonstration at their customer service center. In addition, a design and applications guide was developed for architects and engineers based on lessons learned in this project. A section in a commercial windows book and a downloadable 130-page document on high performance commercial building facades also included early results from this project. A website was created to disseminate project results.

The optical and thermal characterization of EC windows is a fairly tricky affair because the end states can be driven to destructive levels to obtain a favorable solar-optical range. It also takes some time to drive EC devices to its darkest tinted state—one can get a lower reading if one waits 40 minutes versus 10 minutes before taking a measurement. The team participated actively in a variety of national and international activities all involved with building the knowledge infrastructure to support commercialization of these technologies. The team was were involved in early discussions within the IEA Task 27 on Advanced Materials to establish proper standardized procedures for measuring the properties of EC windows. These methods were applied in 2005 to characterize commercially available EC windows. The data are included in the International Glazing Database.

All windows sold in California (and many sold in other states) must be labeled with a standardized NFRC window label. At the start of this project there was no mechanism to label a product whose properties can be altered. The Dynamic Glazings committee of NFRC worked toward a solution that would allow the NFRC to rate such windows and ultimately provide the specifier and consumer with adequate information to compare EC window products. This committee has adopted technical rating and certification procedures that will allow manufacturers to rate products in 2006 with whole-window Tv and SHGC switching ranges which will also appear on the label. There are a number of additional issues of interpretation that need to be addressed as the labels come into use. For example, in terms of complying with Title 24, which of several label values would be used to assess compliance with both prescriptive and performance based implementations of Title 24? The project team is involved with the manufacturers and with NFRC on these issues and will engage the Energy Commission and the utilities so that when products begin to be specified in 2006 they can be addressed by code officials.

The DOE-2.1E building energy simulation software already included electrochromic window control algorithms and generic Window4 data before this project started. This capability was ported to EnergyPlus. The daylighting algorithms implemented in DOE-2 and EnergyPlus proved to be too limited for the visual comfort studies designed. Therefore, the team developed a new method of determining annual performance using Radiance and Mathematica. This method adds a powerful new capability to Radiance. Prior to the implementation of "rtcontrib", Radiance users modeled a limited number of daylight conditions simply because of the computational time needed to compute one image. This new method, which follows methods developed and implemented by Reinhart and Walkenhorst (2001) and Mardaljevic (2000), creates a "daylight coefficient" image database for each patch of a discretized hemispherical sky dome that is then combined with a daylight coefficient image for a particular sun angle to generate an hourly database from which a variety of performance data can be derived (e.g., luminance ratios, vertical illuminance, etc.). It will soon be possible to use these approaches for more routine accurate assessment of daylight quality and quantity in spaces.

Laboratory tours of the electrochromic field test facility were given to countless U.S. and international visitors, including the DOE Secretary of Energy (Figure 31). Visitors were able to make their own assessments of the size, color, view out, and switching speed of EC windows. A similar demonstration is being planned by Southern California Edison (SCE). Design assistance was provided to SCE as they developed designs for an EC window wall at their Customer Technology Application Center (CTAC) in Irwindale, California. At this time, SCE is planning to install the next generation of EC windows that are larger (~42.5x60 in.) than those tested at the LBNL facility in a south-facing large-area opening. Information was also provided to other interested parties investigating use of EC windows for specific commercial buildings, including the Smithsonian. The team provided answers to public inquiries made by architects, engineers, utilities, building owners, investors, researchers, and popular press as to the current status and availability of the technology.

**Figure 31. Stephen Selkowitz leads a tour of the LBNL Window Testbed Facility, January 2006.**

Several information products were developed to explain what switchable EC windows are and describe their likely benefits. Descriptions of the EC window and some limited DOE-2 performance data were included in a commercial windows book published by Norton Press, Inc. (see Appendix A, citation 14). Descriptions of the demand-side potential of EC windows with projected demand savings were included in a website and downloadable 130-page document on high performance commercial building facades (see Appendix A, citation 15). A design and applications guide was developed for architects and engineers based on lessons learned in this project. This guide is available through this project's website (see Appendix A, citation 16).

Public awareness of this technology was increased through participation in key U.S. conferences such as the American Council for an Energy Efficient Economy (ACEEE) 2002 and 2004 summer conferences, LightFair 2004 and 2005, and Greenbuild 2005. Results were also published in popular press, conference proceedings, and journal articles (see Appendix A, citation 17).

# 5.0 Conclusions and Recommendations

## 5.1. Conclusions

### 5.1.1. Systems Engineering

#### 5.1.1.1. EC Window

The EC window provided by the qualified manufacturer met the basic performance requirements dictated by the procurement specifications. Judging based on functional performance (durability was assessed independently from this project), there were no fundamental aspects of the EC-coated window itself that would suggest that its market introduction is premature. The 0.46x0.89 m (18x35 inch) insulating glass units were produced in 2003 using pilot production line manufacturing processes for this project. Newer products, produced by more mature high-speed manufacturing processes, are expected to be larger and of higher quality. The solar-optical properties of the EC window did not change significantly from the 2003 prototypes.

The EC windows had a faint yellow tint when fully bleached and a deep Prussian blue tint when fully darkened (newer products are purported to have a faint green tint when bleached). The tint across each window appeared uniform when the EC was not being switched. The transmittance across the face of the EC window unit was measured and found to vary slightly by Tv=0.03-0.05 across the full switching range. The window had a slight to noticeable non-uniform tint across the window unit when in the process of switching. The EC windows also had a noticeable pink to yellow non-uniform surface reflectance, which was visible under low daylight and nighttime conditions. This and other optical issues were attributed to the pilot manufacturing process. User response to the prototypes was largely positive. Only 5% of the occupants had significant reactions to the color. Five percent of the subjects were slightly dissatisfied because the window panes were too small. Only 2% thought the room color rendering was unnatural.

The EC window was demonstrated to cycle between bleached and colored states within a surface temperature range of –10˚C to 65˚C (14–149˚F) in a limited laboratory test. For rapid glare control, the switching speed presents a problem, particularly at cold temperatures. Switching speed is exponential: it can switch a large percentage of its full range quickly, then take a long time to switch the last percentage to attain the darkest tinted state. At sunrise on a clear sunny but cold day (3–8ºC, 37–46ºF) for example, a 0.40 $m^2$ window took 40 minutes to switch from Tv=0.60–0.08 given irradiance levels of 24–540 $W/m^2$, then another 83 minutes to switch from Tv=0.08–0.05 with irradiance levels of 540–770 $W/m^2$. Larger windows will respond slower. For direct sun control, an interior blind will be required in some applications. On average, occupants found the switching speed of the 0.46x0.89 m (18x35 inch) units to be satisfactory but 12% of the occupants were not satisfied. In cold climate applications, the supervisory control system should be designed to take such speeds into account to avoid control oscillations and occupant dissatisfaction. A sensor could provide useful EC surface temperature data and could help to improve performance, but is not required.

The EC windows had a broad switching range of approximately Tv=0.05–0.60 and SHGC=0.09–0.42, but the low end state transmittance was not low enough to fully control glare from direct sun for all applications. The EC windows were driven to an even lower transmittance (Tv=0.02–

0.03) during the human subjects test, which were conducted during worst-case winter conditions when the sun angle was low. Still, the interior Venetian blinds were lowered by 23% of the occupants. The primary reason for blind use was to reduce glare from sunlight or daylight (57% of responses). The majority (58%) of the subjects responded that they would be more satisfied if the EC windows could darken more. Earlier simulations and field measured data indicate that the EC transmittance would need to get as low as Tv<<0.01 to reduce the sun orb to acceptable luminance levels. Occupants can often reposition their view. If the architecture or interior design forces the occupant to face the sun, then interior or exterior shades should be used to block direct sun. Switchable mirror devices (e.g., reflective hydrides) can potentially achieve these low transmittance levels but are still at the early stage of R&D for window applications.

#### 5.1.1.2. EC Intermediate-State Controller

EC manufacturers must produce accurate and reliable intermediate-state EC window controllers in order to capture the full benefits of EC windows. The alpha controller provided by the manufacturer in this study proved to be unreliable and inaccurate after long-term use (1–2 years). Controller accuracy ensures a uniform appearance to a façade composed of multiple EC window units and enables one to achieve control system objectives reliably. A closed-loop prototype solution devised by LBNL in collaboration with the manufacturer shows promise as a viable technical solution, assuming that small local areas of an EC window are and will remain representative of the tint across the entire window surface. Simple electrical characterization of the EC appears to be inadequate if accurate control is to be maintained over the long term. If switching and control properties change over long periods of time, an appropriate adjustment and recalibration capability will need to be provided.

The EC window controller provided control of individual windows. It was fairly basic in its capabilities given its preliminary alpha status. Commercial products should incorporate broader capabilities in the future, particularly for fault detection and diagnosis of operational problems in the field.

The EC window is powered via low-voltage wiring threaded through grommeted holes in the curtainwall framing system back to the EC controllers located in a junction box within the building (Figure 32). Sensor cabling must be brought back in the same way. For this installation, the low-voltage wiring was limited to 6.1 m (20 ft) lengths (a voltage drop occurs with increased wire length), but newly developed 3-wire solutions will enable 91 m (300 ft) wire lengths. A switching power supply is needed to convert ac power to dc voltage levels of ±3 V. Low-voltage wiring must be run in parallel to each window unit and the cabling must be robust enough to withstand moisture and thermal stress (we used 2 stranded, 18 gauge wire). To facilitate window replacement and troubleshoot wiring, the IGUs should be glazed from the interior if access from the exterior is limited or difficult.

Currently, EC windows are expensive because they are produced in low volume and for this project, were produced using a pilot production line. The cost of producing an EC window coating is expected to be reduced significantly over the next few years given new high-speed manufacturing processes and increases in production volume. The final product cost must include costs for adding wiring, sensors, controls and connections to the building energy management system, as well as the additional design and engineering costs involved with implementing such systems (the manufacturer estimates +5% added cost over the cost of the IGU).

**Figure 32. EC window controllers in the foreground (left) and installation of EC windows using an exterior-mounted curtainwall system (right).**

### 5.1.1.3. Integrated EC Window and Daylighting Control System

A prototype integrated EC window and daylighting system was engineered, tested, and evaluated using an early market EC window product provided by a qualified manufacturer. The integrated control system was iteratively developed and improved. At the conclusion of this development process, the solutions providing significant energy and demand savings and comfort were identified using a combination of field test performance data, subjective survey results, and simulation data.

The final prototype design is applicable to sidelit private offices in typical U.S. commercial buildings. The optimal solution led to a design in which the EC window wall is divided into an upper and lower zone then operated using different control algorithms. The individual EC windows within each zone must be modulated accurately and continuously between the fully bleached and colored states with an appropriate electronic controller and associated sensors. Given the switching range of the EC prototype (Tv=0.60–0.05), a manually operated interior Venetian blind was included to block direct sun. These results should be easily extended to skylighted spaces and can be extended to open plan office spaces with some changes.

The current field test prototype solution controls a lower EC “view window” zone for daylight and glare and controls an upper EC “daylight window” zone for daylight. For the daylight mode, the EC modulates its transmittance to provide the desired work plane daylight illuminance within a specified range. For the glare mode, the EC is switched to its fully colored state when the vertical exterior illuminance exceeds a designated threshold value and when the solar profile angle is lower than a given threshold value. The overhead lighting is dimmed or switched off in proportion to available daylight. More complex control algorithms were modeled with Radiance-Mathematica simulations but were not yet breadboarded and tested in the field. For some window orientations and applications, an interior Venetian blind would be used to block direct sun from view. The blind height and slat angle would be adjusted by the occupant once per season to control for possible direct sun. For example with a south-facing façade, the blind is not lowered during the summer, the blind is lowered over the upper EC zone during equinox periods, and the blind is fully lowered during the winter period. The blind could be automated to insure proper performance but this adds cost.

The integrated system was tested under representative sun and sky conditions and found to work reliably if the EC intermediate-state controller was working reliably. A subjective survey was conducted on an earlier 1-zone system in which the entire window façade was switched to the same state. The automated mode of EC operation (with a manually operated blind available to the occupant) was judged significantly more desirable than a reference static mode with the same blind setup. The preferences were strongly related to perceived reductions in glare as well as measurable reductions in window luminance.

The EC window-daylighting supervisory control system can be networked via conventional gated connections to the main backbone of the building management control system. This would enable these two significant end uses to be included in whole building controls optimization. While our simple engineering study found no additional energy-savings benefit with EC-daylighting-HVAC integration (assuming a conventional VAV system with a COP that varies seasonally, not daily), further study is warranted. Inclusion of the EC systems with whole building controls makes sense for demand response, real-time pricing strategies, and scheduling.

To achieve the objectives of the daylight mode of control reliably, the supervisory control system must be commissioned in the field. Because of the industry trend toward individually controlled ballasts, alternate methods must be identified to make this process easier and more cost-effective.

Provision of a user control interface to the EC window system will ensure user satisfaction and acceptance of this technology. Some users indicated a preference for individual pane control to satisfy other requirements not directly addressed by the automated control system proposed above: view, privacy, etc. Individual pane control will produce a non-uniform checkerboard appearance to the exterior façade that may be aesthetically unacceptable to building owners and architects.

The solutions and results described have general applicability to spaces serving similar functions; e.g., classrooms, conference rooms, etc., but will require fine-tuning to optimize their application in a wider range of real world conditions.

### 5.1.2. Performance Impacts

#### 5.1.2.1. Energy and Peak Demand

EC windows have the potential to capture large savings but the magnitude of energy and peak demand savings is highly dependent on the specific applications and the assumptions for the reference case. The reference case technologies assumed for this study were state-of-the-art: advanced spectrally selective low-e double-pane windows and the same type of daylighting control system as the test case. Savings were isolated to the impacts produced by the EC window alone.

The reference case was also assumed to have manually operated interior Venetian blinds either fully lowered or raised all day. The energy savings likely to result in an occupied building were found to be highly dependent on the assumptions for its manual operation. Manually operated shades are lowered typically when visual or thermal discomfort becomes significant and then are rarely adjusted thereafter—often for days or weeks on end (e.g., Rubins et al. 1978 found that blinds were adjusted more than once per day in only 50 out of 700 windows observed; Inkarojrit 2005 provides a good literature review). Through anecdotal observation, one may conclude that blinds may remain at the same position for days or weeks at a time.

The monitored field study compared EC performance to two reference cases: one with an interior Venetian blind raised all day, the other with the blind fully lowered all day. The DOE-2 simulations modeled reference cases with either no shades at all or hourly deployment of the shades according to direct sun and discomfort glare threshold values. The Radiance-Mathematica simulations modeled reference cases with either hourly deployment of the shades based on visual comfort criteria or a behavioral model based on the empirical and anecdotal studies described above. The Radiance-Mathematica simulations yielded perhaps the most realistic estimates of potential energy performance because the model for the manually operated blind more closely represented reality.

The following summarizes the energy-efficiency results of the various studies conducted in this project:

- Field study data showed that for a two-zone EC window system controlled for daylight and glare, daily lighting energy use savings were 10±15% and cooling load reductions were 0±3% compared to the blinds-down spectrally selective low-e window reference case (Case 7). Maximum cooling peak demand reductions due to reduced solar heat gains were 19–26% compared to the shaded or unshaded reference case.
- Radiance-Mathematica simulations indicated that annual lighting energy use savings for a two-zone EC window system, constrained by visual comfort requirements and optimized for daylight illuminance, would be 48–67% if the reference case blinds were drawn down once at the first instance of visual discomfort.

The field study and Radiance-Mathematica simulation data are given for a large-area EC south-facing window in Berkeley, California. If one attempts to generalize upon these results, it helps to understand the following basic trends that were established for EC windows using the earlier DOE-2 simulations:

- Energy and peak demand savings are greater in hot regions, such as the inland climates of California, because EC windows significantly reduce solar heat gains. One should expect greater cooling load reductions in these climates.
- Exterior shading by attached shading devices, local obstructions (trees), and/or remote obstructions (mountains) reduce savings because they reduce the incident solar radiation on the window. One should expect less energy savings in built-up urban areas.
- Energy and peak demand savings are greater for large-area windows, particularly if oriented south, east, or west. North-facing perimeter zones derived little benefit from EC windows beyond control of sky glare and reflected glare. Although there is a strong international trend to increase window area, existing buildings tend to have smaller areas

(national average window-to-wall area is WWR=0.30). One should expect lower savings for typical commercial buildings designed with small-area windows.

In the short-term (next 2–5 years), the early adopters of dynamic glazing solutions are likely to be motivated by opportunities beyond energy savings alone. Because the first generation of products will be expensive and there will be significant systems engineering needed, there will likely be insufficient economic justification for widespread promotion of EC windows in commercial buildings on the basis of energy savings alone, given the cost of the technology and market barriers to proper deployment. While the lighting energy savings due to EC windows are impressive and cooling load reductions in hot climates equally impressive, the technological solutions for achieving such levels are complicated. The solution is not yet plug-and-play and also depends on other technologies such as dimmable lighting that have costs and complexity associated with them. The direct energy benefits are dependent on the installation details and reference case assumptions, and other potential benefits such as comfort are not easily quantified. Continued work will be needed with architects, engineers and code officials to ease the introduction of these new technologies into the marketplace.

For the long-term outlook, many of these market barriers will be addressed by the technological trend toward more sophisticated and integrated building control solutions. In the 1990s, a large number of flagship buildings were constructed in Europe that implemented complex control of high-performance building façade elements (e.g., air intake louvers, solar-controlled Venetian blinds, etc.). U.S. architects are interested in duplicating such buildings here. The New York Times project (Lee et al. 2004) demonstrates that building owners are interested in investing in high performance, dynamic facades and are interested in occupant comfort, health, and productivity as well as sustainability issues—decision-making for some may not be driven by bottom-line energy payback criteria alone. The trend toward investments in high performance building systems that address energy, comfort and amenity is likely to grow in the future and EC systems will be well positioned to take advantage of them.

#### 5.1.2.2. Occupant Impacts

EC systems show promise in being able to improve satisfaction and comfort in work spaces. Subjective responses and measured data were consistent with the hypothesis that dynamic EC systems can provide higher satisfaction than the reference static mode.

Occupants judged the EC window system as significantly more desirable than the reference window, where preferences were strongly related to perceived reductions in glare, reflections on the computer monitor, and window luminance. The single-zone integrated EC window-daylighting system, which was evaluated in the human subjects study, resulted in significantly less blind use and more access to unobstructed outdoor view. With the EC systems, subjects chose to face the window to do computer-related tasks presumably for view, despite minor complaints of glare and brightness.

Under almost all conditions, the EC window is capable of delivering adequate control of window glare, of maintaining luminance ratios within recommended limits, and reducing blind use (based on probabilistic fit derived from subjective studies), given its transmittance range and proper control operations. Under the worst case direct solar conditions, the EC still permits excessive glare and luminance ratios between the window wall and background luminance, but the increase in glare relative to the reference window with a blind was not statistically significant.

Subjects did not complain about thermal discomfort due to the surface temperature of the window or direct solar irradiance (which they could block with the blind). Four percent reported that they lowered the blind to reduce heat from the sun in all sessions. There was no correlation between measured window surface temperature and occupant subjective temperature ratings. Since the EC coating is on the outboard glazing and the IGU contains a low-E coating, the increase in interior glass surface temperature is minimal, and the EC itself in its lowest transmittance state minimizes direct solar transmission.

We would normally expect that office occupants, who are provided with high quality windows and blinds and who operate the blinds intelligently, can attain satisfactory levels of visual comfort. However, evidence to date indicates that office workers on their own do not consistently optimize blind operations and are more likely leave blinds closed to control glare, thus reducing energy savings potentials. In our studies with automated EC systems, subjects reported less direct glare, fewer reflections on their computer monitor and more satisfaction than in the reference case with blinds, and with a solution that provided greater daylighting savings. An EC window thus provides at least equivalent comfort and does so with increased amenity: view and greater daylighting energy savings. Other studies suggest that stress can be reduced if the occupant has a pleasant view outdoors and that eye fatigue may be reduced. These benefits might be assessed in future studies.

Dynamic windows have the potential of being optically tuned, pane by pane. This would be an amenity, but in some circumstances could also enhance the work environment. With individual pane control, occupants were found to tune the window wall based on additional criteria: view and privacy.

### 5.1.3. Information Resources

Public awareness of the emerging EC window technology was increased via conferences, meetings, tours of our EC test facility, and publications. Some of the groundwork was laid that will enable architects and engineers to compare, rate, and compute the performance impacts of EC windows in buildings. Design guidelines and a website were produced.

## 5.2. Commercialization Potential

At the conclusion of this project, SAGE Electrochromics reports that they have begun shipping large-area EC windows and skylights (up to 1.1x1.5 m, 42.5x60 in.) with on-off switching in early 2006. Other manufacturers who were working on EC products at the beginning of this project are not yet offering commercial products for building applications or have declined to further develop product. DOE has continued to fund new industry partners who claim they have novel technologies with improved performance potentials.

The following technology development tasks would need to be conducted in order for the integrated system proposed in this project to be commercially viable:

- The EC manufacturer produces a reliable, accurate, and cost-effective intermediate-state controller that provides practical features that enable fault diagnostics and controls recalibration in the field as needed over the installed life of the window.

- The EC manufacturer or controls partner develops a supervisory control system that controls the EC window to meet daylight work plane illuminance requirements. The system can be developed independently from lighting controls manufacturers if the EC manufacturer can determine the interior daylight illuminance level independent of electric lighting operations. The system must minimize or automate commissioning requirements.
- The EC manufacturer or controls partner develops a supervisory control system and sensors that address visual comfort requirements. The system must minimize commissioning requirements and be easily tailored to individual preferences. It should provide an appropriate user interface enabling direct occupant control of their work environment.
- The EC manufacturer or controls partner develops gateways between the EC supervisory control system and the energy management control system, working with the lighting and HVAC controls manufacturers to implement integrated building-wide control solutions for demand response, real-time or critical peak pricing, occupancy, and scheduling.
- Given the systems integration needs, the EC manufacturer can probably accomplish such tasks more rapidly if they partner with other manufacturers who have already successfully commercialized products that provide similar functions for commercial buildings.

## 5.3. Recommendations

### 5.3.1. EC Window and Intermediate-State Controller

- EC manufacturers should direct some of their effort towards some of the “long-term” product development tasks listed in Section 5.2, particularly development of the EC intermediate-state window controller. A low-cost sensor is needed to provide accurate, real-time visible transmittance data on installed EC windows. Additional progress toward faster switching speeds, less color in the tinted state, a lower minimum transmittance, and reduced manufacturing costs would all be welcomed by the developing market.

- Human factors tests should be conducted to resolve the issue of whether very low transmittance windows are acceptable or desirable as solutions for controlling direct source glare from the sun. This could significantly reduce the dependence on an interior blind to block direct sun.

### 5.3.2. Integrated EC Window and Daylighting Control System

- Because the EC visual comfort algorithms were based on models that are known to have flaws, further research should be conducted to develop better visual comfort models based on subjective responses then used in future control algorithms.

- There are needs beyond what the EC manufacturers are likely be able to provide. Further work should be conducted to develop better integrated window-lighting control algorithms that are versatile, practical and reliable, and that accommodate different visual tasks, building occupancies, and climate/HVAC conditions.

- Given advances in digital lighting controls, commissioning procedures to establish reliable daylighting control of EC window and daylighting control systems should be automated.

- This system can deliver significant reductions in cooling and lighting demand. The control scenarios for demand response should be investigated in greater detail to better understand potential impacts in California.

### 5.3.3. Performance Impacts

- The estimated energy impacts are highly dependent on the reference case assumptions for the manually operated interior shade. Human factors studies are needed not only to determine when and why shades are lowered but also when and why they are raised. The estimated energy impacts are also highly dependent on the visual comfort control algorithm. When better algorithms are developed, the energy impacts for EC windows should be reassessed.

- The human factors assessment of EC windows was conducted over a short period (3–4 hours). Longer-term assessments should be made to better understand user acceptance and satisfaction with EC window systems.

- The EC windows did not operate as reliably as desired due to problems with the alpha intermediate state controller. Additional field tests should be conducted on more mature EC windows to better quantify performance impacts.

### 5.3.4. Information Resources

- The infrastructure for supporting the design and specification of EC windows in buildings has started to be developed. There is still considerable work to be done to develop simulation tools that can quantify the trade-offs in energy use, peak demand, visual comfort, interior brightness, direct sun control, and view for these dynamic window systems and provide optimized solutions for particular building applications. Architects will be interested in applying the technology to new designs but the subtleties of optimizing glare and energy control will be difficult for most to address; e.g., how to split facades into view and daylight sections.

- Further work is required to implement an infrastructure to support design and specification of EC windows in buildings: rating and labeling systems, codes and standards, design guides and tools.

## 5.4. Benefits to California

A new window technology has now entered the market that is particularly of use in the hot inland climates of California (cooling and daylighting), but also in all climates (daylighting) as an energy efficiency as well as a load management option, providing building owners with a technology to respond to future time dependent price structures for electricity or an emerging demand response requirement. California architects and owners have aggressively adopted "sustainable design" and the Governor's statewide program has aggressive savings goals over the next 10 years. Successfully capturing the daylighting benefits promised in many LEED ratings while minimizing cooling will require the kind of technology demonstrated in this program. Furthermore, the California Public Utilities Commission programs administered by the utilities is looking for a new generation of technologies to promote in their programs. While this technology is unlikely to meeting their criteria now, mainly due to cost, continued refinement, testing and application could provide more cost effective options for these programs in the next five years. This project has already increased public awareness of the technology and will provide objective third-party information about the characteristics of EC windows and their likely performance impacts in commercial buildings. The information in this final report clearly delineates the risks and benefits of using the EC window technology in a typical commercial office application today and the future promise of the technology.

## 6.0 References

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## 7.0 Glossary and Abbreviations

### Glossary

| | |
|---|---|
| EC cycle | Electrochromics are cycled (bleached, colored, bleached) for durability tests. |
| EC device | Electrochromic coatings are often referred to by material scientists as a "device" since the coatings are switchable. |
| I-V | EC windows require a specific pattern of bipolar potential otherwise known as the current (I)-to-voltage (V) waveform to switch or actuate the EC device without causing long-term permanent damage. |
| Tv | Visible transmittance of the glass. All reported values are center-of-glass, not whole window values. |

### Abbreviations

| | |
|---|---|
| ACEEE | American Council for an Energy Efficient Economy |
| AMU | Air mass unit |
| BMCS | Building management control system |
| COP | Coefficient of performance |
| CPUC | California Public Utilities Commission |
| Ctz | Climate zone |
| COG | Center of glass |
| COP | Coefficient of performance |
| CTAP | Customer Technology Application Center |
| DALI | Digital addressable lighting interface |
| DGI | Daylight glare index |
| DOE | Department of Energy |
| DR | Demand response |
| EC | Electrochromic |
| EMCS | Energy Management Control System |
| EU | European Union |
| Ev | Vertical illuminance |
| GUI | Graphical user interface |
| HDR | High dynamic range |

| | |
|---|---|
| HVAC | Heating, ventilation, air-conditioning system |
| IGU | Insulating glass unit |
| IC | Integrated circuit |
| IEA | International Energy Agency |
| ISO | International Standards Organization |
| I-V | Current-to-voltage |
| LBNL | Lawrence Berkeley National Laboratory |
| LAN | Local area network |
| LCD | Liquid crystal display |
| LED | Light-emitting diode |
| NAHB | National Association of Home Builders |
| NFRC | National Fenestration Rating Council |
| NREL | National Renewable Energy Laboratory |
| PIB | Polyisobutylene |
| PTR | Photopic transmittance ratio |
| R&D | Research and development |
| SCE | Southern California Edison |
| SHGC | Solar heat gain coefficient |
| SWIFT | Switchable Facade Technology |
| Tv | Visible transmittance |
| VAV | Variable air volume |
| VDT | Visual display terminal (computer monitor) |

# Appendix A

# List of Related Publications

## List of Related Publications

These related publications provide further information. The references below can be found at the PIER website as Attachments to this final report and at the following website address: http://windows.lbl.gov/comm_perf/electroSys-cec.htm

### Systems Engineering

1. Lee, E.S., S.E. Selkowitz, M.S. Levi, S.L. Blanc, E. McConahey, M. McClintock, P. Hakkarainen, N.L. Sbar, M.P. Myser. 2002. "Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives". Proceedings from the ACEEE 2002 Summer Study on Energy Efficiency in Buildings: Teaming for Efficiency, August 18-23, 2002, Asilomar, Pacific Grove, CA. Washington, D.C.: American Council for an Energy-Efficient Economy. LBNL-50855, Lawrence Berkeley National Laboratory, Berkeley, CA.
2. Lee, E.S., D.L. DiBartolomeo, F.M. Rubinstein, S.E. Selkowitz. 2004. Low-Cost Networking for Dynamic Window Systems. Energy and Buildings 36(6):503-513. LBNL-52198, Lawrence Berkeley National Laboratory, Berkeley, CA.
3. Tavil, A. and E.S. Lee. 2005. The impact of overhang design on the performance of the electrochromic windows. Proceedings of the International Solar Energy Society (ISES) Solar World Congress, Orlando, Florida on August 8-12, 2005. LBNL-57020.
4. Lee, E.S. and A. Tavil. 2005. An assessment of the visual comfort and energy performance of electrochromic windows with overhangs. Submitted to Building and Environment, October 14, 2005. LBNL-59064, Lawrence Berkeley National Laboratory, Berkeley, CA.
5. Fernandes, L., G. Ward, E.S. Lee. 2005. Radiance-Mathematica optimization of electrochromic operations for occupant comfort and non-energy provisions. Technical report, http://windows.lbl.gov/comm_perf/electroSys-cec.htm.

### Performance Impacts

#### Energy Use and Peak Demand Impacts

6. Lee, E.S., D. L. DiBartolomeo. 2002. Application issues for large-area electrochromic windows in commercial buildings. Solar Energy Materials & Solar Cells 71 (2002) 465–491. LBNL Report 45841, Lawrence Berkeley National Laboratory, Berkeley, CA.
7. Lee, E.S., D.L. DiBartolomeo, S.E. Selkowitz. 2005. Daylighting control performance of a thin-film ceramic electrochromic window: Field study results. Energy and Buildings 38 (2006) 30-44. LBNL-54924, Lawrence Berkeley National Laboratory, Berkeley, CA.
8. Lee, E.S., D.L. DiBartolomeo, J. Klems, Ph.D., M. Yazdanian, S.E. Selkowitz. 2005. Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort. To be presented at the ASHRAE 2006 Annual Meeting, Quebec City, Canada, June 24-28, 2006 and published in ASHRAE Transactions. LBNL-58912.
9. Lee, E.S., M. Yazdanian, S.E. Selkowitz. 2004. The Energy-Savings Potential of Electrochromic Windows in the U.S. Commercial Buildings Sector. LBNL-54966, Lawrence Berkeley National Laboratory, Berkeley, CA.

10. Klems, J. 2004. Thermal calibration of the windows testbed facility. Technical report, http://windows.lbl.gov/comm_perf/electroSys-cec.htm.

### Occupant Impacts

11. Clear, R.D., V. Inkarojrit, E.S. Lee. 2005. Subject responses to electrochromic windows. Submitted to Energy and Buildings, February 23, 2005. LBNL-57125, Lawrence Berkeley National Laboratory, Berkeley, CA.

12. Inkarojrit, V. 2004. Analysis of visual comfort using high-dynamic-range luminance images. Poster report. http://windows.lbl.gov/comm_perf/electroSys-cec.htm.

13. Clear, R.D. 2005. Assessment of visual comfort study in a full-scale electrochromic window testbed. Technical report. http://windows.lbl.gov/comm_perf/electroSys-cec.htm.

### Information Resources

14. Excerpt from: Carmody, J., S. Selkowitz, E.S. Lee, D. Arasteh, T. Wilmert. 2004. Window Systems for High Performance Commercial Buildings. New York: W.W. Norton and Company, Inc.

15. Lee, E.S., S. Selkowitz, V. Bazjanac, V. Inkarojrit, C. Kohler. 2002. High-Performance Commercial Building Façades. LBNL-50502. Lawrence Berkeley National Laboratory, Berkeley, CA. http://gaia.lbl.gov/hpbf/main.htm

16. 16. Lee, E.S., S.E. Selkowitz, R.D. Clear, D.L. DiBartolomeo, J.H. Klems, L.L. Fernandes, G.J. Ward, V. Inkarojrit, M. Yazdanian. 2006. A Design Guide for Early-Market Electrochromic Windows. LBNL-59950.

17. Summary of Technology Transfer Activities: Journal articles, conference papers, popular press, and presentations, including copies of articles.

# Attachments

**Note: Attachments are available as separate PDF files that may be downloaded from the Energy Commission's website at:**

**http://www.energy.ca.gov/pier/final_project_reports/CEC-500-2006-052.html**

Attachment 1: Active Load Management with Advanced Window Wall Systems: Research and Industry Perspectives

Attachment 2: Low-Cost Networking for Dynamic Window Systems

Attachment 3: The Impact of Overhang Design on the Performance of the Electrochromic Windows

Attachment 4: An Assessment of the Visual Comfort and Energy Performance of Electrochromic Windows with Overhangs

Attachment 5: Radiance-Mathematica Optimization of Electrochromic Operations for Occupant Comfort and Non-Energy Provisions

Attachment 6: Application Issues for Large-Area Electrochromic Windows in Commercial Buildings

Attachment 7: Daylighting Control Performance of a Thin-Film Ceramic Electrochromic Window: Field Study Results

Attachment 8: Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort

Attachment 9: The Energy-Savings Potential of Electrochromic Windows in the U.S. Commercial Buildings Sector

Attachment 10: Thermal Calibration of the Windows Testbed Facility

Attachment 11: Subject Responses to Electrochromic Windows

Attachment 12: Analysis of Visual Comfort Using High-Dynamic-Range Luminance Images

Attachment 13: Assessment of Visual Comfort Study in a Full-Scale Electrochromic Window Testbed

Attachment 14: Window Systems for High Performance Commercial Buildings

Attachment 15: High-Performance Commercial Building Façades

Attachment 16: A Design Guide for Early-Market Electrochromic Windows

Attachment 17: Summary of Technology Transfer Activities