Better Windows, Better Outcomes: How Electrochromics Improve Health, Productivity, and Efficiency

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Executive Summary

The U.S. building sector has a substantial energy footprint; currently, buildings waste over $200 billion of energy each year.[1] The building façade—including windows—can play a significant role in reducing the size of that footprint (see Figure 1 - LBNL, https://windows.lbl.gov/ec). In the United States, heat loss or gain through windows account for approximately four quads of combined heating and cooling energy use at an annual cost of more than $40 billion.[2] An aggressive program to deploy proven new highly

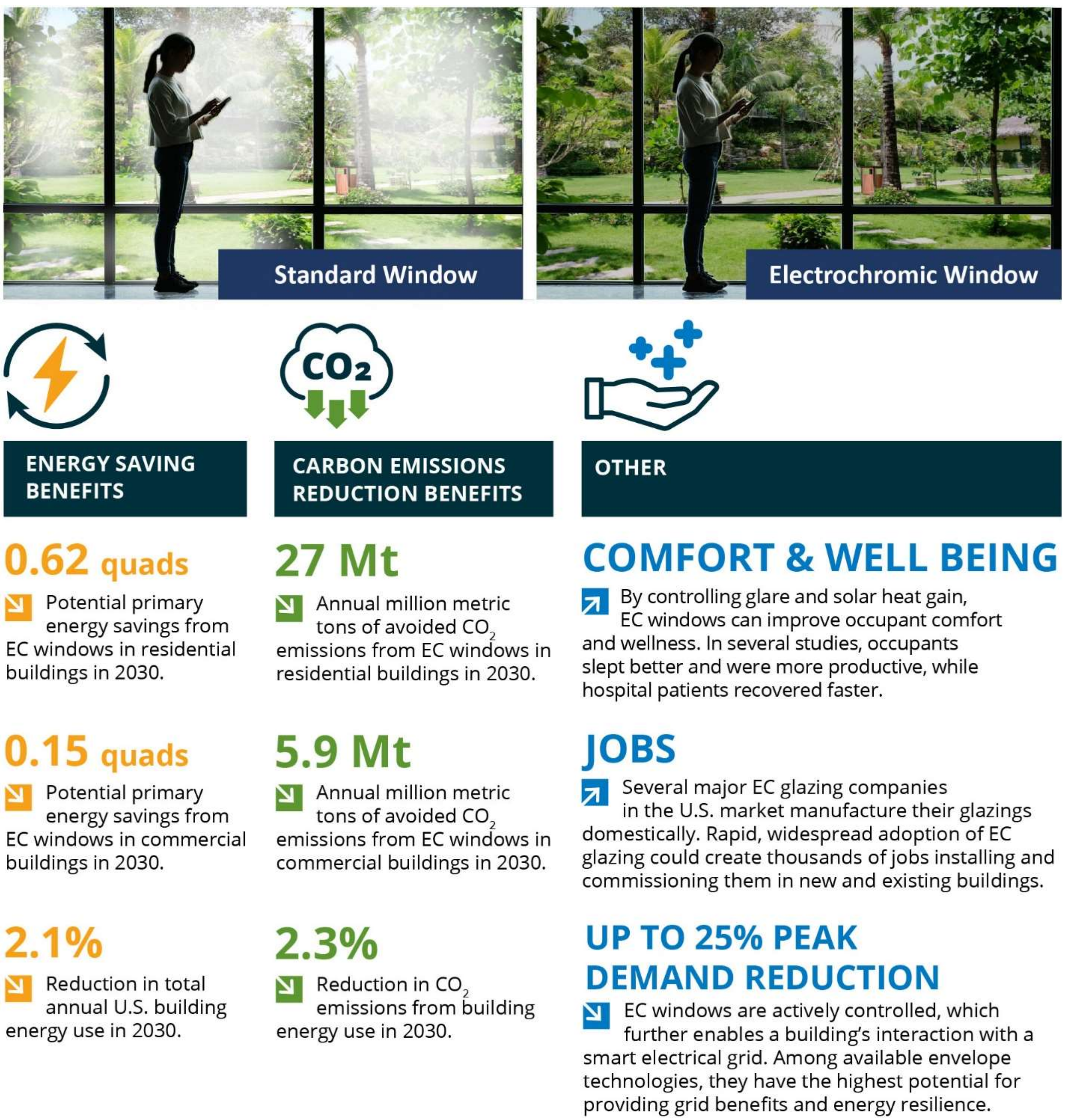

Figure 1. Infographic showing the impact of electrochromic window deployment. Mt = Million Metric Tons.

efficient windows has the potential to save almost a quarter of that each year, nearly $10 billion annually, and thus take a major step in reducing the Nation's annual wasted energy.

High-performance windows are an important pathway to achieving low-energy and decarbonized buildings while maintaining some of the most desirable elements of a building, including natural light and outdoor views. An approach with particular promise is dynamic windows, whose solar and light transmittance properties can be dramatically changed in response to external conditions and/or occupants' preferences, such as sunlight intensity and temperature. Dynamic window technologies offer building energy savings by modulating the transmittance of daylight and solar heat gain. The result is reduced energy consumption for lighting and HVAC and improved thermal and visual comfort. Dynamic facades can also provide electricity grid benefits by enabling changes in the timing of heating, cooling, and lighting loads, and thus influencing electric load shape, peak demand, and demand-side ramp rates. Finally, dynamic glazings can provide significant enhancements to occupants' productivity, as the glazing performance can impact visual and thermal comfort, health, and well-being.

This report focuses on electrochromic (EC) windows, the most technologically mature of available dynamic glazing formulations. In this report, EC windows are defined as a glazing system that uses electricity to change the light and solar transmittance properties of the glazing to enhance building and occupant performance.

The potential energy savings available from EC windows shown in Figure 1 assume that all new windows and window replacements between today and 2030 use EC glazing. In practice, the adoption of EC glazing and the resulting energy and CO_2 emissions savings will depend on the presence of policies and market conditions that promote EC windows. However, Figure 1 does not include the potential to increase the rate of window replacement or the installation of secondary glazing retrofit attachments. Details on the method used to estimate the energy and CO_2 savings can be found in Harris (2022).[3]

Benefits of Electrochromic Windows

Energy and Peak Load Savings

Reductions in lighting and cooling system energy use with EC glazing can yield substantial reductions in peak electricity demand. In simulation results, EC windows have been shown to reduce peak cooling electricity demand between 0.46 and 0.65 W/ft^2 in North American cities, compared to static solar heat gain with control glazing.[4] Another study showed that EC glazing can reduce solar heat gains up to 88.9% compared to code-minimum glazing.[5] A separate laboratory experiment had similar findings: EC windows could save energy in cooling-dominated climates, with annual savings between 6 and 30 kWh/ft^2, amounting to a reduction of up to 40%.[6] Peak cooling loads in a full-scale testbed were reduced 25%–58%, with EC windows compared to spectrally selective low-e windows.[7]

EC windows offer additional cost savings opportunities by enabling the downsizing of heating, ventilating, and air-conditioning (HVAC) systems. Electrochromic windows' ability to reduce the admission of daylight through automated control can reduce the necessary HVAC system capacity for a building to operate comfortably. Realizing this benefit requires a holistic, system-level approach that can be pursued during design for new construction or building renovations. Electrochromic windows could dramatically improve the thermal and optical performance of large glass facades, and the cost savings from installing smaller HVAC systems could help offset window upgrade costs.

Occupant Well-Being

There is growing scientific evidence of the importance of light on human health and well-being. To date, there have been well over 50 studies linking various health aspects to daylight; several of these studies are summarized in the Health Benefits Connected to Enhanced Daylight section of this report. Exposure to natural light through windows has been correlated with indoor environmental quality and associated occupant health benefits, both tangible and intangible: sleep–wake cycle regulation, circadian rhythm, reduced seasonal affective disorder, improved sense of well-being, and scholastic performance.[8,9,10] Sunlight can be selectively transmitted through EC windows to facilitate these advantages.

The Future of the Dynamic Windows Industry

If EC windows are widely adopted, residential and commercial building sectors could reach energy savings of 0.62 and 0.15 quads, respectively.[i] However, meeting that level of adoption requires better cost and performance metrics than those currently achieved by commercially available EC technologies. BTO has set price and performance targets for dynamic window technologies that are projected to enter the market by 2030, and identified three R&D opportunity areas to achieve these targets: reducing manufacturing costs, increasing energy saving potential, and broadening the value to consumers. [11]

EC windows will also benefit from recently-enacted tax incentive provisions in the Inflation Reduction Act – specifically amendments to the Section 48 Investment Tax Credit, the Section 25C Energy Efficiency Home Improvement Credit, and the Section 179d Commercial Buildings Deduction. While analysis presented in this report does not include representation of these amendments, DOE's ongoing work in this area will be informed by the opportunities presented by these new market incentives.

[i] Energy savings and CO_2 emissions reductions calculated with Scout and the published energy conservation measures "Prospective Residential Windows (Dynamic)" and "Prospective Commercial Windows (Dynamic)." Savings are based on a "technical potential" scenario, which assumes that all new and existing buildings receive an EC window upgrade. Baseline energy and CO_2 emissions are from the 2021 U.S. Energy Information Administration Annual Energy Outlook. The energy and CO_2 emissions savings calculation methods used by Scout are described in Langevin, J., Harris, C.B., and J. L. Reyna. 2019. Assessing the Potential to Reduce U.S. Building CO_2 Emissions 80% by 2050. Joule 3 (20). doi.org/10.1016/j.joule.2019.07.013.

ELECTROCHROMIC WINDOW REPORT

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1. Introduction and Background

Buildings have a substantial energy footprint, and windows play a significant role in creating—or reducing—that footprint. In 2021, buildings accounted for 39.7% of total U.S. primary energy use,[12] and windows are responsible for about 10% of energy use in buildings, as well as influencing end uses that comprise more than 40% of building energy use.[11] In the United States, windows account for approximately four quads of combined heating and cooling energy use at an annual cost of more than $40 billion.[2] These building envelope features have substantial potential to reduce energy use in buildings, as well as other benefits.

Improvements to the building envelope, including windows, can have significant impacts on this energy use, as well as on occupant health and comfort. The building envelope consists of transparent and opaque elements that serve as a controllable barrier to help maintain the indoor environment. By leveraging desirable external environmental conditions (e.g., views, fresh air, and natural light) and mitigating the influence of undesirable conditions (e.g., moisture, hot and cold temperatures, and wind), the building envelope can reduce the need for space conditioning and electric light and thus reduce energy use associated with lighting and heating, cooling, and ventilation equipment, while maintaining occupant comfort.

Figure 2. Electrochromic window transitioning from tinted to clear. Figure courtesy of Energetics.

High-performance windows, as part of a high-performance building envelope, are crucial to achieving low-energy buildings while maintaining some of the most desirable elements of a building, including natural light and outdoor views. An approach with particular promise is so-called "dynamic" windows. Switchable or dynamic windows can modulate light transmission, reflection, and/or absorption properties (in specific wavelength ranges). Dynamic technologies offer building energy savings by modulating the light and heat gained from the sun, including providing passive solar heating benefits that are significantly reduced by the latest developments in static, low-emissivity glass. The result is reduced lighting and HVAC-related energy use (space heating and cooling, ventilation fans, pumps). Dynamic facades can also be used to provide grid benefits by enabling changes in the timing of heating, cooling, and lighting loads and thus influencing electric load shape, peak demand, and demand-side ramp rates.

This report focuses on electrochromic windows, the most technologically mature of available dynamic glazing formulations. The function of an electrochromic device is shown in Figure 3. In this report, electrochromic windows are defined as a glazing package that uses a small amount of electricity to change the solar and light transmittance properties of the glazing assembly. These changes can help maintain comfortable conditions in a building through selectively reducing or admitting passive heating from the sun. By modulating daylight transmittance, they can reduce the need for electric lighting but also manage glare and enhance visual comfort. This reversible switching is achieved through the movement of either protons or lithium ions into or out of coatings on the window glass such as tungsten oxide.[11]

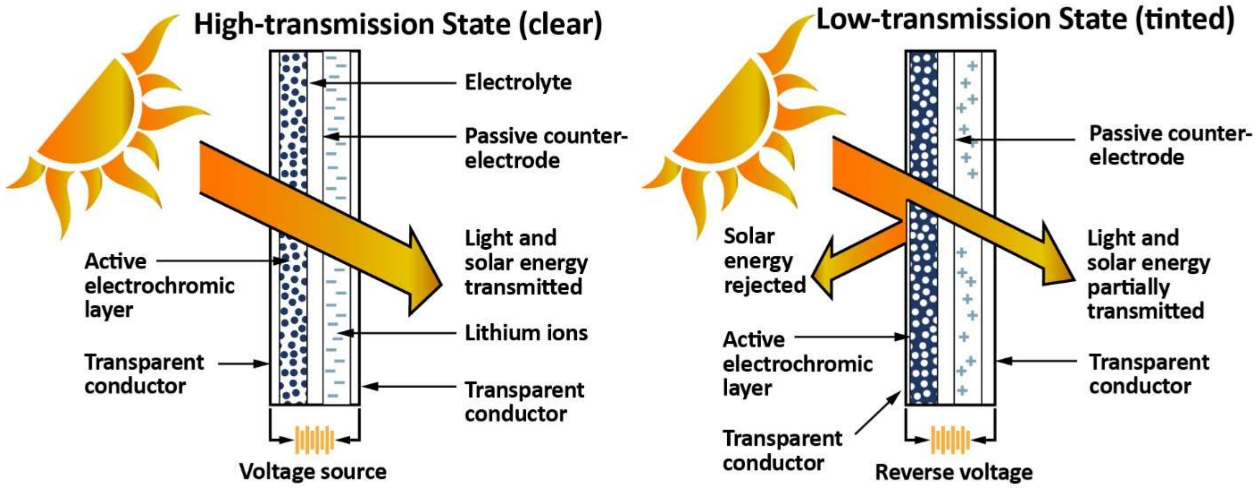

Figure 3. Diagram of an electrochromic device in its clear (left) and tinted (right) states. Figure courtesy of Energetics.

The U.S. Department of Energy (DOE) Building Technologies Office's (BTO's) Windows R&D Program, which was established to foster the development of high-performance windows, has played a major role in the evolution of EC windows to date. In addition, the innovations from understanding of the glass and approaches for smart windows have been supported by the Office of Science's materials and nanoscale science programs. This technology's promise indicates that its continued advancement is part of a successful strategy toward building sector decarbonization. As Secretary of Energy Jennifer Granholm has stated, improving the energy efficiency of America's buildings is key to achieving the Biden administration's goal of a viable net-zero carbon economy. The Biden Administration has prioritized efforts toward sustainable infrastructure as part of a path to net-zero emissions economy-wide. Currently, buildings waste over $100 billion worth of energy each year.[1] The Administration's planned targets include reducing the carbon footprint of the U.S. building stock 50% by 2035,[13] and planned investments include upgrading four million buildings over four years and spurring building retrofits, including more efficient windows.[14]

This report discusses EC window technology, beginning with its potential benefits and the challenges it faces in widescale adoption. The document then covers the research and technology development, including several case studies, that has led to the current status. Non-energy benefits are presented in this section and examined in greater detail later in the document. The report concludes with a look at window technologies in a future low- or zero-emissions building sector, including the steps needed to realize windows' full potential contribution to those emissions targets.

Electrochromic Glazing Energy and Peak Load Savings

Reductions in lighting and cooling system energy use with EC glazing can yield substantial reductions in peak electricity demand. In simulation results, EC windows have been shown to reduce peak cooling electricity demand between 5 and 7 W/m^2 in 10 North American cities, compared to static solar heat gain with control glazing,[4] and another simulation showed that EC glazing can reduce solar radiation gains up to 88.9% compared to code-minimum glazing.[5] A separate laboratory experiment had similar findings: EC windows could save energy in cooling-dominated climates, with savings between 6 and 30 kWh/ft^2 per year.[6] When compared to more energy efficient windows, such as spectrally selective low-e windows, EC windows reduced peak cooling loads by an additional 25%–58% in a full-scale testbed.[7] EC windows offer additional cost savings opportunities by enabling the downsizing of heating, ventilating, and air-conditioning (HVAC) systems. Electrochromic windows' ability to reduce the admission of daylight through automated control can reduce the necessary HVAC system capacity for a building to operate comfortably. Realizing this benefit requires a holistic, system-level approach that can be pursued during design for new construction or building renovations. Electrochromic windows could dramatically improve the thermal and optical performance of large glass facades, and the cost savings from installing smaller HVAC systems can help offset window upgrade costs.

Non-Energy benefits of Electrochromic Windows

In the U.S., people spend an average of nearly 90% of their time indoors, and there is growing scientific evidence of the importance of light on human health and well-being.[15] Exposure to natural light through windows has been correlated with indoor environmental quality and associated occupant health benefits, both tangible and intangible: sleep–wake cycle regulation, circadian rhythm, reduction of seasonal affective disorder, sense of well-being, and scholastic performance.[9, 10, 11] Sunlight and air can be selectively transmitted through windows to facilitate these advantages. Building residents would benefit from future daylight delivery systems that are adaptable to changes in the quantity and quality of daylight to improve occupant comfort, health, and well-being.

In addition to offering energy- and health-related benefits, switchable glazing provides increased architectural freedom: building designs with more glass and open views that still meet codes and standards, improved flexibility and adaptability to future spatial reconfiguration, reduction or elimination of internal or external shading structures, contribution toward green building certification, and increased real estate value.[16]

Challenges Facing Electrochromic Windows

Electrochromic windows have not yet attained widescale adoption. Despite excellent progress in advancing the technology through BTO-sponsored R&D, additional R&D is needed to address remaining performance and cost challenges. Solutions to facilitate the adoption of EC windows into standard construction practices are needed as well. Prevailing construction and building retrofit market conditions and adjacent factors can create significant barriers to technology uptake. These barriers can be financial, knowledge-related, or implementation-related. In addition, the variability of the advantages from dynamic glazing also presents difficulties for rating and comparing windows.

Cost is primary among the barriers that have thus far prevented widespread adoption. Most dynamic glazing currently follows a manufacturing path that leads to high-cost and low-throughput, which has negative impacts on the competitiveness of their pricing. Commercially available EC windows retail for \$50–\$150/ft^2, compared to conventional window prices of approximately \$15–\$30/ft^2.[17]

Additional EC glazing system costs are incurred through installation and maintenance. In general, installation of these systems requires two trades to visit the site, one to install the hardware and one for the electrical connection. Battery-operated dynamic technologies eliminate the need for additional electrical work but unless they have integrated photovoltaic panels they require regular battery maintenance.

In terms of performance challenges, dynamic glazing technologies have historically presented issues with durability, the need to balance between letting in daylight and modulating temperature or controlling glare, switching times, and window coloration. For maturing dynamic glazing technologies, durability concerns have been partially addressed with the development of ASTM E-2141/E-2953, which define accelerated aging methods for dynamic glazing. To date, NREL has validated three companies that have passed ASTM 2141 for their EC window glazing.

Other concerns include adopter preference for a neutral color tone and uniform appearance, and the relatively long time period necessary to fully switch window tint level (5–12 minutes).[18] In addition, most EC windows do not modulate infrared and visible light independently. This means that a window switched to minimize solar heat gain will additionally reduce glare but also reduce available daylight from the window—a drawback for occupants who value daylight. This disadvantage can also have implications for lighting electricity demand, as indoor lighting levels might have to be increased if daylight is reduced. Novel chromogenic formulations with the ability to independently attenuate visible and near infrared (NIR) light would allow greater control over the daylighting and solar heat gain trade-off. This feature would be particularly beneficial in buildings with high heating loads. High-performing laboratory-scale electrochromic devices have been developed toward that end,[19] but achieving highly replicable, large-scale, and inexpensive manufacturing remains a challenge, alongside outstanding technical concerns related to coloration, switching time, and, in some cases, long-term durability.

In addition to cost and performance concerns there are challenges associated with product ratings, which are largely oriented towards static properties that are easily measurable. For example, an energy standard such as ENERGY STAR can require a window to have a maximum solar heat gain coefficient[ii] (SHGC) of 0.25 in areas with warm/hot climates, or a minimum SHGC of 0.32 for cold climates. However, modeling and field tests show that a window whose SHGC can vary from 0.15 to 0.40, a range attainable by today's commercially available electrochromic windows, can enable lower energy use in summer and winter than a window with fixed properties. This is done by continuously providing optimal solar control appropriate to building orientation and climate. As a consequence, the dynamic character of electrochromic windows poses challenging questions in terms of ratings and standards, such as how to give appropriate annual energy credit to a window, how sensitive energy savings are to control sequences and whether those control actions can be guaranteed, what happens when the controls are overridden, and how an inspector verifies the required properties. DOE continues to engage the private sector, code officials, and other program administrators to enable more appropriate performance ratings for EC windows.

[ii] The solar heat gain coefficient of a window represents the fraction of incident solar energy that finds its way through the window into the building interior. I.e., a window with a SHGC of 0.1 blocks most heat from the sun whereas one with an SHGC of 0.8 lets most of that heat through.

2. The Role of the U.S. Department of Energy in Advancing Window Technology

BTO's Windows R&D Program has played a major role in the technological development and market adoption of advanced window technologies. The overwhelming majority of U.S. windows are now designed using DOE-funded software tools that allow researchers to assess and incorporate performance improvements with much less capital compared to the days of building costly prototypes. In addition, DOE-supported developments in low-emissivity (low-e) glass, improved frames, spacers, and gas fills led to development of today's ENERGY STAR® windows, which typically perform two to three times better than windows installed in the 1980s. The Windows R&D Program continues its leadership as window technologies enter the next phase. The Program has contributed significantly to the development of dynamic glazing and the highest thermally performing windows on the market, which offer dramatic improvements over ENERGY STAR windows with static solar control.

Today's window industry is manufacturing much higher-performing products because of this federal investment. Approximately 80% of residential and 50% of commercial windows sold today (and 98% of energy-efficient windows) incorporate low-e coatings. DOE's 40-year continuous support of low-e windows has transformed the windows market and directly contributed to this technology's dominant status in the window industry globally. This technology now serves as a platform for further innovations related to coatings and glazing.

More recent advances include modifications to the window frame (e.g., highly insulated frames and window spacers), higher-performing inert gas fills (e.g., krypton), advanced glazing packages (e.g., thin-triple-pane glazing or vacuum-insulated glazing [VIG]), and subcomponents that may achieve window performance that can surpass ENERGY STAR benchmarks by more than three times.

DOE-funded efforts to develop electrochromic window technology began in the 1970s with ground-breaking research on the electrochromic effect in tungsten oxide materials. This has now become the present dominant technology in the electrochromic dynamic window space. This fundamental discovery was further advanced through an extended DOE development program working with both the private sector as well as the national laboratories. DOE's on-going and sustained effort to advance this technology has led to the formation of multiple U.S. based companies leading the development of high technology manufacturing jobs for U.S. based workers as well as over $2B in private sector investment in this technology.

DOE and the National Laboratories have published hundreds of reports and papers on electrochromic windows and related research areas, through work supported by BTO and the Office of Science. Furthermore, several national lab electrochromic innovations have received R&D 100 Awards. Researchers have made advances in material science, including developing various forms of switchable chromogenic coatings, tuning material properties, and improving longevity under extreme conditions. Scientists have used these innovations as the launching point to develop innovative window applications, assess the human factor in successful technology implementation, and conduct field studies that validate energy performance and enable technologies to evolve and deploy commercially.

DOE and national lab efforts supporting EC technology continue today (see Table 1). DOE has supported a diverse group of companies—including industry leaders View, SageGlass, and Halio —in advancing their technologies; this support takes the forms of both direct funding and in-kind funding through national laboratory partners. The early work funded by DOE has led to more than $2 billion in private sector funding to support commercialization of EC windows, and large-scale product installations are currently under way.[20] Today, there is ongoing research to produce innovative switchable coatings that switch faster and over a broader range, allow a higher degree of flexibility in color including development of neutral tone devices, provide independent control of daylight and solar control, and that can be manufactured at a fraction of the cost of previous devices.

Table 1. Ongoing Windows Research Projects Funded by DOE

Title	Summary	Lead
Core Research Support for BTO Windows Program	This work is facilitating transformation of the installed base of windows in the United States toward high-performance windows.	Lawrence Berkeley National Laboratory
Durability of Emerging Fenestration Technologies	This work assesses the performance of emerging window technologies, including EC, over time to build confidence in the lifetime and long-term return on investment to consumers adopting advanced high-performance windows	National Renewable Energy Laboratory
Highly Insulating Windows	This project seeks to establish market adoption of products capable of capturing the ~2 quads of heating energy lost by windows.	Lawrence Berkeley National Laboratory
International Energy Agency Energy (IEA) in Buildings and Communities (EBC) Annex 80	The United States is contributing to IEA's Annex 80, which is investigating affordable and effective passive/low-energy cooling measures (e.g. window attachments and/or shading) that can help homes and businesses adapt to increasingly frequent extreme heat events while limiting escalation of air conditioning use.	Lawrence Berkeley National Laboratory
Integral Hi-R, Dynamic Window and Wall Panel	Researchers are incorporating highly insulated window glazing and dynamic shading configurations into window units that are fully installed and sealed in a factory and transported to a site as integral units.	Lawrence Berkeley National Laboratory
Integrated Facades National Lab Scoping Study and Field Validation with CBI	This project is identifying gaps in research, technology, and tools that prevent integration of building facades and electric lighting.	Lawrence Berkeley National Laboratory
Low-Cost Vacuum Insulated Glass (VIG) for Retrofit of Single Pane Windows	This project is developing thin, lightweight, low-cost VIG windows that can reduce energy losses by eliminating the gas between the glass panes and using the resulting vacuum as insulation.	University of Maryland – College Park, MD
Low-Cost, High-Performance Electrochromic Devices	This project is working to overcome some of the critical drawbacks of current EC windows by reducing product costs and improving product aesthetics.	Polyceed – Tucson, AZ

Pulse-Strengthened and Laser-Edge-Sealed Vacuum Insulation Glazing	This project is researching a scalable, low-cost processing strategy for glass strengthening and sealing to impact the thermal performance of vacuum insulating glass units (VIGs).	Oak Ridge National Laboratory
Radiance lighting simulation software	Radiance is a set of open-source lighting simulation tools capable of accurately calculating lighting metrics and rendering photorealistic scenes.	Lawrence Berkeley National Lab Anyhere Software –Berkeley, CA National Renewable Energy Lab
Robust Large-Scale Dynamic Windows using Reversible Metal Electrodeposition	The project is employing strategies to construct aesthetically pleasing dynamic window prototypes using high-throughput and inexpensive fabrication methods.	University of Colorado –Boulder, CO
Switchable Photovoltaic Windows	This project seeks to develop a switchable photovoltaic (PV) window that transforms into an efficient solar cell when the sun is shining and then turns back into a window with high visible light transmittance.	National Renewable Energy Laboratory
Vacuum Glass for R10 Window	This project supports development of a highly insulating R10 vacuum glass unit that is cost-effective and thin enough to fit all existing frames with minimal impacts and cost increases.	V-Glass Inc. – Pewaukee, WI
Validation Studies of Highly Insulating Thin Triple Windows	This assessment will investigate potential whole-building impacts and ease of installation of the latest generation of high-R windows.	Pacific Northwest National Laboratory

In addition to R&D support moving forward, DOE is focused on a range of activities and partnerships with the private sector that accelerate adoption and commercialization of the R&D advances. This includes development of upgraded software tools and a standardized labeling program that meet the evolving needs of modern manufacturers, code officials, homebuilders, and the National Fenestration Rating Council. By combining highly insulating and dynamic solar control windows, window performance can be optimized for every building application anywhere in America. Current efforts also make these technologies increasingly cost-effective and contribute to DOE's ultimate vision for windows—producing solutions that are energy-positive and windows that perform even better than insulating walls. BTO recently announced the Partnership for Advanced Window Solutions (PAWS), a new initiative to accelerate the national availability and adoption of advanced and highly efficient windows to improve occupants' comfort and reduce building energy use. Accelerating adoption of electrochromic windows will add new dimensions to the PAWS and related market transformation initiatives to decarbonize the nation's building stock.

Key Electrochromic Case Studies

Architects, engineers and building owners will not specify smart windows until they see convincing evidence that the technology delivers on its promises in a real-world building environment. Over the last 20 years DOE has supported a variety of field tests that have generated useful objective, third party case study data to guide further technology development, window integration, and controls optimization.

The Forrestal Building

This study installed EC windows in a single west-facing conference room in a Federal Government office in Washington, DC.[21] The room was fitted with EC windows divided into three segments. The windows used occupancy-based controls that automatically switched the windows to maximize comfort when the room was occupied, or to minimize heating and cooling loads when it was empty; manual controls were also placed in the meeting room. The study estimated that the total energy savings from both lighting and HVAC were 39%–48%, using the EnergyPlus whole building simulation software. Records show that occupants used the manual tint control in only 24 out of 328 meetings and used the blinds to cover only the top third of the windows.

Figure 4. EC windows installed in a conference room in the U.S. Department of Energy Headquarters in Washington DC. Photo courtesy of DOE Photography.

Portland General Services Administration Building

This study was conducted in an eight-story GSA office building in Portland, Oregon.[22] South-facing windows on four of the eight floors were replaced with EC windows. The windows could be controlled manually or through an automated system that used sensors to determine the intensity of external sunlight and set the windows to, depending on outside conditions, maximize daylight, minimize solar heat gain, and/or minimize glare. The study evaluated the effects of EC windows on lighting and HVAC energy use, as well as occupants' satisfaction with the windows. It found that EC windows reduced annual lighting energy needs by 36%, and that while HVAC energy use was slightly increased (2%) during working hours on weekdays, setting the windows to maximum tint on weekends reduced weekend HVAC energy use by 57%. Of the building occupants, 85% of those in private offices and 92% of those in congregate settings preferred EC windows over conventional windows, although some stated that offices with EC windows were slightly less well-lit than they would prefer.

U.S. Customs and Border Protection Facility

This study tested EC windows at a U.S. Customs and Border Protection (CBP) facility in Donna, Texas.[23] CBP facilities rely on windows not only for occupant comfort but also to observe activity at the border, so reliable visibility is important. EC windows were installed both in the command center and in vehicle inspection booths. The study measured daytime glare and surveyed building occupants. (The researchers could not get meaningful measurements of HVAC loads, as the inspection booth operators often opened the booth doors for long periods to perform their duties.) The EC window installations reduced daytime glare and demand for window shades, improved occupant comfort, and were rated as better than normal windows by almost all occupants. However, the study noted that reflections on the inside of the glass did reduce visibility through the window at night.

Denver Federal Center

This study investigated the effectiveness of both EC and thermochromic windows in reducing HVAC energy use and improving occupant comfort at the Denver Federal Center, a low-rise office building in Denver, Colorado.[24] Both EC and thermochromic windows were installed along the south face of the building, along with a set of low-emissivity windows that served as a control. The study found that actively controlled, near-term chromogenic glazing (including electrochromic windows) can reduce perimeter zone heating, ventilation, and air conditioning and lighting energy use by 10-20% and reduce peak electricity demand by 20-30%, achieving energy use levels that are lower than an opaque, insulated wall. However, cost was found to be a major barrier to adoption. In addition, there can be trade-offs between optimizing EC windows for minimal HVAC load, minimal lighting load, or minimal glare. The study was unable to obtain meaningful data on occupant comfort or view quality, although some occupants complained that, at high tint levels, the windows made clear days appear cloudy.

John E. Moss Federal Building

This study examined the energy and comfort performance of EC windows at the John E. Moss Federal Building, a U.S. General Services Administration (GSA) office building in Sacramento, California.[7] The facility installed EC windows, which had four tint levels and could be controlled automatically by exterior sensors on the roof or manually by wall switches, along its southern face. The study initially suffered problems with the windows at full tint for large amounts of time, causing occupants to complain that building spaces were too dark and the windows provided too little visibility. The manufacturer altered the control software to address this issue. The study evaluated HVAC energy consumption, occupant perception of daylight glare, use of window shades, and lighting energy consumption. It found that daily HVAC energy consumption was reduced by 29%–65%, and peak HVAC energy consumption was reduced by 25%–58%, depending on time of year. Lighting energy consumption increased by 62%, but this is thought to be partially caused by difficulties with the control program early in the experiment, which caused the windows to spend more time than necessary at full tint. Occupant surveys were unable to establish whether there was a statistically significant reduction in perception of glare, but there was a slight reduction in the use of blinds, from 90% to 79%. A majority (60%) of occupants said that they preferred EC windows to older windows. This study concludes that EC windows can be effective at reducing energy costs and improving occupant comfort, but that more research should be done on fine-tuning window control algorithms and redesigning lighting fixtures to take advantage of EC windows' ability to facilitate natural lighting.

3. Electrochromic Windows' Impact on Occupant Comfort and Productivity

While daylight and views have significant benefits, window access can also have unintended side effects. Being too close to a window can create problems with glare and radiant heat gain or loss.[25,26] This may seem trivial, but the effects translate to problems beyond discomfort. In a 1982 study of 235 Canadian office workers, workers in buildings with large glazed areas (68% of office wall area) reported more eyestrain and had higher absenteeism compared to workers in buildings with smaller glazed areas (11% of office wall area).[27] A 2000 study of 1,800 Danish office workers found that the most negative aspects of having access to a window were glare problems and overheating.[28] Since then, the rise in availability of low-e window coatings in the market has reduced the thermal discomfort felt by occupants in the immediate vicinity of the window. However modern studies continue to demonstrate that glare from windows can be correlated with increasing eyestrain and headaches.[29]

These studies highlight the importance of modern window technologies, such as EC windows, that can be used to control natural light while still maintaining the view. To date, a number of EC window studies (including case studies and pilot studies funded by DOE) have addressed occupant comfort, both visual and thermal. [30–34] [7,22–24]

In one such study, EC windows were installed at a CBP port of entry facility in Donna, Texas.[23] As noted in the previous section, reliable visibility to observe activity at the border is very important at the facility, so the study focused on reducing glare while maintaining appropriate visibility, as well as reducing or eliminating the use of shading devices, such as blinds, that block the view. Figure 5 shows a comparison of the view from two booths at the port of entry, one with traditional window glazing and the other with EC glazing. Also shown in the figure is the measured daylight glare probability (DGP) for each. DGP is a metric quantifying the appearance of glare discomfort in daylit spaces; values above 0.4 indicate disturbing glare and above 0.45 indicate intolerable glare. It is clear in both the images and the plotted data that the EC glazing significantly reduces the glare from direct sun to acceptable levels. Additionally, results from occupant surveys showed that officers experienced a significant improvement in not just visual comfort but also thermal comfort after EC windows were installed, without a significant degradation in daytime or nighttime visibility. Officers overwhelmingly stated they would prefer switchable EC windows to conventional windows.

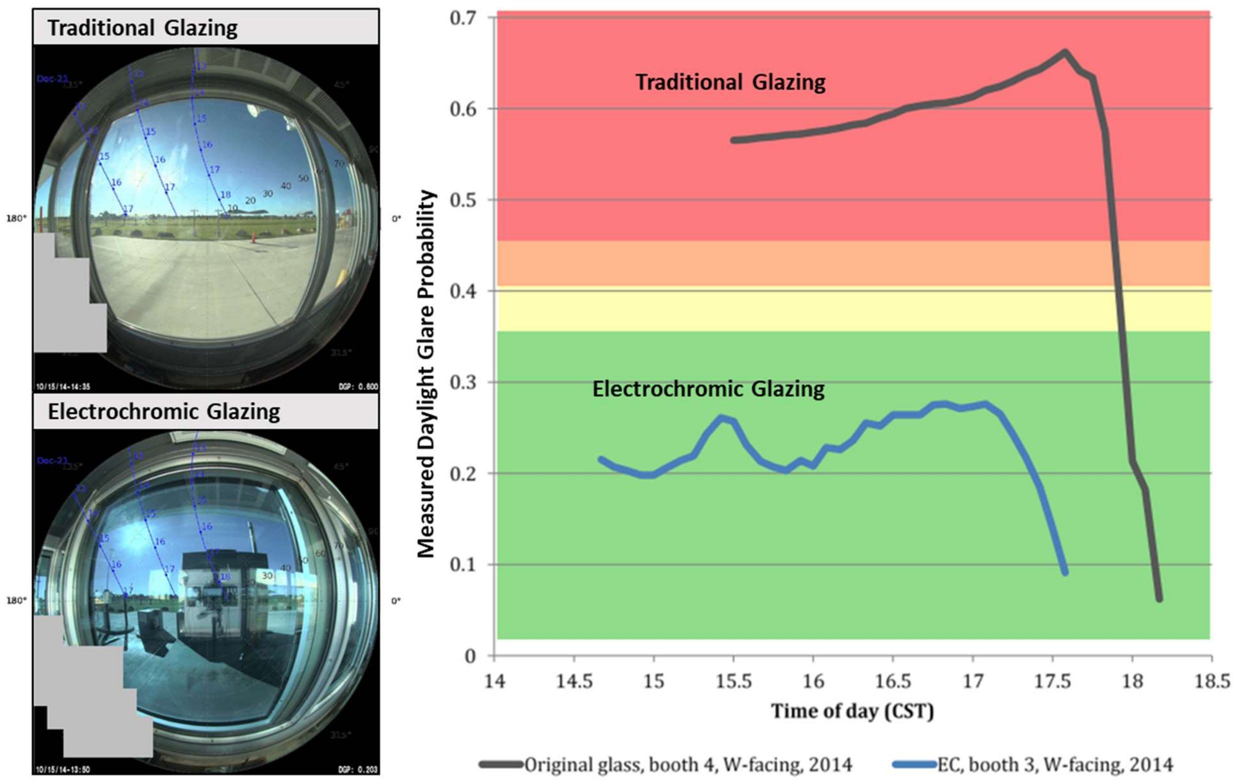

Figure 5. Left: A fisheye view facing west from a CBP booth with traditional glazing (top) and EC glazing (bottom), with sun path superimposed. Right: Measured DGP in vehicle inspection booths with conventional (gray curve) and EC (blue curve) windows, facing west on the afternoon of October 15, 2014, under sunny conditions. Figure from Fernandes, Lee, and Thanachareonkit.[23]

In a similar study funded by DOE, EC windows were installed in a GSA office building in Portland, Oregon.[22] The study evaluated the effects of EC windows on lighting and HVAC energy use, as well as occupants' satisfaction with the windows. Figure 6 shows images with traditional glazing and EC glazing operating in a glare-reduction mode. The accompanying false color images highlight the extent of glare reduction the EC window provides. Measurements indicated that DGP levels were imperceptible during the winter and summer when the EC was controlled automatically within the glare reduction mode. When surveyed, 85% of private office occupants and 92% of public building occupants preferred EC windows over conventional windows. These employees reported less glare and less heat from the sun.

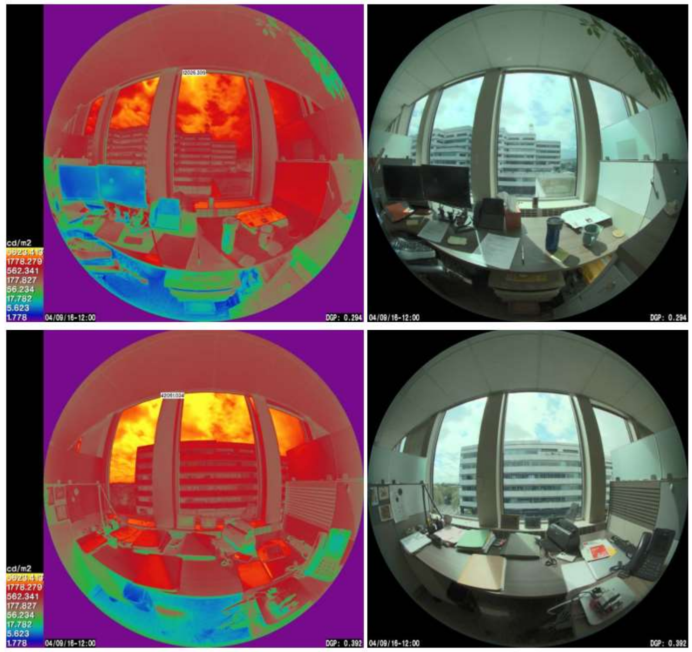

Figure 6. False color images (left) and photographs (right) of a south-facing window in the GSA building, April 9, 2016, at noon. The photos in the upper row show windows with EC glazing, operating in a glare control mode, and the windows in the lower row show windows with a traditional glazing. Figure from Lee et al.[22]

Productivity

Another important factor is the correlation between daylight and productivity. Early research showed that productivity is higher in well-daylit workplaces. The link between daylight and productivity can also encompass retail sales and educational productivity. High-impact studies have shown that retail sales are higher in daylit stores,[35,36] and that children perform better in daylit classrooms with views.[10,37] This report focuses on employee productivity in the workplace.

Windows that provide daylight and view have a marked impact on an employee's wellness and productivity and, as a result, a marked impact on the employer's bottom line. The main causes for deficient workplace productivity are absenteeism, loss of focus, negative mood, and poor health.[38] Access to natural light or a view has been shown to reduce these loss pathways. Multiple case studies have examined results when various companies—of different sizes and different regions across the United States—moved their workers to buildings designed to prioritize daylight. The companies reported lower absenteeism, increased productivity, and fewer mistakes.[35] Employees with more access to window views were more satisfied with their jobs, reported better well-being, spent more time working, and indicated they were less likely to quit their jobs.[39–41]

Dr. Ihad M.K. Elzeyadi conducted a study of an administrative office building at the University of Oregon, investigating the health and human impacts of daylighting strategies and view quality from windows.[41] Within the building, 30% of offices had windows that overlooked trees and a manicured landscape; 31% overlooked a street, building, and parking; and 39% were in the interior of the building, offering no outside view at all. Researchers found that the quality of employees' views from their offices significantly affected how they behaved at work. Employees with the views of trees and the landscape took an average of 57 hours of sick leave per year, whereas employees with no view took an average of 68 hours per year. The study's conclusion was that 10% of employee absences could be attributed to architectural elements that did not connect with nature and that a person's view was a primary predictor of absenteeism.

While absenteeism is a significant avenue for workplace productivity losses, what about employee productivity when they are at work? The Heschong Mahone Group conducted a famous study of the seating arrangements at the Sacramento Municipal Utility District call center. Employees with views of vegetation through large windows handled calls 6%–7% faster (and had far more calls per hour) than employees with no view of the outdoors.[42] Based on this information, the call center underwent construction to maximize all employees' access to views. After the structural changes, profit margins grew significantly. Construction costs for the operable windows and the slight increase in square footage requirements (due to rearranging employee workstations) totaled $1,000 per employee, whereas the annual productivity increases averaged $2,990 per employee. The initial investment payback was achieved within four months, with long-term productivity improvements yielding increased profits.[42,43]

Due to the perceived benefits of daylight and views, many organizations adopt modern workplace architectures that encompass large open areas with abundant windows that provide employees with natural views. Employers hope to foster a positive and productive atmosphere for collaboration and teamwork among employees.

In these workplaces, the EC window industry reports that EC window installation is steadily rising—not only to improve energy efficiency but also to mitigate uncomfortable glare and thermal effects associated with traditional window glazing. EC windows have been installed in the office buildings of companies such as Netflix, Facebook, American Savings Bank, Nestle, UBISOFT, and Siemens.

4. Health Benefits Connected to Enhanced Daylight

The energy savings and occupant comfort benefit of electrochromic windows has been well established in the above sections. The benefits of controlled exposure to daylight through dynamic glazing as well as minimizing solar heat gain and glare, also has a pronounced effect on the occupant's wellbeing. In this section we will discuss the reported health benefits to natural light both in a workplace and a therapeutic setting. We will first present the studies that have documented these benefits and then discuss the origins of the effects.

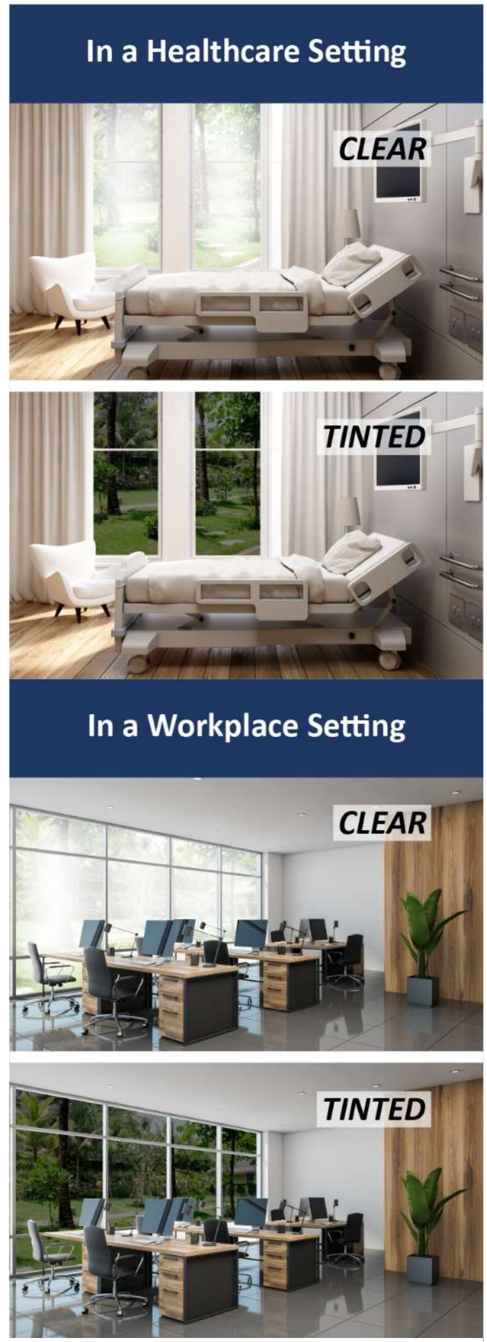

Figure 7. Illustration of the utilization of Electrochromic windows in health care and workplace settings. Figure courtesy of Energetics.

Case Studies of Health Benefits

Office Workers

The advantages of access to a window with natural light extend beyond work productivity, as discussed in the previous section. Access to daylight in the workplace has been correlated with employees' improved physical and psychological wellness.

Thayer et al. conducted one of the first studies to link physiological responses of employees to the work environment.[44] The comparative study examined employees in an old office space characterized by poor lighting and air quality versus a healthy, brightly daylit office. Workers in the daylit office experienced less activation of hormonal stress and significantly fewer headaches. Since then, numerous workplace studies have focused specifically on employee wellness and its association with daylight in particular.[25,30,45,46]

One such study, by Harb et al., showed that working women who were exposed to higher natural light levels through windows during the day reported better sleep and lower depressive symptoms than women working in similar jobs who experienced less natural light exposure.[45] The study demonstrated that lack of exposure to natural light is associated with high levels of the stress hormone cortisol and lower night-time levels of the sleep hormone melatonin, and these, in turn, are related to depressive symptoms and poor quality of sleep. A daylit office (versus an artificially lit office) has also been correlated with reduced eyestrain, higher job satisfaction, and even reduced absenteeism.[38] This and similar studies clearly indicate the benefits of daylight to employee wellness.

However, windows also have drawbacks, such as glare and uncomfortable solar heat gain, making shading systems necessary. This requirement complicates natural daylight's incorporation into an office environment. When fully deployed, traditional shades or blinds obstruct daylight, minimizing its advantages. In a recent study by Boubekir et al.,[33] researchers compared employee nocturnal sleep habits and cognitive performance in two identical electrically lit offices, one of which used traditional shades fixed at 75% down, while the other used automated EC glass to control glare. Researchers found that employees who worked in the office with EC glass slept 37 minutes longer and scored 42% higher on cognitive simulations. This study underscores the need to optimize shading systems to use daylight effectively. In another recent study, Jamrozil et al. tested the impacts of two shading systems on employees of the Mayo Clinic.[30] The study was conducted at the Well Living Lab. The shading systems were motorized shades and automated EC glass. Both were modern systems, designed to provide daylight and view while minimizing glare. Researchers found that, irrespective of the system, the employees with access to daylight and view had higher cognitive function performance (defined as working memory and inhibition), greater environmental satisfaction, and fewer eyestrain symptoms. There were some differences between system performance: employees using the EC glass reported less eye discomfort and less difficulty concentrating than those using motorized shades. Taken together, these studies indicate that modern shading methods that provide access to daylight and view while limiting glare can improve occupants' performance and satisfaction and reduce eyestrain.

Reduced Eye Strain

One physiological benefit of window access is the reported reduction in eyestrain. Such an effect is well documented in the workplace. A view allows the individual to focus beyond the computer screen and four walls of the room. For instance, when sitting and staring at a computer screen or doing any task with a short visual focus, the eye's lens becomes rounded with the contracting of the eye muscles. When these muscles stay contracted for an extended period, i.e., more than 20 minutes at a time, fatigue can occur, manifesting as eyestrain, headache, and physical discomfort. A periodic, yet brief, visual distraction that causes one to look up (for >20 seconds) and to a distance (of >20 feet) allows for short mental breaks, during which the muscles relax and the lenses flatten. A window view encourages workers to take regular breaks from looking at computer screens, allowing the eyes to focus on distant objects and recover. Clinical optometrists often suggest the 20/20/20 rule: after 20 minutes of computer use, workers should look at something 20 feet away for at least 20 seconds. This mechanism could account for the reported correlation in reduced eyestrain and headaches in employees.

Patients in Health Care Facilities

Access to a window with natural light has been correlated with improvements in average length of in-patient stay,[47–49] post-operative recovery,[50,51] and pain relief.[52] In a groundbreaking 1984 study,[51] Ulrich found that patients with a view of a natural setting (rather than a wall) experienced hospital stays that were 8.5% shorter, with fewer negative observational comments from nurses. These patients also needed significantly fewer strong post-surgical analgesics. Since that study, the impact of a hospital's physical environment on patient health and well-being has received extensive academic attention. A growing body of knowledge on evidence-based healthcare facility design has become available in recent years.

To date, there have been well over 50 studies linking various health aspects to daylight. Many of those correlate daylight to faster patient recovery. In 2012, Choi et al. found that, in certain wards, the average length of stay (ALOS) was 16%–41% shorter in daylit areas than in dimmer areas.[47] In 2013, Joarder et al. found that heart surgery patients' ALOS was reduced by 7.3 hours per 100 lux (unit of illuminance) increase of daylight inside in-patient rooms.[48]

Exposure to daylight may enhance recovery from painful medical conditions. Beauchemin and Hays conducted a retrospective study that examined the impact of natural light exposure on mortality and length of hospitalization in myocardial infarction patients.[50] Study results found that individuals in bright rooms had significantly shorter ALOS. Interestingly, the effect was most significant in female patients. Women spent only 2.3 days when in a bright room, compared to 3.3 days when in a dark room. There was also a strong statistical trend toward more deaths in the dark rooms as compared to the bright rooms that was independent of gender.

In 1996, Beauchemin and Hays conducted a separate study of 174 hospitalized patients who suffered from bipolar disorder or depression, again finding a lower ALOS for patients in sunny, daylit rooms than for patients in rooms with artificial lighting.[49] In the study, those staying in naturally daylit units were released after an average of 16.7 days, while patients in dully lit rooms stayed an average of 19.5 days—i.e., an average of 2.6 additional days.

A similar study conducted in 2001 found that the ALOS for bipolar patients in rooms with direct morning sunlight was 3.67 days shorter than for patients who had no sunlight.[53]

In 2005, Walch et al. conducted a prospective study testing whether exposure to sunlight affected the need for pain medication in 89 patients who had undergone spine surgery.[52] Patients were randomly assigned to bright or dim hospital rooms. Bright rooms were exposed to 46% more natural light than dim rooms. Patients in rooms with increased intensity of sunlight experienced less perceived stress, marginally less pain, and required 22% less opioid-equivalent analgesic medications, which resulted in a 21% decrease in medication costs compared to other patients. The fact that recovering in a room with more natural light lowered medication intake is noteworthy, particularly since lower medication intake is associated with fewer side effects and lower costs.

From a purely economic perspective, reducing the ALOS per patient can have significant financial advantages. In a 2015 report commissioned by Terrapin Bright Green, Browning et al. used the national statistic for average hospital stays following major surgery in the United States and applied Ulrich's reported 8.5% reduction in ALOS to estimate the cost savings.[38] The study found that reducing the ALOS in hospitals by 0.41 days can amount to $93 million in reduced hospital costs every year. While actual cost savings will be highly dependent on patient history, procedure, and many other factors, these results do indicate potential for significant macroeconomic impacts.

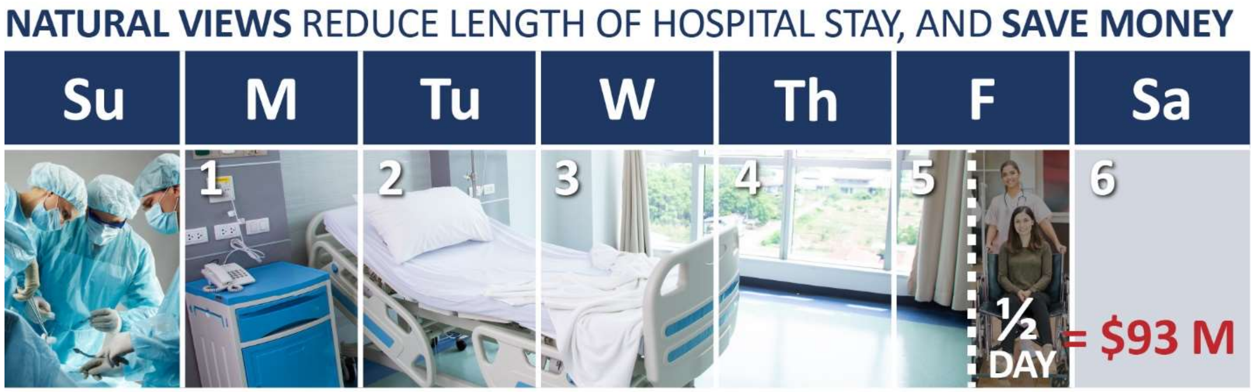

Figure 8. Average length of stay follow surgery is reduced for patients that recover in rooms with view and natural light. This decreases the financial burden on the patient. **Figure courtesy of Energetics.**

Origins of Natural Light's Health Impacts

The natural question then comes to why? Why is it that access to natural light through a window is so beneficial to patients and employees? In all the case studies, natural light has a clear effect on an individual's health. However, there is no established succinct causal mechanism for these results. The convoluting factor is that exposure to daylight may or may not be the true cause of the faster and easier recovery. Daylight is usually delivered through windows, which means that receiving daylight is confounded with having a view. Some researchers argue that it is the psychological effect of the view that matters, while others believe that it is the physiological impact of daylight or sunlight on the circadian cycle that is important.

Psychological Impacts

If it is the view out that matters, the mechanism is psychological in nature and can be described as distraction therapy. In this case, the term "view" does not necessarily mean a view from a window but a visual stimulation that will serve as a diversion to make painful procedures more bearable. Following this line of thought, Diette et al. found that adult patients undergoing a painful bronchoscopy procedure reported less pain if they were assigned to look at a ceiling mounted nature scene rather than a control condition consisting of a blank ceiling.[54] Similarly, Ulrich et al. demonstrated that participants recovered faster from stressful situations when shown a tape of a natural setting.[55] Another distraction technique used virtual reality as a means of managing chronic pain for women receiving chemotherapy.[56] These studies decoupled view from daylight and consistently found that groups exposed to one of these distraction techniques reported significantly reduced pain and stress.

Physiological Impacts

The beneficial mechanism of daylight cannot be psychological alone, as the benefits have shown to scale with the intensity of the light (i.e., the brighter the room, the greater the benefits).[48] Physiological mechanisms hinge on maintaining the body's circadian rhythm, which is the daily cycle of hormonal activity observed in many living organisms. Light entering the eye triggers the circadian rhythm; thus, it follows that sunlit windows provide patients and employees natural cues to maintain a balanced circadian cycle. Throughout the day, sunlight changes color, from yellow in the morning, to blue at midday, to red in the late afternoon and evening; the human body responds to this daylight color transition. Higher content of blue light (similar to daylight) produces serotonin, whereas an absence of blue light (which occurs at night) produces melatonin. The balance of serotonin and melatonin has been linked to sleep quality, mood, alertness, depression, breast cancer, and other health conditions.[57]

To enable our bodies to reach an optimal hormonal balance, daylight can provide the amount of illumination and the specific wavelengths of light needed by the human body to establish and maintain the serotonin–melatonin balance. Although some recent advances in lighting systems can partly compensate for this, in most buildings artificial lighting contains considerably less blue light than daylight, and blue light is the component of the spectrum thought to be highly relevant for achieving non-visual biological effects.

The Role of Electrochromic Windows

Irrespective of the mechanism, it has been established that the views and daylight provided by windows can give the employee/patient/user a significant wellness advantage. However, effectively implementing daylight exposure can be challenging. As mentioned above, uncomfortable factors such as glare and solar heat gain felt by the user make the addition of blinds, shades, or curtains necessary for visual and thermal comfort; these additions can limit use of the window and natural light.

EC windows with tunable tint controlling solar heat gain and glare (as discussed in Section 2) mitigate these detractors, allowing use of the window, daylight, and view for a longer timeframe, effectively maximizing the benefits in wellness. The idea was tested by Boubekir et. al. and Jamrozil et. al., who demonstrated that EC windows that optimize daylight and views provide a working environment that benefits sleep and cognition.

The EC window industry reports that EC glass is being incorporated into many offices and healthcare facilities. Companies such as Google and Netflix have recognized the benefits to their employees and incorporate these state-of-the-art glazings in their headquarters. Table 2 provides a sample list of the hospitals and healthcare facilities that have adopted EC windows (this list represents a fraction of these organizations). Industry-provided preliminary statistics from these facilities highlight a positive effect on environmental impact, energy efficiency, and occupant wellness. In a pilot EC window demonstration at the Children's Hospital of Philadelphia reported that 92% of hospital staff said patients are more comfortable in rooms with access to daylight.[58] The Methodist Olive Branch Hospital experienced a 35% peak load HVAC reduction, helping the hospital become one of the first to attain LEED Gold certification.[59] Future installations are expected to continue providing strong and positive effects in energy efficiency and wellness.

Table 2. Representative Health Care Facilities That Have Incorporated EC Glass

Butler County Health Care Center, David City, NE	McFarland Clinic, Ames, IA
Chestnut Lake Wellness Center, Strongsville, OH	Meeker Memorial Hospital, Litchfield, MN
Children's Hospital of Philadelphia, Philadelphia, PA	Memphis VA Medical Center, Memphis, TN
Choctaw Nation Medical Center, Durant, OK	Orthopedic Specialty Hospital, Mercy Medical Center, Baltimore, MD

Clovis Community Conference Center, Clovis, CA	Methodist Olive Branch Hospital, Olive Branch, MS
Erlanger Children's Hospital Outpatient Center, Chattanooga, TN	Methodist University Hospital, Memphis, TN
Hoag Hospital, Newport Beach, CA	St Luke's Hospital, Allentown, PA
Humber River Hospital, Ontario, Canada	Kaiser Permanente Medical Office, Dublin, CA
Lake Nona Physicians Plaza, Lake Nona, FL	Jerry L. Pettis Memorial Veterans Hospital, Loma Linda, CA
University of Vermont Medical Center, Burlington, VT	Martin County Health Services, Stuart, FL

5. The Future of the Dynamic Windows Industry

EC windows are an emerging technology that can drastically reduce building energy use. As one of the most effective commercially available solutions to improve energy efficiency through windows, EC will have an important role to play in the coming push for less energy-intensive buildings. When combined with highly insulating technologies, America's windows can be energy positive, resulting in a building that uses less energy than a building without any windows.

BTO has set price and performance targets for dynamic window technologies entering the market by 2030 (see

Table 3).[11] Under these metrics, the residential and commercial building sectors could reach energy savings of 0.62 and 0.15 quads, respectively. For perspective, the annual energy use in healthcare facilities is 0.72 quads.[60] However, these savings can be achieved only through adoption across the entire building stock, and that level of adoption requires better performance metrics than are currently achieved by commercially available EC technologies, which have SHGC values of 0.09–0.12/0.41–0.46 (active/inactive) and costs of \$50–\$150/ft^2 (price premiums of \$35–\$85/ft^2 compared to static windows). Clearly, further R&D and large-scale production economies of scale are required to reach these targets and ultimately facilitate wider adoption of EC windows.

Table 3. Dynamic Window and Facade Performance, Installed Price Premium Targets for 2030, and Primary Energy Savings Potential in 2030

Dynamic Windows				
Building Sector	**Performance**		**Installed Price Premium by 2030**	**Primary Energy Savings by 2030**
Residential	0.05/0.65	SHGC (active/ inactive)	6.5 \$/ft^2 window area	0.62 quads
Commercial			11.80 \$/ft^2 window area	0.15 quads
These targets apply to any dynamic window technology and are inclusive of any additional non-glazing installation costs (e.g., electrical connections or site-specific controls configuration). These price premiums should be added to baseline window prices when evaluating the competitiveness of new dynamic windows or equivalent technologies.[11]				

It should be noted here that energy cost savings is not the exclusive determinant of widespread adoption for dynamic glazing and shading technologies. Functionality and characteristics such as more natural tint colors and faster tint switch are critical for occupant-focused advantages such as comfort, and wellness. Industry is currently fine-tuning these properties. Halio has developed an EC glazing that switches tint 10x faster than other products and tints to a neutral cool grey color. Other larger companies such as SageGlass and View offer customers an array of tint options, including white, grey, blue, and green.

BTO has identified three R&D opportunity areas to achieve the above targets: reducing manufacturing costs, increasing energy saving potential, and broadening the value to consumers. **Error! Reference source not found.** summarizes examples of research topics for each opportunity area, and the remainder of this section discusses these topics in more detail.

Table 4. Future Research Opportunities Related to Dynamic Glazing

Objectives	R&D Activity
Reduce total installed price	• Develop novel materials compatible with fabrication methods suited to existing glass and window production processes • Introduce fully encapsulated, low-maintenance, self-powered systems
Increase energy savings potential	• Investigate novel materials that can independently attenuate visible or NIR wavelengths • Develop simplified sensor and control architectures that optimize energy savings and occupant comfort
Broaden value proposition	• Develop PV materials with properties complementary to dynamic glazing • Enable integration with other building technologies such as lighting and HVAC • Combine electrochromics with highly insulating window technologies • Solidify the empirical basis for the quantitative benefits of health, comfort, and productivity benefits • Develop novel control methods and establish communications and data exchange protocols to enable grid-integrated operation

Reducing Manufacturing Costs

Electrochromic glazing is typically manufactured in a largely vertically integrated fashion in distinct locations. This is in contrast to present window manufacturing, which is highly delocalized. This difference negatively impacts product availability and pricing because economies of scale available through the existing high-throughput manufacturing channels are lost. Novel approaches that rely on low-cost, high-throughput production methods could reduce product costs and expand availability, although new EC processing methods must also improve upon performance and durability. In addition, these new approaches must not rely on formulations with expensive materials, precursors, catalysts, or intermediate processing steps, as these might significantly reduce or even offset the product cost improvements gained from the substitution of a lower-cost, higher-throughput manufacturing methods.

In general, novel approaches likely maximize cost savings potential by being compatible with current glass coating and insulating glass unit (IGU) manufacturing processes. These requirements include production rates as well as typical processing, handling and eventually installation conditions, so these methods can then transfer readily to existing production facilities that are already part of the window supply chain. Ideally, a solution that can allow fabrication of dynamic windows to be broadly placed throughout present manufacturing channels will have the highest probability of reducing cost and accelerating diffusion into the market. Furthermore, this will drive job creation by enabling more manufacturers to produce electrochromic glazing.

Increased Energy Savings

Current state-of-the-art EC technologies attenuate both visible and NIR wavelengths simultaneously. Decoupling switching in the visible and NIR ranges would enable independent control of glare (tinting) while admitting some solar heat gains (NIR switching) in the winter or restricting some solar heat gains and allowing in daylight in the summer, particularly for buildings that are occupied during daylight hours. Ideally, these systems would have a wide operating range for SHGC (0.01–0.7) and visible light transmission (T_{vis}) (0.0–0.6). State-of-the-art technologies based on metal oxides and reversible metal electrodeposition are now approaching these wide operating ranges. In cooling-dominated climates, decoupled NIR switching is not especially valuable, but in climate zones with large seasonal temperature swings, fully decoupled T_{vis} and solar heat gain control are valuable.[61] Nanocrystalline transparent conducting oxide films, particularly tin-doped indium oxide and aluminum-doped zinc oxide, have been demonstrated to have EC properties with NIR-only switching.[62,63] To get visible light control with these materials, a separate automated attachment system or glazing layer that switches in the visible wavelengths (e.g., suspended particle device glazing) would be required. In the future, if similar low-cost processing methods can be developed for chemistries that show switching in the visible or NIR spectra, a sandwich system with separate visible- and NIR-controlling EC layers might be viable.

In addition, recent work has demonstrated semi-decoupled control of visible and NIR wavelengths in a single EC coating, where at low voltages, switching is primarily in the NIR range; as voltage is increased, switching begins to occur strongly in both the NIR and visible ranges.[64] A study by DeForest et al.[61] shows that semi-decoupled EC systems deliver greater total energy savings across the United States compared to NIR-only or coupled visible and NIR switching systems, which are better suited to northern and southern climates, respectively. More generally, features such as fully decoupled transmission in the NIR, visible, and even communications wavelengths on a single chromogenic pane might not yield increased energy savings, but these attributes would improve occupant comfort and broaden the value proposition for dynamic glazing systems.

Broader Value Proposition

Several kinds of future developments would further improve the value proposition of EC windows for building owners, operators, and occupants. This includes reducing the cost and complexity of the installation and commissioning process, deepening integration with other building systems such as lighting and HVAC, combining EC with highly insulating window technologies, and establishing a more solid empirical basis for any occupant health, comfort, and productivity benefits.

Reducing cost and complexity of installation and commissioning process

As noted in the introduction to this report, EC glazing systems face additional challenges with respect to installation effort, commissioning, and cost. Systems generally require either complex installation, entailing visits from two tradespersons, or regular battery maintenance.

Systems that have an integrated power system would reduce installation and construction complexity while also avoiding additional ongoing maintenance costs. In a building integrated photovoltaics (BIPV) system, PV modules are integrated into the building envelope (e.g., in the roof or the façade). These systems can use small PV cells surface-mounted to the frame, in series with the EC system or on protruding structures anchored to the frame or attachment system (if externally mounted), to provide electricity for state-change operations. A similar approach is to integrate PV into the outward IGU face of EC windows. However, durability, aesthetics (color neutrality), integration, and efficiency remain challenging for transparent glass PV and are the focus of current research efforts. The advent of switchable PV windows,[11] a third type of window PV technology, circumvents this fundamental trade-off by switching from a visibly transparent state (high T_{vis}) to a darkened state (low T_{vis}) in a manner similar to thermochromic glazing. Dynamic PV glazing is still in its early stages, and durability and switching temperature must be optimized before commercialization of switchable designs will be realized.

If these PV systems generate additional electricity, it could be used in an independent DC power system to operate other dynamic facade components, or if significant additional generation is expected, the additional installation cost required to integrate the glazing PV into the building electrical system should be offset by the value of the electricity generated.

Integration with other building systems

To provide the most benefit, it is important that automated building systems operate in ways that support and avoid conflict with each other. EC windows, via their ability to actively modulate the admission of visible daylight and solar heat gains through the building façade, can have varying impacts on lighting and HVAC systems. Conversely, other building systems often gather information, such as occupancy, that can be useful in the control of EC windows. Because of these interdependencies, some degree of integration at the control and/or hardware level is desirable between EC windows and other building systems.

Despite being technically possible, integration between EC windows and other building systems normally does not take place outside research settings, mainly due to the levels of complexity and customization involved, both in terms of hardware integration as well as control algorithms, which now need to take into account the combined operation of multiple building systems.

Future research and development towards large-scale adoption of integration between EC windows and other building systems includes reducing the complexity and level of customization needed for installation, commissioning, and operation in real buildings, and demonstrating the tangible benefits of integration of electrochromic windows with other building systems. Key for success is also the development of open standards for interoperability between façade systems such as EC windows and other building systems (e.g., HVAC, lighting), and facilitating their acceptance by the industry.

Combination with highly insulating window technologies

As discussed previously, EC windows improve the daytime energy performance of windows by controlling the amount of sunlight that enters the building. However, to reach full potential these technologies need to be integrated with other high thermal performance window technologies that give energy benefits regardless of external conditions or the time of day. The combination of daylight modulation and high thermal performance can help realize a vision of windows that are "energy positive." Energy positive windows means the energy gains from windows through harvesting solar heat and natural daylighting when needed outweigh energy losses from windows over time.

Presently, multiple technologies are being developed to improve the overall thermal insulation properties of windows. This includes a wide breadth of technologies. In the near-term, the development of "thin glass" technologies has led to novel methods of producing multi-pane window architectures that are designed for simple retrofit of existing double pane window technologies. Recent research has demonstrated transparent aerogel materials that are among the best thermally insulating materials ever made. Years of extensive research has gone into vacuum insulating glass (VIG) units which function similarly to a transparent thermos technology.

In the past, EC and highly insulating windows have developed along parallel R&D paths, however, these two technologies have now reached a sufficient level of maturity that integration is now feasible and research efforts are on-going. Key challenges include combating the potential for high cost when integrating two potentially already expensive technologies, as well as making sure that these integrated technologies can take advantage of substantial capacity and cost reductions available through integrating with existing manufacturing channels. However, the realization of energy positive windows is appearing ever more realistic.

Solidifying the empirical basis of health, comfort, and productivity benefits

The picture that is emerging from the EC window studies that are available in the literature is encouraging. Despite this, while research on the benefits of daylight and views through windows is generally supportive a solid scientific basis that allows the quantitative determination of the health, comfort, and productivity benefits of EC windows is not settled. Carefully constructed and performed studies, with a large number of occupants who are observed over long periods, would be crucial in achieving this goal. Topics of research that need to be addressed include quantitative assessments of the benefits in a variety of settings (e.g., offices, schools, healthcare), for a variety of tasks (e.g., computer tasks, in-person interactions), and for a variety of demographic factors (e.g., gender, age), distinguishing the effects of view (and types of view) and daylight, better understanding the human effects of the interactions between EC windows and the spectrum of daylight, and further studying the effect of EC windows on human thermal comfort.

6. References

1. Department of Energy's Building Technologies Office's. *Building Technologies Office Multi-Year Program Plan*. https://www.energy.gov/sites/default/files/2016/02/f29/BTO Multi-Year Program Plan - Final.pdf (2016).

2. Hart, R., Selkowitz, S. & Curcija, C. Thermal performance and potential annual energy impact of retrofit thin-glass triple-pane glazing in US residential buildings. *Build. Simul.* **12**, 79 (2019). https://doi.org/10.1007/s12273-018-0491-3.

3. Harris, C. *Pathway to Zero Energy Windows: Advancing Technologies and Market Adoption*. (2022) doi:10.2172/1866581.

4. Dussault, J.-M. & Gosselin, L. Office buildings with electrochromic windows: A sensitivity analysis of design parameters on energy performance, and thermal and visual comfort. *Energy Build.* **153**, 50–62 (2017).

5. Lin, Y. & Yang, W. Solar energy model and thermal performance of an electrochromic dome-covered house. *Energy Sustain. Dev.* **39**, 82–90 (2017).

6. Piccolo, A., Marino, C., Nucara, A. & Pietrafesa, M. Energy performance of an electrochromic switchable glazing: Experimental and computational assessments. *Energy Build.* **165**, 390–398 (2018).

7. Fernandes, L. L. *et al. Electrochromic Window Demonstration at the John E. Moss Federal Building, 650 Capitol Mall, Sacramento, California*. (2018).

8. Andersen, M., Mardaljevic, J. & Lockley, S. W. A framework for predicting the non-visual effects of daylight – Part I: photobiology- based model. *Light. Res. Technol.* **44**, 37–53 (2012).

9. Figueiro, M. G. *et al.* The impact of daytime light exposures on sleep and mood in office workers. *Sleep Heal.* **3**, 204–215 (2017).

10. Heschong, L., Wright, R. L. & Okura, S. Daylighting Impacts on Human Performance in School. *J. Illum. Eng. Soc.* **31**, 101–114 (2002).

11. Harris, C., LaFrance, M. & Sawyer, K. *Windows Research and Development Opportunity Report*. (2020).

12. US Energy Information Administration. ANNUAL ENERGY OUTLOOK. https://www.eia.gov/outlooks/aeo/tables_side.php (2021).

13. 9 Key Element of Joe Biden's Plan for a Clean Energy Revolution. https://joebiden.com/9-key-elements-of-joe-bidens-plan-for-a-clean-energy-revolution/#.

14. The Biden Plan to Build a Modern, Sustainable Infrastructure and an Equitable Clean Energy Future. https://joebiden.com/clean-energy/.

15. *Report to Congress on indoor air quality. : Volume 2. Assessment and control of indoor air pollution. (Final report)U.S. Environmental Protection Agency Office of Atmospheric and Indoor Air Programs, Office of Air and Radiation, and Office of Research and*.

https://search.library.wisc.edu/catalog/9910010319702121 (1989).

16. Thomson, G. D., Davis, R. G., Fernandes, L. & Wang, T. Achieving Integrated Daylighting and Electric Lighting Systems: Current State of the Art and Needed Research. *Energies* **14**, (2021).

17. How Much Do Smart Glass Windows Cost? *HomeAdvisor.* https://www.homeadvisor.com/cost/doors-and-windows/smart-glass/#vs (2021).

18. Casini, M. Active dynamic windows for buildings: A review. *Renew. Energy* **119**, 923–934 (2018).

19. Llordés, A., Garcia, G., Gazquez, J. & Milliron, D. J. Tunable near-infrared and visible-light transmittance in nanocrystal-in-glass composites. *Nature* **500**, 323–326 (2013).

20. Wesoff, E. Tintable-Glass Unicorn Gets Massive $1.1 Billion Investment From SoftBank Vision Fund. *Greentech Media* https://www.greentechmedia.com/articles/read/view-gets-massive-1-1-billion-investment-from-softbank (2018).

21. Lee, E. S., Claybaugh, E. S. & LaFrance, M. End user impacts of automated electrochromic windows in a pilot retrofit application. *Energy Build.* **47**, 267–284 (2012).

22. Lee, E. S. *et al.* Electrochromic Window Demonstration at the 911 Federal Building, 911 Northeast 11th Avenue, Portland, Oregon. (2016).

23. Fernandes, L. L., Lee, E. S. & Thanachareonkit, A. *Electrochromic Window Demonstration at the Donna Land Port of Entry*. (2015).

24. Lee, E. S. *et al. A Pilot Demonstration of Electrochromic and Thermochromic Windows in the Denver Federal Center, Building 41, Denver, Colorado*. http://gsa.gov/portal/content/187967 (2013).

25. Aries, M. B. C., Veitch, J. A. & Newsham, G. R. Windows, view, and office characteristics predict physical and psychological discomfort. *J. Environ. Psychol.* **30**, 533–541 (2010).

26. Kong, Z., Utzinger, D. M., Freihoefer, K. & Steege, T. The impact of interior design on visual discomfort reduction: A field study integrating lighting environments with POE survey. *Build. Environ.* **138**, 135–148 (2018).

27. Wotton, E. *An investigation of the effects of windows and lighting in offices*. (Health and Welfare Canada, 1982).

28. Christoffersen, J. & Johnsen, K. Windows and daylight. A post-occupancy evaluation of Danish offices. in *Lighting 2000. CIBSE/ILE Joint Conference* 112–120 (2000).

29. Aries, M. B. C., Aarts, M. P. J. & van Hoof, J. Daylight and health: A review of the evidence and consequences for the built environment. *Light. Res. Technol.* **47**, 6–27 (2013).

30. Jamrozik, A. *et al.* Access to daylight and view in an office improves cognitive performance and satisfaction and reduces eyestrain: A controlled crossover study. *Build. Environ.* **165**, 106379 (2019).

31. Day, J. K. *et al.* Blinded by the light: Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies. *Build. Environ.* **154**, 107–121

(2019).

32. Hedge, A. & Nou, D. Effects of Electrochromic Glass on Computer Vision Syndrome. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **62**, 378–382 (2018).

33. Boubekri, M. *et al.* The Impact of Optimized Daylight and Views on the Sleep Duration and Cognitive Performance of Office Workers. *Int. J. Environ. Res. Public Health* **17**, (2020).

34. Choi, J.-H., Loftness, V., Nou, D., Tinianov, B. & Yeom, D. Multi-Season Assessment of Occupant Responses to Manual Shading and Dynamic Glass in a Workplace Environment. *Energies* vol. 13 (2020).

35. Romm, J. J. & Browning, W. D. *Greening the Building and the Bottom Line: Increasing Productivity through Energy-Efficient Design*. (1988).

36. Heschong, L., Wright, R. L. & Okura, S. Daylighting Impacts on Retail Sales Performance. *J. Illum. Eng. Soc.* **31**, 21–25 (2002).

37. Heschong, L. & Heschong Mahone Group. *Daylighting in Schools: An Investigation into the Relationship Between Daylighting and Human Performance*. (1999).

38. Browning, William D., Namita Kallianpurkar, C. O. & Ryan, and L. L. *The Economics of Biophilia*. (2015).

39. Leather, P., Pyrgas, M., Beale, D. & Lawrence, C. Windows in the Workplace: Sunlight, View, and Occupational Stress. *Environ. Behav.* **30**, 739–762 (1998).

40. Figueiro, M. G., Rea, M. S., Rea, A. C. & Stevens, R. G. Daylight and productivity: a field study. in *ACEEE Summer Study* 69–78 (2002).

41. Elzeyadi, I. Daylighting-Bias and Biophilia: Quantifying the Impacts of Daylighting on Occupants Health. in *Thought and Leadership in Green Buildings Research 2011* (USGBC Press., 2011).

42. Heschong, L. *Windows and Offices: A Study of Office Worker Performance and the Indoor Environment.* (2003).

43. Loftness, V. *Sustainable Design for Health & Productivity.* (2008).

44. Thayer, J. F. *et al.* Effects of the physical work environment on physiological measures of stress. *Eur. J. Cardiovasc. Prev. Rehabil.* **17**, 431–439 (2010).

45. Harb, F., Hidalgo, M. P. & Martau, B. Lack of exposure to natural light in the workspace is associated with physiological, sleep and depressive symptoms. *Chronobiol. Int.* **32**, 368–375 (2015).

46. Boyce, P. R. Light, lighting and human health. *Light. Res. Technol.* 14771535211010268 (2021) doi:10.1177/14771535211010267.

47. Choi, J.-H., Beltran, L. O. & Kim, H.-S. Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility. *Build. Environ.* **50**, 65–75 (2012).

48. Joarder, A. R. & Price, A. D. F. Impact of daylight illumination on reducing patient length of stay in

hospital after coronary artery bypass graft surgery. *Light. Res. Technol.* **45**, 435–449 (2012).

49. Beauchemin, K. M. & Hays, P. Sunny hospital rooms expedite recovery from severe and refractory depressions. *J. Affect. Disord.* **40**, 49–51 (1996).

50. Beauchemin, K. M. & Hays, P. Dying in the dark: sunshine, gender and outcomes in myocardial infarction. *J. R. Soc. Med.* **91**, 352–354 (1998).

51. Ulrich, R. S. View through a window may influence recovery from surgery. *Science (80-.).* **224**, 420–421 (1984).

52. Walch, J. M. *et al.* The Effect of Sunlight on Postoperative Analgesic Medication Use: A Prospective Study of Patients Undergoing Spinal Surgery. *Psychosom. Med.* **67**, (2005).

53. Benedetti, F., Colombo, C., Barbini, B., Campori, E. & Smeraldi, E. Morning sunlight reduces length of hospitalization in bipolar depression. *J. Affect. Disord.* **62**, 221–223 (2001).

54. Diette, G. B., Lechtzin, N., Haponik, E., Devrotes, A. & Rubin, H. R. Distraction Therapy With Nature Sights and Sounds Reduces Pain During Flexible Bronchoscopya: A Complementary Approach to Routine Analgesia. *Chest* **123**, 941–948 (2003).

55. Ulrich, R. S. *et al.* Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **11**, 201–230 (1991).

56. Schneider, S., Prince-Paul, M., Allen, M. J., Silverman, P. A. P. & Talaba, D. Virtual reality as a distraction intervention for women receiving chemotherapy. *Oncol. Nurs. Forum* **31 1**, 81–88 (2004).

57. Kandel, E. R. *et al. Principles of Neural Science*. (mcGraw Hill, 2013).

58. SageGlass. IMPROVING THE PATIENT EXPERIENCE: DYNAMIC GLASS IN HOSPITALS. *SageGlass* https://sageglass.com/sites/default/files/mkt_204.0_sageglass_whitepaper_chop_studyhealthcare_en_us.pdf (2021).

59. View. Methodist Olive Branch Hospital. *View Inc.* https://view.com/portfolio/methodist-olive-branch-hospital (2021).

60. US Energy Information Administration. ANNUAL ENERGY OUTLOOK . (2012).

61. DeForest, N., Shehabi, A., Selkowitz, S. & Milliron, D. J. A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings. *Appl. Energy* **192**, 95–109 (2017).

62. Wang, Y., Runnerstrom, E. L. & Milliron, D. J. Switchable Materials for Smart Windows. *Annu. Rev. Chem. Biomol. Eng.* **7**, 283–304 (2016).

63. Garcia, G. *et al.* Near-Infrared Spectrally Selective Plasmonic Electrochromic Thin Films. *Adv. Opt. Mater.* **1**, 215–220 (2013).

64. Kim, J. *et al.* Nanocomposite Architecture for Rapid, Spectrally-Selective Electrochromic Modulation of Solar Transmittance. *Nano Lett.* **15**, 5574–5579 (2015).