Simulating Visual Comfort and Energy Performance of Organic Energy Harvesting Electrochromic Windows (EH-ECWs) in Mid-Size Commercial Office Buildings

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BACKGROUND

Electrochromic Window Technology

Electrochromic (ECW) windows are an optical glazing technology by which the transmittance (T) of a window can be controlled between transparent (T_{max}), less transparent stages, all the way to very dark (T_{min}) thus providing a range of visible light transmittances (T_{vis}) and solar heat gain coefficients (SHGC) under variable applied potentials. ECW technology has been studied over the last two decades, first based on inorganic materials such as tungsten oxide (WO_3) and more recently on organics, e.g., conjugated polymers. Commercially available inorganic ECWs have shown measured building cooling load reductions of 19-26% and lighting power savings of 48%-67% (Lee et al, 2006). The saving potential varies by building type, use, and climate zone, due to variability in heating and cooling loads, solar exposure and glare control requirements. For this reason ECWs are frequently assumed to be modulated by controls that adjust visible and solar transmittances by window or facade to reduce whole building energy consumption and maintain visual comfort. Simulation has identified substantial potential lighting power and HVAC energy savings in commercial buildings in most climate zones (Shen et al, 2009). Much of this savings is directly attributable to reduced heating and cooling by management of solar gains relative to the thermal requirements of perimeter building zones. Lighting power savings associated with ECWs are generally attributable to photocell control of electric lighting, which in some cases may be reduced due to lower visible light transmittances. However increased visual comfort in critical visual task areas from ECWs may result in decreased blinds usage and therefore increased overall daylight performance. ECWs also show promise in residential construction, especially in cooling dominated climates (Roberts, 2009) where the beneficial effects of passive solar heating are ensured via controls that lock the ECWs in the maximum transmittance during heating periods.

Organic Energy-Harvesting Electro-Chromics (EW-ECWs)

Existing commercially available technologies for controllable variable transmittance windows include suspended particle displays (SPDs), and liquid crystal polymers (LCPs). For SDPs and LCPs, contrast ratios come at the cost of constant power consumption. Alternatively, organic electrochromic windows (ECWs) hold the possibility of energy harvesting (EH), not only for self-power but also for providing on-site power generation for other building functions. Recent research and development in solar cells has intensified. Among current solar cell technology, dye-sensitized solar cells (DSSCs) may be the most cost-effective due to fabrication efficiencies (Bull et al, 2009). The combination of organic electrochromics and DSSCs form the energy harvesting electrochromic (EH-ECW) system currently under development at the UW. Fig. 1 shows a 12x20 in^2 organic ECW exhibiting the switching between transparent and dark blue color stages under a modest applied potential at a switching speed of 10 seconds (generally faster than that of inorganic ECWs at 2-20 minutes). For the UW organic ECWs, power is consumed only during switching, due to the color memory effect, thus raising the energy efficiency as compared with commercially available technology.

The proposed EH-ECW system will simultaneously control the amount of light admitted through windows, harvest solar radiation, and dim lights through the fusion of ECW and DSSC technologies. A newly discovered a switchable dye for use in EH-ECW exhibits a power conversion efficiency (PCE) of 2.5% and contrast ratio of $\Delta T = T_{max} - T_{min} = 41.8\% - 3\%$ (Taya et al, 2009). A significant attribute of organic ECWs is that processing is performed at room temperature, promising production costs that are lower when compared with inorganic ECW processed at higher temperatures. Furthermore organic ECWs do not require rare-earth metals such as Indium which is commonly used in current ECW technology. These factors, along with the promise of substantially improved building energy efficiency suggest greatly improved life cycle performance.

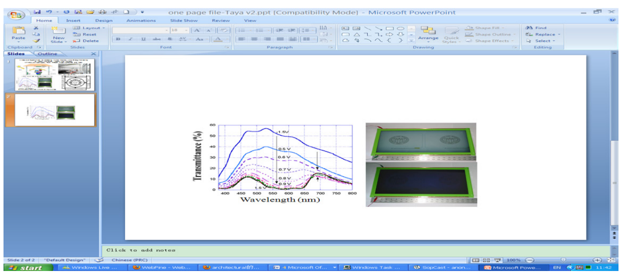

Figure 1. The UW designed ECW of 12 inch × 20 inch, (left) transmission change and (right) photos of the ECW at transparent (above) and colored stage (below) (Xu et al., 2004; Kim et al., 2009).

SIMULATION OVERVIEW

The optimum deployment of EH-ECWs in existing and new commercial office buildings will require the ability to test design alternatives for both visual comfort and thermal performance. A medium sized commercial office building was chosen as the basis for evaluation. A reference model compliant with the ANSI/ASHRAE/IESNA Standard 90.1-2004 energy code was obtained from the Department of Energy (DOE, 2011), to provide a baseline for energy performance evaluation. This model, in its original state, served as the baseline model of our research. High-performance parameters were then added to the baseline model to enable the evaluation of the electrochromic window technology in the context of a "high-performance" building. Template packages for both electrochromic windows (ECW) and photovoltaic (PV) arrays were created in EnergyPlus that could be added to either model for simulation. Building simulations were run in four different climates (Atlanta, Minneapolis, Seattle and Phoenix) without electrochromic windows, with electrochromic windows and with the addition of energy harvesting photovoltaics. This provides a disaggregation of the performance of the ECWs and the energy harvesting (EH) component.

To evaluate visual comfort performance of the EH-ECWs, a proposed new net-zero energy 54,000 square foot office building in Seattle, WA targeting Living Building Challenge (ILBI, 2011) and currently in design serves as a platform for simulation. This provides a model with sufficient detail (interior surface characteristics, workstation layout, primary visual field definition) than is present in the DOE reference models and may better reflect morphological characteristics likely in future net-zero office construction and is synergistic with existing dynamic façade visual comfort simulation research being conducted by the UW.

All modeling and simulations were done with EnergyPlus (US DOE, 2010), the OpenStudio plugin for Google SketchUp (US DOE, 2010), and Radiance (Ward, 2003).

ENERGY SIMULATIONS

Baseline Model

The 53,628 ft^2, 3 story office building, DOE mid-size office building reference model with a rectangular footprint became the base within which the electrochromic window technology was applied. The building model consisted of 15 zones, a core and 4 perimeter zones on each level, plus three plenum zones. Its exterior envelope was constructed of steel frame walls, a built up flat roof, slab-on-grade floor, and had a 33% window to wall ratio, with equal distribution of windows. It should be noted that thermal properties of the envelope varied by climate based on standard construction practice within the respective region. Finally, a packaged multi-zone VAV system, with a boiler/gas furnace and electric reheat for heating, and a packaged direct-expansion system for cooling was used as the HVAC system. This model was used as the baseline model of our research, and also served as the basic geometric template of the high performance model.

"High-Performance" Model

In order to test electrochromic window technology in the context of a high performance building, several variables were added to the baseline model. These included a new HVAC definition, increased thermal resistance on the opaque envelope surfaces, lighting controls and a reduced lighting power density (6.5 w/m2). Specifically, the conductance values for both the wall and roof insulation were cut in half (.024 w/m-K). The thickness of the wall insulation was doubled to (.2023 m) and the roof insulation nearly quadrupled to (.254 m). The following HVAC template objects were used to autogenerate a packaged terminal air-to-air heat pump (PTHP) system: *HVACTemplate:Thermostat:HVAC Template:Zone:PTHP*. All other variables, including schedules, were left the same.

Climate Zone Descriptions

Four cities (Phoenix, Minneapolis, Seattle and Atlanta) were chosen as the setting for testing the electrochromic technology. Each city chosen is located within a different climate zone, as characterized by the Köppen–Geiger climate classification system (Kotek et al., 2006). Phoenix is classified as a type (BWh): *arid climate*. It has a subtropical desert climate, with extremely hot summers and warm winters. Overall rainfall is considered low. Minneapolis is classified as a type (Dfa): *hot summer continental climate*. Winters are cold and dry, while summer is hot and humid. Seattle is classified as a type (Csb): *Dry-summer subtropical or Mediterranean climate*. The climate is usually described as Oceanic or Marine west coast, with fairly mild, wet winters and mild, relatively dry summers. Atlanta is classified as a type (Cfa): *humid subtropical climate*. It has hot, humid summers and mild winters that are occasionally cold.

Energy Harvesting Components

To model the potential performance of the energy harvesting component of the EH-ECWs, template packages were created in EnergyPlus for both the electrochromic windows and photovoltaics. Template objects were inserted into the baseline and high-performance models, and may potentially be copied into any EnergyPlus model. By building the templates separate from the baseline and high-performance models, the templates can act as general tool for studying both electrochromic windows (ECWs) and building-integrated photovoltaic (BIPV) in EnergyPlus.

Energyplus Template Objects And Classes For Simulation Of EH-ECWS

The EnergyPlus example files *Purch Air with Daylighting* and *Shop with PV & Storage* were referenced in the creation of both template packages. Template classes are indicated in the following tables.

Electrochromic Window Object Definitions

EnergyPlus classes in ECW template
Window Material: Glazing
Window Material: Gas
Material Property: Glazing Spectral Data
Construction
Window Property: Shading Control
Fenestration Surface: Detailed

Table 1. EnergyPlus template classes for ECWs.

In the first 3 classes of the template package (*Window Material: Glazing, Window Material: Gas, and Material Property: Glazing Spectral Data*), the physical, optical and spectral properties of the glazing are defined. Properties for three states of glazing need to set, these include: the electrochromic dark state, the electrochromic light state, and a normal inner pane of glass. Target visible light transmission characteristics are defined in the light state as 70% (T_{max}) an in the fully darkened state at 1% (T_{min}) with SHGC values of 0.35 to 0.09 respectively. Once all layers of glazing are defined, they can then be constructed in the appropriate order in the *Construction* class. Two constructions of glazing should exist, a dark state and a light state. In EnergyPlus switching between the light state window construction and the dark state window construction simulates electrochromic windows. Set points to determine when this switch happens are defined within *Window Property: Shading Control.* There are multiple triggers for switching, up to two can be set at once, but for the purposes of our study outdoor air temperature (15.6 degree C), and high solar on window (50 W/m^2) were used. Finally, both window construction states plus shading controls need to be applied to actual window geometry within the *Fenestration Surface: Detailed* class.

Energy Harvesting (Photovoltaic) Object Definitions

EnergyPlus classes in EH/BIPV template:
Generator: Photovoltaic
Photovoltaic Performance: Simple
Electric Loads Center: Generators
Electric Load Center Inverter: Simple
Electric Load Center: Distribution

Table 2. EnergyPlus template classes used for EH photovoltaics.

The photovoltaic template package works similarly to the electrochromic windows template, in the sense that the basic properties of the PV and its solar inverter must be defined before it usable. In terms of the photovoltaic array, each panel of the array must be created and assigned to specific window geometry in the *Generator: Photovoltaic* class. Each of these PV panels is then scheduled in the *Electric Load Center: Generators* class. For the purposes of our study the PV was scheduled to always be on with a PCE of 10%. Finally, performance properties must be defined in the *Photovoltaic Performance: Simple* class, before the PV array can begin generating energy.

The aforementioned classes define turning the PV on for energy harvesting but the energy generated is not usable until it is inverted. Because of this, a solar inverter and its schedule must be defined in the *Electric Load Center: Generators* class. The inverter takes the direct current electricity from the photovoltaic array and converts it to an alternating current for use. This energy is then distributed based on the method the user sets in *Electric Load Center: Distribution*. For this study, energy generated was distributed to the base load of the building, not back to the utility grid.

Energy Simulation Results

The electrochromic windows are responsible for a substantial reduction in cooling, heating and fan loads in the baseline building model across all the climate zones evaluated. This is true on an annual basis (Fig. 2) as well as peak heating and cooling days. Cooling and fan energy is reduced from the lower solar heat gain coefficient (SHGC) triggered by the switchable electrochromics under direct solar radiation. Heating energy is reduced from the reduction of cooling loads in winter (some climates) and thus causing a reduction in simultaneous heating and cooling. Seattle is an exception to this in that there is no cooling load, yet there is a substantial reduction in heating. This may be from reduced re-heat requirements due to lower peak cooling loads resulting from increased solar gain control and therefore more uniform zone temperatures. This should be investigated further.

Electrochromic windows in the context of the high performance model also reduce overall energy use across all the climate zones, though to a lesser extent when compared to the conventional baseline given the reduced overall energy load profile. Cooling and fan energy is reduced while lighting energy increases in all climates. The increased lighting load is to be expected when potential savings from daylighting during hours of direct sun are negated by the effect of the lower light transmittance of the ECWs. The savings in cooling loads from the lower SHGC gives a net benefit in energy performance. In addition to these loads, there is an increase in heating energy in some of the climates. Peak cooling loads are reduced in all climates but peak heating increases in the colder climates.

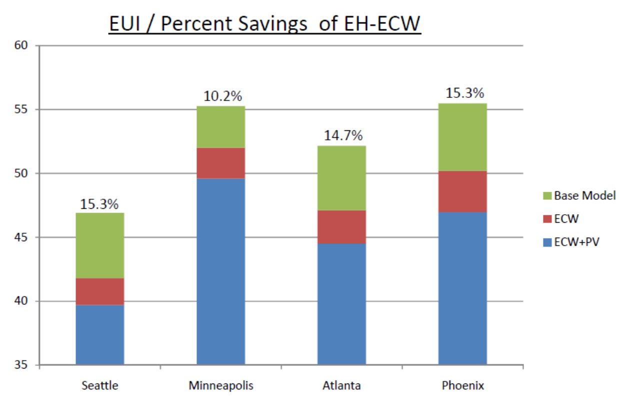

Figure 2. Annual site energy use by location for Baseline, ECW and EH-ECW models.

In all cases, the ECWs reduce net energy use on an annual basis. ECWs demonstrate a greater return on energy savings when added to a conventional building when compared to a building with a host of energy reducing strategies suggesting greatest percentage energy impacts in existing building retrofit scenarios. The greatest savings from ECWs are found in cooling, though added insulation and more efficient HVAC systems reduce these savings. Cooling systems could be downsized in all cases because of significant reductions in peak cooling. Lastly, the added benefit of the energy-harvesting photovoltaics ranges from the low in Seattle of 2.1 kBtu/sf per year to the high in Phoenix of 3.2.

Atlanta: ECWs reduce overall energy use by 9.6% over the baseline model with substantial savings in both cooling and heating and some fan energy. Peak cooling is reduced by 13.9% and peak heating is reduced by 33.9%. ECW in the high performance model reduce the overall energy use by 4.5%, more than half the savings compared with the baseline. Savings in peak cooling drop slightly to 12.1% while peak heating savings drops significantly to 0.4%.

Minneapolis: ECWs reduce overall energy use by 5.9% over the baseline model with nearly equal savings in both cooling and heating and some savings in fan energy. Peak cooling is reduced by 19.8% and peak heating is reduced by 3.4%. ECW in the high performance model reduce the overall energy use by 2.8%, nearly half the savings compared with the baseline. Savings in peak cooling drop to 11.9% while peak heating increases by 2.5%.

Phoenix: ECWs reduce overall energy use by 9.5% over the baseline model with substantial savings in cooling. Peak cooling is reduced by 21.4% and peak heating is reduced by 18.5%. ECW in the high performance model reduce the overall energy use by 7.4%, which is quite high with respect to the other energy-saving strategies employed. Savings in peak cooling drop to 11.4%, nearly half of the baseline savings, while peak heating decreases by 10.2%.

Seattle: ECWs reduce overall energy use by 10.9% over the baseline model with substantial savings in heating energy followed by cooling and fans. Peak cooling is reduced by 24.2% and peak heating is reduced by an impressive 30.2%. ECW in the high performance model reduce the overall energy use by 3.0%, more than a third of the savings compared with the baseline. Savings in peak cooling drop to 15.1% while peak heating increases by 0.9%.

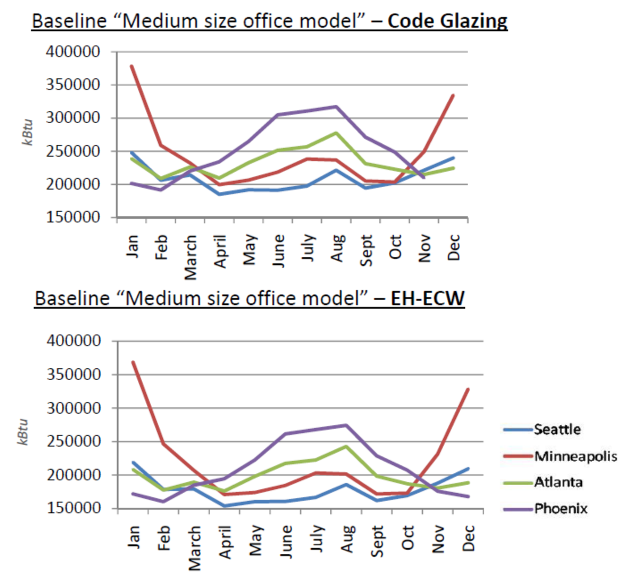

Figure 3. Monthly site energy consumption by for Baseline and EH-ECW models.

VISUAL COMFORT SIMULATIONS

Overview

In addition to evaluating the effect of electrochromic window technology on net energy consumption and thermal performance, we assess the potential effects of electrochromic windows on visual comfort across time and sky conditions. To do so, a 54,000 square foot six-story commercial office building (Bullitt Center) located in Seattle, WA, building designed to achieve net-zero energy goals currently under design by the Miller Hull Partnership was used as a platform for evaluation (Fig. 4). Its aggressive energy efficiency goals and visual comfort requirements make it a suitable choice for a test case building using this technology.

Process

A schedule for electrochromic glazing deployment was developed for the test office for both the summer & winter solstices and the equinox. Deployment of electrochromic glazing was determined per direct beam sunlight on a window by window basis. Each schedule starts at sunrise and ends at sunset, and progresses in 15-minute increments (Fig. 4.).

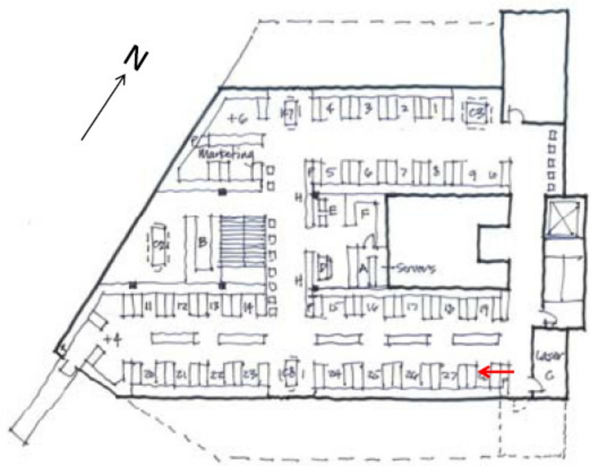

Figure 4. Fourth floor plan of Bullitt Center with workstation location for visual comfort analysis. Diagram: The Miller Hull Partnership.

		ECW Deployment: 21 Sept Clear Sky			
	Facade	SE	S	SW	NE
6:00	Sunrise	1%, 3%, 15%	70%	70%	70%
6:30		1%, 3%, 15%	70%	70%	70%
7:00		1%, 3%, 15%	70%	70%	70%
7:30		1%, 3%, 15%	70%	70%	70%
8:00		1%, 3%, 15%	70%	70%	70%
8:30		1%, 3%, 15%	70%	70%	70%
9:00		1%, 3%, 15%	70%	70%	70%
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16:00		70%	70%	1%, 3%, 15%	1%, 3%, 15%
16:30		70%	70%	1%, 3%, 15%	1%, 3%, 15%
17:00		70%	70%	1%, 3%, 15%	1%, 3%, 15%
17:30		70%	70%	1%, 3%, 15%	1%, 3%, 15%
18:00	Sunset	70%	70%	1%, 3%, 15%	1%, 3%, 15%

Figure 5. Example schedule of EH-ECW switching deployment by façade, per direct beam sunlight exposure at the fourth floor of the proposed Bullitt Center

Once the EH-ECW deployment schedule was established, dynamic simulations were created using the Radiance (Ward, et. al.) synthetic imaging software to assess the visual comfort of electrochromic windows. In theses simulations electrochromic glass was emulated by altering the visual transmittance of the windows. Three levels of visible light transmittance were tested: 1%, 3%, and 15%. When deployed, one of these levels of transmittance was used for glazing, and when not deployed, average transparent state windows, with a visual transmittance of 70% was used. These results were then compared to a dynamic simulation of the average transparent state window (visual transmittance of 70%). The 15% case is intended to provide an "intermediate" state.

Visual Comfort Findings

Although electrochromic glazing does eliminate high luminance levels on interior work surfaces, potential still exists for occupants to be affected by glare where views to the exterior include the path of the solar disc. As indicated by the red and orange areas of our false color luminance maps using potential glare indices (2000-2500+ cd/m^2) in the comparison, even at 1% visible light transmittance in December, the disc of the sun and/or sky brightness could cause possible glare (Fig. 5). However, when illuminance was evaluated, lux levels for the majority of the office fall around 300, rendering the interior zones of the building very dark. This would result in the additional need of electric lighting to compensate for the low illuminance values.

To alleviate this problem, a secondary shading device would be needed at targeted locations. Preliminary findings point to the combination of EH-ECWs in conjunction with the deployment of opaque, diffuse, or other optically robust mechanisms for light redirection where glazing is optimized for delivering prescribed diffuse distribution and range of interior illuminance.

DISCUSSION

This research demonstrates through simulation that electrochromic windows have the potential to simultaneously reduce solar heat gains and glare in four different climate zones. This translates into both energy savings from reduced cooling loads and increased visual comfort for building occupants during hours of direct sun. Peak cooling loads were sub-

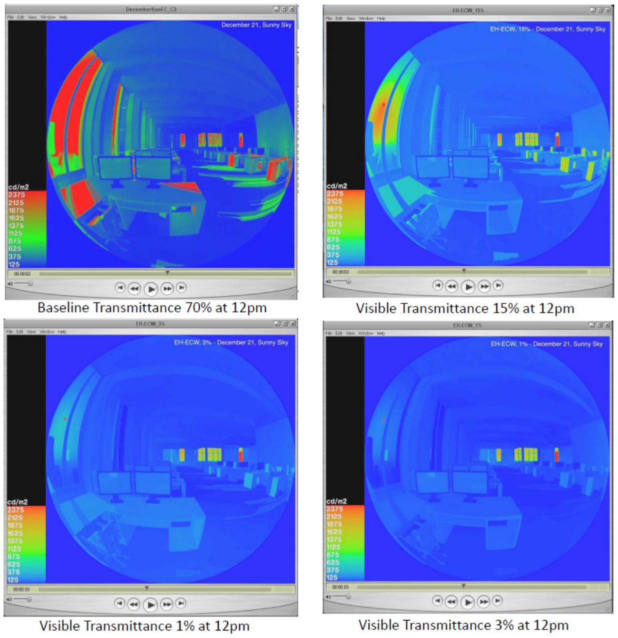

Figure 6. Stills from dynamic luminance maps indicating luminance values in cd/m2 and contrast ratios on September 21 at noon. Note solar disc in glazing at left.

stantially reduced in all climates indicating that first costs could be reduced by downsizing HVAC systems. This study looked at a control algorithm that accounts for both outdoor air temperature and solar radiation. The goal of these controls was to limit solar radiation on warm days yet allow it on cold days for passive heating. Designers must prioritize what strategies are most effective according to program and climate, and set the controls accordingly.

The performance of ECW cannot be fully understood without whole building energy analysis and hourly or sub-hourly visual comfort studies. The effect of the ECWs on cooling, lighting, and visual comfort is dynamic and at times at cross purposes. While cooling loads may decrease when the ECWs are deployed from the reduced SHGC, electric lighting loads will increase from the decreased visible transmittance. ECWs are not a silver bullet in terms of providing for visual comfort throughout the day and year. Reducing the visual transmittance as low as 1% is effective at reducing glare yet it does not eliminate views of the disk of the sun at low angles. A secondary glare control strategy, such as venetian blinds, is still required. Finally, the efficacy of ECW as a distinct energy-saving strategy may decreases as other strategies are integrated into a project.

There is opportunity for future research into the integration of architectural form and the use of ECWs. This study focused on a conventional office floor plate with a shallow perimeter surrounding a core. Buildings designed for daylight with narrow floor plates, atriums, courtyards and various toplighting configurations will provide opportunities for the novel deployment of EH-ECW technology. Especially promising for building energy performance is the integration of EH-ECW technology in conjunction with architectural elements designed in response to weather-specific phenomena. This might include diffuse skylight systems that can be sized for performance under overcast sky conditions yet maintain the capacity to reduce solar heat gain coefficients and visible light transmission values during periods of direct sunlight, or when other conditions such as audio-visual needs require space darkening. Applications to vertical glazing might include EH-ECW technology in fixed horizontal or vertical exterior shading systems. Such an application would allow for the deployment in a dark state to reduce solar gain when sunlight is present at a specific window or facade of a building and to allow for a clear state during periods of overcast or when a façade is in shadow (e.g. the west façade prior to 1pm). This type of application would allow for substantially increased levels of diffuse daylight transmission from the external reflected component of daylight illuminance, since the windows themselves would not need to be tinted to a very low visible light transmission for control of solar radiation. Organic polymer based ECWs offer aesthetic and communicative potential as well. Organic polymers can potentially be imprinted in patterns and in a range of colors. This offers unlimited potential to create facades that convey way-finding or other messages to building occupants and to the surrounding landscape. Multiple layers of organic ECW polymers could offer color changing glazing systems and dynamic patterning.

Future research activities include the teaching of multi-disciplinary studio courses that will explore the combined architectural and engineering application of polymer-based EH-ECWs

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REFERENCES

Bull, T. A., Pingree, L. S. C., Jenekhe, S. A., Ginger, D. S. and Luscombe, C. K., (2009). "The Role of Mesoscopic PCBM Crystallites in Solvent Vapor Annealed Copolymer Solar Cells" ACS Nano 3, 627.

Google SketchUp 8. Retrieved September 1, 2010, from http://sketchup.google.com/intl/en/download/index.html

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel. (2006) "World Map of the Koppen-Geiger Climate Classification Updated." Meteorologische Zeitschrift. 15.3: 259. Print.

Lee, E., Clear, R., Ward, G., & Fernandes, L. (2007). "Commissioning and Verification Procedures for the Automated Roller Shade System at The New York Times Headquarters"; Berkeley, LBNL.

Lee, ES, Selkowitz, SE, Clear, RD, ViBartolomeo, DL, Klems, JH, Fermandes, LL, Ward, GJ, Inkarojrit, V, Yazdanian, M, (2006). "Advancement of Electrochromic Windows", California Energy Commission, PEIR, Pub. No. CEC-500-2006-052.

OpenStudio Plug-in for Google SketchUp (Version 1.0.6). Retrieved November 15, 2010, from http://apps1.eere.energy.gov/buildings/energyplus/openstudio.cfm

Roberts, D. (2009) "Preliminary Assessment of the Energy-Saving Potential of Electrochromic Windows in Residential Buildings", National Renewal Energy Lab, NREL/TP-550-46916

Shen, E. and Hong, T. (2009) "Simulation-based assessment of the energy savings benefits of integrated control in office buildings", Building Simulation, 2: 239-251

Taya, M, Kim, SY and Yu Rong, (2009). CIMS report to Boeing, April, 2009.

US DOE EnergyPlus (Version 6.0). Retrieved October,18 2010, from http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm

Ward, G. (2003). The RADIANCE 3.5 Synthetic Imaging System. Retrieved May 27, 2009, from http://radsite.lbl.gov/radiance/refer/ray.html

Wu, J. J., Hseih, M. D., Liao, W. P., Wu, W. T. and Chen, J. S., (2009). "Fast-switching photovoltachromic cells with tunable transmittance", ACS Nano 3, 2297.