Toward Net Zero Energy Buildings with Energy Harvesting Electrochromic Windows (EH-ECWs)

Christopher Meek[1] and Amanda Bruot[1]

[1]University of Washington, Seattle, Washington, USA

ABSTRACT

Recent developments in material science offer the potential for energy harvesting electrochromic (EH-ECW) windows. This technology offers a glazing system that will enable switching of visible light transmission (Tvis) and solar heat gain coefficient (SHGC) to admit heat and light relative to interior comfort requirements as well as allowing for the conversion of unwanted solar radiation through windows into electric current while in a darkened state. Concurrently, efforts have been underway to develop net-zero energy buildings through a combination of climate-responsive design, efficient systems, and on-site renewable energy generation. EH-ECWs provide the potential to amplify this process by simultaneously reducing building energy demand while increasing on-site energy production.

This paper presents simulation-based research to identify zone-level and whole building energy production and consumption in a medium-sized office building based on three primary variables: (1) climate, (2) orientation, and (3) window-to-wall ratio. It proposes optimization curves for energy performance based on zone-level aggregate heating cooling and lighting coupled with the resulting energy harvesting potential. Furthermore, we include a discussion of perimeter-zone versus core zone energy performance with design implications for building massing and surface-to-volume ratios.

BACKGROUND

It is estimated that approximately 4% of all energy in the United States is consumed by windows (Apte, 2006). Much of this is through unwanted heat gains and losses through glazing. The advent of spectrally selective and multi-pane glass has improved the energy balance of windows. However, the benefits of this are limited as static glazing sytems are based on the dominant conditions present at the thermal envelope and the internal heating requirements of a zone. In most cases this provides a sub-optimal condition since beneficial gains or appropriate solar shading is lost during periods that do not reflect the most common thermal condition (e.g. lost solar heat gain in winter for windows design to reduce peak cooling load in summer via low solar heat gain coefficient).

Conventional passive solar design currently provides the potential for substantial energy conservation in many climates (Hastings, 1994), though its application at the commercial building scale is currently limited. Electrochromic glazing systems offer the possibility to dynamically respond to local climate and immediate solar conditions, as well as actual internal loads within a building zone. Emerging technology combining electrochromic window technology and dye sensitized solar cells (DSSCs) offers the added ability to capture available solar radiation for local building use. Combined, these technologies offer the opportunity to create a net-positive energy balance in a broader range of window configurations and to accelerate the development of net-zero energy buildings.

Electrochromic Windows

Electrochromic (ECW) windows are an optical glazing technology by which the transmittance (T) of a window can be controlled between a transparent state (T_{max}), to a very darkend state (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% when combined with photo-responsive lighting controls (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 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 attributed to photocell control of electric lighting in response to available daylight, which in some cases may be reduced due to lower visible light transmittances when ECW glazing is in the darkened state. However increased visual comfort (reduced glare) 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.

Energy-Harvesting Electro-chromic Windows (EH-ECWs)

Energy harvesting electrochromic (EH-ECW) windows offers a glazing system that will enable switching of visible lighting transmission (Tvis) and solar heat gain coefficient (SHGC) to admit heat and light relative to interior comfort requirements as well as allowing for the conversion of incident solar radiation into electric current while in a darkened state. This is particularly valuable in buildings where unwanted solar heat gains can be converted to electricity rather than rejected to the surrounding site. Organic electrochromic windows (ECWs) hold the possibility of energy harvesting (EH), not only for self-power of window controls and switching but also for providing on-site power generation for other building functions. 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 electrochromic windows and DSSCs form the energy harvesting electrochromic (EH-ECW) system currently under development at the University of Washington Center for Intelligent Materials. 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). These EH-ECWs consume power only during switching, due to the color memory effect, thus improving energy efficiency as compared with existing commercially available technology. Currently, the switchable dye used in the prototype EH-ECW exhibits a power conversion efficiency (PCE) of 2.5% (Taya et al, 2009), however target PCE is in the 10% range. 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 improved building energy efficiency suggest the opportunity for greatly improved life cycle performance.

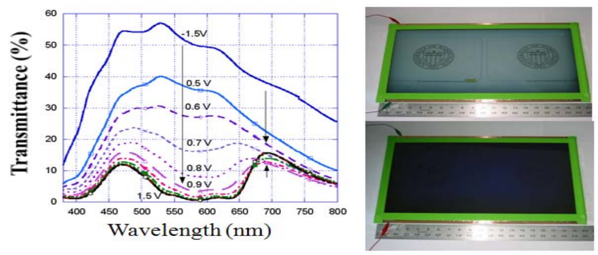

Fig. 1 The UW designed ECW of 12 inch × 20 inch, (left) transmission change and (right) photos of the ECW at transparent (above) and colored stage (below) (Xu et al., 2004; Kim et al., 2009).

SIMULATION OBJECTIVES

Energy-harvesting electrochromic windows hold the potential to contribute to net-zero energy buildings by reducing heating and cooling requirements based on specific weather conditions and zone-level energy demand, providing improved visual comfort and realized electric lighting power savings from daylight, and enabling on-site power generation. The research described in this paper seeks to identify energy conservation and production potential of EH-ECWs using a code-compliant mid-size office building in a range of North American climates. By investigating zone-level energy performance and power generation potential of EH-ECWs under energy-optimized switching control we seek to identify architectural configurations that yield peak energy performance potential. The architectural variables studied include window-to-wall ratios and zone orientation. Furthermore, the frequency and durations of ECW switching is tabulated to identify operational expectations and energy harvesting potential under a range of climates and window orientations. The data and findings from these simulations provide design guidance as to the most suitable climates and architectural configurations for the deployment of EH-ECWs in buildings.

The energy performance impacts of EH-ECWs result from three primary actions: (1) Dynamic visible light transmission (Tvis) of glazing; (2) Dynamic solar heat gain coefficients (SHGC); and (3) Energy Harvesting (EH) of unwanted solar gains. These parameters are discussed briefly below.

Visible Light Control

In buildings the size, location, orientation, and visible light transmission (Tvis) of windows affect the quality and quantity of daylight entering an interior volume. Electrochromic windows enable dynamic switching from a high visible light transmission T(max), through intermediate states, to a T(min). By modulating visible light transmission, electrochromic glazing system can manage exterior views, brightness and interior illuminance levels. Since most electrochromic systems provide specular trans-mission, optical light-redirecting devices such as blinds or shades may be required where changes in light distribution as well as intensity are desired.

Solar Heat Gain Control

Electrochromic windows can reduce both peak and annual energy demand by dynamically modulating the solar heat gain coefficient (SHGC) of the window based on localized building heating and cooling requirements. Solar gain through windows has a substantial impact on the energy performance of buildings. When a zone is in cooling, the reduction of solar radiation through glazing can decrease both peak and annual energy use. Changes in peak energy demand can result in reduced HVAC equipment size, improving a building's energy performance and reducing first costs of mechanical equipment. Conversely, the controlled admission of passive solar gains through windows can reduce heating requirements, especially in climates where clear skies are common during the heating season.

Energy Harvesting

Dye sensitized solar cells (DSSC) offer the potential for an energy-harvesting substrate to be applied to the electrochromic glazing. This substrate would allow the window to act as a photovoltaic array, converting direct and diffuse solar radiation to electric current during times when the electrochromic glazing is in its darkened state (intercepting unwanted solar heat). The on-site production of electricity via energy-harvesting electrochromic windows is therefore dependent on climate, location, solar orientation, overshadowing from adjacent objects, as well as the frequency and duration of switching.

METHODOLOGY

To characterize the opportunities for energy savings and on-site power generation and to investigate optimum deployment of EH-ECWs in buildings we have completed a matrix of building energy simulation cases. The platform for simulation is the United States Department of Energy mid-size office building (DOE, 2011) reference model. It is a 53,628 ft^2, three-story office building with a rectangular footprint with the longer sides facing north and south. The building model consists of 15 zones, a core and 4 perimeter zones on each level, plus three ceiling plenum zones. Heating, cooling and ventilation are delivered to each zone by a packed single-zone VAV unit. Zone-level data is reported via an individual fuel meter to disaggregate zone level energy use intensity. The exterior envelope is constructed of steel frame walls, a built up flat roof, slab-on-grade floor, and has a 33% window-to-wall ratio, with equal distribution of windows by orientation. It should be noted that thermal properties of the envelope varied by climate based on standard construction practice and code within the respective region. Simulations were conducted using DOE 2.2/eQUEST (US DOE, 2013).This model serves as our baseline.

Our simulation cases investigate the impact of three primary variables. These modifications to the baseline model include: (1) the addition of photo-responsive "daylight" controls; (2) the addition of ECWs; and (3) the addition of EH-ECWs (the energy harvesting component). Data for each of these cases is reported discreetly. Simulation output is collected at three scales. The first is whole building site energy use intensity in seven North American cities (Atlanta, Boston, Los Angeles, Minneapolis, New York, Phoenix, and Seattle) representing the primary ASHRAE Climate Zones (Fig 2); The second is zone-level energy use intensity by zone orientation for each city; and (3) relative energy performance of window-to-wall ratios from 10% to 100% in increments of 10%.

EH-ECW Operational Parameters and Related Energy Efficiency Measures

Whole building and end-use energy are calculated to track energy performance of specific components of the models under the operational parameters described below.

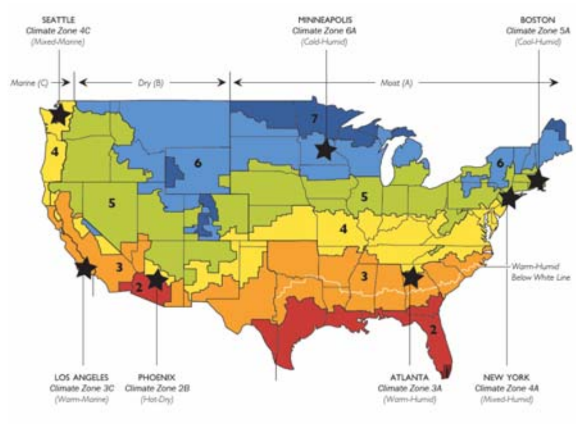

Fig. 2 Simulation Case Sites

1. Baseline Model

The baseline model represents the unmodified regionally specific code-compliant mid-size office model with energy use calculated using TMY files associated with the specific site locations. TMY files were selected based on greatest proximity to the downtown core of the selected site. The baseline building represents 33% window to wall ratio and is divided into four 15'-0" (5m) feet deep perimeter zones and one core zone per floor. The building's HVAC system is one packaged single zone system per zone, with direct expansion cooling and electric resistance heating. Mechanical systems power off during the night, weekends, and holidays.

2. Baseline with photo-controls

Photo-responsive lighting controls were applied to lighting in all perimeter zones. This measure was established to dis-aggregate the impact of photo-responsive lighting power reductions from daylight. Lighting power densities are set at 1.15W/ft2. For all scenarios but the baseline, photo-controls are specified to maintain 30 foot-candle (300 lux) set point at 15'-0" (5m) into the interior space. The controls system is modeled on a 0-10v dimming system with a 100-10% dimming range and a maximum power savings of 80% due to ballast losses.

3. ECW model

The ECW model includes photo-responsive lighting controls and adds dynamically responsive visible light transmission (Tvis) and solar heat gain coefficient (SHGC) properties to all windows. This Tvis modulation occurs at the individual window level. The Tvis switches from a transparent state of 65% (max) to a darkened state of 3% (min). The SHGC switches from 0.65 (max) and 0.10 (min). The relatively high SHCG in the transparent state was chosen to enable the realization of beneficial passive solar gains possible during periods of heating demand. Consequently, ECW switching is only enabled during periods of zonal cooling.

Cooling seasons for the baseline model are as follows:

- Seattle: April 14 - October 21
- Phoenix: January 4 - December 20
- Minneapolis: April 15 - October 9
- Atlanta: February 16 - November 26
- New York: May 1 - October 29
- Los Angeles: Always On
- Boston: April 18 - October 25

During these periods two triggers are established for the deployment of ECWs from the transparent to the darkened state. These are: (1) affected zone in cooling mode, and (2) 50W/m of incident solar radiation on windows. All other times windows revert to maximum transparency to provide maximum lighting power savings from daylight-responsive photo-controls. It should be noted that ECW control is optimized on building and zone energy and that no trigger is provided based on likely visual discomfort during times when the deployment of ECWs would increase energy consumption (e.g. times when passive solar gains provide heating benefits, yet direct beam sunlight would simultaneously cause glare).

4. EH-ECW model

The EH-ECW model adds the energy harvesting component to the ECW model. In this model the windows act as a photovoltaic array converting solar radiation to site-electricity at a 10% power conversion efficiency (PCE) rate. Since maximum PCEs are achieved only when the EH-ECWs are in the darkened state, power generation is calculated only during these times. Direct and diffuse solar radiation incident on the window surface is converted to site-energy and deducted from total building energy consumption on an annual basis. This reflects a "net metering" approach where the electrical grid is assumed as an energy storage mechanism for harvested energy.

FINDINGS

In all cases, the ECWs reduce net energy use on an annual basis. Average savings percentage of all measures across all climates zones are 13% of total site energy (fig. 3). The electrochromic windows are

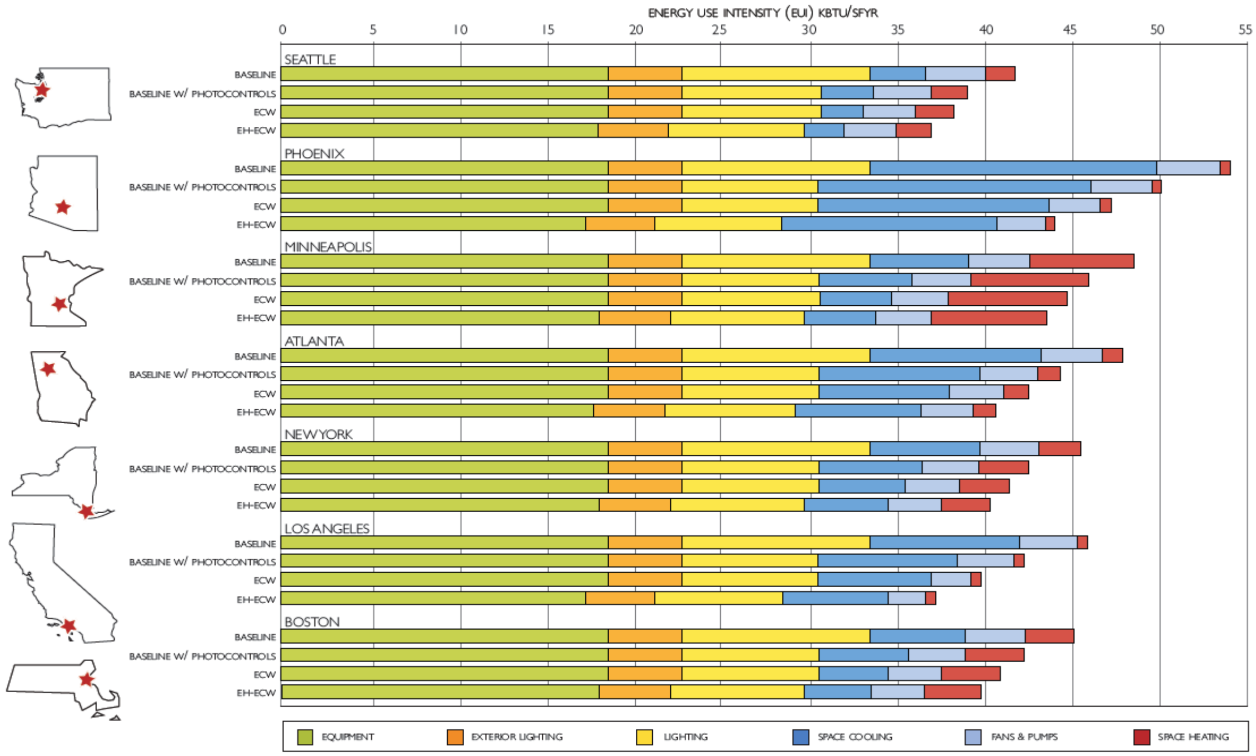

Fig. 3 Whole building energy results table by site location.

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. 3) as well as peak heating and cooling days.

The single largest end-use energy savings reported is from photo-responsive lighting controls- which it should be noted could be realized independent of the ECW control. After lighting, cooling represents the greatest savings potential with magnitudes being greatest in climates where the cooling season is of the longest duration (Los Angeles and Phoenix followed by Atlanta). 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. Heating energy is reduced from the increased solar gain in winter (primarily Minneapolis, Boston, and New York). In all cities very modest increases in heating were required to account for reduced internal loads from photo-controlled electric lighting during the heating season.

In multi-zone HVAC systems, where simultaneous heating and cooling occur, it is likely that savings would be greater due to reduced re-heat requirements. This is due to lower peak cooling loads resulting from increased solar control and would therefore result in more uniform zone temperatures and therefore lower HVAC system imposed loads.

Since EH-ECW switching enables weather responsive control of solar energy entering the interior space through windows (via variable SHGC), EH-ECW switching should be disabled when zones will benefit from passive solar gains. However, since energy is only harvested when the windows are switched on, this greatly reduces the energy harvesting potential of the window in climates that have an extended heating season with predominately clear skies. Additionally, ECWs conserve very little energy on the north façade, even when the EH-ECWs are switched on frequently, making little case for the application of EH-ECWs on the north facade in any climate. Figure. 4 Indicates the annual heating and cooling impact of the EH-ECW in Seattle, WA by zone orientation. The EH-ECWs reduce the cooling load in Seattle from the baseline results, as indicated by the light blue line. However, in the case of heating, the baseline (red) out performs the EH-ECW (dark red) by a small margin. The areas of gray specify periods of switching. Since energy is only harvested when the windows are in a darkened state,

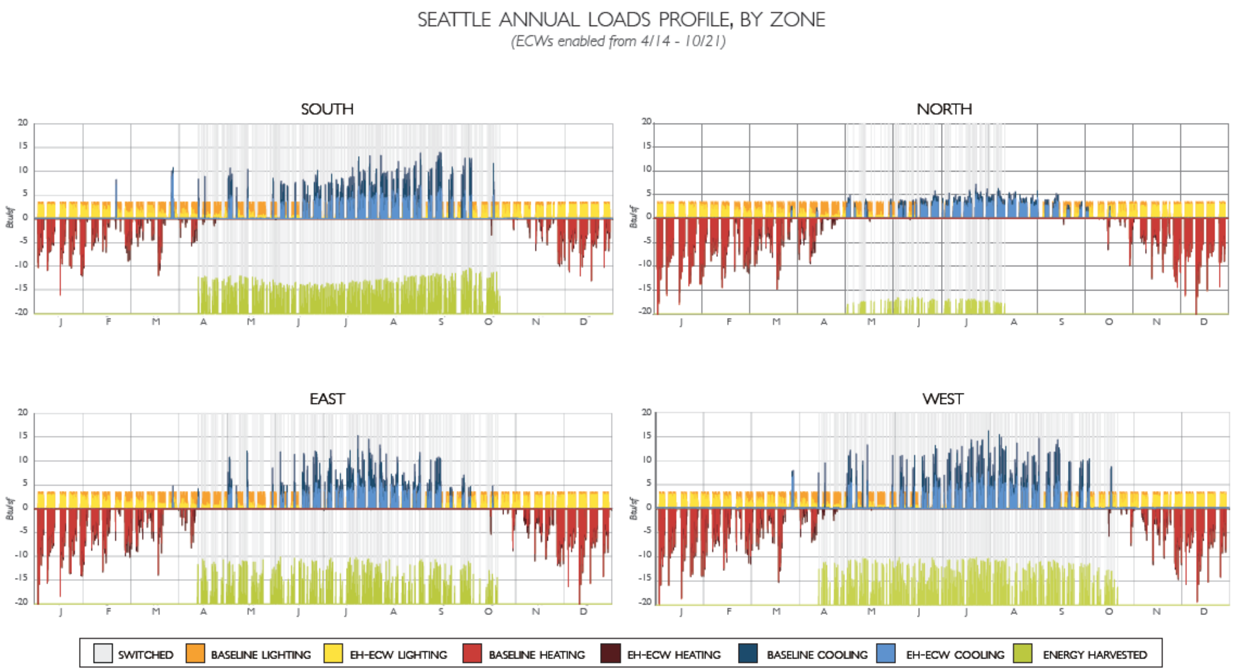

Fig. 4 Zone-level annual heating, cooling, and lighting load profile of EH-ECWs vs. baseline energy showing zone-specific switching frequency and energy harvested (Seattle, WA).

the gray lines directly correspond to the frequency of harvested energy (green).

The pattern and frequency of zone-level switching is illustrated by the vertical bars relative to the building heating and cooling load profile. In this case, substantial cooling load reductions can be seen during ECW switching. The magnitude of energy harvested relative to heating and cooling loads is indicated in green at the base of the diagram coincident with the periods of switching. The slight increase in heating between the baseline and EH-ECW heating results from reduced internal gains from photo-responsive lighting.

Window Area Optimization

Parametric analysis of window to wall area ratios (0% to 100%) were conducted in a heating dominated climate (Boston, MA), a cooling dominated climate (Phoenix, AZ), and a temperate climate (Seattle, WA) to identify an optimization curve relative to cumulative heating, cooling, lighting, and energy harvesting at the whole building level and at the zone level, by orientation. This data identifies optimum window areas relative to maximizing a net-positive energy balance with EH-ECWs.

Figure 5 depicts an example parametric analysis of window-to-wall ratios (0% to 100%) in a heating dominated climate (Boston, MA). In the baseline case whole building energy consumption increases as the window to wall ratio is increased. In the photo-controls case the EUI drop initially then begins to climb at window areas exceeding 40% net area. In the ECW case, as the window area is increased, the building energy consumption is lower than the 0% case until glazing reaches 60% the of wall area. For the EH-ECWs, any percent up to 100% has lower building energy consumption than that of 0%. In fact any amount of EH-ECW glazing reduces energy consumption over a building with no glazing at all or a building with traditional glazing, including

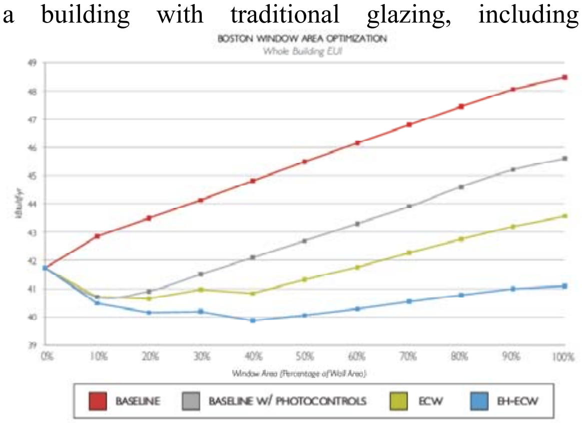

Fig. 5 Whole building EUI data for baseline building, Photo-controls, ECWs and EH-ECWs in a south facing perimeter zone in Boston, MA.

comparing 100% EH-ECW glazing against 0% glazing. In this case optimum whole building energy is found at a 40% window to wall ratio.

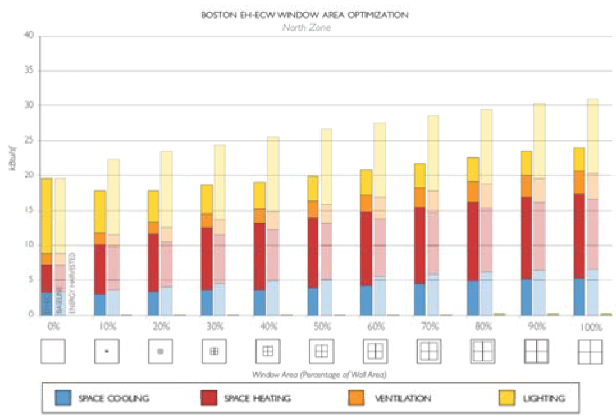

Fig. 6 Zone-level EUI data for EH-ECWs in a north-facing perimeter zone in Boston, MA.

Perimeter vs. Core Zone Energy

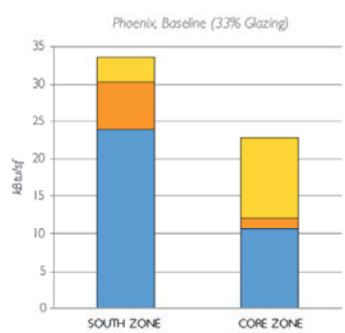

Fig. 7 Baseline south perimeter zone EUI with 33% glazing area versus data for adjacent core zone.

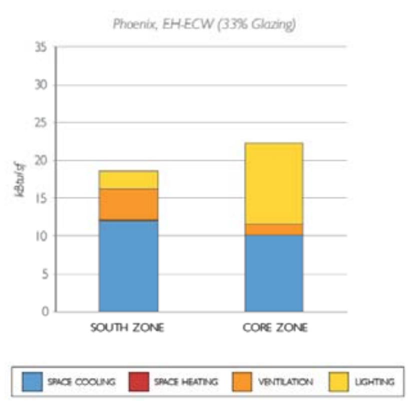

Fig. 8 Baseline south perimeter zone EUI with 33% glazing area versus data for adjacent core zone. Phoenix, AZ.

These optimum window areas differ when looking at orientation-specific zone levels. For example in a north-facing zone, optimum energy is found at 20% window-to-wall ratio and, as expected, the inclusion of the energy harvesting component does not increase the ideal window to wall ratio. Though cooling is slightly reduced from the action of the ECWs and heating is increased, again due to lowered internal lighting loads.

Typically in both heating and cooling dominated climates, perimeter zones consume more energy than interior zones due to heat transfer through the building envelope. In order to minimize losses and gains through the fabric of a building, a compact shape that minimizes perimeter zones is desirable. However, this excludes a large portion of the building from perimeter daylighting, ventilation and views to the exterior.

Energy analysis of perimeter zones with various glazing systems orientated north, south, east and west was conducted and compared to the energy performance of an interior zone in a mid-sized commercial office. The data suggests that the inclusion of EH-ECWs can enable a perimeter zone to use less energy than an interior zone in typical commercial construction.

DISCUSSION

Simulation indicates sizable energy conservation potential and on-site power generation with EH-ECWs in a conventional mid-sized office building model, especially in clear sky dominated cooling climates. Sufficient and appropriately timed solar control and a mechanism for the conversion of unwanted solar gains to on-site electricity enable many perimeter zone configurations to require less energy than core zones. The implication of this on building massing, window area, and floor plate geometry is substantial.

Many building designers target low surface-to-volume ratios to enclose maximum area with a minimum exposure to exterior envelope. EH-ECWs offer the opportunity to upend the negative energy balance associated with perimeter zones through improved control of heat gains and losses in more climates and under more orientations and to more fully realize climate as a site resource. The development of architectural conditions that prioritize perimeter zones will expand the opportunity for deeper integration of passive design technology. Effective EH-ECW technology will provide heating and cooling load reductions that enable improved geometries and the greater use of passive/hybrid design technologies such as natural ventilation, night ventilation of thermal mass and others. Narrower building sections provide more occupants with light and views, as well as provide more opportunities for further lighting power savings via broader inclusion of photo-responsive lighting controls.

Simulation results indicate that the decoupling of switching in the visible and infrared spectrum (and the energy harvesting component) has the potential for deeper savings and increased thermal performance, especially in mild climates where glare control, daylighting potential, and available solar radiation are out of alignment with occupied periods and zone heating and cooling requirements.

In buildings where the external envelope becomes a primary source of comfort control and energy generation, qualitative benefits will accrue to the occupants. These will include improved proximity to windows, views, daylight and increased thermal comfort. Current window technology can inhibit designers from fully realizing available site solar resources in buildings, however dynamically responsive energy harvesting glazing can greatly expand the role of windows in meeting net-zero energy building design.

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