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Regional performance targets for transparent near-infrared switching electrochromic window glazings

Nicholas DeForest [a,*], Arman Shehabi [a], Guillermo Garcia [c], Jeffery Greenblatt [a], Eric Masanet [b], Eleanor S. Lee [a], Stephen Selkowitz [a], Delia J. Milliron [c]

[a] Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Building 90R4000, Berkeley, CA 94720, USA
[b] McCormick School of Engineering, Northwestern University, 2145 Sheridan Road, Room L494, Evanston, IL 60208, USA
[c] The Molecular Foundry, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

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A B S T R A C T

With building heating and cooling accounting for nearly 14% of the national energy consumption, emerging technologies that improve building envelope performance have significant potential to reduce building energy consumption. Actual savings from these technologies will depend heavily upon their performance in diverse climate and operational conditions. In many cases, early-stage research can benefit from detailed investigation in order to develop performance thresholds and identify target markets. One example, a dynamic, highly transparent, near-infrared switching electrochromic (NEC) window glazing, is the focus of this investigation. Like conventional electrochromics, the NEC glazing can dynamically tune its optical properties with a small applied voltage. Consequently, the glazing can block or transmit solar heat to reduce cooling or heating loads, respectively. Unlike conventional electrochromics, NEC glazings remain transparent to visible light, causing no adverse effect to daylighting or building aesthetics. This study utilizes the software COMFEN to simulate a broad range of NEC performance levels, for commercial and residential buildings in 16 climate-representative reference cities. These simulations are the basis for identifying performance levels necessary to compete with existing static technologies. These results indicate that energy savings are strongly influenced by blocking-state performance. Additionally, residential applications have lower performance requirements due to their characteristic internal heat gains. Finally, the most dynamic NEC performance level is simulated in competition with high performing static alternatives. Here heating and cooling energy savings range from 5 to 11 kWh/m^2 yr for commercial and 8–15 kWh/m^2 yr for residential, in many regions on the order of 10%.

1. Introduction

Energy consumption for space heating and cooling in buildings currently accounts for nearly 14.4 quads, approximately 35% of national building energy demand, or over 14% of total national demand [1]. Given the influence of windows on building envelope thermal performance, energy efficient window technologies have significant potential to reduce heating, ventilation and air conditioning (HVAC) energy consumption [2]. Emerging technologies, like dynamic, electrically actuated glazings provide even greater potential for energy savings by adjusting in real time to changes in internal and external conditions. Among these dynamic window technologies, electrochromic glazings are especially promising [3–8]. Electrochromic glazings, having been developed over the past 20 years, are capable of adjusting their optical properties, most importantly transmittance, by varying an applied voltage [9]. In so doing, this technology can be used to either block or transmit solar energy into the building interior. Typical electrochromic glazings exhibit broadband switching, where the transmission of near infrared (NIR) and visible light are reduced in unison [10]. In both commercial and residential applications, occupants often want high visible light transmission but would benefit from glazings that transmit NIR in the winter season to supplement heating demand while blocking NIR during the summer season to minimize cooling load [8,11]. The loss of visible light transmission and noticeable tint in typical electrochromic glazings stands as a possible obstacle to widespread adoption [4]. Recently, research efforts have demonstrated a new transparent

* Corresponding author. Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS: 90-1121, Bldg 90 Room 1139, Berkeley, CA 94720, USA. Tel.: +1 510 486 6188; fax: +1 510 486 4089.
E-mail address: ndeforest@lbl.gov (N. DeForest).

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electrochromic film that modulates NIR solar heat gain without affecting visible light transmission [12]. Because this approach can reduce solar gain without reducing daylighting, this technology may be better positioned against competing window glazings. This technology is based on a plasmonic electrochromic effect that dynamically modulates the localized surface plasmon of doped semiconducting nanocrystals. To operate, an applied voltage is used to alter the optical properties of the glazing. In a dynamic window construction, voltage control strategies are tied to HVAC setpoints to ensure effective operation. Currently, the technology is in a prototype phase of development where 40% of solar near infrared modulation has been achieved [13]. Further improvements are currently being investigated to enhance the glazing performance and establish market deployment in the next 3–5 years. Ultimately, the potential for success will depend on how effectively this technology performs in reducing building HVAC loads through blocking or transmitting NIR heat, and reducing lighting energy by transmitting visible light [8].

As with any building envelope technology, the actual energy benefits from highly transparent NIR-switching electrochromic (NEC) glazings will vary with local solar and climate conditions, as well as with the specific building design and operational characteristics. A growing number of tools and software allow architects and engineers to assess multiple configurations of technologies and designs to improve thermal performance under a wide variety of these climate and building conditions [14–16]. Such tools can also be applied more broadly to help researchers determine performance targets for nascent window technologies. Because this NEC glazing is still in the early stages of development, its optical properties and the extent to which it can change them is still somewhat unknown. Only by exceeding certain performance thresholds will NEC glazings become competitive with mature static technologies. These performance thresholds have a strong dependence on climate, and thus will vary regionally.

This paper presents regionally dependent performance targets, which have been developed for NEC glazings in commercial and residential applications through building energy simulation. Also presented are estimates of HVAC energy intensity savings from implementing a highly dynamic form of this technology, which were determined across a range of climate zones. Results are used to identify regions in the U.S. where NEC glazings perform favorably against static glazings. These results can provide researchers insight into how improved performance can expand the number of competitive regions, helping to accelerate and establish market success.

2. Methods

This simulation study has been conducted with the modeling tool COMFEN 4, an EnergyPlus interface for comprehensive performance analysis of commercial building facades [15]. While COMFEN employs an hourly whole-building thermal and HVAC simulation model (EnergyPlus), it is designed to model individual spaces in the building, and is used in this study to establish a comparative ranking of window technologies under the specific reference conditions of a south-facing facade. Given variation in climate and insolation throughout the U.S., simulations are conducted for a number of regions. Additionally, technologies are compared for both commercial and residential applications by imposing sector-specific building characteristics, such as occupancy and load schedules.

2.1. Developing representative regions

A spatial disaggregation of the U.S. has been selected based on climate zones defined by International Energy Conservation Code [17]. Typically applied to thermal standards for windows and insulation, the IECC climate zone map consists of 8 regions. Each of these regions may also contain up to 3 subregion types: dry, humid and marine. In total, this study considers 16 subregions that represent the range of climate conditions across the entire U.S. From reference cases developed by U.S. Department of Energy's (DOE) Commercial Building Initiative [18], representative cities have been selected for most subregions. The 7B subregion has not been modeled, as it represents only a small number of counties and a population below 180,000 or approximately 0.06% of the national total. Given the high population of the Los Angeles metropolitan area, subregion 3B has been divided into coastal and inland subsets. Regions and cities are illustrated in Fig. 1, with details located in Table 1, including heating and cooling degree days (HDD, CDD) for each region.

2.2. Characterizing building stock

While COMFEN considers only a single façade and building interior, important building geometry metrics can be incorporated into the simulation in order to characterize the building stock. These metrics include window to wall ratio (WWR), which is the fraction of the external wall area that is composed of windows, and shell to floorspace ratio (SFR), which is the ratio of external shell area (both window and wall and excluding rooftop area) to internal floorspace. Stock average values for these ratios have been derived from the 2003 Commercial Building Energy Consumption Survey (CBECS) data [19] for all U.S. office buildings, which are assumed to be most applicable for electrochromic deployment among the CBECS building types. Based on this evaluation of CBECS data, WWR is defined as 0.35 while SFR is defined as 0.9. The Residential Energy Consumption Survey does not include similarly detailed information on residential building geometry, so the commercial metrics are also used in the residential case and is intended to represent a mid-rise residential building. As a consequence of this assumption, residential results are only relevant to buildings with similar geometries, but provide insight in how differences between residential and commercial occupancy schedules impact performances requirements and savings potential. The WWR requirement is satisfied with two windows, 1.5 m in height by 2.17 m in length. Each window is constructed of a glazing placed on the inner surface of the outer pane, air fill, and an inner pane of clear glass. Each pane is approximately 6 mm in thickness. Windows are located on a south-facing façade and are unobstructed.

HVAC systems in both cases are packaged single zone. Schedules of occupancy and non-HVAC loads, both being major sources of internal heat gains (IHGs), will also influence the thermal requirements in the space. Fig. 2, which shows typical summer weekday IHG profiles, illustrates the fundamental difference between commercial and residential simulations. These IHG profiles play a significant role in differentiating commercial and residential results. The commercial IHG peak typically occurs between 9am and 12pm, while the residential IHG peak occurs in the evening between 6pm and 8pm. In both cases, the portion of IHG from occupants and equipment peak near a value of 12 W/m^2. Lighting contributes the remainder of the IHG value, depending on illuminance demand, source efficiency, controls and available daylight. In the residential case, high demand for lighting in the evening and little available daylight increase the total IHG peak to approximately 24 W/m^2. Peak lighting power density is assumed to be 10.76 W/m^2. Continuous lighting controls are assumed, meaning the simulation results show the upper bound on utilization of available daylight. Additionally, in real-world applications, operable internal or external shading would be necessary to control for glare and ensure occupant comfort because the glazings have a high visible transmittance in both blocking and transmitting states. However, glare control is not considered in this