Title	United States energy and CO2 savings potential from deployment of near-infrared electrochromic window glazings
Authors(s)	DeForest, Nicholas, Shehabi, Arman, O'Donnell, James, et al.
Publication date	2015-07
Publication information	DeForest, Nicholas, Arman Shehabi, James O'Donnell, and et al. "United States Energy and CO2 Savings Potential from Deployment of near-Infrared Electrochromic Window Glazings" 89 (July, 2015).
Publisher	Elsevier BV
Item record/more information	http://hdl.handle.net/10197/11022
Publisher's statement	This is the author's version of a work that was accepted for publication in Building and Environment. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Building and Environment (89, (2015)) https://doi.org/10.1016/j.buildenv.2015.02.021
Publisher's version (DOI)	10.1016/j.buildenv.2015.02.021

Manuscript for *Building and Environment*

United States Energy and CO_2 Savings Potential from Deployment of Near-infrared Electrochromic Window Glazings

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Keywords:
Dynamic windows; electrochromic glazings; NIR-switching; national energy reduction; solar heat gain

Highlights

- We model a transparent electrochromic window glazing in six building types.
- Simulations are conducted for 16 cities to determine energy and carbon savings.
- Transparent electrochromic glazings outperform alternatives in Northern climates.
- The best regions see 3%-9% savings for heating, cooling, and lighting consumption.
- Full U.S. deployment saves 8 TWh primary energy and 1.56 billion kg CO_2 per year.

Abstract

This paper presents a simulation study of the energy and CO_2 benefits of a transparent, near-infrared switching electrochromic (NEC) glazing for building applications. NEC glazings are an emerging dynamic window technology that can modulate the transmission of NIR heat without affecting transmission of visible light. In this study, a hypothetical NEC glazing is simulated on clear and tinted glass in six building type models in 16 U.S. climate regions using Energy Plus 7.1. The total annual energy consumption for lighting, heating, cooling, and ventilation for the NEC glazings are compared with high performance static windows and conventional tungsten-oxide EC glazings. Using regional CO_2 intensities and building stock totals, the results from individual building model simulations are scaled up to national totals. The U.S. national savings from NEC deployment is found to be 167 TWh/yr (600 PJ/yr) compared to the existing building stock, but only 8 TWh/yr (29 PJ/yr) or 1.56 million tonnes of CO_2 per year when compared to high performance static glazings with lighting controls installed.

NEC performance varied significantly by building type and location. This analysis reveals that 50% of the total energy savings can be realized by deploying NEC glazings in only 18% of the total window stock, and 75% of the savings in only 39% of the stock. The best performing locations include medium offices and midrise residential buildings in northern climates, where energy savings per unit window area range from 50 to 200 kWh/m^2-yr.

Introduction

Dynamic window glazings are emerging as a promising class of technologies to reduce energy use for heating and cooling in buildings, which currently accounts for 14.4 quads (15.2 EJ) in the U.S. annually, or approximately 14% of the total U.S. energy demand [1]. Prominent among these technologies are electrochromic glazings, whose transmittance of visible and infrared solar energy can be modulated under an applied voltage [2]. By varying its transmittance state, electrochromic glazings can selectively block or transmit solar heat, thus reducing building heating, ventilation, air-conditioning (HVAC) loads. Electrochromic state control strategies are typically linked to HVAC setpoints and to photosensors for lighting control to ensure effective operation. Earlier studies of electrochromic glazings have found that the technology could save 10%-20% primary energy consumption in perimeter building zones in commercial buildings across much of the U.S. relative to stock-typical windows [3]. A recent simulation study found cooling energy savings as high as 37 kWh/m^2 of glass for east and west facing facades in a Mediterranean climate compared with single and double pane windows [4]. Another simulation study found dynamic glazings applied to a split-pane window produced lighting savings of 37%-48% compared with a static window with occupant controlled blinds [5]. The energy benefits of electrochromic glazings have been simulated in a number of additional investigations [6-12].

Conventional electrochromic glazings exhibit broadband switching, meaning near-infrared (NIR) and visible transmittance are reduced in unison [13], which has the potential for glare control and solar control but may also have adverse effects on daylighting and building aesthetics when the daylight is welcome but solar gain should be minimized. Recent research efforts have led to the development of a transparent electrochromic film capable of modulating NIR transmission without affecting visible light transmission [14]. This feature may give the transparent NIR-switching electrochromic (NEC) glazing a performance advantage over conventional electrochromic glazings. The NEC glazing is based on a plasmonic electrochromic effect that dynamically modulates the localized surface plasmon of doped semiconducting nanocrystals [15]. Because of the novel coating design, NEC glazings can also be manufactured using lower cost methods, including spray or blade coating of a nanocrystal based ink, followed by an annealing process to fix the film to the substrate,as opposed to conventional dynamic coatings, which often require more energy-intensive sputter coating to manufacture . This potential manufacturing cost savings could increase the market competitiveness of NEC glazings.

Previous simulations for a broad range of NEC performance in south-facing perimeter zones showed that high performing NEC glazings could produce energy savings ranging from 6-11% for commercial buildings and 8-15% for residential buildings in middle and northern U.S. latitudes, relative to high performing static glazings [16]. However, that analysis found total energy savings to be highly sensitive to blocking state performance and climate because the high visible light transmission of transparent NEC increases the solar gain and thus the cooling load required in hot, cooling dominated climates. In most other U.S. climates, where solar heat gains can be beneficial, a highly effective NEC glazing outperformed static glazing alternatives, due to the additional heating season energy savings garnered when the NEC glazing was in the transmitting state.

This paper expands on previous NEC energy analyses by utilizing whole building simulation modeling to quantify the potential energy and carbon benefits from the broad deployment of a highly dynamic NEC glazing technology throughout the applicable U.S. building stock. Hypothetical, high performance NEC glazings are simulated in building models representative of five commercial building types and a single residential building type, across 16 U.S. climate zones. Results are used to identify regions and building types where NEC glazings achieve the highest savings potentials, which can help inform decision-making to effectively develop and implement this emerging energy efficient technology. NEC glazing energy performance is presented in comparison with high performance static glazings as well as commercially available conventional electrochromic glazings. Simulations results are also scaled with region and building specific floorspace stock totals to estimate the potential national impact of NEC deployment on electricity and natural gas consumption and corresponding CO_2 emissions from reduced building energy demand.

Methodology

NEC Glazing Properties

Projected performance properties for the infrared blocking and transmitting states of a high performance NEC glazing are estimated using two existing static glazings as references to bound performance. It is important to note that the NEC technology in development does not currently, and may never achieve the level of performance represented by these reference technologies. They have been selected to represent high performance archetypes for visibly transparent, NIR blocking and transmitting states. As a consequence of this assumption, the results provided in this investigation illustrate the technical potential of a hypothetical, high performance NEC glazing, as opposed to the glazing as it currently exists.

The transmitting NEC state is represented by PPG Sungate 400, a high solar gain low-e glazing [17], while the blocking state is represented by PPG Solarban 72, a high visible light transmitting, low NIR gain glazing [18]. Spectral transmittances of these two glazings are plotted in Figure 1a, illustrating the extent of NIR modulation between NEC states. Spectral data describing these glazing technologies have been collected from the International Glazing Database (IGDB) [19]. The spectral properties of the modeled states of the conventional EC glazings are shown in Figure 1c. The properties of this glazing have also been collected from the glazing database [19]. The individual states of the NEC glazing are also modeled as static glazings, referenced to as static transmitting and static blocking.

Previous simulation work emphasized the importance of blocking solar radiation when the building is in cooling modes [16]. In some locations the relatively high total solar gain of the NEC's blocking state, due to high visible transmittance, limited NEC glazing applicability even when accounting for the benefits of the transmitting state. In these locations a lower solar heat gain coefficient (SHGC) in both states could produce additional reductions to overall building energy consumption. To address this concern, the NEC glazing has also been modeled on a tinted surface with a slight blue appearance [20]. The spectral transmittance of the two reference states on tinted glass is also given in Figure 1b. Note that on tinted glass the NIR modulation between states is reduced relative to the same glazing on clear glass. For building simulations, each glazing is modeled in a two-pane construction. Static blocking glazings are placed on surface 2 (the inner surface of the outer pane). Static transmitting glazings are placed on either surface 2 or surface 3 (outer surface of the inner pane), to ensure the model can identify which configuration provides the optimal performance baseline. Figure 2 gives additional detail on surface location and transmitting behaviors of each state. For all clear glass cases, irrespective of glazing type and placement, both panes are clear glass. For tinted cases, only the outer pane of glass is tinted. A total of six static window configurations are simulated. For the dynamic cases, the NEC glazing is applied only to surface 2 and switches between blocking and transmitting states, resulting in only two NEC configurations: clear and tinted. Conventional EC glazings are also modeled as binary states. In this investigation, conventional EC glazings refer to solid-state tungsten-oxide based glazings applied to a single glass substrate, such as those manufactured by View Glass [21]. The properties of View's EC glazings, as described in the IGDB are used to define the conventional EC glazings here. Five combinations of conventional EC pairs have been modeled using the states described in Figure 1c (60%-40%, 60%-20%, 60%-4%, 40%-20%, and 40%-4%).

Thermal and optical properties of each glazing configuration have been calculated with the software Window 6.3, which uses algorithms consistent with ASHRAE SPC 142 and ISO 15099 standards for determining thermal performance of windows [22]. These properties, including U-factors and SHGC, of each of these glazing configurations in a two-pane construction are given in Table 1. The front and back emissivities of the reference static blocking and transmitting glazings are very similar. To isolate the effect of the dynamic switching of SHGC, an average front (0.1) and back (0.84) emissivity are used for both these states. This allows the modeled dynamic glazing to maintain a constant U-factor between electrochromic states. Note that states with very low SHGC have correspondingly low visible transmission (Tvis). Differences in emissivity result in a disparity in U-factors between high performance static and NEC glazings (1.63 W/m^2K) and conventional EC glazings (1.91 W/m^2K). This disparity will have some impact on overall thermal performance of these window types.

Climate Zones

A spatial disaggregation of the U.S has been selected based on climate zones defined by the International Energy Conservation Code [23]. This climate zone map, Figure 3, consists of 8 regions, containing up to 3 sub-region types: dry, humid and marine. In total, this study considers 16 sub-regions, represented by 16 U.S. cities. The 7B sub-region has not been modeled separately, as it accounts for only a small number of counties and a population below 180,000 or approximately 0.06% of the national total. Instead buildings in this region are represented by the 7A reference city. Given the high population of the Los Angeles metropolitan area, sub-region 3B has been divided into coastal (3Bc) and inland (3B) subsets.

Building Models

Static and dynamic glazings are simulated using EnergyPlus 7.1 [24, 25] and whole building reference models developed by the Commercial Building Initiative at the U.S. Department of Energy (USDOE) [26-28]. EnergyPlus is a publicly available simulation tool for modeling thermal loads and performing energy analysis of whole buildings or building zones. EnergyPlus models are defined by building geometry, envelope characteristics, mechanical system characteristics, and occupancy and setpoint schedules. The tool has been developed over the past 20 years and is commonly applied to building energy simulation and analysis [24, 25]. EnergyPlus has been extensively tested and validated. Additional details of testing and validation methods and results are available on the USDOE website [29]

The reference buildings are intended to represent realistic building characteristics and construction practices for each of 16 building types. Select geometric properties for the New Construction category of these reference building models are outlined in Table 2. These properties include total floorspace, total and non-north facing window area, window-wall ratio (WWR), window-floorspace ratio, and daylit floorspace ratio, which gives the fraction of floorspace in building zones with external windows. Beyond the provided characteristics, additional data to define each building type are required, including mechanical system properties and setpoint schedules. A complete inventory of the building characteristics and definitions can be found by directly examining the latest model files at the USDOE website [28]. Based on these characteristics, six different building types have been selected as suitable for NEC deployment and are considered for this investigation: large office, medium office, small office, primary school, secondary school, and midrise apartment. These types were selected as having a sufficiently high window-to-wall ratio (WRR>20%) and representing a sufficiently high amount of total national building stock (total floorspace > 100 million m^2). The New Construction category was used to best capture the future implementation of this emerging dynamic window technology. The most significant difference between between secondary and primary schools is total floorspace, with the secondary school having three times the total floorspace as the primary school. Set points and occupancy schedules between these two building types are otherwise similar. The midrise residential building model was selected to represent a typical multi-family building. A model was not selected to represent single-family buildings due to high variability in single-family house geometry and other properties. Single-family homes were assumed to be a poor application for the examined dynamic window and were not investigated.

High-rise residential was not modeled separately, as it does not have a predefined building model.

The building files were edited to include the glazing technologies described above in all windows. Conventional interior shades, such as horizontal blinds, have not been applied to the building models. The reference glazings are simulated both as static, to represent high performance static glazings, and as binary dynamic windows, to represent NEC glazings. All electrochromic windows are modeled using a simple control mechanism which switches to the blocking state when the internal zone temperature reaches 0.5°C below the set point temperature for cooling. So, as the interior temperature approaches the point at which cooling begins, dynamic glazings will modulate to a blocking state to reduce transmitted insolation. Automated daylighting controls have also been added to the reference building files. Continuous dimming is employed to maintain the specified minimum illuminance for a reference point at a height of 0.8 m in the center of each perimeter zone. Daylighting control can reduce lighting output to 5% of maximum output with a minimum input power of 20%.

Building simulations are conducted for each building type in each location for each static and dynamic glazing, resulting in a total of 1248 simulations. Hourly facility data is produced by major building end-use, including electricity for heating, cooling, ventilation, interior lighting and equipment and natural gas use for heating.

Technology Comparison

Hourly end-use consumption is summed to produce annual values. To consider consumption of both natural gas and electricity, primary energy consumption (PEC) is used as the primary metric for comparison, assuming U.S. national electricity grid conversion efficiency of 32% [1]. Total PEC values consider only end-uses heating, cooling, ventilation and interior lighting, as these are the only end-uses which vary with glazing type. Comparisons based on annual CO_2

emissions from building energy use are also presented in following sections. Additional metrics, such as peak demand, time of use pricing, annual energy costs, and occupant comfort, may be relevant to glazing selection but are not used here. For each building type and location, a total of 13 windows have been simulated: six static glazings, two NEC glazings, and five conventional EC glazings. Whichever static glazing produces the lowest total PEC is considered as the regionally-appropriate point of comparison. For the both the conventional EC and NEC-deployment cases, the lowest PEC dynamic glazing for each type is compared with the previously selected static glazing. The dynamic glazings are not deployed in instances where the static technology produces lower PEC values. The high performance static glazings selected as the base case exceed the thermal performance of the existing U.S. building stock. However, this comparison provides a more direct look at the technical savings potential that dynamic functionality enables. The comparison between conventional EC and NEC glazings provides insight on the energy benefits of NIR-switching vis-à-vis broadband switching.

National Building Stock

Total floorspace by building type is determined from the Commercial Building Energy Consumption Survey (CBECS) [30]. Data in CBECS are not disaggregated by the same building type and regional indices used in this investigation. To create this, detailed regional data from CBECS is used to create population-weighted county-level estimates for floorspace. County estimates are then mapped to IECC climate zones to produce total floorspace amounts represented by each of the 16 reference locations. Offices and schools are disaggregated by size. The large office model is selected to represent all office space with floorspace greater than 4650 m^2 (50,000 ft^2), while medium represents floorspace between 465 and 4,650 m^2 (5,000 – 50,000 ft^2), and small with floorspace less than 465 m^2 (5,000 ft^2). The secondary school building model is used to represent education buildings with floorspace larger than 1860 m^2 (20,000 ft^2) while the primary school represents the remainder. Total floorspace estimates by building type and climate zone are given in Table 3. This approach assumes that the population density of building floorspace for each building type remains the same across all climate zones, for instance that there is the same amount of large office floorspace per person in the climate zone representing New York City and Chicago as the zone representing northern Alaska. While is certainly not always the case, data limitations prevent a more detailed scaling approach.

Total PEC values and savings are determined by applying EnergyPlus simulation results at individual building level to these building stock values, using Equation 1, where *r* and *b* indicate the climate region and building type, A_b represents the floorspace in m^2 of reference building *b*,and $S_{r,b}$ represents the total stock in m^2 of building type *b* in each region *r*. Total CO_2 emissions are similarly determined using Equation 2, which disaggregates building energy use by source (E_{elec}, E_{NG}) and applies region- and source-specific carbon intensities (*I*). Regional carbon intensities for electricity, $I_{elec,r}$, are presented in g CO_2(e)/kWh and weighted based on state disaggregated source electricity mixes from the EPA's Emissions & Generation Resource Integrated Database (eGRID) [31]. A standard value of 181 g CO_2(e)/kWh is used across all regions for the carbon intensity of direct natural gas use, I_{NG} [32].

$$PEC_{total} = \sum_r \sum_b \frac{PEC_{r,b}}{A_b} * S_{r,b} \quad (1)$$

$$C_{total} = \sum_r \sum_b \frac{I_{elec,r}E_{elec,r,b} + I_{NG}E_{NG,r,b}}{A_b} * S_{r,b} \quad (2)$$

Results & Discussion

Individual Building Simulation Results

For each building type and region, simulation results are used to produce annual PEC values by end-use and glazing technology. The results from a medium office in Chicago are given as an example in Figure 4, which separates results by end-use and glazing. In this example, blocking static glazings outperform transmitting static glazings; some conventional EC glazings outperform the best static glazings, and NEC glazings perform best. This figure suggests however, that changes among the best static and dynamic glazing configurations are small. This trend occurs in many of the regions and building types, and is partially due to building geometry. As Table 2 shows, the ratio of window area to building floorspace never exceeds 0.10, indicating large internal spaces within the buildings that are not adjacent to windows, and therefore insensitive to window performance. Additionally, while the SHGC of each glazing in Figure 4 varies significantly, the U-factors, which also impacts overall thermal performance, are all comparably low, as indicated by Table 1. The slightly higher U-factor of the conventional EC glazings arises from its emissivity and produces a slightly poorer overall thermal performance relative to the other glazing types.

Technology Comparison

Tables 4-6 indicate the static, conventional EC, and NEC glazings with the lowest PEC values for each region and building type. For the static case (Table 4) the blocking glazing dominates in many of the building types, even in colder climates. These results are in line with previous NEC simulation results [16]. The predominance of the static blocking likely arises from internal heat gain profiles during hours that coincide with high insolation, particularly in the case of commercial buildings [16]. Consequently, commercial buildings tend to be cooling more frequently than heating, and glazings which transmit solar heat are of less value. In the midrise residential building, which has a different internal heat gain profile than the other commercial buildings, the static transmitting glazing produces a lower annual PEC in some colder northern locations.

From Table 5, it can be seen that, with the exception of region 1A, NEC glazings produce PEC savings in a majority of simulated buildings. NEC glazings on tinted glass outperform static glazings in most large offices and some medium offices, due to the higher WWR of these building types. The larger window area means that daylighting benefits can still be captured with darker windows, which also reduce cooling loads. Conventional EC glazings (Table 6) do not perform as well as NEC glazings in the simulated cases. Some PEC benefit is realized in most large and medium offices and residential buildings. However, the conventional EC only outperforms high performance statics in only two secondary school cases, and no primary school or small office cases. There are a number of possible reasons for this. First, the simulated control presents only a limited use case for conventional EC glazings. It switches between binary states to control exclusively for zone cooling. In a real-world application, conventional EC glazings have the ability to modulate continuously between high and low states, and to control for lighting and cooling setpoints simultaneously. The simplified representation of conventional EC glazings in this analysis may reduce their overall performance. Second, due to difference in the glazing properties, the U-factors of simulated conventional EC glazings are slightly worse than the other simulated glazings. Finally, the mechanical systems modeled within each building type may not be designed to respond efficiently to thermal changes caused by dynamic windows, leading to reduced performance for both NEC and conventional EC glazings, relative to static glazings. Mechanical system inefficiencies are discussed further in the following section.

Technology Energy Savings

A PEC comparison between the static and NEC cases is given in Table 7. Savings are given relative to static case PEC for the end-uses affected by window performance: heating, cooling, ventilation and interior lighting. As the results show, total savings from NEC glazings are low in the hot, southern regions, varying from 0%-1%, and negative in some cases. In colder, northern regions, the savings are more significant and reach as high as 9% for some building types. Because the base case is a blocking glazing in many instances, the savings from NEC glazing will come predominately from heating reductions due to capture of useful winter solar gain. It follows then that the regions with the highest savings will be those with significant heating loads. The comparison between conventional EC and static glazings is given in Table 8. Here the trends are quite different than the NEC cases. Savings are consistent across climate regions in large and medium offices (1%-3%) but none produces savings as high as the best NEC case. The conventional EC performs particularly poorly in primary school buildings (-2%- -5%).

Within a given region, some building types produce significantly different PEC savings than others. For NEC glazings, secondary schools in particular produce very small savings percentages, even in regions where the NEC glazing performs well in other building types. Conventional EC perform in primary schools is significantly worse than in other building types within the same region. Examining the hourly simulation outputs of the lower performing cases, some counterintuitive trends emerge. In some hours, the energy consumption for heating is higher for transmitting glazings than the blocking glazings. In these timesteps, heating and cooling energy consumption that are not always proportional to sensible thermal loads in building zones. The equipment sizing and operational characteristics of an HVAC system will determine the sensitivity of the system to thermal loads within each zone [33]. Under certain conditions, complex HVAC systems may not be capable of reacting efficiently to small changes in sensible loads in various building zones, resulting in higher building energy consumption. The school building models have a more complex construction than the other building types considered. This might contribute to their unusual heating load behavior in some regions. Transmitting glazings may also adversely affect heating loads by allowing more visible light into the building. With daylighting controls deployed, the building will consequently consume less electric lighting, and internal heat gains from lighting are reduced. This trend in reduced lighting demand for higher transmitting glazings is reflected in the hourly simulation results. In either case, the effect produces a reduction to the benefit of dynamic glazing deployment in school buildings.

The variability in performance by building type is also evident in Figure 5, which shows annual PEC reductions from NEC deployment, normalized by non-north facing window area. North-facing windows have been neglected from this area figure, as they do not experience direct insolation in the U.S., and thus are less suitable for NEC glazings. Given the benefit of NEC glazings to heating loads, colder regions appear to realize the highest savings. Medium offices produce the highest primary energy savings potential of 207 kWh/m^2-yr in region 7. Midrise residential buildings also produce some meaningful savings across several regions, with a high of 172 kWh/m^2-yr in region 6A. The higher savings in these two building types are likely due to more favorable building geometries and load schedules, as mentioned above.

Similarly, Figure 6 shows PEC savings from conventional EC deployment relative to high-performance static glazings, normalized by non-north facing window area. The trends for this EC type are quite different than that observed for NEC glazings. PEC savings are zero or negative from most or all locations in small offices, and primary and secondary schools. This arises from the conventional EC's higher U-factor relative to the high performance static, which results in lower overall thermal performance. Its lower visible light transmission in the blocking state can also negatively impact daylighting for building types with smaller WWR such as small offices. For buildings types with positive savings, the savings appear more evenly distributed among climate regions, slightly favoring hotter climate zones in both large offices and midrise residential buildings. The highest savings occur in region 2A for large offices (49 kWh/m^2-yr), in region 6A for medium offices (66 kWh/m^2-yr), and in region 3B for midrise residential (70 kWh/m^2-yr).

National Savings Potential

Using the regional building stock (Table 3), PEC savings determined from individual building simulations are scaled to a national total comprised of the six modeled building types for a number of technology scenarios. The first scenario presents a base case using the envelope characteristics and windows of the existing building stock and no daylighting controls, as represented by the unedited building models. The second scenario uses the same windows, but adds daylighting control to perimeter zones of all buildings. The high performance alternatives: static, NEC and conventional EC glazings are modeled in scenarios 3-5, respectively, each using daylighting controls. The stock total PEC for heating, cooling, ventilation and lighting for each of these scenarios is given in Figure 7. As this indicates, the largest savings come from fully installing daylighting controls (55 TWh/yr) and from improving the overall thermal performance of the windows (94 TWh/yr). Each of the three high performance glazing scenarios (3-5) has improved U-factors over the default windows, defined generically to comply with minimum ASHRAE 2010 requirements for each climate zones. The U-factors of these windows range from 5.8 to 3.2 $W/m^2 \cdot K$ depending on location. Among the alternative glazings, the difference in total PEC is quite small. Relative to high performance static glazings, the NEC glazing realizes a modest reduction to heating (9.3 TWh/yr) and lighting (1.2 TWh/yr) and a slight increase to cooling (2.3 TWh/yr). In total the NEC glazing reduced PEC consumption for relevant end-uses by only 1.2% over the entire modeled building stock, amounting to approximately 1.56 million tonnes of CO_2 per year. Savings from conventional EC glazings relative to static glazings come predominately from cooling (9.7 TWh/yr) with smaller savings in heating (1.8 TWh/yr) and ventilation (1.4 TWh/yr), but are largely undone by increased lighting consumption (10.1 TWh/yr) due to lower visible transmission. In total, conventional EC glazings only reduce total modeled stock PEC by 0.5%.

It is important recognize that the savings from NEC glazings are not realized homogeneously over the window stock. As Figures 5 and 6 illustrate, there is a great deal of variability in performance across climate regions and building types, indicating that some sites are much more favorable to NEC deployment than others. Figure 8 presents a cumulative PEC savings curve for NEC glazings relative to high performance static glazings that ranks building types and regions by highest PEC savings per unit window area (most favorable sites) to lowest (least favorable). Figure 8 also separates the savings curve into segments to illustrate the differences in NEC effectiveness. In the most favorable sites (18.0% of the window area), half of all PEC savings can be realized. 75% of the savings can be realized by the top 39% of the window stock. The top 56% of the window stock could achieve 90% of the saving. Finally, nearly 10% of the stock would produce no savings at all if NEC glazings were deployed there.

Carbon Reduction Potential

CO_2 reduction potential provides another important metric to assess the overall impact of NEC deployment. To better understand the effect of geography on NEC deployment, CO_2 savings potential per unit area of glazing have been applied to a map of climate regions (Figure 9). These values take into account regional differences in the carbon intensity of electricity. By examining this map, the trend in regional performances of NEC glazings becomes more apparent. Intuitively, NEC glazings reduce CO_2 emissions in more northerly climate regions, where heating loads are more significant, but they also produce higher savings in the humid (A) sub-region, relative to the dry (B) and marine (C) sub-regions. This trend holds for every region with both humid (A) and dry (B) sub-regions. The NEC CO_2 reduction potential reaches a maximum of 23 kg/m^2-yr in region 7, then drops slightly to 19 kg/m^2-yr in region 8. As this map makes clear, the Northeast and Great Lake states appear to be the most favorable markets for this technology. In southern states and along the West Coast, the benefits of deployment are quite low.

Conclusions

In this investigation, the national savings potential of a hypothetical, high performance near-infrared switching electrochromic (NEC) glazing has been assessed using building energy simulation. To capture the influence of local weather, building geometry and use patterns, the dynamic NEC technology has been compared with several static and dynamic glazings in six reference buildings across 16 U.S. climate regions. The NEC glazing is modeled on both clear and tinted glass.

The results indicate that the largest national energy savings result from installing daylighting controls (55 TWh/yr) and improving the U-factor of windows (94 TWh/yr) of current U.S. building stock. The savings potential arising directly from NEC deployment is less significant. Deployed throughout all applicable U.S. building stock, this NEC glazing could produce an additional savings up to 8 TWh of PEC and 1.56 million tonnes of CO_2 per year. At individual sites, the NEC savings are more significant, ranging between 3% and 9% PEC reductions for heating, cooling, ventilation and lighting in the most favorable buildings and regions. A market analysis of NEC deployment found that 50% of total savings could be achieved by upgrading only 18% of the window stock, and 75% from upgrading only 39% of the stock. This analysis showed that approximately 10% of the window stock produced no benefit from NEC deployment, relative to high performance static glazings. The NEC was also compared with conventional EC, which modulate NIR and visible light transmission simultaneously. The conventional EC outperformed the NEC in locations where cooling loads were high. Across all locations and building types, however, the NEC produced higher total savings. The reasons for this include a higher U-factor than the NEC, as well as reduced daylighting potential from lower SHGCs of conventional EC. The simple control for switching electrochromic states may also underestimate the benefits of conventional EC glazings for glare control and cooling reduction. Finally, the geographical dependence of CO_2 reduction potential was investigated to determine the best markets for the NEC glazing. This analysis identified the Northeast and Great Lakes regions as producing the highest savings potentials (15-23 kg CO_2/m^2 window annually). The South, Southwest and West Coast regions did not see substantial savings.

As a caveat to these results, it should be noted that this investigation compares a hypothetical NEC glazing to static and dynamic alternatives that are currently commercially available. Rather than examining the current state of the NEC glazing, this investigation is intended to show the technical potential a high performance NEC glazing could have if deployed throughout the U.S. building stock. Additional development is required before a NEC glazing could achieve these performance characteristics. In addition to performance, the capital cost for purchase and installation, operations and maintenance costs, electricity and natural gas cost savings, and window lifetime will determine if this glazing can be economically viable throughout the U.S.

Future work on this topic will include simulation of more complex EC control schemes. This will provide a more realistic model of switching between multiple EC states for both NEC and conventional EC glazings. These controls will also be constructed to take better consideration of glare conditions within the building zone and respond accordingly, which is necessary for occupant comfort and will have implication on overall building energy use. Simulation of additional building types will also be undertaken, to investigate the impact of building geometry such as window-wall ratio on glazing performance.

Acknowledgements

This research was supported by Laboratory Directed Research and Development funding at the Lawrence Berkeley National Laboratory. Lawrence Berkeley National Laboratory is operated for US Department of Energy under Contract Grant No. DE-AC02-05CH11231.

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Figures

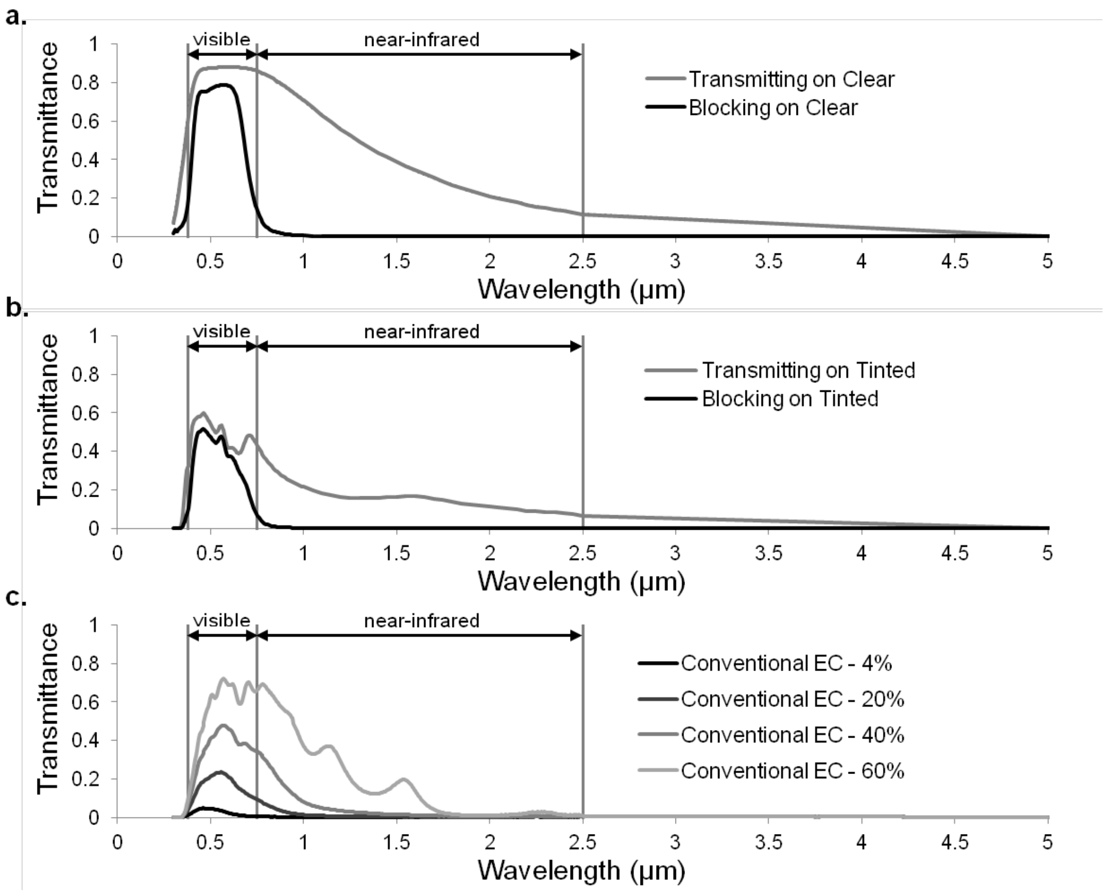

Figure 1. Transmittance profiles of reference transmitting and blocking glazings used to approximate NEC performance on clear glass (a), on tinted glass (b), and four simulated states of conventional EC on clear glass (c). Glazing properties are collected from IGDB [17-20].

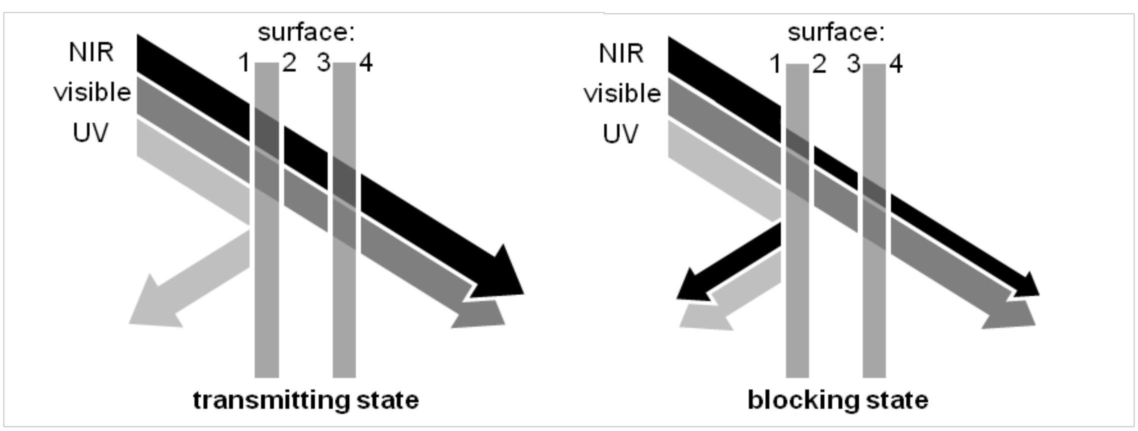

Figure 2. Illustration of transmittance behavior of transmitting and blocking states of an NEC glazing. This diagram also indicates the surface names of a two-pane construction. Glazings are typically applied to surface 2 or 3.

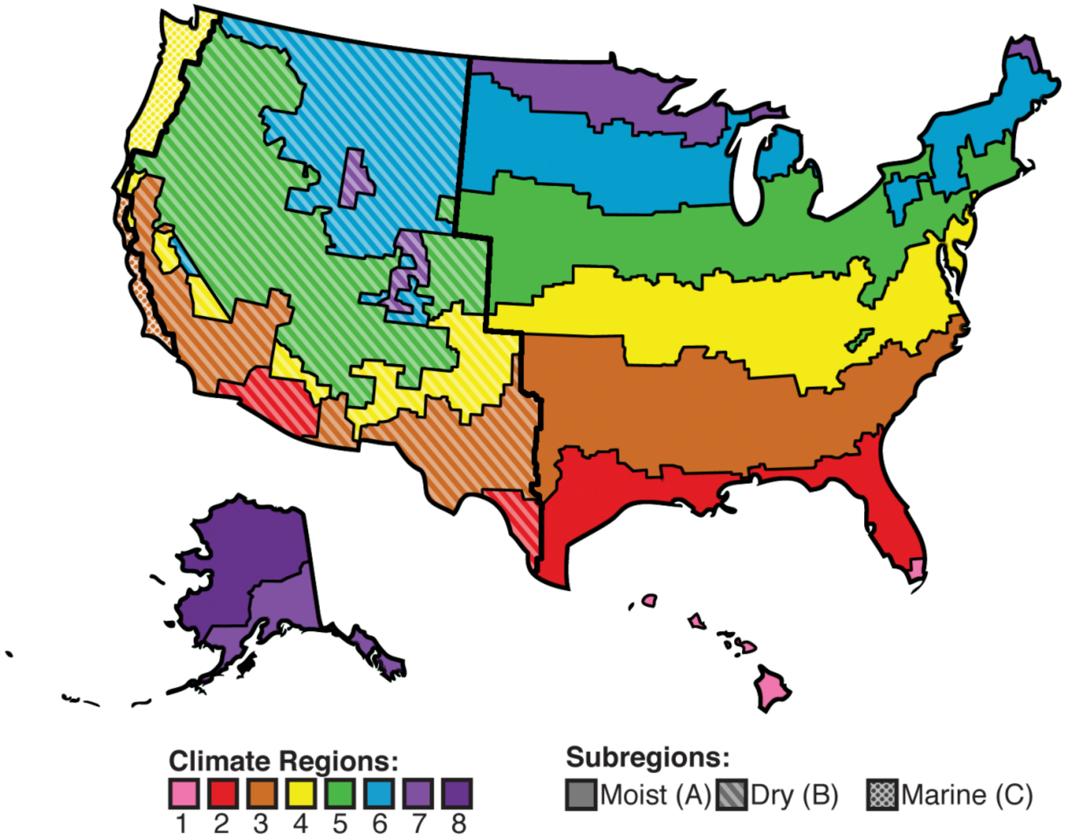

Figure 3. Climate zone disaggregation of the U.S. There are 16 total sub-regions represented by 16 reference cities. Sub-region 3B is represented for both coastal and inland locations. Sub-region 7B is represented as part of 7A.

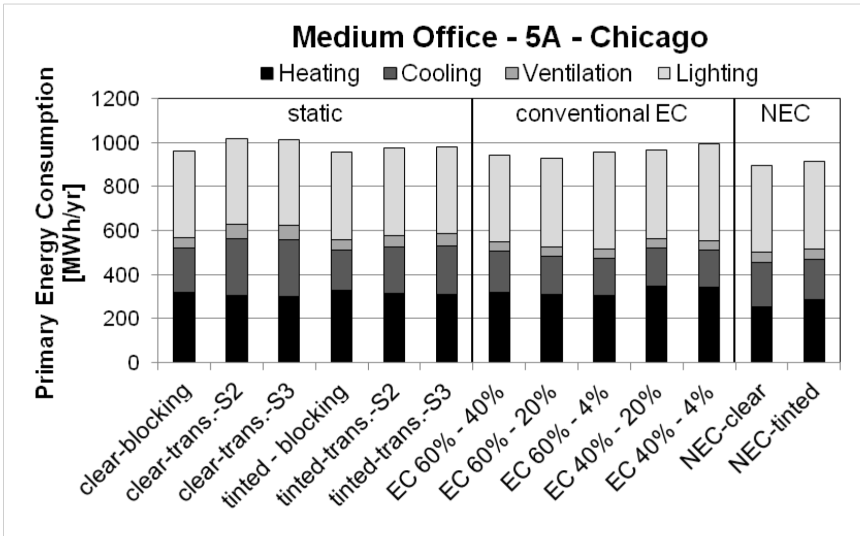

Figure 4. An example of primary energy consumption (PEC) by end-use for a medium office in Chicago. Results are given for several static glazings (left), conventional EC glazings (middle), and clear and tinted NEC glazings (right). Overall performance variations between glazing types are small but non-negligible.

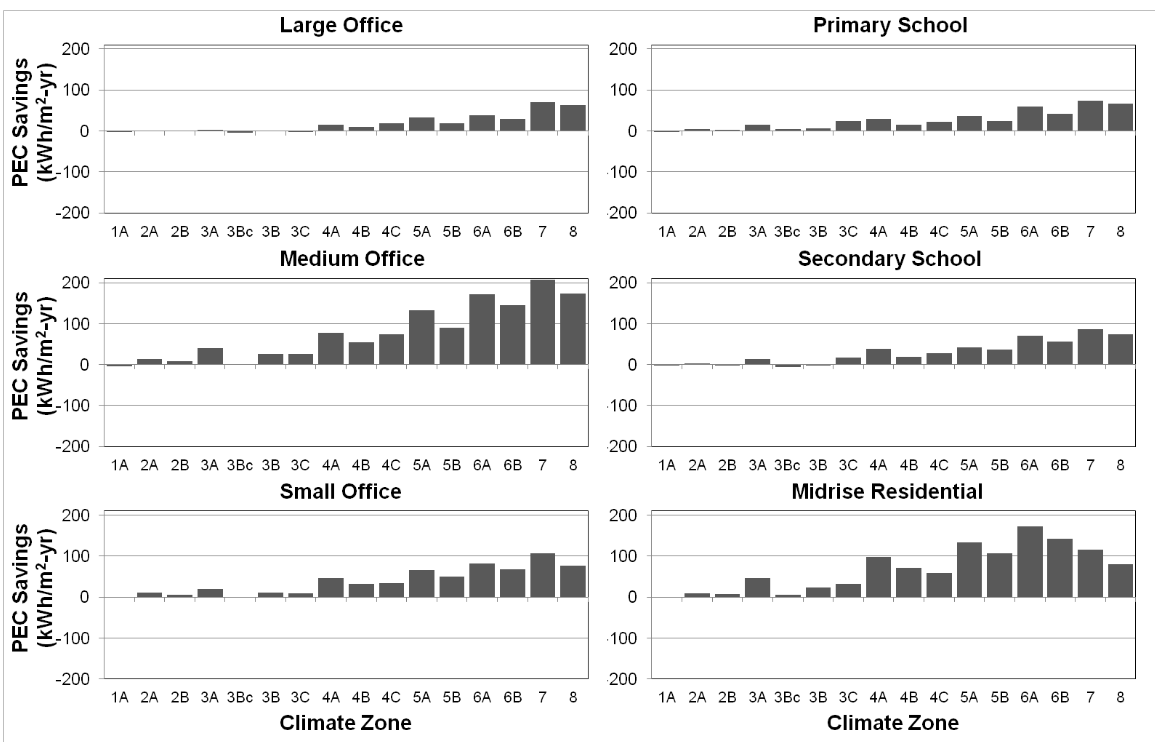

Figure 5. Primary energy savings (PEC) from NEC deployment, normalized by non-north facing window area indicate the variation in savings potential across regions and building types.

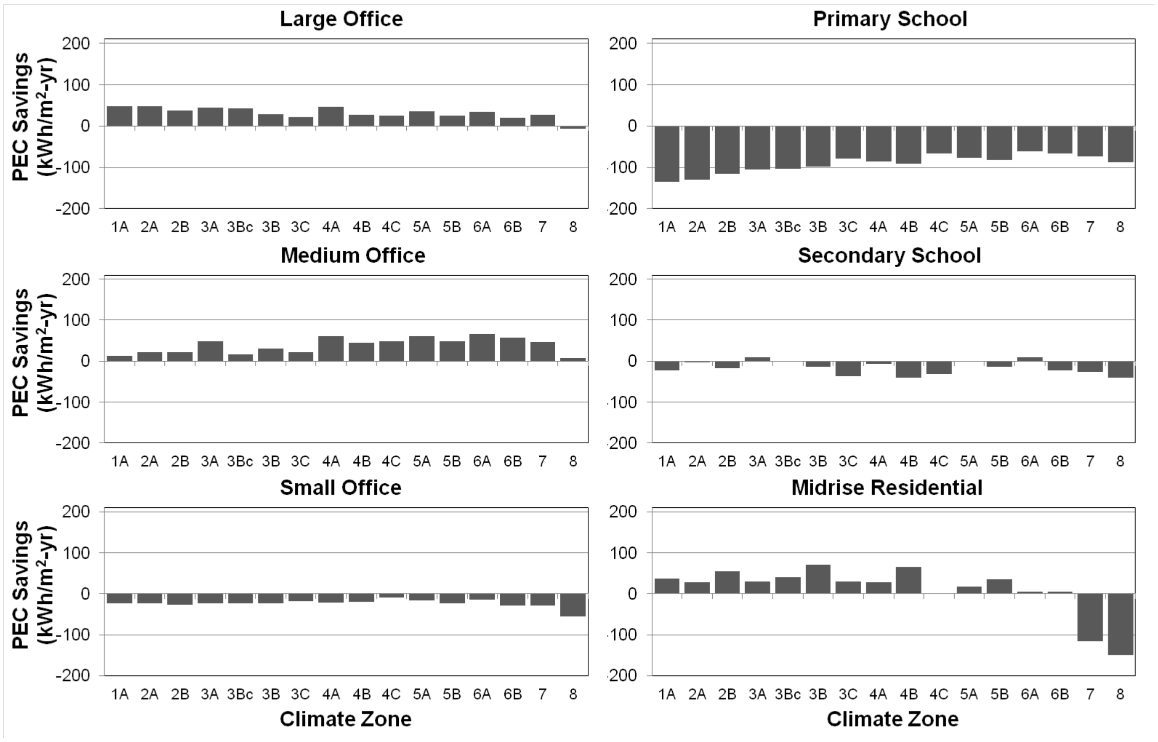

Figure 6. Primary energy savings (PEC) from Conventional EC deployment, normalized by non-north facing window area indicate the variation in savings potential across regions and building types.

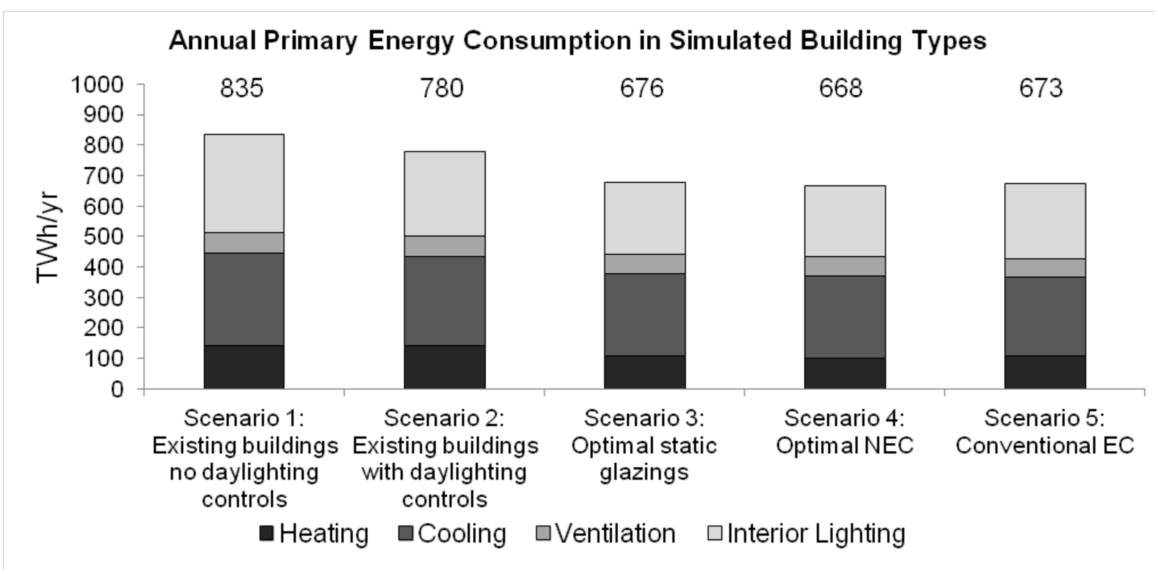

Figure 7. Total primary energy consumption for end-uses affected by building shell performance by window scenario.

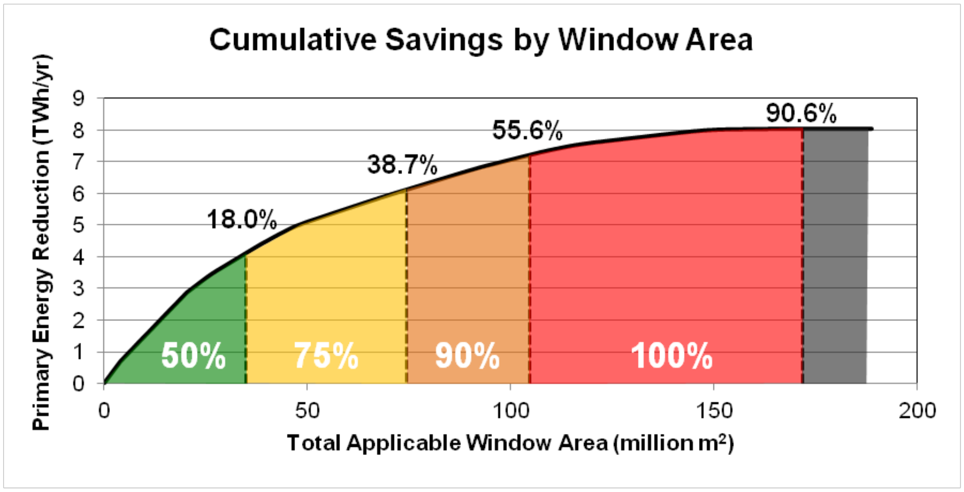

Figure 8. Cumulative primary energy savings plotted against window area in descending order of savings potential. Bottom percents indicate fraction of cumulative savings, while upper number indicates the fraction of window area necessary to achieve those savings. For instance the top 18.0% of window area correspond to 50% of the total PEC savings.

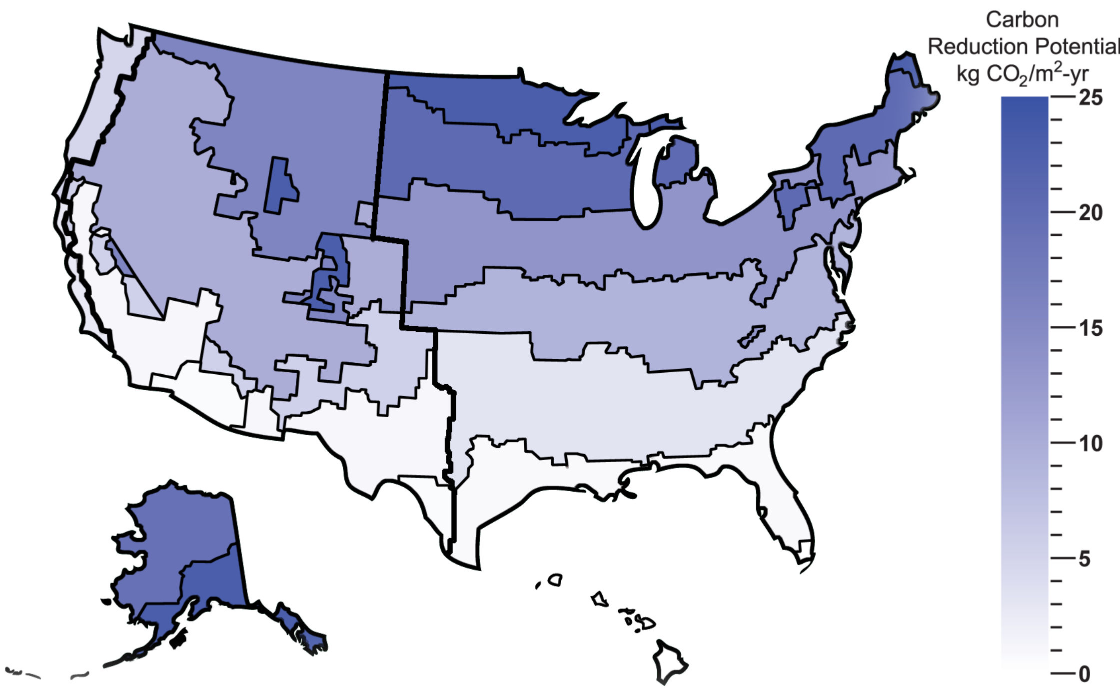

Figure 9. The carbon reduction potential from NEC deployment is indicated for each climate region. These values are the total climate region CO_2 reduction (kg/yr) normalized by that region's total non-north facing window area (m^2) for the six building types considered.

Tables

Table 1. Properties of each glazing in a two-pane construction with 16 mm air fill. U-factor indicates thermal losses due to internal-external temperature differences, solar heat gain coefficient (SHGC) gives the transmitted fraction of total insolation, and Tvis the fraction of visible light which passes through the window. For dynamic glazing, the left value gives the property for the blocking state, the right for the transmitting state.

Glazing Description	substrate	surface	U-factor W/m^2K	SHGC	Tvis
static blocking	clear	2	1.63	0.297	0.689
static transmitting	clear	2	1.63	0.667	0.78
static transmitting	clear	3	1.63	0.646	0.78
static blocking	tinted	2	1.63	0.185	0.387
static transmitting	tinted	2	1.63	0.356	0.438
static transmitting	tinted	3	1.63	0.424	0.494
NEC	clear	2	1.63	0.297 / 0.667	0.689 / 0.78
NEC	tinted	2	1.63	0.185 / 0.356	0.387 / 0.438
conv. EC 60%-40%	clear	2	1.91	0.465 / 0.280	0.60 / 0.40
conv. EC 60%-20%	clear	2	1.91	0.465 / 0.165	0.60 / 0.20
conv. EC 60%-4%	clear	2	1.91	0.465 / 0.099	0.60 / 0.04
conv. EC 40%-20%	clear	2	1.91	0.280 / 0.165	0.40 / 0.20
conv. EC 40%-4%	clear	2	1.91	0.280 / 0.099	0.40 / 0.04

Table 2. Characteristics of the six simulated building types, including building floorspace, total and non-north facing window area, window to wall (WWR) ratio, and the total fraction of building floorspace adjacent to windows

Building Type	Floorspace (m^2)	Window Area (m^2)	E-S-W Window Area (m^2)	Window Floorspace Ratio (-)	Total WWR (-)	Daylit Fraction
Office (Large)	46320	4636	3245	0.07	0.38	0.29
Office (Med)	4982	653	457	0.09	0.33	0.41
Office (Small)	511	59.7	43	0.08	0.21	0.71
School (Primary)	6871	879	554.4	0.08	0.35	0.76
School (Secondary)	19592	2089	1336	0.07	0.33	0.58
Apartment (Midrise)	3142	231	147.9	0.05	0.15	0.89

Table 3. Total floorspace for each building type and climate region in millions m^2.

Region	Large Office	Medium Office	Small Office	Primary School	Secondary School	Midrise Residential
1A	11.9	7.4	1.9	3.9	19.2	3.2
2A	75.2	37.4	9.7	21.5	106.0	10.1
2B	6.9	8.7	2.9	4.2	14.0	0.2
3A	83.2	48.8	11.8	23.9	120.8	12.9
3Bc	35.3	23.1	6.7	14.3	22.9	7.6
3B	31.9	21.8	6.6	13.1	27.9	5.3
3C	17.7	11.6	3.4	7.2	11.5	3.8
4A	164.5	112.4	26.8	24.7	217.4	96.3
4B	3.8	3.2	1.0	1.7	5.4	0.3
4C	17.9	11.7	3.4	7.2	11.6	3.8
5A	197.0	131.3	33.3	18.5	251.1	84.2
5B	14.5	18.2	6.1	9.0	26.9	1.2
6A	38.5	34.4	9.9	5.5	55.0	15.0
6B	2.9	4.1	1.4	2.0	6.3	0.1
7	1.1	0.7	0.2	0.4	0.7	0.2
8	0.3	0.2	0.1	0.1	0.2	0.1

Table 4. For each region and building type, the static glazing with the lowest PEC glazing is indicated. This static glazing represents the base case for comparison between dynamic glazings.

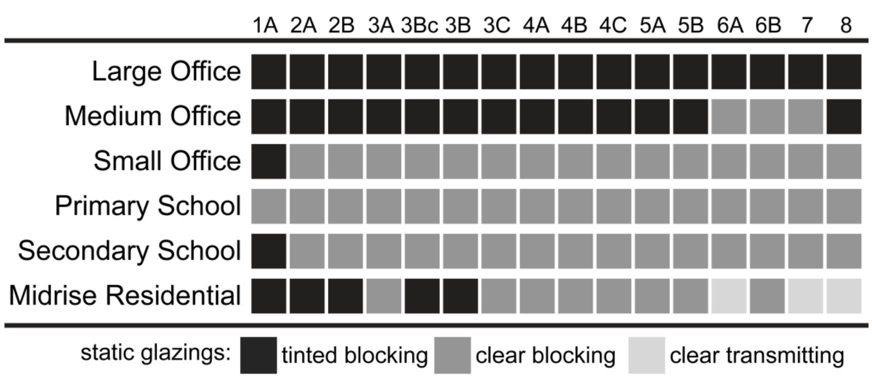

Table 5. For each region and building type, the NEC glazing with the lowest PEC glazing is indicated. Locations where the NEC does not outperform the best static glazing are also indicated.

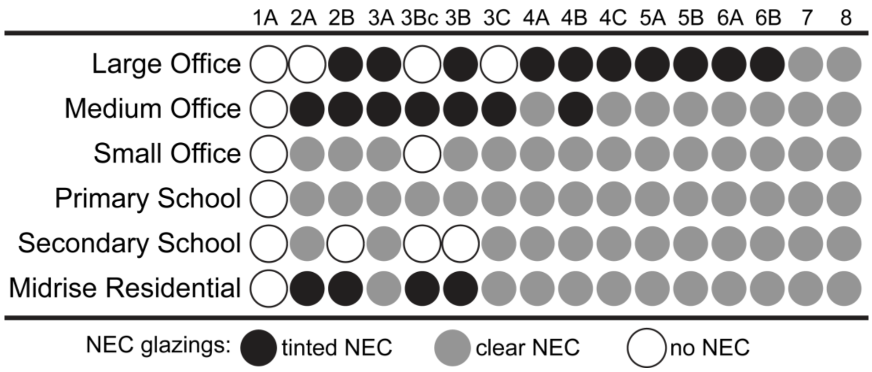

Table 6. For each region and building type, the conventional EC glazing with the lowest PEC glazing is indicated. Locations where the EC does not outperform the best static glazing are also indicated. Symbols illustrate the SHGC of the transmitting state (top) and blocking state (bottom) for each case.

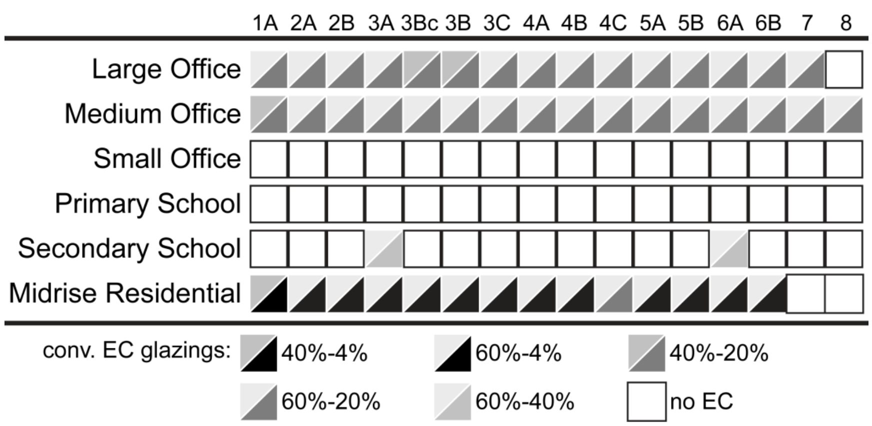

Table 7. The PEC reduction potential from NEC deployment relative to high performing static glazings. Values are normalized by static window PEC for the end-uses heating, cooling, ventilation and interior lighting only.

Region	Large Office	Medium Office	Small Office	Primary School	Secondary School	Midrise Residential
1A	-0.03%	-0.20%	0.00%	-0.02%	-0.01%	-0.02%
2A	0.00%	0.61%	0.42%	0.18%	0.02%	0.34%
2B	0.04%	0.41%	0.22%	0.08%	-0.02%	0.27%
3A	0.04%	2.05%	0.93%	0.61%	0.23%	2.10%
3Bc	-0.20%	0.08%	-0.12%	0.23%	-0.15%	0.30%
3B	0.02%	1.30%	0.46%	0.26%	0.00%	0.93%
3C	-0.01%	2.15%	0.59%	1.28%	0.47%	2.38%
4A	0.55%	3.75%	2.15%	1.14%	0.65%	4.34%
4B	0.43%	3.10%	1.60%	0.64%	0.41%	3.54%

4C	0.93%	4.62%	1.89%	1.07%	0.67%	3.58%
5A	1.28%	6.35%	2.89%	1.44%	0.72%	5.71%
5B	0.90%	5.18%	2.52%	1.08%	0.83%	5.32%
6A	1.49%	7.30%	3.50%	2.18%	1.15%	6.52%
6B	1.43%	7.34%	3.19%	1.77%	1.22%	6.50%
7	3.01%	9.17%	4.64%	2.71%	1.57%	4.32%
8	2.22%	5.17%	2.76%	1.83%	1.06%	2.08%

Table 8. The PEC reduction potential from conventional EC deployment relative to high performing static glazings. Values are normalized by static window PEC for the end-uses heating, cooling, ventilation and interior lighting only.

Region	Large Office	Medium Office	Small Office	Primary School	Secondary School	Midrise Residential
1A	1.27%	0.53%	-0.80%	-4.20%	-0.26%	1.07%
2A	1.44%	1.00%	-0.91%	-4.57%	-0.04%	1.02%
2B	1.21%	1.03%	-0.99%	-4.08%	-0.22%	1.86%
3A	1.57%	2.50%	-1.12%	-4.31%	0.14%	1.36%
3Bc	1.71%	1.13%	-1.33%	-5.40%	-0.03%	2.54%
3B	1.16%	1.55%	-1.11%	-3.75%	-0.21%	2.84%
3C	1.09%	1.75%	-1.23%	-4.23%	-0.98%	2.15%
4A	1.72%	2.93%	-0.98%	-3.42%	-0.11%	1.22%
4B	1.23%	2.54%	-0.98%	-4.04%	-0.88%	3.28%
4C	1.25%	3.01%	-0.53%	-3.16%	-0.78%	0.09%
5A	1.39%	2.95%	-0.75%	-3.03%	-0.02%	0.73%
5B	1.24%	2.77%	-1.19%	-3.70%	-0.32%	1.79%
6A	1.32%	2.83%	-0.62%	-2.21%	0.16%	0.17%
6B	0.95%	2.87%	-1.38%	-2.79%	-0.48%	0.20%
7	1.15%	2.02%	-1.28%	-2.71%	-0.49%	-4.36%
8	-0.25%	0.25%	-1.77%	-2.43%	-0.59%	-3.84%