Utility and Economic Benefits of Electrochromic Smart Windows

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Windows have very significant direct and indirect impacts on building energy consumption, load shape, and peak demand. Electrochromic switchable glazings can potentially provide substantial reductions in all aspects of cooling and lighting electricity usage. The solar-optical properties of electrochromic coatings vary over a wide range in response to an applied electrical signal. This control signal can be driven by a combination of occupant needs, external environmental conditions, building operating strategies, and electricity demand minimization requirements. The impact of an electrochromic glazing depends on the intrinsic properties of the coating, the placement of the coating within a window system, and many parameters related to building type, operating strategy, orientation, and location.

This study explores the potential benefits of electrochromics in comparison to other currently available and emerging glazing technologies. These effects are explored in office buildings in a hot southern California climate as a function of window size, orientation, and building operating characteristics. The DOE-2 building energy simulation program was used to model the performances of these dynamic coatings, accounting for both thermal and daylighting impacts. Very substantial savings are demonstrated compared to conventional glazings, but specific impacts on component and total energy consumption, peak demand, and HVAC system sizing vary widely among the options analyzed.

Electrochromic glazings appear to represent a very important future building design option that will allow architects and engineers a high degree of design freedom to meet occupant needs, while minimizing operating costs to building owners and providing a new and important electricity demand control option for utilities. Utility demand-side management programs can accelerate the market penetration of electrochromics by offering incentives to reduce net first cost and payback periods.

Introduction

Windows have significant impacts on peak demand, load shape, and energy consumption in commercial buildings. The transmission of solar radiation through windows is the primary energy flow through many commercial building envelopes. Solar heat gains often inflate building cooling loads, especially in such regions as southern California. On the other hand, through the use of effective lighting control strategies, daylight admitted through windows can be used to offset electric lighting requirements and lighting-induced cooling requirements, thus reducing building peak demand and energy usage [Johnson et al. 1985; Usibelli et al. 1985; Sweitzer et al. 1987; Sullivan et al. 1987]. These factors, in turn, influence mechanical system sizing and cost.

Demand and energy savings associated with daylighting and with the use of currently available window glazings are limited by the time dependency, quantity, spectral content, and spatial distribution of incoming light. Savings could be maximized by optimizing these factors to maintain specified light levels in a space throughout the day while minimizing solar heat gain. To do this would require the following: (1) transmission of only the visible portion of the incident solar radiation, (2) modulation of the intensity of transmitted light, and (3) even distribution of the transmitted light throughout the building space.

Currently available tinted, reflective, low-E, and spectrally selective solar control glazings are not entirely adequate for these purposes because of the static (i.e., unchanging) nature of their solar-optical properties. Mechanical shading devices are typically used to reduce solar gains and occupant visual discomfort resulting from glare or directly transmitted sunlight. Switchable glazings, glazings whose solar- and visible-optical properties are variable, may meet the above requirements and eliminate the need for shading devices.

Electrochromics are switchable glazings whose solar-optical properties vary continuously with an applied electrical current from a clear or bleached, high-transmittance state to a colored, absorptive or reflective, low-transmittance state.

Preliminary studies on the use of switchable glazings in commercial buildings have indicated significant potential for reducing peak demand and energy consumption [Neeper and McFarland 1982; Coutier et al. 1983; Rauh et al. 1986; Fine and McElroy 1990]. Electrochromic glazings have the greatest potential in commercial building applications because the control of their solar-optical properties can be linked directly to a building's energy management system. The solar radiation entering a building space can be actively maintained at an optimum level by directly controlling the transmittance of an electrochromic glazing, rather than passively controlling the transmittance with incident solar radiation or glazing temperature. Active control with direct links to building energy management systems will generally result in maximum demand and energy savings, and will thus be of greatest interest for application in utility demand-side management programs.

The economic viability of an electrochromic glazing material depends on the material's spectral response, visual uniformity, response time, reversibility of charge, power requirements, and durability, as well as the ability to economically manufacture large expanses of coated glazing. Current research efforts are focused on the ultimate goal of developing electrochromic devices that can be mass-produced at an incremental cost to building owners of approximately $15/ft^2 more than standard double glazing. This would make switchable window glazings economically viable since, in addition to their operating savings, they are intended to eliminate the need for most operable shading devices, which typically cost $5/ft^2 to $10/ft^2 and require periodic maintenance at additional cost. The smaller HVAC systems needed to handle lower peak cooling loads represent additional first cost savings.

This study is designed to provide additional performance data for gauging the market requirements for a successful electrochromic device, as well as the potential benefits for utility demand-side management programs.

Methodology

Window Prototypes

We chose five window prototypes representing a range of solar control options to evaluate the peak demand and energy savings potentials of electrochromic windows in comparison to static solar control windows. The fragile nature of some selective and electrochromic coatings may limit their use to insulated glazing units (IGU's) or laminated glazings in which the coating is not exposed to the surroundings. For this reason, all five window prototypes were treated as IGU's. In order to isolate the effects of window solar-optical properties, the single U-value of 0.35 Btu/hr-ft^2-°F, typical of many IGU's incorporating coatings, was used for all five prototypes. Lower U-values are easily attainable, but would provide little additional benefit in southern California.

The five window prototypes are defined below. Their performance properties are listed in Table 1.

Static solar control window prototypes:

1) Tinted: an IGU with a gray tinted glazing (with no coating) on the outside and a clear glazing on the inside.

2) Reflective: an IGU with a bronze reflective glazing (with a coating on the #2 surface) on the outside and a clear glazing on the inside.

3) Spectrally selective: an IGU with a green tinted glazing (with a spectrally selective coating on the #2 surface) on the outside and a clear glazing on the inside.

Electrochromic window prototypes:

4) Broad-band electrochromic: an IGU with an electrochromic glazing (with the electrochromic coating on the #2 surface) on the outside and a clear glazing on the inside. The electrochromic glazing switches from transmitting to absorbing over the entire solar radiation spectrum, as shown in Figure 1a. Therefore, for a given visible transmittance, the corresponding shading coefficient is higher than it would be if the window switched to a more reflective state. This results in higher solar heat gain through the window.

5) Narrow-band electrochromic: an IGU with an electrochromic glazing (with the electrochromic coating on the #2 surface) on the outside and a clear glazing on the inside. The electrochromic glazing switches from transmitting to reflecting in the visible portion of the solar spectrum while maintaining a minimum transmittance and a high reflectance in the infrared portion of the solar spectrum, as shown in Figure 1b. Therefore, for a given visible

transmittance, the shading coefficient and the corresponding solar heat gain are minimized. For any visible transmittance value, the narrow-band electrochromic thus has a lower solar heat gain than the broad-band electrochromic window.

Table 1. Properties of Window Prototypes Used in Analysis

Prototype	Outer Glazing		IGU	
	T_{sol}	T_{vis}	SC	T_{vis}
Tinted	.46	.43	.54	.38
Reflective	.12	.12	.20	.10
Spectrally selective	.22	.41	.30	.37
Broad-band electrochromic	.80/.10	.80/.10	.84/.26	.70/.09
Narrow-band electrochromic	.48/.10	.80/.10	.50/.11	.71/.09

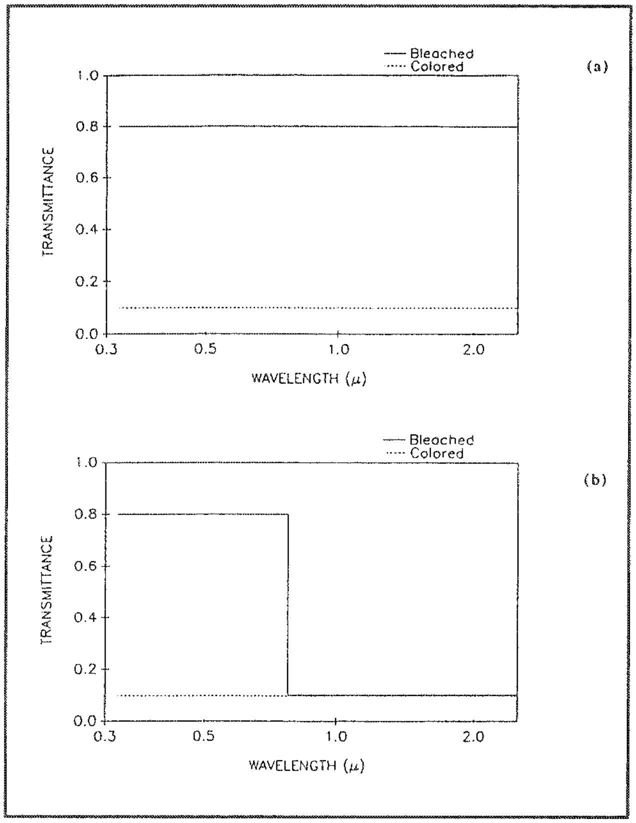

Figure 1. Solar Transmittance Spectra of the (a) Broad-band Electrochromic and (b) Narrow-band Electrochromic Glazing Prototypes

The two electrochromic window prototypes considered in this study are idealized. In practice, electrochromic windows would not have such sharply defined property boundaries. It is possible to design many other electrochromic window configurations whose performances are intermediate between those of the two electrochromic window prototypes examined in this study. The descriptions and energy performance characteristics of several more configurations are provided in Reilly et al. [1991].

Building Module for Energy Simulation

In order to estimate the relative impacts of electrochromic windows on building peak electricity demand and total and component electricity consumption, we used the DOE-2.1D building energy analysis program [Curtis et al. 1984] to simulate the energy performance of a prototypical office building module. The building module consisted of a 100-ft-square core zone surrounded by four identical 100-ft-by-15-ft perimeter zones facing the cardinal directions. Each perimeter zone was divided into ten office spaces of equal size (Figure 2). Other details of the office building module are given in Johnson et al. [1985]. Blythe, representing a hot inland southern California climate, was chosen for analysis purposes. Cooling loads that are heavily influenced by solar heat gains often comprise the largest portion of electricity demand and consumption in the perimeter zones of commercial buildings in this climate.

Each zone in the office building module was assumed to be served by its own constant-volume, variable-temperature HVAC system. This simplified mechanical system configuration was used to isolate building zones and their window-related energy consumption.

The window-to-wall ratio (WWR), the window area expressed as a fraction of the total exterior facade area, was varied from 0 to 0.6 (0 to 0.85 of the floor-to-ceiling wall area) on all building module orientations. The average speculative office building might have a WWR of 0.25 or 0.3, while a WWR of 0.6 would be representative of an executive office space.

Operable shading devices are installed in most commercial buildings. However, we have observed that they are rarely used effectively with conventional static windows. Electrochromic windows, on the other hand, are intended to alleviate the need for most mechanical shading devices. Therefore, the use of operable shades was not considered in this analysis. Previous analyses of conventional windows with operable shading devices are described in Johnson et al. [1985] and Usibelli et al. [1985].

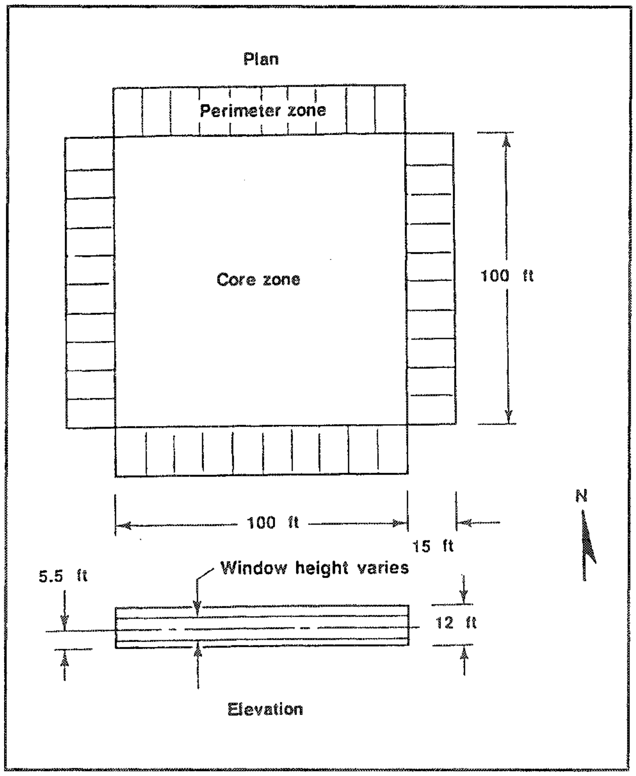

Figure 2. Office Building Module Used in the DOE-2 Building Energy Simulations

The perimeter zones were modeled both with no lighting controls and with continuous dimming lighting controls. The reference point for the continuous dimming lighting controls was located 10 feet deep along the center line of each perimeter office space. An interior illuminance of 50 fc was to be maintained at this reference point. The dimming system consumed a minimum of 10% of full power due to parasitic losses. To meet the lighting needs in the building module, we modeled a lighting hardware system with an installed lighting power density of 1.5 W/ft^2, representing the current State of California Title 24 standard.

The lighting setpoint requirement was used to modulate the visible transmittances of the electrochromic windows in the simulations to provide adequate daylight without glare or excessive solar gain. If the interior daylight level exceeded 50 fc, the electrochromic windows were modulated between their minimum and maximum visible transmittances to provide 50 fc at the reference point, with the minimum electric lighting power being used. If the interior daylight level fell below the lighting setpoint with the electrochromic windows at their maximum visible transmittance, the continuous dimming controls adjusted the electric lights to provide the remainder of the required 50 fc at the reference point.

Results

Our simulation results indicate that electrochromic windows can be highly effective in reducing peak electricity demand and electricity consumption in commercial buildings in southern California in comparison to static windows. Several categories of simulation results are useful in comparing the performances of electrochromic and static windows. For best understanding, we begin by presenting lighting and cooling electricity usage results, followed by total electricity consumption, peak electricity demand, HVAC equipment sizing, and, finally, economic impacts.

All energy results are presented in terms of the floor areas of the perimeter zones involved. Because the core zone is not affected by window energy performance, it is omitted from the results.

We emphasize the benefits of using electrochromic windows and lighting controls together to take advantage of as much daylight as possible, while minimizing solar heat gain and controlling glare. Lighting controls would not typically be used with static reflective windows, which have a low visible transmittance. They could be used with tinted or spectrally selective windows, but their use in existing buildings is rare, due in part to the difficulties of managing the associated shading systems in an effective manner. For reference, many of the static window results are given both without lighting controls and with continuous dimming lighting controls.

Annual Lighting Electricity Consumption

Figure 3 displays annual lighting electricity usage with the five window prototypes in the west perimeter zone at a lighting power density of 1.5 W/ft^2. Lighting electricity usage remains constant at 4.1 kWh/ft^2 for all five windows at all WWR's if electric lighting controls are not used (ND). When they are employed (CD), the relative benefits of each window type become obvious. The higher the visible transmittance of a window, the more daylight it admits into a space at a given time. This affords more frequent opportunities to reduce electric lighting usage.

The two electrochromic windows have a higher visible transmittance and, therefore, outperform all three static windows in terms of lighting electricity reduction. (Clear glazing would yield a curve similar to those of the electrochromics, but would not typically be used in southern California climates due to the associated excessive glare and high cooling loads.) The tinted and spectrally selective windows chosen for this study have nearly the same visible transmittance and perform

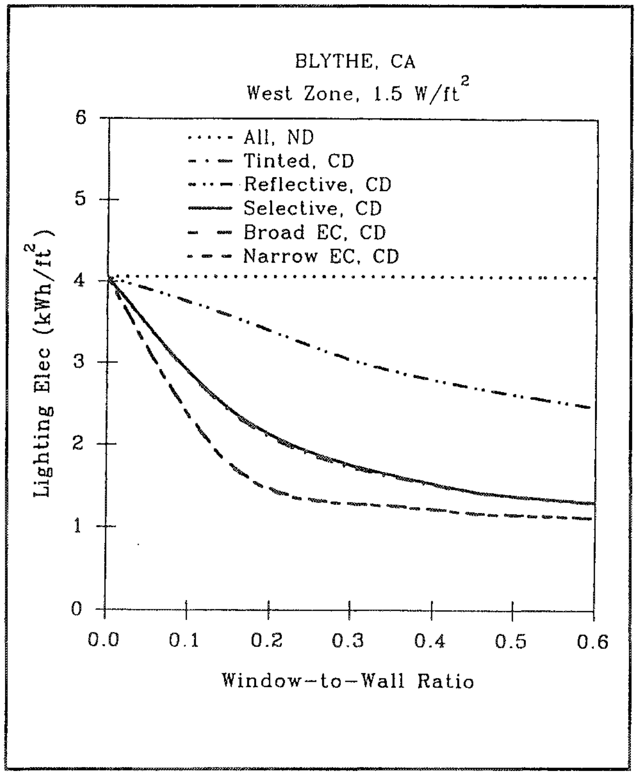

Figure 3. Annual Lighting Electricity Consumption for the Five Window Prototypes in the West Perimeter Zone

similarly. Note that it takes a WWR of about 0.6 with a tinted or selective window to achieve the same level of lighting electricity savings that the electrochromic windows provide at a WWR of 0.3. Far less lighting electricity savings are associated with the reflective window because of its low visible transmittance (0.10).

The amount of daylight that enters a space over time increases with increasing WWR, resulting in an increased potential for lighting energy savings. Annual lighting energy consumption falls rapidly for transmissive glazings as WWR increases initially, then begins to level out. The WWR at which incremental lighting energy savings begin to vanish is determined by the visible transmittance of the window. The electrochromic windows reach this point of marginal returns at a WWR of about 0.3 because of their high visible transmittance in the bleached state. Lighting energy consumption associated with the static windows continues to decrease throughout the WWR range shown in Figure 3, although it never quite reaches the lowest level realized with the electrochromic windows.

Annual Cooling Electricity Consumption

Annual cooling electricity usage results in the west perimeter zone at a lighting power density of 1.5 W/ft^2 are shown in Figure 4. The narrow-band electrochromic window, used in conjunction with continuous dimming lighting controls, clearly outperforms the other four window prototypes used with or without lighting controls. This is a result of its dynamic switching over a range of low shading coefficients, which minimizes solar heat gain, as well as its switching over a wide range of visible transmittances, which allows for the most effective use of daylight to offset the use of heat-producing electric lights. The annual cooling energy usage associated with the narrow-band electrochromic window does not increase with increasing WWR, as it does with the other windows.

The broad-band electrochromic window yields much lower cooling loads than does the tinted window, even though the shading coefficient of the broad-band electrochromic window in its bleached state (0.84) is much higher than that of the tinted window (0.54). This result is

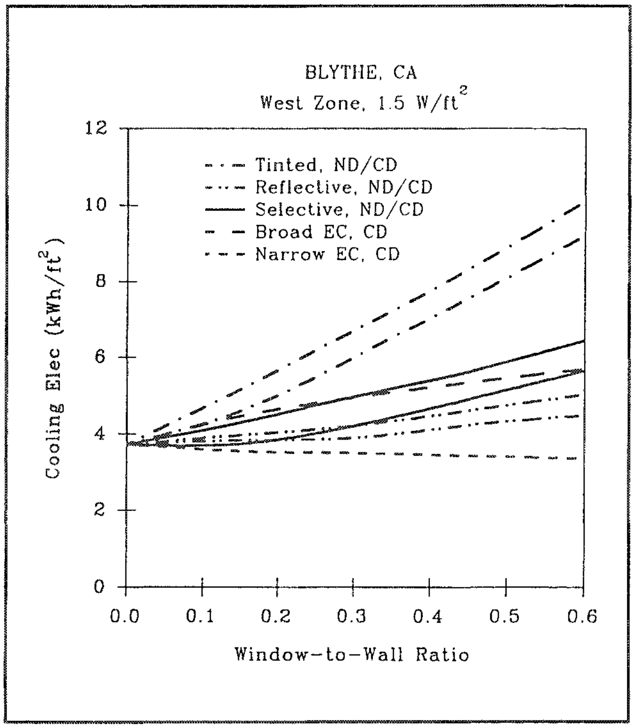

Figure 4. Annual Cooling Electricity Consumption for the Five Window Prototypes in the West Perimeter Zone

attributable to the operation of the broad-band electrochromic window at visible transmittances with corresponding shading coefficients that are lower than that of the tinted window throughout most of the year. However, the broad-band electrochromic window can be outperformed by the reflective and spectrally selective windows. The shading coefficients of these windows are lower than the annual average shading coefficient at which the broad-band electrochromic window operates.

Alternatively, the broad-band electrochromic window could be controlled to minimize the cooling load, rather than being controlled to meet the lighting requirements in a space. Using such a control strategy with this window could decrease the cooling load to less than that associated with the spectrally selective window. However, the reflective window will always yield a lower cooling load because its shading coefficient (0.20) is lower than the minimum shading coefficient of the broad-band electrochromic window (0.26).

Cooling energy requirements in the south and east perimeter zones are somewhat smaller in magnitude, but the trends are otherwise similar to those in the west zone.

Figure 5 shows annual cooling electricity usage results in the north perimeter zone, analogous to the west perimeter zone results shown in Figure 4. It is clear that the electrochromic windows do not provide a substantial quantitative advantage over the static windows in terms of cooling electricity usage in the north zone, where cooling loads are much lower than those in the other perimeter zones. In fact, when used with lighting controls, the spectrally selective window yields virtually the same cooling energy results as the narrow-band electrochromic window. This is a consequence of the reduction in electric lighting-induced cooling, attributable to daylighting, which has a more substantial effect on cooling energy requirements by percentage in the north zone.

Total Annual Electricity Consumption

We now examine total annual electricity consumption, the major components of which are the cooling and lighting consumption discussed previously. We begin with a "baseline" building module (i.e., a building module with no windows) to assess the impact of windows on total electricity consumption in the building. Figure 6 shows that 10.0 kWh/ft^2 of electricity are consumed annually in a windowless perimeter office of the building module, of which lighting electricity accounts for 4.1 kWh/ft^2 at a lighting power density of 1.5 W/ft^2. Figure 6 illustrates the influence of increasing area for each window type on the building perimeter total electricity consumption. Results

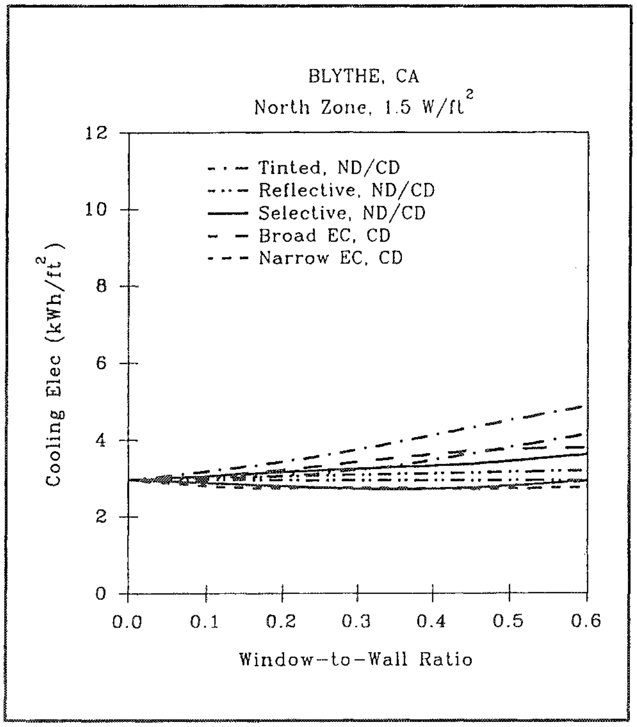

Figure 5. Annual Cooling Electricity Consumption for the Five Window Prototypes in the North Perimeter Zone

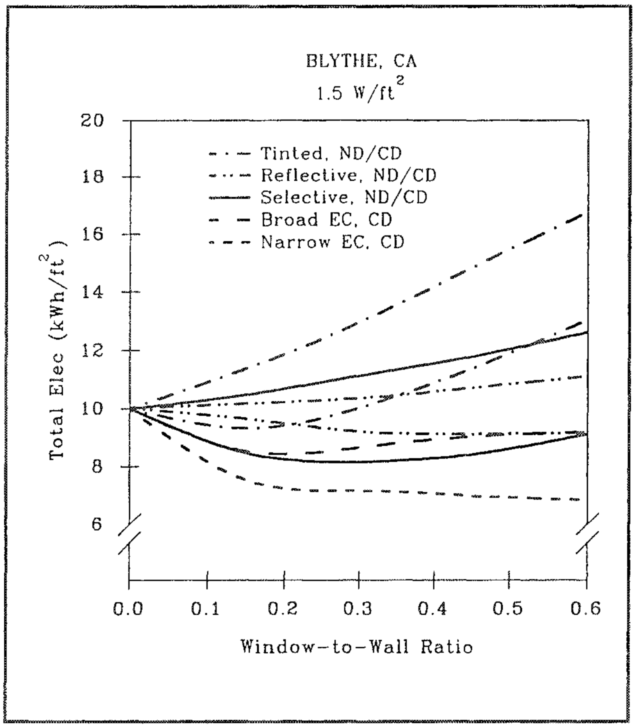

Figure 6. Total Perimeter Zone Annual Electricity Consumption for the Five Window Prototypes

are shown for the tinted, reflective, and spectrally selective windows with (CD) and without (ND) lighting controls, along with results for the two electrochromic windows with lighting controls.

The performance characteristics of the window type, the use of lighting controls, and the relative magnitudes of the lighting and cooling loads determine whether an electricity consumption curve reaches a minimum and then increases, or decreases steadily with increasing WWR. Lighting electricity consumption is independent of WWR without lighting controls, but decreases with WWR when lighting controls are employed. In general, the greater a window's area, the greater is its impact on building energy performance. Consequently, the electricity consumption curves diverge most at the maximum WWR examined, 0.6. The increases in cooling electricity consumption with increasing WWR and decreases in lighting energy consumption (in a daylighted building) cause this divergence.

Total electricity consumption is always greater for the building module with static windows of any size without lighting controls than for a windowless building. The introduction of dimming lighting controls to take advantage of daylighting initially reduces electricity consumption below that of a building with no windows. The selective window and broad-band electrochromic window electricity consumption curves reach minimum levels, then slowly increase, but they never rise above the baseline consumption. The electricity consumption curves for the reflective window and the narrow-band electrochromic window decrease monotonically with increasing window area. However, the consumption associated with the narrow-band electrochromic window is approximately 2 kWh/ft^2 less than that associated with the reflective window at WWR's greater than 0.15, making it the lowest total electricity usage associated with any window at each WWR. In fact, the total electricity usage in the building perimeter with the narrow-band electrochromic window remains nearly constant at 6.8 kWh/ft^2 at WWR's greater than 0.2.

The impacts of lighting control use and of relative cooling and lighting load sizes on annual electricity consumption can be seen by comparing the performance of the selective window with lighting controls to the performance of the broad-band electrochromic window. The broad-band electrochromic window does not outperform the static selective window at any WWR. This is because the incremental lighting electricity savings achieved with the broad-band electrochromic window beyond a WWR of 0.2 are consistently less than the associated cooling electricity increase, causing the total consumption to rise. The incremental cooling electricity with the selective glazing is lower than that with the broad-band electrochromic because its fixed shading coefficient of 0.30 is lower than the average shading coefficient of the electrochromic, which varies from 0.26 to 0.80. However, as explained previously, the broad-band electrochromic window could be controlled in response to solar heat gain in an office building, thereby reducing the cooling load while still providing some lighting energy savings through daylighting. In the future, we will explore this and other more sophisticated control algorithms designed to minimize total consumption and operating cost.

Control of the narrow-band electrochromic window by interior illuminance level is effective in minimizing lighting, cooling, and total electricity consumption. Cooling electricity usage remains constant with increasing WWR, and is approximately equal to that in the baseline building. Cooling consumption above that in the baseline building would signify inadequate control of solar heat gain through the window. Lighting electricity savings reach the point of marginal returns at a WWR of about 0.3; thus, the narrow-band electrochromic window has a stable and low impact on building energy performance at larger WWR's.

The total electricity consumption curves for the two electrochromic windows show the significance of the difference in their shading coefficient switching ranges. Because illuminance levels are used to control the visible transmittances of the windows, lighting electricity savings are the same for the two windows. Thus the higher total electricity consumption associated with the broad-band electrochromic is attributable to its higher shading coefficient switching range.

Peak Electricity Demand

Figure 7 shows building perimeter peak electricity demand results for the five window types at a lighting power density of 1.5 W/ft^2. As a frame of reference, note that the baseline peak electricity demand is 4.2 W/ft^2. The trends demonstrated for total electricity consumption also apply to the peak demand results. As an exception, the peak electricity demand associated with the broad-band electrochromic window is nearly the same as that associated with the spectrally selective window at all WWR's. Recall that the broad-band electrochromic window performed slightly worse than the spectrally selective window in terms of total electricity consumption.

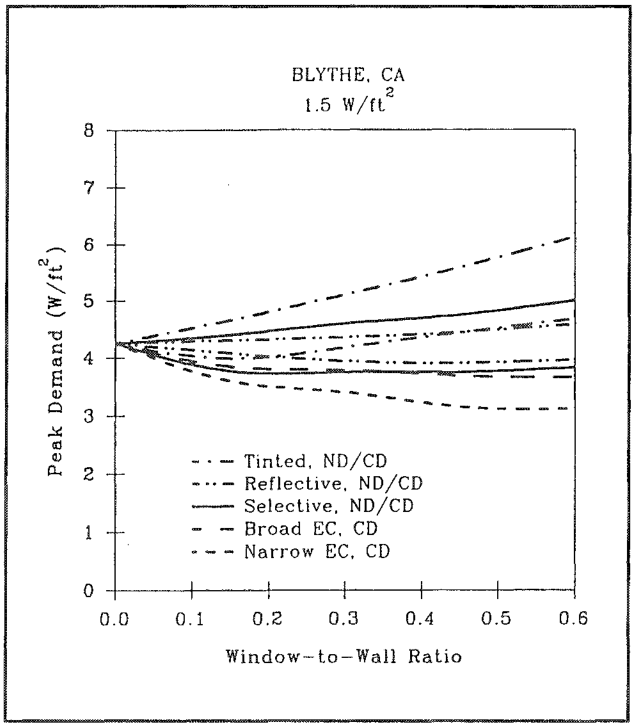

Figure 7. Total Perimeter Zone Peak Electricity Demand for the Five Window Prorotypes

Once again, the narrow-band electrochromic window outperforms the other four windows at all WWR's. The peak demand associated with the narrow-band electrochromic is between 3.1 W/ft^2 and 3.7 W/ft^2 at WWR's between 0.15 and 0.6. In contrast, a building perimeter with tinted windows and no lighting controls has a peak demand of 6.2 W/ft^2 at a WWR of 0.6.

HVAC Equipment Sizing

The use of electrochromics, particularly in larger windows, will result in significant reductions in chiller size and associated HVAC system component size. Figure 8 shows the required chiller capacity associated with three window options and two window sizes in the four perimeter zones. At a WWR of 0.3, the narrow-band electrochromic window reduces chiller capacity by 13% compared to the tinted window without lighting controls, and by 9% compared to the same window with lighting controls. At the larger WWR of 0.6, the corresponding chiller reductions are 25% and 20%. The related reductions in peak cooling loads should also result in the downsizing of many associated HVAC system components (e.g., ducts), as well as additional annual energy savings due to fan power reductions. The savings ultimately realized will depend on specifics of HVAC system design, operation, and control.

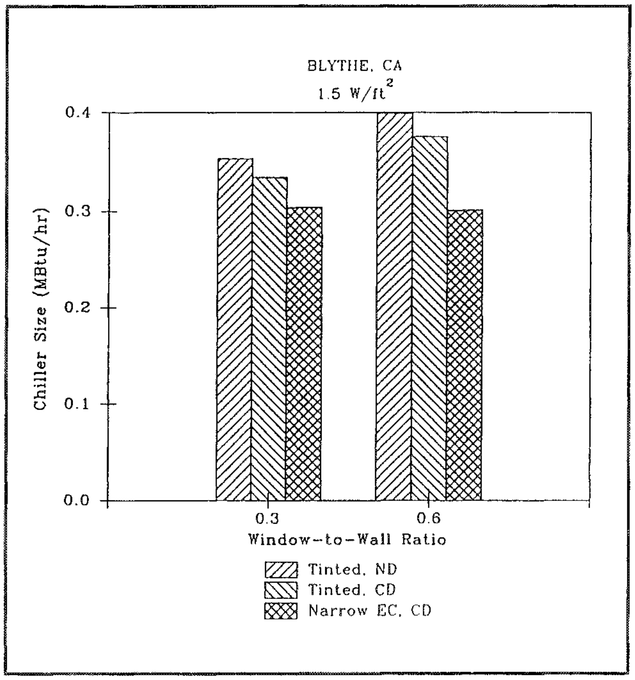

Figure 8. Total Perimeter Zone Chiller Sizing for Selected Window Prototypes

Economic Benefits

To obtain a true picture of the cost-effectiveness of electrochromic glazings, we must examine all of the costs and benefits associated with their use. The use of electrochromic windows will reduce building operating costs by reducing the annual cost of electricity, in terms of both energy and demand. It may also facilitate first-cost savings by eliminating the need for conventional interior shades, blinds, or drapes. Electrochromics will reduce the initial cost of the HVAC system since a smaller system will be required. In some instances, a smaller chiller delivering reduced air volumes through smaller ducts in a multistory building will result in a smaller floor-to-floor dimension, since the plenum depth can be reduced. This will provide very substantial first-cost savings. Other economic benefits of electrochromic windows include the indirect benefits of improved thermal and visual comfort resulting from the ability of electrochromics to reduce overheating and glare. The value of worker productivity far exceeds energy costs in buildings, so that even a small improvement in productivity can greatly increase the cost effectiveness of this application. Additional studies are needed to quantify these indirect benefits.

Figure 9 shows the annual energy usage and costs by load component for three window options (the tinted window with and without lighting controls and the narrow-band

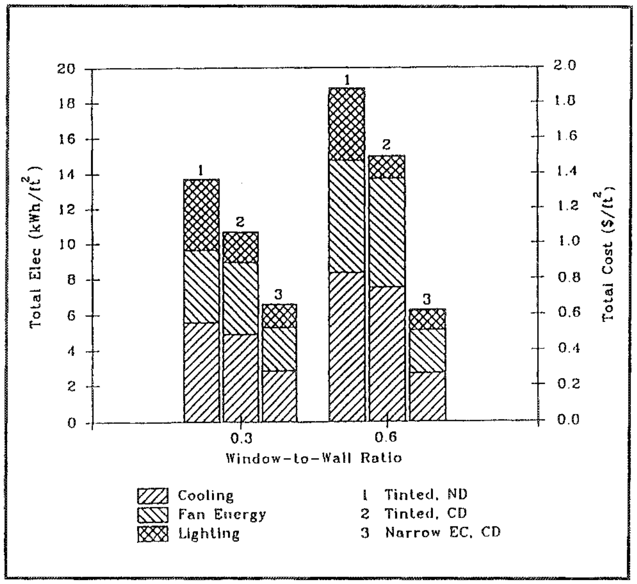

Figure 9. Annual Electricity Consumption and Cost by Load Component for Selected Window Prototypes in the West Perimeter Zone

electrochromic) and two window sizes in the west perimeter zone. At a WWR of 0.3, the use of the narrow-band electrochromic window saves 51% of the energy consumed with the tinted window without lighting controls and 37% of the energy used with that window with lighting controls. At the larger window size, a WWR of 0.6, the corresponding savings rise to 66% and 57%. With larger windows, cooling electricity reductions (i.e., reductions in energy consumed by the chiller and fans) account for the greatest share of the savings. Note that as window area increases, the energy usage with the electrochromic window decreases slightly, while the energy usage with the conventional window rises sharply.

Significant additional savings result from reductions in peak demand. Comparing the same three window options at a WWR of 0.6 for the perimeter zones as a whole, peak demand is reduced from 6.1 W/ft^2 for the tinted, nondaylighted case, to 4.7 W/ft^2 (a 23% savings) for the tinted, daylighted case, and then to a minimum of 3.1 kW/ft^2 (a 49% savings) for the electrochromic, daylighted case, as shown in Figure 7. The percentage savings for peak demand are not as high as those discussed above for electricity consumption because the peak demand results are for all four perimeter zones, rather than the west perimeter zone only.

Note that these values, which are expressed in terms of perimeter zone floor area, can also be expressed in terms of window area. Since the ratio of perimeter zone floor area to window area is approximately 2, each square foot of narrow-band electrochromic window reduces peak demand by an average of 6.0 W in a highly glazed building perimeter.

Electrochromics will first impact niche markets in which their performance provides benefits that are not attainable with other technologies. Commercial buildings in which large windows are required for the owners' marketing needs are one example of this. Therefore, in the economic calculations that follow, we consider the building with large view windows (a WWR of 0.6), comparing the conventional tinted window type without lighting controls to the narrow-band electrochromic window with lighting controls in a west-facing zone. We use the results discussed above and the cost implications of utility rebate and incentive programs to estimate the economic impacts of electrochromics.

The annual energy savings shown in Figure 6 are converted to electricity cost savings at a rate of \$.10/kWh. This figure represents an average of summer and winter (on-peak and mid-peak) time-of-use rates for large commercial buildings in SCE's service area. Annual operating costs are reduced by \$1.26/ft^2 with the electrochromic window in the case of the large window area. Savings in electricity demand of 3 W/ft^2 add \$.20/ft^2 per year, assuming peak demand charges of \$.017/W over a period of four months per year. (Note that these assumptions are conservative, since we are applying total building perimeter average values to the west zone.) Therefore, total annual energy and demand savings of \$1.46/ft^2 of floor area are expected.

As previously noted, electrochromic windows wired to a building's energy management system will allow for reductions in chiller and associated HVAC system sizing. For estimation purposes, we assume a total installed system cost of \$1000/ton. Therefore, the HVAC savings provide for a reduction in chiller capacity of 0.0014 ton/ft^2 and a corresponding cost savings of \$1.40/ft^2.

At a WWR of 0.6, our building module contains approximately 0.5 ft^2 of glazing for each square foot of perimeter zone floor area, as noted above. Thus, the savings estimated above for each square foot of floor area can be readily converted to savings per square foot of electrochromic window area by multiplying by two.

Utilities are increasingly offering financial incentives and rebates to builders who use energy efficiency technologies that reduce demand and consumption. SCE has been among the leaders in the electric utilities community who are aggressively promoting demand-side management programs by offering a variety of incentive payments. SCE's "Design for Excellence" program (1991) provides the following incentives that are relevant to our example.

Prescriptive incentives:

1) High-performance glass: $3/ft^2$ of glass (Tv $\geq$ SC, with lighting controls).

2) Lighting controls: $75/kW of reduced demand.

Comprehensive incentive: $.05/kWh of reduced consumption for high-performance glass + lighting controls + high efficiency HVAC system (paid in addition to prescriptive measures).

"Performance Plus" incentive: $.35/kWh of reduced consumption if the total energy budget is reduced by more than 25% below the California Title 24 code requirement.

For the purposes of our cost/benefit analysis, we consider only the prescriptive incentive for high-performance glass. Since the narrow-band electrochromic glazing outperforms the "high-performance glass," we assume an equivalent incentive payment for the electrochromic glazing.

We estimate that mass-produced electrochromic windows will sell for approximately $15/ft^2$ more than conventional double glazing. For the early markets, we assume a somewhat higher incremental cost of $25/ft^2$. Note that there would be an additional cost for lighting controls, but that this cost is typically small compared to the cost of glazing and is covered in part by the incentive payments listed above. Although it is not considered in this analysis, there may also be a first-cost savings if blinds or drapes can be eliminated. Four different cost/benefit scenarios for the two different glazing first costs are presented in Table 2.

For the range of costs and benefits assumed in this analysis, the simple payback period for the narrow-band electrochromic window varies from three to ten years. The annual energy and demand savings alone result in a five-to-ten-year payback of the added glazing cost. First-cost credits for chiller size and utility incentives pull the paybacks to very low values of three to four years, and to 6.6 to 7.6 years in the case of the higher glazing first cost. Note that SCE's "Performance Plus" incentive payment could produce even shorter payback periods.

Although these calculations are simplified, we conclude that electrochromic window technology can be readily justified from a narrow engineering/economic perspective. Additional benefits, such as improved comfort and aesthetics, are not evaluated in this analysis, nor are certain economic factors, such as the ability to command premium rentals. Even for the speculative developer, these results show promise, particularly since the developer may want a high-performance, "visible" technology to provide a competitive edge in the rental market. For a corporate developer/owner, the building is a long-term investment in which comfort, productivity, and image should all be enhanced by the use of electrochromic windows. In this case, the relatively short payback periods, coupled with the user amenity, should result in significant market acceptance.

Utility demand-side management programs can have three interrelated positive impacts on the market acceptance of electrochromics. First, the promotion of this technology to the customer base through a full range of information, education, and design assistance programs will build confidence in the technology and allow potential users to carefully evaluate the complex benefits. Second, incentive payments for glazing/daylighting will directly reduce the added cost and shorten payback periods. Third, encouraging the thoughtful use of multiple, integrated energy efficiency strategies will help customers realize the cost savings resulting from downsizing HVAC systems. This will require monitored data from demonstration buildings to prove to skeptical engineers that chiller reductions will not compromise occupant comfort.

Impacts of Climate and Location

Using the same building module, we simulated the relative performances of the five window prototypes in other climates: Los Angeles, CA, Lake Charles, LA, and Madison, WI. Electricity demand and lighting, cooling, and total electricity savings in these locations are similar in magnitude and exhibit the same trends as those demonstrated in Blythe. In Madison, a heating-dominated climate, heating penalties are associated with the electrochromics. For example, at a WWR of 0.6, annual heating energy consumption with the narrow-band electrochromic window is 14.1 $kBtu/ft^2$ higher than that with the tinted window with lighting controls and 16.2 $kBtu/ft^2$ higher than that with the tinted window without lighting controls. However, assuming a typical gas cost of $ 0.60/therm, the incremental heating cost associated with the electrochromic window is less than $0.10/ft^2$ of floor area. This cost is a small fraction of the total monetary savings from the reduced cooling and lighting consumption associated with the electrochromic window. Furthermore, a more sophisticated heating/cooling optimized control algorithm would be used for electrochromics in such climates. During heating periods, the electrochromic transmittance would be increased to

Table 2. Cost-Effectiveness of Electrochromic Windows[a]

	Energy Savings ($/ft^2)		Add Demand Savings ($/ft^2)		Add Chiller Credit ($/ft^2)		Add Incentive Credit ($/ft^2)	
(1) Added glazing cost/ft^2	15.00	25.00	15.00	25.00	15.00	25.00	15.00	25.00
(2) First-cost credits								
(a) Chiller	-	-	-	-	2.80	2.80	2.80	2.80
(b) Incentive	-	-	-	-	-	-	3.00	3.00
(3) Net added first cost: 1-2a-2b	15.00	25.00	15.00	25.00	12.20	22.20	9.20	19.20
(4) Annual energy savings	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52
(5) Annual demand savings	-	-	.40	.40	.40	.40	.40	.40
(6) Total annual savings: 4 + 5	2.52	2.52	2.92	2.92	2.92	2.92	2.92	2.92
(7) Simple payback (yrs): 3 ÷ 6	6.0	9.9	5.1	8.6	4.2	7.6	3.2	6.6

(a) All values are given per square foot of glazing.

allow additional light and solar heat into the space, until a glare limit was reached. We will explore such control strategies in future studies.

Conclusions

The impacts of electrochromic windows on electricity consumption, peak electricity demand, and HVAC equipment sizing were analyzed for office buildings in a hot southern California climate. Key results are summarized below.

1) Electrochromic windows can provide significant reductions in peak electricity demand and cooling, lighting, and total electricity consumption in commercial buildings in comparison to conventional tinted and reflective solar control windows, and even in comparison to recently introduced spectrally selective windows. HVAC equipment size can also be reduced using electrochromic windows. Similar savings can be achieved in a wide variety of U.S. climates.

2) The use of dimming lighting controls to take advantage of available daylight is important to the success of electrochromic windows in reducing peak electricity demand and total electricity usage.

3) For the range of window-to-wall ratios examined (0.0 to 0.6), the demand and energy benefits of electrochromic windows in comparison to conventional windows generally increase with increasing window-to-wall ratio.

4) The most significant benefit of electrochromic windows in north-facing building zones, where the associated energy and demand savings are modest, is the reduction of glare.

5) The narrow-band electrochromic window, with its wide dynamic range of visible transmittances and low shading coefficients, affords the greatest electricity savings of the window types examined in this study.

6) The broad-band electrochromic window is outperformed in certain cases by the static spectrally selective window and the reflective window because the cooling load associated with the broad-band electrochromic is higher than those associated with the other windows. The elevated cooling load is due to the range of higher shading coefficients over which the broad-band electrochromic switches (i.e., in comparison to the narrow-band electrochromic window). The addition of a reflective or selective coating on the #3 glazing surface to lower the effective shading coefficient of this electrochromic

window would reduce the associated cooling load and boost its energy performance beyond that of any static window.

7) The illuminance level control strategy used with the narrow-band electrochromic window is very effective in greatly reducing the associated lighting and cooling loads. A solar heat gain control strategy could increase the energy performance of the broad-band electrochromic window. We will explore the fine-tuning of control algorithms for energy usage and cost optimization in future work.

8) First-cost savings can accrue with electrochromics due to reduced chiller size and utility incentive programs. Collectively, these benefits can offset one-third of the target $15/ft^2 incremental cost of electrochromics. The elimination of manually operated shading devices can create additional savings.

9) By reducing solar heat gain and glare, electrochromics will provide the intangible benefits of increased thermal and visual comfort for building occupants. Additional market benefits resulting from improved image and aesthetics are similarly difficult to quantify.

10) Utilities can play an important role in facilitating market adoption and penetration of this technology by providing design tools and assistance services to help analyze electrochromic performance, and by supporting demonstration projects that provide empirical data on operation and performance.

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Endnote

1. Now with Enermodal Engineering, Inc.

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