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Abstract

This paper presents the results of a study investigating the energy performance of electrochromic windows in heating-dominated geographic locations under a variety of state-switching control strategies. We used the DOE-2.1E energy simulation program to analyze the annual heating, cooling and lighting energy use and performance as a function of glazing type, size, and electrochromic control strategy. We simulated a prototypical commercial office building module located in Madison, Wisconsin. Control strategies analyzed were based on daylight illuminance, incident total solar radiation, and space cooling load. Our results show that overall energy performance is best if the electrochromic is left in its clear or bleached state during the heating season, but controlled during the cooling season using daylight illuminance as a control strategy. Even in such heating dominated locations as Madison, there is still a well-defined cooling season when electrochromic switching will be beneficial. However, having the electrochromic remain in its bleached state during the winter season may result in glare and visual comfort problems for occupants much in the same way as conventional glazings.

Introduction

The energy performance evaluation of electrochromic glazings in commercial buildings has focused primarily on their ability to reduce cooling load by minimizing solar heat gains and reduce electric lighting by the use of natural light or daylighting [1-4]. These studies indicated that if one considers only annual and peak cooling performance, currently available electrochromic prototype devices perform about the same as conventional low-E tinted glazings at small window-to-wall area ratios and as reflective glazings at large window-to-wall area ratios. Idealized electrochromics glazings which may be available at some future date significantly outperform all types of conventional glazings. The daylighting performance of electrochromics was shown to be better than the conventional glazings that generally would be used in locations which require solar gain control. Electrochromic control strategies investigated included daylight illuminance control, variable incident solar radiation control, and space cooling load control. It was shown that daylight illuminance control provides the best overall cooling and lighting energy performance because of the large decrease in required lighting due to daylighting. Without daylighting, space cooling control was the best design option.

To date, not much work has been completed analyzing the performance of electrochromics in geographic locations which are dominated by large heating loads. Reference [5] was one such study, however, which investigated performance in Winnipeg and Toronto, Canada using

daylighting illuminance and space cooling control strategies. Results from this study indicated that electrochromics do not save as much heating energy as conventional windows with light-dimming systems and that the benefits of using electrochromics in such locations are still related to annual cooling load reduction, peak cooling demand reduction which affects the size of the air conditioning system, and lighting discomfort - all issues which are also especially important in cooling dominated locations which we have reported on previously.

Complementing our past work, we present in this report a detailed analysis of electrochromic performance in the heating-dominated location of Madison, Wisconsin. Madison is located at 43N latitude and has 4347 (7825) heating degree-days at a base temperature of 18C (65F) and is characterized by having cold winters and hot and humid summers. Results are presented for several types of currently available prototype electrochromic devices as well as devices which could be produced in the future. We also investigated the performance of a variety of electrochromic control strategies. The analysis to follow deals with annual heating energy requirements because that is the primary focus of the work; however, an analysis of cooling, lighting, and total electric energy required is also presented.

Model Description

The performance of electrochromic windows was analyzed by completing hour-by-hour DOE-2 building energy simulations to evaluate the annual energy consumption and peak demand of a prototypical commercial office building module. The module consisted of a 30.5m (100ft) square core zone, surrounded by four identical perimeter zones, each 30.5m x 4.6m (100ft x 15ft) facing four cardinal directions, Figure 1. Each perimeter zone was divided into ten office spaces of equal size with a floor-to-floor height of 3.7m (12ft) and floor-to-ceiling height of 2.6m (8.5ft). Each zone was assumed to have its own constant-volume variable-temperature HVAC system. The window-to-wall area ratio (window area expressed as a fraction of the floor-to-floor facade) was varied from 0.0 to 0.6. This represents 0.0 to 0.85 of the floor-to-ceiling wall area. The maximum available overhead lighting provided 538lux (50fc) with a power density of 16.1 W/m² (1.5 W/ft²).

We compared the performance of six electrochromic windows. Table 1 shows the solar/optical/thermal properties of the glazings. Two of the electrochromic materials have low reflectance levels typical of most devices; these are designated as types (80/20) and (80/10) representing the minimum and maximum visible transmittance levels of the electrochromic layer. These devices function primarily by changing absorptance and are intended to represent readily achievable performance. Two additional materials have reflectance levels that increase significantly in the colored state; these are designated (G) and (GX) and represent devices that may be available sometime in the future.

Each of the two low reflective glazings, (80/20) and (80/10), was combined with either of two idealized types of low-E glazings. The first, which is designated (E) is a clear glass with a low emittance; the second, designated (S), is a spectrally selective glazing with the same emittance as the (E) glazing, but a greatly enhanced reflectance in the solar infrared. The (G) and (GX) glazing types have their own selectivity and so we only combined them with the clear glass with a low emittance. Thus, the six glazings as defined in Table 1 are designated: 80/20E, 80/20S, 80/10E, 80/10S, GE, GXE. The U-factors for all the glazings were almost the same at 2.54 W/m²-K (0.45 Btu/h-ft²F) under ASHRAE winter conditions. Realistically, in such a location as

Table 1. Glazing Solar/Optical/Thermal Properties				
Electrochromic	Bleached/Colored			
	SHGC	SC	Tvis	U-Factor W/m ² -K (Btu/h-ft ² F)
80/20E	0.64/0.23	0.67/0.27	0.65/0.16	2.54 (0.45)/2.62 (0.46)
80/20S	0.52/0.20	0.55/0.24	0.65/0.16	2.58 (0.45)/2.64 (0.46)
80/10E	0.64/0.16	0.67/0.20	0.65/0.08	2.54 (0.45)/2.64 (0.46)
80/10S	0.52/0.15	0.55/0.18	0.65/0.08	2.58 (0.45)/2.64 (0.46)
GE	0.64/0.12	0.67/0.15	0.65/0.06	2.54 (0.45)/2.54 (0.45)
GXE	0.64/0.03	0.67/0.06	0.65/0.00	2.54 (0.45)/2.53 (0.45)

Note: Solar Heat Gain Coefficient (SHGC), Shading Coefficient (SC), Visible Transmittance (Tvis), and U-Factor are center-of-glass values at ASHRAE summer conditions: 35C (95F) outdoor air and 23.8C (75F) indoor air temperature, with 12.1 km/h (7.5mph) outdoor air velocity and near-normal solar radiation of 781.8 W/m² (248.2 Btu/h-ft²).

Madison, we might expect to be using glazings with lower U-factors because of the expected high heat loss in winter; however, the electrochromic prototypes used in our analysis are sufficiently insulated so that adequate heating performance is obtained.

Electrochromic window properties were varied using control strategies based on the following:

- (1) **Daylight Control:** The visible transmittance of the window was linearly modulated between bleached (unswitched) and colored (fully switched) states in order to provide a daylight illuminance of 538lux (50fc) whenever possible at a reference point located 3.05m (10ft) deep along the center line of each perimeter office space.
- (2) **Solar Control:** The properties of the window were varied linearly as a function of the incident total solar radiation between low and high switching set points. The unswitched state was assumed for incident total solar radiation values less than or equal to 63 W/m² (20 Btu/hr-ft²). Three different values for the fully-switched state were examined; i.e., the fully-switched state was assumed for incident total solar radiation values greater than or equal to 189 W/m² (60 Btu/hr-ft²), 315 W/m² (100 Btu/hr-ft²), or 630 W/m² (200 Btu/hr-ft²).
- (3) **Space Load Control:** The properties of the window changed between the unswitched and switched states based on the existence of a cooling load in the space during the previous hour. If a cooling load was not present during the previous hour, the electrochromic was set to its bleached (unswitched state); if a cooling load was present during the previous hour, the electrochromic was set to its colored (switched state).

Heating Energy Performance

The heating performance of electrochromic devices is the same as that of a conventional glazing which has the same the same U-factor and solar heat gain coefficient. However, this is only true for an electrochromic control strategy which does not result in state-switching during the winter months; in our example, which we discuss below, such a situation occurs with space cooling load control. Electrochromic devices that switch in winter and thus result in a smaller amount of beneficial solar heat gain can be expected to result in larger heating requirements than conventional glazings. The magnitude would be similar to what is seen here for the different control strategies compared to space cooling control.

We present heating energy requirements for a south-facing window on Figures 2 and 3. Figure 2 gives a presentation of heating energy variation as a function of window-to-wall area ratio and electrochromic controls strategy for each of the glazing types analyzed; while Figure 3 shows results as a function of electrochromic glazing type for each of the control strategies. In Figure 2, we see that for the electrochromic devices that are currently available; i.e., 80/10E, 80/10S, 80/20E, and 80/20S, there is a maximum difference in performance of only 10% at the largest window size for the different control strategies. For these glazings, space cooling load control yields the best results. This is because space cooling is generally not required in the winter heating season and therefore the electrochromic devices are in their clear state resulting in more beneficial solar heat gain. Beneficial winter solar heat gain is also provided using incident solar control with a wide setpoint range of 63-630 W/m² (20-200 Btu/hr-ft²).

For the GE and GXE devices, we see a large difference in heating performance in Figure 2 for the different control strategies, especially the results using space cooling load control (where there is really no control since there is no required cooling in the winter heating season) which yields substantially lower heating than any of the other strategies - up to 30% lower, for example when compared to daylight illuminance control. The wide setpoint range for incident solar radiation control strategy results in about a 15% reduction in required heating when compared to daylight illuminance control or the smaller setpoint range solar radiation control.

Figure 3 compares the performance of the different electrochromic glazings for each of the control strategies. We see that the E-type low-E clear glazings have about 10% lower heating energy values than the S-type spectrally selective glazing for each of the window-to-wall area ratios and control strategies. This is a direct result of the higher solar heat gains associated with the E-type glazings. The GE glazing consistently performs better than the GXE glazing, from 10-20%, for all control strategies except for space cooling load control, in which case the performance is about equal. As stated previously, space cooling control is not implemented in winter and so the heating performance of the GE and GXE should be the same because their bleached properties are the same.

Cooling, Lighting, and Total Electric Energy Performance

Cooling performance, including fan energy, is shown on Figure 4. With the exception of the GE and GXE glazings, the variation is typical; i.e., increased cooling with increased window-to-wall area ratio. In general, the E-type glazings require about 10% more cooling than the S-type glazings with not much variation between the different electrochromic control strategies. The largest amount of cooling occurs when using incident solar control with a wide setpoint range of

63-630 W/m² (20-200 Btu/hr-ft²). For the E-type glazings, this control strategy requires 25% more cooling than the others; for the S-type glazings, 10-15% more cooling is required.

There is not much variation in required cooling with window size for the GE and GXE glazings except for the space cooling load control device. These glazings have very low solar transmission in the colored state and cooling performance can be made almost independent of window size. Work reported in [2], which analyzed other types of electrochromic devices, showed that space cooling load control provides optimum cooling; however, for the particular electrochromics analyzed in this study, this was not the case and such counter-intuitive results indicate that further analysis is warranted. In all probability, these results are more related to the part load characteristics of the cooling system than to electrochromic glazing or control strategy performance.

Figure 5 presents required lighting energy for the electrochromic glazings and control strategies. Daylight illuminance provides the best control followed by incident solar radiation control in order of decreasing setpoint range; space load control provides the least amount of lighting energy savings from daylighting. Daylight saturation is achieved using daylight illuminance control for a window-to-wall area ratio approaching 0.25. The other control strategies do not achieve saturation, if at all, until window-to-wall area ratios approaching 0.60.

Total electricity consumption due to cooling, fan energy for cooling and heating, and lighting is presented on Figure 6 and 7. Figure 6 gives a presentation as a function of window-to-wall area ratio and electrochromic control strategy for each of the glazing types analyzed; while Figure 7 shows results as a function of electrochromic glazing type for each of the control strategies. Performance results are much more dependent on electrochromic control strategy than on glazing type.

The trends with window-to-wall ratio are very similar to those seen in Figure 5 for lighting energy use. Daylight illuminance control provides the best overall electric energy performance with minimum values occurring at window-to-wall area ratios of 0.25-0.30 for the 80/10 and 80/20 glazing types. The GE and GXE glazings, however, have a minimum extending to window-to-wall area ratios of 0.45-0.50 when using daylight illuminance control. This is a direct result of the reduced cooling energy required combined with lighting energy reduction from daylighting.

Space cooling load control of the electrochromic results in the largest amount of total electricity use, primarily because such control does not provide an adequate daylight increment to reduce the lighting energy use. This is also the situation when using a narrow setpoint incident solar radiation control. As the setpoint range increases, total electric performance tends toward that resulting from daylight illuminance control. This is more clear in Figure 7 for each of the glazings where we see the progression from essentially optimum total electricity use using daylight illuminance control, followed by the wide, medium, and narrow setpoint incident solar control, and lastly, space load control.

One of the surprising results of the work reported in [2] was that peak electricity consumption for a particular electrochromic glazings was insensitive to control strategy. This also appears to be the case with the electrochromic devices analyzed in this report. Figure 8 shows almost no variation in peak demand for the 80/10 and 80/20 as the control strategy is changed. The GE and

GXE glazings have a slight spread in peak demand because of the space cooling load control data, as mentioned previously. The GE and GXE peak demand is almost constant with window size. In general, we can say that the E-type glazings have larger peak demand values than the S-type glazings and the 80/20 glazing has a larger peak demand than the 80/10 glazings, as expected.

We did not specifically compare the cooling performance of electrochromic devices with conventional glazings in this study. That topic has been addressed in several other reports [1-4]. In summary, the cooling performance of currently available electrochromics is about the same as conventional reflective glazings; however, the daylighting performance of electrochromics is much better. Thus, the overall electric energy and peak performance is best with electrochromics. Electrochromic devices that may be available in the near future will outperform all types of conventional glazings, both on an annual basis and under peak cooling conditions. In addition, electrochromics facilitate better control over the thermal and visual comfort aspects within a space.

Conclusions

1. The performance of electrochromic windows in heating dominated climates will be the same as that of conventional glazings with the same U-factor and solar heat gain coefficients provided the electrochromic is prevented from changing state to a more colored condition in which beneficial solar heat gain is reduced. In our study, this condition occurs with space cooling load control. However, this is unlikely to represent a viable control strategy since it provides no glare control, which is a critical requirement for unshaded glass in non-northerly orientations.
2. There is a maximum difference in heating performance of 10% at the largest window size for the different control strategies for the 80/10 and 80/20 electrochromic glazings. This increases to a 30% difference for the GE and GXE glazings. The E-type glazings have smaller required heating than the S-type glazings for the same electrochromic control strategy because they have more beneficial solar heat gain. However, even the 30% difference in heating energy represents a cost typically of less than \$0.54/m² (\$0.05/ft²).
3. The E-type glazings require about 10% more cooling than the S-type glazings with not much variation in the difference due to control strategy. However, a control strategy based on incident solar radiation control with a wide setpoint required 25% more cooling with the E-type glazings than the other control strategies.
4. Daylight illuminance provides the best control for lighting energy use followed by a wide setpoint incident solar radiation control. Space cooling load control does not yield adequate daylighting characteristics.
5. The amount of total electric energy use is closely related to lighting energy use and therefore good daylighting performance will result in good overall electric energy performance; i.e., daylight illumination control of the electrochromics yields the best lighting performance and also the best overall electric performance; whereas, space cooling load requires the largest amount of electricity use because it does not have good daylight response.

6. There is only a small variation in peak electric demand for the different control strategies for the 80/10 and 80/20 electrochromic glazings. This is consistent with past studies. However, the peak demand for the GE and GXE glazings does vary somewhat, most probably due to the part load characteristics of the cooling system used in the analysis. Further work is required in this area.

Future Studies

Future studies of electrochromics will focus on continued evaluation of industry electrochromic prototypes as follow: (1) Analysis of additional control strategies such as incident direct solar radiation, transmitted total and direct solar radiation, space air temperature and variations in the scheduling and mixing of electrochromic control strategies. (2) Analysis of the thermal and visual comfort aspects of electrochromic glazings and comparison with more conventional type glazings. We have completed some preliminary work in this area, but correlation of comfort to specific electrochromic property variations must be documented. (3) Development of effective solar heat gain and visible transmittance parameters for electrochromic devices to give an indication of expected energy and comfort performance. This requires a statistical analysis of the hourly variation of the solar/optical properties of the electrochromic devices. (4) Continuing analysis of daylight illuminance as a control strategy using different reference points in the space.

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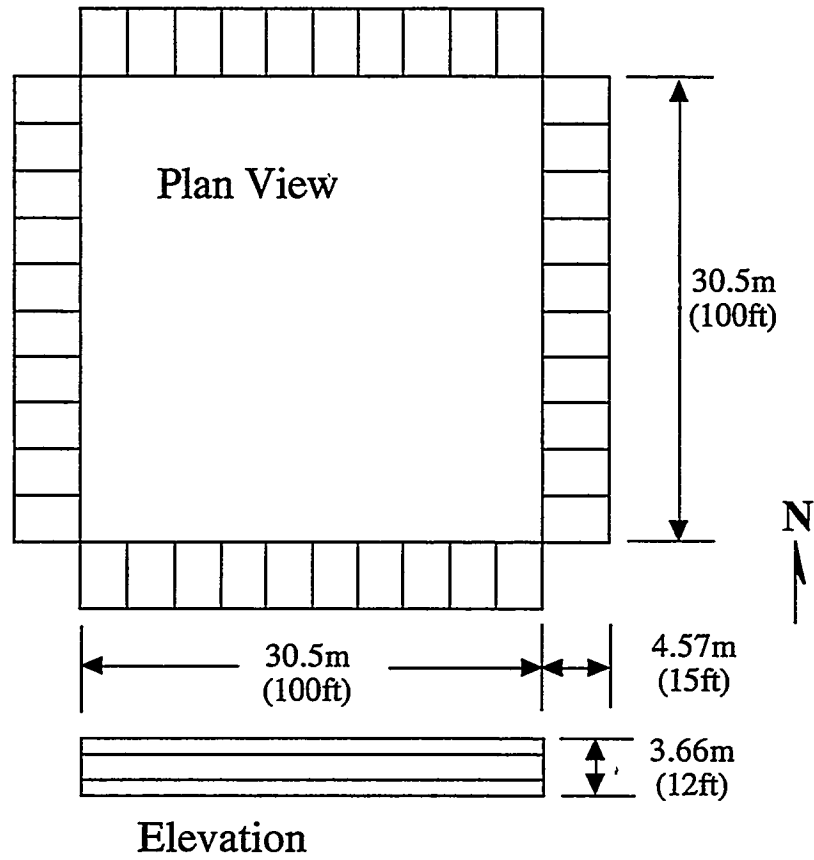


Figure 1: Commercial office building module used in the annual simulations.

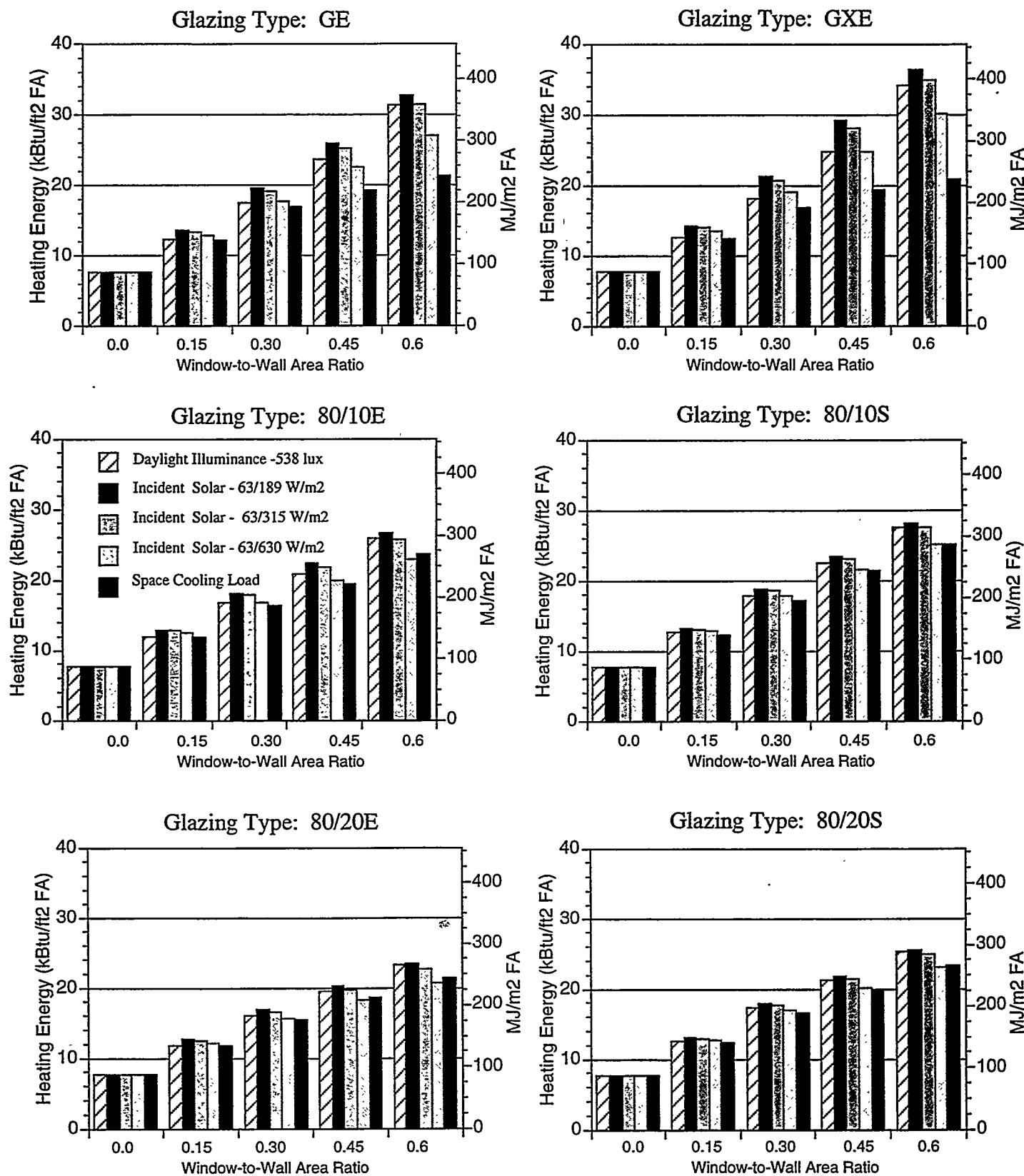


Figure 2: Annual heating energy consumption per unit floor area for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for six electrochromic glazing types and five control strategies for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m² (1.5 W/ft²).

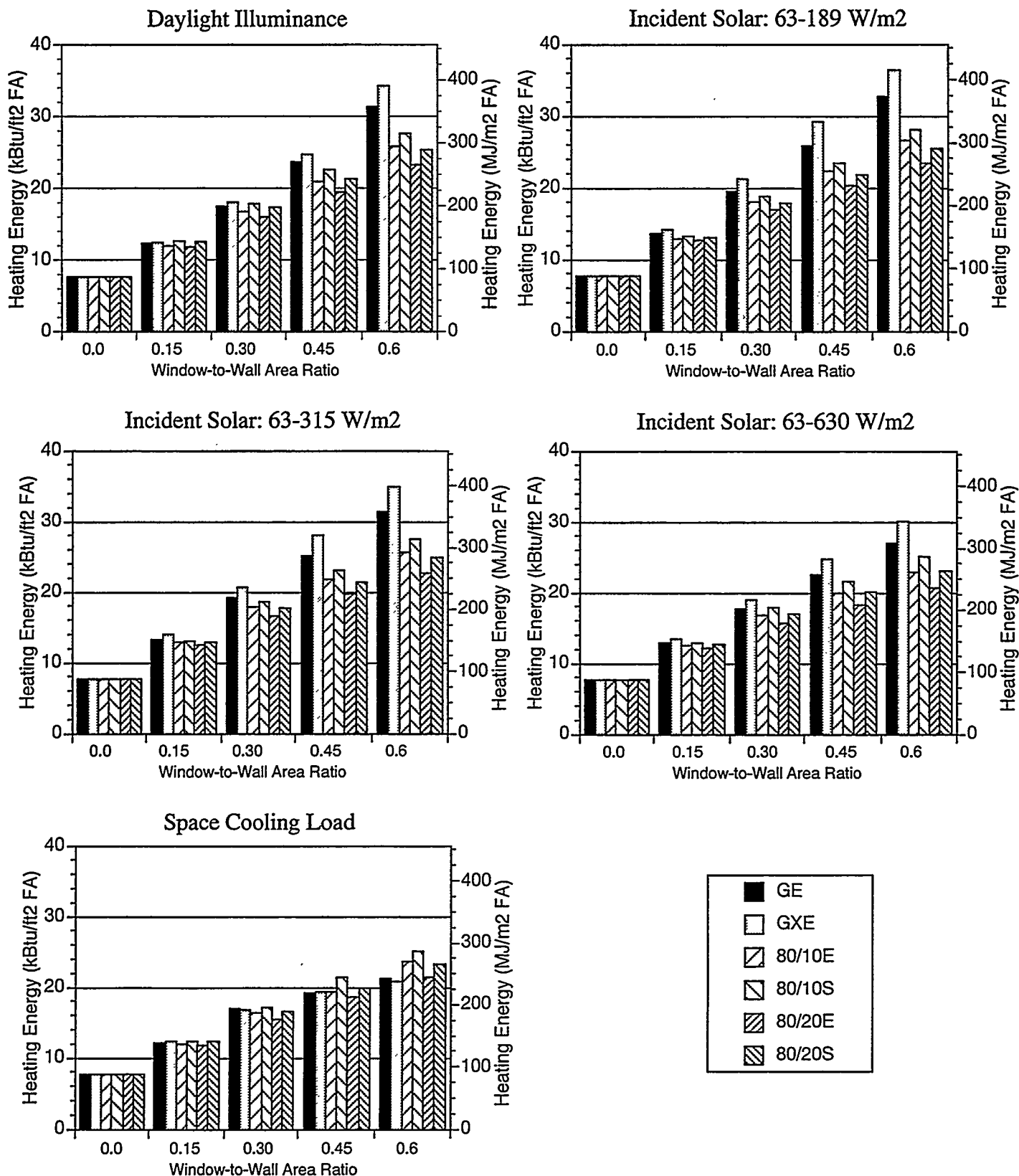


Figure 3: Annual heating energy consumption per unit floor area for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for five electrochromic strategies and six glazing types for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m² (1.5 W/ft²).

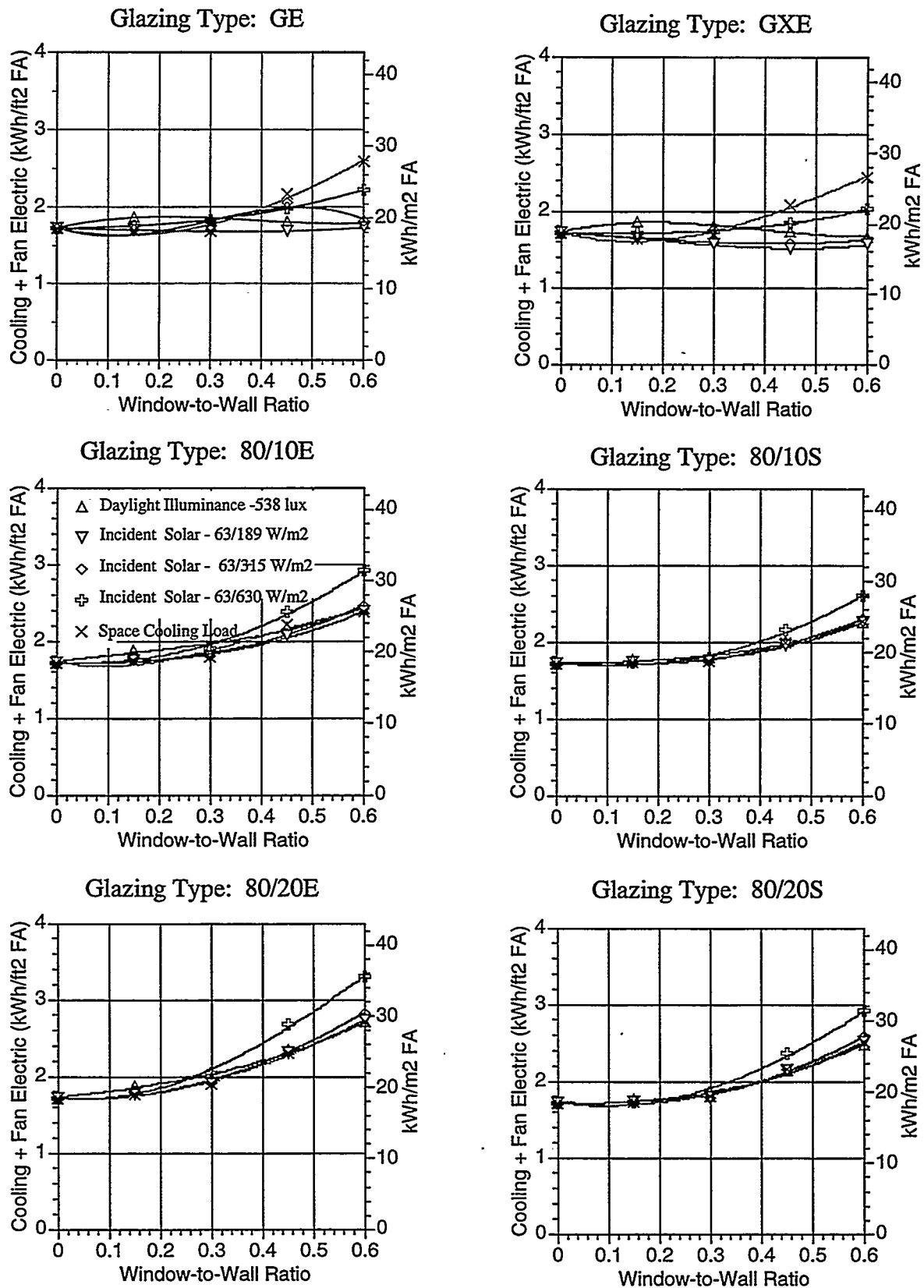


Figure 4: Annual cooling and cooling fan energy consumption per unit floor area for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for six electrochromic glazing types and five control strategies for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m² (1.5 W/ft²).

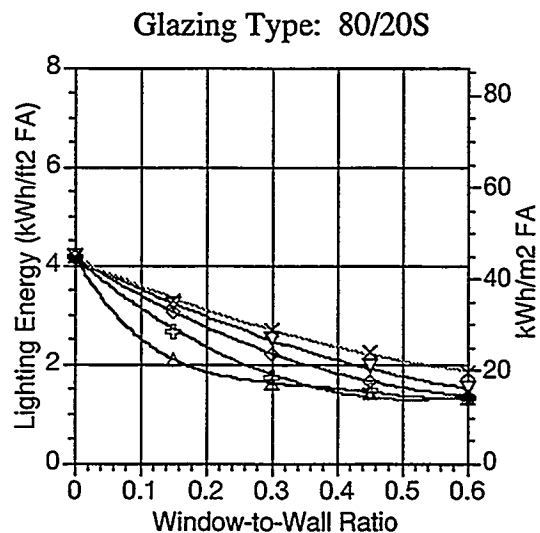
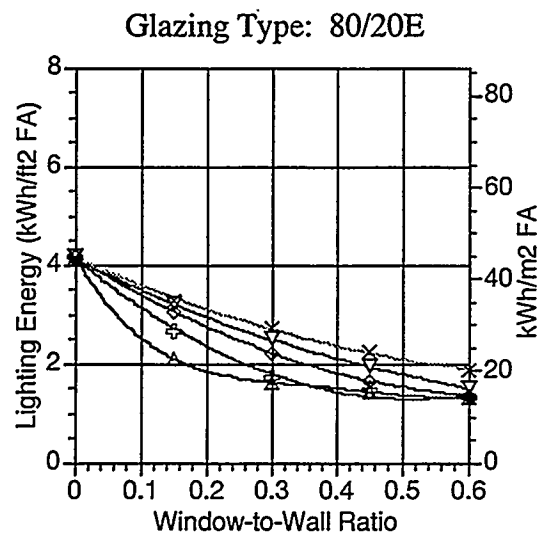
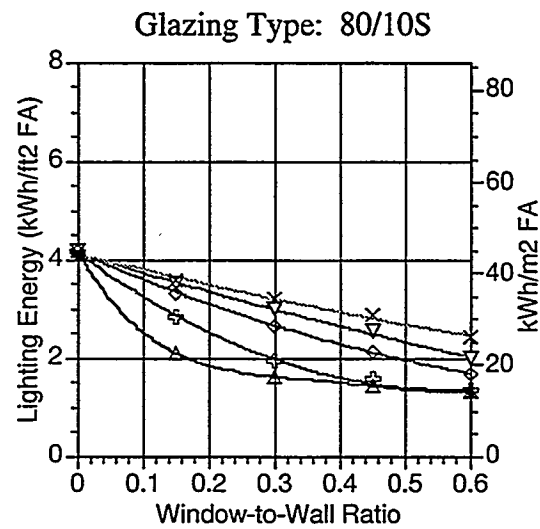
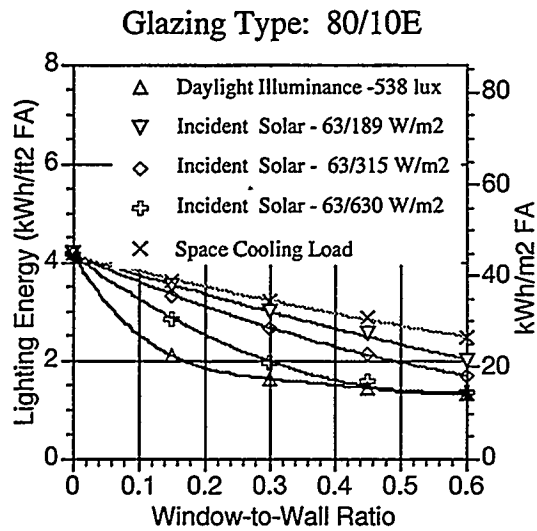
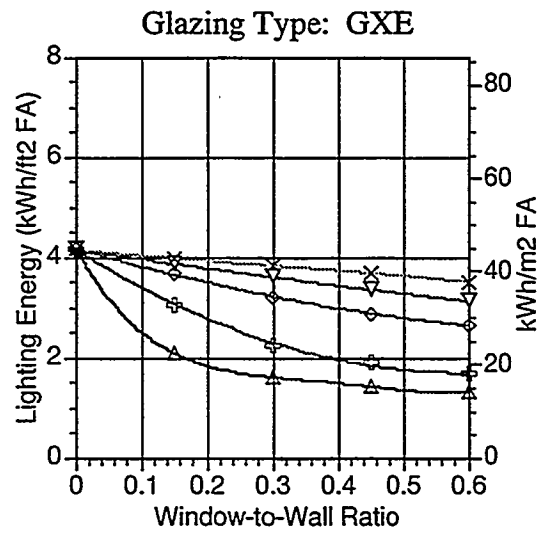
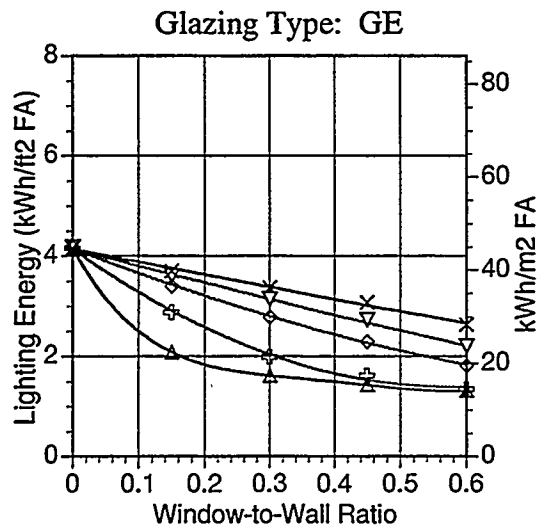


Figure 5: Annual lighting energy consumption per unit floor area for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for six electrochromic glazing types and five control strategies for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m² (1.5 W/ft²).

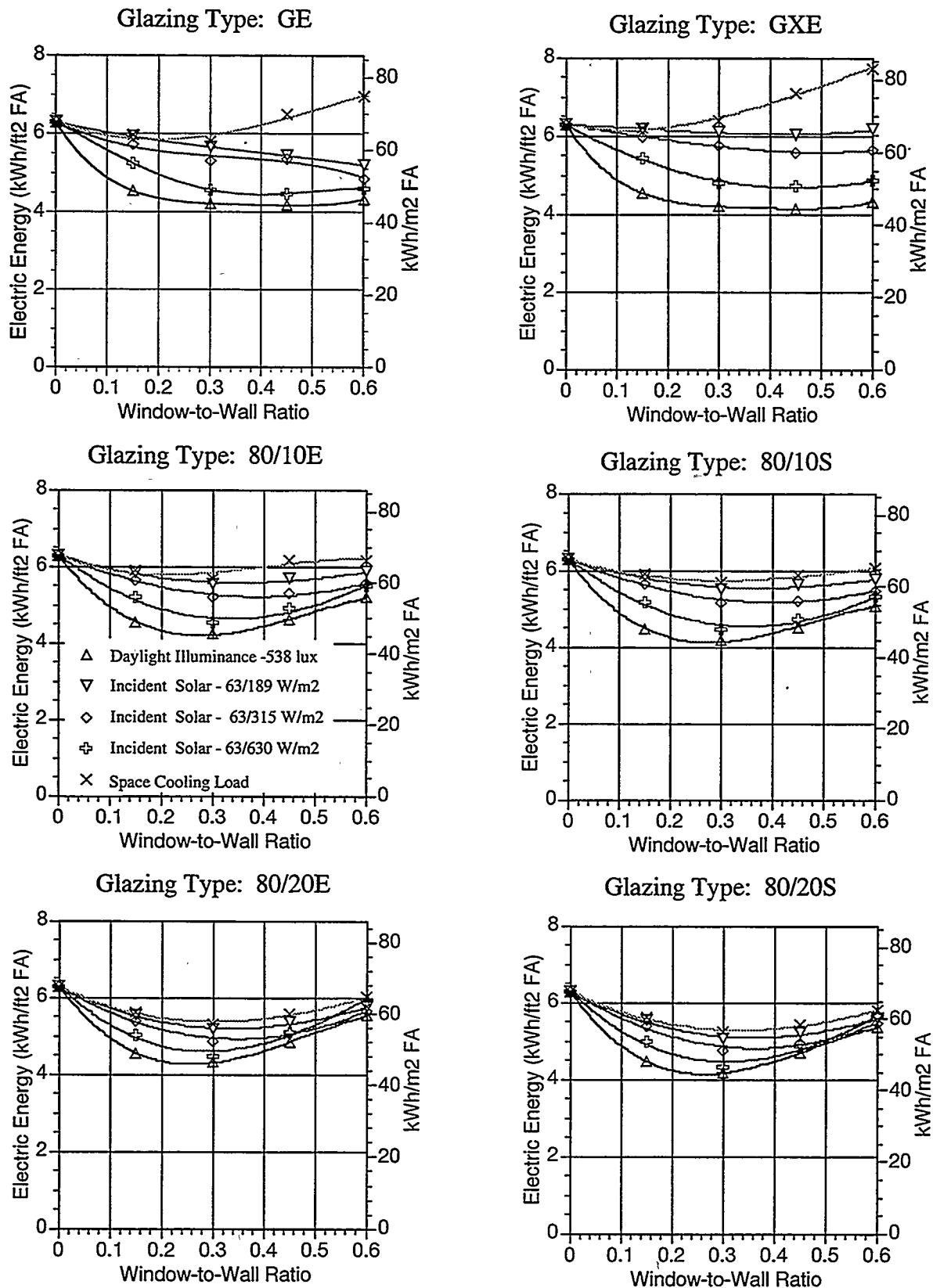


Figure 6: Annual electricity energy consumption per unit floor area due to cooling, fans for cooling and heating, and lighting for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for six electrochromic glazing types and five control strategies for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m2 (1.5 W/ft2).

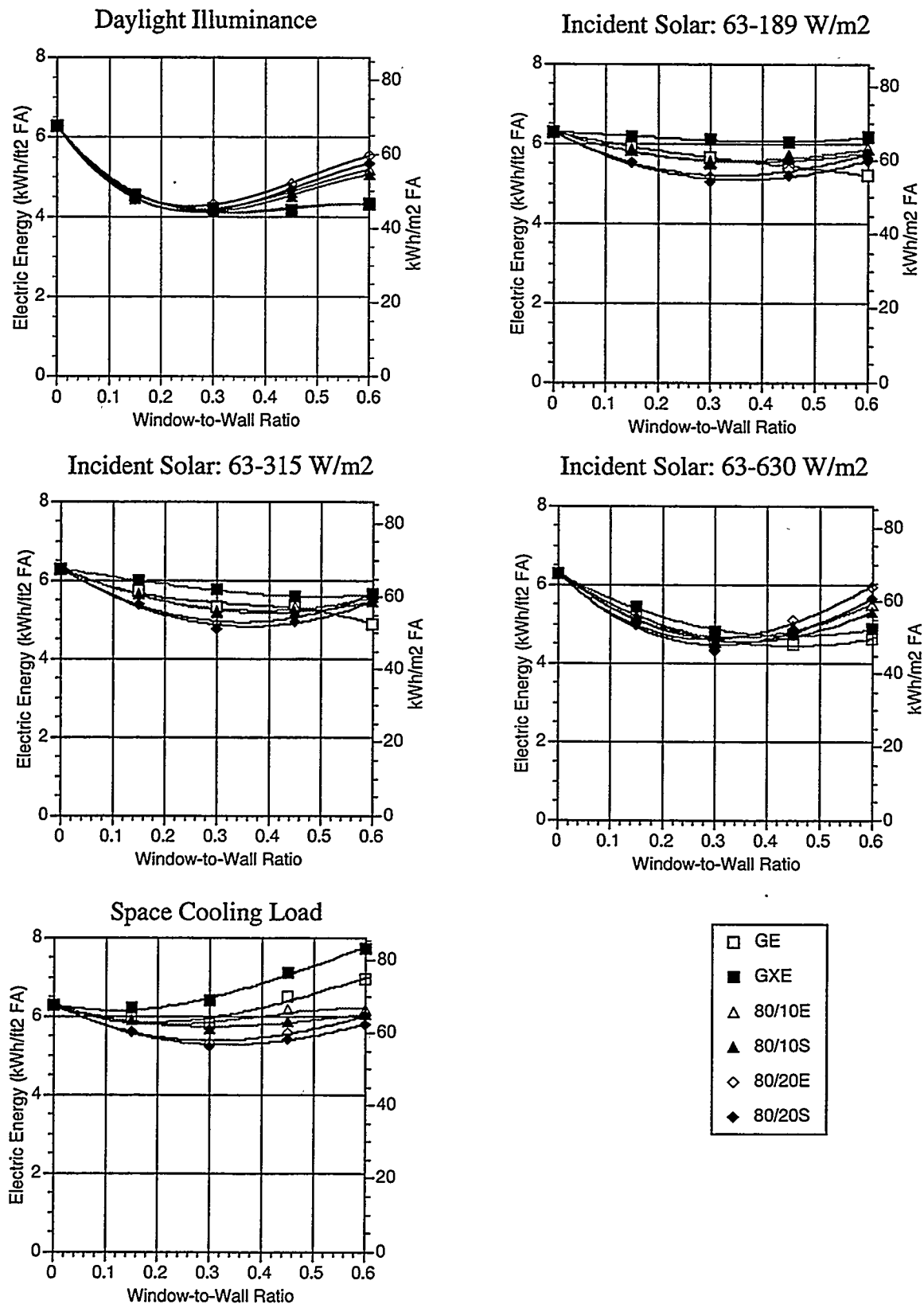


Figure 7: Annual electricity energy consumption per unit floor area due to cooling, fans for cooling and heating, and lighting for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for five electrochromic control strategies and six glazing types for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m² (1.5 W/ft²).

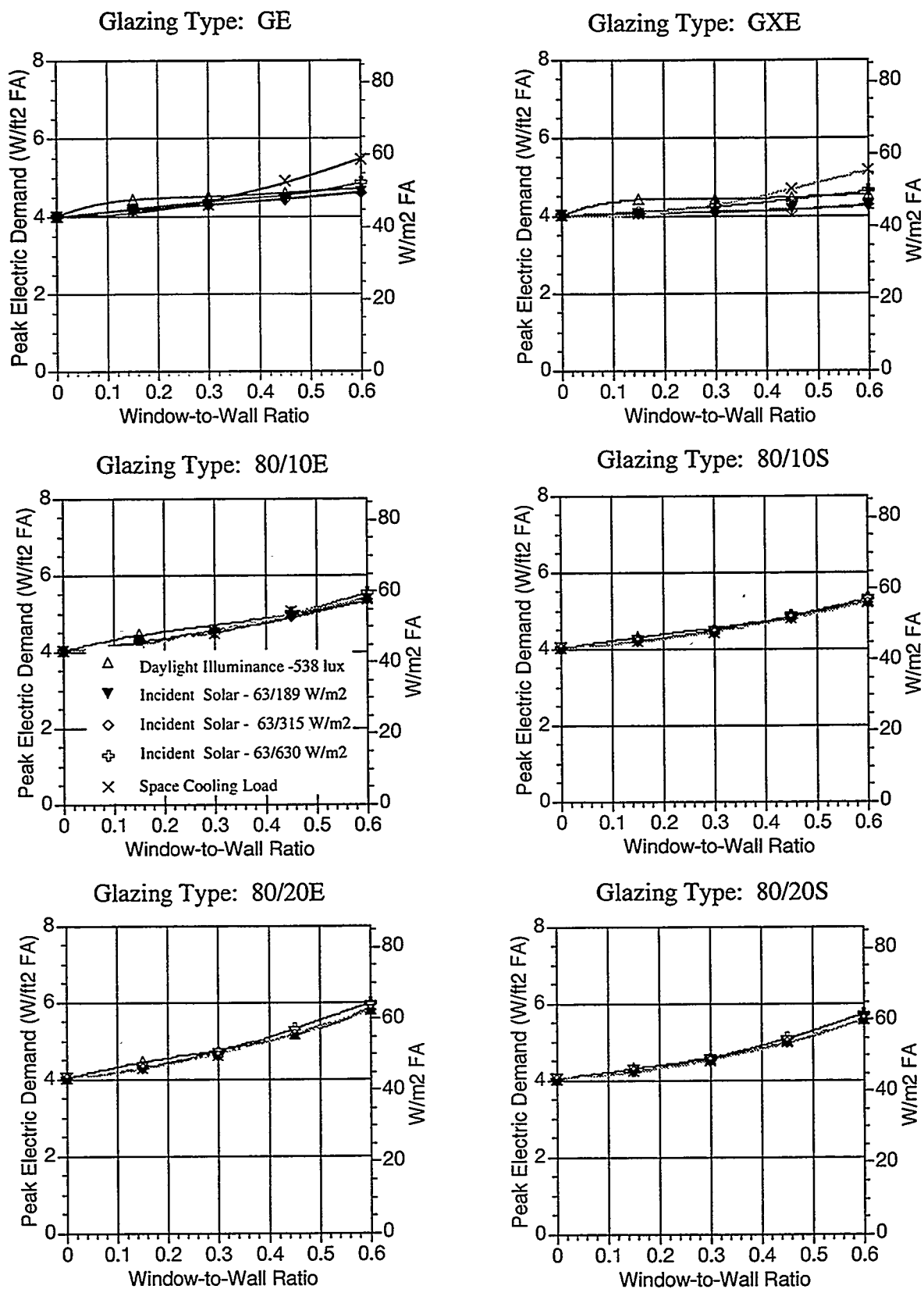


Figure 8: Peak electric demand per unit floor area for a south-facing perimeter zone in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for six electrochromic glazing types and five control strategies for varying window-to-wall area ratio. All systems use continuous dimming daylight controls and a lighting power density of 16.1 W/m² (1.5 W/ft²).