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Abstract

This paper presents the results of a study investigating the energy performance of three newly developed prototype electrochromic devices. The DOE-2.1E energy simulation program was used to analyze the annual cooling, lighting, and total electric energy use and peak demand as a function of window type and size. We simulated a prototypical commercial office building module located in the cooling-dominated locations of Phoenix, AZ and Miami, FL. Heating energy use was also studied in the heating-dominated location of Madison, WI. Daylight illuminance was used to control electrochromic state-switching. Two types of window systems were analyzed; i.e., the outer pane electrochromic glazing was combined with either a conventional low-E or a spectrally selective inner pane. The properties of the electrochromic glazings are based on measured data of new prototypes developed as part of a cooperative DOE-industry program.

Our results show the largest difference in annual electric energy performance between the different window types occurs in Phoenix and is about 6.5 kWh/m^2 floor area (0.60 kWh/ft^2) which can represent a cost of about \$.52/m^2 (\$.05/ft^2) using electricity costing \$.08/kWh. Much larger differences exist when electrochromic windows are compared to conventional glazings in use today. At large window sizes, such energy savings can be as large as 90 kWh/m^2 (8.4 kWh/ft^2). Specific electrochromic performance varies with window-to-wall area ratio; i.e., at low ratios, one type electrochromic performs best, while at large ratios, another type performs best. In general, an electrochromic glazing combined with a spectrally selective glazing is better than one combined with a low-E glazing; however, at low-window-to-wall area ratios, this situation reverses slightly. There is almost no difference in peak electric demand for the different electrochromic windows analyzed.

In heating-dominated locations, the electrochromic should be maintained in its bleached state during the heating season to take advantage of beneficial solar heat gain which would reduce the amount of required heating. This also means that the electrochromic window with the largest solar heat gain coefficient is best. The largest heating energy performance difference in Madison for the various window types is 43 MJ/m^2 floor area (4.0 kBtu/ft^2). This represents a cost of about \$.26/m^2 floor area (\$.024/ft^2) using gas costing \$0.60/therm (\$5.69/GJ, \$6.00/MBtu). However, a non-switching electrochromic will not provide desired glare control so that a control strategy that minimizes winter heating use may not be routinely desirable in many buildings.

Introduction

Electrochromic windows have received much attention recently by both government and industry representatives. The U.S. Department of Energy has been sponsoring an "Electrochromics Initiative" aimed at developing viable electrochromic window prototypes. Various U.S. manufacturers are participating in the initiative and several national laboratories are working with them to improve their devices and evaluate device energy performance. The primary reason for this activity is because electrochromics are the most promising futuristic "smart windows" in the sense that they have the ability to change their solar/optical properties using control variables such as incident or transmitted solar radiation, daylight illuminance, ambient air temperature, space thermal load, etc. Thus, unlike more conventional glazings, they provide an opportunity to optimize the energy and comfort performance of windows, and to change dynamically to meet changing functional building requirements.

In the case of buildings located in cooling-dominated locations, electrochromic windows can significantly reduce cooling loads by providing a very low solar heat gain coefficient. They can also reduce lighting loads by maintaining a sufficiently high visible transmittance to achieve good daylighting characteristics but providing glare control when needed. In heating-dominated locations, electrochromic windows can be controlled during the heating season to provide desired solar heat gain and thus reduced heating load; and, if there is also a brief cooling season, the windows can function as they would in a cooling-dominated location.

The work reported in this paper continues past efforts (Refs. 1, 2, 3, 4) in which various aspects of the energy performance of electrochromics windows were analyzed. Unlike these previous studies, however, in which the simulated electrochromic windows were hypothetical, the windows in this report are state-of-the art prototypes currently under development. Optical properties of the electrochromic layer were measured in our laboratory and then combined with other glazing layers to create several types of double glazed electrochromic systems. We analyzed these devices by completing hour-by-hour DOE-2 building energy simulations (Ref. 5) of a prototypical commercial office building module. Results from three geographic locations were obtained: cooling-dominated locations of Phoenix, AZ (hot and dry) and Miami, FL (hot and humid) and the heating dominated location of Madison, WI which also has a mildly hot and humid summer.

The building module, shown in Figure 1, consisted of a 30.5m (100ft) square core zone, surrounded by four identical perimeter zones, each 30.5m by 4.6m (100ft x 15ft) facing four cardinal directions. 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 parametrically from 0.0 to 0.60. Lighting power density was 16.1 W/m^2 (1.5 W/ft^2).

We simulated six window systems from three manufacturers (M1, M2, M3), each consisting of an outer pane of clear glazing with an electrochromic layer on the number 2 surface and an inner pane which was either a conventional high transmittance low-E or a spectrally selective low-E glazing selected for its low value of solar heat gain coefficient and high visible transmittance.

Table 1 presents the solar/optical/thermal characteristics of the window systems. We varied the solar/optical properties of the electrochromic windows using a daylight control strategy in which 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) at a reference point located 3.5m (10ft) deep along the center line of each perimeter office space:

Table 1. Window Solar/Optical/Thermal Properties

	SHGC	SC	Tvis	U-Factor - COG
Electrochromic	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored	W/m^2-K (Btu/h-ft^2F) Bleached/ Colored
M1/ Clear-Low E	0.45/0.11	0.52/0.13	0.61/0.07	1.77 (0.31)/1.77 (0.31)
M1/ Clear-SpecSel	0.38/0.10	0.44/0.12	0.57/0.06	1.69 (0.30)/1.69 (0.33)
M2/ Clear-Low E	0.46/0.10	0.53/0.12	0.66/0.06	1.77 (0.31)/1.77 (0.31)
M2/ Clear-SpecSel	0.38/0.10	0.44/0.12	0.60/0.05	1.69 (0.30)/1.69 (0.30)
M3/ Clear-Low E	0.37/0.10	0.43/0.12	0.51/0.08	1.72 (0.30)/1.72 (0.30)
M3/ Clear-SpecSel	0.31/0.10	0.36/0.12	0.47/0.08	1.67 (0.29)/1.67 (0.29)
Conventional				
Tinted Bronze	0.49	0.57	0.47	2.74 (0.48)
Reflective Clear	0.17	0.20	0.13	2.35 (0.41)
Spectrally Selective	0.29	0.34	0.41	1.67 (0.29)

Note: SHGC, SC, and Tvis are values at ASHRAE summer conditions: 35C (95F) outside temperature, and 24C (75F) inside temperature, 3.3 m/s (7.5 mph) wind speed, and near-normal incident solar radiation of 783 W/m^2 (248 Btu/h-ft^2). U-factor are values at ASHRAE winter conditions: -17.8C (0F) outside temperature, and 21.1C (70F) inside temperature, 6.71 m/s (15 mph) wind speed, and zero incident solar radiation.

Discussion

Figures 2 and 3 present, for a west-facing perimeter zone, cooling and fan energy, lighting energy, and the summed total electric energy for each of the six electrochromic windows in Phoenix and Miami. Past studies (Refs. 1, 2, 3) have shown the value of separating cooling and fan and lighting energy to better understand the performance of window systems. The cooling and fan energy component gives an indication of a window's solar heat gain characteristics; whereas, the lighting energy component shows daylighting performance.

In both locations, cooling and fan energy increases with window size. Also, since the colored state of all the windows is about the same with a solar heat gain coefficient of 0.10, the relative performance of the windows is proportional to the bleached state of the electrochromic. For example, in Phoenix, the M1 and M2 devices with a conventional low-E (SHGC = 0.45 and 0.46 in the bleached state) require 72 kWh/m^2 floor area (6.7 kWh/ft^2) at a window-to-wall ratio of 0.60; the M3 device with the spectrally selective glazing (SHGC = 0.31) requires 65 kWh/m^2 (6.0 kWh/ft^2). In Miami, the comparable values are 62 kWh/m^2 (5.8 kWh/ft^2) and 57 kWh/m^2 (5.3 kWh/ft^2), respectively.

With daylighting, lighting energy performance is a function of the window-to-wall area ratio and the visible transmittance of the glazing for a given control strategy. Typically, performance improves with increasing window-to-wall area ratio until daylight saturation occurs. At this point, the 538 lux (50fc) illumination level is met under cloudy or sunny conditions, so that making the window larger provides almost no additional savings. Also, the smaller the visible transmittance, the larger is the required lighting energy. In Phoenix, the M3 device with the spectrally selective glazing requires 12.3 kWh/m^2 floor area (1.15 kWh/ft^2) at a window-to-wall ratio of 0.60; the M1 and M2 devices with the conventional low-E require 11.4 kWh/m^2 (1.06 kWh/ft^2). Lighting performance in Miami is essentially the same as in Phoenix. In addition, the difference in required lighting energy for the various windows is somewhat larger at window-to-wall area ratios less than 0.60.

Figures 2 and 3 also show the summed electric energy for the six window systems, however, we also present this data on Figure 4. We see that in Phoenix a window-to-wall area ratio of 0.60, the M3 device with a spectrally selective glazing requires the least amount of total electric energy [77 kWh/m^2 floor area (7.2 kWh/ft^2)]. The largest difference in annual electric energy performance between the different electrochromic windows at this window-to-wall ratio is about 6.5 kWh/m^2 floor area (0.60 kWh/ft^2) which can represent a cost of about $\$.52/m^2$ ($\$.05/ft^2$) using electricity costing \$.08/kWh. At a window-to-wall ratio of 0.15, the M2 device with either conventional low-E or spectrally selective requires the least amount of electric energy [68 kWh/m^2 (6.4 kWh/ft^2)]. However, we also note that the differences are relatively small at small window sizes. It is important to realize that the performance of these window systems could be made identical by simply introducing additional controls to limit the bleached or colored states of the electrochromic.

Figure 5 compares the total annual electric energy use of the spectrally selective electrochromic windows to more conventional glazings. Results are very similar to past studies. For annual cooling and fan energy, a reflective glazing with a low solar heat gain coefficient compares favorably to electrochromic devices. However, the lighting energy performance of a reflective glazing is not very good and therefore the summed energy of the electrochromics is better. In Phoenix, the difference between the best performing electrochromic window and the reflective window is 28 kWh/m^2 floor area (2.6 kWh/ft^2) at a window-to-wall ratio of 0.60 which can represent a cost of about $\$2.24/m^2$ ($\$.21/ft^2$) using electricity costing \$.08/kWh. In Miami, the difference is 23 kWh/m^2 (2.2 kWh/ft^2). A spectrally selective glazing, because of its solar control and daylighting capability, performs better than the reflective glazing at small window-to-wall area ratios.

Figure 6 compares peak electric demand for the electrochromic spectrally selective windows with the conventional glazings. The electrochromics have approximately the same peak demand at each window-to-wall ratio because, under peak conditions, the electrochromics are in their most colored states, which are very similar for the windows analyzed. The nearest conventional window being the reflective glazing. In Phoenix, the difference in peak demand between the electrochromic windows and the reflective window is about is 12.5 W/m^2 floor area (1.2 W/ft^2) at a window-to-wall ratio of 0.60. In Miami, the difference is 8.5 W/m^2 (0.8 W/ft^2).

Heating energy use in Madison for four orientations is presented on Figure 7 and 8. In Ref. 5, we suggested that the electrochromic maintain its bleached state during that time of the year when heating is required so that beneficial solar heat gain can be used to reduce the amount of required heating. This is further substantiated when comparing Figures 7 and 8. Figure 7 shows the required heating with the electrochromic being controlled to maintain a daylight illuminance level of 500 lux (50fc), while Figure 8 presents results in which the electrochromic is held in its bleached state throughout the heating season (performance in this case would correspond to a conventional glazing with the same solar/optical properties). There is a significant difference in heating performance for south-, east-, and west-facing windows for window-to-wall ratios equal to 0.30 and larger. At smaller window-to-wall ratios, there is not as much solar gain to utilize. For west-facing windows, using an M1 device with a conventional low-E, required heating is 286 MJ/m^2 (25.1 $kBtu/ft^2$) when controlling the electrochromic window. If maintained in its bleached state, required heating is 159 MJ/m^2 (14.0 $kBtu/ft^2$). This difference represents a cost of about \$.90/m^2 floor area (\$.084/ft^2) using gas costing \$0.60/therm (\$5.69/GJ, \$6.00/MBtu).

There is almost no difference in heating performance for the various electrochromic windows when they are being controlled, as seen on Figure 7. However, when not controlled (Figure 8), electrochromic devices with a high transmission low-E result in lower heating than those with a spectrally selective glazing. This is because of the higher solar heat gain coefficient of the low-E. In addition, the higher SHGC of the M1 and M2 windows compared to the M3, also results in lower required heating. For a west-facing window, the largest difference in performance occurs at a window-to-wall area ratio of 0.60 between the M2 low-E and the M3 spectrally selective and is 43 MJ/m^2 floor area (4.0 $kBtu/ft^2$). This represents a cost difference of about \$.26/m^2 floor area (\$.024/ft^2) using gas costing \$0.60/therm (\$5.69/GJ, \$6.00/MBtu).

The strategy of maintaining electrochromics in their bleached state during the heating season should be qualified since, in occupied buildings, there may be the need for glare control and blocking of direct sunlight. In such cases, control of the electrochromic will probably be necessary.

Conclusions

The following conclusions can be stated for the electrochromic devices analyzed in this study.

1. In general, there is not much difference in energy performance between the electrochromic devices simulated because their solar/optical properties are similar; however, there are larger differences with respect to conventional glazings.

2. The annual cooling and lighting electric energy performance of the electrochromic windows varies as a function of window-to-wall area ratio and each particular window's solar heat gain coefficient and visible transmittance.

3. For small window-to-wall ratios, the reduction in lighting energy due to daylighting is generally larger than the increase in required cooling energy due to solar heat gain. Therefore, an electrochromic with a high visible transmittance in the bleached state is recommended.

4. At large window-to-wall ratios, daylight saturation occurs for all the electrochromic windows at about the same level of required lighting and so performance is mostly a function of the window's solar heat gain coefficient.

5. There is almost no difference in peak electric demand between the different electrochromic windows.

6. In the case of heating, the electrochromic should be maintained in its bleached state during the heating season to take advantage of beneficial solar heat gain which would reduce the amount of required heating. However, this may conflict with the need to provide glare control as well as control of direct sunlight in some cases.

Acknowledgments

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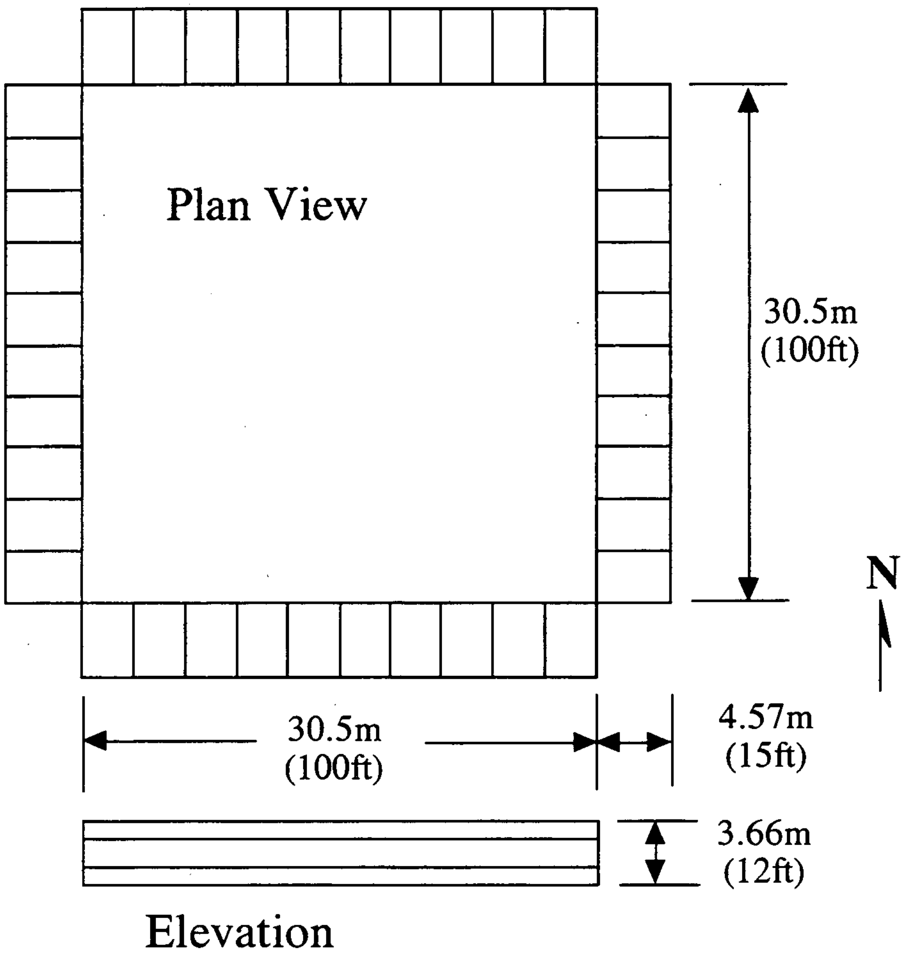


Figure 1. Commercial office building module used in the simulations.

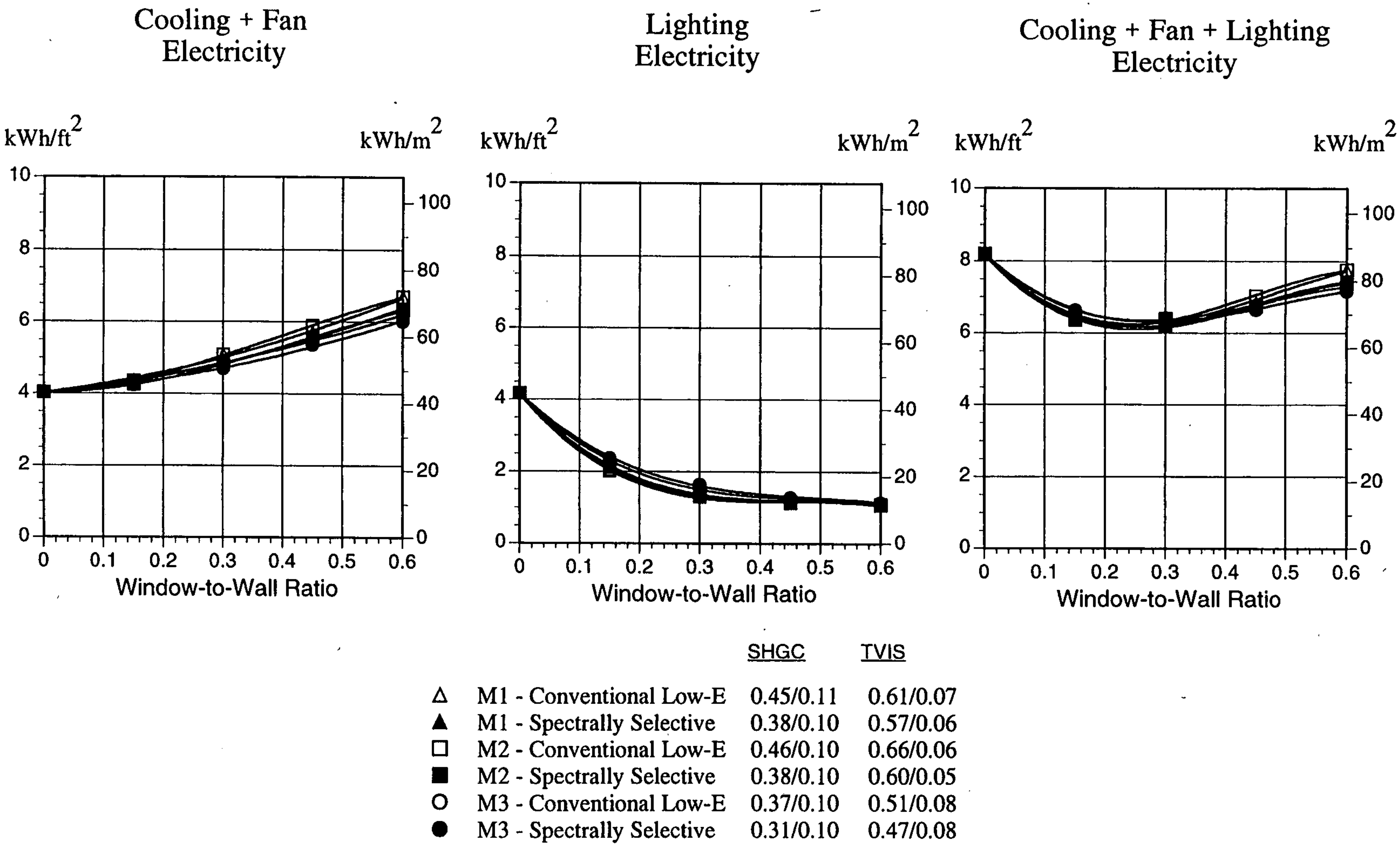
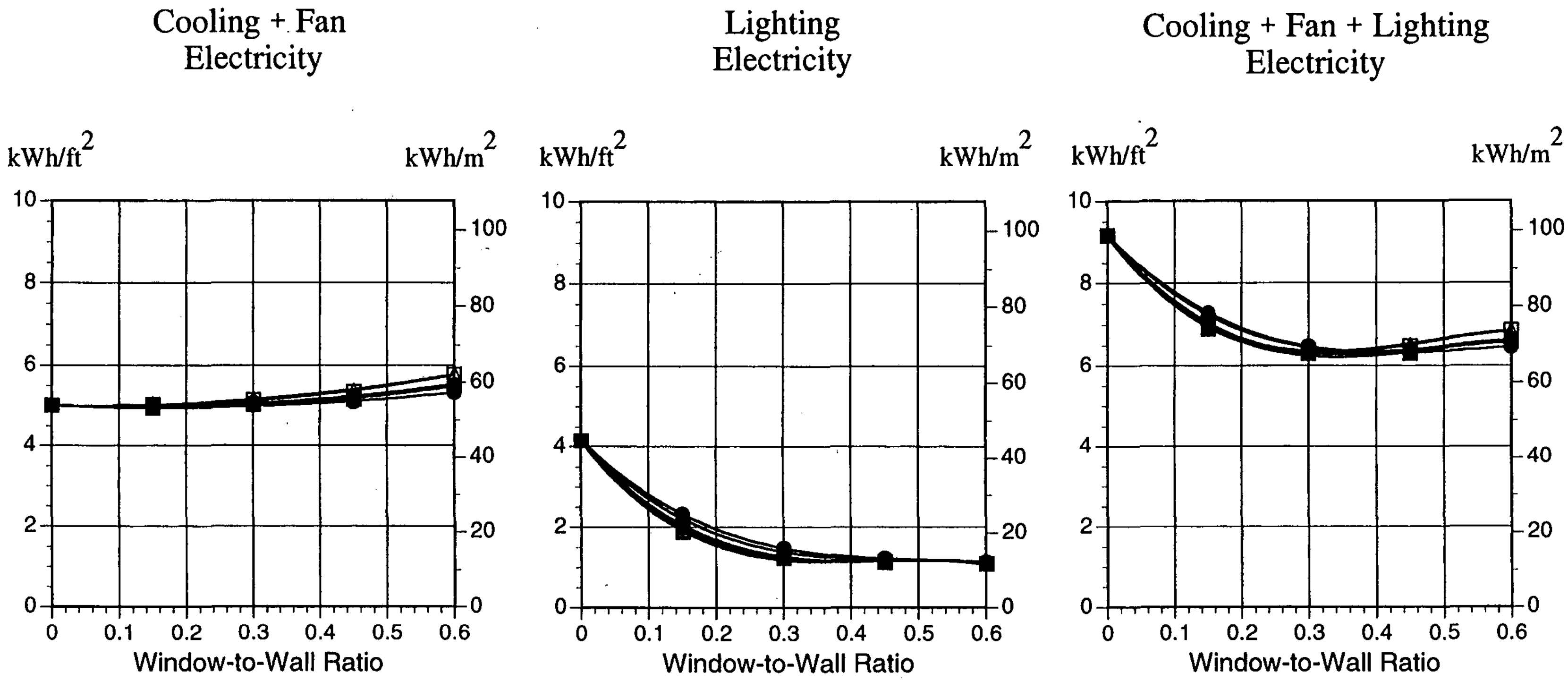
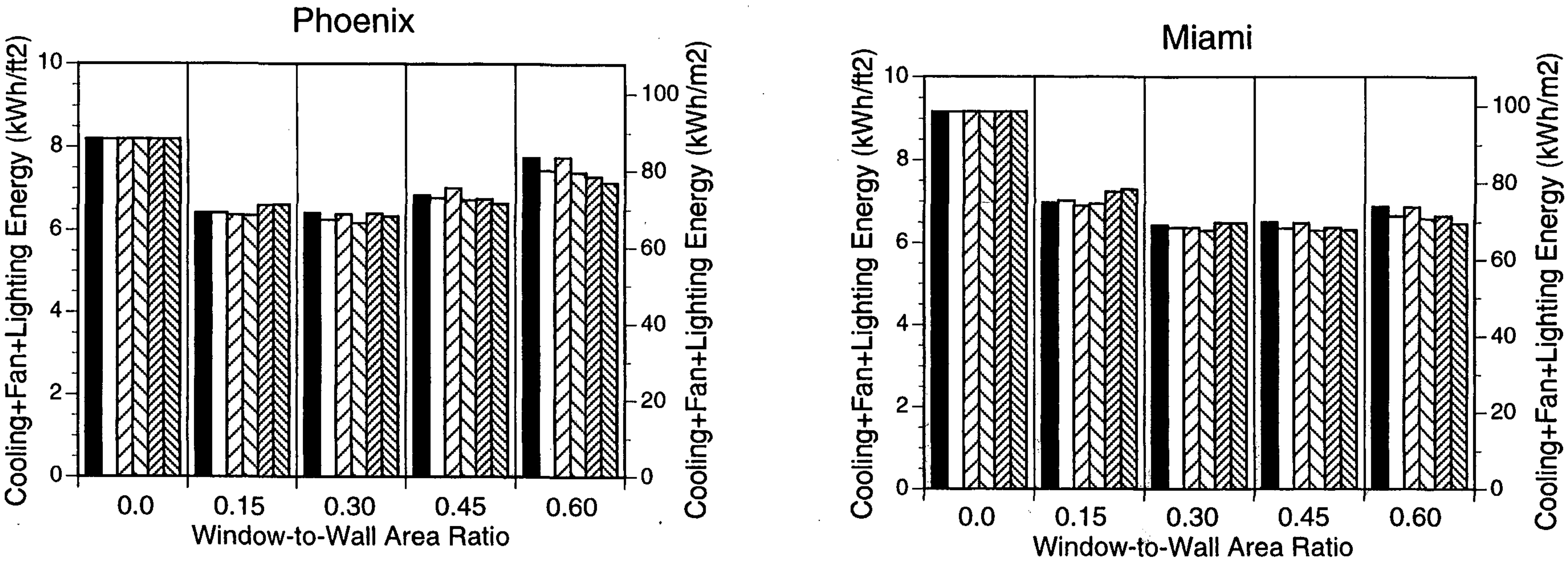


Figure 2. Annual electricity consumption due to cooling, fans, and lighting for a west-facing perimeter zone in a prototypical commercial office building module located in Phoenix Arizona. Results are shown for M1, M2, and M3 electrochromic devices in two types of windows (spectrally selective and conventional low-E). The electrochromic windows are controlled to maintain an illuminance level of 50 fc (538 lux). All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/ft^2 (16.1 W/m^2).



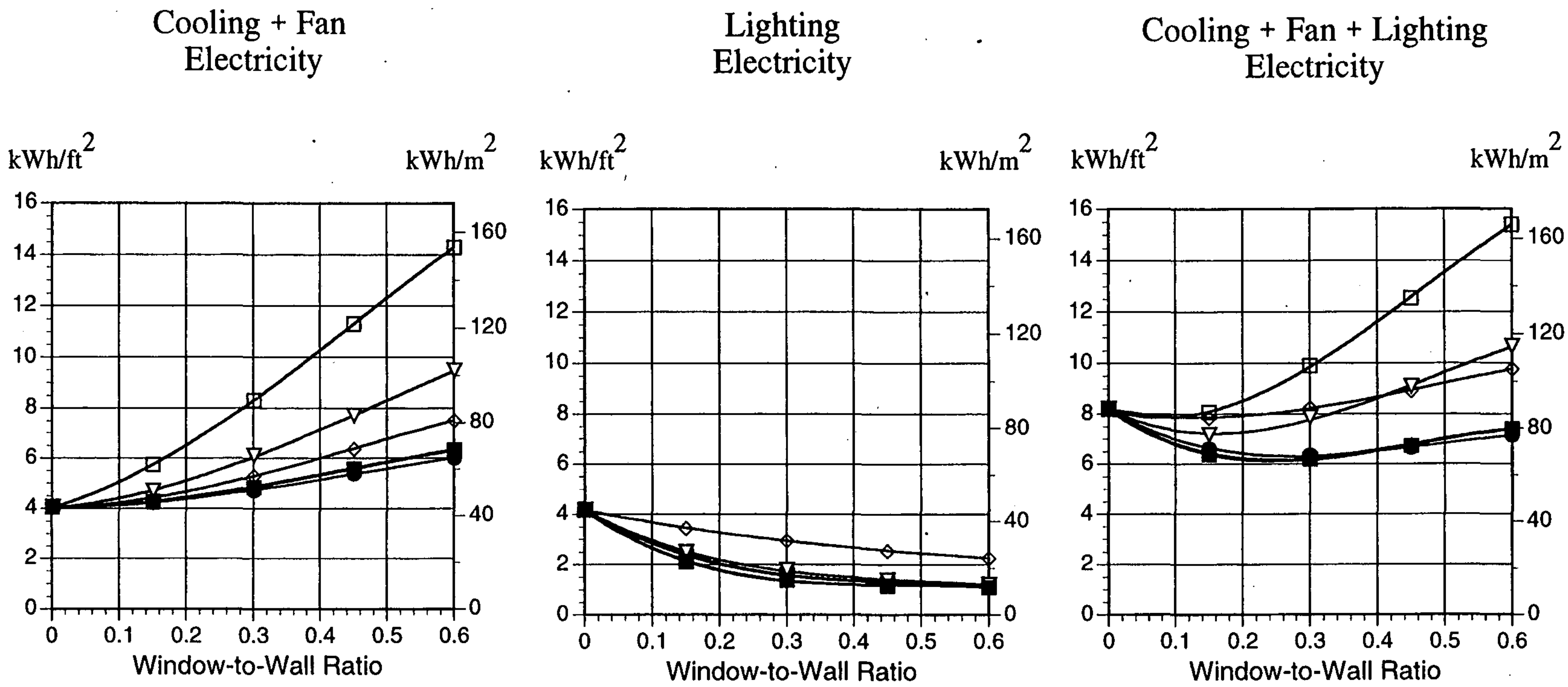
		SHGC	TVIS
△	M1 - Conventional Low-E	0.45/0.11	0.61/0.07
▲	M1 - Spectrally Selective	0.38/0.10	0.57/0.06
□	M2 - Conventional Low-E	0.46/0.10	0.66/0.06
■	M2 - Spectrally Selective	0.38/0.10	0.60/0.05
○	M3 - Conventional Low-E	0.37/0.10	0.51/0.08
●	M3 - Spectrally Selective	0.31/0.10	0.47/0.08

Figure 3. Annual electricity consumption due to cooling, fans, and lighting for a west-facing perimeter zone in a prototypical commercial office building module located in Miami, Florida. Results are shown for M1, M2, and M3 electrochromic devices in two types of windows (spectrally selective and conventional low-E). The electrochromic windows are controlled to maintain an illuminance level of 50 fc (538 lux). All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/ft^2 (16.1 W/m^2).



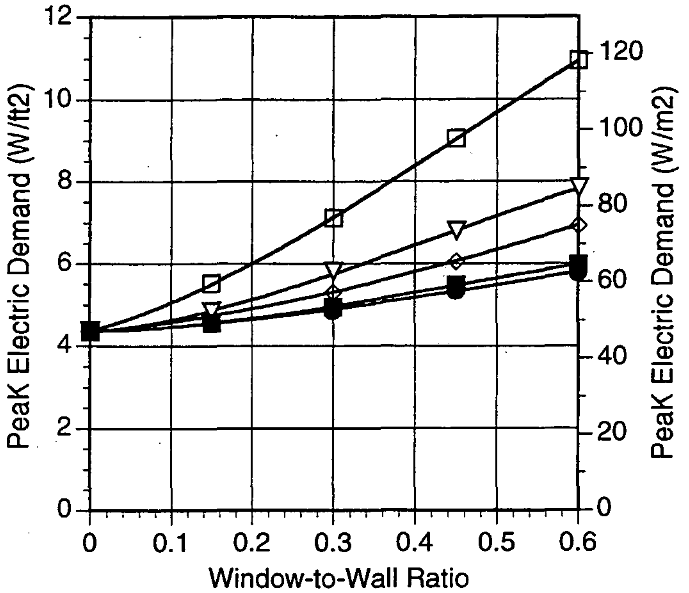
	SHGC	TVIS	U-Factor
M1 - Conventional Low-E	0.45/0.11	0.61/0.07	1.86 (0.33)/1.99 (0.35)
M1 - Spectrally Selective	0.38/0.10	0.57/0.06	1.73 (0.30)/1.85 (0.33)
M2 - Conventional Low-E	0.46/0.10	0.66/0.06	1.88 (0.33)/2.01 (0.35)
M2 - Spectrally Selective	0.38/0.10	0.60/0.05	1.75 (0.31)/1.87 (0.33)
M3 - Conventional Low-E	0.37/0.10	0.51/0.08	1.81 (0.32)/1.91 (0.34)
M3 - Spectrally Selective	0.31/0.10	0.47/0.08	1.74 (0.31)/1.83 (0.32)

Figure 4. Annual electricity consumption due to cooling, fans, and lighting for a west-facing perimeter zone in a prototypical commercial office building module located in Phoenix, AZ and Miami FL. Results are shown for M1, M2, and M3 electrochromic devices in two types of windows (spectrally selective and conventional low-E). The electrochromic windows are controlled to maintain an illuminance level of 50 fc (538 lux). All systems use continuous dimming daylighting and a lighting power density of 1.5 W/ft^2 (16.1 W/m^2).



		SHGC	TVIS
□	Tinted Bronze	0.49	0.47
∇	Spectrally Selective	0.29	0.41
◇	Reflective	0.17	0.13
▲	M1 - Spectrally Selective	0.38/0.10	0.57/0.06
■	M2 - Spectrally Selective	0.38/0.10	0.60/0.05
●	M3 - Spectrally Selective	0.31/0.10	0.47/0.08

Figure 5. Annual electricity consumption due to cooling, fans, and lighting for a west-facing perimeter zone in a prototypical commercial office building module located in Phoenix, Arizona. Results are shown for three conventional glazings and M1, M2, and M3 electrochromic devices with a spectrally selective inner layer. The electrochromic windows are controlled to maintain an illuminance level of 50 fc (538 lux). All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/ft^2 (16.1 W/m^2).



		SHGC	TVIS
□	Tinted Bronze	0.49	0.47
▽	Spectrally Selective	0.29	0.41
◇	Reflective	0.17	0.13
▲	M1 - Spectrally Selective	0.38/0.10	0.57/0.06
■	M2 - Spectrally Selective	0.38/0.10	0.60/0.05
●	M3 - Spectrally Selective	0.31/0.10	0.47/0.08

Figure 6. Peak electric demand for a west-facing perimeter zone in a prototypical commercial office building module located in Phoenix, Arizona. Results are shown for three conventional glazings and M1, M2, and M3 electrochromic devices with a spectrally selective inner layer. The electrochromic windows are controlled to maintain an illuminance level of 50 fc (538 lux). All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/ft2 (16.1 W/m2).

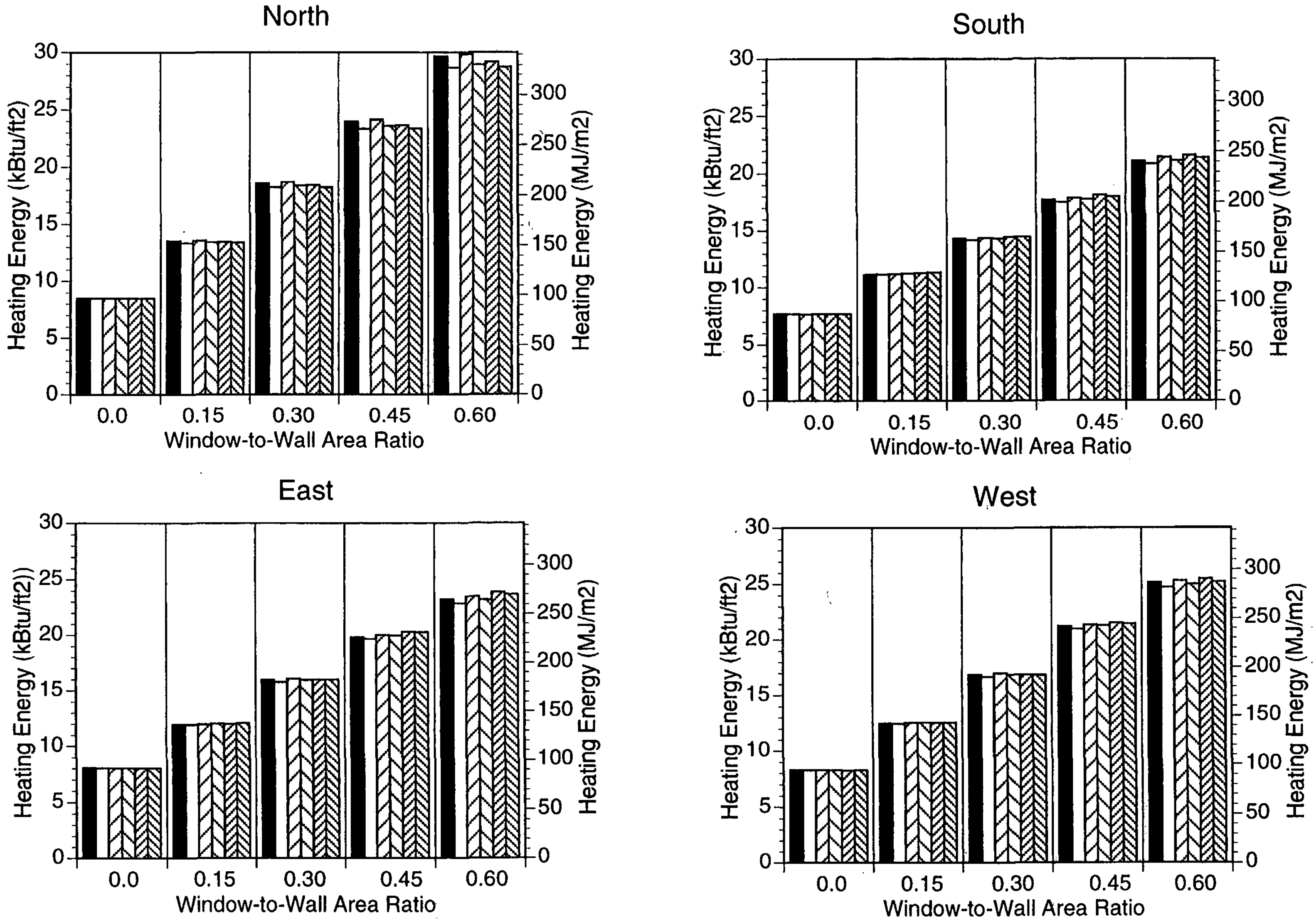


Figure 7. Annual heating energy for perimeter zones in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for M1, M2, and M3 electrochromic devices in two types of windows (spectrally selective and conventional low-E). The electrochromic windows are controlled to maintain and illuminance level of 50 fc (538 lux). All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/ft^2 (16.1 W/m^2).

	SHGC	TVIS	U-Factor
M1 - Conventional Low-E	0.45/0.11	0.61/0.07	1.77 (0.31)/1.77 (0.31)
M1 - Spectrally Selective	0.38/0.10	0.57/0.06	1.69 (0.30)/1.69 (0.33)
M2 - Conventional Low-E	0.46/0.10	0.66/0.06	1.77 (0.31)/1.77 (0.31)
M2 - Spectrally Selective	0.38/0.10	0.60/0.05	1.69 (0.30)/1.69 (0.30)
M3 - Conventional Low-E	0.37/0.10	0.51/0.08	1.71 (0.30)/1.72 (0.30)
M3 - Spectrally Selective	0.31/0.10	0.47/0.08	1.77 (0.31)/1.77 (0.31)

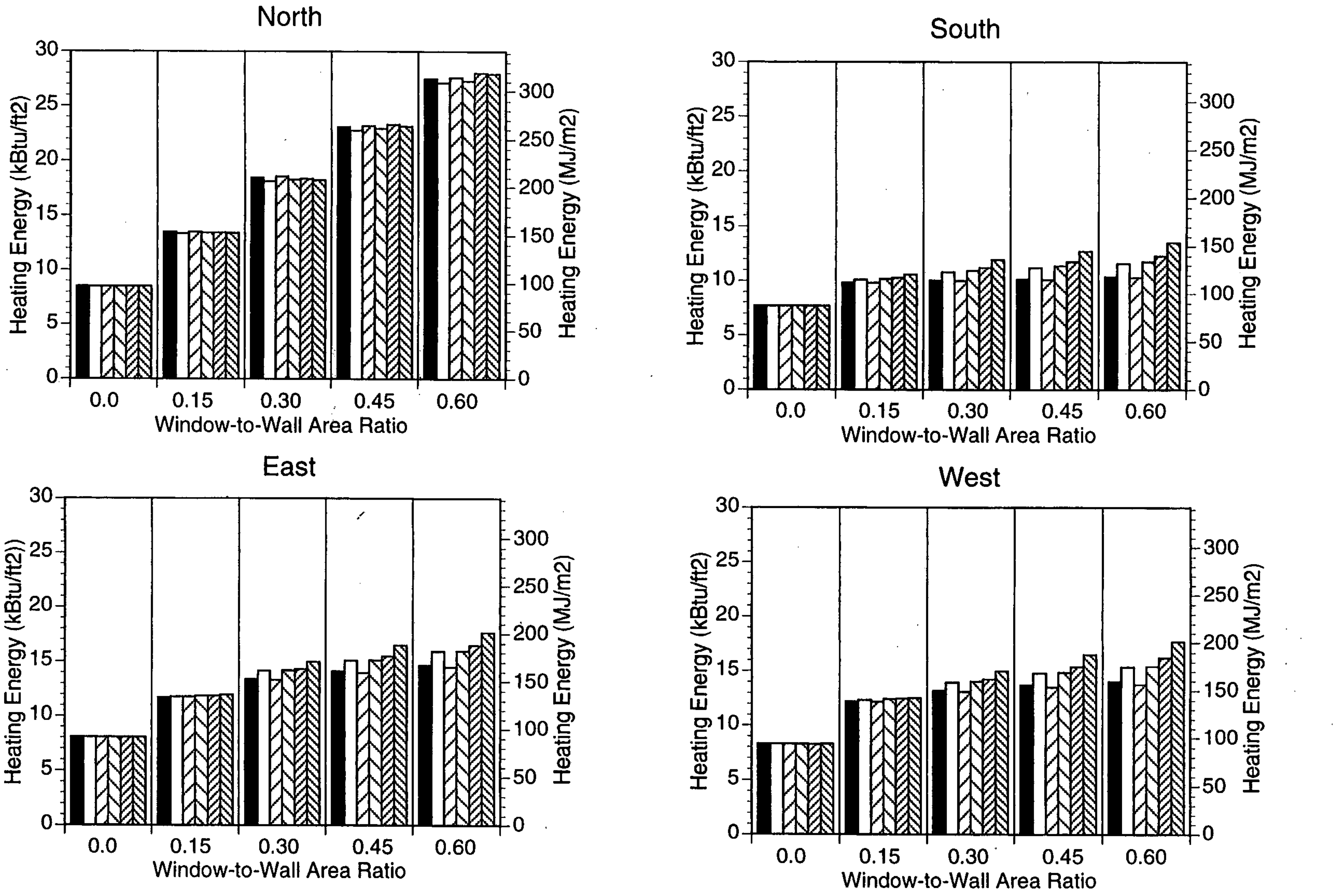


Figure 8. Annual heating energy for perimeter zones in a prototypical commercial office building module located in Madison, Wisconsin. Results are shown for M1, M2, and M3 electrochromic devices in two types of windows (spectrally selective and conventional low-E). The electrochromic windows were maintained in their bleached state during the heating season. All systems use continuous dimming daylighting to maintain an illuminance level of 50 fc (538 lux). The lighting power density was 1.5 W/ft^2 (16.1 W/m^2)

	SHGC	TVIS	U-Factor
M1 - Conventional Low-E	0.45/0.11	0.61/0.07	1.77 (0.31)/1.77 (0.31)
M1 - Spectrally Selective	0.38/0.10	0.57/0.06	1.69 (0.30)/1.69 (0.30)
M2 - Conventional Low-E	0.46/0.10	0.66/0.06	1.77 (0.31)/1.77 (0.31)
M2 - Spectrally Selective	0.38/0.10	0.60/0.05	1.69 (0.30)/1.69 (0.30)
M3 - Conventional Low-E	0.37/0.10	0.51/0.08	1.72 (0.30)/1.72 (0.30)
M3 - Spectrally Selective	0.31/0.10	0.47/0.08	1.77 (0.31)/1.77 (0.31)

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