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Reducing Residential Cooling Requirements Through the Use of Electrochromic Windows

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Abstract

This paper presents the results of a study investigating the energy performance of electrochromic windows in a prototypical residential building under a variety of state switching control strategies. We used the DOE-2.1E energy simulation program to analyze the annual cooling energy and peak demand as a function of glazing type, size, and electrochromic control strategy. A single-story ranch-style home located in the cooling-dominated locations of Miami, FL and Phoenix, AZ was simulated. Electrochromic control strategies analyzed were based on incident total solar radiation, space cooling load, and outside air temperature. Our results show that an electrochromic material with a high reflectance in the colored state provides the best performance for all control strategies. On the other hand, electrochromic switching using space cooling load provides the best performance for all the electrochromic materials. The performance of the incident total solar radiation control strategy varies as a function of the values of solar radiation which trigger the bleached and colored states of the electrochromic (setpoint range); i.e., required cooling decreases as the setpoint range decreases; also, performance differences among electrochromics increases. The setpoint range of outside air temperature control of electrochromics must relate to the ambient weather conditions prevalent in a particular location. If the setpoint range is too large, electrochromic cooling performance is very poor. Electrochromics compare favorably to conventional low-E clear glazings that have high solar heat gain coefficients that are used with overhangs. However, low-E tinted glazings with low solar heat gain coefficients can outperform certain electrochromics. Overhangs should be considered as a design option for electrochromics whose state properties do not change significantly between bleached and colored states.

Introduction

Cooling energy performance in residential buildings is closely linked to the amount of solar radiation that is transmitted through the windows. To control cooling and maintain comfort, windows with low solar heat gain coefficients are used in addition to various types of shading devices such as overhangs, interior shades, or exterior obstructions like trees and vegetation. These design options, however, cannot be universally applied to all buildings; therefore, researchers continue to develop new techniques to help reduce unwanted solar heat gain. Electrochromics is one of the more recent methods being used to produce advanced glazings. These glazings, whose solar/optical transmission properties can change as a function of a variety

of exterior and interior environmental conditions, provide an alternative to more conventional static devices. Because of their capability to change state, electrochromic windows provide an opportunity to improve and optimize the energy and comfort aspects of a building. For example, improved cooling and thermal comfort can be obtained by reducing the amount of solar transmission of a window while simultaneously maintaining a satisfactory level of visible transmission for view and glare control. Electrochromic windows have varying performance capabilities based on the particular design options used in creating the electrochromic material and overall window system.

Although electrochromics are still in the prototype development phase, past energy simulation studies on commercial buildings (Refs. 1, 2, 3, 4) have shown the viability of these windows in reducing cooling energy and peak load. However, not much work has been done on understanding electrochromic performance in the context of typical residential buildings. This paper aims to complement this past work by analyzing a prototypical single-story residential model using the DOE-2 (Ref. 6) hour-by-hour building energy simulation program. Annual and peak cooling energy requirements were obtained as a function of window size, electrochromic system type, and electrochromic state-switching control strategy. Results were compared to the performance of conventional glazings using several types of shading devices.

Residential Model Description

We modeled a single-story, slab-on-grade, one-zone house with a floor area of 143 m^2 (1540 ft^2) in two cooling dominated geographic locations: Miami, FL (hot and humid) and Phoenix, AZ (hot and dry). We analyzed results in these locations to better understand the impact of electrochromics with and without the effect of humidity. In Miami, for example, a large portion of the cooling energy use is directed toward humidity control (latent cooling); whereas, in Phoenix, most of the cooling is related to air temperature and solar radiation (sensible cooling). Table 1 gives an indication of the differences in several climatic variables for these locations.

Wood-frame construction for the residence was used with a wall U-Factor of 0.30 W/m^2K (0.053 $Btu/hr\text{-}ft^2F$, R19) and a roof U-Factor of 0.17 W/m^2K (0.03 $Btu/hr\text{-}ft^2F$, R34). These insulation levels represent medium values between the thermal transmittance requirements specified in ASHRAE 90.2 (Ref. 5) for new residential construction located in such warm and cold climates. Internal loads for occupants, lights, and appliances were modeled by considering a composite process heat gain input with a maximum value of 10721 kJ/hr (10163 Btu/hr) which is equivalent to a daily heat input of 56932 kJ/day (53963 Btu/day) sensible and 12875 kJ/day (12156 Btu/day) latent.

Infiltration was calculated using an average level of building leakage area, 0.071m^2 (0.77 ft^2). The leakage area is a parameter that describes the tightness of the structure which is obtained from pressurization tests. Both temperature-induced and wind-induced infiltration components were calculated on an hourly basis. Natural ventilation of 10 air-changes per hour was also provided by opening the windows. The windows were opened only if the following conditions were both met: (1) if the act of opening the windows provided more cooling than would be provided by the mechanical system with the windows closed; and (2) the enthalpy of the outside

air was less than the enthalpy of the inside air (this condition eliminates the possibility of introducing a latent load into the house.

A dual setpoint thermostat was used to control the space conditioning system. Heating was set at 21.1C (70F) from 7 a.m. to 11 p.m. with a night setback to 15.6C (60F) from 12 p.m. to 6 a.m.. Cooling was set at 25.6C (78F) for all hours. A direct-expansion air-cooled airconditioning unit was used for cooling and a forced-air gas furnace for heating. Cooling system COP was 2.2 and furnace steady state efficiency was 0.74.

Fenestration Systems Descriptions

The residence was modeled with windows facing north, east, south, and west. We varied the glazed portion of the window simultaneously on each facade at values corresponding to 0%, 2%, 4%, 8% and 12% of the residence floor area. Overall glazed area for the complete residence was therefore 0%, 8%, 16%, 32%, and 48% of the floor area. An external flush glazed thermally-broken aluminum frame was used for each window with a frame conductance of 4.6 W/m^2K (0.8 $Btu/hr\text{-}ft^2F$) and an area equal to 12% of the respective glazed area.

We compared the performance of six electrochromic windows. Table 2 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 material types 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 2 are designated: 80/20E, 80/20S, 80/10E, 80/10S, GE, GXE. The solar/optical properties of these electrochromic windows were varied using control strategies based on solar radiation, thermal load, or air temperature. Our study is not concerned with how these strategies would be implemented, which will be the subject of a future study, but with obtaining a basic understanding of how the strategies affect electrochromic performance. The control strategies analyzed include the following:

(1) *Solar Control.* The properties of the window were varied linearly as a function of the incident total (direct plus diffuse) solar radiation between low and high switching setpoints. The bleached or unswitched state was assumed for incident total solar radiation values less than or equal to 63 W/m^2 (20 $Btu/hr\text{-}ft^2$). Three different values for the colored or 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/m^2 (60 $Btu/hr\text{-}ft^2$), 315 W/m^2 (100 $Btu/hr\text{-}ft^2$), or 630 W/m^2 (200 $Btu/hr\text{-}ft^2$).

(2) *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).

(3) *Outside Air Temperature Control.* The properties of the window were varied linearly as a function of the outside air temperature between low and high switching setpoints. The unswitched state was assumed for a temperature less than or equal to the thermostat cooling setpoint temperature 25.6C (78F); the fully-switched state was assumed for temperatures greater than or equal to 32.2C (90F).

The performance of the electrochromic glazings described above were compared to three conventional double pane low-E glazings obtained from the DOE-2 Window Library. As shown in Table 2, the solar heat gain coefficients for the three glazings were 0.64, 0.44, and 0.29 with corresponding shading coefficients of 0.75, 0.51, and 0.33. Although the U-factors for the conventional glazings were lower than the electrochromic glazings, previous work reported in Ref. 7 indicated that U-factor does not have a significant effect on annual cooling energy performance; however, one could expect a decrease in peak cooling with lower U-factors. Three shading schemes were also modeled for use with the conventional glazings. In order of increasing solar control effectiveness, they were as follows:

(1) *Interior Shade.* Interior shading in which the solar heat gain was reduced by 35% if the transmitted direct solar radiation through the window was greater than or equal to 95 W/m^2 (30 $Btu/hr\text{-}ft^2$).

(2) *Exterior Obstruction.* Exterior shading provided by trees or vegetation with a 50% solar transmittance located at a distance of 3.1m (10ft) from the wall with a height of 3.7m (12ft) along the length of each window.

(3) *Exterior Overhang.* Exterior shading provided by an overhang with a depth of 0.61m (2ft) along the length of each window tilted downward 20 degrees.

Combined obstruction and overhang and combined interior shades, obstruction, and overhang were also modeled. In addition, we also simulated the overhang with the electrochromic windows to ascertain performance variations with such a device.

The next part of this study discusses electrochromic performance for each of the above control strategies. Annual cooling energy use is first discussed followed by peak cooling performance. The electrochromics are then compared to more conventional glazings with various shading devices. We also show the effect of the use of overhangs with electrochromics.

Electrochromic Glazing Performance

Figures 1 and 2 present annual cooling energy use for Miami and Phoenix for each of the electrochromic windows and controls strategies analyzed in this study. Results are presented as a

function of window area expressed as percent floor area with windows being equally distributed on each facade of the residence. In the upper portion of each figure (Figs. 1a, 1b, 1c, 2a, 2b, 2c) are data comparing the three variations in incident total solar radiation switching setpoints; the lower portion (Figs. 1d, 1e, 2d, 2e) shows results using space cooling load and outside air temperature control.

Interestingly, the overall annual cooling energy use does not vary much between the two geographic locations. For both locations, for a particular electrochromic material, performance for all control strategies is best with the spectrally selected glazing (S) than with the clear glazing (E). Also, for the six electrochromic window types, cooling energy is generally proportional to the lower value of solar heat gain coefficient of the electrochromic corresponding to the colored or switched state. The glazing properties presented in Table 2 are presented in such an order. The one exception is when using incident solar radiation with a large setpoint range, 63-630 W/m^2 (20-200 $Btu/hr\text{-}ft^2$), as the controlling strategy. In this case, performance is not as easily predictable except for the GXE electrochromic which in every case has the lowest cooling energy use.

Required cooling is about 4500 kWh for a residence without windows in both Miami and Phoenix. As the window size increases, required cooling increases to a maximum value of 13700 kWh in Miami and 12000 kWh in Phoenix which occurs for the largest window area using outside air temperature control in Miami (Fig. 1e) and incident solar radiation control in Phoenix (Fig. 2a). The smallest required cooling is obtained using space cooling load control; i.e., for the largest size window, the value is about 5100 kWh in Miami (Fig. 1d) and 6500 kWh in Phoenix (Fig. 2d). A cost can be associated with these figures by simply assuming, for example, an electricity cost of $0.10/kWh, which results in a maximum absolute range in the cost of cooling due to windows of from $450 to $1370 per year in Miami and $450 to $1200 in Phoenix and a minimum range of from $450 to $510 in Miami and $450 to $650 in Phoenix.

When using incident solar radiation to control state switching, as the setpoint range decreases, required cooling also decreases; but the differences in performance between each of the electrochromics increases. Decreasing the setpoint range yields cooling energy quantities that are more sensitive to the solar heat gain performance characteristics of the electrochromic, especially the solar properties near the colored state. In Miami, for example, for the largest window size and a large setpoint range (Fig. 1a), 63-630 W/m^2 (20-200 $Btu/hr\text{-}ft^2$), the 80/20E glazing requires 12000 kWh with a maximum difference in performance between the 80/20E and best-performing GXE electrochromic devices of about 1600 kWh or about 13%. For a small setpoint range (Fig. 1c), 63-189 W/m^2 (20-60 $Btu/hr\text{-}ft^2$), the 80/20E requires about 9600 kWh with a maximum difference of 3200 kWh or 33%. In Phoenix, for the large setpoint range (Fig. 2a), the 80/20E requires 12000 kWh with a maximum difference between the 80/20E and GXE devices of 2500 kWh or 21%; for a small setpoint range (Fig. 2c), the 80/20E requires 10750 kWh with a difference of 3250 kWh or 30%.

As mentioned previously, space cooling load control (Figs. 1d, 2d) of the electrochromics results in the lowest cooling energy requirements, and also the largest variation in performance for the different electrochromic devices, about 3650 kWh for both locations. Recall, space load control is an on/off device and all the electrochromics, regardless of orientation, are either bleached or colored with no intermediate state. This results in there being almost no difference in

performance of the (E) and (S) type glazings because their colored states are very similar. Also, the control does not differentiate between sensible or latent cooling. Therefore, in Miami, the electrochromic is in its colored state more often than in Phoenix resulting in lower overall cooling energy requirements for all the glazing types. Actually, the performance of the GXE glazing in Miami is almost constant with window size.

Using outside air temperature for controlling electrochromic switching (Figs. 1e, 2e) yields the largest performance difference between Miami and Phoenix. Table 1 shows that there is a significantly greater number of cooling degree days in Phoenix than in Miami, which results in lower electrochromic solar transmission properties and thus lower cooling energy requirements. Outside air temperature control also affects the linearity of the results. In Miami (Fig. 1e), we see that the (S) type glazings actually outperform the GE and GXE glazings. This is because the selected setpoint range of 25.5C-32.2C (78F-90F) is such that the glazings in Miami are probably closer to the bleached state most of the time and the 80/20S and 80/10S glazings have lower solar heat gain coefficients than the other glazings. In Phoenix (Fig. 2e), because the outside air temperatures during the cooling season are no doubt greater than the upper setpoint temperature, the electrochromics would be more often in the colored state and thus performance resembles the other control strategies. In general, it does not seem advisable to use outside air temperature to control electrochromic switching.

Peak cooling demand is presented on Figures 3 and 4 for Miami and Phoenix. Peak cooling will affect HVAC equipment sizing and also influence electricity demand load requirements. Unlike annual cooling energy, there is a significant difference in cooling peak for the two locations. Although the peak at each location occurs at about the same time of year and time of day, the ambient air temperatures are significantly different. In Miami, temperatures are in the vicinity of 32C (90F) whereas in Phoenix the value is 39C (103F). This results in a peak cooling load in Phoenix which is twice as large as Miami in a residence with no windows; i.e., 1.5 kW is the peak in Miami and 3.0 in Phoenix. The largest peak occurs with the 80/20E glazing with the largest size window using incident solar radiation control with a large setpoint range (Figs. 3a, 4a); in Miami the value is 4.2 kW; in Phoenix, it is 6.7 kW. The smallest peak occurs using space cooling load control (Figs. 3d, 4d); in Miami, the value is 2.2 kW and in Phoenix, the value is 4.3 kW.

In general, the trends experienced with annual cooling energy, which were discussed above, are also prevalent with peak cooling; i.e., electrochromic performance improves with decreasing setpoint range when using incident solar radiation as the control strategy; space cooling load control results in the smallest peak cooling; outside air temperature control remains unpredictable and nonlinear. These results are different than what was reported in Ref. 1 which was an analysis of electrochromics in a commercial office building module. In that study, we indicated that peak demand did not vary much for different electrochromic control strategies. Peak demand in Ref. 1, however, was defined for each thermal zone with windows facing only one direction. Our residential model is a single zone with windows facing four directions which complicates the thermal interactions.

Conventional Glazing and Shading System Performance

We present data in Figures 5 and 6 for Miami and Phoenix to give some indication of electrochromic performance when compared to conventional glazings that use various types of shading devices to reduce cooling energy use. Results are shown for three low-E glazings that have very different solar gain characteristics and five shading systems including, in order of solar control effectiveness, interior shades, exterior obstructions, exterior overhangs, combined obstructions and overhangs, and combined shades, obstructions, and overhangs. Also presented on each of these plots are data for the GXE electrochromic glazing using incident solar radiation control with an intermediate setpoint range of 63-315 W/m^2 (20-100 $Btu/hr\text{-}ft^2$).

As was the case with the electrochromics presented in Figures 1 and 2, there is not much difference in cooling for the two locations, regardless of glazing and shading system type. The most cooling required for the largest size window occurs with the low-E clear glazing with the largest solar heat gain coefficient (Figs. 5a, 6a), SHGC=0.64: 15623 kWh in Miami and 16879 kWh in Phoenix. Using a $0.10/kWh utility electricity cost, one can understand why solar control glazings and/or shading is desired in these locations, in addition, of course, to other reasons related to thermal and visual comfort. The least amount of cooling occurs with the low-E tinted glazing (Figs. 5c, 6c), SHGC=0.29, using combined exterior obstructions and overhangs or combined shades, obstructions, and overhangs: 6851 kWh in Miami and 7520 kWh in Phoenix. By comparison, the GXE glazing for the largest size window requires 7979 kWh in Miami and 8287 kWh in Phoenix.

The shading systems, with the exception of the interior shades in Miami, perform reasonably well. A greater percentage of the required cooling in Phoenix is due to solar radiation than is the situation in Miami where humidity is more a factor; and the interior shades are controlled by the amount of incident solar radiation. Actually, for the low-E clear glazing with high SHGC, the reduction in cooling for all shading systems is greater in Phoenix (Fig. 6a) than in Miami (Fig. 5a). For example, in Miami, cooling is reduced by the following percentages for the five shading systems: 6%, 14%, 27%, 39%, and 39%; in Phoenix, the values are: 13%, 17%, 29%, 41%, and 43%. The GXE electrochromic glazing is 49% and 52% lower in Miami and Phoenix respectively. As the solar heat gain coefficient of the conventional glazing is reduced, shading system performance is mitigated and there is less of a difference in performance as a function of geographic location.

In general, almost all the electrochromics and control strategies studied and presented in Figures 1 and 2 have lower cooling requirements than the high SHGF low-E clear glazing with overhangs. The exceptions are several of the electrochromics in Miami when using outside air temperature control; in this case, the electrochromics have lower cooling than the configuration with exterior obstructions. With the shading systems becoming less necessary or effective in reducing solar heat gain with decreasing glazing SHGC, as explained above, some of the electrochromic devices do not perform as well as conventional glazings. This is particularly apparent for the low-E tinted glazing with SHGC equal to 0.29, where in Miami required cooling is 9693 kWh and in Phoenix 10507 kWh. Almost all the electrochromics that use incident solar radiation with a large setpoint range do not perform as well as this conventional glazing.

Although not shown in this report, the peak cooling demand trends for the conventional glazings are similar to that for the annual cooling energy use data. In Miami, the peak varies from a high of 5.1 kW for the low-E clear high SHGC glazing to a low of 2.6 kW for the low-E tinted glazing with overhang and obstruction. In Phoenix, the values are 8.3 kW and 4.5 kW respectively.

Figures 7 and 8 present electrochromic results using the same overhang that was used for the conventional glazings. There is a definite performance improvement for the 80/20 and 80/10 devices; some improvement with the GE device; but hardly any improvement in performance with the GXE electrochromic except when using outside air as a control strategy. In fact, cooling requirements increase for the GXE electrochromic in both locations when using incident solar radiation control with the smaller setpoint ranges; i.e. 63-315 W/m^2 (20-100 Btu/hr-ft^2) and 63-189 W/m^2 (20-60 Btu/hr-ft^2). This is because the amount of incident solar radiation striking the window is reduced because of the overhang and so the SHGC of the electrochromic would be higher than without the overhang. This is also true for the other electrochromics, but the range of SHGCs of these glazings is not as large as the GXE (Table 2).

The most dramatic change in performance of the electrochromics with overhangs occurs when using outside air temperature for control. Recall in our previous discussion, such a control strategy used in Miami resulted in the largest amount of required cooling. This occurred because the temperature setpoint range of 25.5C-32.2C (78F-90F) was too broad to adequately provide control, and thus there remained unwanted solar heat gain. With the overhang in place, however, the solar gain has been reduced and the electrochromics perform similar to a control strategy using incident solar radiation with a mid-level setpoint range.

Conclusions

1. Cooling energy use patterns in Miami, FL and Phoenix, AZ are very similar for the electrochromic glazings and control strategies analyzed. The only exception is the electrochromic control strategy that uses outside air temperature; in this case, the higher ambient air temperatures associated with Phoenix provide better control.

2. The GXE electrochromic glazing performs the best under most circumstances. GXE consists of an electrochromic material having a high reflectance in the colored state combined with a low-E clear glass.

3. In general, cooling performance is proportional to the colored or switched state properties of the electrochromic devices. The electrochromic materials that are combined with the spectrally selective low-E glazing outperform those combined with the low-E clear glazings.

4. The smallest required cooling is obtained with the GXE electrochromic using space cooling load control. In Miami, there is only a 14% increase in cooling for the largest size window above that due to a windowless residence; in Phoenix, the increase is 48%. One reason for this difference is that space load control does not differentiate between sensible and latent cooling.

5. There is not much difference in cooling for the low-E clear (E) and low-E selective (S) type electrochromic glazings when using space load control.

6. Required cooling decreases when using incident solar radiation control as the setpoint range decreases. However, performance differences among the electrochromics increases. At larger window sizes, a small setpoint range is desirable to facilitate better solar gain control.

7. The low-E clear (E) and low-E selective (S) type electrochromic glazings outperform the high reflectance (G) and (GX) electrochromics when using outside air temperature control in Miami. An improvement in performance could be obtained by reducing the high setpoint temperature which was 32.2C (90F). If using outside air temperature control, the upper temperature should be correlated to the expected ambient weather conditions.

8. There is a large difference in peak cooling between Miami and Phoenix, primarily due to the higher values of ambient air temperature experienced in Phoenix. Peak performance trends are very similar to annual energy variations.

9. Cooling performance in Miami and Phoenix is similar for the conventional glazings and shading systems analyzed.

10. Most of the electrochromics and control strategies studied have better performance than a conventional low-E clear glazing (SHGC=0.64) used with an overhang.

11. The low-E tinted conventional glazing (SHGC=0.29) without shading outperforms the electrochromics that use incident solar radiation control with a large setpoint range. This is also true for control using outside air temperature.

12. The use of overhangs with electrochromic devices is a viable design option, particularly for electrochromic devices whose state properties may not change significantly between bleached and colored states. Also, overhangs tend to reduce the cooling performance differences among electrochromics devices.

Future Studies

Future residential studies of electrochromics will focus on the following items: (1) 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) Simulation of electrochromic devices in heating-dominated geographic locations. (5) Analysis of the effects of orientation on electrochromic performance.

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TABLE 1
Representative Cooling Load and Heating Load Parameters for the Cities Used in the Analysis

City	Lat	Long	Alt	HDD 18.3C (65F)	CDD 23.9C (75F)	LED	CID
Miami, FL	25.8	80.3	7	123 (222)	604 (1087)	1155	869 (276)
Phoenix, AZ	33.1	112.0	1117	733 (1320)	967 (1740)	97	769 (244)

NOTES:
(1) LED is Latent Enthalpy-Days at a base temp of 23.9C (75F) and base humidity ratio of .0116 and gives an indication of the effect of latent cooling. Defines the amount of energy that must be removed from the air each hour to lower it to the a reference humidity ratio without changing the drybulb temp.
(2) CID is Cooling Insolation-Days, kW/m^2 (kBtu/hr-ft^2), at a base temp of 21.1C (70F). Represents the total insolation hitting an average 0.09 m^2 (1 ft^2) vertical surface (avg of N, E, S, W) when temperatures are above a designated value. Correlates with cooling load penalties due to unwanted solar gain.

TABLE 2
Glazing Solar/Optical/Thermal Properties

	SHGC	SC	Tvis	U-Factor W/m^2-K (Btu/h-ft^{2}F)
Electrochromic	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored
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)
Conventional				
Low-E Clear (2641)	0.64	0.75	0.77	1.91 (0.34)
Low-E Clear (2661)	0.44	0.51	0.70	1.69 (0.30)
Low-E Tint (2667)	0.29	0.33	0.41	1.77 (0.31)

NOTES:
(1) 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/m^2 (248.2 Btu/h-ft^2).
(2) Low-E Clear (2641) has a metallic coating on the inside surface of the inner pane with a thermal emissivity of 0.1. The gap width is 12.7 mm with each pane 3.0 mm thick; Low-E Clear (2661) has a low-E metallic coating on the inside surface of the outer pane with a thermal emissivity of 0.04. The gap width is 12.7 mm with each pane 3.0 mm thick; Low-E Tint (2667) has a low-E metallic coating on the inside surface of the outer pane with a thermal emissivity of 0.04. The gap width is 12.7 mm with each pane 6.0 mm thick.

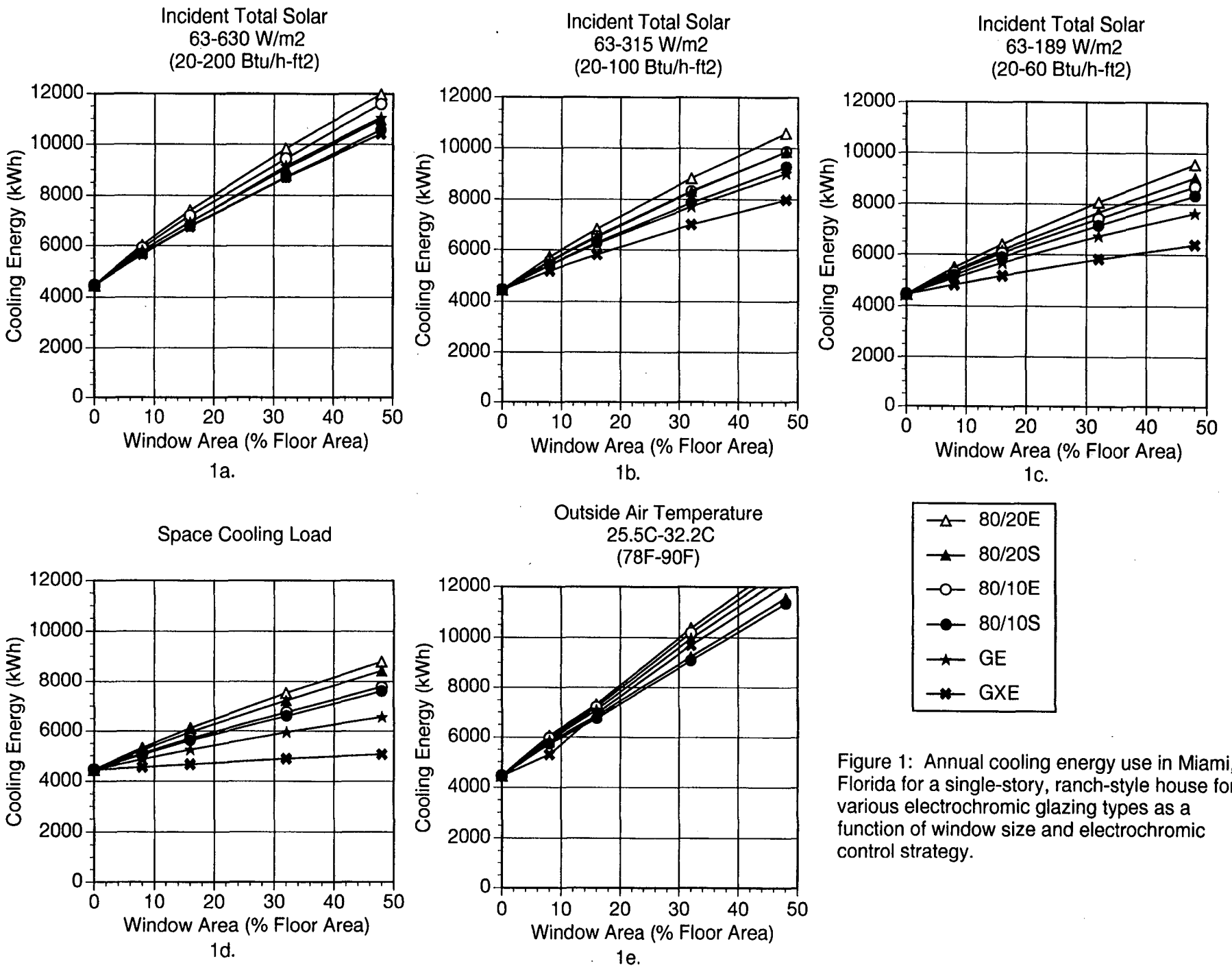


Figure 1: Annual cooling energy use in Miami, Florida for a single-story, ranch-style house for various electrochromic glazing types as a function of window size and electrochromic control strategy.

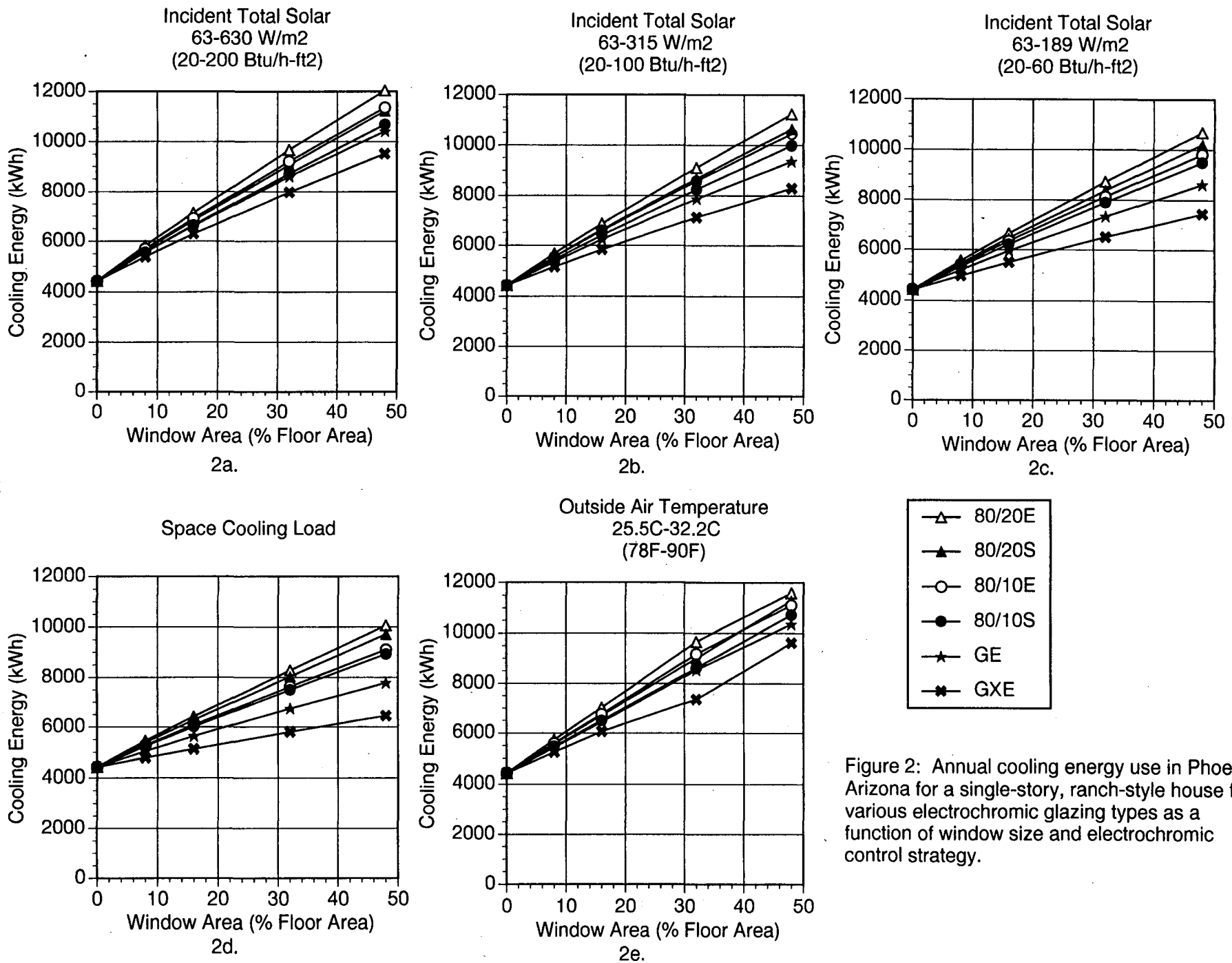
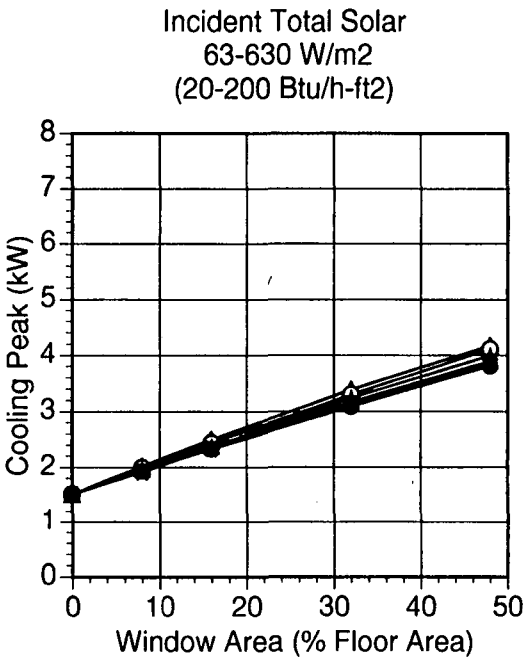


Figure 2: Annual cooling energy use in Phoenix, Arizona for a single-story, ranch-style house for various electrochromic glazing types as a function of window size and electrochromic control strategy.



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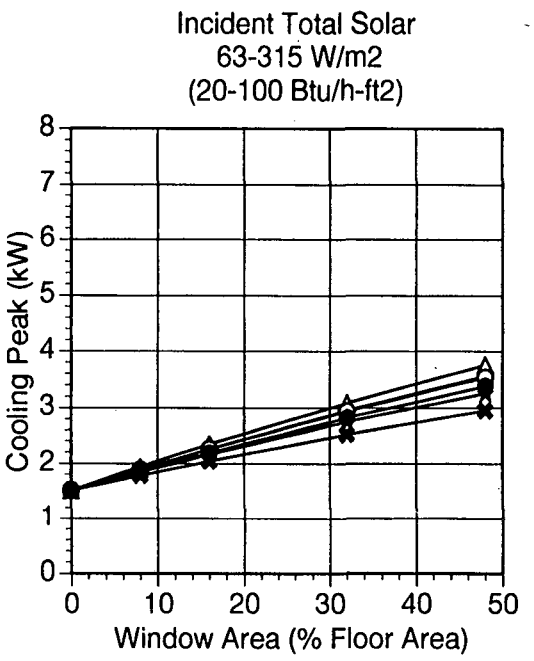

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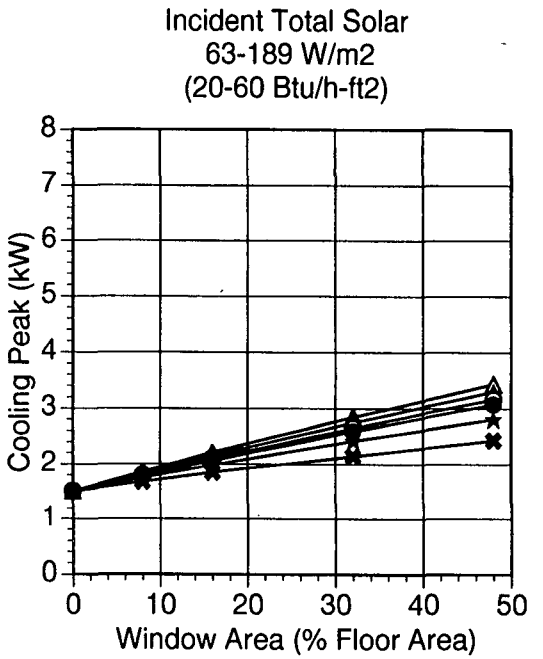

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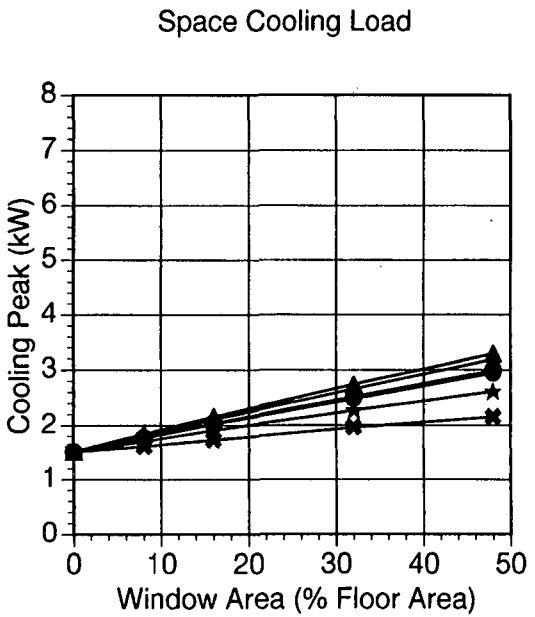

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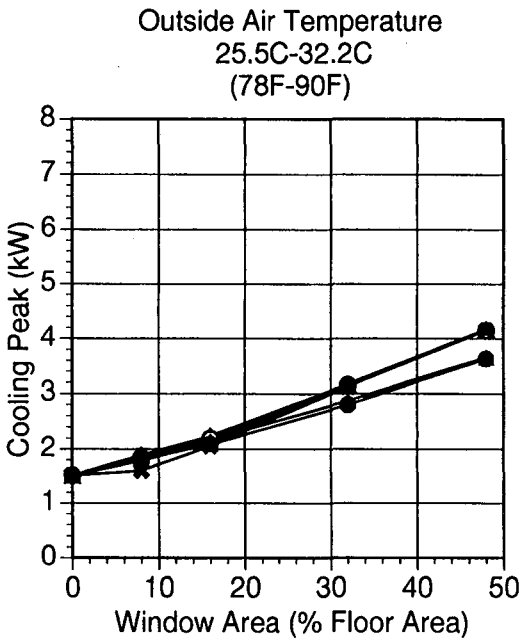

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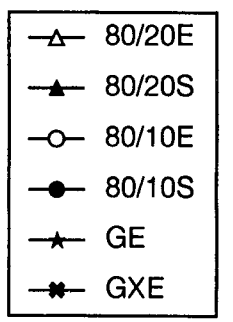
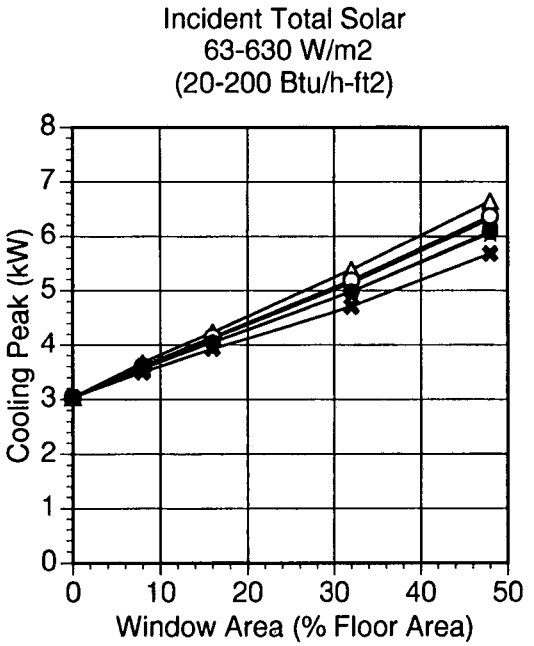


Figure 3: Annual cooling energy peak demand in Miami, Florida for a single-story, ranch-style house for various electrochromic glazing types as a function of window size and electrochromic control strategy.



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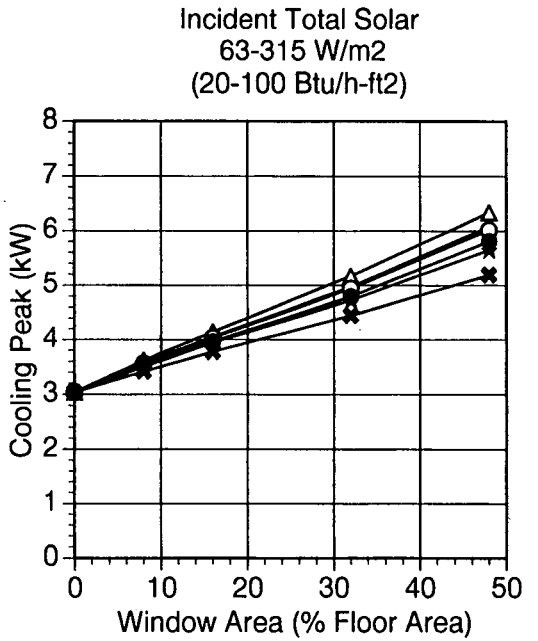

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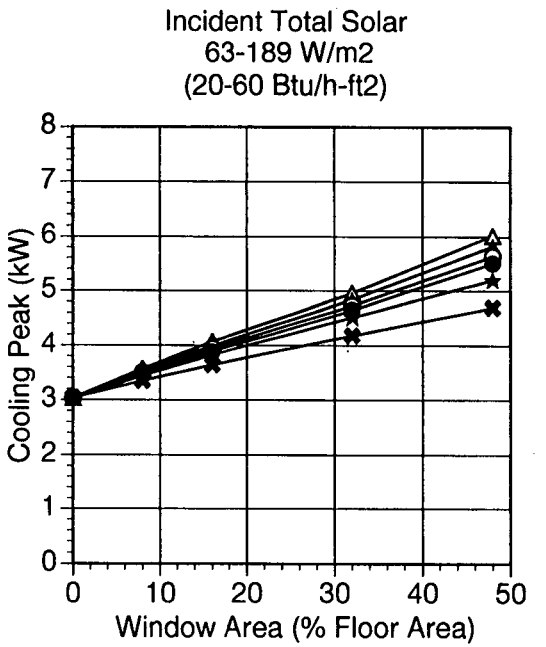

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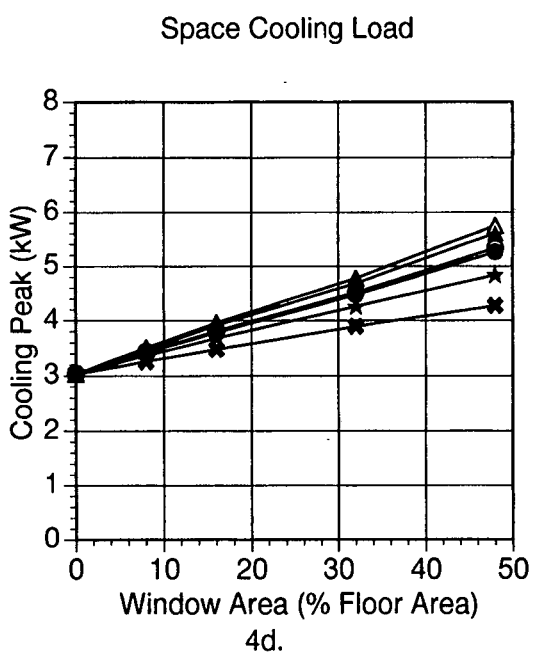

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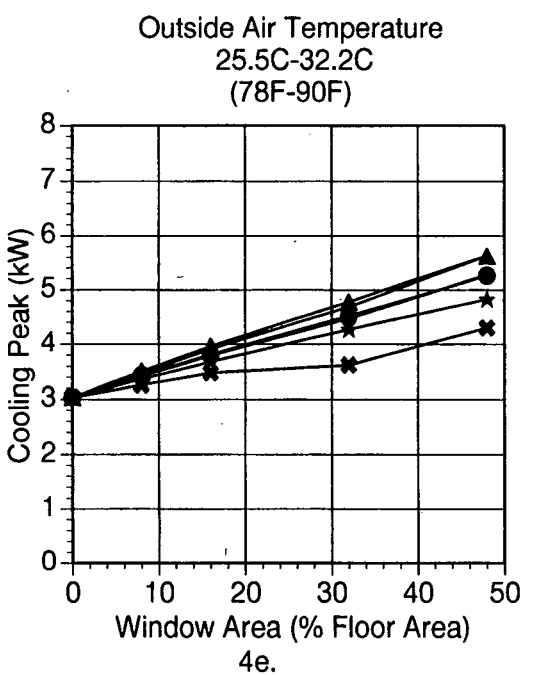

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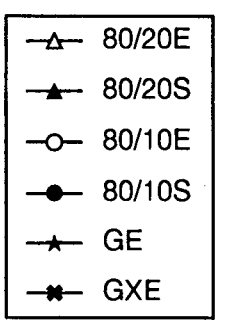


Figure 4: Annual cooling energy peak demand in Phoenix, Arizona for a single-story, ranch-style house for various electrochromic glazing types as a function of window size and electrochromic control strategy.

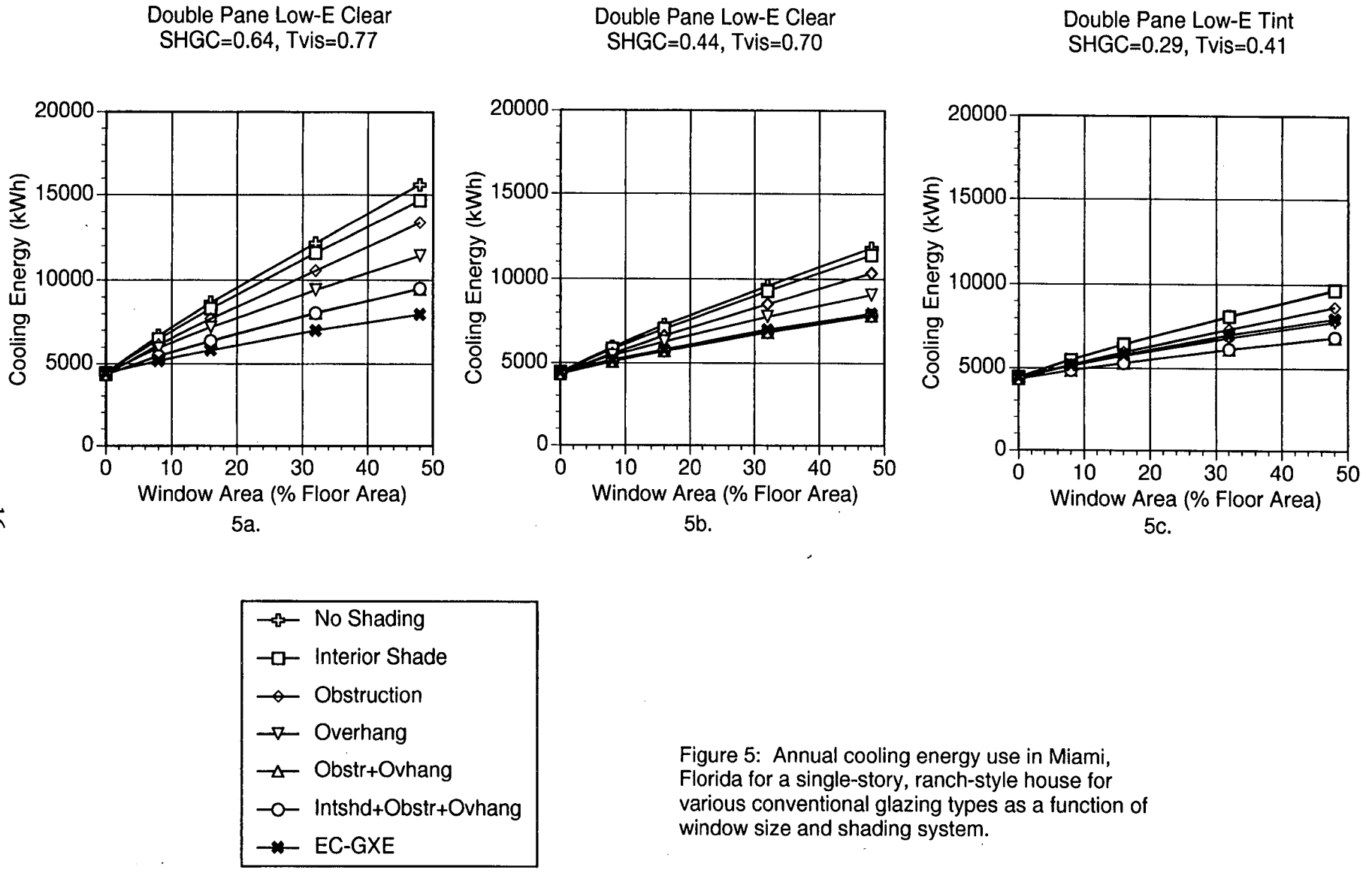


Figure 5: Annual cooling energy use in Miami, Florida for a single-story, ranch-style house for various conventional glazing types as a function of window size and shading system.

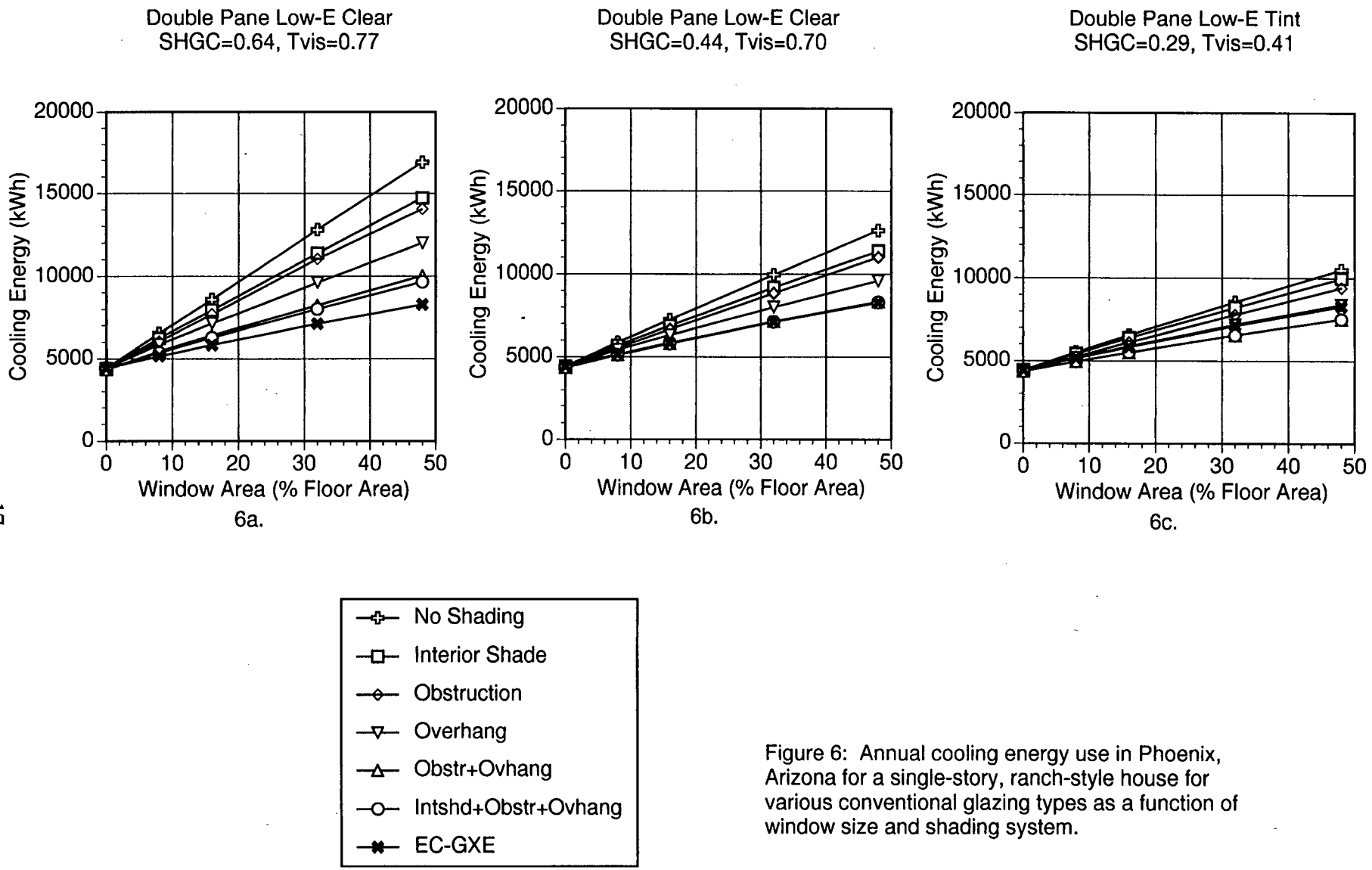
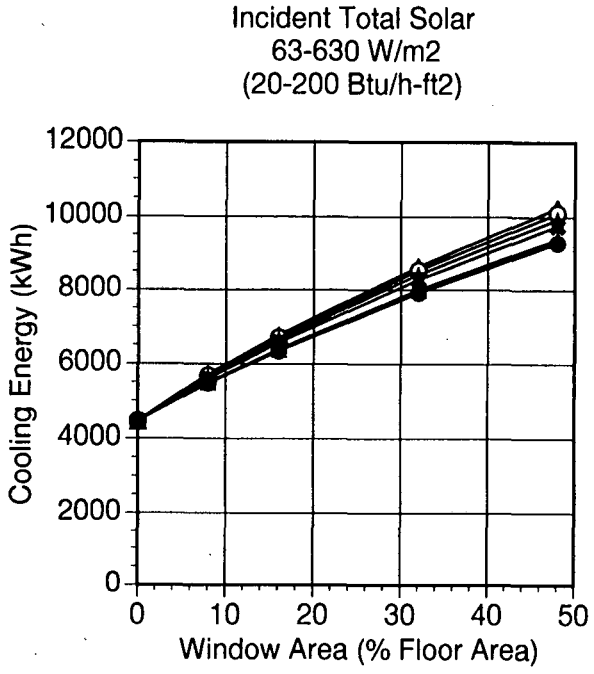


Figure 6: Annual cooling energy use in Phoenix, Arizona for a single-story, ranch-style house for various conventional glazing types as a function of window size and shading system.



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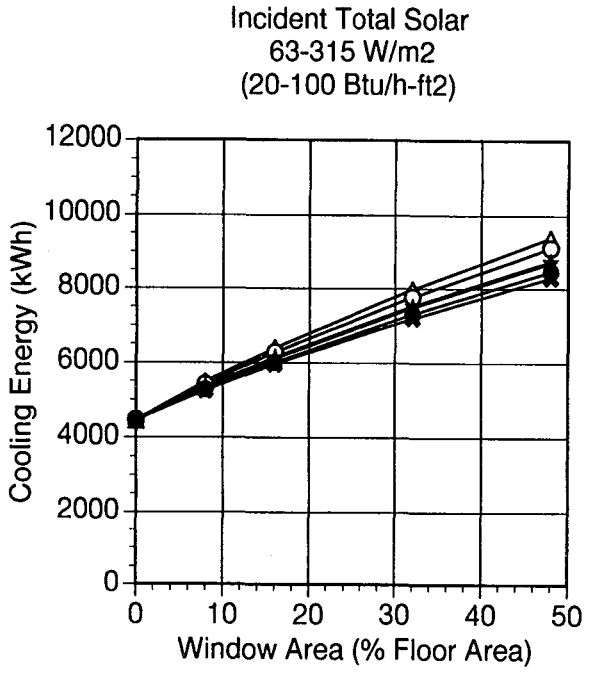

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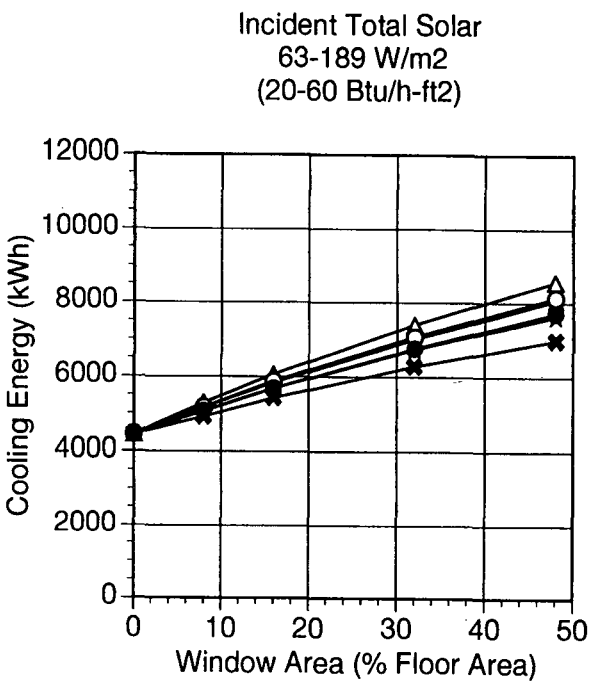

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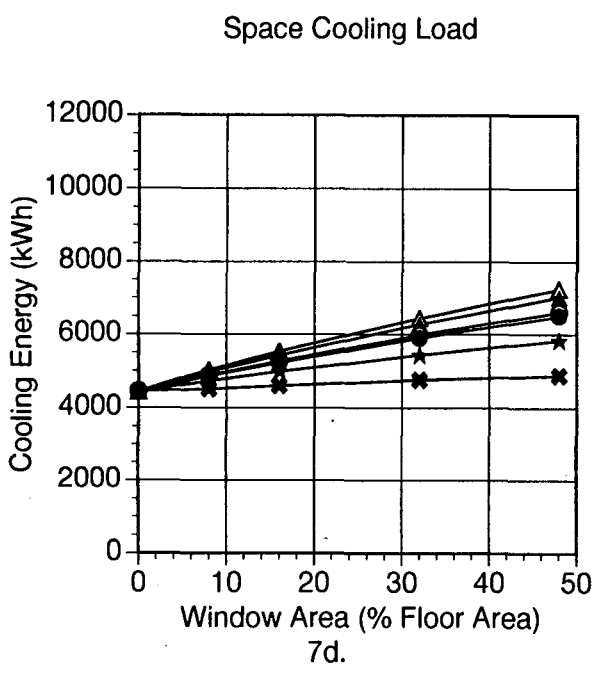

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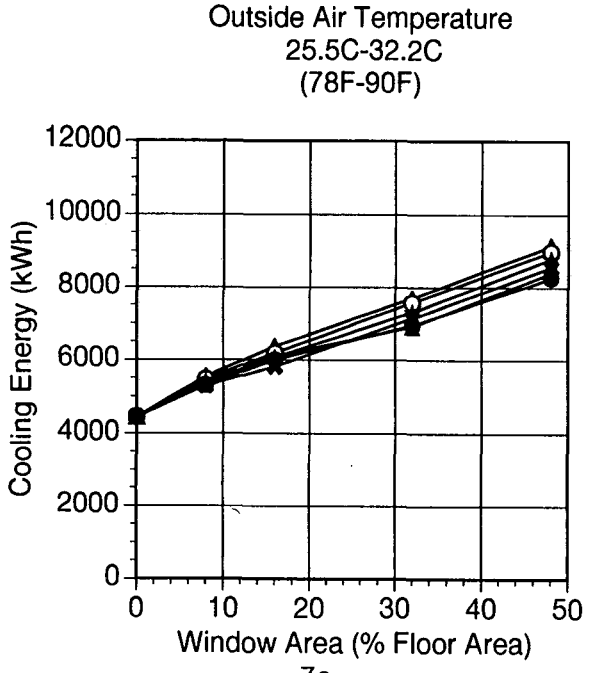

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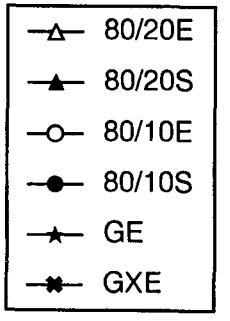

Figure 7: Annual cooling energy use in Miami, Florida for a single-story, ranch-style house with overhangs for various electrochromic glazing types as a function of window size and electrochromic control strategy.

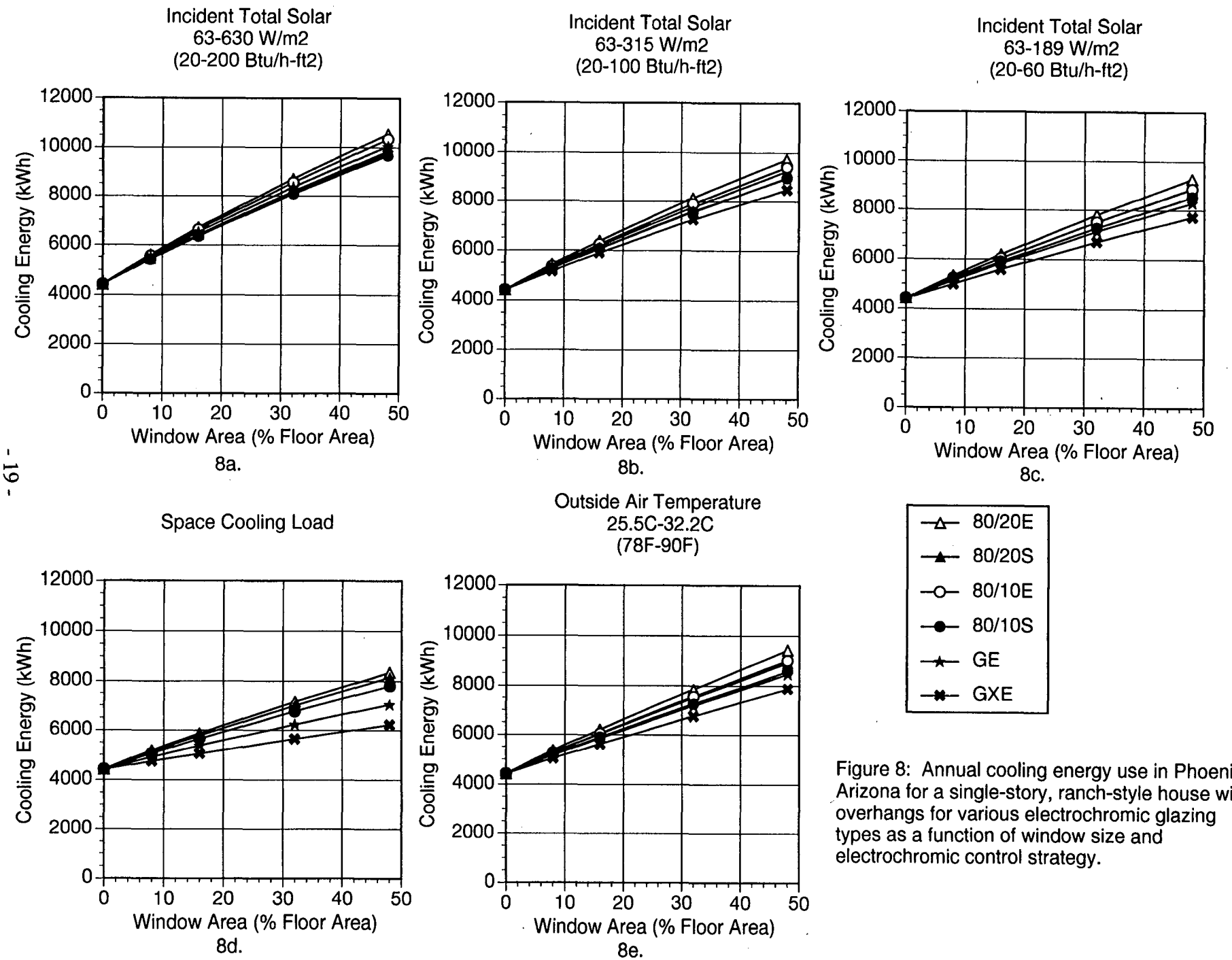

Figure 8: Annual cooling energy use in Phoenix, Arizona for a single-story, ranch-style house with overhangs for various electrochromic glazing types as a function of window size and electrochromic control strategy.

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