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R. Sullivan and S. Selkowitz
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Dr. P. Lyons, P.C. Thomas
Mathematics Department, UNSW
University College, ADFA
Canberra ACT 2600 Australia

I. Andresen, Prof. O. Aschehoug
SINTEF
Architecture and Building Technology
N-3034 Trondheim, Norway

I. Heimonen
VTT Building Technology
P.O. Box 1804
SF-02044 VTT, Finland

H. Simmler, P. Eggimann, T. Frank
EMPA Building Physics Section
CH-8600 Duebendorf
Switzerland

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Abstract

Researchers participating in IEA/SHC Task 18 on advanced glazing materials have as their primary objective the development of new innovative glazing products such as high performance glazings, wavelength selective glazings, chromogenic optical switching devices, and light transport mechanisms that will lead to significant energy use reductions and increased comfort in commercial and residential buildings. Part of the Task 18 effort involves evaluation of the energy and comfort performance of these new glazings through the use of various performance analysis simulation tools. Eleven countries (Australia, Denmark, Finland, Germany, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, and the United States) are contributing to this multi-year simulation study to better understand the complex heat transfer interactions that determine window performance. Each country has selected particular simulation programs and identified the following items to guide the simulation tasks: (1) geographic locations; (2) building types; (3) window systems and control strategies; and (4) analysis parameters of interest. This paper summarizes the results obtained thus far by several of the research organizations.

Introduction

The goal of the International Energy Agency (IEA) Solar Heating and Cooling Program (SHC) Task 18 Advanced Glazing and Associated Materials for Solar and Building Applications is to reduce the energy consumption of buildings through improved glazing technologies. This task was formed as a five-year effort in January 1992. It is the world's largest coordinated effort in glazings research, with more than 60 researchers participating worldwide. In addition to developing the scientific, engineering, and architectural basis for development of new technologies, the Task 18 research also focuses on application and technology transfer issues. The emphasis is on near or emerging market applications.

Task 18 intends to increase general awareness of advanced glazings, plus aid industry, universities, and standards organizations in the proper measurement, application, energy benefit, and use of these advanced materials on an international level. Task 18 is organized into two Subtask areas: Subtask A focuses primarily on anaylses required to identify the energy and environmental benefits and building applications of various potential glazing materials and Subtask B involves the laboratory characterization of glazings and daylighting component materials. Task 18 activity is expected to promote trade and standardization of new glazing products, and augment activities at national laboratories, in the glazing industry, and in organizations such as National Fenestration Rating Council (NFRC) in the United States.

A major focus in Subtask A, categorized as the Modeling and Control Strategies Project, involves evaluating the energy and comfort performance of advanced glazing systems and dynamic control strategies in realistic commercial and residential building environments through mathematical simulation of the heat transfer processes. Another interest is to evaluate the ability of current window and building simulation tools to properly characterize the dynamic and annual performance of these systems and improve tools as necessary to create common technical approaches for simulation. Eventually, it is hoped to create models that can meet the simulation needs of groups such as ISO, CEN, and NFRC in developing national and international window rating systems.

The USA is coordinating the efforts of researchers from eleven countries participating in the Modeling and Control Strategies Project. A total of 96 person-months is expected to be utilized over the course of three years. Countries include: Australia, Denmark, Finland, Germany, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, and the United States. Specific activities to be performed are: (1) completing a literature review; (2) defining the analysis methods and computer tools to be used; (3) defining the performance variables to be evaluated; (4) completing the simulations and evaluating the results; and (5) writing a final technical report. The remainder of this paper will discuss in more detail the definition phase of the project and specific simulation results of several participating countries.

Project Definition

The Modeling and Control Strategies Project is structured so that participating countries can evaluate the performance of advanced glazings within the context of their own particular environment. This includes not only geographic location, but also the commercial and/or residential buildings to be simulated as well as window systems and control strategies to be analyzed. In addition, each country will also have the option of using whatever analysis tool best fits their needs and desires. Selected simulation programs include: CHEETAH (AUS); DOE-2.1E (AUS, USA); HELIOS (CH); TRNSYS (FIN, IT, GER, NOR); and TSBI3 (DK). We see the results from each country as complementary, yet totally independent and individualized.

Table 1 shows the cities for each country whose weather patterns will be simulated. Locations vary from Darwin, Australia at 12 degrees south latitude characterized as tropical, hot and humid to Sodankylaa, Finland at 67 degrees north latitude which has very cold winters and mild summers. While most of the locations can be associated with significant winter heating requirements primarily because they are located in northern Europe, cities located in Australia, Italy, and the United States will insure adequate cooling performance analysis for the selected advanced glazings.

Both commercial and residential buildings are being simulated by most countries. The commercial buildings vary from prototypical single-floor office building modules to multi-floor buildings with ground floors, intermediate floors, and rooftop floors. Residential buildings are either single-story or two-story with floor plans and construction typical of the participating country. The orientation of each of these buildings is varied so that its effect on window performance can be obtained.

Tables 2 and 3 show the advanced glazings and control strategies that are being analyzed by each country. We see that the representative glazings reflect an interest in one or more of the glazing property characteristics that effect energy and comfort performance; i.e. thermal, solar, and optical. For example, aerogel, superinsulated, and TIM glazings focus on insulation performance as well as solar gain performance; whereas, angular selective, electrochromic, and light redirection systems tend to focus on the solar and optical characteristic performance. In all cases, however, performance of these advanced glazings are being referenced to baseline double-pane low-E glazings.

Control strategies effecting both the building envelope and lighting system are being studied. Envelope strategies include those being used with electrochromic windows to control state-switching and those used with conventional shading systems such as venetian blinds, diffusing shades, etc. Lighting system strategies are related specifically to window daylight performance and several types of dimming controls are being analyzed.

We now present results from several studies already completed or in progress. These include: Australia, Finland, Norway, Switzerland, and the United States.

Simulation Results: Australia

The preliminary simulation studies presented for Australia (Ref. 1) are for residential applications. Conventional single- and double-pane glazings have been compared to high performance solar control glazings and highly insulated glazings in three climate zones. The locations vary from the tropical heat of Darwin, to Sydney with its Mediterranean climate and mild winter, and to cool temperate Canberra which has sunny, frosty winters and hot dry summers. The thermal modeling software used was CHEETAH, which is a PC-based dynamic program based on the ASHRAE response-factor method. It is the chosen tool for the development of Australia's Nationwide House Energy Rating Scheme (NatHERS) and the new Window Energy Rating Scheme (WERS).

The Australian house is a rectangular single-story, slab-on-grade design of 170 m^2 (1830 ft^2) floor area with construction typical for houses built after about 1970 in the eastern states of Australia. Windows are distributed as follows: North (equator-facing) 21.1 m^2 (227 ft^2); East 2.1 m^2 (22.6 ft^2); South 14.8 m^2 (159 ft^2); and West 2.0 m^2(21.5 ft^2) . Eaves 0.600 m (2 ft) deep and 0.25 m (10 in) above the window head were assumed for the north and south facades of the building.

Table 4 shows the seven windows that were analyzed. They vary from a single pane clear unit with a total U-factor of 6.0 W/m^2K (1.1 Btu/h-ft^2F) and solar heat gain coefficient of 0.84 to a highly insulated evacuated double pane window with low-E coating with a U-factor of 0.80 W/m^2k (0.14 Btu/h-ft^2F) and solar heat gain coefficient of 0.53. Also simulated was a single pane glazing with solar control laminate and lowE coating with a U-factor of 3.3 W/m^2k (0.58 Btu/h-ft^2F) and solar heat gain coefficient of 0.31.

Heating and cooling thermal load results are presented in Figure 1. The data, at this point in the study, do not include gas furnace efficiencies or air-conditioning system COPs. The space thermostat setpoints were 20C (68F) for heating and 25C (77F) for cooling. Most obvious is that the heating and cooling loads are very climate-dependent. Darwin requires no heating, but more than twice the cooling of Sydney. Canberra's heating loads are about three times those of Sydney which is consistent with their respective heating degree days.

The ranking of the seven windows varies with climate. In the warmer climates (Darwin, Sydney), the windows with the lowest solar heat gain coefficients perform the best. Another frequently-observed trend in cooling loads may also be seen; i.e. cooling load increases slightly as the U-factor of the window is reduced. We assume that this is due to stored heat being "trapped" more by insulating glazing than by less insulating glass. Of course this could be an artifact of the rather rigid simulation methodology which lacks the commonsense of a real human occupant.

For Darwin, where only cooling is a concern, the clear "winner" is window #6 with its low solar heat gain coefficient (0.18). However, its associated visible transmittance of 0.24 would be too low for many homeowners. There is little point having gloomy interiors which largely negate cooling energy savings because of high lighting loads that may be required. Option #2 with a visible transmittance of 0.54 is a better compromise. An alternative to low solar heat gain glazings is the judicious use of either external shades or reflective internal shades or blinds. However such devices are also extra-cost items which must be included in the total cost of the window system.

In Sydney, a similar conclusion to Darwin may be drawn; i.e., a high-performance spectrally-selective single-glazed design offers considerable heating and cooling load improvements. This points to a large market for glazings with high luminous efficacies and similar high-daylight solar-control films for retrofit applications. These findings are in accord with other studies for cooling-dominated climates, such as Southern California (Ref. 2) and Florida (Ref. 3). In most cases, high-performance single pane glazings can be selected for warm-to-hot climates where their good solar rejection is much more beneficial than a very low U-factor.

In Canberra and other heating dominated locations, which can have heating degree days exceeding 4000 with a base temperature of base 18C (7200 HDD base 65F), such as in mountainous areas of southeast Australia, in most of Tasmania, and in the South Island of New Zealand, the lowest U-factor windows yield the best results. Cooling load performance become less important. The passive-solar benefit of high solar heat gain and low U-factor is seen clearly in the Canberra results. Increased thermal mass in zones receiving direct gain would also enable such glazings to perform even better.

Simulation Results: Finland

The initial work in Finland (Ref. 4) has been concerned with the energy effects of window systems used in typical commercial and residential buildings located in Helsinki (60N). These simulations are part of Finnish research project "Development of the Future Building Window" which is financed by the National Energy Technology Programme RAKET.

Commercial Building

The commercial building has four floors each with a floor area of 389 m^2 (4187 ft^2). Total building floor area is 1556 m^2 (16749 ft^2). Each floor is separated into three south-facing and north-facing spaces which have different occupancy and usage patterns. Rotating the building forty-five degrees facilitates an east/west orientation analysis. The total window area along each facade is 230.4 m^2 (2480 ft^2) which represents a window-to-wall area ratio of 0.37 and window-to-floor area ratio of 0.30. Table 5 shows the five glazings simulated. They vary from a double pane unit with clear/low-E glazing with air gas fill with a total U-factor of 1.93 W/m^2K (0.35 $Btu/h\text{-}ft^2F$) and center-of-glass solar heat gain coefficient of 0.76 to a triple pane unit using clear, low-E, and heat mirror layers and argon gas fill with a U-factor of 1.33 W/m^2k (0.17 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.40.

Figure 2 presents the annual heating and cooling energy demand for the five glazings as a function of orientation. Heating demand varies by 16-18% for the different orientations and glazings. For U-factors below the value of the triple pane low-E glazing #3, i.e. 1.47 W/m^2k (0.26 $Btu/h\text{-}ft^2F$), there is no noticeable difference in heating performance as the solar heat gain coefficient varies. However, there is a significant difference in cooling performance, both for orientation and glazing type. The cooling demand in spaces with windows facing north is half of that required for south-facing windows; while spaces with east- or west-facing windows require an amount of cooling somewhere between these extremes. Utilizing shading devices would mitigate these differences. Further studies will include the effects of daylighting on energy performance.

Residential Building

The residential building is a single-story house with a floor area of 134 m^2 (1442 ft^2). Windows are distributed as follows: North - 1.44 m^2 (15.5 ft^2); East - 3.24 m^2 (34.9 ft^2), South - 7.92 m^2 (85.3 ft^2), and West - 1.8 m^2 (19.4 ft^2). Table 5 shows the four glazings simulated. They vary from a double pane unit with clear/low-E glazing with air gas fill with a total U-factor of 1.93 W/m^2K (0.35 $Btu/h\text{-}ft^2F$) and center-of-glass solar heat gain coefficient of 0.76 to a triple pane unit using clear, low-E, and heat mirror layers and argon gas fill with a U-factor of 1.18 W/m^2k (0.21 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.57.

Figure 3 presents the monthly heating demand for the four glazings. On an annual basis, the glazings perform very similarly with about an 8% difference in overall heating performance. This is due to the fact that for the selected glazings, as the U-factor is decreased resulting in a smaller conductive heat loss, the solar heat gain coefficient has also been reduced resulting in lower solar heat gain, thus negating the benefits associated with lower U-factor. This is more clearly seen also in Figure 3 which shows the monthly variation of window heat loss and solar gain.

An economic analysis was completed based on the present value of the total energy savings of each window compared to the double pane low-E glazing #1. An energy price of 0.40 Finnish Markka/kWh (0.085 US Dollar/kWh) and a discount rate of 7% and a window lifetime of 25 years was used in the calculation. Results are as follows: TRIPLE (#2) - 29 Markka/m^2 of window (6.13 US$/$m^2$, 0.57 US$/ft^2); TRIPLEe (#3) - 201 Markka/m^2 (42.51 US$/$m^2$, 3.95 US$/ft^2); and TRIPLEe88g (#6) - 289 Markka/m^2 (61.12 US$/$m^2$, 5.68 US$/ft^2).

Simulation Results: Norway

Work in Norway (Ref. 5) has focused on a parametric study of high performance glazings in residential buildings at high latitudes (Oslo: 59.9N and Tromsø: 69.7N) with an emphasis on conventional present value economic analysis. A typical Nowegian single-story wood-frame dwelling with a floor area of 105.1 m^2 (1131 ft^2) was chosen as a base case and levels of wall/roof/floor thermal insulation levels and internal gains were varied. Both direct gain windows and sun spaces were analyzed. Results showed that the window solar energy transmittance can be sacrificed in favor of U-factor to obtain higher energy savings. Also, the insulation value of the walls, roof, and floor and the internal heat gains have little effect on the definition of an optimum glazing.

Since, window prices vary significantly and are dependent on window size, sales quantity, and manufacturer, the economic analysis was based on average marginal costs compared to a selected base case glazing. Using conventional present value economics, the optimum glazing for a standard Norwegian dwelling was a double pane window with one low-E coating and an argon gas fill. Applying the same present value methodology to analyze the cost effectiveness for an add-on sunspace to the dwelling, it was shown that the optimum glazing was a double pane with one low-E coating when the sunspace temperature was kept at a minimum of 10C-15C (50F-59F). If the temperature was permitted to go as low as 5C (41F), a single glazing with a low-E coating was the most cost-effective.

Table 6 shows the glazings that were analyzed during the course of the study. They vary from a standard double pane clear glazing with a total U-factor of 2.9 W/m^2K (0.51 $Btu/h\text{-}ft^2F$) and center-of-glass solar heat gain coefficient (SHGC) of 0.75 to a quadruple pane superwindow with a U-factor of 0.8 W/m^2K (0.14 $Btu/h\text{-}ft^2F$) and SHGC of .40. In addition, two hypothetical glazings: vacuum and aerogel were also simulated. The vacuum glazing provides better solar transmission than the quadruple glazing while maintaining the same level of conductance; the aerogel provides better conductance than the quadruple glazing while maintaining the same level of solar transmission.

Figure 4 shows the annual heating energy consumption for several of the above glazing types for different residential envelope insulation standards. Windows were distributed on the four facades as follows: North - 3.9 m^2 (42 ft^2); South - 22.2 m^2 (240 ft^2); East - 1.4 m^2 (15 ft^2; and West -

0.5 m^2 (5.4 ft^2). Results show a steadily decreasing heating energy demand as the U-factor of the glazing decreases, even though the amount of beneficial solar heat gain also decreases. For the vacuum window #7, the solar gain increases and there is a corresponding further decrease in required heating. We see that a poorly insulated building with vacuum windows performs about the same as a well insulated building with double pane low-E windows #2. As expected, the differences between the various window types and insulation standards are more significant for the colder and less sunny climate of Tromsø. The overall heating demand is about 20% higher for Tromsø than for Oslo.

The economic analysis was based on the Present Value Method with an energy price of 0.50 Norwegian Krone/kWh (0.075 US Dollar/kWh) a discount rate of 7% and a window lifetime of 25 years. We compared the cost effectiveness of replacing all the standard double pane windows of the residence with more advanced window types. Results are presented in Table 7. Cost effectiveness is expressed as the difference between the present value of the energy savings and the investment cost associated with a particular glazing. A positive value signifies a cost effective investment.

In general, one can see that the advanced windows are more cost effective in Tromsø than in Oslo. This is due to its colder climate and the longer heating season. For all cases, the double pane window with one low-E coating and argon gas fill (window #3) is the most cost effective. It is important to note that the double pane glazings with low-E have been on the market for several years and have become a standard, mass-produced product. The triple- and quadruple-pane glazings are sold in much smaller quantities and are priced higher. The vacuum and aerogel windows are still in the development phase and so there are no market prices as yet.

Simulation Results: Switzerland

Switzerland (Ref. 6) is investigating the performance of highly insulated glazings and transparent insulation in a thermally massive multi-family building located in four geographic locations varying from Davos (46.8N) which has an alpine climate and is at an altitude of 1590 m (5217 ft) to Magadino (46.1N) at an altitude of 197 m (646 ft) and is characterized by having moderates winter and warm and sunny summers. The multi-family house has four floors, each with a floor area of 362 m^2 (3897 ft^2). There are 16 flats in the building with a total of 61 rooms. It is elongated with the main facades having a total surface area of 350 m^2 (3767 ft^2 containing 90% of the windows.

The four glazings presented on Table 8 were simulated. They vary from double pane with clear glazing and air gas fill with a total U-factor of 2.70 W/m^2K (0.48 $Btu/h\text{-}ft^2F$) and center-of-glass solar heat gain coefficient of 0.78 to triple pane using clear and low-E glazing layers and krypton gas fill with a U-factor of 0.69 W/m^2k (0.12 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.40. Window area varied from 0% to 30% of the floor area.

Results for Davos are shown on Figure 5 for east- and south-facing facades. We see that the energy consumption depends strongly on the orientation of the main facade; e.g., for a window size equal to 20% of the floor area, heating is reduced from 278 GJ (264 MBtu) to 189 GJ (179 MBtu) or 32% for the base case glazing (window #1). For south orientations, all the glazings analyzed use less energy than the wall with no windows [227 GJ (215 MBtu)]; however, for east-facing windows, only the higher insulated glazings perform better than the windowless wall. The reason for this is related to the increased amount of beneficial solar heat gain that is apparent with south-facing windows. The largest incremental reduction in energy use occurs between the base case double pane window and the other windows. This shows the dramatic effect window conduction has on performance since in each case, the solar heat gain coefficient of the higher insulated glazings is less than the base case glazing resulting in less beneficial solar heat gain.

There is not a significant difference in performance between the higher insulated glazings unless the window size is very large and only for east-facing triple pane, low-E glazing with krypton gas fill (window #4) which has a very low total U-factor of 0.8 W/m^2-K (0.14 Btu/h-ft^2F). For south orientations, however, the reduction in glazing solar heat gain coefficient offsets the beneficial aspects of lower conduction.

Comfort was also examined by calculating the glass inside surface temperature distribution and comparing the temperature to the room air temperature. The room air temperature varied between 17.5C (63.5F) and 25.2C (77.5F) with a mean value of 20C (68F) for all glazings. This is because all the heating energy is convected to the air and 70% of the additional incoming radiation is absorbed by the walls, floors and ceilings. However, there was a big difference in the glass surface temperatures for the base case double pane clear window #1 and the other highly insulated windows.
Figure 6 shows the distribution for the windows facing east in Davos. The window-to-floor area ratio was 30%. The left scale shows the number of hours with temperatures higher than the temperature indicated on the horizontal axis; the right scale shows the percentage of the total simulated time; i.e., results for the base case window #1 indicates that during 40% of time or 2034 hours the inside surface temperature was greater than 14C and the surface temperature decreases to a minimum of 3C (37.4F). Correspondingly, the triple pane, low-E with krypton gas fill window #4 is below 18C (64.4F) only 10% of the time. Changing orientation has no influence on the lower temperatures but does cause a significant rise in temperature, for example, the double pane low-E window #2 can go as high as 36C (96.8F). However, in general, the highly insulated glazings perform very well and have surface temperatures similar to the room air temperature which results in a more comfortable environment.

Simulation Results: United States

Work in the United States thus far has been concerned with the performance of electrochromic windows in commercial (Ref. 7) and residential buildings (Ref. 8). Each analysis simulated the performance in cooling dominated locations with an emphasis on understanding the influence of electrochromic state-switching control strategies. The DOE-2.1 E simulation program was used to calculate annual electric energy use and peak electric demand for a variety of electrochromic glazings as a function of window size and control strategy. Results were also compared to conventional glazing and shading systems.

Commercial Building

A prototypical commercial office building module consisting of a 30.5 m (100 ft) square core zone, surrounded by four identical perimeter zones, each 30.5 m by 4.6 m (100 ft by 15 ft) located in the cooling-dominated location of Blythe, California was simulated. Blythe is located in southern California and is characterized as hot and dry most of the year. Control strategies analyzed were based on daylight illuminance, incident total solar radiation, and space cooling load. The bleached and colored state properties of the electrochromics are shown on Table 9.

Results showed that when daylighting is used to reduce electric lighting requirements, control algorithms based on daylight illuminance results in the best overall annual energy performance. If daylighting is not a design option, controls based on space cooling load yielded the best performance through solar heat gain reduction. The performance of incident total solar radiation control strategies varied as a function of the switching setpoints; for small to moderate window sizes which resulted in small to moderate solar gains, a large setpoint-range was best since it provided increased illuminance for daylighting without much cooling penalty; for larger window sizes, which provided adequate daylight, a smaller setpoint-range was best to reduce unwanted solar heat gains and the consequential increased cooling requirement. Of particular importance was the result that reduction in peak electric demand was found to be independent of the type of control strategy used for electrochromic switching. This was because the electrochromics are generally in their most colored state under peak conditions, and the mechanism used for achieving such a state was not important.

An example of the results obtained can be seen in Figure 7 which shows the cooling and lighting electricity use components for west-facing low-E electrochromic windows as a function of window-to-wall ratio for several control strategies. For all glazings and window sizes, daylight control provides the best overall performance, implying that modulation of daylighting results in good solar control modulation as well. At window-to-wall area ratios less than about 0.35, total electricity performance is more a function of lighting electricity decrease than cooling electricity increase. Therefore, the more daylight available from these window sizes, the better overall performance; i.e. control strategy performance follows the pattern: daylight control, solar control setpoints 63-630 W/m^2(20-200 Btu/hr-ft^2), solar control setpoints 63-315 W/m^2 (20-100 Btu/hr-ft^2), solar control setpoints 63-189 W/m^2 (20-60 Btu/hr-ft^2), and lastly space load control. At larger window-to-wall area ratios, the increase in associated solar gains causes an increase in cooling electricity use and the solar control setpoint strategies reverse their position; i.e. the 63-189 W/m^2 (20-60 Btu/hr-ft^2) strategy performs better than the 63-630 W/m^2 (20-200 Btu/hr-ft^2) strategy. The smaller setpoint range does a better job of minimizing solar heat gains. For a given window size, it should therefore be possible to develop a set of control algorithms that are sensitive to both lighting levels and solar heat gain and that work well under all climatic conditions.

The use of space cooling load as a control strategy results in the smallest cooling electricity, but also the smallest lighting electricity use reduction due to daylighting. As a result, use of space cooling load results in the largest summed electricity use for all glazings modeled. Cooling load control, however, can be a preferable strategy for those building configurations that do not incorporate daylighting as an energy saving design option. It may also be an important strategy to minimize chiller size or to maintain comfort under conditions when a building HVAC is not able to provide its rated cooling output.

Residential Building

A single-story ranch-style home with a floor area of 143 m^2(1540 ft^2) located in the cooling-dominated locations of Miami, Florida and Phoenix, Arizona was simulated. Control strategies analyzed were based on incident total solar radiation, space cooling load, and outside air temperature. Table 9 shows the electrochromic properties in the bleached and colored states. 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.

Figure 8 shows the annual cooling energy use in Miami, Florida for each of the electrochromic windows and control strategies analyzed. 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 Figure 8 are data comparing the three variations in incident total solar radiation switching setpoints; the lower portion shows results using space cooling load and outside air temperature control. 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 as shown on Table 9. The one exception is when using incident solar radiation with a large setpoint range, 63-630 W/m^2 (20-200 Btu/hr-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.

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. For example, for the largest window size and a large setpoint range, 63-630 W/m^2(20-200 Btu/hr-ft^2), the GXE glazing requires 10400 kWh with a maximum difference in performance between the GXE and 80/20E electrochromic devices of about 1600 kWh. For a small setpoint range, 63-189 W/m^2 (20-60 Btu/hr-ft^2), the GXE requires 6400 kWh with a the maximum difference of 3200 kWh.

Space cooling load control 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. 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.

Conclusions

Researchers from eleven countries are participating in a multi-year study which has as its goal the energy and comfort performance evaluation of advanced glazing systems in commercial and residential buildings. Defined as the Modeling and Control Strategies Project of IEA/SHC Task 18 Advanced Glazing & Associated Materials for Solar & Building Applications, participants have undertaken computer simulation studies that will assist future glazing system development efforts. In addition, we see the international cooperation fostered by IEA/SHC Task 18 influencing organizations such as ISO, CEN, and NFRC in developing window rating techniques that effect the environment in a positive manner.

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Table 1. Geographic Locations

Location	Latitude	Weather	Heating Degree Days Base Temp 18C (65F)	
Australia				
Canberra	35degS	Cool/temperate/dry	HDD=2160	(3888)
Darwin	12degS	Tropical/hot/humid	HDD=0	(0)
Sydney	34degS	Mild winter, warm humid summer	HDD=743	(1337)
Denmark				
Copenhagen	56degN	Temperate	HDD=2990	(5382)
Finland				
Helsinki	60degN	Cold winter, mild summer	HDD=4716	(8489)
Jyvaaskylaa	62degN	Cold winter, mild summer	HDD=5274	(9493)
Sodankylaa	67degN	Cold winter, mild summer	HDD=7112	(12802)
Germany				
Freiburg	48degN	Mild continental	HDD=3400	(6120)
Italy				
Milano	45degN	Cold winter, hot/humid summer	HDD=2615	(4707)
Roma	42degN	Mild winter, hot/humid summer	HDD=1606	(2891)
Norway				
Oslo	60degN	Cold winter, mild summer	HDD=4077	(7339)
Tromsø	69.7degN	Cold winter, mild summer	HDD=6029	(10852)
Switzerland				
Davos	47degN	Alpine	HDD= 5866	(10558)
Geneva	46degN	Cold winter, mild summer	HDD= 3191	(5743)
Magadino	46degN	Moderate winter, warm summer	HDD= 2919	(5254)
Zurich	47degN	Cold winter, mild summer	HDD= 3469	(6244)
United States				
Blythe	33degN	Mild winter, hot/dry summer	HDD=580	(1044)
Madison	43degN	Cold winter, hot/humid summer	HDD=4347	(7825)
Miami	26degN	Warm winter, hot/humid summer	HDD=103	(1854)
Phoenix	33degN	Mild winter, hot/dry summer	HDD=1066	(1919)

Table 2. Advanced Glazings to be Studied

Commercial Buildings	
Aerogel	(DK, NOR)
Angular selective	(AUS, SWE)
Electrochromic	(AUS, FIN, IT, NOR, SWE, CH, USA)
Light redirection systems	(AUS, NOR, USA)
Superinsulated	(DK, FIN, SWE)
Thermochromic	(CH)
Thermotropic	(GER)
TIM	(IT)
Residential Buildings	
Aerogel	(DK, NOR, CH)
Electrochromic	(AUS, USA)
Evacuated	(NOR, SWE, USA)
Antireflective coating	(SWE)
Superinsulated	(DK, FIN, NOR, SWE, CH)
Thermotropic	(GER)

Table 3. Control Strategies to be Studied

Commercial Buildings		
Electrochromic devices		
	Daylight illuminance	(AUS, FIN, IT, NOR, USA)
	Glare	(AUS)
	Solar radiation	(IT, NOR, CH, USA)
	Space air temperature	(NOR)
	Space thermal load	(AUS, FIN, IT, USA)
Shading devices		
	Solar radiation	(AUS, DK, IT, NOR, CH, USA)
	Space temperature	(DK)
Residential Buildings		
Electrochromic devices		
	Daylight illuminance	(AUS)
	Glare	(AUS)
	Solar radiation	(USA)
	Space thermal load	(AUS, USA)
Shading devices		
	Solar radiation	(AUS, DK, NOR, CH, USA)

Note:
Lighting System: Daylight illuminance using continuous dimming, stepped, on/off control, or probablistic.

Table 4. AUSTRALIA Glazing Properties

GLAZING	FRAME	SHGC	SC	Tvis	U-Factor, Total W/m2-K (Btu/h-ft2F)
1. Single clear	Alum w/o TB	0.84	0.96	0.82	6.00 (1.10)
2. Single solar control, low-E, air	Wood	0.31	0.35	0.54	3.30 (0.58)
3. Double clear, air	Alum, improved	0.66	0.75	0.67	3.50 (0.62)
4. Double clear, low-E, air	Alum, improved	0.63	0.72	0.63	2.70 (0.48)
5. Double clear, low-E, Argon	Wood	0.60	0.68	0.63	1.80 (0.32)
6. Double reflective, low-E, air	Wood	0.18	0.21	0.24	2.10 (0.37)
7. Double, low-E, low-E, vacuum	Wood	0.53	0.60	0.57	0.80 (0.14)

Notes:
(1) Solar/optical properties are for the total window.
(2) Windows modelled were horizontal slider with one centre mullion; dimensions 1.5 m (4.92 ft) wide by 1. 2 m (3.94 ft) high.
(3) "Improved: aluminum frame denotes thermal break or other feature designed to reduced thermal bridging. U-factors are typical for the technology; variations may occur between products.
(4) Spacer width was 12.7 mm (0.5 in) except for the vacuum glazing.
(5) Low-E is hard coat, emittance=0.2, except for #2 which is special laminated low-E.
(6) User-defined weather conditions:
Winter —Tout = 0C (32F), Tin = 20C (68F), Wind Speed = 3.4 m/s (7.5 mph) windward
Summer —Tout = 35C (95F), Tin = 25C (77F), Wind Speed = 3.4 m/s (7.5 mph) windward,
Solar Radiation = 880 W/m2 (279 Btu/h-ft2)

Table 5. FINLAND Glazing Properties

GLAZING		SHGC	SC	Tvis	U-Factor, Total/Center W/m2-K (Btu/h-ft2F)
Commercial Building Study					
1. DGUe	1 CL,1LE,air	0.76	0.87	0.77	1.93 (0.35) / 1.74 (0.31)
2. TRIPLE	3 CL,air	0.71	0.82	0.76	1.80 (0.32) / 1.76 (0.31)
3. TRIPLEe	2 CL,1 LE,air	0.68	0.78	0.71	1.47 (0.26) / 1.38 (0.24)
4. TRIPLE66g	3 CL,1 HM66,argon	0.40	0.46	0.51	1.33 (0.23) / 1.17 (0.21)
5. ASUN	1 CL,1 LE,1 ABS,argon	0.44	0.51	0.59	1.35 (0.24) / 1.20 (0.21)
Residential Building Study					
1. DGUe	1 CL,1LE,air	0.76	0.87	0.77	1.93 (0.35) / 1.74 (0.31)
2. TRIPLE	3 CL,air	0.71	0.82	0.76	1.80 (0.32) / 1.76 (0.31)
3. TRIPLEe	2 CL,1 LE,air	0.68	0.78	0.71	1.47 (0.26) / 1.38 (0.24)
6. TRIPLEe88g	2 CL,1 LE,1 HM88,argon	0.57	0.66	0.64	1.18 (0.21) / 0.94 (0.17)

Note:
(1) Solar/optical properties are for the center-of-glass.

Table 6. NORWAY Glazing Properties

GLAZING		SHGC	SC	U-Factor, Total/Center W/m2-K (Btu/h-ft2F)
1. Double	Double, air (4-12-4)	0.75	0.86	2.7 (0.48)/2.9 (0.51)
2. DoubleLE	Double, 1 LE, air (4-12-4KEK)	0.61	0.70	2.0 (0.35)/1.8 (0.32)
3. DoubleLEg	Double, 1 LE, argon (4-12A-4KEK)	0.61	0.70	1.7 (0.30)/1.5 (0.26)
4. TripleLEg	Triple, 1 LE, air, argon (4-12-4-12A-4KEK)	0.54	0.62	1.5 (0.26)/1.2 (0.21)
5. Triple2LEg	Triple, 2 LE, air, argon (4KEK-12A-4-12A-4KEK)	0.45	0.52	1.3 (0.23)/0.9 (0.15)
6. Quadruple	Quadruple, 3 LE, argon (4KEFL-18-4KEK-16A-4-16A-4KEK)	0.40	0.46	0.8 (0.14)/0.5 (0.09)
7. Vacuum	Double, 2LE, vacuum	0.52	0.60	0.8 (0.14)/0.8 (0.14)
8. Aerogel	Double, aerogel (4-20-4)	0.64	0.74	0.7 (0.12)/0.5 (0.09)

Notes:
(1) Solar/optical properties are for the center-of-glass.
(2) 4-12-4-12A-4KEK = 4mm glass pane - 12mm air - 4mm glass pane - 12mm argon - 4mm glass pane with low E coating (KEK=Kappa Energi Klar; KEFL-Kappa Energi Float).

Table 7. NORWAY Cost Effectiveness of Glazing Types

	OSLO NOK/m2 (US$/m2, US$/ft2)		
GLAZING	Present Value Savings	Investment Cost	Cost Effectiveness
DoubleLE	460 (68, 6.32)	160 (24, 2.23)	300 (45, 4.18)
DoubleLEg	690 (103, 9.57)	230 (34, 3.16)	**460 (69, 6.41)**
TripleLEg	740 (110, 10.22)	500 (75, 6.97)	240 (36, 3.34)
Triple2LEg	840 (125, 11.61)	650 (97, 9.01)	190 (28, 2.60)
Quadruple	1190 (178, 16.54)	1850 (276, 25.64)	-660 (-98, -9.10)
Vacuum	1300 (194, 18.02)	---	---
Aerogel	1420 (212, 19.69)	---	---
	TROMSØ NOK/m2 (US$/m2, US$/ft2)		
DoubleLE	560 (84, 7.80)	160 (24, 2.23)	400 (60, 5.57)
DoubleLEg	850 (127,11.79)	230 (34, 3.16)	**620 (93, 8.64)**
TripleLEg	910 (136, 12.63)	500 (75, 6.97)	410 (61, 5.67)
Triple2LEg	1020 (152, 14.12)	650 (97, 9.01)	370 (55, 5.11)
Quadruple	1470 (219, 20.35)	1850 (276, 25.64)	-380 (-57, -5.30)
Vacuum	1620 (242, 22.48)	---	---
Aerogel	1770 (264, 24.53)	---	---

Table 8. SWITZERLAND Glazing Properties

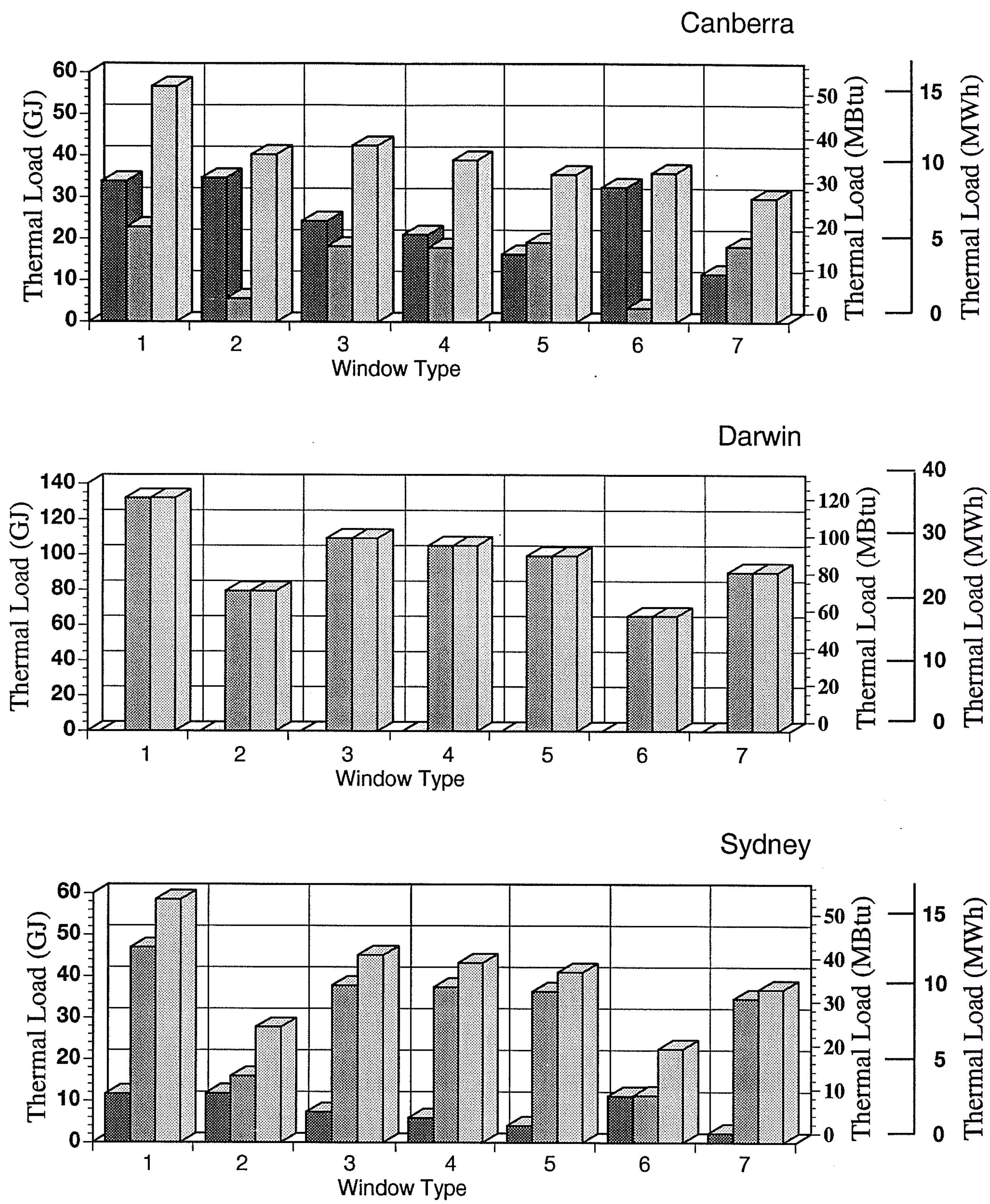
GLAZING		SHGC	SC	U-Factor, Total/Center W/m2-K (Btu/h-ft2F)
1. Double	Double, air (4-16-4)	0.78	0.90	2.7 (0.48) / 2.9 (0.51)
2. DoubleLEg	Double, 1 LE, argon (4-16-4LE)	0.65	0.75	1.5 (0.26) / 1.3 (0.23)
3. TripleLEg	Triple, 2 LE, argon (4-12A-4LE-12A-4LE)	0.44	0.51	1.0 (0.18) / 0.8 (0.14)
4. Triple2LEg	Triple, 2 LE, krypton (4-12K-4LE-12K-4LE)	0.40	0.46	0.7 (0.12) / 0.5 (0.09)

Notes:
(1) Solar/optical properties are for the center-of-glass.
(2) 4 -16-4LE = 4mm glass pane - 16mm argon - 4mm glass pane with Low-E
(3) 4-12A-4LE-12A-4LE = 4mm glass pane - 12mm argon - 4mm glass pane with Low-E 12mm argon - 4mm glass pane with Low-E
(4) 4-12K-4LE-12K-4LE = 4mm glass pane - 12mm krypton - 4mm glass pane with Low-E - 12mm krypton - 4mm glass pane with Low-E

Table 9. USA Electrochromic Glazing Properties

	SHGC Bleached/ Colored	SC Bleached/ Colored	Tvis Bleached/ Colored	U-Factor, Center W/m^2-K (Btu/h-ft^2F) Bleached/ Colored
		Commercial Building Study		
Electrochromic				
Clear Absorptive	0.73/0.18	0.85/0.21	0.76/0.12	2.68 (0.47)/2.73 (0.48)
Clear Reflective	0.63/0.17	0.73/0.20	0.73/0.14	2.67 (0.47)/2.72 (0.48)
Low-E Absorptive	0.49/0.16	0.57/0.18	0.66/0.10	2.58 (0.45)/2.59 (0.46)
Low-E Reflective	0.46/0.16	0.54/0.18	0.64/0.12	2.57 (0.45)/2.57 (0.45)
Idealized	0.64/0.03	0.67/0.06	0.65/0.00	2.55 (0.45)/2.53 (0.45)
Conventional				
Tinted Grey	0.47	0.54	0.38	3.32 (0.58)
Reflective Clear	0.18	0.20	0.13	2.80 (0.49)
Low-E Tinted	0.30	0.35	0.41	2.60 (0.46)
		Residential Building Study		
Electrochromic				
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	0.64	0.75	0.77	1.91 (0.34)
Low-E Clear	0.44	0.51	0.70	1.69 (0.30)
Low-E Tinted	0.29	0.33	0.41	1.77 (0.31)

Notes:
(1) Solar/optical properties are for the center-of-glass.
(2) U-Factors 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).



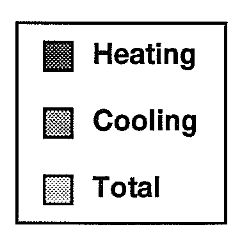
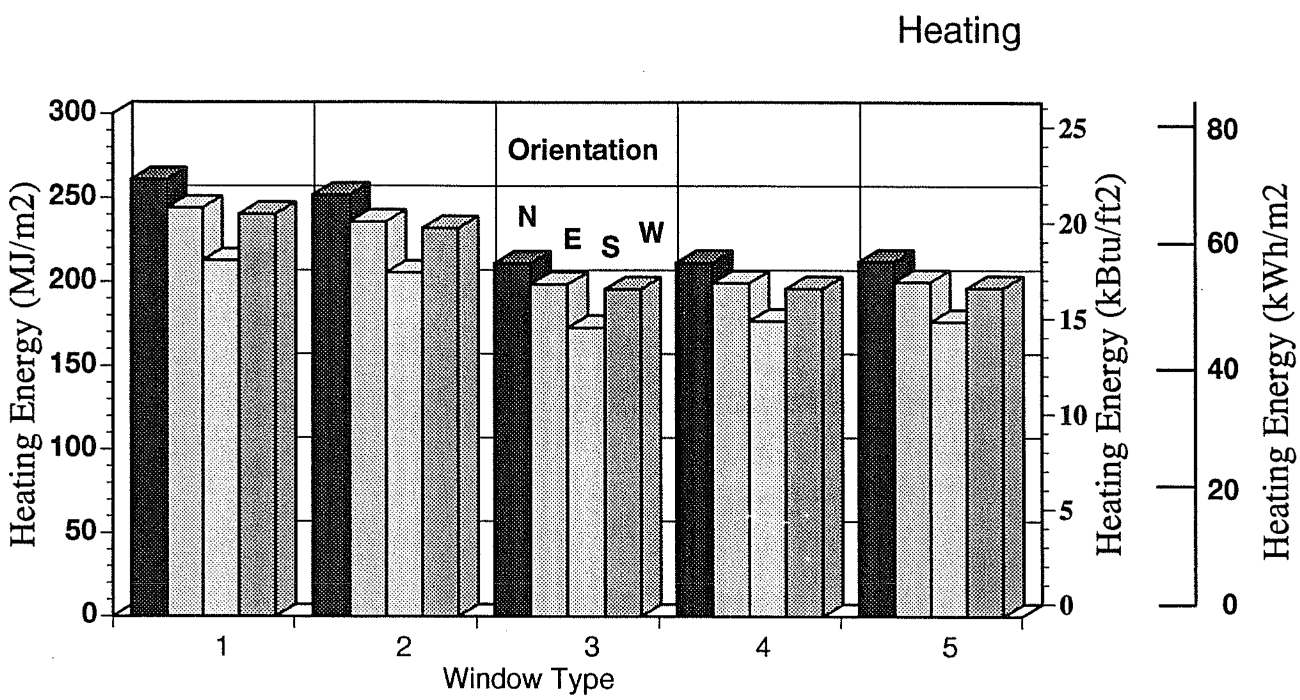


Figure 1: Simulation results for Australia. Annual heating, cooling, and total thermal loads are shown for three locations for a single-story residential building of 170 m2 (1830 ft2) floor area for seven window types (see Table 4).



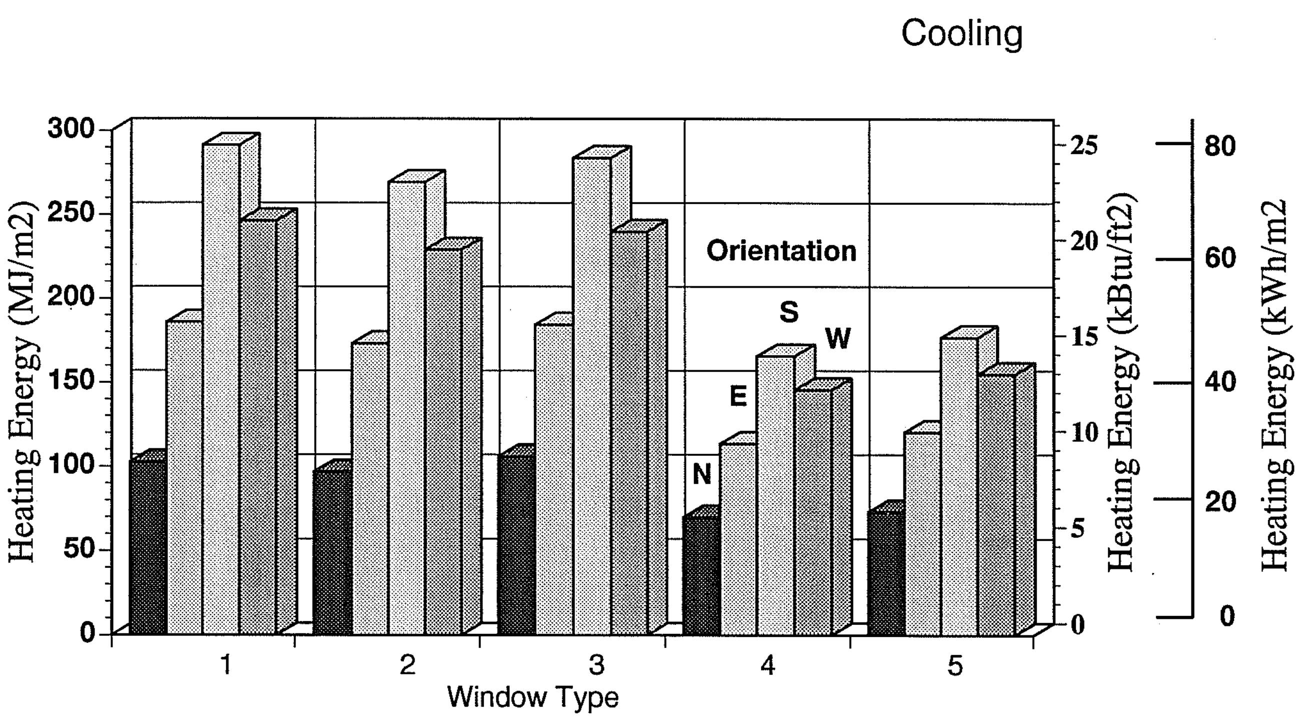


Figure 2: Simulation results for Finland Annual heating and cooling energy demand per unit floor area is shown for Helsinki for four building orientations for a commercial office which has four floors each with a floor area of 1556 m2 (16749 ft2) for five window types (see Table 5). Window-to-wall area ratio was fixed at 0.37.

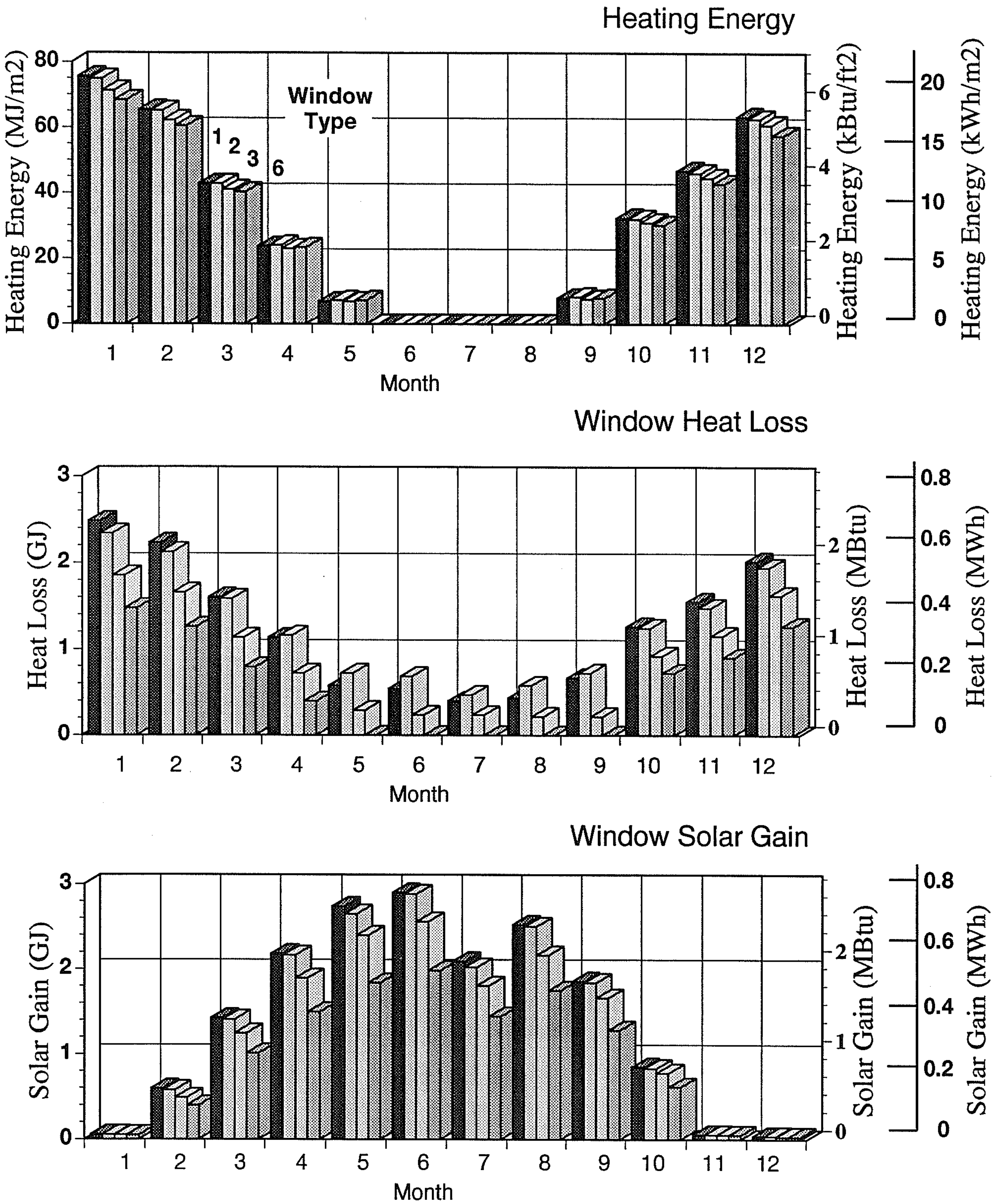
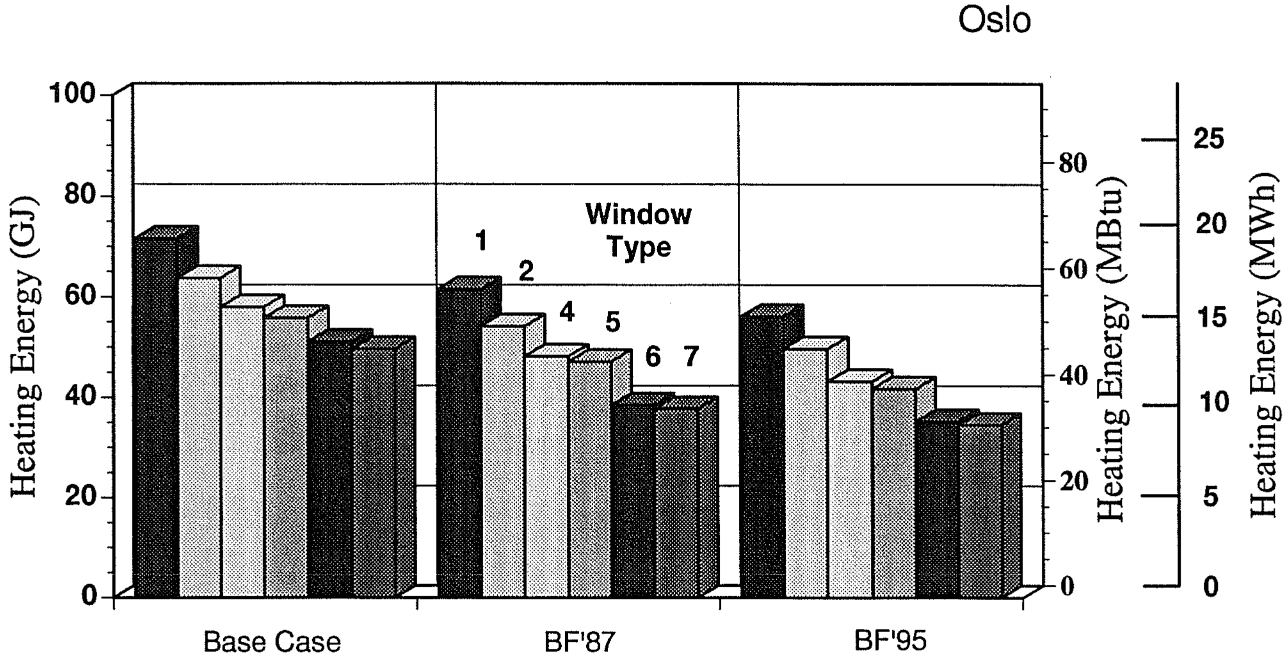


Figure 3: Simulation results for Finland. Annual heating energy demand per unit floor area is shown for Helsinki for a single-story residential building of of 134 m2 (1442 ft2) floor area for four window types (see Table 5). Also shown are window heat loss and solar gain fo windows distributed as follows: North - 1.44m 2 (15.5ft 2); East - 3.24 m2 (34.9 ft2); South - 7.92 m2 (85.3 ft2); and West - 1.8 m2 (19.4 ft2).



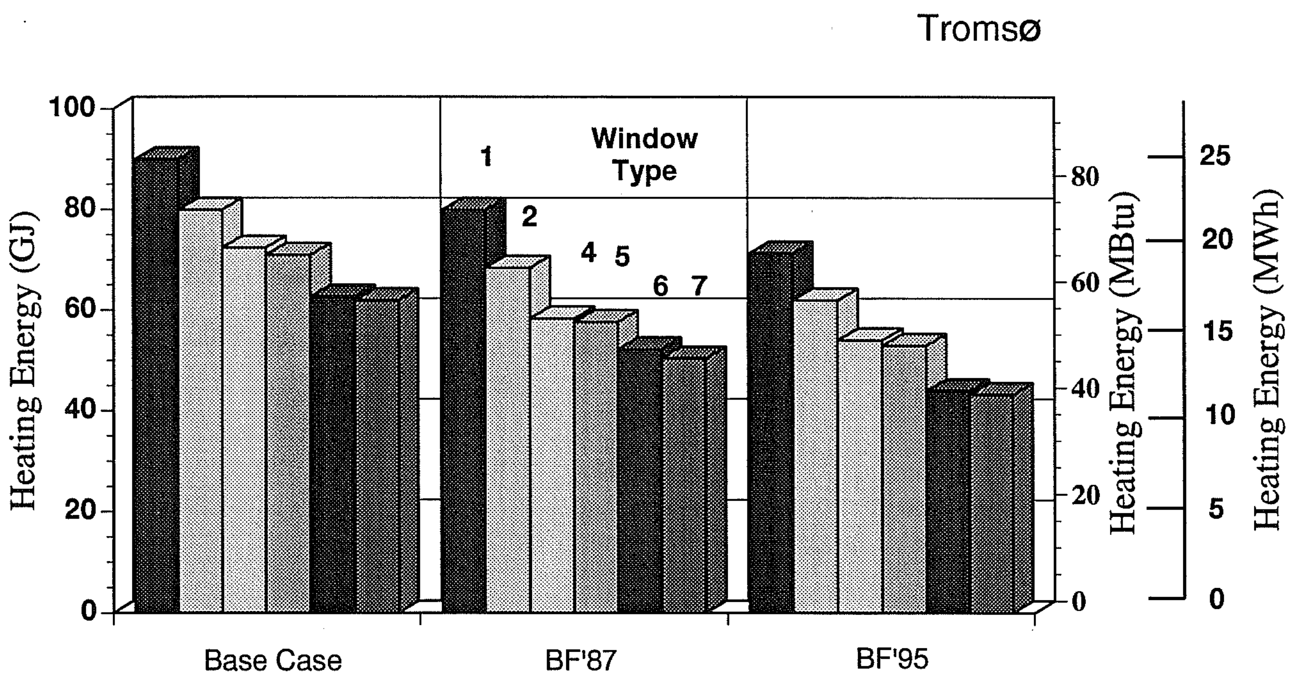


Figure 4: Simulation results for Norway. Annual heating energy demand is shown for two locations for a single-story residential building of 105.1 m2 (1131 ft2) floor area for six window types (see Table 6) and three residential building envelope insulation standards.

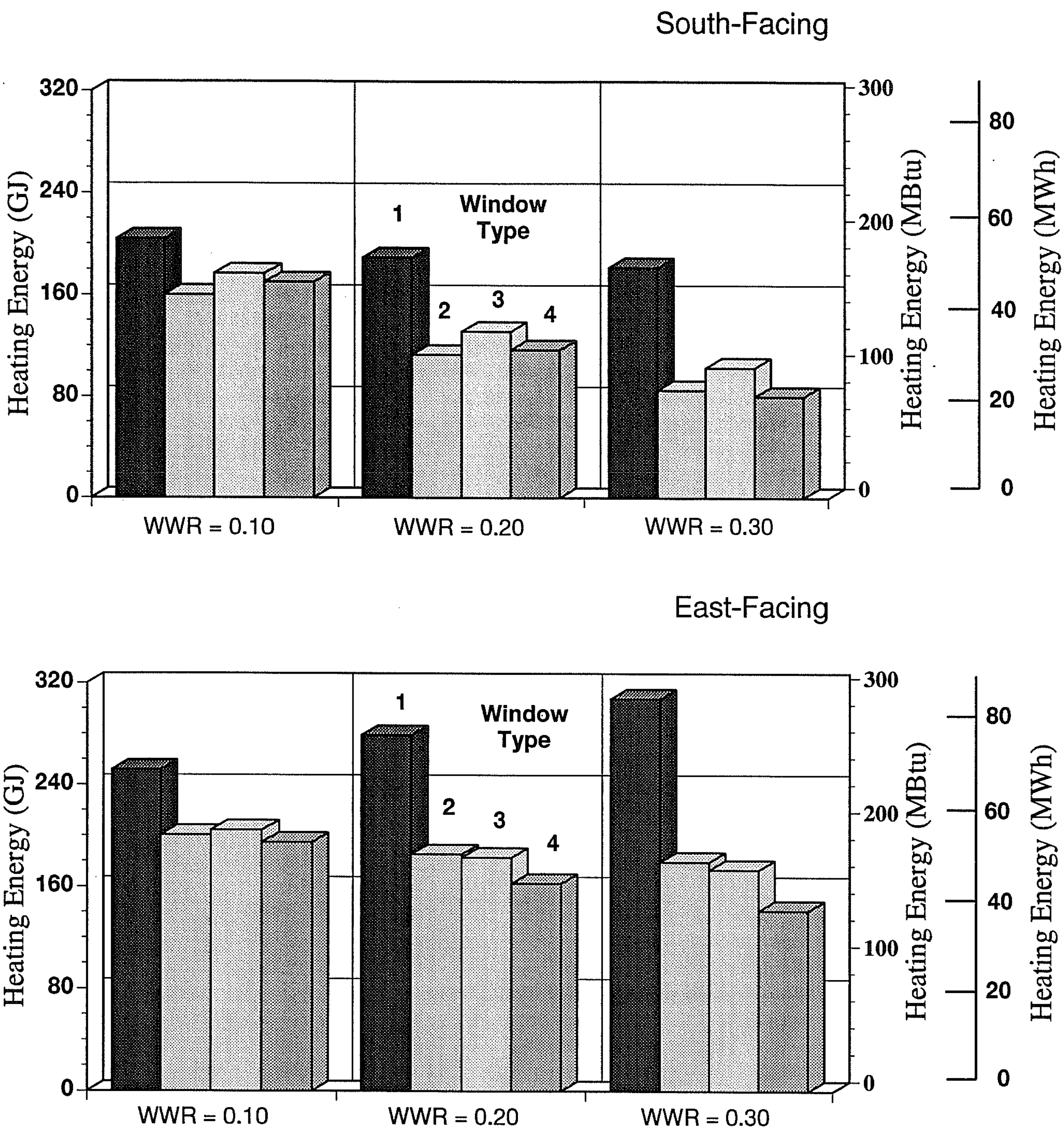


Figure 5: Simulation results for Switzerland. Annual heating energy demand is shown for Davos for two building orientations for a multi-family dwelling which has four floors each with a floor area of 362 m2 (3897 ft2) for four window types (see Table 8) and three window-to-wall area ratios. A wall with no windows requires 227 GJ (215 MBtu, 63 MWh).

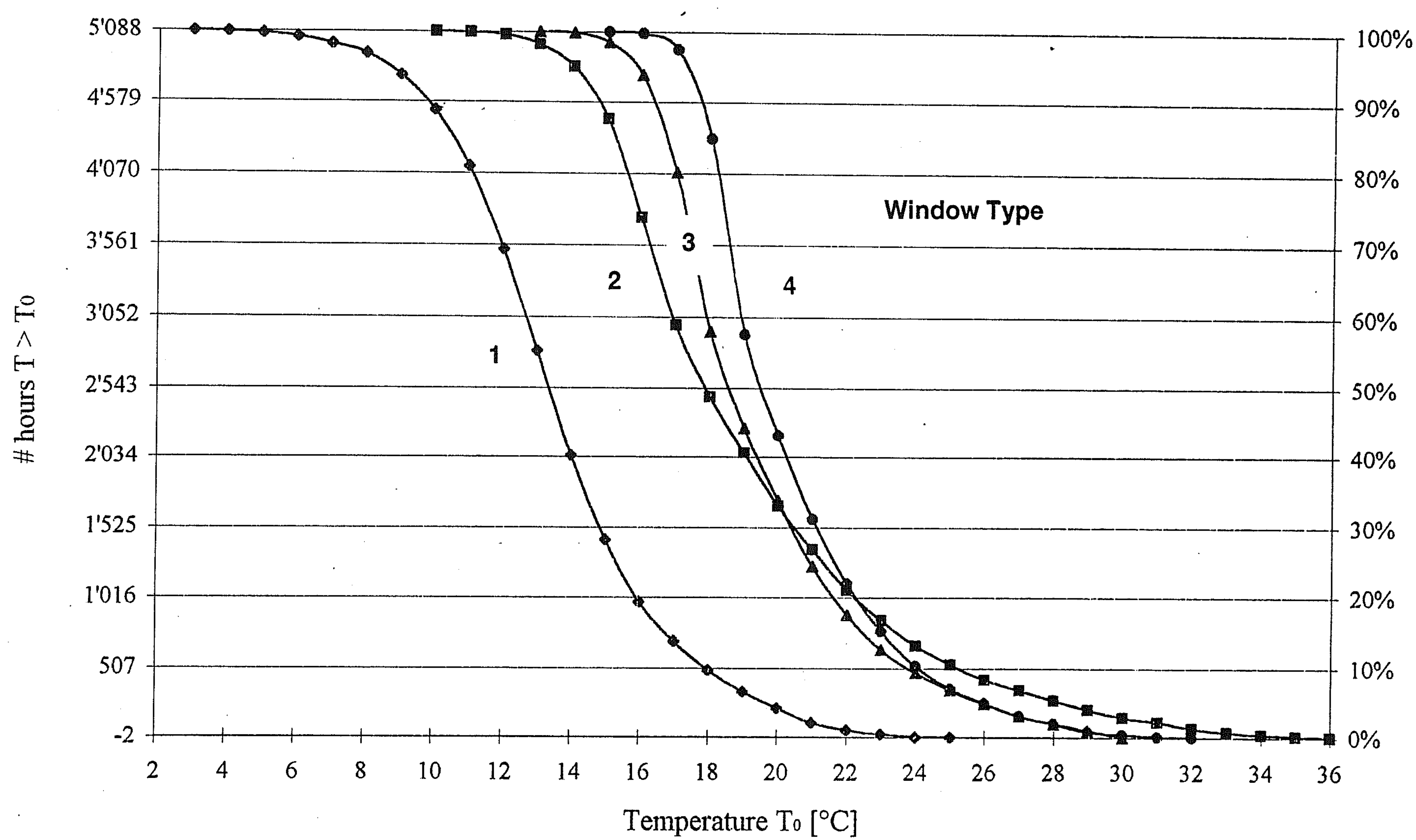


Figure 6: Simulation results for Switzerland. Distribution of the inside temperature of four windows (see Table 8) facing east in Davos. Window-to-floor area ratio is 0.30.

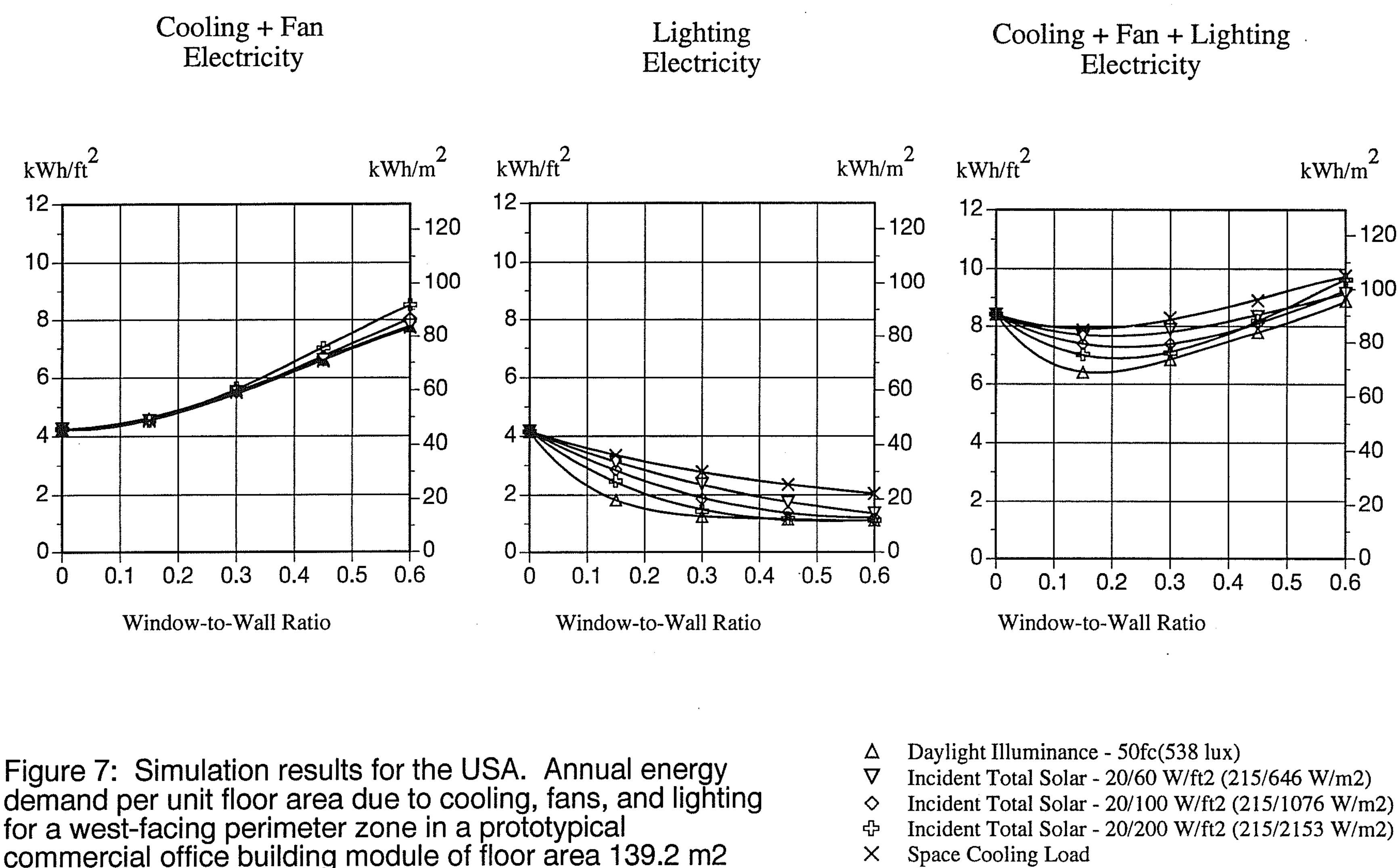


Figure 7: Simulation results for the USA. Annual energy demand per unit floor area due to cooling, fans, and lighting for a west-facing perimeter zone in a prototypical commercial office building module of floor area 139.2 m2 (1500 ft2) located in Blythe, California. Results are shown for a low-E reflective electrochromic window for varying window-to-wall area ratios and electrochromic control strategies. All systems use continuous dimming daylight controls and a lighting power density of 1.5 W/ft2 (16.1 W/m2).

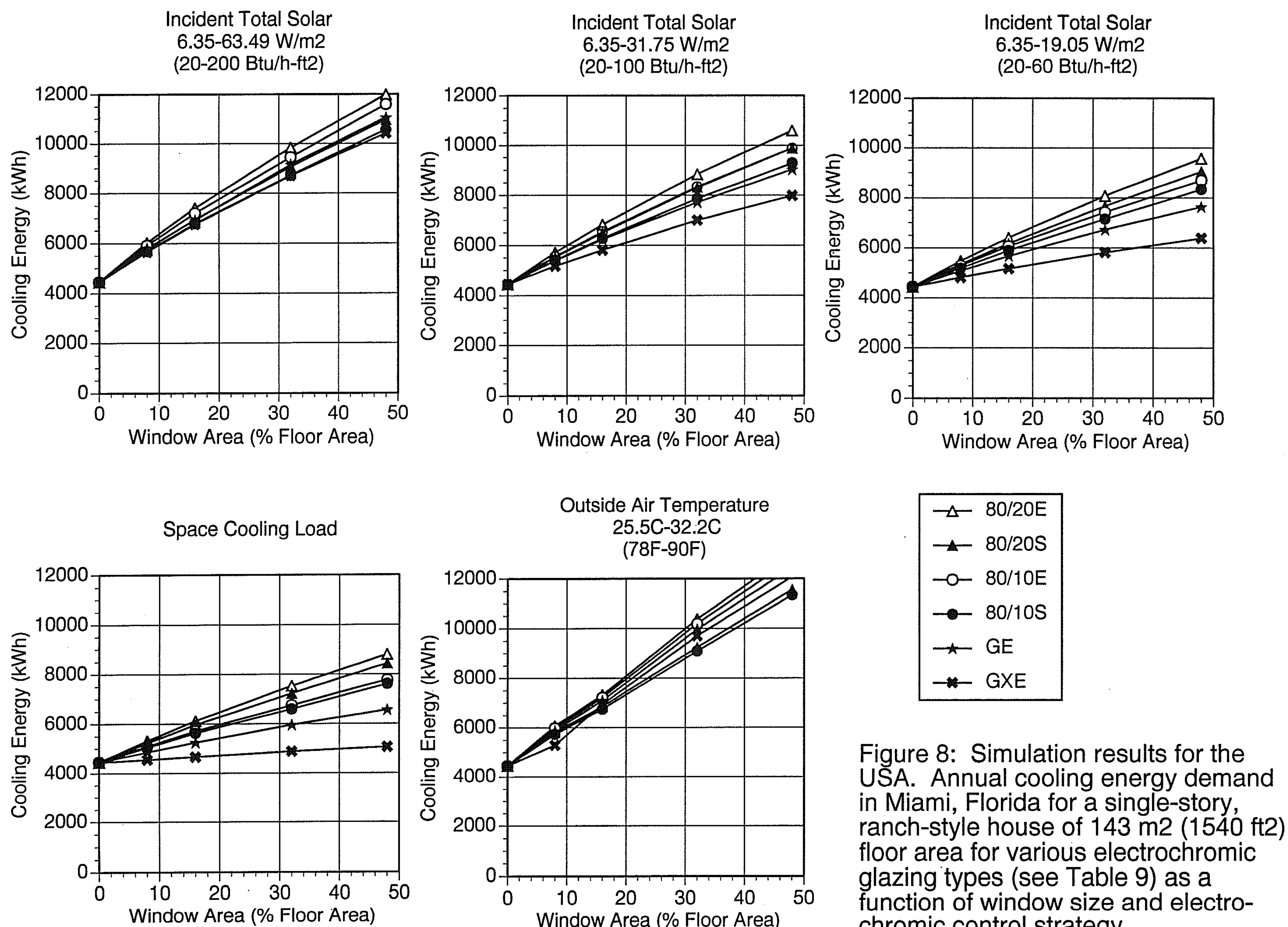


Figure 8: Simulation results for the USA. Annual cooling energy demand in Miami, Florida for a single-story, ranch-style house of 143 m2 (1540 ft2) floor area for various electrochromic glazing types (see Table 9) as a function of window size and electrochromic control strategy.