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RESIDENTIAL HEATING AND COOLING ENERGY COST IMPLICATIONS ASSOCIATED WITH WINDOW TYPE

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Residential Heating and Cooling Energy Cost Implications Associated with Window Type

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ABSTRACT

We present a comparative study in which residential heating and cooling energy costs are analyzed as a function of window glazing type, with a particular emphasis on the performance of windows having low-emittance coatings. The DOE-2.1B energy analysis simulation program was used to generate a data base of the heating and cooling energy requirements of a prototypical single-family ranch-style house. Algebraic expressions derived by multiple regression techniques permitted a direct comparison of those parameters that characterize window performance: orientation, size, conductance, and solar transmission properties. We use these equations to discuss the energy implications of conventional double- and triple-pane window designs and newer designs in which number and type of substrate, low-emittance coating type and location and gas fill are varied. Results are presented for the heating-dominated climate of Madison, WI, and cooling-dominated locations of Lake Charles, LA, and Phoenix, AZ. The analysis shows the potential for substantial savings but suggests that both heating and cooling energy should be examined when evaluating the performance of different fenestration systems. Coating and substrate properties and the location of the coating in the glazing system are shown to have moderate effects as a function of orientation and climate. In addition, with the low-conductance glazing units, the window frame becomes a contributor to overall residential energy efficiency.

INTRODUCTION

Window systems are an important aspect in the design of most buildings. They play a role in defining a building's aesthetics both from the viewpoint of appearance as well as occupant considerations of visual and thermal comfort and general feelings of well-being. Windows are also a major factor in design because of their influence on building energy use. In the case of residential units, which are heavily envelope dependent, windows strongly influence annual heating and cooling requirements. Recently, with the introduction of low-emittance windows into the marketplace, the awareness of the public mind with respect to the energy savings aspects of windows has increased dramatically. Generally, these savings have been associated with lower heating costs in northern geographic locations; however, it is now becoming apparent that savings can also be obtained in cooling-dominated locales.

The beneficial aspects of the reduced conductance of low-emittance windows are often accompanied by a reduction in solar transmission properties, which directly affects summer cooling. Relatively unknown outside the fenestration industry, but also important in creating lower overall system conductance, is the use of gas fills other than air between the glazing panes. At the present time, argon is being marketed as a gas fill and provides an additional 16% reduction in window U-value for certain double-pane low-e units. Krypton, a gas with even lower conductivity but which is more expensive, may soon be introduced into the marketplace.

The Windows and Lighting Program at Lawrence Berkeley Laboratory has been involved in research concerned with new window product definition and development and also with understanding product implications to whole building design and performance. An essential part of our work is specifically related to the energy performance of windows in a residential setting. This report details the results of an analysis in which ten window types are examined for a ranch-style single-family dwelling. Four of the systems were selected as useful in climates where reduced cooling is desired, and eight have primary applications in heating-dominated environments. All of the systems investigated are now commercially available or should be in the near future.

We modeled a prototypical single-family ranch-style house using the DOE-2.1B energy analysis program. The building configuration consisted of a single-story, 16.67 m (55 ft) by 8.53 m (28 ft), one-zone structure of wood-frame construction with window sizes fixed on three sides at 15% of the wall area (Figure 1). A data base was constructed for changes in heating, cooling, and total energy due to variations in the fourth or primary side window characteristics of orientation, size, conductance, and solar transmission. Window size was varied from 0% to 60% of the wall area (0% to 17.1% floor area). We used a range of glass conductance values corresponding to ASHRAE winter design values for single-, double-, and triple-pane glass; i.e. 6.25 W/m^2C (1.1 $Btu/h{\cdot}ft^2{\cdot}F$) for single through 1.76 (0.31) for triple. We also used a highly insulated glazing with a conductance of 0.56 (0.098). The range of shading coefficients was 0.4 to 1.0. Results were obtained for eight orientations of the primary glazing covering a complete 360° rotation in 45° increments.

We also included a shade management scheme to reduce the summer cooling loads. Management was simulated by deploying a shade that reduced solar heat gain by 40% if the direct solar gain on a particular window exceeded 63 W/m^2 (20 Btu/ft^2). More details of the thermal and operational characteristics of the prototype are provided in Sullivan (1985). Three standard year (WYEC) weather profiles (Crow 1980) were used in in the study. We selected the heating-dominated location of Madison, WI, and the cooling-dominated cities of Lake Charles, LA, and Phoenix, AZ.

METHODOLOGY

The data base generated by the DOE-2.1B simulations was used to develop a simplified algebraic expression to predict energy use and cost for the model. We accomplished this through multiple regression procedures, using the method of least squares to define the best fit to the data base. Sets of independent variables (configuration parameters) were defined from which dependent variables (heating and cooling energy) were predicted. The general form of the equation used in our analysis consisted of the explicit definition of the conductive and solar radiation effects of the primary fenestration system as follows:

$$\Delta E = \beta_1 (U_f A_f + U_g A_g) + \beta_2 (SC_g A_g)^2 + \beta_3 (SC_g A_g) \qquad (1)$$

where β represents the regression coefficients and U, A, and SC are the U-value, area, and shading coefficients of the glass (subscript g) and window frame (subscript f). A correction factor was applied to the shading coefficients to account for the implementation of shade management. ΔE represents either the annual heating or cooling energy effect of the primary fenestration system, with the total energy being determined by the sum of the two. The energy cost solution was found by modifying the energy terms to account for the unit costs of gas and electricity. We used $.60/therm ($6.00/MBtu, $5.69/GJ) for gas (heating) and $.07/kWh ($20.50/MBtu, $19.43/GJ) for electricity (cooling) in the analysis. Realistically, these cost figures vary with geographic location; however, our study uses the same values for all three cities and thus a direct comparison can be made of the relative costs.

We used Equation 1 to evaluate the energy performance characteristics of the window systems presented in Table 1 (Arasteh 1986). Standard double- and triple-pane glass with winter U-values of 2.8 $W/m^2 \cdot C$ (0.50 $Btu/h \cdot ft^2 \cdot F$) and 1.86 (0.33), respectively, with shading coefficients of 0.88 and 0.79 were compared with various types of sputtered and pyrolytic low-emittance coated windows. The selection of emittances was somewhat arbitrary and does not mean to imply that such values cannot vary for the coating processes involved.

For the heating-dominated climate of Madison, we compared three systems with two different gas fills (air and argon). These consisted of double pane with a pyrolytic low-e coating on the third surface (from the outside) with an emittance of 0.35 (G-EpG); double pane with a sputtered low-e coating on the third surface with an emittance of 0.15 (G-EsG); and a triple-pane system with a sputtered coating also on surface 3 (G-EsG-G). In this latter system, the middle glazing layer could be a plastic film. U-values for these systems varied from a low winter value of 1.11 $W/m^2 \cdot C$ (0.19 $Btu/h \cdot ft^2 \cdot F$) for the triple-pane, low-e, argon-filled unit to a high value of 2.34 (0.41) for the double-pane pyrolytic air-filled window. Shading coefficients varied from 0.71 to 0.86.

Four window types were analyzed for the cooling-dominated locations of Lake Charles and Phoenix. We compared standard double pane with a system having a sputtered low-e coating on the third surface (G-EsG); a single-pane pyrolytic-coated unit on the inside surface (GEp); and a double-pane system consisting of an outer pane of bronze-tinted glass with a low-E coating on the second surface (GbEs-G). U-values for these windows varied from a summer value of 4.54 (0.80) for the single pane to 2.05 (0.36) for the bronze unit. The shading coefficient for the latter was 0.37 and for the former 0.92.

Normally, in cooling climates, the low-emittance coating in a double-pane unit is applied to the second surface, as in system GbEs-G, rather than on the third surface as in system G-EsG. This construction results in a slightly lower shading coefficient that is useful for solar gain control. However, we decided that at least two of the window types (G-G and G-EsG) should be the same for both the heating and cooling locations to enable a more direct comparison of the results.

We also investigated the effect of varying window frame conductance. Such a task was deemed necessary because of the very low window conductance associated with some of the glazing systems. The frame area was assumed to be 20% of the overall window area and the U-values were based on a study by Standaert (1986) in which two-dimensional edge effects as well as typical one-dimensional heat flow components were used to define the thermal transmittance.

A very conservative frame U-value of 2.0 $W/m^2 \cdot C$ (0.35 $Btu/h \cdot ft^2 \cdot F$) representing a well-insulated frame served as the standard for the basic window system analysis. This was compared to a value of 5.2 $W/m^2 \cdot C$ (0.92), which corresponds to an aluminum frame with a thermal barrier. Without the thermal barrier, the value would be 11.9 $W/m^2 \cdot C$ (2.09). These were selected as nominal properties; the actual values for specific windows will vary greatly. Note that these values do not correspond well to the implied values suggested in ASHRAE Fundamentals (1985). It is widely acknowledged that the Handbook values are inappropriate for use with glazing systems whose conductance is lower than that of standard double glazing.

DISCUSSION

Prior to discussing the cost implications associated with window type, it is instructive to know the variation of the heating and cooling energy components that contribute to the total. This is especially important because of the cost differential of gas (heating) and electricity (cooling). If consideration is given to energy quantities alone, a somewhat different impression might be arrived at than by considering energy costs.

We present Figure 2 as an example of window performance at the most basic level, i.e., daily clear and cloudy day energy use profiles. Here, standard double-pane glazing (G-G) is compared to double glazing with a low-e coating (G-EsG) for a south-facing primary window in Madison. The design day outside air temperature varied from a high of 10^oC (50F) at 3 p.m. to a low of -1.1^oC (30F) at 5 a.m. The major contribution of low-e windows is shown on this figure, i.e., the low-e unit, because of its smaller conductance, requires less heating at night or on cloudy days and also less cooling during a sunny day due to the lower shading coefficient. Thus, beneficial aspects are obtained for both heating and cooling. It may happen at times, however, that the higher shading coefficient of the double-pane unit would require less heating during the daytime than the low-e unit.

On an annual basis, Figure 3 presents incremental heating and cooling energy requirements as a function of orientation for the 18.39 m^2 (198 ft^2) primary window. Data for three locations are shown for the relevant window types analyzed. Heating requirements in Madison are approximately proportional to window conductance with negative cost increments being obtained for U-values less than 2.5 $W/m^2 \cdot C$ (0.44 $Btu/h \cdot ft^2 \cdot F$) for a southern orientation. Cooling energy increments are almost the same for all window types and only exceed heating requirements for orientations close to south. Also, cooling in Madison is essentially independent of orientation. This stems in part from the use of shade management. Lake Charles and Phoenix cooling energy values, however, vary with orientation, as does the incremental heating energy. Cooling is approximately proportional to shading coefficient and only for orientations approaching north is heating at a level near cooling.

Translating energy usage into energy costs requires the consideration of the unit costs of gas (heating) and electricity (cooling). The values \$.60/therm for gas and \$.07/kWh for electricity yields an electric/gas ratio of 3.4, which has a definite influence on the comparison of the various window types. For example, whereas in Figure 3 one could consider cooling to be of minor importance in Madison, application of the cost ratio increases the impact of cooling in any configuration analysis. Likewise, in Lake Charles and Phoenix, the importance of heating is significantly reduced. It is therefore important in studies of this kind to be aware of the particular parameters being defined and analyzed. The remainder of this report discusses total incremental energy cost for the various window types.

Energy Cost Comparisons for Madison

Figure 4 presents the incremental annual energy costs in Madison due to changes in the type of glazing of the primary fenestration system. These data are given as a function of orientation and window area. For each particular size, the total energy cost differences due to window type are approximately proportional to the conductance value of the glass and are mostly a direct result of the heating requirement. This is better seen by observing Figure 5, which presents the conductance and solar gain components for the heating, cooling, and total energy for the 18.39 m^2 (198 ft^2) window.

We have only shown the component curves for the double-pane sputtered low-e (G-EsG) window, since this one type is representative of the observed trends. However, the range of the total solar component is given for the eight window systems studied. This solar component is the sum of the heating and cooling solar energy cost components, and there is not much variation with window type. The increased cooling associated with higher shading coefficients is balanced by decreased heating, with the result that the net solar gain or loss for the different window types does not change. This partially stems from the electricity (cooling) to gas (heating) cost ratio. Because the total solar difference between types does not change, the total cost increments are essentially proportional to the glass conductance heating cost component, the conductance cooling component being quite small. It should also be noted that the cost increments are nearly orientation independent, i.e., the difference in energy cost between standard double glazing and double glazing with a pyrolytic coating is the same for both northern and southern orientations. The cost difference, of course, does vary with window size, as is apparent in Figure 4.

The importance of considering the cooling cost component in determining the absolute energy cost magnitude in northern locations is apparent in Figure 5. For orientations with large solar gains, neglecting the cooling requirement or using an unrealistic cost multiplier will tend to negate its influence in affecting the favorable trends established by heating cost reduction due to solar gain. The influence of cooling also tends to decrease the significance of the quadratic term in Equation 1 and thus make the incremental annual cost for similar conductances and shading coefficients linearly related to glass area. This can be seen in Figure 4, where the cost values for the window of area 24.53 m^2 (264 ft^2) are about twice the levels of the 12.26 m^2 (132 ft^2) window. Generally, if considering only heating in northern locations, it is possible to optimize window area and obtain a maximum area for minimum cost. However, this cannot be done in the same manner with total energy costs, which include cooling energy requirements.

Cost comparisons across the orientation spectrum in Figure 4 indicate that it is possible to obtain the same relative energy cost for a low-e triple-pane primary window system facing north as a system using a standard double pane unit facing south. The same cost also results for these same units using a window area of 24.53 m^2 (264 ft^2) for the low-e and a 12.26 m^2 (132 ft^2) area for the double pane, regardless of orientation. This fact permits the pursuit of alternative design options when using low-e glass without energy-related penalties.

The energy cost difference for all orientations between the standard double pane unit (highest U-value) and the low-e triple-pane (lowest U-value) argon filled window of area 12.26 m^2 (132 ft^2) is about \$35/year or about \$2.85/year $\cdot m^2$ (\$0.26/year$\cdot$ ft^2). This is a little more than doubled to \$75/year for twice the window area, \$3.05/year $\cdot m^2$ (\$0.28 /year$\cdot ft^2$) so the cost per unit area remains about the same. A standard triple-pane unit and double-pane unit with a sputtered low-e coating are equivalent in U-value and yield about half these differences. The incremental cost associated with the use of argon is only about \$5/year (\$0.40/year $\cdot m^2$, \$0.04/year $\cdot ft^2$) for the small window and does not vary with orientation or window type. Overall, cost figures vary from a low of \$10/yr for the triple pane low-e argon filled window of area 12.26 m^2 (132 ft^2) facing south (\$0.81/year$\cdot m^2$, \$0.08/year$\cdot ft^2$) to a high of \$165/yr for the standard double-pane unit of area 24.53 m^2 (264 ft^2) facing northwest (\$6.72/year$\cdot m^2$, \$0.63/year$\cdot ft^2$).

Energy Cost Comparisons for Lake Charles and Phoenix

Figures 6 and 7 present results for Lake Charles and Figures 8 and 9, the Phoenix data. For these cooling-dominated locations, four window types have been compared, varying from a single pane with a pyrolytic low-e coating to a double pane with bronze tinting and a sputtered low-e coating. The trends in both Figures 6 and 7 show the influence of shading coefficient quite clearly, with the largest cost associated with the largest shading coefficient. For example, the double-pane low-e units with or without the bronze tint have about the same U-value; therefore, the difference in energy costs between the two is directly related to the shading coefficient difference. Also, the damping effect of the shading coefficient in reducing the solar gain is apparent in the similarity of the costs for changing orientations when using the bronze-tinted low-E unit.

For the low-conductance window types, about 90% of the cost is from cooling. This is best seen at the component level in figures 7 and 8. The conductance loss and solar gain heating cost components in both locations cancel each other, yielding a net incremental heating cost close to zero. The influence of shade management as a function of solar gain magnitude is seen in comparing the solar cooling costs in Lake Charles on Figure 7 with the Phoenix data on Figure 8. Hourly insolation values in Phoenix are larger than in Lake Charles and also more variable with orientation, which is apparent in the cost variation shown on the figures. In general, unlike Madison, the incremental cost differences among window types vary slightly with orientation, with north yielding the lowest cost differences.

In Lake Charles, total costs vary from a low of about \$50/year for the bronze tinted small-size window for almost all orientations (\$4.08/year·m^2, \$0.38/year·ft^2), to a high of \$300/year for the large single-pane unit facing east (\$12.23/year ·m^2, \$1.14/year·ft^2). In Phoenix, the lowest cost is similar to Lake Charles for either a northern or southern orientation; however, the high cost is almost \$365/year for the large window facing southwest (\$14.88/year·m^2, \$1.38/year·ft^2).

Window Frame Effects

The influence of window frame conductance is shown in Figure 10a for a primary window area of 18.39 m^2 (198 ft^2) for the three climatic locations. Standard double-pane glass was used in the comparison so that the most conservative incremental costs would be apparent. The lower conductance of the low-e windows would yield much higher relative differences than shown on Figure 10a. This is apparent on Figure 10b, which presents the variation in cost with window conductance for northern and southern primary orientations in Madison. The base frame conductance of 2.0 W/m^2 (0.35 Btu/h ·ft^2·F) is compared to a value of 5.2 W/m^2·C (0.92).

Only in heating-dominated locations is the performance of the window frame of concern. For the example cited in Figure 10a, there is about a \$30/year (\$1.63/year ·m^2, \$0.15/year·ft^2) cost increase, which is invariant with orientation, due to the larger frame U-value. This cost is also fixed for the different window types; however, the frame's percentage effect would be much larger for the lower conductance glazings. In fact, in some instances, the energy costs associated with the frame exceed the costs resulting from the glazing. In Lake Charles and Phoenix, the frame does not exert much influence due to the decreased importance of total heating costs.

CONCLUSIONS

This paper has discussed results of a study that compared the heating, cooling, and total energy costs of various window types used in a ranch-style single-family residence. The analysis has presented incremental energy cost data due to changing primary fenestration parameters. Simultaneous changes in the off-primary window characteristics will affect the presented results. Particular emphasis was placed on the performance of low-emittance windows. The following conclusions have resulted from the analysis:

1. The available selection of windows designed with low-E coatings and their resultant energy performance leaves designers a greater amount of control on sizing and placement of windows in residences.
2. Low-emittance windows provide greater energy savings than conventional windows. Both conductance and solar optical properties are important in judging overall performance.
3. Optimal window design solutions depend on whether energy or cost is being used to rank the systems.
4. Cooling costs in heating-dominated locations represent a significant portion of the overall energy costs for primary window orientations with large solar gains. Thus, net energy cost gains associated with reduced heating and glazing conductance can

become net economic losses.

5. The incremental costs due to window frame U-value changes are important in heating-dominated locations and such costs do not vary with window orientation. Percentage energy cost due to the frame can be substantial and actually larger than the glazing unit the frame supports.
6. For cooling dominated locations, annual incremental energy costs due to changes in primary window size were almost the same for south through east and west orientations. Cost differences for a north orientation were somewhat lower because of the reduced solar gain cooling cost.
7. The net heating cost in Lake Charles and Phoenix was close to zero due to the cancelling effects of conductance loss and solar gain. Therefore, the shading coefficient values of low-E windows becomes an important parameter in reducing costs.

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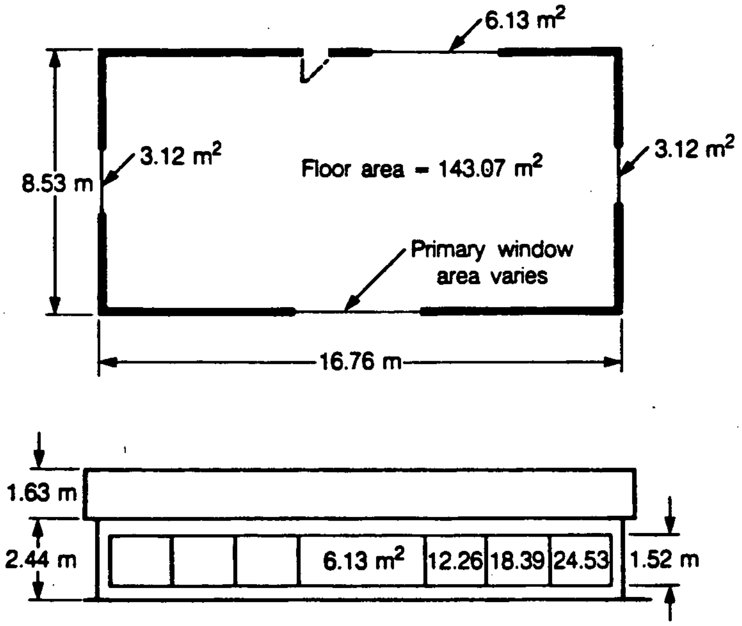
TABLE 1

WINDOW SYSTEM U-VALUES AND SHADING COEFFICIENTS ANALYZED

Window Design	Gas Fill	Winter U-Value	Summer U-Value	Shading Coefficient	Solar Transmittance	Visible Transmittance
* G-G	Air	2.85 (0.50)	3.16 (0.56)	0.88	0.71	0.82
G-G-G	Air	1.86 (0.33)	2.20 (0.39)	0.79	0.61	0.74
G-EpG	Air	2.34 (0.41)	2.63 (0.46)	0.86	0.64	0.73
* G-EsG	Air	1.94 (0.34)	2.00 (0.35)	0.73	0.58	0.74
G-EpG	Argon	2.09 (0.37)	2.38 (0.42)	0.86	0.64	0.73
G-EsG	Argon	1.62 (0.28)	1.68 (0.30)	0.73	0.58	0.74
G-EsG-G	Air	1.32 (0.23)	1.53 (0.27)	0.71	0.52	0.71
G-EsG-G	Argon	1.11 (0.19)	1.30 (0.23)	0.72	0.52	0.71
* GEp	-	5.05 (0.89)	4.54 (0.80)	0.92	0.75	0.80
* GbEs-G	Air	1.94 (0.34)	2.05 (0.36)	.37	.26	.46

Notes:

1. U-value units are $W/m^2 \cdot C$ ($Btu/h \cdot ft^2 \cdot F$).
2. G denotes glazing layer; Ep, a pyrolytic low-E coating (e = 0.35) and Es, a sputtered low-E coating (E=0.15) on one side of the glazing; Gb denotes bronze tinting. For the G-EsG-G and G-EpG-G units, the middle layer can be low-E-coated glass or a low-E-coated polyester film. Also, several other coatings on polyester film offer lower SCs with equivalent conductances to those shown.
3 Gap width between glazing layers is 12.7 mm (0.5 in).
4. (*) indicates windows examined in cooling-dominated locations.



XBL 845-8909

Figure 1. Residential model description.

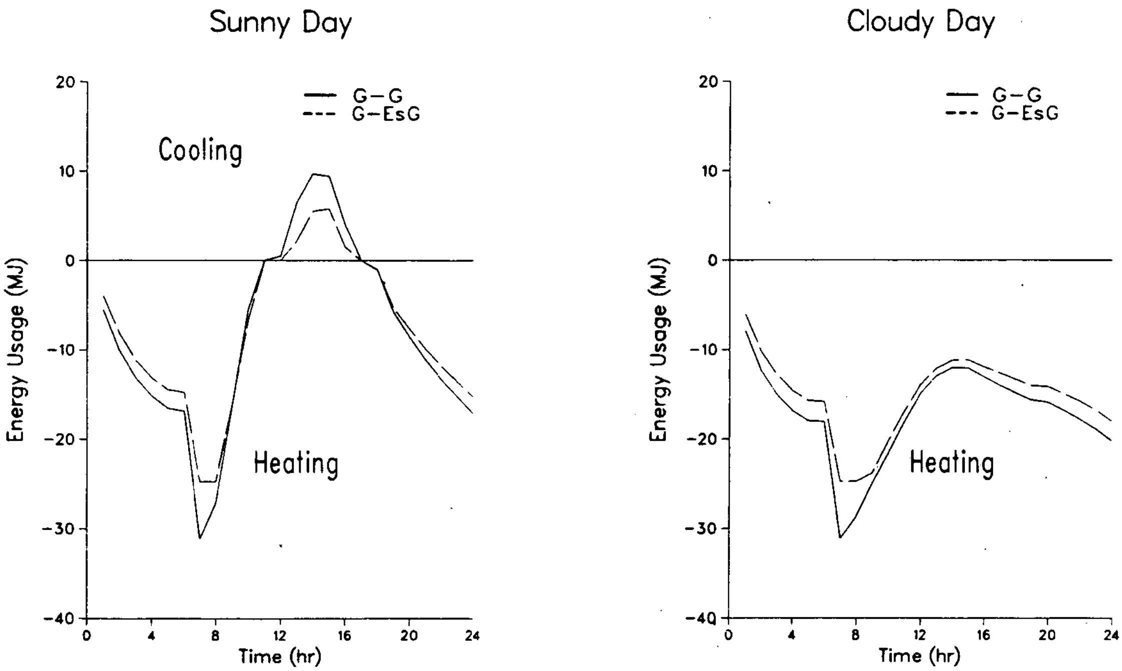


Figure 2. Daily heating and cooling energy use profile for a single-family residence with a south-facing primary window of size 18.39 m^2 (198 ft^2) in Madison. Standard double-pane glass is compared with double-pane having a sputtered low-e coating.

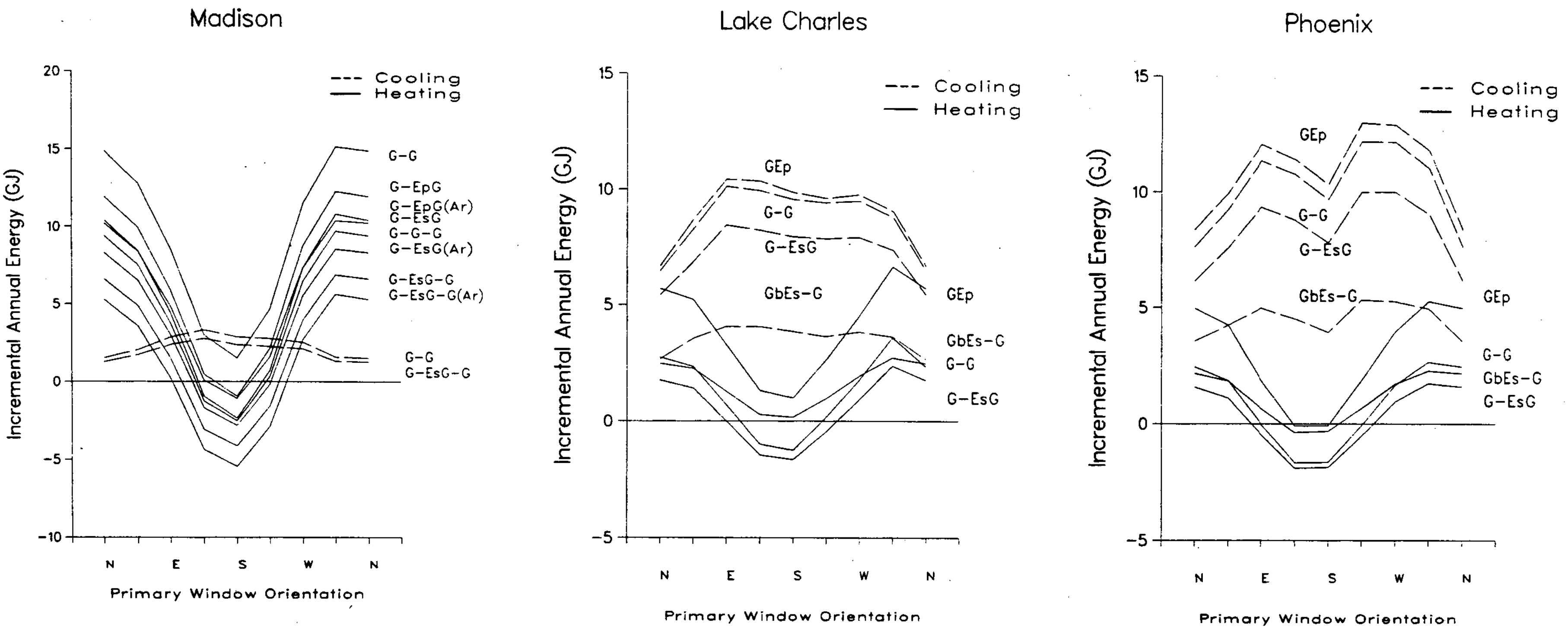
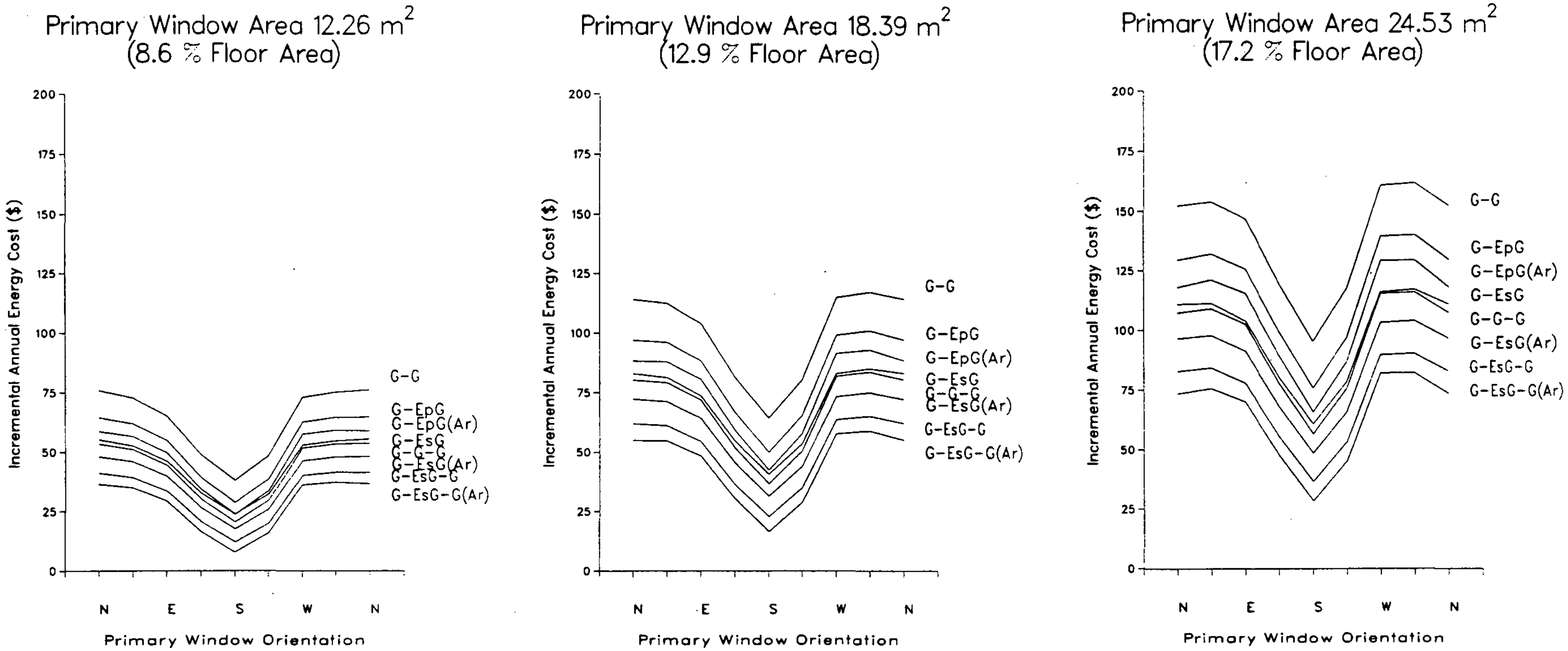


Figure 3. Annual incremental heating and cooling energy use for varying primary window orientations, geographic locations, and window frame U-values for a primary window of size 18.39 m^2 (198 ft^2).



Primary Window Area 12.26 m^2 (8.6 % Floor Area)

Primary Window Area 18.39 m^2 (12.9 % Floor Area)

Primary Window Area 24.53 m^2 (17.2 % Floor Area)

Figure 4. Incremental annual energy cost for varying primary window orientations, sizes, and glazing types in Madison, WI.

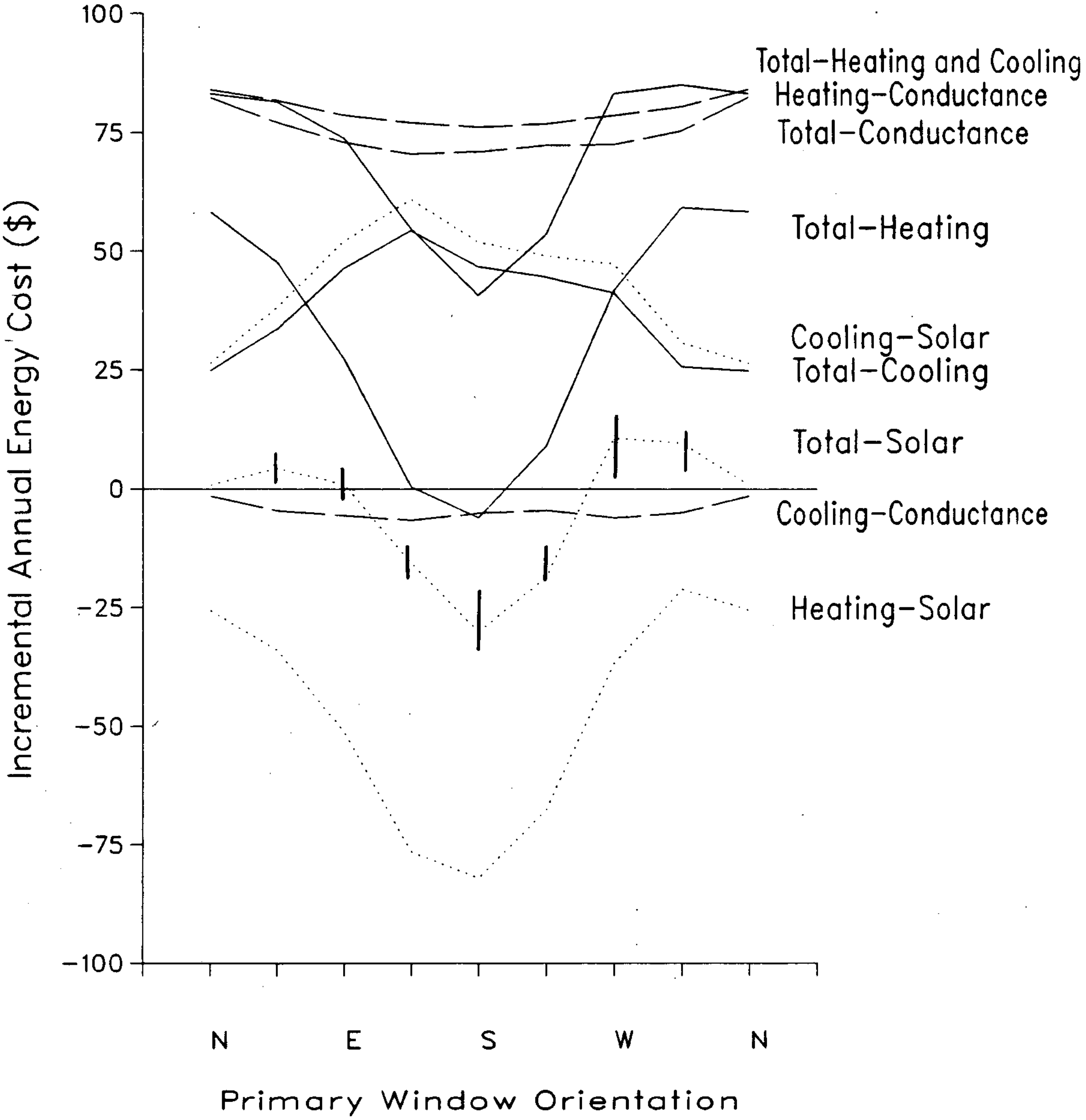


Figure 5. Incremental annual energy cost components for varying primary window orientations for glass type G-EsG with a winter U-value of 1.94 W/m^2C (0.34 $Btu/hr\text{-}ft^2F$) and shading coefficient of 0.73 in Madison, WI, for a window of size 18.39 m^2 (198 ft^2).

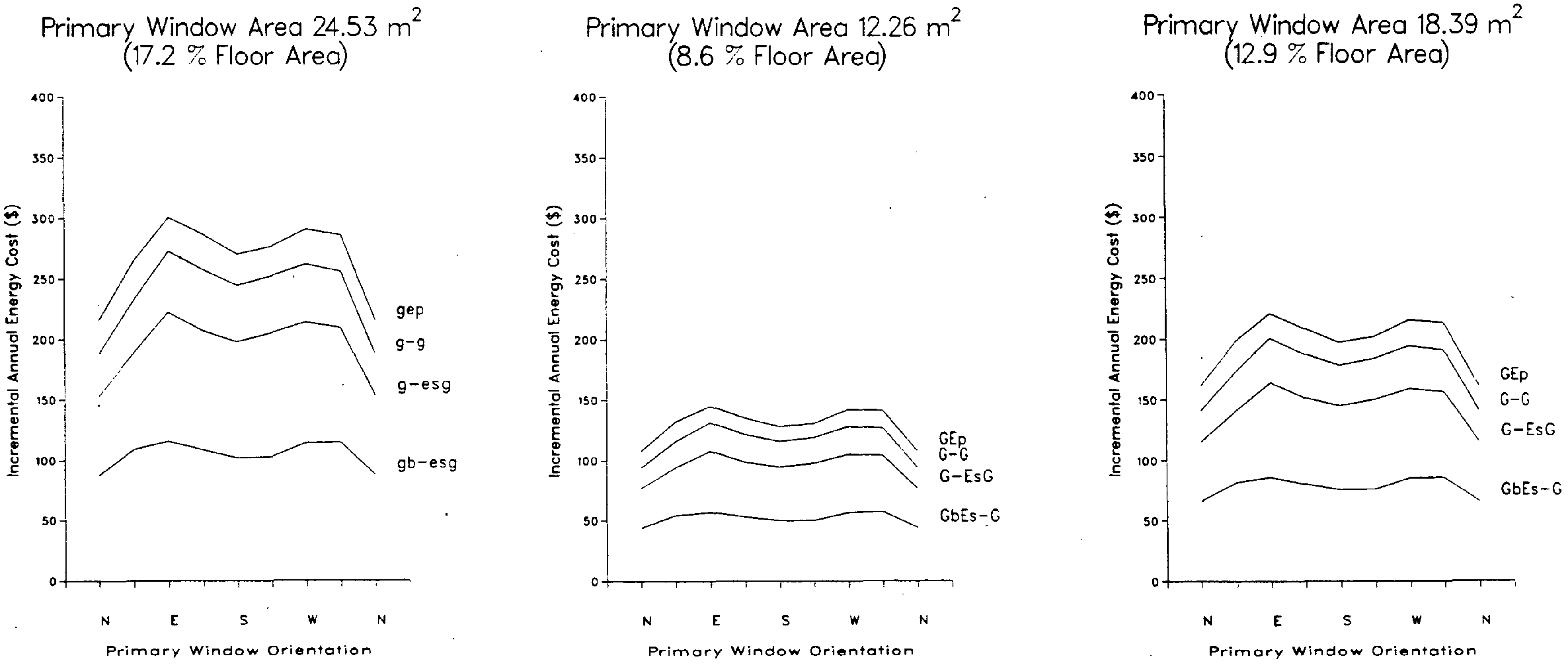


Figure 6. Incremental annual energy cost for varying primary window orientations, sizes, and glazing types in Lake Charles, LA.

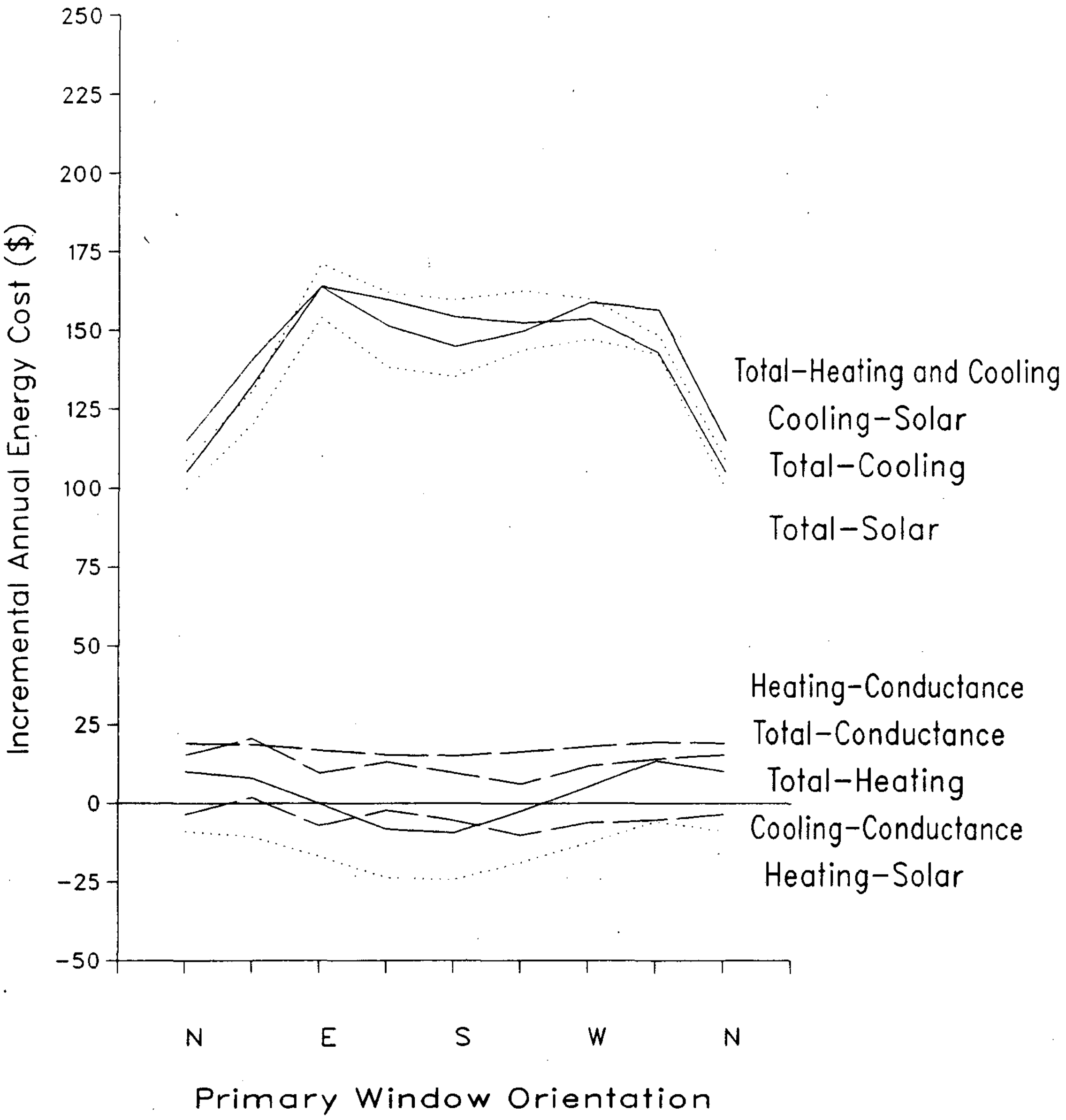


Figure 7. Incremental annual energy cost components for varying primary window orientations for glass type G-EsG with a summer U-value of 2.0 W/m^2C (0.35 $Btu/hr\text{-}ft^2F$) and shading coefficient of 0.73 in Lake Charles, LA, for a window of size 18.39 m^2 (198 ft^2).

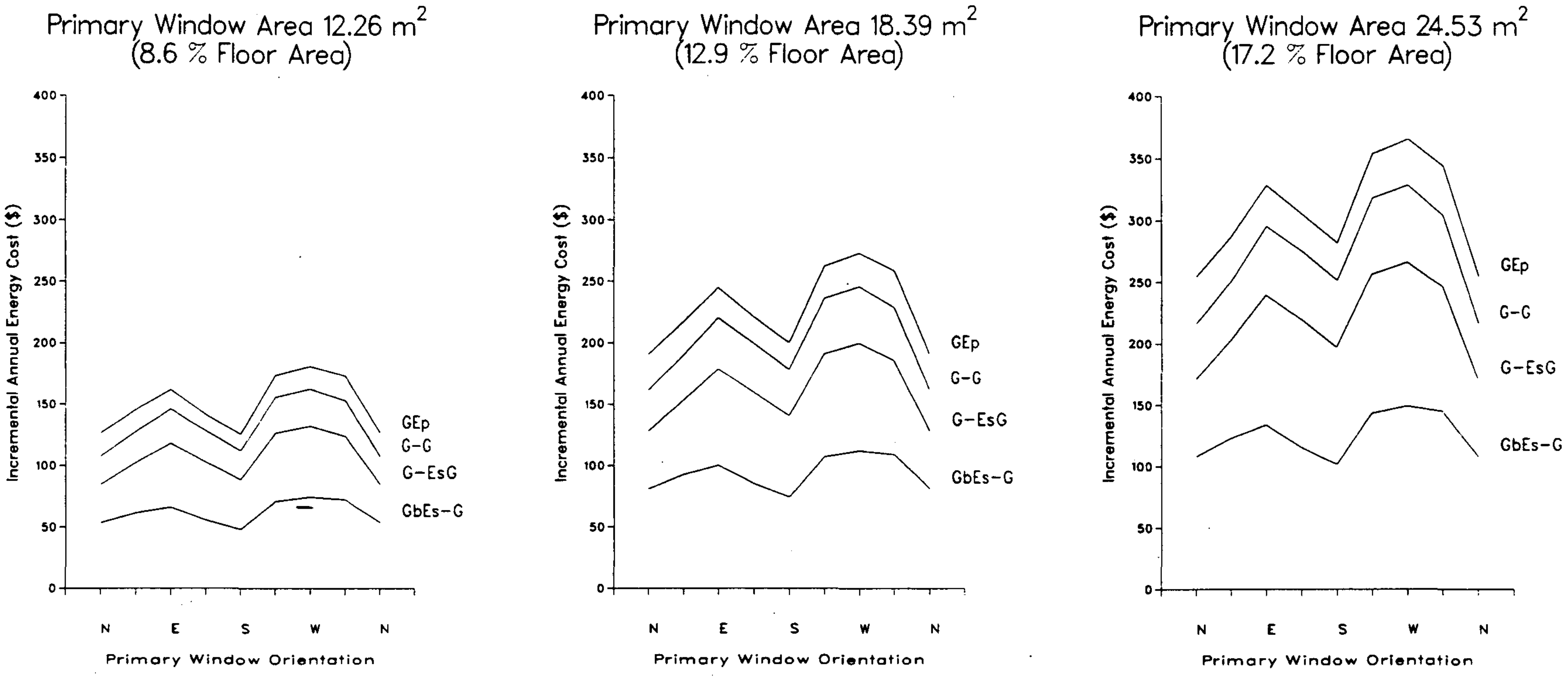


Figure 8. Incremental annual energy cost for varying primary window orientations, sizes, and glazing types in Phoenix, AZ.

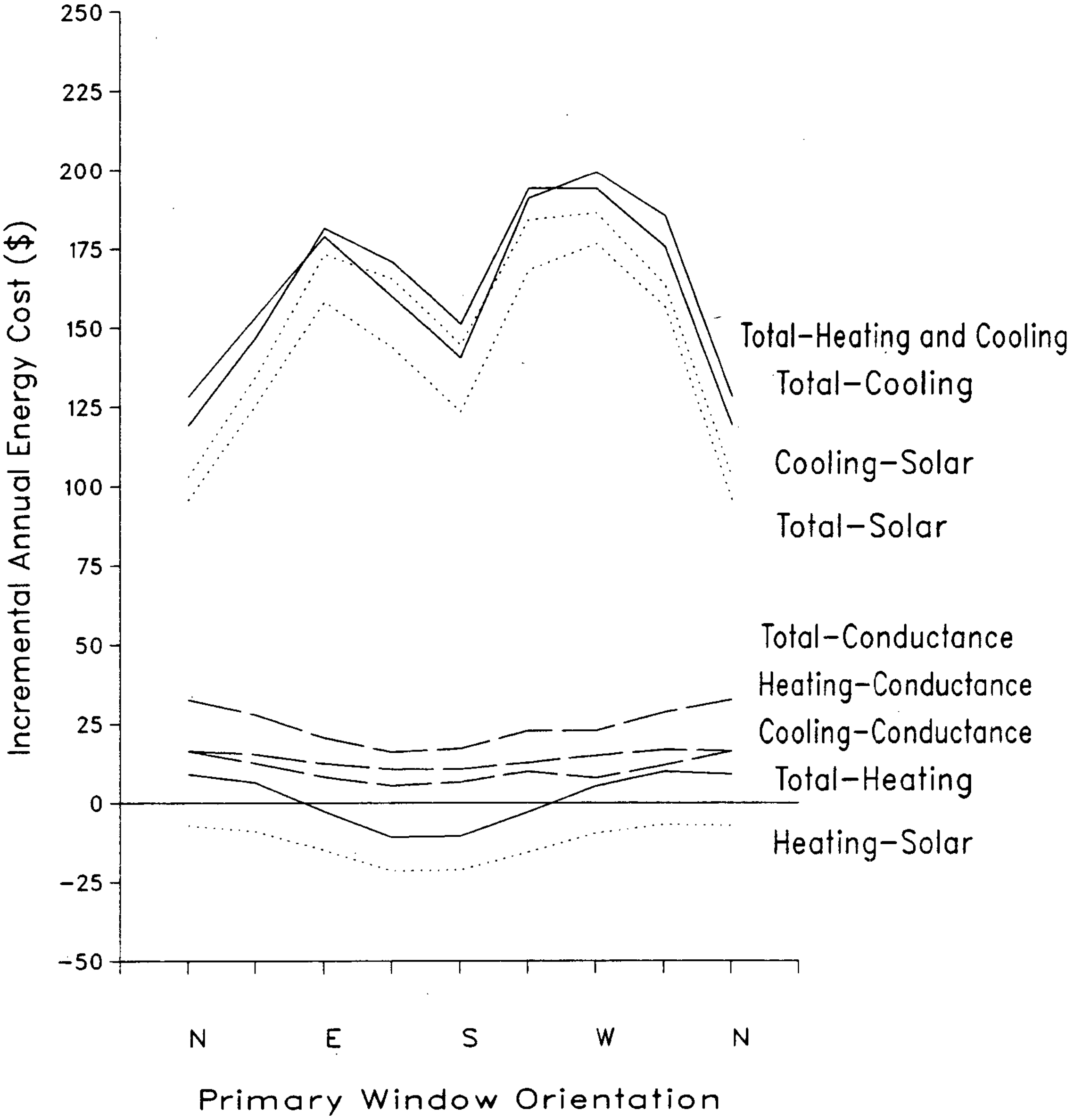


Figure 9. Incremental annual energy cost components for varying primary window orientations for glass type G-EsG with a summer U-value of 2.0 W/m^{2}C (0.35 Btu/hr-ft^{2}F) and shading coefficient of 0.73 in Phoenix, AZ, for a window of size 18.39 m^2 (198 ft^2).

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