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ABSTRACT

Spectrally selective glazings can substantially reduce energy consumption and peak demand in residences by significantly reducing solar gains with minimal loss of illumination and view. In cooling-dominated climates, solar gains contribute 24-31% to electricity consumption and 40-43% to peak demand in homes with single pane clear glazing – standard practice for residential construction built before the implementation of building energy efficiency standards. The existing residential housing stock therefore offers a prime opportunity for significant demand-side management (DSM), but the energy and cost savings must be weighed against retrofit first costs in order for the technology to achieve full market penetration. Using DOE-2.1D for numerical simulation of building energy performance, we quantify the energy and peak demand reductions, cost savings, and HVAC capacity reductions using spectrally selective glazings for five cooling-dominated climates in California. The cost-effectiveness of various material and installation retrofit options is discussed. Glazing material improvements for retrofit applications that are needed to achieve a prescribed cost savings are also given.

INTRODUCTION

The total 1987 primary electricity use in California for the residential sector is 0.54 Quads ($1.58x10^{14}$ Wh), 7% or 37,800 GBtu (11,100 GWh) of which can be directly attributed to cooling electricity use by central, room, and evaporative air-conditioning (CEC 1990). The existing residential sector offers a substantial opportunity for energy and peak demand savings because 76% of the buildings were constructed prior to the implementation of the 1978 Title-24 California building energy efficiency standards and 17% were built during the following ten years before spectrally selective glazings became available (Herrera 1992). Spectrally selective glazings have the potential to significantly reduce energy consumption and peak demand by targeting the largest contributor to residential energy consumption in cooling-dominated climates: solar gains. In moderate to hot regions, about 24-31% of the building's total electricity consumption and 40-43% of peak demand is due to solar gains for homes with single pane clear glazed windows, standard practice for pre-1978 construction.

Approximately 50% of the energy in sunlight is visible light, with the remaining near-infrared energy contributing to solar heat gains. Spectrally selective glazings are a relatively new class of products that admit a high proportion of visible daylight while excluding most of the heat gain arising from the solar infrared, with minimal loss of illumination and view. Figure 1 represents the ideal spectrally selective glazing which would have high transmission throughout most of the visible portion of the solar spectrum and high reflection in the ultraviolet and infrared. Some clipping of the red and violet extremes of the visible region is acceptable because the eye makes inefficient use of these colors. Although some color sensitivity is lost in clipping of the visible, a significant additional reduction in solar transmission can be achieved. Too much clipping, however, can compromise the neutral appearance of the light and view and may alter the color rendition of furnishings or artwork. If maximum daylight or night view is not required, the height of the transmission band can be lowered to further reduce solar heat gain.

This selectivity is most effectively achieved by using silver-based multi-layer thin films in a sealed insulated glass unit or in a laminated glass/film/glass configuration. Green or blue tinted monolithic glazings can have a sharp spectral response but they absorb rather than reflect the solar infrared and, in single glazing applications, some of this absorbed radiation will reradiate to the interior (Figure 2). An alternative to the non-durable silver-based coatings is an all-dielectric multi-layer coating without any metal layers. This has the potential to achieve any desired level of optical performance but is prohibitively expensive at this time due to the large number of layers required to make the coatings. Two approaches using polymer multilayers produced by coextrusion or sequential evaporation are under development. Research is now underway to improve production equipment to make such coatings competitive in the next few years. Another

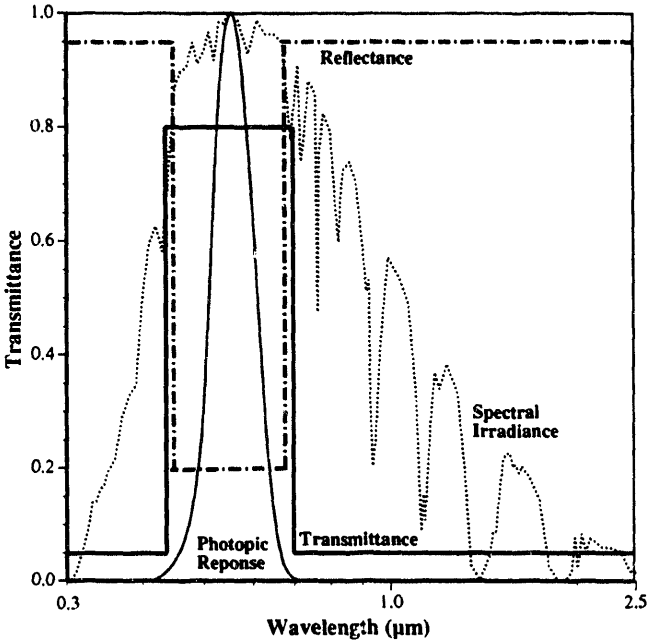

Figure 1. Solar spectral properties of an ideal spectrally selective glazing. The shaded region of the solar spectrum represents the response of the eye to light.

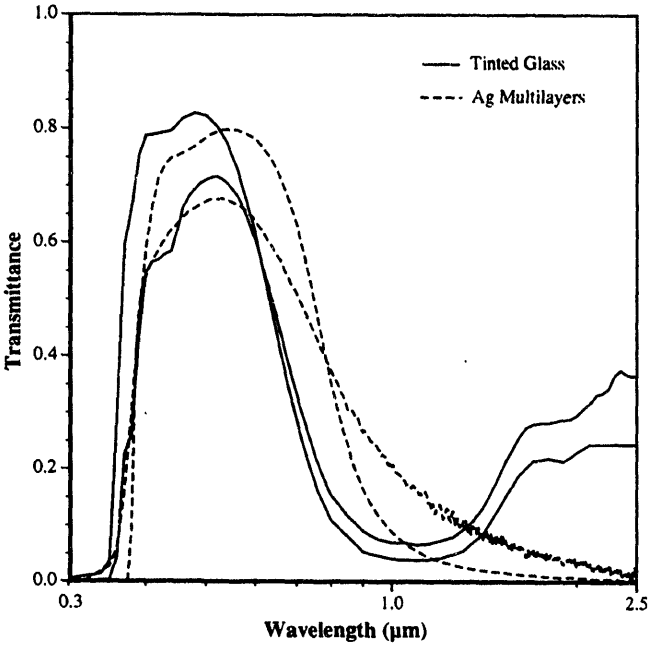

Figure 2. Solar transmission spectra of the best available spectrally selective glazings.

promising approach involves vacuum deposition of transition-metal and rare-earth oxides that would have optical properties comparable to the silver-based coatings but with improved durability. The deposition process involves ion-assisted techniques which are suitable for low temperature deposition on plastic film (Rubin 1992).

The cost of this retrofit technology must be scrutinized carefully. Glazing upgrades can be achieved fairly cheaply with glue-on films or by replacement of the glass pane or, at greater cost, by replacing the window sash or even replacing the entire window unit if the window, after 20-30 years, is in poor shape. Many manufacturers presently offer spectrally selective coated plastic substrates that can be glued on at about \$1.25 to \$2.00/ft^2 (\$13.45 - \$21.53/m^2) including installation, but some controversy still exists over the resistance of these products to damage at the unsealed edges of the film. Coating failure, edge degradation, or delamination after five years have been reported, particularly in wet or humid climates or in corrosive/ abrasive environments. For glass replacement, an advanced monolithic absorbing glass is available now at the material cost of \$1.50/ft^2 (\$16.15/m^2) for tinted glass to as much as \$3.75/ft^2 (\$40.36/m^2) for coated glass (Means 1992). Additional materials research and product testing are needed to develop coated or laminated replacement glass with better optical performance and durability than currently available options. The best option, as well as the most expensive, is to replace the window sash or entire window with a sealed insulating glass unit (IG). Proven coating technology with excellent optical characteristics can then be used in a sealed environment, well protected from moisture and abrasion. The IG unit also offers the benefits of lower emissivity and increased thermal resistance. With optional gas fills, thermal resistance can be increased even further. A cheaper alternative would be to add a second pane with a spacer to the existing window, although caulks or sealants would need periodic maintenance and the appearance of this option may be objectionable to the homeowner.

The two most important performance variables for spectrally selective glazings are the visible transmittance and the shading coefficient. The shading coefficient (SC)[a], a measure of total solar heat gain including both directly transmitted solar radiation and the indirect component of inward flowing heat due to absorption by the glazing, is directly related to cooling energy consumption. The visible transmittance (Tv), a measure of the percentage of visible light transmitted, is unrelated to energy performance but can indicate how well the glazing meets homeowner preferences; a high Tv usually implies minimal alteration to interior daylight levels and view, and a clearer rather than tinted or mirrored glazing appearance that some homeowners find architecturally detracting. In terms of these performance variables, optimum spectrally selective products have a high visible transmittance and a low shading coefficient. The use of spectrally selective glazing over conventional single pane, clear glazing will therefore result in four changes related to energy perfor-

[a] The transition to using the solar heat gain coefficient (SHGC) was not made when the research was done for this study. SHGC represents the solar heat gain through a glazing system relative to incident solar radiation. The shading coefficient represents the solar heat gain through a glazing system relative to a single light of double-strength sheet glass under the same conditions. To translate SC to SHGC, multiply SC by 0.87 (standard summer conditions).

mance. (1) Cooling energy due to solar gains will decrease due to a lower shading coefficient. (2) Required heating energy will increase due to a reduction in solar gains. This may be offset, however, by a reduction in thermal conductance due to possible reduced emissivity for some glazing configurations (e.g., glue-on films). Since the cost ratio of the heating fuel, typically natural gas, to electricity is low, the significance of increased heating diminishes with respect to total cost. (3) The summer peak demand due to cooling will also decrease due to a reduction in solar gains. (4) Since peak demand is used to size the cooling equipment, a downsizing of capacity may be in order if the homeowner wishes to replace or upgrade the existing air conditioning system. In some cases, this window retrofit option in conjunction with other simple retrofit strategies may even eliminate the need for air-conditioning.

This study focuses on the potential energy and cost savings that may result with the introduction of spectrally selective glazings to the residential retrofit market. Using numerical simulation, we define the relationship of energy cost, peak demand, and chiller size to glazing performance characteristics for various housing characteristics in five cooling-dominated climates in California. We also invert the problem by determining what glazing characteristics (namely, SC) are required to achieve a given cost savings to assist utilities in assessing demand-side management (DSM) potential, to aid homeowners or the architectural design team in weighing annual energy cost savings against variable first costs for materials and installation, and to inform the material scientist and manufacturer of cost benefits given incremental glazing material improvements. Glazing material improvements are also discussed with respect to cost and occupant preferences.

METHOD

We used numerical simulation to study the whole building energy impact of spectrally selective glazings. The DOE-2.1D Building Energy Simulation Program (Birdsall *et al.* 1990) allows one to simulate the thermodynamic behavior of a building, to determine hour-by-hour energy consumption, and to test the sensitivity of this behavior to selected building parameters. A 1540 ft^2 (143 m^2) single story ranch style prototype, derived from comprehensive building simulation development work (Sullivan *et al.* 1992), was used as the basis of this analysis. The building has a single zone, 39.2 ft (11.9 m) square floor plan constructed of 0.5 inch (1.27 cm) stucco over insulated wood frame walls with 0.5 inch drywall, a wood shingle roof, and a carpeted wood floor over a crawl space. Internal loads of 53,963 Btu/day (15,804 Wh/day) were modeled. The HVAC system consists of an air conditioner with a peak condition COP of 2.2 and a gas furnace with a peak efficiency of 0.74. Additional parametrics were performed to capture the variety of building characteristics prevalent in California residential buildings, e.g., overhangs, interior drapes, slab-on-grade construction, etc. A description of the geometry, construction, and equipment used for the base case and alternate prototypes is provided in Table 1. A more detailed description of the development of these housing characteristics can be found in a study by the Energy Analysis Program (1985).

Five California climates were selected based on population and the severity of the climate. Blythe was chosen to represent the extreme of the cooling-dominated climates in California; the cooling degree days (CDD, base 75°F (23.9°C)) for this location are 2280. Red Bluff, Fresno, Riverside, and Sacramento all have CDD less than 700, but have a substantial population. Other areas, such as the Los Angeles metropolitan areas (coastal climate), all fall under 200 CDD and thus were not considered in this analysis; however, many houses in these zones are air-conditioned and would benefit from the use of glazing retrofits. Weather data have been provided for these five cities in Table 2.

In 1982, the California Public Utilities Commission redesigned the tariff structure to include a "baseline" allowance based on demographic studies and a climatic zoning of the utility territories (Doughty 1992). Houses in these territories are allowed a winter and summer allocation of energy use per day above which there is an additional charge. The electricity and gas rates for the associated utility areas (effective January 1992) have been provided in Table 3. Initial simulations were run on the base case prototype to determine if and when the prototype exceeded this baseline allowance per climate. For all climates, the baseline was exceeded throughout the winter and summer billing months for a 12% window-area-to-floor-area ratio (3% WFR per facade) with a conservative SC of 0.5. Therefore, we simplified the tiered seasonal rate structure by using a fixed electricity rate of $0.13/kWh that is slightly higher than the baseline rate throughout the year.

The performance analysis is comprised of three parts: (1) multiple regression analysis to facilitate the computation of energy for any arbitrary combination of building parameters, (2) comparison of performance between alternate housing characteristics and the base case prototype, and (3) calculation of the required SC in order to achieve a prescribed cost savings.

The multiple regression analysis focused on the relationship of energy, peak demand and cost to three key parameters: SC, window orientation, and glazing area. A large database was created by parametrically simulating the full range of fenestration characteristics for all five climates. Multiple regression analysis was then used to correlate the key parameters to total building energy performance. This method of analysis is well established and fully documented in a national fenestration study by Sullivan et al. (1992). The SC was varied by increments of 0.25 for the full range from 0 to 1.0. Forty combinations of glazing area were modeled, varying from a 0% to 12% window-area-to-floor-area ratio (WFR) or from 0% to 60% of the exterior wall area per facade. All window parameters represent total window values, including frame,

TABLE 1
Building Description of the DOE-2.1D Simulation Prototype

Building Geometry	
Ranch Floor Area (ft^2)	1540
Two-Story Floor Area (ft^2)*	3080
Building Width (ft)	39.2
Building Depth (ft)	39.2
Floor-to-Ceiling Height (ft)	8.0
Crawl Space Height (ft)	2.75
Concrete Slab on Grade Thickness (in)*	4.0
Construction	
Wood frame with stucco exterior and drywall interior	
Low insulation level: R6 walls, R11 roof, R0 floor	
Medium insulation level: R11 walls, R30 roof, R5 floor*	
Glazing	
Shading Coefficient (increments of 0.25)	0 to 1.0
Visible Transmittance	0.88
U-value, single-pane (Btu/h·ft^2·°F)	1.3
U-value, double-pane* (Btu/h·ft^2·°F)	0.5
Area: 0 to 12% WFR, 40 combinations for the four cardinal orientations	
Area: 14% WFR, distributed equally on all four orientations*	
Obstructions	
Built-up Area: 39.42 ft wide x 8 ft high adjacent residences spaced 20 ft away from each facade*	
Interior Shade Management: Reduce solar heat gain by 40% when direct solar gain exceeds 30 Btu/h·ft^2*	
Overhang: 2 ft projection at head of window matching the exact width of the window*	
Other Loads and Mechanical Equipment	
Internal Loads (Btu/day)	53,963
Occupant Loads (Btu/h)	10,163
Infiltration, Average, Sherman-Grimsrud (% of total floor area)	0.0005
Gas furnace and central air conditioning	
Heat pump*	
Electricity Rate ($/kWh)	$0.13
Gas Rate ($/MBtu)	$6.00

* These parameters were varied individually over the base case prototype configuration for a 14% window-area-to-floor-area ratio, 3.5% WFR per orientation.

sash, and divider effects. Four cardinal directions were used for window orientation. Hence, for each city, 200 prototype configurations were correlated using the equation:

$$E_i = \beta_{1i} \cdot U_g \cdot A_i + \beta_{2i} \cdot (U_g \cdot A_i)^2 + \beta_{3i} \cdot SC \cdot A_i + \beta_{4i} \cdot (SC \cdot A_i)^2 \quad (1)$$

where,

- E = Annual incremental cooling or heating energy consumption (kBtu/h) or Incremental cooling or heating peak demand (kBtu) due to the glazing;
- β = Regression coefficients for the energy performance variable;
- SC = Shading coefficient of the window;
- U_g = U-value of the window, U_g=1.3 Btu/h·ft^2·°F;
- A = Area of the window, 0-185 ft^2;
- i = North, east, south, or west orientation of the window.

The incremental cooling or heating peak demand or energy consumption due to the glazing area can be determined for any orientation and for any combination of glazing area and SC using the equation above. *Incremental* is defined as the difference in energy use or demand between the prototype building with windows and the same building without windows. The regression coefficients, ß1 through ß4, are provided for each city in Tables 4a and 4b. Correlation of the energy consumption calculated by the DOE-2.1D simulation program to that predicted by the above equation is very good (r^2=0.9997).

In order to study the range of energy performance for various housing characteristics present in pre-1978 construction, we ran a second set of parametric simulation runs where we set a base case condition and then varied one building parameter. The relationship of an alternate prototype to a base case prototype is known to be linear with changes in geographic location (Sullivan *et al.* 1986). To establish this proportional relationship, we simulated a subset of the combinations studied for the base case prototype. For the base case prototype, we assume a fixed glazing area of 3.5% WFR per orientation. The energy savings were calculated based on a reduction of SC from 1.0, the prevalent single pane clear glazing type in most existing pre-1978 homes, to SC=0.5, representative of the best clear spectrally selective glazing that is currently available. The total energy use and peak demand were determined for the alternate characteristics and then related to the base case energy performance for each of the five climates.

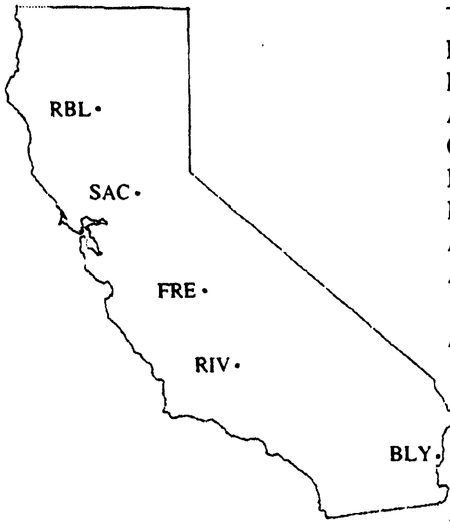

TABLE 2
Weather Data for Five California Climates

Location	BLY	RBL	FRE	RIV	SAC
Latitude	33.6	40.2	36.7	33.9	38.5
Longitude	114.6	122.2	119.8	117.2	121.5
Altitude (ft)	390	342	326	1543	17
CDD (75°F)	2280	679	417	252	191
HDD (65°F)	1065	2904	2685	2103	2764
No. Days Max. Temp. > 90 °F	168	97	94	80	69
Avg. Annual Dry-Bulb Temp. (°F)	74	62	62	62	60
Avg. Annual Wet-Bulb Temp. (°F)	55	51	52	52	52
Avg. Daily Tot. Vert. Solar (Btu/h·ft^2):					
North-facing Surface	403	411	410	444	423
East-facing Surface	1009	936	986	942	972
South-facing Surface	1228	1226	1180	1290	1232
West-facing Surface	1000	963	965	1027	994

BLY Blythe, RBL Red Bluff, FRE Fresno, RIV Riverside, SAC Sacramento

TABLE 3
Energy Rates for California Utility Districts for Residential Customers
in Single-Family Dwellings with Gas Space Heating

Electricity	Baseline Cost $/kWh	Over Baseline $/kWh	Baseline Allowance kWh/day	Billing Months	Baseline Allowance kWh/mon
BLY	$0.106	$0.141	39.3	Jun - Sep	1179
	$0.106	$0.141	10.9	Oct - May	327
RIV	$0.106	$0.141	10.9	May - Oct	327
	$0.106	$0.141	9.2	Nov - Apr	276
RBL/ FRE	$0.111	$0.139	15.7	May - Oct	471
	$0.111	$0.139	11.8	Nov - Apr	354
SAC	$0.081	$0.127	23.4	May - Oct	702
	$0.074	$0.118	20.7	Nov - Apr	621

Natural Gas	Baseline Cost $/MBtu	Over Baseline $/MBtu	Baseline Allowance MBtu/day	Billing Months	Baseline Allowance MBtu/mon
BLY/ RIV	$4.676	$6.726	6.2	May - Oct	186.3
	$4.676	$6.726	16.6	Nov - Apr	497.1
RBL/ FRE	$5.040	$8.242	5.0	May - Oct	150
	$5.040	$8.242	24.0	Nov - Apr	720
SAC	$5.040	$8.242	6.0	May - Oct	180
	$5.040	$8.242	24.0	Nov - Apr	720

TABLE 4
Regression Coefficients for the Basecase Prototype

		BLY	RBL	FRE	RIV	SAC
Cooling Energy (kBtu)						
ß1N	U x A	13.7787	5.6414	2.6724	3.4989	3.0048
ß2N	(U x A)^2	-0.0140	-0.0108	-0.0076	-0.0125	-0.0086
ß3N	SC x A	31.5829	18.6651	16.1687	11.4808	11.7771
ß4N	(SC x A)^2	0.0123	0.0218	0.0227	0.0617	0.0367
ß1E	U x A	13.3012	4.5822	2.3699	2.7404	2.8855
ß2E	(U x A)^2	-0.0178	-0.0103	-0.0103	-0.0137	-0.0118
ß3E	SC x A	76.8262	53.3981	39.8068	33.7779	35.0205
ß4E	(SC x A)^2	0.0060	-0.0070	0.0246	0.0804	0.0498
ß1S	U x A	13.7254	5.5770	3.3952	3.1675	3.7812
ß2S	(U x A)^2	-0.0187	-0.0152	-0.0131	-0.0146	-0.0139
ß3S	SC x A	69.0528	50.7779	34.5168	32.9458	31.4650
ß4S	(SC x A)^2	0.0640	0.0706	0.0796	0.1547	0.0923
ß1W	U x A	13.7949	5.9691	2.7314	3.1147	3.3264
ß2W	(U x A)^2	-0.0202	-0.0172	-0.0117	-0.0141	-0.0140
ß3W	SC x A	108.1789	63.1605	58.0782	41.1238	46.1771
ß4W	(SC x A)^2	0.0384	0.0597	0.0722	0.1339	0.0976
Peak Cooling Energy (kBtu/h)						
ß1N	U x A	0.0159	0.0183	0.0080	0.0077	0.0064
ß2N	(U x A)^2	0.0000	0.0000	0.0000	0.0000	0.0000
ß3N	SC x A	0.0180	0.0180	0.0163	0.0211	0.0181
ß4N	(SC x A)^2	0.0000	0.0000	0.0000	0.0000	0.0000
ß1E	U x A	0.0151	0.0162	0.0075	0.0074	0.0065
ß2E	(U x A)^2	0.0000	0.0000	0.0000	0.0000	0.0000
ß3E	SC x A	0.0203	0.0330	0.0197	0.0331	0.0200
ß4E	(SC x A)^2	0.0000	-0.0001	0.0000	0.0000	0.0000
ß1S	U x A	0.0154	0.0177	0.0076	0.0079	0.0084
ß2S	(U x A)^2	0.0000	0.0000	0.0000	0.0000	0.0000
ß3S	SC x A	0.0192	0.0397	0.0221	0.0296	0.0110
ß4S	(SC x A)^2	0.0000	0.0000	0.0000	0.0000	0.0001
ß1W	U x A	0.0160	0.0191	0.0079	0.0073	0.0083
ß2W	(U x A)^2	0.0000	0.0000	0.0000	0.0000	0.0000
ß3W	SC x A	0.0905	0.0778	0.0821	0.0424	0.0696
ß4W	(SC x A)^2	0.0000	0.0000	0.0000	0.0000	0.0000

An equation for determining the required shading coefficient to achieve a desired cost savings per year for a given orientation and area of glazing can be derived using the quadratic equation with the regression equation provided above. This relationship can be used to define the cost-effective boundary conditions of the required shading coefficient per climate and may assist material scientists/manufacturers, homeowners, or utility DSM planners in determining the cost benefits for an incremental gain in material improvements.

$$SC_{i,r} = (-b + (b^2 - 4ac)^{0.5}) / 2a \qquad (2)$$

$$a = E \cdot \beta_{4i} \cdot A_i^2 + G \cdot \mu_{4i} \cdot A_i^2$$

$$b = E \cdot \beta_{3i} \cdot A_i + G \cdot \mu_{3i} \cdot A_i$$

$$c = E \cdot (\beta_{1i} \cdot U_g \cdot A_i + \beta_{2i} \cdot (U_g \cdot A_i)^2) + G \cdot (\mu_{1i} \cdot U_g \cdot A_i + \mu_{2i} \cdot (U_g \cdot A_i)^2) - C_i \cdot A_i$$

$$C_i = C_{i,SCe} - C_d$$

TABLE 4 (continued)
Regression Coefficients for the Basecase Prototype

		BLY	RBL	FRE	RIV	SAC
Heating Energy (kBtu)						
ß1N	U x A	53.3276	109.6819	97.2862	90.5839	107.2567
ß2N	$(U \times A)^2$	-0.0103	-0.0241	-0.0174	-0.0209	-0.0246
ß3N	SC x A	-33.4958	-49.8654	-52.2192	-66.8644	-55.6066
ß4N	$(SC \times A)^2$	0.0997	0.1021	0.1169	0.2205	0.1102
ß1E	U x A	54.9042	110.9435	99.7590	93.4927	109.2633
ß2E	$(U \times A)^2$	-0.0198	-0.0316	-0.0321	-0.0309	-0.0358
ß3E	SC x A	-84.9665	-110.2062	-139.8577	-140.8216	-139.9845
ß4E	$(SC \times A)^2$	0.2242	0.2489	0.3285	0.4125	0.3241
ß1S	U x A	55.5375	113.1868	101.6543	93.7543	111.8666
ß2S	$(U \times A)^2$	-0.0200	-0.0354	-0.0327	-0.0279	-0.0394
ß3S	SC x A	-131.2264	-185.3336	-193.1663	-205.1931	-210.1960
ß4S	$(SC \times A)^2$	0.4101	0.4642	0.5623	0.7212	0.5655
ß1W	U x A	53.6839	110.8239	98.4168	89.9917	109.2561
ß2W	$(U \times A)^2$	-0.0104	-0.0287	-0.0179	-0.0170	-0.0274
ß3W	SC x A	-52.2802	-76.0575	-75.7731	-107.2468	-76.9391
ß4W	$(SC \times A)^2$	0.1558	0.1959	0.2024	0.3613	0.1775
Peak Heating Energy (kBtu/h)						
ß1N	U x A	0.0450	0.0455	0.0359	0.0361	0.0311
ß2N	$(U \times A)^2$	0.0000	0.0000	0.0000	0.0000	0.0000
ß3N	SC x A	0.0057	0.0095	0.0537	0.0571	0.1023
ß4N	$(SC \times A)^2$	0.0000	0.0000	-0.0003	-0.0004	-0.0006
ß1E	U x A	0.0449	0.0449	0.0325	0.0343	0.0284
ß2E	$(U \times A)^2$	0.0000	0.0000	0.0000	0.0000	0.0000
ß3E	SC x A	0.0064	0.0130	0.0645	0.0731	0.1049
ß4E	$(SC \times A)^2$	0.0000	0.0000	-0.0004	-0.0004	-0.0007
ß1S	U x A	0.0454	0.0459	0.0363	0.0395	0.0325
ß2S	$(U \times A)^2$	0.0000	0.0000	0.0000	0.0000	0.0000
ß3S	SC x A	0.0057	0.0150	0.0595	0.0657	0.1161
ß4S	$(SC \times A)^2$	0.0000	-0.0001	-0.0003	-0.0004	-0.0007
ß1W	U x A	0.0457	0.0469	0.0508	0.0443	0.0653
ß2W	$(U \times A)^2$	0.0000	0.0000	0.0000	0.0000	-0.0001
ß3W	SC x A	0.0235	0.0316	0.0869	0.0863	0.1769
ß4W	$(SC \times A)^2$	-0.0001	-0.0001	-0.0004	-0.0005	-0.0010

where,

$SC_{i,r}$ = Required shading coefficient of the retrofit glazing for a desired energy cost savings and orientation;

SC_e = Shading coefficient of the existing glazing;

C_d = Desired incremental annual energy cost savings ($/ft²·gl);

$C_{i,SCe}$ = Annual incremental heating and cooling energy cost savings for the existing glazing ; (SC_e) and orientation ($/ft²·gl);

E = Electricity cost ($/kWh) / 3.414 (kBtu/kWh);

G = Gas cost ($/MBtu) / 1000;

ß = Regression coefficients for the incremental cooling energy due to the glazing;

μ = Regression coefficients for the incremental heating energy due to the glazing;

U_g = U-value of the glazing (assumed to be the same for the existing and retrofit glazing), U=1.3 Btu/h·ft²·°F;

A = Area of the window (ft²);

i = North, east, south, or west orientation of the window.

DISCUSSION

We discuss the key building and climatic parameters that have the most significant impact on the feasibility of spectrally selective glazings. All energy and cost results are presented on a per square foot of glazing area per year basis ($/ft^2·gl·yr)[b] to facilitate direct comparisons to material and installation costs. The incremental cost and energy is defined as the additional energy or cost required for the window over an insulated wall. The glazing area is expressed as a ratio of the fixed floor area of 1540 ft^2 (143 m^2). For reference, annual energy consumption and peak demand for a base case condition of 3.5% WFR per orientation is given in Table 5.

The orientation of the glazing has the most significant influence on the cost-effectiveness of using spectrally selective glazings because of the impact of solar radiation on cooling energy consumption (Figure 3). Variable incident solar radiation (Table 2) and the thermal lag due to the capacitance of the building mass contributes to these differences in cooling energy with orientation. For all climates and for all values of SC, the incremental cooling energy cost due to a west-facing window is approximately 40% more than that required for a south- or east-facing window. The energy cost of the south and east windows is approximately the same and the energy cost of a north-facing window is 50% less than for the south or east windows. Homes in all cities except Blythe yield a cooling electricity savings of $0.40 to $1.50/ft^2·gl·yr for an SC reduction of 0.50. For the hot climate of Blythe, these savings range from $0.50 for a north-facing window to $2.15 for a west-facing window.

Cooling energy cost is slightly sensitive to the area of glass used. For all orientations except north in Blythe (Figure 4), the slope of the lines is nearly horizontal, indicating insensitivity of cost to changes in window area. Small energy differences are due to window and non-window factors such as glass conductivity and interactive energy effects due to higher loads from increased glazing area. For window areas ranging from 2% to 12% WFR (SC=0.50), the incremental cooling energy cost decreases from $1.98 to $1.88/ft^2·gl·yr (5%) for south-facing glazing and from $2.09 to $1.92 (8%) for east-facing glazing. Cooling energy cost *savings*, however, are dependent on glazing area and orientation. This can be visualized by comparing the difference in slope between the $3 and $1/ft^2·gl·yr cost lines for south-facing glazing as opposed to the same cost line slopes for east-facing glazing. Note that the south lines converge as window area is increased, whereas the east lines remain nearly parallel. For an SC reduction from 1.0 to 0.5, the cooling energy cost savings increase from $1.37 to $1.66/ft^2·gl·yr (21%) for 2% to 12% WFR for south-facing glazing and $1.47 to $1.50/ft^2·gl (2%) for east-facing glazing.

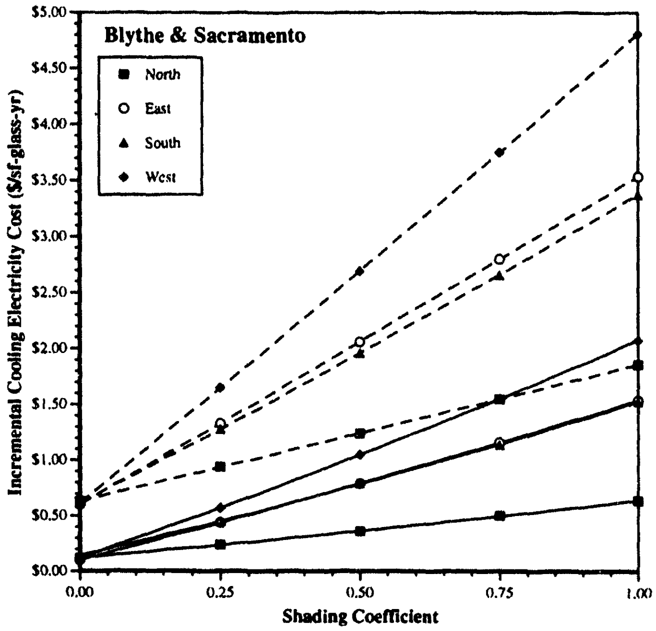

Figure 3. Incremental cooling electricity cost ($/ft^2·glazing·yr) for a 1540 ft^2 (143 m^2) residence in Sacramento (solid lines) and Blythe (dotted lines), California with a glazing area of 3.5% window-area-to-floor-area ratio per orientation. Incremental is defined as the difference in energy cost between a window and an insulated wall.

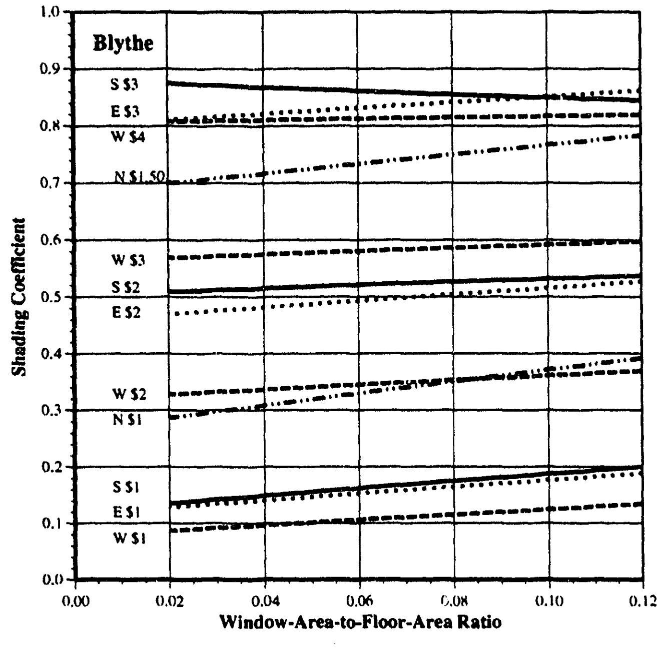

Figure 4. Incremental cooling electricity cost (z-axis: $/ft^2·glazing·yr) given variable window area for a 1540 ft^2 (143 m^2) residence in Blythe, California. Notation on graph is: N=North, E=East, S=South, W=West window orientation.

[b] To convert from $/ft^2·gl·yr to $/m^2·gl·yr, multiply by 10.76.

TABLE 5
Annual Incremental Cooling and Heating Energy Consumption

	Cooling Energy (kWh)				Heating Energy (kBtu)			
SC	N	E	S	W	N	E	S	W
Blythe				***5300**				***22,010**
0.00	263	247	255	254	3686	3750	3793	3711
0.25	388	551	531	683	3253	2646	2099	3035
0.50	515	855	813	1116	2856	1623	554	2415
0.75	642	1160	1103	1553	2495	682	-842	1852
1.00	772	1465	1399	1995	2170	-178	-2089	1345
Fresno				***1226**				***45,850**
0.00	44	34	51	39	6732	6833	6963	6808
0.25	109	192	191	272	6049	5008	4462	5824
0.50	176	353	340	513	5409	3302	2165	4913
0.75	246	517	498	761	4812	1716	72	4076
1.00	319	683	663	1018	4257	248	-1816	3312
Red Bluff				***1703**				***54,610**
0.00	100	79	93	98	7568	7619	7757	7625
0.25	175	290	297	350	6914	6179	5344	6636
0.50	252	499	508	609	6298	4830	3100	5718
0.75	332	708	728	874	5719	3570	1024	4871
1.00	413	916	954	1146	5177	2402	-884	4095
Riverside				***811**				***34,900**
0.00	54	36	44	44	6245	6400	6433	6222
0.25	102	174	182	213	5384	4577	3799	4843
0.50	158	320	337	397	4603	2904	1426	3594
0.75	219	475	508	595	3902	1381	-684	2477
1.00	288	638	696	807	3282	8	-2532	1491
Sacramento				***658**				***50,080**
0.00	49	42	58	48	7395	7481	7645	7521
0.25	98	183	187	236	6666	5653	4915	6517
0.50	150	329	326	433	5976	3943	2391	5577
0.75	206	481	474	642	5327	2351	72	4701
1.00	267	638	633	860	4718	877	-2042	3890

Incremental annual energy consumption given for a 1540 ft^2 (143 m^2) residence with a glazing area of 3.5% WFR or 53.9 ft^2 per orientation.

* Incremental energy consumption is defined as the difference in energy use between a window and an insulated wall. To determine total energy use add the above base line values shown in boldface italics to the incremental energy use per window, e.g., the total cooling energy for four 3.5% WFR windows facing N,E,S,&W with a shading coefficient of 1.00 in Blythe is 5300+772+1465+1399+1995=10,931 kWh/yr.

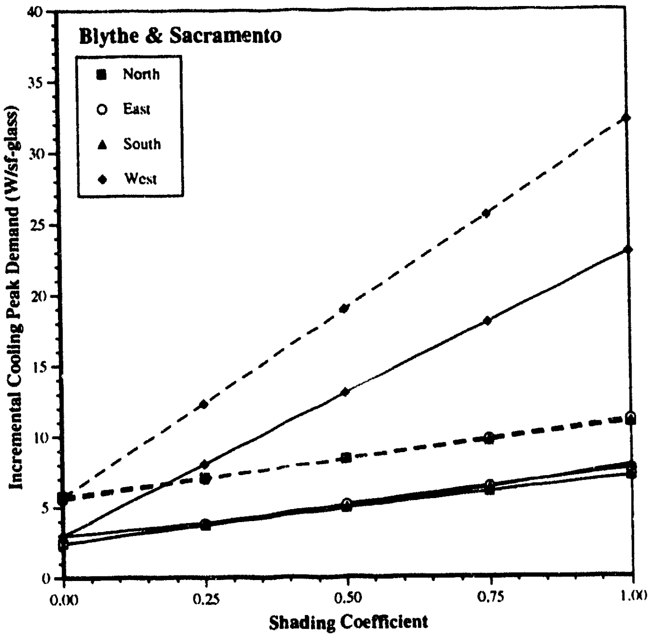

Figure 5. Incremental peak demand due to cooling (W/ft²·glazing) for a 1540 ft² (143 m²) residence in Sacramento (solid lines) and Blythe (dotted lines), California with a glazing area of 3.5% window-area-to-floor-area ratio per orientation.

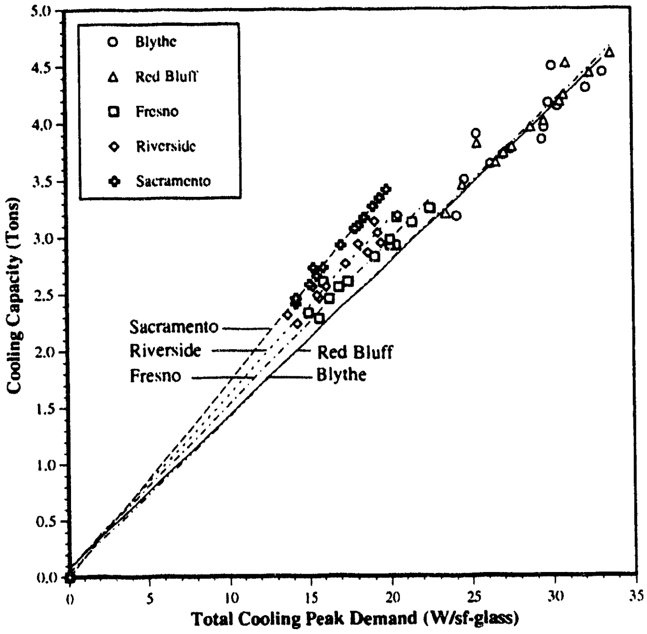

Figure 6. Total peak demand due to cooling (W/ft²·glazing) versus cooling capacity of air-conditioning equipment for a 1540 ft² (143 m²) residence in five California climates with a glazing area of 3.5% window-area-to-floor-area ratio per orientation. Datapoints include the base case prototype and all alternate housing characteristics for glazing shading coefficient values of 0.5 and 1.0.

Peak demand due to cooling is largely dependent on the solar gain loads that occur during that hour and from previous hours due to the thermal lag of the building and, to a lesser extent, the glazing conductance gains associated with the elevated outdoor air temperature. Orientation, again, is the most significant factor affecting cooling peak demand. For example, for a west-facing window in Blythe, the percentage of the total cooling peak loads due to solar gains is 27% and the percentage due to glazing conductance is 10%. For a north-facing window, the percentages are 7% and 11%, respectively (SC=1.0, 4% WFR). West-facing windows produce two times the incremental cooling peak demand of south, east and north windows for all five climates (Figure 5). For an SC reduction of 0.5, incremental cooling peak demand reductions for hot climates range from 24% to 41% depending on orientation; for moderate climates, reductions range from 31% to 43% (3.5% WFR). For demand side management programs, this may aid in leveling loads today and reducing the need for future peak capacity.

Cooling peak demand reductions are directly related to the sizing of the air conditioner or chiller. If peak demand is reduced, additional first cost savings to the homeowner may be obtained by downsizing the air-conditioning equipment. For many of the older homes, this equipment is often due for replacement after 15-20 years; these savings may then be captured upon system upgrades. Several factors can contribute to the differences in cooling capacity reductions per climate; for example, a higher outdoor dry-bulb temperature – and hence large differences in temperature across the cooling coil – increases the efficiency of the chiller. The sizing of the supply fan can also impact chiller size. For a given peak demand, Blythe, Red Bluff, and Fresno (CDD > 417) require nearly the same cooling capacity, whereas Sacramento and Riverside (CDD < 252) require a slightly larger cooling capacity (Figure 6). The first cost savings for HVAC replacement can help reduce the payback period of the retrofit (assuming capacity reductions result in a lower standard equipment size). For example in Blythe, a reduction in SC of 0.5 reduces the total cooling peak demand from 33.2 to 27.6 W/ft²·gl (357 to 297 W/m²·gl, 3.5% WFR per orientation). This translates to a decrease in cooling capacity of 0.67 tons (12.37 MW) of refrigeration or $3.11/ft²·gl (at $1000 per ton). Added to an annual total electricity savings of $1.38/ft²·gl·yr, the first year savings is $4.49/ft²·gl. For Sacramento, the first year savings is $3.64/ft²·gl. Note the difference between *total* (Figure 6) and *incremental* cooling peak demand (Figure 5). Incremental cooling peak demand is due to a single window orientation relative to an insulated wall, total is the cooling peak demand of the entire building with four windows (3.5% WFR per orientation). Both quantities are normalized by glazing area.

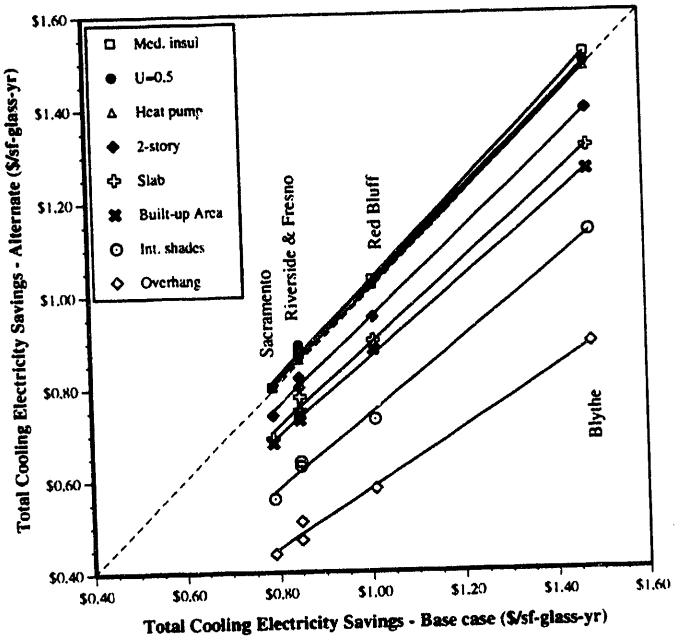

Figure 7. Total cooling electricity savings ($/ft²·glazing·yr) due to a reduction in glazing shading coefficient of 0.5 for alternate housing characteristics in five California climates. Glazing area is 3.5% window-area-to-floor-area ratio per orientation.

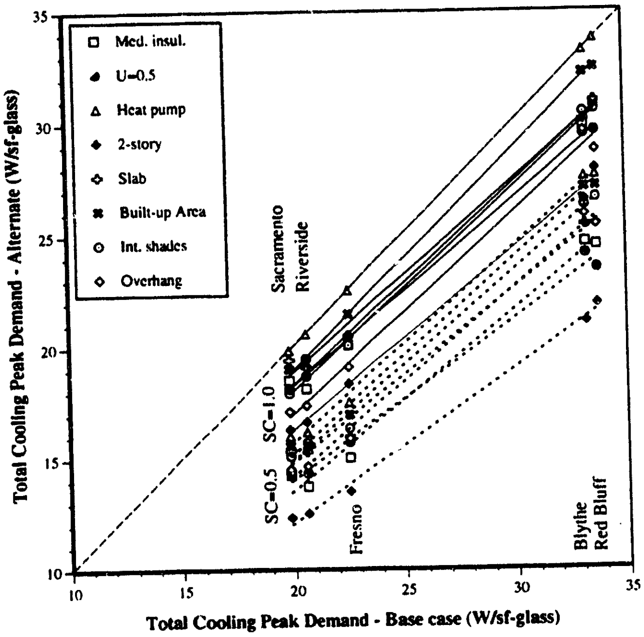

Figure 8. Peak demand (W/ft²·glazing) for glazing shading cc ffi-cient values of 0.5 (dotted lines) and 1.0 (solid lines) for alternate housing characteristics in five California climates. Base case prototype glazing shading coefficient is 1.0. Glazing area is 3.5% window-area-to-floor-area ratio per orientation.

Alternate Housing Characteristics

Alternate housing characteristics can often significantly impact predictions for cost savings attributable to glazing. According to a California survey (CEC 1990b), the computer model used to develop and update state energy standards and used by building designers to demonstrate compliance with standards for new residential construction typically overestimates cooling energy consumption by 50% because of inaccurate modeling of occupancy patterns and site conditions. Although the CEC study pertains to new construction and does not conclusively correlate cooling energy due to the small sample size, we acknowledge that a wide range of housing characteristics and occupant preferences do exist and will, therefore, impact energy saving estimates.

To understand this impact, we have established a base case prototype and altered one building characteristic at a time to quantify changes in window energy savings. Total cooling energy savings for an SC reduction from 1.0 to 0.5 are given for alternative configurations of the base case prototype in Figure 7. Housing characteristics that reduce solar gains either inside or outside the building decrease the cost-effectiveness of spectrally selective glazings for all climates: exterior overhangs or awnings reduce base case cost savings estimates by 41-47%, interior drapes or shades by 24-29%, or siting in built-up suburban areas by 14-15%. For example, a 2 ft (0.61 m) overhang in Sacramento reduces the total cooling energy savings from $0.79 to $0.44/ft²·gl·yr; in Blythe, from $1.48 to $0.89/ft²·gl·yr (SC reduction of 0.5). All other housing characteristics such as double-pane glazing, increased insulation levels, or a heat pump cause less than a 12% reduction in cooling energy savings from the base case for all climates. Combinations of housing characteristics, such as a house with an overhang in a built-up area, would further reduce energy saving estimates.

The same conclusions can be made for reductions in total cooling peak demand. Overhangs and interior shades or drapes are the two most significant factors that affect total cooling peak demand. All other housing characteristics affect total cooling peak demand to a smaller degree (Figure 8). For example, for an SC reduction of 0.5, the total cooling peak demand of a building with a 2 ft (0.61 m) overhang in Sacramento decreases from 17.12 to 14.52 W/ft²·gl (184.28 to 156.29 W/m²·gl) or 15%; in Red Bluff, from 28.76 to 25.42 W/ft²·gl (309.57 to 273.62 W/m²) or 11%. For a building without overhangs, these reductions are larger: in Sacramento from 19.85 to 16.00 W/ft²·gl (213.66 to 172.22 W/m²), or 19%, and in Red Bluff, from 33.72 to 27.64 W/ft²·gl (362.96 to 297.51 W/m²), or 18%. To simplify comparison, we have assumed in these cases that the total cooling peak loads for the alternate housing characteristics occur at the same time in the summer. Residential loads are dominated by the envelope of the building, so the particular ambient weather conditions during which the different peaks occur do not vary significantly.

Cost-Effective Boundaries of SC

We can define the cost-effective boundaries of required glazing characteristics by inverting the problem from determining the cost savings for a fixed SC reduction to determining the SC required to yield a defined cost savings (see Equation 2). For these calculations, heating and cooling energy costs have been used to define total energy cost savings. Heating energy costs have been included, since, for the climates of Sacramento and Red Bluff (HDD at 65°F (18.3°C) = 2764 and 2904, respectively), increases in these costs due to reduced solar gains can be significant. Fan energy decreases insignificantly with reductions in SC and, therefore, has not been included in the cost savings calculation. Electricity due to plug loads and appliances do not change. For example, in Blythe, the total building energy savings of $1.38/ft²·gl·yr for an SC reduction from 1.0 to 0.5 consists of +$1.48 due to cooling, -$0.15 heating, and +$0.05 fan (3.5% WFR per orientation). In Sacramento, however, the total savings of $0.54/ft²·gl·yr consists of +$0.79 due to cooling, -$0.27 heating, and +$0.02 fan energy savings. If HVAC equipment replacement is necessary, there may be additional economic savings, as noted above, which can significantly improve total cost savings. We have not, however, included these savings here.

These cost-effective boundaries are illustrated in Figures 9a and 9b for Blythe and Sacramento for varying desired energy savings and a pre-retrofit SC of 1.0; data are given in Table 6. For a homeowner to recover material plus installation costs of $150 (at $2.50/ft²·gl) for a 60 ft² (5.57 m²) glazing area within 5 years, a spectrally selective glazing with an SC of 0.39 for the east and 0.74 for the west would be required for Sacramento; SC of 0.47 for the east, 0.21 for the south, and 0.79 for the west for Fresno; and SC of 0.55 for the north, 0.81 for the east, 0.79 for the south, 0.89 for the west for Blythe (missing orientations indicate that this cost could not be recovered within this payback period). These material and installation costs are reasonable for glue-on film options. For the more expensive options of glass or window replacement, the payback period would need to be extended or the required SC decreased. If the building has any of the alternate housing characteristics such as an overhang or interior shades/ drapes, the required SC would need to be further reduced. Glass or window replacement costs are difficult to assess due to regional differences in labor rates, the extent of the retrofit, type of window/wall construction, and other factors. Using building construction cost data (Means 1992) typical for new construction and large scale projects, it is estimated that glass replacement will cost $6-8/ft²·gl (including materials, labor, overhead and profit), glass plus sash replacement will cost $17-20/ft²·gl, and window replacement will cost $14-16/ft²·gl. Retrofit costs can often cost 50% more. For the example above, if the homeowner decided to replace the windows at $15/ft²·gl, the simple payback period would be 30 years if the required SC was met for each orientation.

TABLE 6

Required Shading Coefficient for a Given Glazing Area and Desired Heating and Cooling Energy Cost Savings

		Cooling and heating cost savings ($/ft²·glazing·yr) over SC=1.0 for base case prototype:			
	WFR	$0.50	$1.00	$1.50	$2.00
Sacramento					
E	2%	0.218			
	4%	0.394			
	6%	0.516			
	8%	0.601			
	10%	0.661	0.147		
	12%	0.707	0.291		
S	6%	0.397			
	8%	0.620			
	10%	0.717	0.072		
	12%	0.773	0.435		
W	2%	0.687	0.334		
	4%	0.742	0.424	0.070	
	6%	0.787	0.501	0.176	
	8%	0.823	0.567	0.271	
	10%	0.852	0.621	0.354	0.026
	12%	0.876	0.667	0.426	0.130
Riverside					
N	10%	0.393			
	12%	0.536			
E	2%	0.235			
	4%	0.471			
	6%	0.604			
	8%	0.686	0.212		
	10%	0.741	0.383		
	12%	0.779	0.492		
S	4%	0.475			
	6%	0.692			
	8%	0.779	0.464		
	10%	0.828	0.609	0.241	
	12%	0.859	0.689	0.461	
W	2%	0.632	0.156		
	4%	0.747	0.357		
	6%	0.825	0.508	0.097	
	8%	0.881	0.617	0.287	
	10%	0.921	0.698	0.427	0.044
	12%	0.952	0.760	0.531	0.231
Fresno					
N	10%	0.131			
	12%	0.246			
E	2%	0.377			
	4%	0.469			
	6%	0.542			
	8%	0.600	0.051		
	10%	0.647	0.166		
	12%	0.684	0.262		
S	4%	0.211			
	6%	0.529			
	8%	0.659			
	10%	0.732	0.308		
	12%	0.779	0.474		
W	2%	0.758	0.490	0.215	
	4%	0.792	0.541	0.278	0.001
	6%	0.822	0.588	0.338	0.070
	8%	0.849	0.630	0.394	0.136
	10%	0.872	0.667	0.444	0.199
	12%	0.892	0.700	0.491	0.259

Example: Mr. Jones has an east-facing window that will cost $1.00 per square foot of glazing to retrofit. The area of the glazing is 8% of the floor area. His home is in Riverside. The required glazing shading coefficient is 0.212 if costs are recovered in the first year.

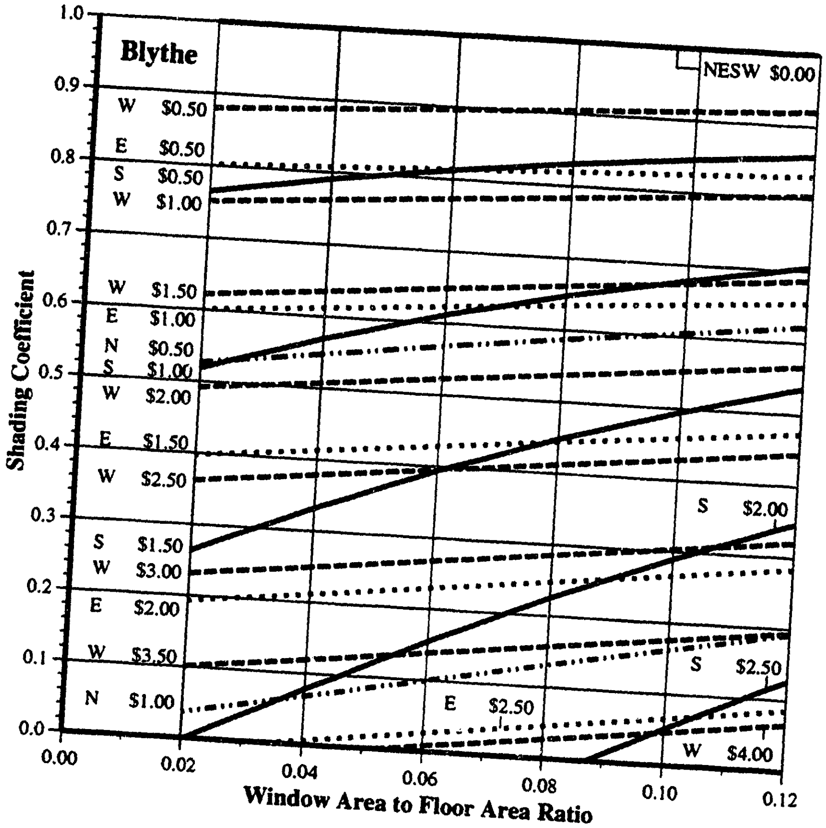

Figure 9a. Total cost savings (z-axis: $\$/ft^2$·glazing·yr) due to a reduction in shading coefficient from 1.0 to the y-coordinate value of SC and x-coordinate WFR for a 1540 ft^2 (143 m^2) residence in Blythe, California. Notation on graph is: N=North, E=East, S=South, W=West window orientation.

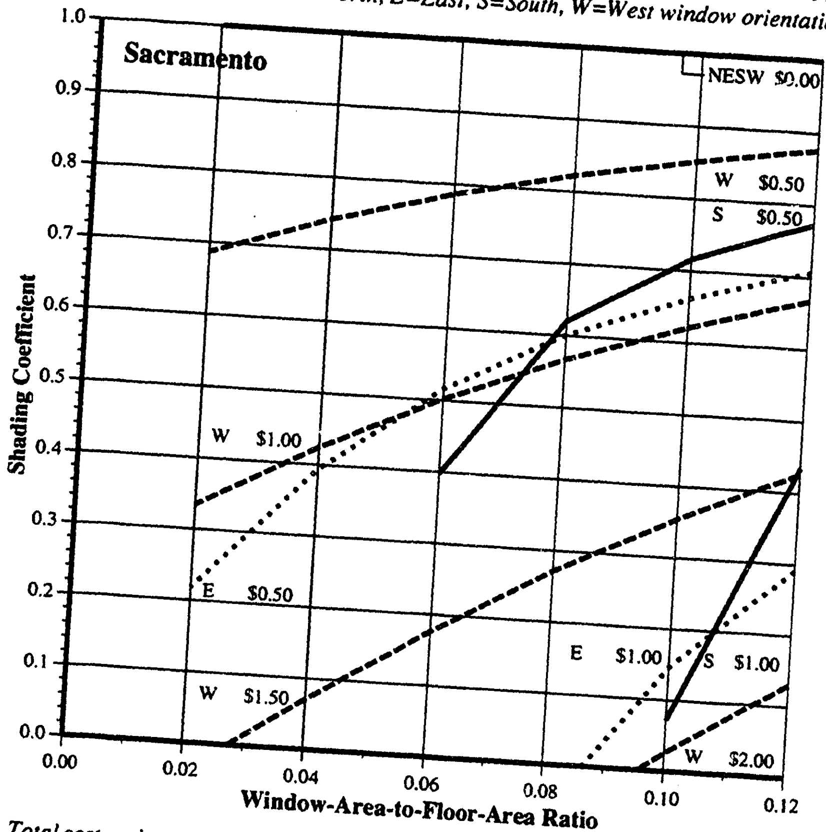

Figure 9b. Total cost savings (z-axis: $\$/ft^2$·glazing·yr) due to a reduction in shading coefficient from 1.0 to the y-coordinate value of SC and x-coordinate WFR for a 1540 ft^2 (143 m^2) residence in Sacramento, California. Notation on graph is: N=North, E=East, S=South, W=West window orientation.

TABLE 6 (continued)

Required Shading Coefficient for a Given Glazing Area and Desired Heating and Cooling Energy Cost Savings

Cooling and heating cost savings ($/ft²·glazing·yr) over SC=1.0 for base case prototype:

	WFR	$0.50	$1.00	$1.50	$2.00	$2.50
Red Bluff						
N	4%	0.003				
	6%	0.106				
	8%	0.200				
	10%	0.282				
	12%	0.352				
E	2%	0.653	0.298			
	4%	0.667	0.321			
	6%	0.681	0.344			
	8%	0.693	0.367	0.017		
	10%	0.705	0.388	0.044		
	12%	0.716	0.409	0.071		
S	2%	0.539				
	4%	0.637	0.181			
	6%	0.703	0.332			
	8%	0.751	0.443			
	10%	0.785	0.526	0.171		
	12%	0.812	0.588	0.297		
W	2%	0.776	0.532	0.283	0.030	
	4%	0.803	0.571	0.331	0.083	
	6%	0.827	0.608	0.378	0.136	
	8%	0.849	0.641	0.421	0.187	
	10%	0.869	0.672	0.462	0.236	
	12%	0.887	0.700	0.499	0.282	0.044
Blythe						
N	2%	0.527	0.036			
	4%	0.548	0.068			
	6%	0.568	0.100			
	8%	0.587	0.131			
	10%	0.605	0.162			
	12%	0.622	0.192			
E	2%	0.802	0.600	0.397	0.193	
	4%	0.808	0.612	0.413	0.211	0.006
	6%	0.814	0.623	0.429	0.230	0.026
	8%	0.820	0.634	0.444	0.248	0.046
	10%	0.825	0.645	0.459	0.266	0.065
	12%	0.831	0.655	0.473	0.283	0.085
S	2%	0.764	0.519	0.263		
	4%	0.791	0.569	0.332	0.078	
	6%	0.813	0.611	0.394	0.154	
	8%	0.831	0.648	0.448	0.225	
	10%	0.846	0.678	0.495	0.290	0.051
	12%	0.858	0.705	0.536	0.347	0.126

	WFR	$0.50	$1.00	$1.50	$2.00	$2.50	$3.00	$3.50	$4.00
Blythe									
W	2%	0.879	0.751	0.622	0.492	0.362	0.232	0.101	
	4%	0.888	0.762	0.635	0.507	0.379	0.250	0.119	
	6%	0.896	0.773	0.648	0.523	0.396	0.268	0.138	0.007
	8%	0.905	0.784	0.661	0.538	0.412	0.285	0.157	0.027
	10%	0.913	0.794	0.674	0.552	0.429	0.303	0.176	0.046
	12%	0.920	0.804	0.686	0.566	0.444	0.320	0.194	0.065

Material Improvements

The most cost-effective retrofit solution for all orientations and climates is the glue-on film option if durability is not in question. Although existing products available today can give SC values from as low as 0.15, decreased interior daylight and night views due to the low visible transmittance (Tv) of these products will typically discourage even the best intentioned homeowner. In addition, the mirrored appearance of some films may be architecturally detracting, unless it is part of the design aesthetic.

Data on the optical and thermal properties of available spectrally selective products were taken from product literature, measured in our laboratory, or calculated using WINDOW 4.0 (Windows and Daylighting Group 1992) from raw data supplied by manufacturers (Figure 10). Ideally, glazings should have a low SC and a high Tv, meaning that they should be as close to the lower right corner of the graph as possible. Because daylight also carries heat, it is not possible to have zero shading coefficient with a finite visible transmission. Thus, there is a "forbidden zone" in which no glazing can exist. We also define a somewhat subjective "color zone" in which there is no possibility of creating a glazing which is colorless. In the "neutral zone" glazings may but do not necessarily have a neutral color.

By comparison to Figure 11, which shows products mainly intended for new construction, the retrofit products are shifted away from the ideal. Until recently, in the transmission range above 0.5, no laminate products were available with high selectivity. In order for spectrally selective glazing products to be fully adopted by the residential retrofit market, the cheaper glue-on film materials must be developed with Tv characteristics that more closely approximate their new counterparts in construction.

Two factors are involved in this technology gap. First, coating on plastic film is more difficult than coating on glass because of problems with adhesion, temperature range of the substrate, diffusion, and bending stress. Second, the edges of the coating in a retrofit installation are prone to damage from water vapor and corrosive agents in the atmosphere. The materials used in highly selective coatings are especially prone to this type of damage. Furthermore, most laminate manufacturers have been content to produce lower transmission, less spectrally selective coatings such as aluminized polyester, because of lower cost, ease of handling, and the

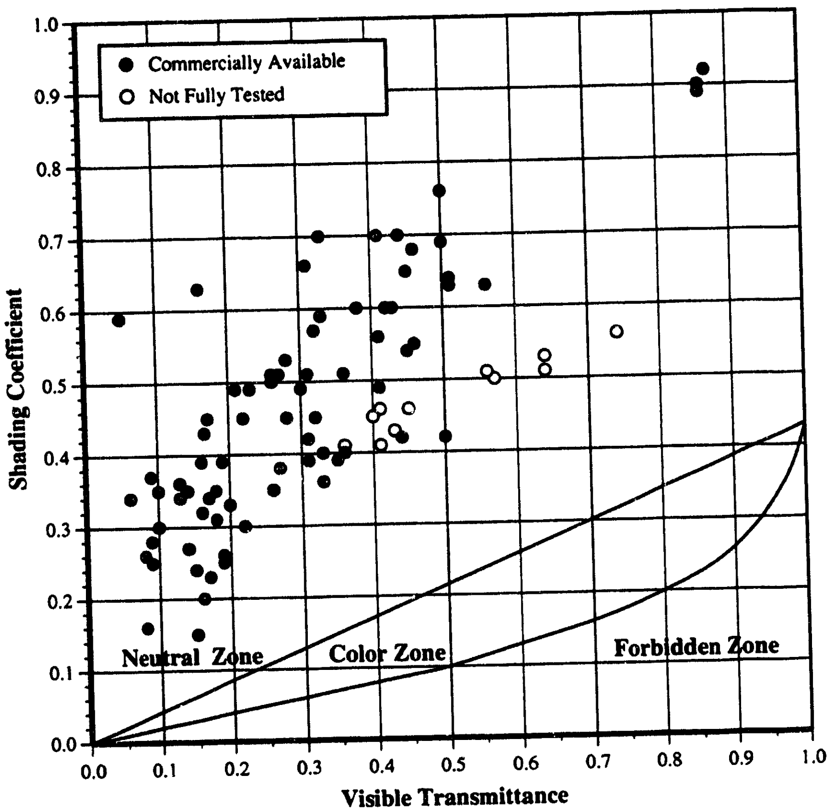

Figure 10. Spectral selectivity of coatings on plastic film that are laminated to clear or heat absorbing glazings. Open symbols represent new products that have not been fully tested.

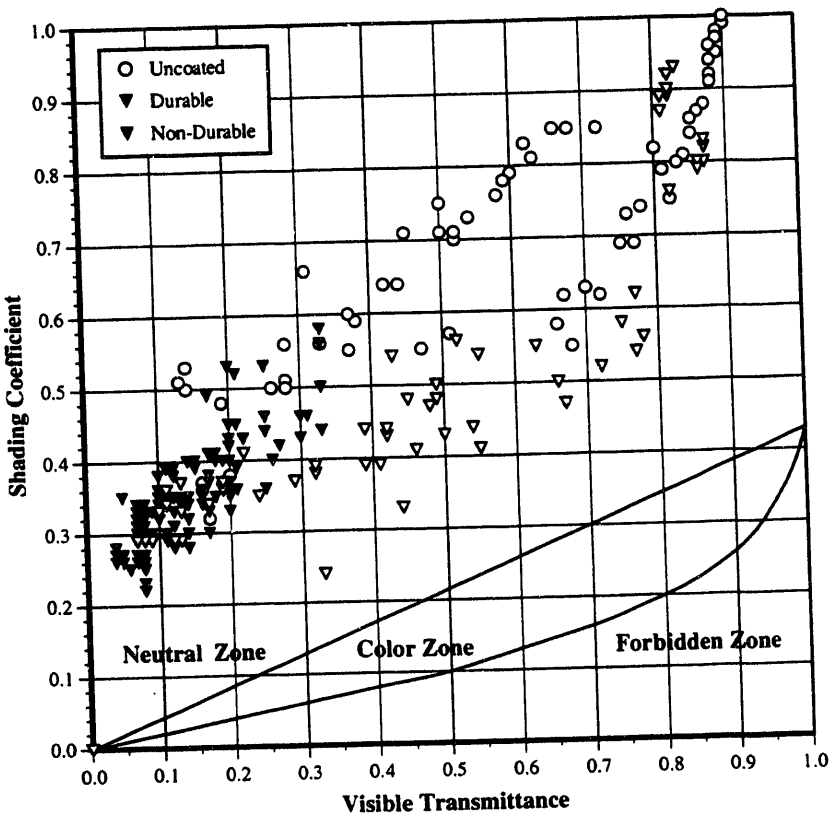

Figure 11. Spectral selectivity of commercial glazings and coatings applied to glass.

existence of a ready market. These manufacturers now perceive, however, that plastic laminates must catch up to their glass counterparts. Several glass companies have developed a new type of laminate coating that has spectral selectivity nearly equal to the best coatings on glass but with less durability outside a sealed environment.

Until cheaper alternatives to the currently available products are developed with higher transmission characteristics, spectrally selective glazings can be used cost-effectively for selected orientations and climates. Utility incentive or rebate programs should be designed to reconcile the disparity between the cost of the retrofit and the realized cost savings. Homeowners do not make buying decisions on energy savings alone. Amenities such as improved thermal comfort, reduced fading of interior furnishings, a more streamline window appearance, and glare control are only some of the reasons why the currently available and less than perfect products are widely used today. These real world qualitative benefits should be emphasized in marketing spectrally selective glazing products.

Several California utilities are beginning to offer incentives or rebates that will encourage the use of these technologies in residences. One California utility is considering a residential program that will offer shading coefficient incentives for *new* construction; e.g., for an SC between 0.51 and 0.65, there is a $1.00/ft^2·gl incentive; for an SC between 0.41 to 0.50, $2.00/ft^2; and for an SC less than 0.41, $4.00/ft^2. Other California utilities are offering similar incentives. These incentives are intended to help overcome the market barriers and may be effective in spurring adoption of these new technologies.

CONCLUSIONS

Based on the high proportion of existing residences built with clear single-glass windows and the results of our performance modeling, we conclude that there is a large potential to save energy in the cooling-dominated climates of California through the use of retrofitted spectrally selective glazings. These results can be summarized as follows:

1. For hot California climates, such as Blythe, a west-facing window retrofit with spectrally selective glazing (SC=0.5) will save a total of $2.00-$2.25/ft^2·gl·yr, increasing with area of glazing; south windows $1.00-$1.60, east windows $1.25-$1.40, and north windows $0.50-$0.60. For moderate climates such as Sacramento, however, a west-facing window will save $0.75-$1.25/ft^2·gl·yr; south windows $0.00-$0.80, east windows $0.00-$0.75, and north windows $0.00. Since orientation, window area in some cases, and exterior overhangs/awnings significantly impact energy savings, retrofit of west-facing windows, large area windows, and unshaded windows will normally be the most cost-effective solutions.

2. Cooling peak demand reductions for hot climates range from 41% for west-facing glazing (SC=1.0 to 0.5, 3.5% WFR) to 24% for north-, east-, and south-facing glazing. For moderate climates, reductions range from 43% to 33%. Total cooling peak demand reductions range from 17% in Blythe to 22% in Fresno (SC=1.0 to 0.5, 3.5% WFR all orientations).

3. Downsizing of HVAC chiller capacity due to reduced peak demand can result in added first-cost savings if the mechanical system is due for replacement. Utility programs could provide combined incentives to retrofit windows and upgrade air-conditioning systems at the same time. For hot and moderate climates, this can add-first cost savings of $3.11/ft^2·gl (SC=1.0 to 0.5, 3.5% WFR per orientation) or more for higher glazing areas.

4. To achieve the highest market penetration, spectrally selective glazing products must offer the highest glazing transparency with minimal coloration. Homeowners typically object to color distortion of the view outdoors, decreased interior daylight illuminance levels, a reflective or mirrored appearance of the glazing, and perceptible green/ blue glazing coloring for architectural or aesthetic reasons. Double-pane, insulating glass units that protect selective coatings and films from moisture and abrasion offer the best appearance and optical/ thermal properties. Replacing a window unit or the glazing and sash, however, can lead to long payback times, on the order of 10 to 20 years or longer depending on orientation. Glue-on films are the most cost-effective solution but their appearance, optical/ thermal properties, and in some cases durability, are inferior to those of the new IG options. Development of new materials and improvements in production equipment must be made before spectrally selective glazings can be fully adopted by the retrofit market. Additional work must be accomplished to test and demonstrate new products in the field.

5. Utility incentive and rebate programs can spur the adoption of existing spectrally selective glazing products by making them more cost-effective to the homeowner. These programs should be designed to incorporate differences in material and installation costs for the various retrofit options. These programs can also be designed to target hot climates, west orientations and/or orientations without exterior shading. Combining these incentives with air-conditioning system upgrades can further reduce simple payback periods.

Further work should be performed to investigate the impact of glazing conductance on energy savings. For the climate of California, the U-value of the glass had insignificant impact on total energy savings; for other climates, this effect may be larger. Demonstrations with utilities have been started for several homes in the Sacramento region to test durability and to verify energy savings under conditions of occupancy. Additional demonstrations may be useful in other regions of California.

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