Measured Cooling Load, Energy, and Peak Demand Savings from High-Performance Glass in a California Production House

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ABSTRACT

In the spring of 2000, two identical new homes were purchased from a local production builder in a bedroom community near Sacramento, California. Both homes came equipped with clear double glass. After a series of careful measurements to ensure the houses were really identical, all the glass in one home was replaced with high-performance, low solar gain, low-emmissivity (LSLE) glass. During July of 2001, the air-conditioning system in the house with LSLE was downsized by one ton (from 12.3 kW to 8.8 kW, or a 3.5 kW reduction) to demonstrate the real cooling load savings from the glass. The two unoccupied homes were kept comfortable and monitored with extensive hourly data for over a year to document the energy and peak demand savings from the high-efficiency glass. The house with LSLE glazing and reduced air-conditioning capacity met the cooling load and saved 25% of the cooling kWh and over one-third of the air-conditioning system peak demand (1.8 kW less) compared to the house with clear double glazing.

INTRODUCTION

Residential Air Conditioning

Air conditioning has become a standard feature of new homes built in the United States. A related trend is that new homes are increasingly being built in areas where air conditioning is necessary for summer comfort. As a result, residential air conditioning is one of the biggest contributors to peak electricity demand in many areas. Air conditioning consumes about 20% of the annual electricity used in houses built in the hot central valley of California (Wilcox 1995) but it is all used on hot summer days when residential and commercial air conditioning are the two largest contributors to the electricity peak demand. Figure 1 (Borenstein et al. 2002) shows daily peak demand during 2000 for the California Independent System Operator (ISO), which supplies 85% of the state's electricity. Each tooth in the graph is a week and each downward spike is a weekend. The bar in the center shows that residential and commercial air conditioning each contribute about 7 GW or about 30% of the additional demand above the annual base load. For this reason, measures that reduce residential peak cooling load and improve peak cooling efficiency are of great interest because they directly impact electricity peak load shortages and the need to build new power plants.

Low Solar, Low Emmissivity Glazing

Low solar, low emmissivity (LSLE) glazing can be defined by its performance in the following three areas:

1. It provides a window solar heat gain coefficient (SHGC) that is 0.40 or less.
2. It has a visible transmittance of 0.70 or greater (nearly as clear as regular glass).
3. It reduces window U-factor by 15% to 30% compared to clear double glazing in the same frame.

This performance is achieved by a thin film coating that selectively transmits and reflects different wavelengths of solar energy to reduce solar heat gain transmitted through windows without reducing visibility and daylight. The coating also has a low emmitance that provides the low window U-factor.

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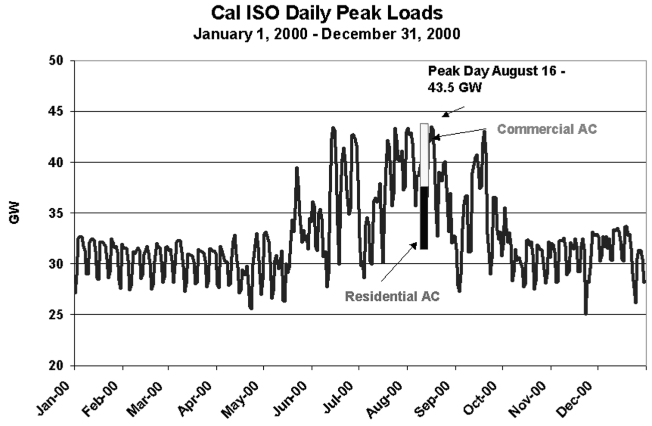

Figure 1 *Contribution of air conditioning to California peak electrical demand.*

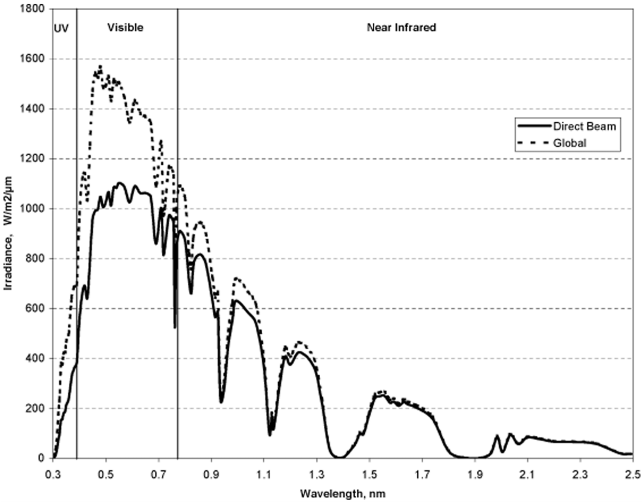

Figure 2 *Spectral irradiance of incident direct beam and global solar.*

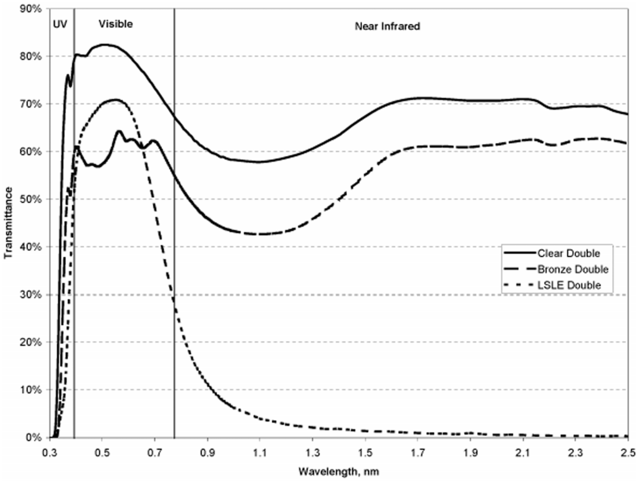

Figure 3 *Spectral transmittance of clear, tinted, and LSLE double glazing.*

Figure 2 shows the spectral distribution of incident direct and global radiation at the ground (ASTM 1987). About 35% of the energy in the global irradiance is in the near infrared wavelengths between 0.85 and 2.5 nm. Figure 3 shows the spectral transmittance at normal incidence for clear, tinted, and LSLE double glazing calculated by Optics5 (Arasteh et al. 1998). The LSLE glazing has a relatively high transmission in the visible region and a very low transmission in the near infrared region compared to the other two glazings.

ROSEVILLE EXPERIMENT

Roseville

Roseville is a bedroom community in California's central valley east of Sacramento (latitude 38.7, longitude 121.2, elevation 160 ft [49 m]). The central valley has hot, dry summers with clear sunny skies almost every day. The cooling design conditions for Roseville are summarized in Table 1. The mean daily range is defined as the difference between the average daily maximum and minimum outdoor dry-bulb temperatures during the hottest month. Roseville's large mean daily range means that nights are cool even during peak periods. With low night temperatures and outdoor relative humidity at peak conditions around 20%, cooling loads are typically dominated by daytime sensible solar and conduction gains.

Experimental Houses

The two houses were identical single-story 1854 ft^2 (172 m^2), two bedroom production homes located on the same block with identical orientation, colors, and solar exposure. Figure 4 shows the front of the house that faces east. The lots were selected to demonstrate performance in the most important and demanding orientation, with 58% of the glass in the rear facing west (Figure 5). This orientation is critical because production builders typically size air conditioning for a model in the worst orientation and install the same size air-conditioning unit in every instance of that model regardless of its orientation. As in many of California's current production homes, there were 10 ft (3.0 m) ceiling heights, R-13 (R-2.3) stud walls with synthetic stucco over R-4 (R-0.7) foam sheathing, and uninsulated slab-on-grade floors that were carpeted except in the bathroom and kitchen. Concrete tile roofs were installed over ventilated attics with R-38 (R-6.7) loose fill insulation. The air-conditioning systems featured 3.5 ton (12.3 kW), SEER 11 split-system air conditioners with air handlers and R-4 (R-0.7) flex ducts located in the attic. Figure 6 shows the floor plan of the house.

Table 1. Roseville Cooling Design Conditions: Design Values of Dry-Bulb (DB) with Mean Coincident Wet-Bulb Temperature (MCWB) (CEC 2003)

	Annual Percentage Values								Mean Daily Range
	0.1%		0.5%		1.0%		2.0%		
Units	DB	MCWB	DB	MCWB	DB	MCWB	DB	MCWB	
IP, F	105	71	102	70	100	70	96	68	36
SI, C	41	22	39	21	38	21	36	20	20

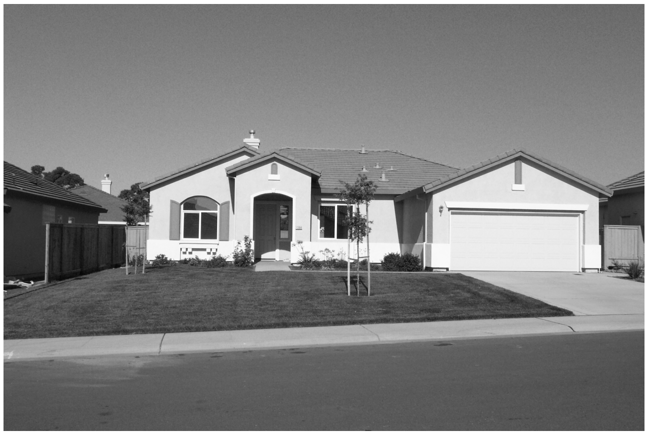

Figure 4 Front facing east.

Figure 5 Back facing west.

Commissioning

Particular care was taken during construction and commissioning to eliminate differences between the houses that would affect the comparison of the glazing.

1. An experienced construction supervisor conducted weekly inspections during construction and worked with the builder to achieve identical framing, insulation, and finishes.
2. Blower door tests verified that infiltration air leakage was low and both houses were within 2% of each other (3.95 air changes per hour at 50 Pa [ACH50] for the clear glass house and 4.02 ACH50 for the LSLE house).
3. Air-conditioning ducts in both houses were sealed using the aerosol sealant technique to achieve total duct leakage of less than 5% of air handler fan flow.
4. Air conditioner charge was checked and airflows were measured to make sure the systems were operating according to specifications.

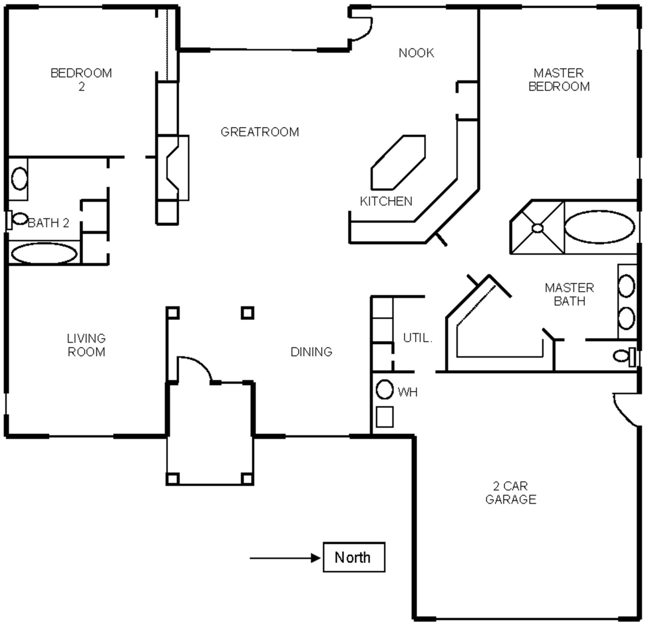

Figure 6 Plan.

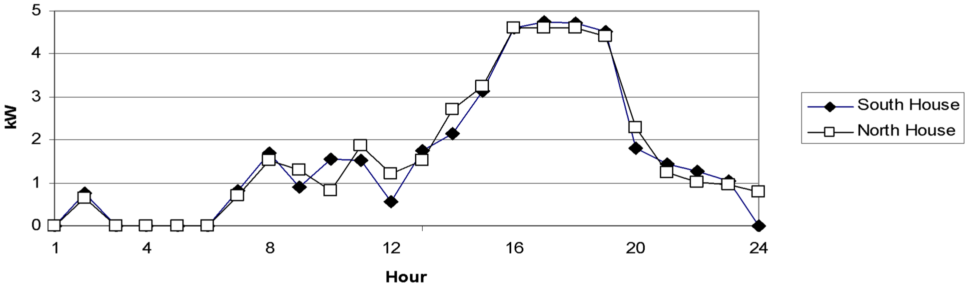

Figure 7 Cooling electricity consumption with clear double glass in both houses, August 15, 2000.

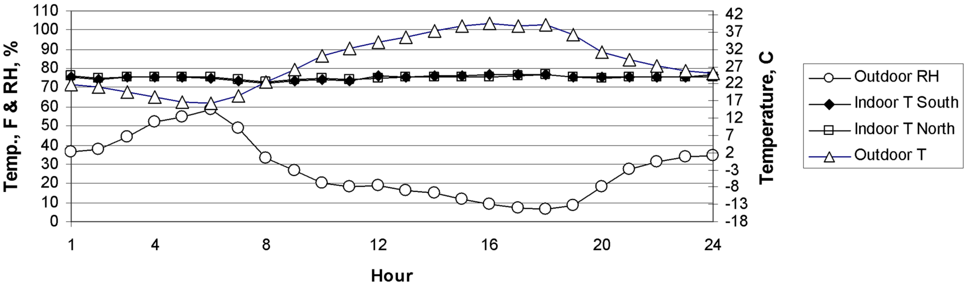

Figure 8 Temperatures and relative humidity August 15, 2000.

Table 2. Window Area by Façade

	North (Right)	East (Front)	South (Left)	West (Back)	Total
ft^2	36	63	35	186	320
m^2	3.3	5.9	3.3	17.3	30
% of total	11	20	11	58	

Table 3. Average Window Properties

Glazing	U-Factor, $Btu/ft^2 \cdot h \cdot °F$ ($W/m^2 \cdot K$)	Solar Heat Gain Coefficient (SHGC)	Visible Transmittance (VT) (Center of Glass)
Clear double (CLR)	0.49 (2.8)	0.65	0.81
Low solar low E (LSLE)	0.34 (1.9)	0.31	0.70

5. After commissioning all of the systems, with clear double glass in both houses, the cooling energy consumption of the two houses was within 1%, with the eventual clear glass house (south house) using slightly less cooling energy. Figure 7 shows hourly cooling electricity consumption (outdoor compressor plus indoor air handler fan) on a sunny, hot (103°F [39.6°C]) day with clear double glass in both houses. The air conditioners in both houses ran continuously for four hours (hour 16-19, 4-8 PM, PDT), maintaining both houses at the cooling setpoint. Figure 8 shows outdoor temperature (outdoor *T*) and relative humidity (outdoor RH) and the average indoor temperatures of each house (indoor T south and north).

Windows

The builders provided clear double-glazed windows in vinyl frames (CLR). Window area by orientation is shown in Table 2. Based on a coin flip, we selected one of the houses and replaced all of the glazing with LSLE glazing units in frames identical with the original units. Table 3 compares the two window systems as rated by the manufacturer according to the industry standard rating system (NFRC 2001). The NFRC procedure provides rated properties for windows of a standard size. We averaged the rated properties of the different operator types according to area. There was no interior shading in either house.

Experimental Operation

The unoccupied, unfurnished houses were operated to simulate normal residential occupancy. Variable occupant behavior in areas such as thermostat settings has been shown to significantly affect energy use in homes (Wilcox 1990a, 1990b), but these effects were not included in this study. Thermostats were set to maintain 68°F (20°C) for heating and 75°F (24°C) for cooling. There was a data logger in each house that recorded hourly temperatures and electricity and gas use for cooling and heating. The system also included a complete weather station with outdoor temperature, relative humidity, and wind and solar measurements. Electric heaters controlled by the data loggers simulated sensible heat generated by occupants using the California Energy Commission standard internal gain profile, which varies by hour and month. The total internal gain during the cooling periods reported here is shown in Table 4. There was no internal latent load and internal humidity was not monitored. Data were downloaded daily by telephone to remote computers for analysis and archiving.

RESULTS

First Summer

The glazing change was completed and the experiment started in September 2000 just in time to catch the end of the intense California central valley cooling season. Table 5 summarizes the data for the 50 days from September 6 through October 26, 2000. Daytime temperatures were regularly over

Table 4. Sensible Internal Gain Schedule

Hour	August		September		October	
	Btu	kWh	Btu	kWh	Btu	kWh
1	1009	0.296	1124	0.329	1227	0.360
2	925	0.271	1030	0.302	1125	0.330
3	883	0.259	984	0.288	1074	0.315
4	883	0.259	984	0.288	1074	0.315
5	883	0.259	984	0.288	1074	0.315
6	1094	0.320	1218	0.357	1330	0.390
7	1598	0.468	1780	0.522	1943	0.569
8	2482	0.727	2764	0.810	3017	0.884
9	2355	0.690	2623	0.769	2864	0.839
10	2524	0.739	2810	0.823	3068	0.899
11	2482	0.727	2764	0.810	3017	0.884
12	1935	0.567	2155	0.631	2352	0.689
13	1893	0.555	2108	0.618	2301	0.674
14	1262	0.370	1405	0.412	1534	0.450
15	1178	0.345	1311	0.384	1432	0.420
16	1304	0.382	1452	0.425	1585	0.465
17	2397	0.702	2670	0.782	2915	0.854
18	2692	0.789	2998	0.878	3273	0.959
19	2692	0.789	2998	0.878	3273	0.959
20	2187	0.641	2436	0.714	2659	0.779
21	2103	0.616	2342	0.686	2557	0.749
22	2313	0.678	2576	0.755	2813	0.824
23	1851	0.542	2061	0.604	2250	0.659
24	1136	0.333	1265	0.371	1381	0.405
Total	42060	12.323	46839	13.724	51141	14.984

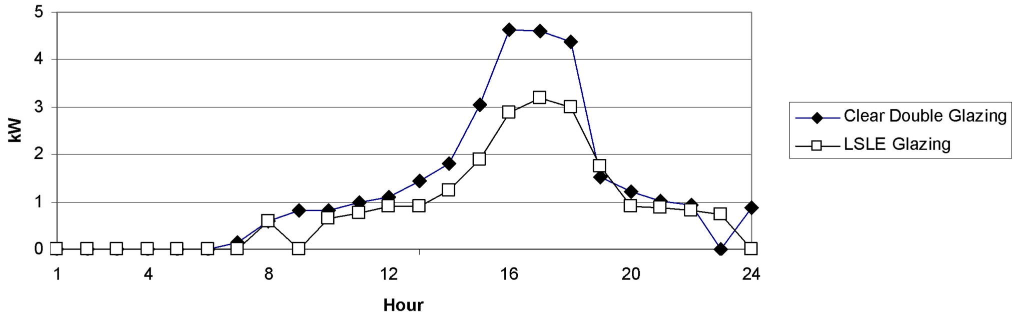

Figure 9 *Typical day cooling electricity consumption after glass change, September 15, 2000.*

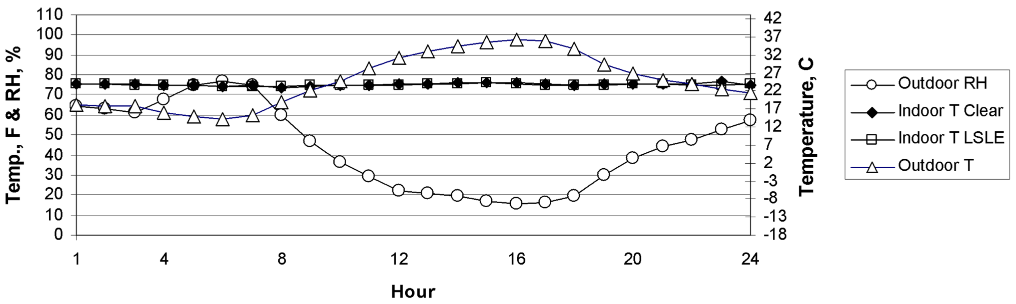

Figure 10 *Weather and indoor temperatures, September 15, 2000.*

Table 5. First Summer Results

	Glazing Type		Comparison
Conditions	CLR	LSLE	LSLE/CLR
Average Indoor Temp	74.4°F (23.6°C)	74.2°F (23.4°C)	
Maximum Indoor Temp	80.7°F (27.1°C)	78.8°F (26.0°C)	
AC Runtime, h	197	141	0.72
Energy			
AC Outdoor Unit, kWh	649	453	0.70
AC Air Handler, kWh	170	124	0.73
Total AC kWh	818	577	0.71
Demand			
Peak Outdoor Unit kW	4.02	3.86	0.96
Peak Air Handler kW	0.83	0.80	0.97
Peak Total AC kW	4.85	4.67	0.96

100°F (38°C), and the skies were clear almost every day. The average outdoor temperature was 75°F (24°C), with a maximum of 106°F (41°C). The average outdoor relative humidity was 33%, and the relative humidity at the maximum outdoor temperature was 14%. During this first year test period, the LSLE glazing saved 29% of the air-conditioning electricity used in the house with clear double glazing.

Figure 9 shows the hourly cooling electrical consumption on a sunny, moderately hot (maximum outdoor temperature 98°F [36.5°C]) day (see Figure 10) during the first year test

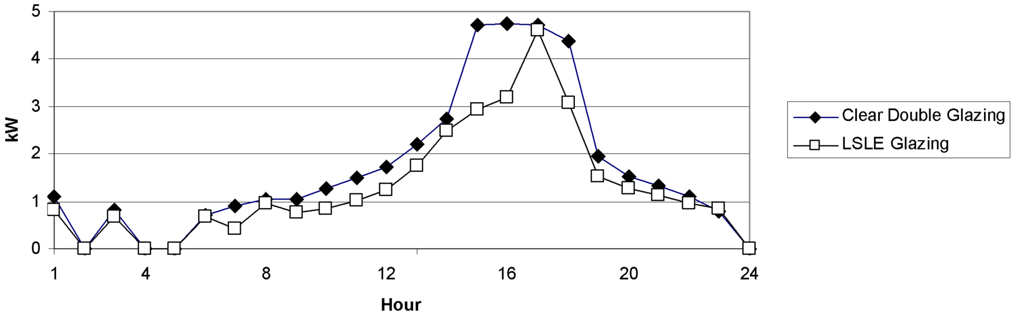

Figure 11 Peak day cooling electricity consumption after glass change, September 19, 2000.

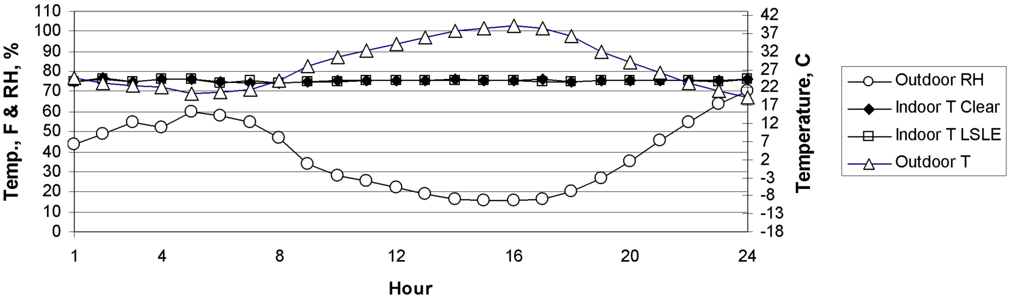

Figure 12 Weather and indoor temperatures, September 19, 2000.

period. The air conditioner in the house with clear double glazing runs full on for about three hours during the peak period. The identical air conditioner in the house with LSLE glazing cycles on and off throughout the peak period, running about 70% of the time.

Figure 11 shows the hourly cooling electrical consumption on a sunny, significantly hotter day that has a maximum temperature above the 1% cooling design temperature (maximum outdoor temperature 103°F [39.3°C]) (see Figure 12). The higher outdoor temperature increases the cooling load and reduces the cooling capacity of the air conditioners enough so that the unit in the LSLE house also runs full on for more than an hour. Although it is not visible in the figure, during this peak event, the average temperature in the clear double-glazing house floats up 1.2°F (0.65°C) higher than the average temperature in the LSLE house. The oversized air conditioner in the LSLE house allows it to maintain indoor comfort conditions at the setpoint with outdoor temperatures above the design conditions, but doing so eliminates the on-peak demand savings of the LSLE glazing.

Second Summer Downsizing

The experimental results during the first year showed that the LSLE glass significantly reduced the cooling load. The air conditioner in the LSLE house ran fewer hours and used less energy. For hours when the clear glass house air conditioner ran full on just meeting the load, the LSLE air conditioner ran about two-thirds of the time. Based on these data, we decided to install a smaller air conditioner in the LSLE house to demonstrate the reduced loads. In July of 2001, we replaced the air handler and outdoor unit of the low SHGC house with a similar 2.5 ton (8.8 kW) nominal system from the same manufacturer. It would have been ideal if the downsized system was identical to the original system in every way—just smaller—but, unfortunately, this was not possible due to several practical issues:

1. The cooling capacity of the new system as installed was less than we had expected and it therefore ran about 7% more hours than the system in the clear glass house.
2. Since we did not replace the ducts, they were oversized for the new smaller system and the losses from the extra surface area reduced the efficiency of the new smaller system slightly. The oversized ducts could have reduced static pressure and the fan energy for the new smaller system, but, as shown in Table 6, the relative fan energy of the LSLE house actually increased slightly after downsizing.
3. The peak demand of the smaller system was less than we had expected, probably related to the lower than expected capacity.

In spite of the reduced capacity and efficiency of the new downsized system, it maintained temperatures in the LSLE house that were slightly lower than those in the clear glass house, even at peak conditions, and demonstrated the load savings we expected.

Table 6 compares the results for 50 days of post-downsize data during August and September 2001. Both houses maintained indoor temperatures that, on average, were near the setpoint, with the LSLE house slightly cooler. The indoor temperature floated up in both houses during peak periods when the outdoor temperature was high, but the maximum temperature (in any single room) in the LSLE house was lower than the corresponding temperature in the clear glass house. The energy savings were about the same as the first summer, with the LSLE house using 27% less cooling electricity. The big change was in the electricity demand where the smaller air-conditioning system in the LSLE house used a maximum of 3 kW and saved 1.8 kW compared to the original system in the clear glass house.

Figure 13 shows the hourly cooling electrical consumption with the smaller air conditioner in the LSLE house on a sunny, very hot day that has a maximum temperature significantly above the 1% cooling design temperature (maximum outdoor temperature 106°F, 40.9°C) (see Figure 14). Both air conditioners run full on for several hours and the temperatures in both houses float up slightly, as would be expected with outdoor temperatures above design. However, the smaller air conditioner in the LSLE house maintains the indoor temperatures (average 1.6°F or 0.9°C above setpoint) better than the larger unit in the clear double-glazing house (average 2.2°F or 1.2°C above setpoint). This demonstrates that the 1 ton reduction in load was actually realized. With the downsized air conditioner, the LSLE house maintains equal comfort at peak conditions with a significant reduction in electrical demand.

SUMMARY AND DISCUSSION

The Roseville experiment shows that high-performance low solar heat gain glazing can provide significant cooling energy, cooling load, and cooling peak demand savings in typical production houses with badly oriented windows in hot sunbelt areas such as the California central valley.

Cooling Energy

Replacing clear double glass with LSLE glazing reduced the cooling load and saved 27% to 29% of the cooling system energy regardless of whether the system was downsized or not.

Cooling Load

Replacing clear double glass with LSLE glazing allowed the air conditioner to be downsized by 1 ton (3.5 kW) of rated cooling capacity while still meeting the cooling loads and providing equal or lower indoor temperatures. We believe the cost a builder saves by installing a smaller air conditioner will partially or fully offset the increased cost for the LSLE glazing.

Peak Demand

Replacing clear double glass with low SHGC glazing and downsizing the air conditioner will provide peak demand savings approximately proportional to the reduction in air conditioner capacity. At Roseville, the LSLE glazing saved over one-third (1.8 kW) of the air-conditioning electrical demand during the peak hour of the hottest day when it was 105°F (40.2°C) outdoors.

Future Work

A new experimental project is exploring heating and cooling performance of LSLE glazing in a climate with colder winters and humid summers.

Table 6. Second Summer Results

	Glazing Type		**Comparison**
Conditions	CLR	LSLE	LSLE/CLR
Average Indoor Temp	75.3°F (24.1°C)	75.0°F (23.9°C)	
Maximum Indoor Temp	82.6°F (28.1°C)	79.6°F (26.4°C)	
AC Runtime, h	329	353	1.07
Energy			
AC Outdoor Unit, kWh	1095	800	0.73
AC Air Handler, kWh	279	207	0.74
Total AC kWh	1374	1007	0.73
Demand			
Peak Outdoor Unit kW	4.0	2.48	0.62
Peak Air Handler kW	0.82	0.56	0.68
Peak Total AC kW	4.9	3.0	0.63

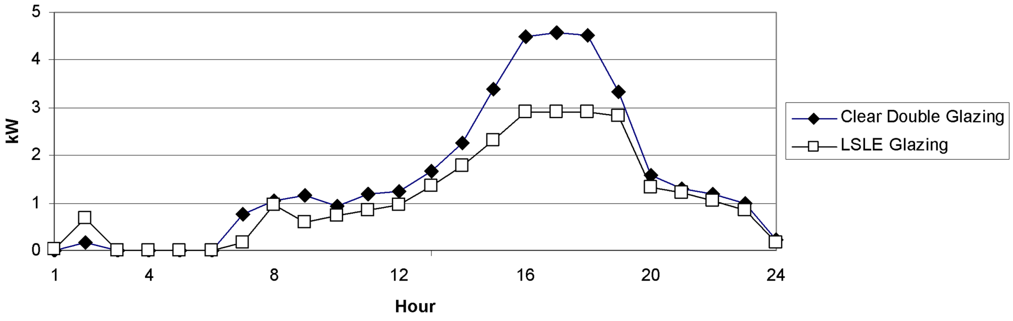

Figure 13 *Peak day cooling electricity consumption after downsizing in the LSLE house, August 16, 2001.*

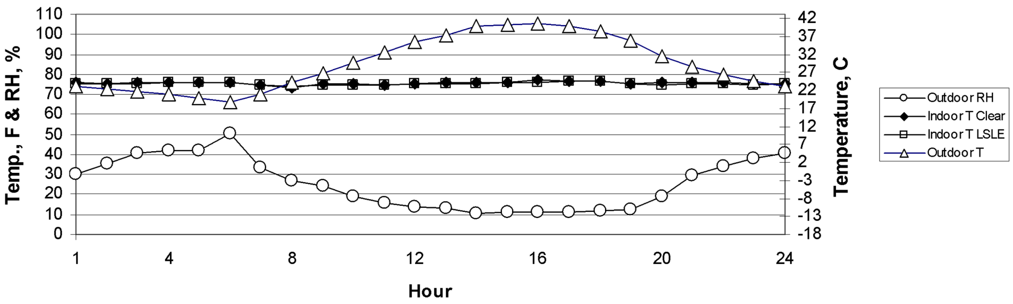

Figure 14 *Weather and indoor temperatures on August 16, 2001.*

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