Impacts of Shading and Glazing Combinations on Residential Energy Use in a Hot Dry Climate

Sara Farrar-Nagy, National Renewable Energy Laboratory
Paul Reeves, Partnership for Resource Conservation
C. E. Hancock
Ren Anderson, National Renewable Energy Laboratory

ABSTRACT

A residential building in Tucson, Arizona, was studied to evaluate opportunities for reducing cooling energy use in a hot dry climate. The reduction of solar heat gain was strongly influenced by spectrally selective windows, architectural shading, and site shading from adjacent buildings. The study emphasized accurately modeling these features to account for effects on the energy load. Building performance was modeled using a detailed hourly energy simulation tool and was measured while unoccupied for a period of 12 days. Model inputs included direct measurements of the net air exchange rate, surface reflectance, and window transmittance. Model results showed good agreement with the direct measurements of cooling loads and air-conditioning energy use. A parametric study of annual energy use is presented showing the impacts of glazing type, architectural shading, site shading, and building orientation. It is important to understand these interactions to optimize energy savings in community-scale housing developments.

Introduction

A prototype house was built in 1998 in Tucson, Arizona, as part of the Building America Program with an integrated package of energy-saving features. These features included structural insulated panels for the wall and roof construction, white coating on the roof, spectrally selective windows, architectural shading, interior location of air handler and ducts, high-efficiency air-conditioning equipment, and solar water heating. This study describes the modeling and testing procedures used to evaluate the prototype house and summarizes the relative impacts of several solar load control strategies.

The Building America Program is an industry-driven research program sponsored by the U.S. Department of Energy that applies systems engineering approaches to accelerate the development and adoption of advanced building energy technologies in new residential buildings. This program works with five building industry teams to produce advanced residential buildings on a community scale. The systems incorporated in these houses are evaluated by conducting successive design, test, redesign, and retest iterations until cost and performance trade-offs yield innovations that can be cost-effectively implemented in production-scale housing.

Analyzing the interactions between building performance and solar load control strategies in a prototype house will facilitate the optimization of cost and performance trade-offs in large-scale production. Since several hundred houses of this or similar designs will be built in a neighboring community, it is important to evaluate the impact of site shading on cooling loads and equipment sizing.

Objectives

The primary objective of this study is to evaluate the interactions of solar heat gain reduction measures that impact the energy use of a specific house design located in a hot dry climate. Another publication evaluated combinations of measures that effect solar heat gain in a generic house design (Carmody et al. 1996), but did not include impacts of shading by adjacent buildings. The secondary objective is to report on short-term, whole-building field test and modeling analysis procedures that are used to evaluate the system impacts of design changes on cooling energy use. These field test procedures build on previously developed techniques for measuring cooling load (Rudd et al. 1996) and evaluating energy use (Farrar et al. 1998).

Description of Building

The prototype house incorporates several re-engineered features in its structural and mechanical equipment systems. Envelope changes include a sealed, insulated, and conditioned crawlspace foundation (a shallow basement) and structural insulated panels (SIPs). The foundation stem walls are 6-inch-thick reinforced concrete, insulated on the interior with a 2-inch-thick rigid foam board of R-10 that serves as the concrete form. Each wall and roof panel consists of a polyurethane foam core sandwiched between 7/16-inch-thick oriented strand board (OSB) sheathing. SIPs with a 4.5-inch thickness are used for the walls and 6.5-inch-thick SIPs form the flat low-slope ceiling/roof assembly. The walls are finished using 0.5-inch-thick fiber cement board with synthetic stucco on the exterior and gypsum board with paint on the interior. The roof panels are finished with a white single-ply rubberized fabric coating on the exterior and gypsum board with paint on the interior (no attic space). The windows have vinyl frames with a thermal break, double panes, and spectrally selective coatings on surface two of the tinted glazing. Mechanical system features include air handler location in an interior chase, ductwork within the conditioned space, and a 12 seasonal energy efficiency ratio (SEER) air conditioner. A batch-type solar water heater preheats domestic hot water. The gas-fired water heater is coupled with an integrated hydronic space-heating coil in the air handler. The house has a controlled ventilation system consisting of a separate, single-speed and manual switch fan that supplies fresh air from the outside to the air handler return plenum. A detailed summary of the specifications of the prototype test house (Sain 1998) is provided in Table 1.

This ranch-style house is located in a high-density, single-family residential development. The architectural plan is approximately 1,170 square feet of floor area, including two bedrooms and two bathrooms. The house has 272 square feet of window area; four sliding glass doors facing a patio make-up about 80% of the total window area. The sliding glass doors are partially shaded by the patio cover that is 24 feet long, 6 feet wide, and 10 feet above ground level. The front entrance is a solid wood door. Another overhang on the front elevation of the house is an open horizontal trellis made of nominal 2-inch by 6-inch lumber; vegetation has been planted and is intended to grow over it. Prior to testing, the interior of the house was fully finished and landscaping was complete. Approximately 40% of the floor area was covered with ceramic tile and 60% covered with carpet. No interior window coverings were installed during the test period. A photograph of the front elevation is provided in Figure 1.

Table 1. Characteristics of the Test House

Characteristic	Specification	
Location	Tucson, Arizona	
Size	One-story, 1,170-sq. ft. floor area, 10-ft.-high ceiling	
Orientation	South (most of the window area faces east)	
Foundation	Shallow concrete basement, R-10 interior foam insulation	
Walls	4.5-in. SIPs: R-27 nominal, R-26 effective	
Roof	6.5-in. SIPs: R-41 nominal, R-37 effective	
Fenestration	Windows	Sliding Glass Doors
U-factor (center of glass):	0.296	0.345
SHGC:	0.32	0.50
Shading Coefficient:	0.37	0.57
Visible Trans.:	0.599	0.635
Glazing:	Double, low-e (surface 2)	Double, low-e (surface 2)
Frame:	Vinyl	Vinyl
Architectural Shading:		6-ft. overhang
Heating	Hydronic coil combined with DHW - natural gas, 65 kBtu/h input, 50 gal., 76% recovery efficiency Batch-type solar water preheat	
Cooling	2.5 tons, 12 SEER, 11 EER	
Ventilation	Supply fan with duct to return plenum, manual switch	
Air distribution		
Air handler location:	Interior (bulkhead/chase space)	
Supply ducts:	Interior, R-4 flexduct with high wall registers	
Return ducts:	Interior, one central high wall register at plenum, bedroom transfer grills	

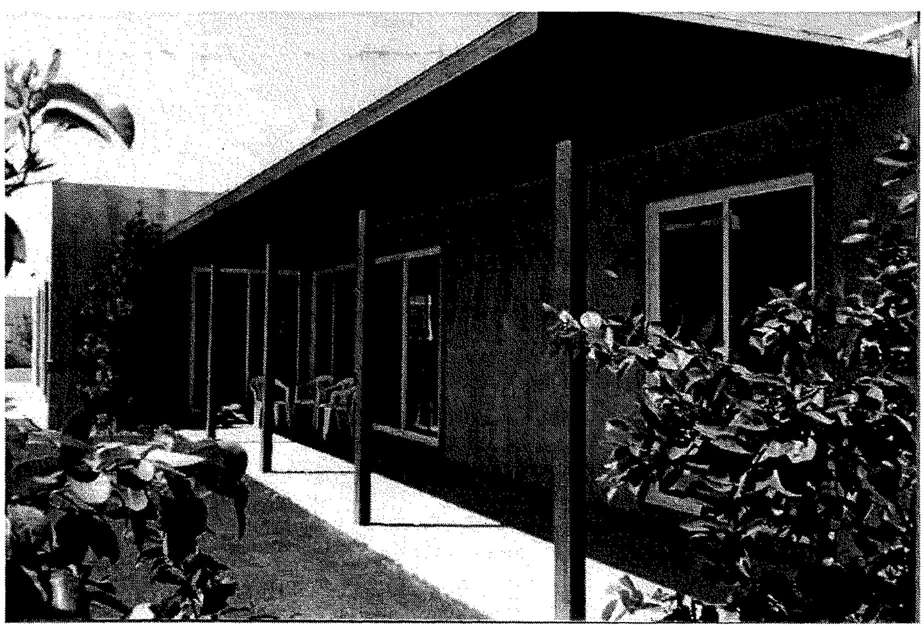


Figure 1. Photograph of the East Elevation of the Test House

Typical new production-scale houses in the Tucson market are framed on a slab-on-grade foundation with stucco exterior finish and a sloped concrete tile or flat built-up bituminous roof. These standard practice houses employ standard construction materials and techniques including nominal 2-inch by 4-inch wood framing, fiberglass batt insulation, 1-inch polystyrene sheathing, and double-pane, clear-glass, aluminum-frame windows. The slab foundation has no insulation, and the attic is usually vented. A forced-air distribution system provides space heating and cooling with the air handler located in the garage and flex duct in the attic. This system is typically supplied by a 10-SEER air conditioner and an 80% annual fuel utilization efficiency (AFUE) gas furnace.

Compared to standard construction practices, the prototype house has a well-insulated and air-tight envelope, spectrally selective windows, minimized air-distribution losses, high-efficiency air conditioning equipment, and solar water heating. This package of energy-saving features that minimize the energy demand, plus the large ratio of window to floor area in the design, cause window contributions to be relatively more important than in conventional housing, particularly in the Tucson climate.

Methodology

Building performance was modeled using a detailed hourly energy simulation tool (LBNL et al. 1998). One of the objectives of the simulation effort was to anticipate conditions for short-term testing. This information aided in designing an effective test protocol and in calibrating expectations for the measurement results. The building performance was then measured for nearly two weeks during unoccupied summer-time conditions. Measurements included environmental conditions, net air exchange rate, and electric power during normal operation of the building. In addition, cooling loads were measured using a "co-cooling" test protocol in which a six-zone, portable air-conditioning unit was substituted for the building's air conditioner. The modeled and measured results were compared, showing good agreement for cooling loads and air-conditioning energy use. The model was then used to evaluate annual energy usage and the impacts of alternative solar load control strategies over a broader range of conditions than could be measured in the field.

Description of Measurements

The thermal performance of the house was measured for a period of 12 days in July and August 1998. Environmental conditions, total and latent cooling load, and electricity used by the air conditioner were measured.

Thermal performance. A portable monitoring system was installed in the house. The monitoring system included a data logger with a 32-channel multiplexer and a 16-channel digital output module. The sensors installed at the house included a weather station that measured ambient dry-bulb temperature, relative humidity, wind speed, and horizontal and vertical solar radiation. The air temperature in each room and the crawlspace was measured using type-T thermocouples with the measuring junction mounted in a cylindrical radiation shield and positioned near the center of the room. Interior relative humidity was also measured in each room of the house. Total electric power was measured at the main service entrance using a Hall-effect watt transducer. Air conditioner compressor power was measured separately. The data logger was programmed to sample each channel (except for electric power) at 30-second intervals. The electric power transducers were sampled at 1-second intervals. All data were averaged over a period of 1 hour and stored in the data logger memory.

The primary measure of performance in these tests was the electricity used for air-conditioning. Hourly kilowatt-hours (kWh) were recorded. The hourly peak kW and daily total kWh were compared. The interior temperatures and humidity maintained by the air conditioning system were also measured. The thermostat setpoint temperature was 76°F.

Cooling load. To separate the performance of the shell measures and system measures, a completely independent cooling system was deployed during the cooling load test. The system (referred to as "co-cooling") is intended to provide a direct measurement of the cooling load without the system losses associated with the conventional air-conditioning system. The cooling load is defined in this case as the rate of heat removal required to maintain a constant and uniform interior air, dry bulb temperature. The direct measurement of cooling load of the shell of the building is useful in making direct evaluations of the performance of the shell components. It is also uniquely useful in calibrating a building performance simulation model with measured data.

The co-cooling system consists of a portable 5-ton capacity water chiller with its associated pumps and controls located outside the house, insulated water piping installed in a temporary opening, and a fan coil unit located inside the house. Cooled air was distributed from the fan coil unit to each room of the house by flexible ducts, which were temporarily installed across the floor. A separate fan was used for each duct so that a constant and uniform temperature was maintained as the load on each room changed throughout the test period. The total heat removed at the cooling coil was accurately determined by measuring the water flow rate and temperature difference across the coil. The water flow rate was set at a constant value and measured continuously using a turbine flow meter with an accuracy of ±1%. The temperature difference of the water was measured using a multi-junction type-T thermopile with an accuracy of ±0.02°C. The moisture removed was measured by metering the flow rate of condensate off the cooling coil. Measuring the heat flows on the liquid side of the coil is less complicated and has the potential for significantly better accuracy than attempting to measure the same heat flows on the air-side of the coil.

Infiltration/ventilation. Tracer gas decay tests were performed in the house to measure the net air exchange with outside air. Sulfur hexafluoride (SF_6) was injected periodically in the house, the gas concentration was measured by a photo-acoustic spectrometer, and the decay of concentration was used to calculate the net air-exchange rate expressed in ACH. A sample of four points around the house was mixed to measure an average concentration. The natural infiltration rate, the infiltration due to air handler operation, and the ventilation rate were measured. To better evaluate the other energy-efficient features of the prototype house, the ventilation system was disabled during most of the testing period. To measure the natural air-exchange rate, the co-cooling system was used to maintain constant interior temperatures without the building's air-handler fan and ducts. Infiltration and ventilation rate measurement results are shown in Table 2.

The house's air-distribution system airflow was measured using a flowhood with a 0-500 CFM range and back pressure compensation. The supply airflow is given in Table 2.

Window solar heat gain. A window treatment was applied to the house to create a limiting case of eliminating all solar gains through the windows. Opaque exterior shades were constructed to completely block all beam radiation from entering the windows. These shades were made using 0.75-inch thick sheets of foil-faced polyisocyanurate foam supported approximately 8 inches away from the exterior surface of each window. The shades were slightly larger than the dimensions of the windows to block most of the incident radiation. The 8-inch supports allowed airflow between the shade and the glass to minimize changes in window U-factor while blocking the solar gains. Comparing the performance of the house with and without shades indicates the maximum influence that window solar gains have on cooling energy use.

Transmittance/reflectance. Direct measurements of window transmittance and outside-surface reflectance were made to verify performance characteristics and input assumptions for the building energy simulation model. Transmittance and reflectance were measured using a spectroradiometer with a 350-2,500-nm spectral range and a 10-nm spectral resolution. Results for total normal solar transmittance for the windows and sliding glass doors are given in Table 2. Both types of windows had the same level of tint but had a different thickness and a different type of spectrally selective coating, resulting in different values for solar transmittance. Solar reflectance values for outside surfaces adjacent to the building are also shown in Table 2.

Table 2. Summary of Measurements

Measurement and Units		Result
Effective Leakage Area @ 4 Pa, sq. in.		46
Natural Infiltration (summer-time), ACH		0.05
Air Distribution (cooling mode)	Air Handler Fan Power, W:	320
	Total Supply Air Flow, CFM:	550
	Fan-Induced Infiltration, ACH:	0
Ventilation	Fan Power, W:	45
	Air Flow, CFM:	80
	Ventilation Rate, ACH:	0.45
Solar Normal Transmittance	Window:	0.28
	Sliding Glass Door:	0.36
Solar Reflectance	Fence (concrete blocks):	0.26
	Patio Floor (colored cement):	0.34
	Wall of Adjacent House (stucco finish):	0.42
	Wall of Prototype House (stucco finish):	0.43

Model Description

The simulation model input was initially based on construction documents supplied by the builder. An audit of the building led to a number of modifications to the simulation input. The following sections describe the modeling details for each building component.

Structure. The overall wall thermal resistance is modeled with an R-value of 26 °F-ft^2-hr/Btu, and the roof is modeled as R-37 (not including the outside film resistance). Six inches of the crawlspace walls are exposed to the above grade exterior, another 2.5 feet of crawlspace walls are modeled as being connected through 2 feet of dirt to ambient conditions. The crawlspace floor is modeled as mass only. The floor over the crawlspace is uninsulated and is covered with sub-flooring and either carpet or ceramic tile.

Windows and doors. The shading coefficient (SC) for the spectrally selective windows is 0.37 and the center-of-glass U-factor is 0.296 Btu/hr-ft^2-°F. The sliding glass doors are made with the same frames and a tempered, spectrally selective glazing that has a SC of 0.57 and a center-of-glass U-factor of 0.345. Total frame areas were determined for each fenestration size. For the evaluation of solar gain control trade-offs, simulations were also run using standard clear double glazing.

Building geometry and shading. The simulation model includes accurate building geometry to account for the effects of shading on windows and walls. The windows are all generally well shaded, either by overhangs or by the adjacent houses. The simulation model was imported into a three-dimensional graphic representation program that has rotational view capabilities (EPRI 1998) to check building geometry. Figure 2 shows the location of exterior walls, windows, doors, and overhangs. Crawlspace walls are evident in this view.

The front overhang is an open horizontal trellis with growing vegetation. An average transmittance of 50% is used to model this trellis. For the annual simulation, a lower transmittance value is used to account for the expanding vegetation. The side patio overhang is completely opaque.

The simulation for the testing period can mimic the measurement protocol and can also investigate design changes not practical during the short-term test. For example, the model is used to determine the effect of eliminating the architectural overhangs that shade the front and side porches.

Shading from adjacent houses is significant at this site. The geometry of houses and fences to the east and west are modeled as measured at the site. These shading surfaces are also shown in Figure 2.

Building equipment operation. The building model was used to simulate three different scenarios of building operation: co-cooling conditions, normal operation testing conditions, and occupied conditions.

The testing conditions, for both co-cooling and normal operation scenarios, include a constant thermostat setpoint of 76°F, minimal internal gains from appliances and people, no window management based on solar glare or solar gain (no opening and closing of shades), and low ventilation rate (ventilation fan turned off). For the co-cooling test, the equipment maintains a constant and uniform temperature throughout the house. For the normal operation test, the existing 2.5-ton air conditioning unit is used with the measured supply flow rates. In this case, the model controls the air-conditioning unit from a thermostat in the kitchen/dining room, and the temperatures of the front and back bedrooms are allowed to float.

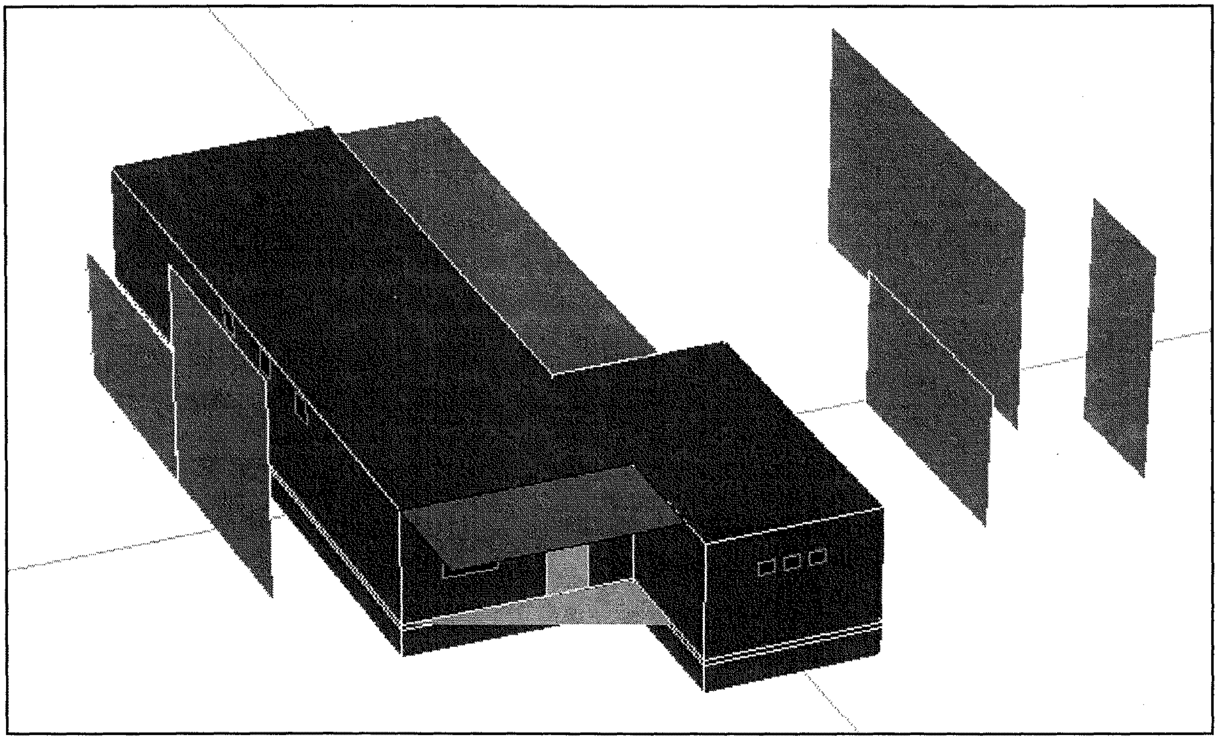


Figure 2. Building Geometry, View from Southwest with Overhangs and Site Shading

The occupied conditions include occupant effects in the prediction of annual energy use. People are added to the space with a varying schedule of when they are home. The occupants are assumed to use internal blinds and to open windows if the outdoor air temperature is above 68°F and cooler than the indoor temperature. Internal gains including lights, appliances, and cooking are added to the space. The ventilation fan is assumed to be on at all times with an air-exchange rate of 0.45 ACH (as installed). The cooling system is sized as the 2.5-ton unit that is standard with this house.

The measured supply airflow rates were used to compare the measured versus simulated test conditions. The measured total supply flow rate is 550 CFM, significantly below the design flow rate. For the annual simulations, the supply flow rates are increased to the design total of 1,000 CFM, providing better temperature control when the cooling loads are increased. Adjustments were made the overall system efficiency to account for this difference in airflow.

Comparison of Modeled and Measured Results

Once the data were collected, predictions from the simulation model were compared to the measured data to investigate the accuracy of the simulation model and the validity of the annual predictions. The comparison of measured and simulated cooling load and equipment electricity use led to revisions in the simulation model. Most notably, it became clear that it was important to accurately model site shading and window characteristics.

To compare the measured and simulated data, a weather file was created using the measured values of global solar radiation, outdoor temperature, and relative humidity. A correlation (Perez et al. 1992) was used to determine the direct normal radiation based on the global radiation and the relative humidity. The weather data file used by the simulation (TMY2 weather file for Tucson) was modified for the period July 31 through August 12 with the actual temperature, solar, and humidity data.

The simulated cooling load for two days of the co-cooling period are shown in Figure 3 along with the cooling load determined from the co-cooling test. The magnitude and the shape of the measured cooling load profile are very similar in the simulation results. The peak and minimum loads match to within a few percent. The time period shown on this and following graphs is from 6 a.m. to 6 a.m., which we define as the beginning and end of a "test day." The test day begins when the cooling load is at its minimum and when the effects of the previous day's test protocol have dissipated.

The monitored electricity use of the house air-conditioning system provided another opportunity to check the predictive capability of the simulation model. A comparison of the air-conditioning equipment electric use as measured during the field test and as simulated offers significant insight since the monitored period includes both normal operation and a two-day period with the opaque exterior shades installed. If the model predicts actual cooling equipment use during the two periods, it provides high confidence that the model properly accounts for the fenestration solar gains. The cooling equipment electric power for the testing periods with normal operation and with opaque exterior shades are shown in Figure 4, along with simulation results for the same conditions. The simulation matches measured trends very well, with an RMS error of less than 20 watts.

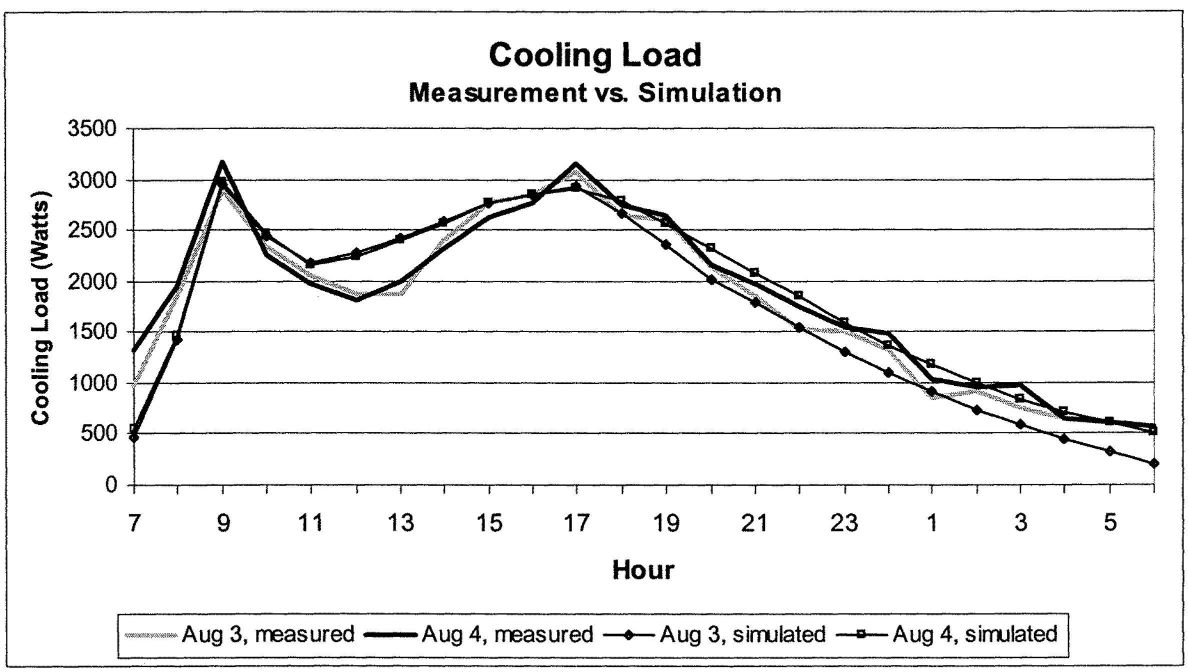


Figure 3. Daily Profiles of Cooling Load for Measured and Simulated Results

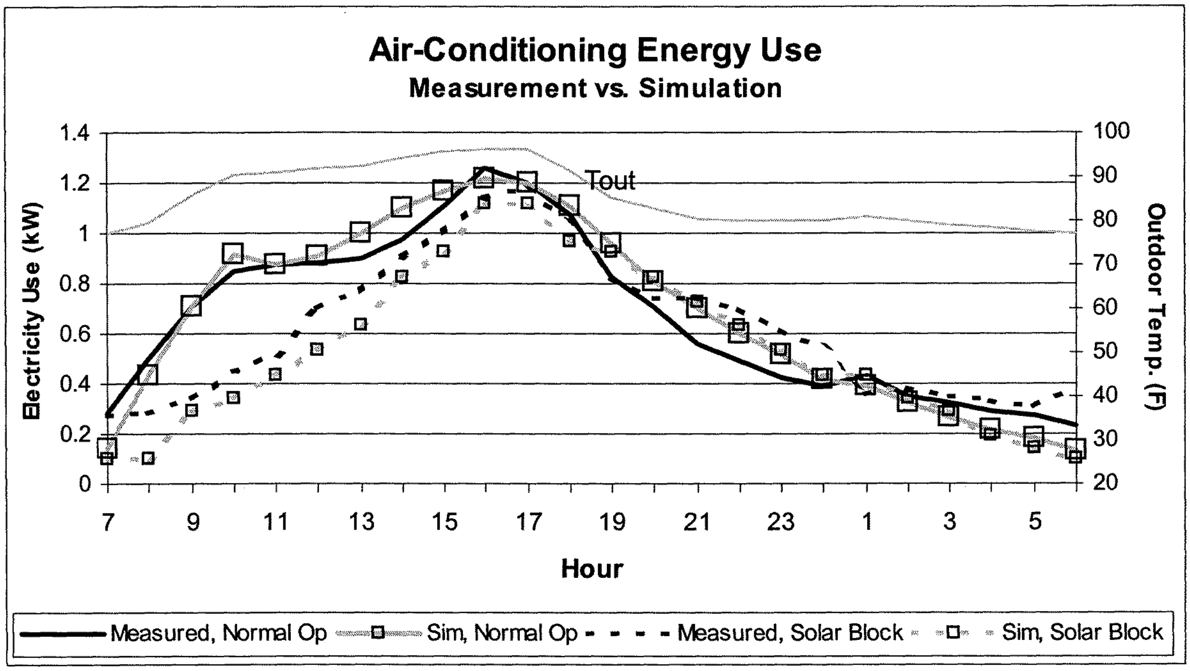


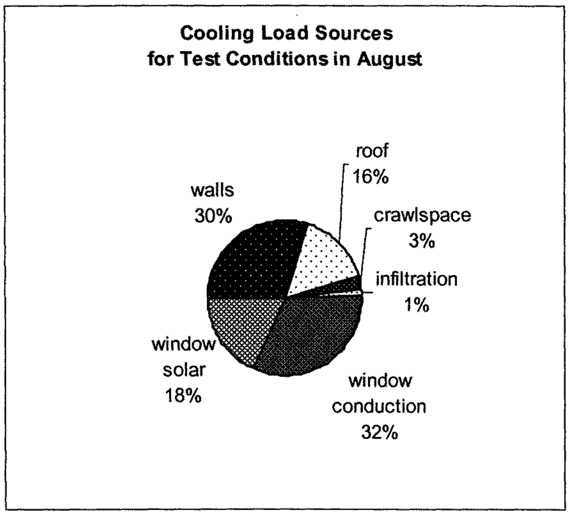
Figure 4. Daily Profiles of Air-Conditioning Energy Use for Measured and Simulated Results

Results

For the determination of annual heating and cooling energy, occupied building operation is simulated instead of the testing conditions used for all the previous simulations. The simulation of occupied conditions in this building for a full year predicts that 3,285 kWh of cooling energy and 71 therms of heating energy is required per year. Heat gain through the windows is the largest component of envelope load and more than 30% of the total cooling energy load as shown in Figures 5 and 6.

Effects of Glazing and Shading

Figure 7 presents the daily load profiles of air-conditioning electricity use on a typical cooling day for four combinations of glazing and shading. These combinations are: (1) standard glazing without shading, (2) spectrally selective glazing without shading, (3) standard glazing with shading, and (4) spectrally selective glazing with shading. In this case, the shading includes both the architectural overhangs and the site-shading from adjacent buildings. Standard glazing without shading represents the worst case and spectrally selective glazing with shading (the existing building) is the best case. The combination of high-performance glazing and shading achieves a 0.4 kW (14%) reduction in afternoon peak electricity demand and a 12.4 kWh (30%) reduction in daily total electricity used for air conditioning. Architectural and site shading has a greater impact on reducing daily cooling use than upgrading the windows. The shading combination reduces daily cooling energy use by 9.4 kWh (22%) while the reduction due to only upgrading the windows is 4.4 kWh (11%).



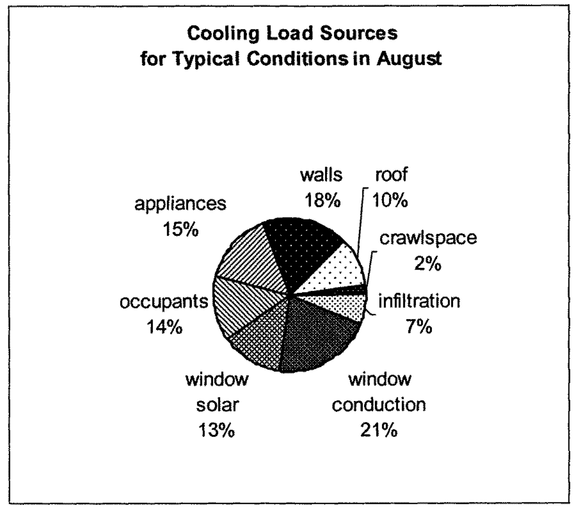


Figure 5. Cooling Load Sources under Unoccupied Test Conditions in August

Figure 6. Cooling Load Sources under Simulated Occupied Conditions in August

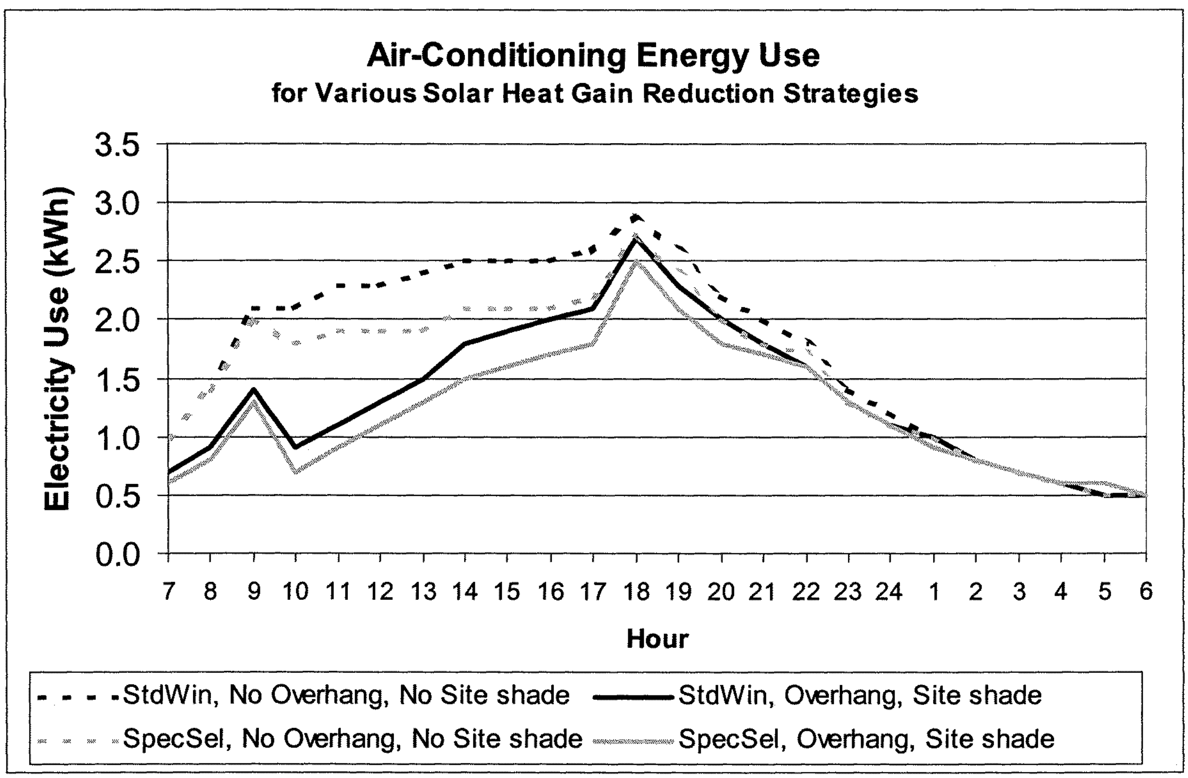


Figure 7. Daily Load Profiles Comparing Standard Windows (StdWin) with and without Shading, and Spectrally-Selective Windows (SpecSel) with and without Shading

Architectural shading is clearly a very important feature in reducing cooling loads. Architectural shading reduces the annual cooling requirement by approximately 23%, whether starting with standard double-pane glazing or the spectrally selective glazing. In both of these cases, there is an increase in the heating load as the solar gain is reduced, but the combination of the Tucson climate and the well-insulated tight building shell cause this to be a small impact. The worst case scenario shows less than 80 therms/year of space heating required.

In this housing development, site shading plays an important role in reducing morning and evening direct solar gain. The test house is shaded to the east and west by adjacent, two-story houses. This site shading not only reduces the solar gain through the windows, but effectively shades much of the exterior wall area, reducing overall conductive gains as well. Table 3 shows how much annual cooling energy savings would be over-predicted if site shading were not taken into account. Depending on the combination of glazing type, overhang, and orientation, the range of over-stating energy savings without site shading would be 6%–24%.

Table 3. Over-Estimate of Annual Cooling Energy by Not Including Site Shading

Building Configuration		Front Orientation			
Window Type	Architectural Shade	North	East	South	West
Standard	No Overhang	18%	8%	18%	6%
Standard	Overhang	24%	9%	23%	9%
Spectrally Selective	No Overhang	17%	7%	16%	6%
Spectrally Selective	Overhang	22%	7%	20%	7%

Annual Energy Costs

The cooling and heating loads are combined into a single value by converting the energy requirements to costs. Electricity costs $0.105/kWh, and natural gas costs $0.79/therm for the first 20 therms/month and $0.75/therm above that. Figure 8 shows annual cooling and heating costs as a function of glazing type, two types of shading, and orientation of the front of the house. Using the data from this figure and referencing a base case building with standard windows with no overhangs but with adjacent buildings, Table 4 presents the reduction in cooling and heating costs for a subset of combinations.

The existing building has a south orientation, and the combined features lead to a 26% reduction in the cooling and heating costs. The total cost of cooling and heating is reduced by more than 10% by adding the presence of the adjacent houses. As expected, the maximum effect from architectural shading occurs if the front of the house faces west, which orients most of the window area to the south. The maximum effect of site shading occurs if the front of the house faces north, which orients most of the window area to the west. With the front of the house facing east, the majority of windows are on the north side of the house, and both architectural and site shading have very little effect on cooling and heating costs.

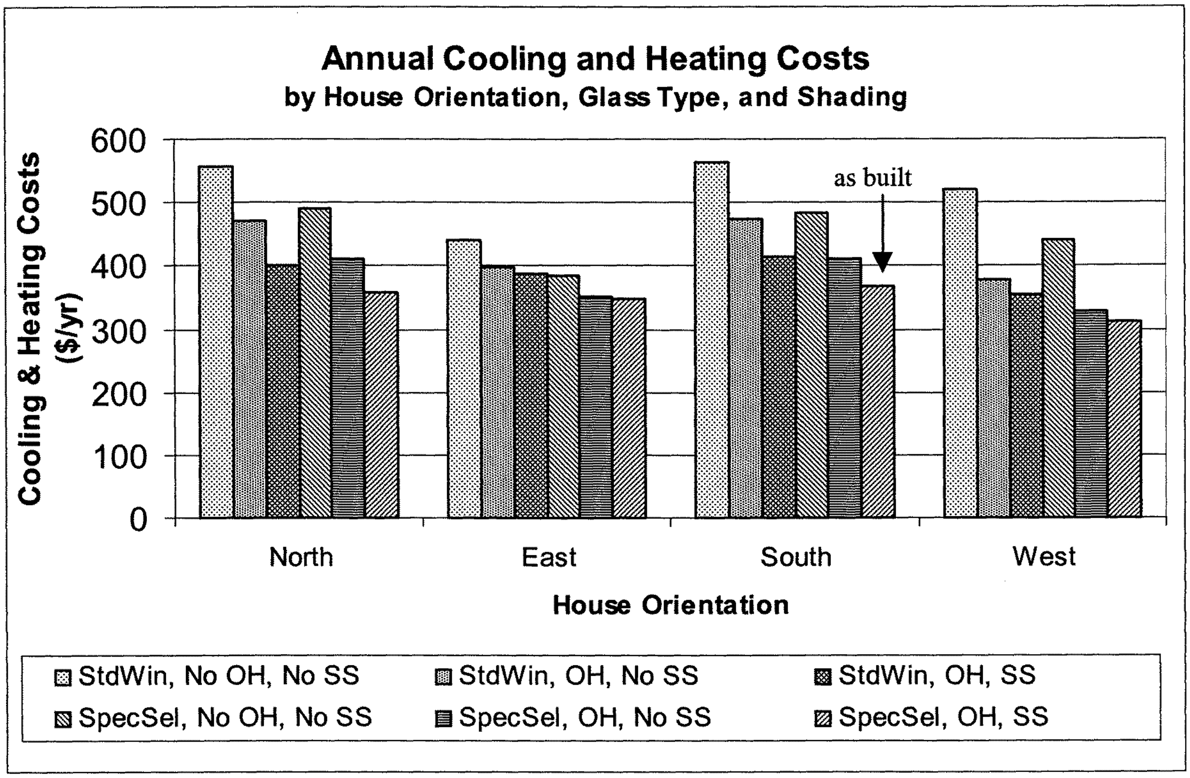


Figure 8. Annual Cooling and Heating Costs by Orientation, Glass Type (StdWin = standard glazing, SpecSel = spectrally-selective), Overhangs (OH), & Site Shading (SS)

Table 4. Reduction in Cooling and Heating Costs*

Solar Load Control Strategy	Front Orientation			
	North	East	South	West
Overhang	18%	10%	17%	28%
SpecSel	12%	12%	13%	14%
SpecSel + Overhang	27%	19%	26%	37%

* Base case is standard glass with site shading.

Conclusions

The primary objective was to evaluate the interactions of solar heat gain reduction measures that impact the energy use in a hot dry climate. A complementary combination of modeling and measurement techniques was applied to evaluate the interactions of features in a prototype house.

The detailed hourly energy simulation proved to be a useful tool for planning the on-site testing protocol. In particular, the predicted hourly profiles focused attention on measuring interactive effects of windows and architectural shading. Testing results provided direct inputs to the model and gave strong confidence in the model predictions for the house as built. Various system responses were verified and daily load profiles matched. This process highlighted the impact of site shading by adjacent buildings. The "calibrated" model was then used to extrapolate the test results to annual energy and a parametric comparison.

The model predicted 3,285 kWh of cooling energy and 71 therms of heating energy required per year. Heat gain through the windows is the largest component of envelope load and more than 30% of the total cooling energy load. The combination of high-performance glazing and shading achieves 0.4 kW (14%) reduction in peak electric demand and 12.4 kWh (30%) reduction in daily cooling energy, compared to the same house with standard double-pane windows and no shading. Architectural shading reduces the annual cooling requirement by approximately 23%, whether starting with standard glazing or spectrally selective glazing. Architectural and site shading has a greater impact on reducing daily cooling use than upgrading the windows. Site shading plays an important role in reducing morning and evening direct solar gain. Depending on the combination of glazing type, overhang and orientation, the predicted energy savings could easily be more than 20% too high.

Acknowledgments

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