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Environmental Energy Technologies Division

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Abstract

In summer of 1992, we monitored peak power and cooling energy savings from shade trees in two houses in Sacramento, CA. The collected data include air-conditioning electricity use, indoor and outdoor dry bulb temperatures and humidities, roof and ceiling surface temperatures, inside and outside wall temperatures, insolation, and wind speed and direction. Shade trees at the two monitored houses yielded seasonal cooling energy savings of 30%, corresponding to an average daily savings of 3.6 and 4.8 kWh/d. Peak demand savings for the same houses were 0.6 and 0.8 kW (about 27% savings in one house and 42% in the other). The monitored houses were modeled with the DOE-2.1E simulation program. The simulation results underestimated the cooling energy savings and peak power reductions by as much as twofold.

Keywords: Peak power savings; Cooling energy savings; Shade trees; California

1. Introduction

Increasing urban vegetation holds great potential for reducing urban summertime air temperatures and saving cooling energy use in buildings. Our prototypical building simulations for a few cooling dominant cities show that shading homes with trees can save over 30% of residential peak cooling demand on a hot summer day. However, some important consequences of tree shading related to actual building operation and both macro- and microclimate variations are not easy to evaluate using simulations alone. Therefore, in order to understand the realistic savings potential of shade trees, it is necessary to carry out field experiments to identify unforeseen implementation problems, and to measure and document actual savings.

Data on measured energy savings from urban trees are scarce. In one experiment, Parker [1] measured the cooling energy consumption of a temporary building in Florida before and after adding trees and shrubs, and found cooling electricity savings of up to 50%. In another study, mobile homes were used to measure the windbreaking effects of trees on energy use [2]. In a follow-up experiment, Heisler [3] measured the effect of trees on wind and solar radiation in a residential neighborhood. Huang et al. [4] used the data provided by Heisler and simulated the impact of shading and wind reduction on residential buildings heating and cooling energy use. Their simulations indicated that a reduction in infiltration because of trees would save heating energy use. However, the impact on cooling is fairly small compared to shading effects of trees and depending on climate it could save or increase cooling energy use.

This study has focused only on the impact of trees on cooling energy use. The paper summarizes a recent effort to (i) document energy savings from shade trees by instrumenting and monitoring air-conditioning energy use in a few houses in Sacramento and (ii) compare simulation results with monitored data. This project was designed as a collaborative effort between the Sacramento Municipal Utility District (SMUD) and Lawrence Berkeley Laboratory (LBL). The project design, data collection, and data analysis were performed by LBL, while SMUD supplied and installed the monitoring equipment.

2. Experimental design and data handling

We identified two houses and developed a detailed experiment design protocol for each of the sites. These houses (T1 and T2) are described in Table 1. At these sites, our objective was to shade directly south and west facing walls and windows, and the air conditioner condenser unit. Sixteen trees, eight tall (~ 6 m) and eight short (~ 2.4 m), were first placed on the southeast corner, along the southeast wall, and at the southwest corner of Site T2. The tall trees included 1 Chinese hackberry, 1 Chinese flametree, 2 raywood ashes, 4 tulip trees; the short trees were 8 eastern redbud. The trees were placed around the house in their original wooden containers and were regularly watered during the experiment. Later, these trees were moved to Site T1, and aligned along the west

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Table 1
Characteristics of the monitored houses

	Site T1 [a]	Site T2 [a]
Building description		
Floor area [b] (m^2)	135	84
Perimeter length (m)	58	44
Exterior wall height (m)	2.6	2.4
Age (y)	10	8
No. of stories	1	1
Roof material	composite shake	composite shingle
Roof albedo	0.16, medium brown	0.16, medium brown
Roof insulation	R-19	R-19
Ceiling construction	attic	attic and vaulted
Wall material	stucco	stucco
Wall albedo and color	0.45, off-white	0.30, tan
Wall insulation	R-11	R-11
Windows	2-pane	2-pane
Foundation	slab	slab
Internal load [c] (kWh/d)	22.5	16.0
Air conditioner	central (38.0 MJ/h, COP 2.77)	heat pump (25.3 MJ/h, COP 2.1)
Heater	gas furnace (44.3 MJ/h, eff. 0.70)	heat pump (22.2 MJ/h, COP 3.1)
Air flow ($m^3 s^{-1}$)	0.57	0.38
Duct locations	ceiling	ceiling
Thermostat setting		
Heating (°C)	20.0	21.1
Cooling (°C)	25.6	27.8

[a] Appear as Site C and D in Akbari et al. [6].
[b] Excluding garage.
[c] Internal loads include heat gain from all household appliances such as refrigerator, washer and dryer, oven, etc. as well as heat from occupants.

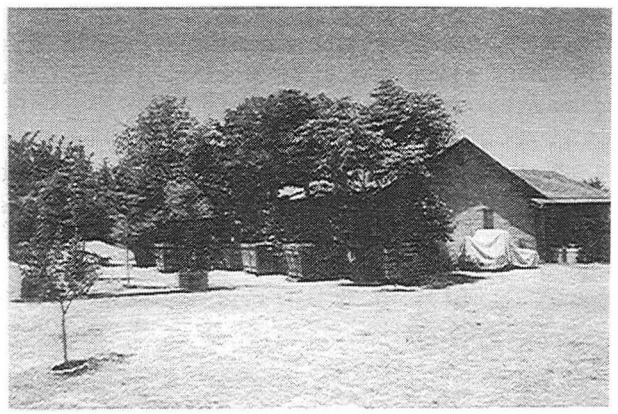

Fig. 1. Picture of Site T_1 after trees were planted on the west and south sides.

and south walls. Fig. 1 shows Site T1 after the trees were placed on its west and south side.

During the first monitoring period, from June 8 to August 3, both houses were in the base case, unshaded condition. During the second monitoring period, between August 4 and August 31, trees were placed at Site T2. Before the third monitoring period, from September 1 to October 14, the trees at Site T2 were removed, and placed around Site T1. This schedule is summarized in Table 2.

To isolate the effect of the modifications on cooling energy use, standard building operating procedures were devised. We requested from the occupants that (i) windows be closed at all times, (ii) thermostat settings be identical and invariant, and (iii) lights be turned on and off in a consistent, similar, and predictable fashion.

2.1. Measured data

At both sites, we measured indoor and outdoor temperatures, indoor and outdoor humidities, wind speed and wind direction (at 1 m above roof level), roof and ceiling temperatures, outside and inside wall temperatures, horizontal inso-

Table 2
Monitoring schedule and number of days suitable for analysis in the 1992 monitoring season

Monitoring period	Dates	Condition		Monitoring days	Days suitable for analysis	
		Site T1	Site T2		Site T1	Site T2
First	6/8–8/3	Unshaded	Unshaded	57	28	36
Second	8/4–8/31	Unshaded	Shaded	28	27	28
Third	9/1–10/14	Shaded	Unshaded	44	41	44

lation, air-conditioning cooling energy use [1]. In addition, at Site T2, we measured insolation on walls and made measurements of ceiling and roof temperatures at two locations. Measurements were made every 20 min with automated sensors and a data logger. The equipment used and the procedures employed to convert and calibrate the data obtained are described in detail in Refs. [5,6].

Both exterior surface temperature and interior air temperature measurements were examined to assess their validity. We measured surface temperature by adhering a thermocouple to the desired surface from the outside with plastic tape. This approach was flawed because of the weathering effect on the measuring system. This resulted in degradation of the contact between the thermocouple and the surface, so that sensors may actually be recording the temperature of an air bubble separating the thermocouple from the building surface. These effects placed our surface temperature measurements in doubt. We compared the external wall surface temperatures measured in this experiment with calculated sol–air temperatures for sunny days during the monitoring period. Within an acceptable deviation, the surface temperatures calculated and measured agreed well at both sites.

Indoor air temperatures were measured by a thermometer six inches below the ceiling, protected from sunlight reaching into the house through windows. The placement of these sensors caused a systematic bias in the readings. For example, in mid-summer at Site T2, indoor air temperature measurements continued to rise even after air conditioning kicked in and return duct air temperatures began to fall. This was caused by the strong influence of the high ceiling temperatures on the indoor air measurements. Later in the summer, ceiling temperatures were lower (because of less sunlight on roof) and their influence on indoor air temperature measurement was smaller.

3. Analysis of measured data

The monitoring season spanned 129 days. In our analysis, we considered only days with complete data coverage. This left 96 useful days at T1 (55 unshaded, 41 shaded) and 108 days at T2 (80 unshaded, 28 shaded) (see Table 2).

The analysis of data collected at these two sites addressed the following questions:

(i) What are the energy savings when a previously unshaded site is shaded with trees?

(ii) How do the thermophysical properties and microclimate of the house change to achieve those savings?

Because the climatic conditions before and after the tree plantings were different, some correlator was needed so that different periods could be compared. Two types of correlation were employed. One used the climate data collected during the monitoring and compared the dependence of cooling energy use on various forcing factors. However, since these forcing factors were themselves strongly correlated and hard to separate (e.g., outside temperature and insolation), a second, fruitful method of analysis involved parallel comparisons of simultaneous conditions at the two sites. In this manner, all forcing factors were combined.

3.1. Measurements of cooling energy savings by parallel comparison

Fig. 2 shows the daily cooling energy use at Site T2 plotted against the daily cooling energy use on corresponding days at Site T1. The squares represent measurements taken during the first monitoring period, when both houses were in the base condition. The solid line gives the linear least-squares fit to those points. The diamonds and dashed line represent data and their linear regression fit for the second period, when the trees shaded Site T2. These points are shifted to the left of those from the first period, indicating that the cooling energy at Site T2 had been reduced. Likewise, the triangles and the dotted regression line, which represent data measured during the third monitoring period, when Site T1 was shaded, are shifted downward from the base case line, indicating a reduction in cooling energy use at Site T1.

The shift from the base case regression line was quantified to measure the energy savings achieved during the shaded period at each site. For example, the savings at Site T2 were calculated by first finding the best linear expression for the cooling energy use at Site T2, as a function of the cooling energy use at Site T1, when both were in the base condition. For days in the second monitoring period, the cooling energy use at Site T2, in its base case, is estimated using the linear fit. The error in our prediction was estimated as the error in

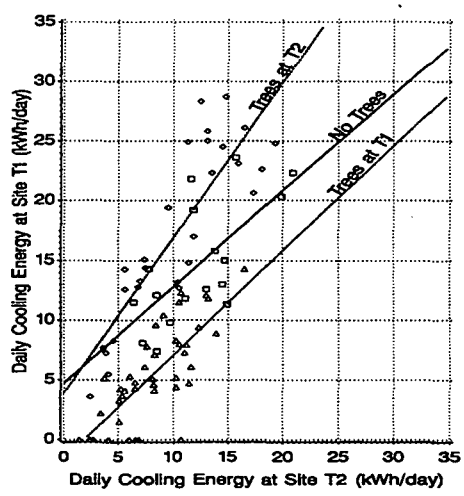

Fig. 2. Comparison of daily cooling energy use at Sites T1 and T2. Squares and solid line represent 17 days in the first monitoring period. Diamonds and dashed line represent 28 days in the second monitoring period, when Site T2 was shaded. Triangles and dotted line represent 41 days in the third monitoring period, when Site T1 was shaded. The regression line for the second monitoring period is shifted to the left, indicating savings at Site T2. The regression line for the third monitoring period is shifted downward, indicating savings at Site T1.

[1] At Site T1, we only measured the energy use in the condenser unit which consist of compressor and condenser fan.

Table 3
Savings achieved through shade trees at sites T1 and T2

Period	Site	Cooling energy use (kWh)			Daily savings	Percent savings
		Unshaded	Shaded	Saved	(kWh)	
2	T2	394±18	292	102±18	3.6±0.7	26±5
3	T1	423±26	225	198±26	4.8±0.6	47±6

predicting individual measurements, σ_p, as determined by regression theory [2]. The daily savings at Sites T1 and T2 are the difference between the predicted and measured values, with an estimated error of σ_p. We added such savings over the period to find the total achieved savings and estimated the error as the sum of the daily errors in quadrature. The savings determined in this manner are shown in Table 3.

It should be noted that our savings estimates depend on the assumption that the base case relation is valid and that it does not change over the season. This approach is invalid if the houses respond differently to changing conditions during the monitoring season, such as weather patterns, number of daytime hours, and sun angle. We have considered this change in our simulation effort, described later in this paper, and find that while a shift in base case relation is indicated by our models, it affects our savings measures only slightly.

3.2. Measurements of cooling energy savings using climate-based correlators

While the use of test and control sites allows us to determine the energy savings actually achieved, it sheds no light on the manner in which the response of a building to climate conditions changes through the planting of shade trees. Thus, an additional analysis was undertaken considering each site individually. The daily totals of energy consumption and climate measurements were analyzed to determine the cooling energy use of a shaded building, E_s and of a non-shaded building, E_{ns}, on any given day. We sought equations of the following form:

$$\text{Savings} = E_{ns}(T,I,\Phi,V) - E_s(T,I,\Phi,V)$$

where T represents temperature, I represents solar intensity, Φ represents the altitude of the sun, and V represents wind speed.

Our analysis revealed that among several candidates, the daily average temperature, $\bar{T}$, served as the best indicator of the cooling energy use at the two sites. The correlation at Site T1 between the cooling energy use and $\bar{T}$ is shown in Fig. 3. The solid and dashed lines represent linear regression fits to the pre- and post-modification data, respectively. The shaded regression line is shifted downward from the base case line, indicating a savings of about 4 kWh/d during the shaded period. As the regression lines indicate, the air conditioning during the base condition begins to operate at a daily average temperature of 18.7°C. In the shaded condition, this starting temperature is increased to 20.3°C.

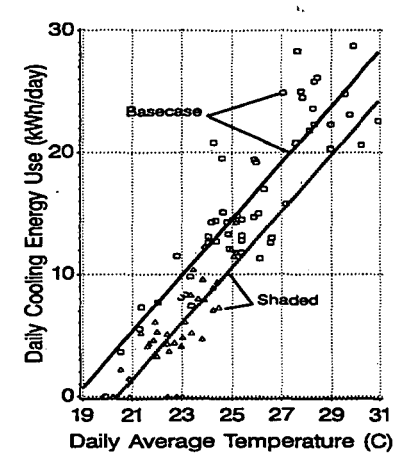

Fig. 3. Daily cooling energy use at Site T1 vs. daily average temperature. Squares and solid line represent 55 days in the first and second monitoring period, when Site T1 was not shaded. Triangles and dashed line represent 41 days in the third monitoring period, when Site T1 was shaded. The lines are linear regressions to the data. The dashed line is shifted down from the solid line, indicating savings at Site T1 of about 4 kWh/d because of the shade trees. The daily average temperature at which air conditioning begins rises from 18.7 to 20.3°C because of the trees.

Fig. 4 shows the correlation at Site T2. The squares represent measurements made in the first monitoring period, with the solid line showing the linear regression fit to those points. Triangles and a dashed line represent the measurements during the second monitoring period, and their linear regression fit. Site T2 was shaded during this time. Measurements from the third monitoring period, when Site T2 was again in the base condition, are represented by the circles and the dotted regression line. Between the first and third monitoring period, a significant change occurs in the dependence of cooling use on daily average temperature. We believe this is caused by the lower sun angle in the fall, which increases the solar heat gain through the walls and windows. The savings indicated by Fig. 4 lie between 1 and 4 kWh/d, depending on the position of the base case correlation between daily cooling energy use and average outdoor temperature.

[2] In the theory of linear regressions, error estimates can be made concerning two different types of predictions. One estimate, the error of predicted expected values, quantifies the error in the placement of the regression line at the point of prediction. Another, the error of predicted individual values, adds to the previous estimate a measure of the standard deviation of the measurements away from the regression line. Thus the error estimate for predicted individual values is larger than that of predicted expected values. Both error estimates increase as the point of prediction moves farther from the center of the range of measurements upon which the regression is based [7].

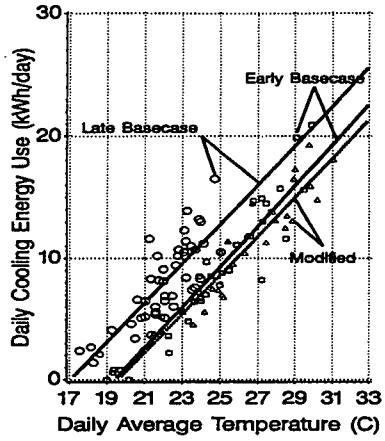

Fig. 4. Daily cooling energy use at Site T2 vs. daily average temperature. Squares and solid line represent 36 days in the first monitoring period, when Site T2 was not shaded. Triangles and dashed line represent 28 days in the second monitoring period, when Site T2 was shaded. Circles and broken line represent 44 days in the third period, when Site T2 was again not shaded. Although both represent basecase data, the broken regression line lies about 3 kWh/d above the solid line, showing the effect of seasonal changes. The dashed line lies below both basecase regression lines, indicating cooling energy reductions between 1 and 4 kWh/d.

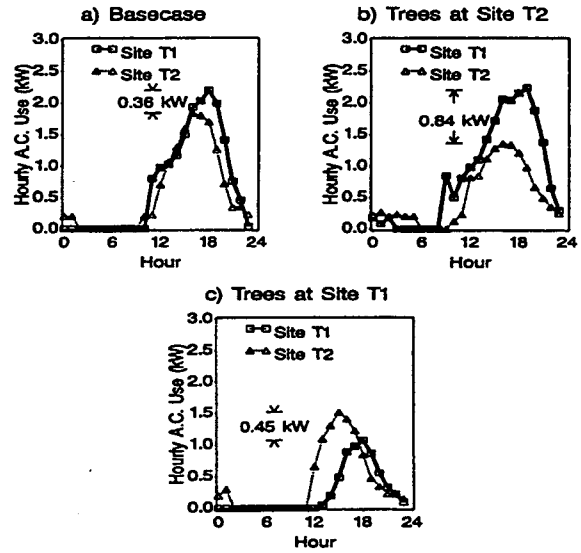

Fig. 5. Cooling load shapes for Sites T1 and T2, averaged over hours when either of the sites used air conditioning, during (a) the first; (b) the second; (c) the third monitoring periods. Squares and solid line represent average load shape for Site T1. Triangles and dotted line represent average load shape for Site T2. In the base condition, the site loads are different, with a higher average peak at Site T1. When Site T2 is shaded, its peak drops to 0.84 kW below that of Site T1. When Site T1 is shaded, its peak drops to 0.45 kW below that of Site T2.

3.3. Changes in load shapes and reductions in peak power

We examined the average cooling energy load shapes at the two sites during each of three periods. Hourly totals were obtained by combining three 20-minute measurements. We considered hours when non-problematic data were available at both sites and at least one of the air conditioners operated. (Outliers and missing data were defined as problematic.) For each hour of the day, these data were averaged over the monitoring period and plotted.

The average load shapes for the first period, when both sites were unshaded, are shown in Fig. 5(a). The average load shape at Site T2 peaks at 4 p.m., while at Site T1 it peaks at 6 p.m. at a peak power of 0.36 kW greater than that at Site T2. Fig. 5(b) shows the average load shapes during the time when Site T2 was shaded. The cooling load at T2 is clearly reduced, even in the morning and early afternoon. The peak power at Site T2, at 4 p.m., drops to 0.84 kW below that of Site T1, which occurs at 7 p.m. The load shapes for the third monitoring period are shown in Fig. 5(c). Here the cooling energy use at Site T1 is reduced, peaking at a value 0.45 kW lower than the peak at T2.

The peak reductions determined from these load shapes are indicative of the average difference between the power consumption of the two sites at specific hours when the average load shapes reach their peaks. The actual difference in peak power usage at the two houses, on a given day, is found by taking the difference between the power consumption at the sites when that day's peaks occur. To correctly measure the reduction in peak demand, we found the average peak difference for all days when air conditioning took place at both sites, and estimated the variance of the peak power differences about the mean. The results are given in Table 4. When both houses are in the base condition, their peak power consumptions differ. Assuming that this difference in peak power is the same for the entire cooling season, we estimate the savings achieved by the shade trees as the change in the difference of peak power usage between the houses.

3.4. Thermophysical and microclimate changes from shade trees

When an exterior building surface is exposed to sunlight, its surface temperature rises above that of the outside air by an amount proportional to the insolation. The effect of shad-

Table 4
Average difference in daily peak cooling power between site T1 and site T2 during 1992 monitoring periods. Includes only days when air conditioning occurred at both sites

Period	Number of days	Average peak difference (kW)	Estimated peak savings (kW)
Unshaded	17	0.6 ± 0.1	
Trees at T2	28	1.2 ± 0.1	0.6 ± 0.1 at Site T2
Trees at T1	33	−0.2 ± 0.1	0.8 ± 0.1 at Site T1

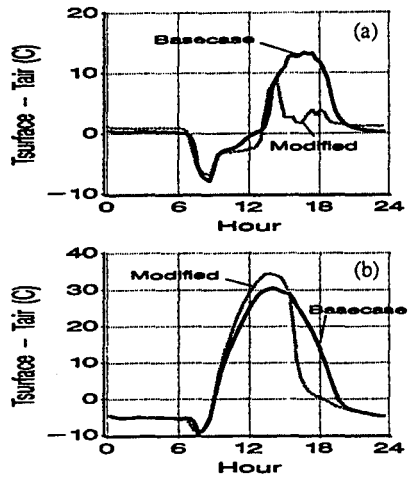

Fig. 6. Difference between measured surface temperatures and outdoor air temperature for days before and after the placement of shade trees (September 1) at Site T1, (a) wall; (b) roof. Solid line represents the average for 7 clear days between August 17 and August 31, when the surfaces were not shaded. Dotted line represents average for 10 clear days between September 1 and September 15, when the surfaces were shaded. The shaded wall is cooled beginning around 2 p.m., by as much as 12°C. In the presence of shade trees, the roof is slightly warmer in the morning and early afternoon. Beginning around 3:30 p.m., the surface is shaded and cooled as much as 20°C.

ing is to reduce this difference in temperature. We examined this effect by comparing surface temperature measurements made in the 15 days preceding and the 15 days following the tree placements, excluding cloudy days. Thus, for Site T1, the days from August 17 to September 15 were considered, excluding 14 partly cloudy days. For Site T2, comparisons were made both for the above period, during which the trees were removed, and for the days surrounding the placing of the trees on August 4, excluding 8 cloudy days.

Fig. 6 shows the comparison of pre- and post-modification exterior wall surface temperature elevations at Site T1. As shown in Fig. 6(a), shading lowers the temperature of the wall from 13°C higher than the outdoor air temperature to only 2°C higher. These temperature reductions are achieved between 2 and 7 p.m., when the sun shines on the southwest wall. On the roof of Site T1, the surface temperature sensor was shaded beginning around 3 p.m., as shown in Fig. 6(b), whereupon the roof temperature drops as much as 20°C. Larger wall temperature reductions were measured at Site T2; the shade trees caused a 15°C reduction on the south wall, and a 25°C reduction on the west wall, on August 4. The reductions observed during the days surrounding the removal of the trees on September 1 are as high as 25°C at the south wall and 20°C at the west wall. This is expected since the wall albedos of Site T2 are lower than those of Site T1.

Trees also affect the nearby microclimate by reducing wind speeds. We compared wind speeds (measured above the roof) during the shaded and unshaded periods, using measurements at another site as control. Wind speeds at Sites T1 and T2 are reduced by $13 \pm 3\%$, and by $16 \pm 2\%$, respectively. Wind speed reductions on the roof and walls of the shaded house may be larger than the measured reductions. In reducing wind speed, the shade trees reduce the convective heat transfer between the outside air and the house, and the infiltration rate of outside air into the conditioned space. During the summer, these two physical phenomena have opposite effects on air-conditioning use: the reduction in convective transfer raises the cooling energy use; the reduction in infiltration reduces it [3]. During the winter, reductions in both convection and air infiltration act to reduce the heating load of the building. For instance, Akbari and Taha [8] have estimated 5% to 30% savings in heating energy use of nine prototypical houses in four Canadian cities.

Finally, trees may reduce nearby air temperature through evapotranspiration. Given the experimental design for monitoring in this study, the effects of evapotranspiration proved difficult to isolate. Using the measured temperature and relative humidity and assuming a constant pressure of 1 atm, we calculated the hourly humidity ratio at each house. Through parallel comparison of the humidity ratios at the two sites, we found no significant differences due to the trees. However, the calculated humidity ratio is a crude test for evapotranspiration, the effect of which may still have been significant.

3.5. *Estimates for monthly and seasonal cooling energy savings and peak power use reductions*

As discussed previously, we obtained cooling energy savings and peak power reduction measures for days when the sites were monitored in modified conditions. We avoided extrapolating our findings to energy use for the modified sites during times when they were not monitored in the modified conditions. Such extrapolations, using data based on correlations between climate characteristics and cooling energy consumption, do not account for systematic changes in these correlations over the monitoring season.

In spite of these difficulties, we sought to estimate the cooling energy savings and peak power use reductions over the entire cooling season. We used the correlations between cooling energy use and daily average temperature shown in Figs. 3 and 4 [4]. Daily average temperatures were determined from the weather data collected at the site. Days with incomplete data coverage or failures in the outdoor air temperature sensor were assigned a daily average temperature equal to the average daily temperature over the month in which they occurred.

We limited our estimates to the period of actual monitoring, again in an attempt to limit the error introduced by our extrap-

[3] The reduction in infiltration reduces cooling energy use when the temperature of the outside air is higher than the thermostat setting. In a well-operated house, infiltration is increased by opening windows when the outdoor air temperature is lower than the thermostat setting.

[4] The correlation between cooling energy use and daily average temperature at Site T2 showed a marked variation between the early and late base case periods. For the purposes of our estimates, we used the linear regression obtained from a combination of all basecase data to estimate cooling energy use for the unshaded condition.

Table 5
Estimated base case and modified cooling energy use, peak power, and savings for 1992 cooling season

Site	Period	Case	Energy (kWh)					Total	Peak power (kW)
			June [a]	July	Aug.	Sept.	Oct. [a]		
T1	June 28 to Oct. 12	Unshaded	1	484	512	274	75	1346	3.6
		Shaded	0	361	390	160	39	950	2.8
		Savings (%)	100	25	24	42	48	29	22
T2	June 2 to Oct 14	Unshaded	14	332	557	287	84	1274	3.0
		Shaded	3	253	433	171	45	905	2.3
		Savings (%)	78	24	20	40	46	29	23

[a] Estimates only include days during the monitoring period.

olations. Thus, the results for June and October, shown in Table 5, are estimates for energy consumption and savings for only part of the month. The estimates of savings for Site T1 for the summer months of July and August are around 23%, while during the months of September and October the savings are about 45%. The resulting savings estimates for Site T2 are similar to those for Site T1. Overall, the savings over the season are about 30% for both sites.

We also estimated the maximum peak power reductions we expect to occur over the season. We assumed that the measured reduction in peak savings would be valid during the day with the highest peak power usage. For Site T2, the highest cooling energy use days occurred when the house was shaded, we added to the highest hourly cooling energy use measured peak savings in order to estimate the peak power for the base case. At Site T1, the highest cooling energy use days occurred when the house was unshaded, so we subtracted from the highest hourly cooling energy use the measured peak savings and estimated the peak power for the shaded condition. The peak power savings amount to about 22%.

4. Simulation of monitored buildings

To understand the measured data better, we modeled the monitored buildings using the DOE-2.1E building energy analysis program, using the information in Table 1. A detailed description of simulation methodology, the modeling program, and inputs can be found in Akbari et al. [5]. Surface characteristic data include the type of surface materials used in roofs and walls and their albedos. Inputs for HVAC system types, capacities, and air flow rates were taken from site reports, and supplemented by cooling equipment product literature as appropriate. The thermostat settings were originally based on the experimental design control, calling for constant 78°F (25.5°C) setpoints in both houses. Measured data, however, suggested that setpoints have been changed. We chose to modify the simulated thermostat setpoint that would best match the measured and simulated cooling energy use. However, these adjustments were limited within the range provided by the indoor temperature measurements.

Climate data were obtained from two sources. Data for August 1 through October 31, 1991, and May 1 though October 31, 1992, covering the period of monitoring, were obtained from the National Climatic Data Center (NCDC). These data, measured at the Sacramento Executive Airport, include hourly dry-bulb and wet-bulb temperatures, wind speed and direction, and cloud cover. Measurements made at each of the sites during the monitoring provided another source of climate data. Since microclimate variations influence climate measurements, we chose to use the climate information measured at the sites whenever possible.

The DOE-2.1E models were supplemented with a model that estimated inefficiencies in duct systems. Previous work has shown that duct systems in California suffer significant reduction in efficiency due to air leakage and conduction, which vary widely for different buildings [9,10]. The effect of this inefficiency depends on the location of the duct system, since a leaky duct reduces efficiency by exchanging conditioned air with the zones through which it passes.

4.1. Simulation results and comparison with measured data

Fig. 7 shows the simulated daily cooling energy and peak power use plotted against measured data for Site T1. At periods of high cooling energy use, the model overpredicts actual use by a large margin. In contrast, the model underpredicts peak cooling power during these conditions. When the house is shaded, the model overpredicts both cooling energy and peak power use.

The comparisons of simulated and measured daily cooling energy data for Site T2 are presented in Fig. 8. The simulation performance at Site T2 is similar to that at Site T1: total daily cooling energy consumption is overpredicted by the model, especially on the days with high cooling use. In addition, the model overpredicts cooling by a larger amount during the early periods than during the fall. Also, it overpredicts cooling more for the shaded period than for the unshaded periods. Model predictions of peak cooling power over the unshaded period are similar to the measured data, but predictions of daily peak cooling power during the shaded period are high.

The effect of shade trees was quite difficult to simulate. To determine the sensitivity of the simulation results to tree shad-

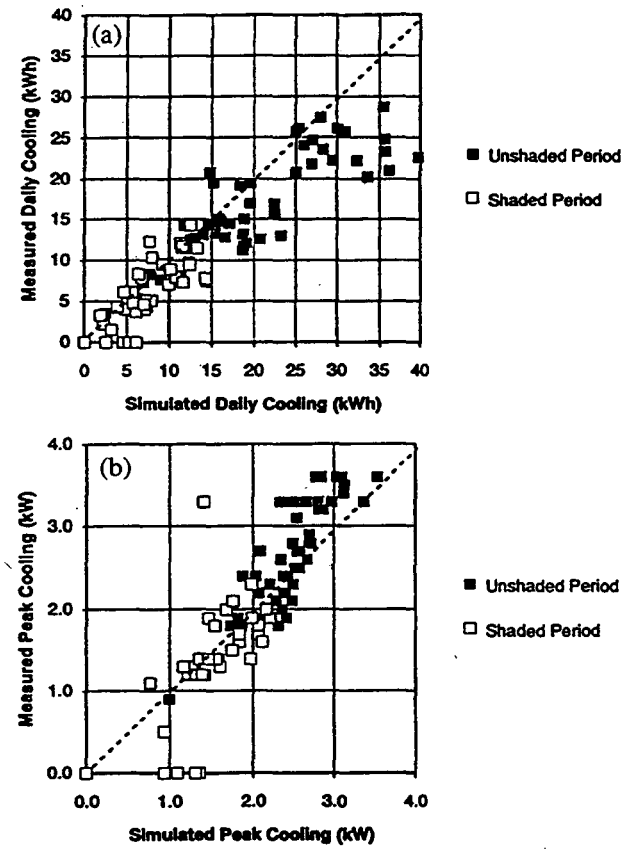

Fig. 7. Measured vs. simulated (a) daily cooling energy; (b) peak power usage at Site T1 during 1992. Simulations use weather data measured at the site. One week of data (June 27 to July 4) and some outliers were removed. When measured and simulated data are equal, they fall along the diagonal line. The plots indicate that the model overpredicts daily energy cooling use and underpredicts cooling load at peak conditions.

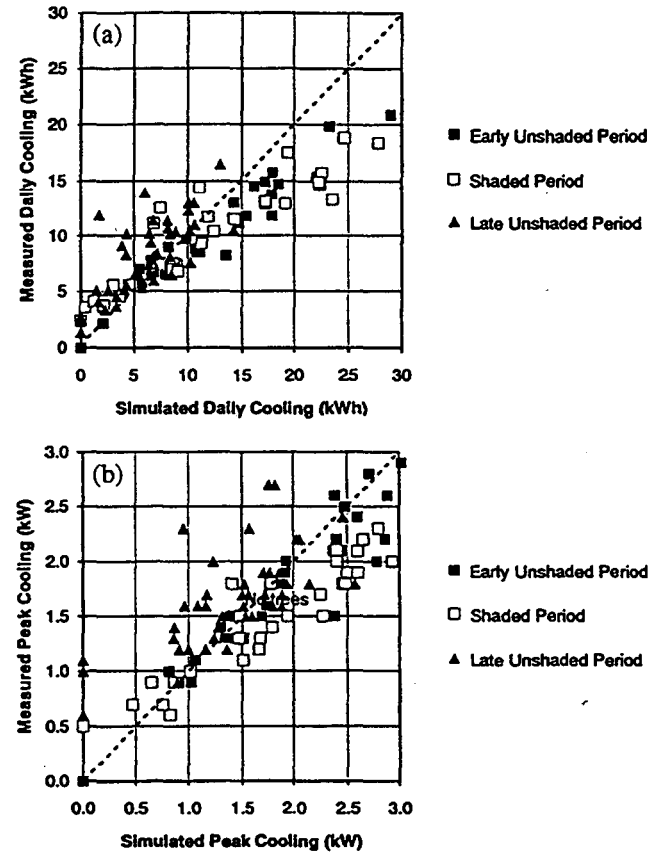

Fig. 8. Measured vs. simulated (a) daily cooling energy; (b) peak power usage at Site T2 during 1992. Days with partial data coverage were removed. When measured and simulated data are equal, the points fall along the diagonal line. The model overestimates cooling energy use at high cooling use and underestimates it at low cooling. The model overestimates peak usage when the site is shaded and underpredicts peak usage for the late unshaded period.

ing, we performed simulations using various methods to represent the shade trees at Sites T1 and T2. For each variation in the representation of shade trees, we compared the measured cooling energy use and peak power demand over the shaded period with the simulation results over the same period. These comparisons are shown in Table 6.

In our original method for representing shade trees, the trees were modeled as rectangular forms, sized according to the size of the trees, with transmissivities of 0.10. At both sites, these initial simulations overestimated cooling energy use and peak power demand.

For the second variation in the treatment of shade trees, we lowered the transmissivity of the tree representations to zero, making them completely opaque. We improved the weather data and increased the natural and attic ventilation at the sites. At both sites, the effect of this variation was to lower the cooling energy and peak power use over the monitoring period, but not enough to bring the simulation and measured results into agreement.

The third variation was to remove the rectangular shades and to model the effect of shading by setting the window shading coefficient to zero. At Site T1, this resulted in simulated energy use and peak power demand higher than that for the previous variation. This indicated that, in the simulations, the energy savings from wall shading are quite significant. At Site T2, this variation lowered the energy use and peak power demand in comparison with the first variation. It reflects the fact that at Site T2 a large window at the south facing wall of the building was not shaded by the shade trees; a translucent overhang prevented the placement of trees near the window.

As a final variation in the treatment of shade trees, we again removed the rectangular forms and represented the effect of shading by eliminating insolation on both the windows and the walls. At Site T1, even this exaggeration in the effect of shading could not bring the simulation results in line with the measurements. At Site T2, the measured and simulation results were brought into agreement, presumably because the model simulated the building as if the large window in the southern wall were shaded, although during the experiment it was not shaded.

Overall, the amount of savings determined by the simulations and by the measured data differs substantially. This discrepancy arises from two failures: the failure of the DOE-2.1E model to simulate correctly the energy use of the build-

Table 6
Measured and simulated daily cooling energy and peak power use over the shaded periods using several methods to model shade trees

Measured use		Simulated use		Method of tree representation
Energy (kWh/d)	Power (kW)	Energy (kWh/d)	Power (kW)	
Site T1				
5.6	1.3	7.6	1.38	Rectangular forms, transmissivity = 0.10
		6.8	1.41	Rectangular forms, completely opaque
		7.1	1.44	Complete window shading
		6.0	1.25	Complete wall and window shading
Site T2				
10.4	1.5	13.2	1.99	Rectangular forms, transmissivity = 0.10
		12.2	1.77	Rectangular forms, completely opaque
		10.2	1.55	Complete window shading
		10.0	1.49	Complete wall and window shading

ing described by the model input, and the failure of the user to provide the model with inputs which accurately describe the monitored buildings. The objectives of this study did not include a thorough examination of these sources of disagreement which would be necessary to truly 'calibrate' the model. However, as Table 6 shows, the measured energy savings and reductions in peak power demand are consistently higher than the simulation estimates. Thus, predictions of cooling energy savings from albedo and tree shade modifications made with the DOE-2.1E simulation program may be lower than actual savings by as much as twofold.

5. Conclusions

We have measured substantial cooling energy savings in two houses by shading them with sixteen trees. By comparing measurements at the two sites, we estimated the cooling energy savings achieved during the shaded periods at Sites T1 and T2 to be 47% and 26%, respectively. The peak cooling power usage was reduced by 0.8 ± 0.1 kW at Site T1, and by 0.6 ± 0.1 kW at Site T2. The savings at Site T1 do not include those achieved in the motor energy consumption of the distribution fan, which may account for an additional energy savings of 3–6%. The shade trees dramatically reduced both the temperature of exterior surfaces and the wind speed.

Our analysis revealed that total daily cooling energy use at each site is well correlated with the daily average temperature. Using this correlation, we estimate savings over the entire monitoring period of 396 kWh (29% of total) at Site T1, and 369 kWh (29% of total) at Site T2.

We used the DOE-2.1E program to simulate the cooling energy use of the monitored buildings. The comparison of daily cooling energy use and peak cooling power revealed some discrepancies between simulation estimates and measured data. We also compared the simulation estimates of cooling energy savings and peak power reductions with measurements, finding the simulations to underestimate savings and load reductions by as much as twofold. The differences between simulation results and measured data arise from two possible failures: the failure of the model to simulate the cooling energy use of the buildings and the failure of the user to accurately describe the buildings in the model inputs. A thorough calibration study is needed to assess these failures.

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References

[1] J.H. Parker, *Use of Landscaping for Energy Conservation*, Department of Physical Sciences, Florida International University, Miami, FL, 1981.

[2] D.R. DeWalle, G.M. Heisler, R.E. Jacobs, Forest home sites influence heating and cooling energy, *J. Forestry, 81* (1981) 84.

[3] G.M. Heisler, Effects of trees on wind and solar radiation in residential neighborhoods, Final report on site design and microclimate research, *ANL No. 058719*, Argonne National Laboratory, Argonne, IL, 1989.

[4] Y.J. Huang, H. Akbari, H. Taha, The wind-shielding and shading effects of trees on residential heating and cooling requirements, *Proc. American Society of Heating, Refrigeration, and Air conditioning Engineers, Atlanta, GA, Feb., 1990;* see also *Rep. No. LBL-24131*, Lawrence Berkeley Laboratory, Berkeley, CA.

[5] H. Akbari, S. Bretz, J. Hanford, D. Sailor, H. Taha and W. Bos, Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento Municipal Utility District (SMUD) service area: Project design and preliminary results, Final Report Prepared for California Institute of Energy Efficiency and SMUD, *Rep. No. LBL-33342*, Lawrence Berkeley Laboratory, Berkeley, CA, 1992.

[6] H. Akbari, S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha, Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento Municipal Utility District (SMUD) service area: Data analysis, simulations, and results, *Rep. No. LBL-34411*, Lawrence Berkeley Laboratory, Berkeley, CA, 1993.

[7] A. Sen and M. Srivastava, *Regression analysis: Theory, methods and applications*, Springer-Verlag, New York, 1990.

[8] H. Akbari and H. Taha, The impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities, *Energy, the International Journal, 17* (1992) 141; see also *Rep. No. LBL-30131*, Lawrence Berkeley Laboratory, Berkeley, CA, 1991; also published as *The Tree-House Effect: The Impact of Trees and White Surfaces on Residential Heating and Cooling Energy Use in Four Canadian Cities*, Friends of the Earth, Ottawa, Canada, 1991.

[9] M. Modera, D. Dickerhoff, R. Jansky and B. Smith, Improving the energy efficiency of residential air distribution systems in California: Final report, Phase I, Report prepared for the California Institute of Energy Efficiency and US Department of Energy, *Rep. No. LBL-30886*, Lawrence Berkeley Laboratory, Berkeley, CA, 1991.

[10] J. Proctor and R. Pernick, Getting it right the second time: measured savings and peak reductio66n from duct and appliance repairs, *Proc. ACEEE 1992 Summer Study on Energy Efficiency in Buildings*, American Council for an Energy-Efficient Economy, Washington, DC, 1992.

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