Title
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Journal
Energy and Buildings, 25(2)

Author
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Publication Date
1997-03-30

LBNL-41292
Preprint

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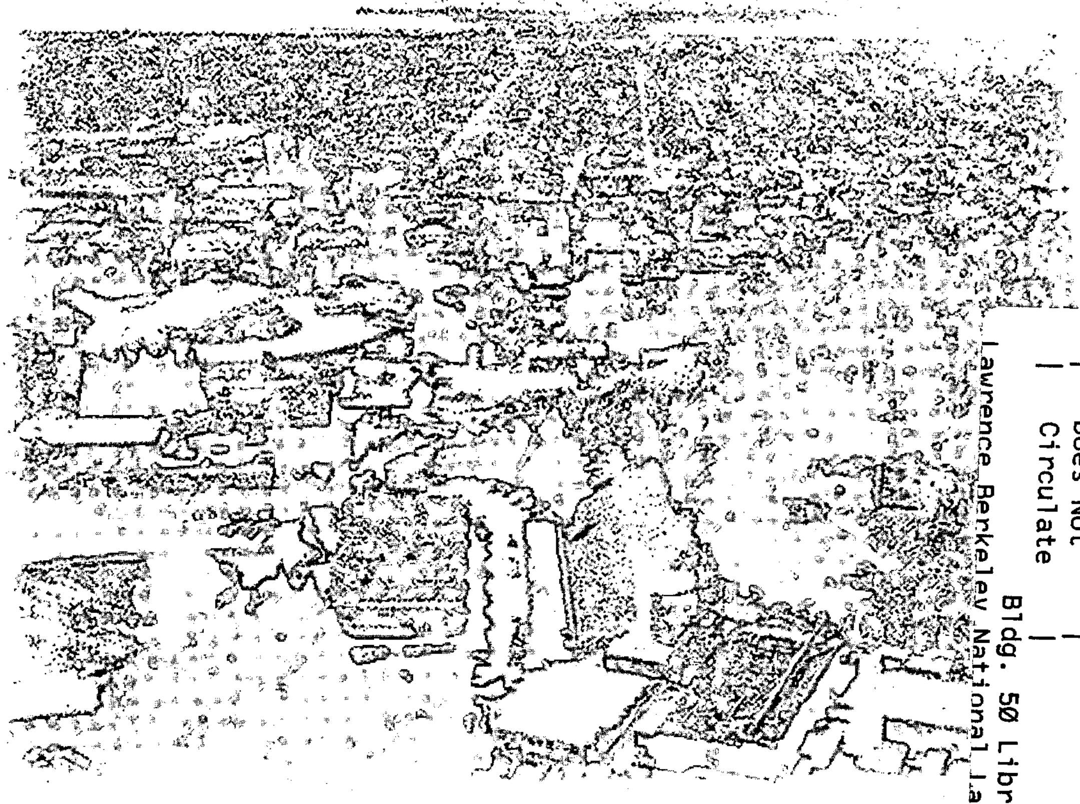
**Environmental Energy
Technologies Division**

March 1997

Submitted to
Energy and Buildings



LBNL-41292
UC-000

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This work was supported by the California Institute for Energy Efficiency, the Sacramento Municipal Utility District, and the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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ENERGY AND BUILDINGS

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Peak power and cooling energy savings of high-albedo roofs

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Abstract

In the summers of 1991 and 1992, we monitored peak power and cooling energy savings from high-albedo coatings at one house and two school bungalows in Sacramento, California. We collected data on air-conditioning electricity use, indoor and outdoor temperatures and humidities, roof and ceiling surface temperatures, inside and outside wall temperatures, insolation, and wind speed and direction. Applying a high-albedo coating to one house resulted in seasonal savings of 2.2 kWh/d (80% of base case use), and peak demand reductions of 0.6 kW. In the school bungalows, cooling energy was reduced 3.1 kWh/d (35% of base case use), and peak demand by 0.6 kW. The buildings were modeled with the DOE-2.1E program. The simulation results underestimate the cooling energy savings and peak power reductions by as much as twofold.

Keywords: Peak power savings; Cooling energy; High-albedo coatings; Residential buildings

1. Introduction

Increasing the albedo of urban surfaces is expected to reduce cooling energy use both through direct savings in buildings built with high-albedo materials, and through indirect savings as urban air temperatures are reduced. While ample anecdotal evidence supports this expectation, a literature search at the beginning of this project revealed no measured data on the effect of white surfaces on building cooling energy use. Since then, Parker et al. [1] have monitored six homes in Florida before and after applying high-albedo coatings to their roofs. Air-conditioning energy use was reduced by 11%–43%, with an average savings of 9.2 kWh/d. Peak demand between 5 and 6 p.m. was reduced by 0.4–1.0 kW, with an average reduction of 0.7 kW (27% of the low albedo case). The amount of energy savings was inversely correlated with the amount of ceiling insulation: large savings in poorly-insulated homes, and smaller savings in well-insulated homes.

Our simulations show that increasing the roof albedo of a typical house in Sacramento, California, should result in direct cooling energy savings of 10% to 20%. In addition, changing the overall albedo of the city from an existing ~15–20% to a 'whitewashed' 40% may result in additional savings of ~40–50%. However, while simulations help estimate energy savings, they neglect important elements such as actual building operation and micro- and local-scale climate variations.

Thus, we carried out field experiments to measure actual savings and identify unforeseen problems. A multi-year collaborative project was designed by the Sacramento Municipal Utility District (SMUD) and the Lawrence Berkeley Laboratory (LBL) to measure cooling energy savings in a few buildings and to compare simulation results with monitored data. 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 chose one house (A) and two school bungalows (B1, B2) for this experiment. Specifications for these buildings are given in Table 1. At each site, we measured the characteristics of the buildings and the surroundings (see Table 1), and made running measurements of microclimate and energy use. The running measurements at Sites A, B1, and B2 included air-conditioner electricity use, roof and ceiling surface temperatures, inside and outside wall surface temperatures, supply and return air temperatures, and indoor air temperature and humidity. In addition, microclimate measurements were made at Sites A and B1, including wind speed and direction, outdoor air temperature and humidity, and horizontal insolation. Measurements were made every 20 min with automated sensors and a data logger. Climate data measurements at B1 were often faulty in the first few weeks of the 1992 monitoring season, so we replaced outdoor temperature

Published by Elsevier Science S.A.
PII S0378-7788(96)01001-8

Table 1
Site and building characteristics

	Site A (house)	Site B (school)
Site characteristics		
Site vegetation [a]	heavy	low
Neighborhood vegetation	moderate–heavy	low
Albedo [a]	low	moderate–low
Neighborhood albedo	moderate–high	moderate
Building description		
Floor area [b] (m^2)	170	89
Perimeter length (m)	61	39
Exterior wall height (m)	2.4	3
Age (y)	29	2
No. of stories	1	1
Roof material	roofed composite	corrugated metal
Roof albedo	0.18, silver	0.34, dull white
Roof insulation (m^2 °C/W)	1.94	3.34
Ceiling construction	low-pitch vaulted	dropped ceiling
Wall material	plywood	plywood siding
Wall albedo and color	0.30, khaki wood	0.30, tan wood
Wall insulation (m^2 °C/W)	1.41	1.94
Windows	1-pane	2-pane
Foundation	crawl space	crawl space
Internal load (kWh/d)	9.1	19.9 [c]
Air conditioner	central, 44.3 MJ/h	heat pump, 36.5 MJ/h
Heater	gas, 9.5 MJ/h	heat pump
Air flow (m^3 s^{-1})	0.5	0.83
Duct locations	crawl space	ceiling
Thermostat setting		
Heating (°C)	20	Not available
Cooling (°C)	26.7	varies 21–26

[a] Pre-monitoring conditions.
[b] Excluding garage.
[c] Lighting load 16.1 W/m^2. 25 students at 370 kJ/h per student [3]. Bungalow occupied 9 a.m. to 3 p.m. with reduced load 12–1 p.m. School occupied week days beginning Sept. 7.

data with those measured at a nearby site (Site T1 in Ref. [2]).

To isolate the effect of the albedo modifications on cooling energy use, users of the monitored buildings were requested that (i) windows be closed at all times, (ii) thermostat settings be identical and invariant, and (iii) lights be used in a consistent, similar, and predictable fashion.

Collected data were downloaded from the sites via modem and sent electronically to LBL, where the data were converted to physically-meaningful units, calibrated, and plotted. Data were checked on a weekly basis to address promptly data collection problems such as failing sensors.

We encountered problems with the measurement of outdoor surface temperatures, made by adhering thermocouple wire to the surface with plastic tape. We suspected that, over time, thermal effects and exposure to moisture and sunlight degraded the contact between the thermocouple and the surface. Thus, we checked the measurements by comparing them with calculated sol–air temperatures for sunny days during the monitoring period. We found that the roof temperature measurements at Sites A and B2, as well as both outside wall surface measurements at the school site were invalid.

3. Energy savings at Site A

The house, Site A, was monitored in 1991 for 20 days (August 21 to September 10) in its base condition, with a roof albedo of 0.18. On September 11, 1991, we painted its roof with a high-albedo coating which raised the roof albedo to a measured value of 0.79, and monitored the house in this condition until October 20, the end of the 1991 monitoring season. In 1992, we washed the roof, which had dirtied over the year (albedo of about 0.60), to restore the albedo to 0.73. We continued to monitor the effects of the white roof throughout the summer of 1992 (June 8 to October 15). Table 2 summarizes the different monitoring periods.

During the 1991 low-albedo period, there were four days of missing data, and two days of incomplete coverage. This left 13 complete days for comparison with the high-albedo data. During the 1991 high-albedo period, we obtained 26 complete days of data. However, during four of these days, the only ones with cooling energy use, the thermostat had been set back. These days were removed from the data prior to analysis.

The 1992 monitoring season spanned 130 days, from June 8 to October 15. Nineteen of these days were excluded from analysis due to partial data gaps, and data logger or sensor malfunctions. This left 111 full days of data suitable for analysis, a substantial improvement over the rate of data collection in 1991.

To determine cooling energy savings, we compared high- and low-albedo daily cooling energy use data using the daily average temperature as a correlator. This comparison is shown in Fig. 1. The squares represent data collected when the roof albedo was 0.18, the low-albedo condition. Points marked by a cross represent measurements during the 1991 high-albedo period, excluding those days when the thermostat was reset at low settings. These points indicate that after

Table 2
Monitoring schedule and number of days suitable for analysis at Site A

Year	Days	Roof albedo	Monitoring days	Days suitable for analysis
1991	8/21/91–9/10/91	0.18 (low)	20	13
1991	9/11/91–10/20/91	0.77 (high)	36	26
1992	6/8/92–10/15/92	0.73 (high)	130	111

Table 3
Savings measurements over 1991 low and 1992 high albedo days at Site A

Measurement period	No. of days	Cooling energy use (kWh)			Daily savings	Percent savings
		Low albedo	High albedo	Saved		
1991 low	9	**37.1** [a]	16 ± 1.1	21 ± 1.1	2.3 ± 0.1	57 ± 3
1992 high	55	173 ± 7.0	**53.5**	120 ± 7.0	2.2 ± 0.1	69 ± 2

[a] Bold-faced figures are direct measurements. All others are estimated using the correlation in Fig. 1. Errors are one standard deviation.

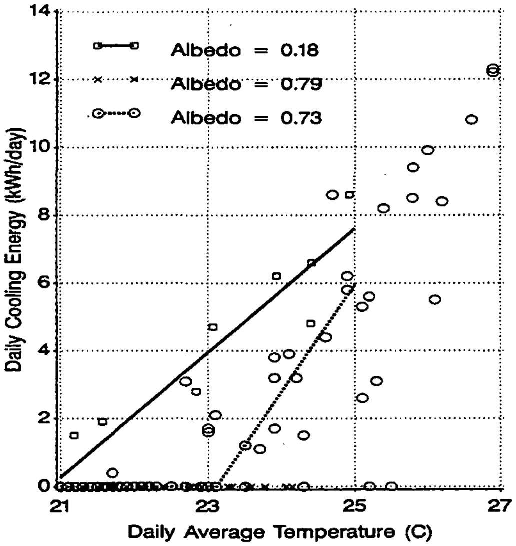

Fig. 1. Daily cooling energy at Site A vs. daily average temperature. Squares represent data collected during the 1991 low albedo period (roof albedo = 0.18). Solid line is a regression fit to the data. Data from the 1991 high albedo period (roof albedo = 0.79) are represented by crosses, showing no cooling energy use at daily average temperatures below 24°C. Circles represent data collected in 1992 (roof albedo = 0.73). The rising dashed line is a regression fit to 1992 data at temperatures between 23 and 25°C. Below 23.1°C, we predict no cooling energy use.

painting the roof, cooling energy use was eliminated entirely for days with average temperatures below 24°C. The circles represent data collected during the 1992 monitoring season, when the roof albedo was 0.73. For some of these days, the daily average temperature rose above 25°C, beyond the range covered in the low-albedo period. Thus, no comparison is possible for these days, and they were excluded from the linear regression fits. The solid line shows the least-squares linear fit to the low-albedo data. For high-albedo data, regression was performed on all data points with daily average temperatures between 23 and 25°C. Days with daily average temperatures below 23°C were assumed to use no cooling energy in the high-albedo period.

We used the linear approximations as an empirical model to estimate energy savings. [1] For example, for each low-albedo day, we compared the measured cooling energy use to that predicted for a similar day in the high-albedo period. The error in such a prediction was estimated as the error of predicted individual values [4], except for predictions of no air-conditioning use, for which the error was estimated as zero. Table 3 shows the estimated savings during the low- and high-albedo periods. The estimates do not include days with average temperatures above 25°C.

3.1. Changes in load shapes and reductions in peak power

To compare average load shapes during the low- and high-albedo periods, we selected all days with daily average temperature between 21.6 and 25°C in both the low and the 1992 high-albedo periods. Only days with cooling energy use were included so that the load shapes would reflect differences in the cooling load of the building. All in all, six complete days were considered for the low-albedo period and 17 for the high-albedo period. Cooling energy use was computed on an hourly basis and the use at each hour was averaged over all available days.

The resulting comparison is shown in Fig. 2. The cooling load is clearly reduced by the high-albedo coating, and the time of the peak is delayed by two hours. This delay is expected since for a low-albedo building, solar heat gains are high, and cooling loads reach their maximum near solar noon. For a high-albedo building, solar heat gains are substantially reduced, and cooling loads are governed more by the outside temperature, which peaks a few hours later.

To measure the reduction in daily peak power, we used daily average temperatures to compare the low- and high-albedo data. Again, we considered a subset of the total data, including only those days with cooling energy use and daily average temperatures between 21.6 and 25°C. According to this comparison, shown in Fig. 3, the peak power is reduced by 0.6 ± 0.2 kW (also see Table 4).

4. Energy savings at Site B

At Site B, two school bungalows (B1, B2) were monitored under a series of modifications, allowing a comparison of the energy use of the two buildings to determine energy savings. In 1991, bungalow B2 was used as the control site, left in its initial condition (metal roof and yellow wall) throughout the summer, while the roof and south east wall of the test bun-

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[1] If one considers all the days monitored in 1992, including those days with high average temperatures, it appears that the relation between daily cooling energy and average temperature is non-linear. This is not surprising, since the number of cooling degree hours increases non-linearly with increasing daily average temperature, for not only are the temperatures higher, but also the number of hot hours is greater.

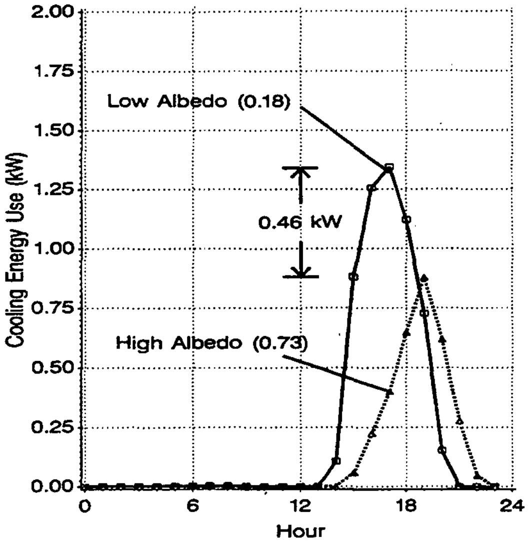

Fig. 2. Average cooling load shapes at Site A for days in the 1991 low and 1992 high albedo periods, with daily average temperatures between 23.1 and 25.0°C. Squares and solid line represent hourly load averages using six 1991 low albedo days with cooling energy use. Triangles and dashed line represent hourly load averages using seventeen 1992 high albedo days with cooling energy use. The high albedo average daily peak load lies about 0.5 kW below, and two hours after, the low albedo peak.

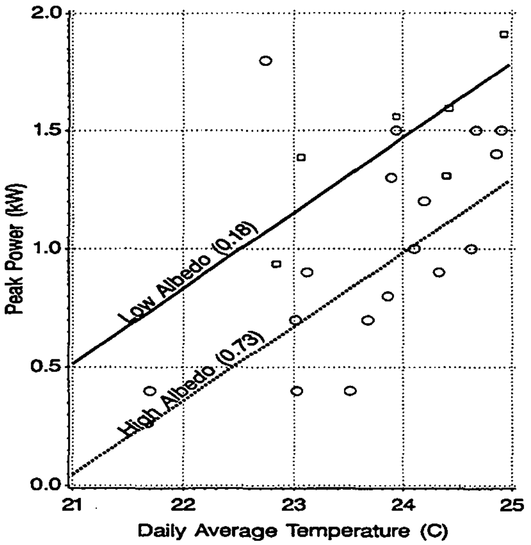

Fig. 3. Daily peak cooling power vs. average daily temperature at Site A, for days in the 1991 low and 1992 high albedo periods, with daily average temperatures between 23.1 and 25.0°C. Squares and solid regression line represent data from the 1991 low albedo period. Circles and dashed line represent days in the 1992 high albedo period. The regression lines indicate peak reductions of 0.6 kW.

galow, B1, were painted with high-albedo white paint. During this year, bungalow B1 was fully instrumented while B2 was only partly instrumented.

In 1992, the roles of these buildings were reversed: after a cleaning, which restored its high albedo, B1 was used as the control site, while B2 underwent a number of modifications. The monitoring season was divided into four periods. During the first, from June 7 through August 9, B2 was left in its unmodified condition with a metal roof and yellow south east wall. During the next period, from August 10 through August 27, the roof and south east wall of B2 were brown. Finally, the period between September 7 through October 15, when the roofs and south east walls of both sites were white, was divided into two periods: one included weekdays when school was in session, and the other included weekends during the school year. These monitoring periods are described in Table 5.

For 1992, data were available from June 17 through October 15. We did not analyze days with partial data coverage at either bungalow, several days when the carpets were cleaned in bungalow B1, and the eleven days from August 28 to September 6 because of frequent changes in occupancy and thermostat settings. In all, out of 121 days of monitoring, 87 days of complete, non-problematic data coverage were available. In 1991, only 31 of 74 monitoring days were suitable for analysis.

We determined the cooling energy savings in the white-coated bungalow by comparing the simultaneous energy use at the two buildings. Fig. 4 shows daily cooling energy use at B2 against that at B1 (from 1992). Only days when both sites used cooling energy are shown. Points marked by triangles and crosses represent data collected when the buildings were vacant and occupied, respectively (both white coated). As the dotted regression line through these points shows, the air-conditioning use at the two sites is nearly the same. The points marked by squares, and their solid regression line, describe data collected during the first period (metal roof). The points marked with diamonds, and their dashed regression line, represent data collected during the second period (brown roof). During both these periods, the cooling energy use at B2 is higher than that at B1, indicating savings at the white-roofed site.

We used these regressions to quantify the cooling energy saved at bungalow B1. For each day in the first two periods (metal or brown roofs), the regression line through data when both sites were white roofed was used to transform the measured cooling energy use at B1 to a prediction of the cooling energy use at B2, were it white roofed. Comparing the pre-

Table 4
Average daily peak power use and time of peak in the low and 1992 high albedo periods at Site A (includes days with daily average temperatures between 21.6 and 25°C)

Period	No. of days considered	Average daily peak power (kW)	Average time of peak (24 h clock)
Low albedo	6	1.5 ± 0.1	17.0 ± 0.45
High albedo	23	0.89 ± 0.09	18.9 ± 0.24

Table 5
Monitoring periods, number of complete days, and conditions of building surfaces at Sites B1 and B2

Period	Dates	B1	B2		Occupied	Days available	Days complete
		Roof and SE wall	Roof	SE wall			
Metal roof	6/17–8/9	W [a]	M [b]	Y [c]	no	55	33
Brown roof	8/10–8/27	W	B [d]	B	no	18	17
Occupied white building	9/7–10/15	W	W	W	yes	29	27
Vacant white building	9/7–10/15 (weekends)	W	W	W	no	10	10

[a] White (albedo = 0.68, emissivity = 0.91).
[b] Metal (albedo = 0.34, emissivity = 0.30).
[c] Yellow (albedo = 0.30, emissivity ~ 0.95).
[d] Brown (albedo = 0.08, emissivity ~ 0.95).

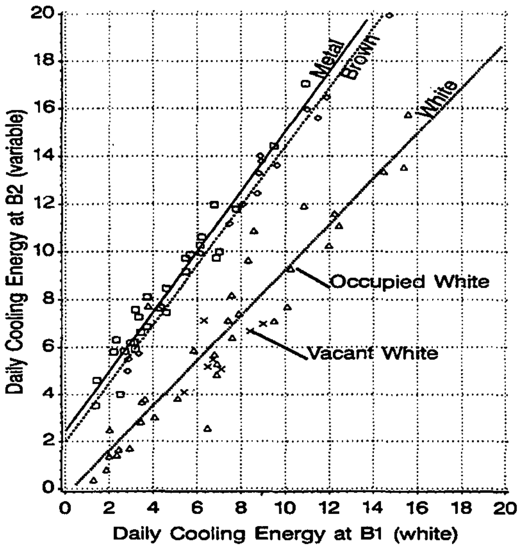

Fig. 4. Comparison of daily cooling energy use at Sites B1 and B2 for 1992 monitoring periods. Triangles and dotted regression line represent data collected during the vacant and occupied white roof periods. Squares and solid regression line represent data collected in the metal roof period. Diamonds and dashed regression line represent data collected in the brown roof period. Both the metal and the brown roof period regression lines are higher than the white period line, indicating cooling energy savings at B1 of 3–5 kWh/d.

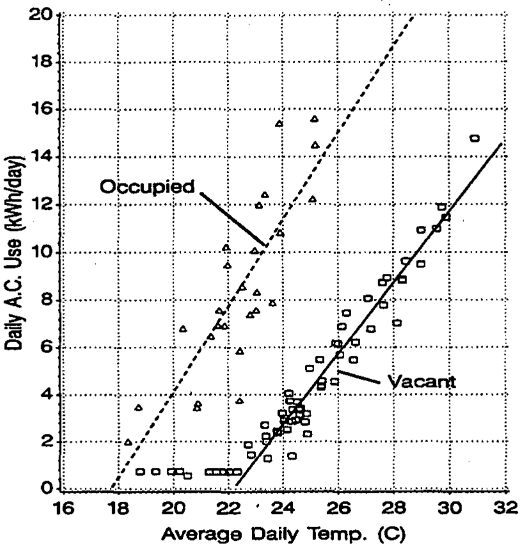

Fig. 5. Daily cooling energy use at B1 vs. daily average temperature. Squares and solid line represent data collected during the vacant periods. Triangles and dashed line represent data collected during the occupied white roof period. Cooling energy use is increased by 8 kWh/d due to the presence of students in the classroom.

diction to the measured cooling energy use at B2, we estimated the energy savings for that day. These savings are shown in Table 6.

We also compared data collected throughout the season using the daily average temperature as a correlator. Fig. 5 shows data collected at site B1. The squares represent data collected before the school session began, and during the white-coated roof period (vacant), fitted with a solid regression line. Points marked by triangles, and their dotted regression line, describe data collected for occupied school weekdays. Of the cooling energy use during occupied school days, around 8 kWh/d are caused by the presence of students inside the classroom.

The cooling energy use at B2 is described by Fig. 6. The metal roof period is represented by circles and the dot–dash regression line, the brown roof period by diamonds and a dotted regression line. The temperature relations for the two

Table 6
Cooling energy use savings from albedo modification for metal and brown monitoring periods at Site B

Period	No. of days	Cooling energy use (kW)			Daily savings	Percent savings
		Non-white	White	Saved		
Metal	32	231.0	113 ± 8	118 ± 8	3.7 ± 0.2	51 ± 3
Brown	17	194.5	117 ± 6	78 ± 6	4.6 ± 0.44	40 ± 3

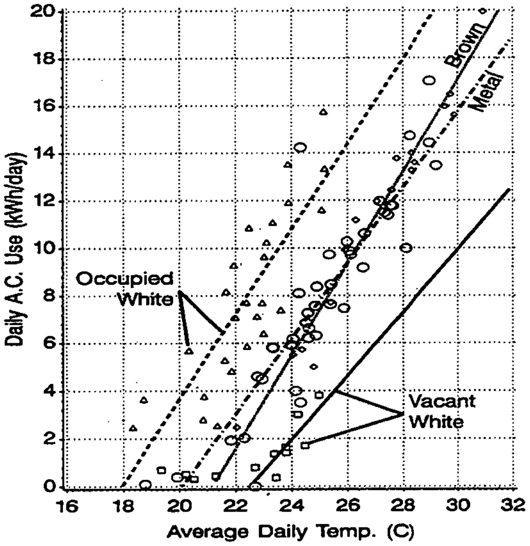

Fig. 6. Daily cooling energy use at B2 vs. daily average temperature. Squares and solid line represent data collected during the vacant white roof period. Triangles and dashed line describe data collected during the occupied white roof period. Circles and dot–dash line represent data collected in the metal roof period. Diamonds and dotted line represent data collected in the brown roof period. Comparing regression relations for the metal, brown, and vacant white roof periods, one sees the daily cooling energy use of the white-roofed bungalow is around 4 kWh/d lower than that of a dark-roofed bungalow.

periods are nearly identical.[2] The squares and solid line represent the period during which the roof was white and the building was vacant, while the triangles and dashed regression line represent the white roof occupied period. These data and regression lines agree with those describing the data from B1.

4.1. Changes in load shapes and reductions in peak power

To compare the load shapes at the two bungalows, we selected days with complete data coverage at both bungalows, including only those hours when either of the air-conditioning systems was operating, and computed the average hourly cooling energy use. Fig. 7(a) shows the average load shapes at the two bungalows during occupied school days. Cooling begins around 10 a.m. at both sites, peaking at 2 p.m. Soon after 2 p.m., school ends and the cooling energy consumption is reduced, since the students leave the classroom. Weekend days during the school year are averaged in the load shapes of Fig. 7(b). In the absence of the students, cooling does not begin until around 2 p.m., peaking at 6 p.m., and the cooling load is much smaller.

Fig. 7(c) shows average load shapes for the two bungalows during the metal roof period. The cooling load at B1, represented by the squares and solid interpolating line, is consistently lower than the load at B2. At the 6 p.m. peak, the average cooling power consumption is around 0.5 kW lower for the white-roofed bungalow. Average load shapes for the brown roof period are shown in Fig. 7(d). Again, the white-roofed building cooling load is consistently lower, with a peak power difference of about 0.5 kW.

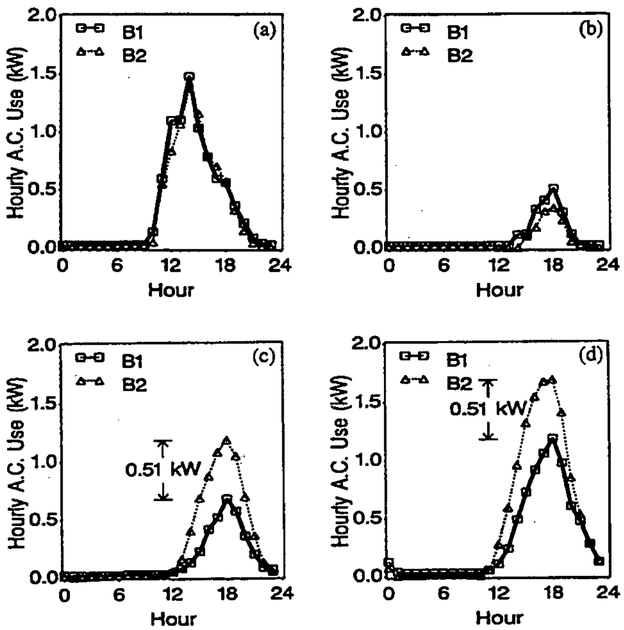

Fig. 7. Average load shapes for Sites B1 and B2 for (a) occupied white roof; (b) vacant white roof; (c) metal roof; and (d) brown roof monitoring periods. Squares and solid line represent hourly averages for B1. Triangles and dashed line represent hourly averages for B2. During occupied and vacant white roof periods, the cooling energy uses of the two bungalows are nearly the same. In the metal and brown roof periods, the average load peak of B2 is around 0.5 kW higher than that of B1.

To estimate the peak savings, we examined the difference in daily peak cooling energy consumption at the two sites. We calculated the average difference for each period, with results shown in Table 7. Not surprisingly, there is a small difference in peak energy use between the two school bungalows during the white roof vacant period, caused by slight differences in the thermophysical properties of the two sites, weathering effects which dulled the white coating at B2[3], and differences in air-conditioning system operation and occupancy conditions. This peak energy difference may increase the peak savings measures for the first two periods (metal and brown roofs).

The albedo modification also gave rise to a slight but noticeable shift in the average time of the peak. We find that the white-roofed building peaks half an hour later than the brown- or metal-roofed building.

Further examination of the data revealed a surprising temperature correlation in the daily peak savings during the brown roof period, shown in Fig. 8. The correlation suggests that peak cooling energy savings on the hottest summer days in Sacramento may be 10–20% higher than the peak savings on average days. If the cooling energy peaks always occur

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[2] Although albedo decreases significantly when a metal roof is painted brown, the thermal emissivity of the surface is simultaneously increased and the surface can cool faster through thermal radiative heat transfer. Thus, the energy use during the metal and brown periods is nearly identical.

[3] We measured a difference of 0.10 between the albedos of the white roofs of B1 and B2.

Table 7
Average difference between peak cooling power consumptions and times of peak at B1 and B2 (difference is value for B2 minus value for B1)

Period	No. of days considered	Average difference in daily peak power (kW)	Average difference in time of peak (h)
Metal	8	0.57 ± 0.06	−0.4 ± 0.2
Brown	16	0.56 ± 0.07	−0.4 ± 0.3
Occupied white	26	−0.08 ± 0.07	0.5 ± 0.3
Vacant white	8	−0.17 ± 0.03	0.1 ± 0.4

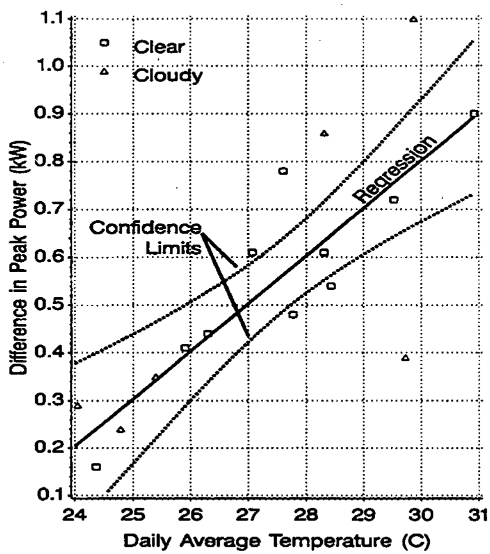


Fig. 8. Difference between daily peak power of Sites B2 and B1 vs. daily average temperature for days in the brown roof period. Difference taken as peak power at B2 minus peak power at B1. Squares represent data for clear days, while the triangles represent cloudy days. The solid line shows the linear regression fit to clear day data, and dashed lines show the 95% confidence region. The difference in peak power is significantly correlated with daily average temperature.

under the same solar conditions, then we should not expect any temperature dependence, for the difference between a high-albedo and low-albedo roof derives only from the difference in absorbed sunlight, which is the same on hot and cold days. However, during a hot day, the peak thermal load may occur earlier in the afternoon, when the insolation is higher, and thus the difference in heat gain through the exterior surface would be greater. This would result in a rise in peak savings with increasing temperature. Perhaps the correlation exists only for the brown-roofed period since it included the hottest days of the summer, with daily average temperatures exceeding 30°C. Furthermore, there were several cloudy days during that period. During a cloudy day, the peak savings should be decreased due to the decrease in insolation, and since the temperature on a cloudy day is usually lower, the cloudiness would also yield a temperature correlation. Indeed, several of the lowest peak savings days were cloudy.

4.2. Savings estimates for occupied school bungalows

During the periods of metal and brown roofs the school bungalows were vacant, and differences in cooling energy consumption were caused by physical differences between the bungalows, independent of their occupancy conditions. Thus, we expect daily cooling energy savings to be the same, regardless of building occupancy. The peak savings, however, might change since the presence of students in the classroom shifts the hourly cooling energy peak to 2 p.m. Thus, the measured difference for vacant bungalows in cooling energy use at 2 p.m. should constitute the peak power reductions for occupied bungalows.

To determine accurately the savings at 2 p.m., we considered days in the metal and brown roof periods when air conditioning use began by 1 p.m., so that the cooling energy use during the ensuing hours would reflect the heat gain into the bungalow. For these days, we took the difference in average hourly cooling energy use between 2 and 3 p.m. For the metal roof period, only two days were available. From these days we estimate peak savings of 0.6 kW during school days between the metal and white roof conditions. For the brown roof period, five days were available, with an average cooling use reduction of 0.6 ± 0.2 kW.

5. Estimates for monthly and seasonal cooling energy savings and peak power reductions

Using the correlations between cooling energy use and daily average temperature discussed above, we estimated the cooling energy savings which would accrue over an entire cooling season. Days with incomplete data coverage or failures in the outdoor air temperature sensor were assigned a daily temperature equal to the average daily temperature over the month in which they occurred. We chose to limit our estimates to the period of actual monitoring in an attempt to limit extrapolation errors. Thus, the results for June and October, shown in Table 8, are estimates of energy consumption and savings for only part of the month. Since the relations between cooling energy and daily average temperature were not available for Site A for days with average temperatures above 25°C, we assumed savings equal to those observed at 25°C. We also estimated the maximum percentage reduction in peak power by assuming the measured peak reductions would be valid during the day with the highest observed power usage.

During the months of June, September, and October, cooling energy use at Site A for the low-albedo case is small, and entirely eliminated by the use of the high-albedo coating. During the hotter months of July and August the cooling

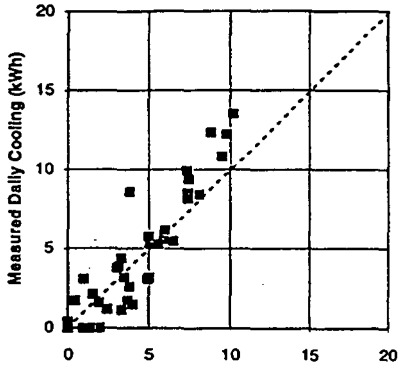
Table 8
Estimated high and low albedo cooling energy use and savings for 1992 cooling season

Site	Dates	Cooling energy	June [a]	July	Aug.	Sept.	Oct.	Total	Peak power
A	6/2–10/14	low albedo (kWh)	0	129	151	50	3	333	3.0 kW
		high albedo (kWh)	0	15	51	0	0	66	2.5 kW
		savings (%) [b]	0	88	66	100	100	80	17%
B [c]	6/28–10/12	low albedo [d] (kWh)	2	256	298	306	93	955	1.9 kW
		high albedo (kWh)	0	144	188	228	65	625	1.3 kW
		savings (%)	100	44	37	25	30	34	32%

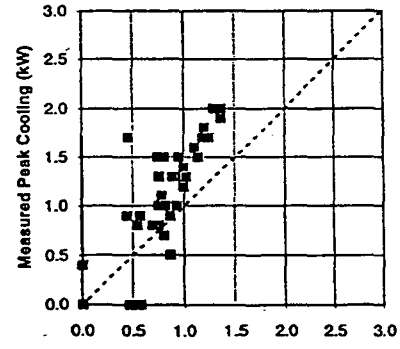
[a] Estimates only include days during the monitoring period.
[b] Savings are for the condenser of the air-conditioner unit only.
[c] If cooling were used only during the school year, seasonal savings would be 80 kWh, 23% of total cooling energy use, for both brown and metal cases.
[d] These numbers represent estimates for a bungalow with metal roof and yellow south east wall. Estimates for brown-roofed and brown-walled bungalow are nearly identical.

energy savings are high. Overall, we estimate savings in cooling energy use of 80% over the monitoring season.

The estimates for the school site were derived under the assumption that the buildings were vacant from June through August, and occupied during weekdays thereafter. The effect of building occupancy was determined using the 1992 comparison of vacant-to-occupied days at site B1. A more realistic scenario for cooling energy use assumes that the cooling system is operated only on school days. Under this assumption, we estimate that, during September and October, a metal- or brown-roofed bungalow would use 350 kWh in cooling energy and a white-roofed bungalow would use 270 kWh, resulting in a 23% savings.



(a) Simulated Daily Cooling (kWh)



(b) Simulated Peak Cooling (kW)

Fig. 9. Measured vs. (a) simulated daily cooling energy and (b) peak power usage at Site A during 1992. Days 161–189 and two high energy usage days have been removed. The diagonal line represents equality between measured and simulated data. Simulations tend to underpredict cooling energy use on high cooling days and to generally underpredict peak cooling power usage.

6. Simulation models of monitored buildings

We modeled Sites A and B using the DOE-2.1E building energy program. A detailed description of the modeling program and inputs can be found in Akbari et al. [5,6]. We supplemented the building-energy simulation program with an empirical duct-inefficiency model as suggested by Modera et al. [7] and Proctor and Proctor [8]. Input data for the DOE-2.1E simulations in this study are given in Table 1. Insulation characteristics were determined from engineering drawings (Site B) and from a resident survey (Site A). Roof albedos were measured, while wall albedos were estimated from photographs. Information on HVAC systems were gathered from site reports and supplemented with cooling equipment product literature. We chose to use the climate data gathered at the sites (instead of typical meteorological year data) for model inputs to avoid errors introduced by systematic temperature variations of several degrees between the various sites and the Sacramento Executive Airport, upon which TMY data are based. Finally, although we had requested building occupants to maintain the thermostat settings at 78°F (25.5°C), our data indicate that the settings had been slightly changed. In our DOE modeling, thermostat setpoints were varied according to indoor temperature data.

6.1. Simulation results and comparison with measured data

A comparison of daily total cooling energy use and peak power at Site A is shown in Fig. 9.[4] The model slightly overestimates cooling energy consumption in the early summer and underestimates cooling during periods of higher

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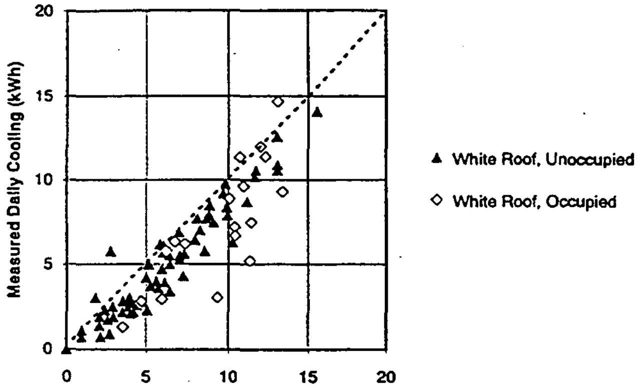
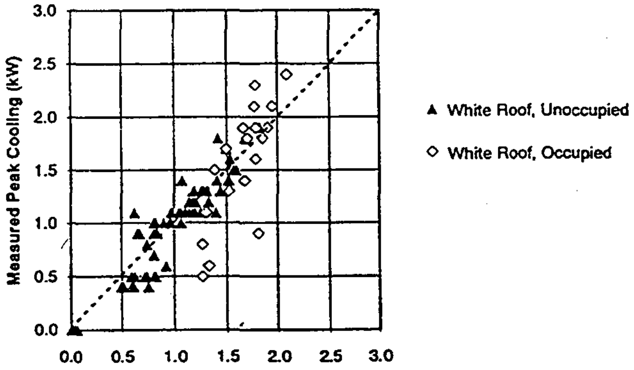
[4] Two days of unusually high measured cooling have been removed from this figure, due to abnormal occupancy of the building.

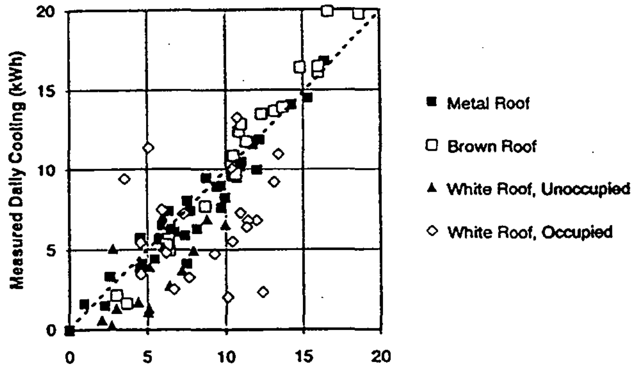


(a) Simulated Daily Cooling (kWh)

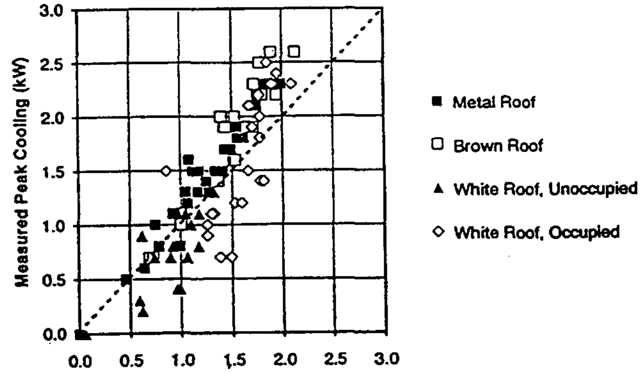


(b) Simulated Peak Cooling (kW)

Fig. 10. Measured vs. (a) simulated daily cooling energy and (b) peak power usage at B1 during 1992. Diagonal line represents equality between measured and modeled data. Simulations overpredict daily cooling energy, particularly for unoccupied days. Simulations predict peak power usage consistently for all days.



(a) Simulated Daily Cooling (kWh)



(b) Simulated Peak Cooling (kW)

Fig. 11. Measured vs. (a) simulated daily cooling energy and (b) peak power usage at B2 during 1992. Diagonal line represents equality between measured and modeled data. Simulations predict daily cooling energy use well except during the occupied white roof period. Cooling power use is underpredicted during brown roof period and high cooling days in occupied white roof period, and overpredicted on low cooling days in white roof periods.

energy use. Similar comparisons for B1 are shown in Fig. 10 and for B2 in Fig. 11. The agreement between simulated and measured data for B1 is fairly good, although there is a consistent overprediction of energy use. At B2, there is good agreement in the metal and brown roof periods, but overprediction in the white roof periods. Both figures show that cooling energy use is more erratic when the building is occupied than when it is vacant.

To assess the reliability of DOE-2.1E in predicting the cooling energy savings resulting from albedo modifications, we compared measured and simulated savings over the periods in which the measurements were made (see Table 9). For Site A, the measured and simulated cooling energy savings compare well, while peak power savings are underestimated by the simulations. For Site B, the cooling energy uses and peak power demands for both the metal- and brown-roofed conditions are overestimated in the simulations. This leads to an underestimation of the savings for both cases.

Thus, large discrepancies exist between measured and simulated savings for the buildings we monitored, even though the modeling of albedo modifications is simple. The discrepancy is most unexpected at Site B, since the school buildings are essentially simple one-room structures that are supposedly easy to model with DOE-2. However, the underpredictions of savings may arise from two failures: the failure of the DOE-2.1E model to simulate correctly the energy use of the building described by the model input, and the failure of

Table 9
Measured and simulated average daily cooling energy savings and peak power reductions at monitored sites for the 1992 monitoring season

Site	Cooling energy savings (kWh/d)			Peak power savings (kW)		
	Measured	Simulated	Ratio (m/s)	Measured	Simulated	Ratio (m/s)
A	2.2 ± 0.1	2.3	0.96	0.6 ± 0.2	0.35	1.6
B (metal versus white)	3.7 ± 0.2	2.9	1.3	0.57 ± 0.06	0.31	1.8
B (brown versus white)	4.6 ± 0.3	2.9	1.6	0.56 ± 0.07	0.28	2.0

the user to provide the model with inputs which best 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 'calibrate' the model. With the available information we cannot definitively explain why the measured results and simulated estimates for energy savings are different.

7. Conclusions

We have measured and documented large cooling energy savings from high-albedo roofs and walls in a house and two school bungalows in Sacramento, California. At a residential site we measured cooling energy savings of ~2.2 kWh/d from changing the roof albedo from 0.18 to 0.73. Peak cooling demand was reduced by 0.6 ± 0.2 kW. Extending our findings to an entire cooling season, we estimate the change from low to high roof albedo would save 264 kWh in cooling energy (80% of total).

Comparison of data from two school bungalows revealed that a white-roofed (albedo of 0.68) bungalow used $51 \pm 3\%$ of the cooling energy used by a bungalow with a metal roof and yellow south east wall. Compared to a bungalow with a brown roof and south east wall, savings were $40 \pm 3\%$ of total cooling energy use. The measured reductions in peak cooling power were 0.57 ± 0.06 kW during the metal-roofed period, and 0.56 ± 0.07 kW during the brown-roofed period. We estimate that the cooling energy savings and peak power reductions would be similar if the buildings were occupied. Over the entire cooling season, we estimate savings of ~330 kWh (35% of total) for both the metal and brown roof cases under the monitored operating schedule. If the cooling system were operated only during school days, energy savings would be about 80 kWh (23% of total) in either the metal or brown roof cases.

We used the DOE-2.1E program to simulate the cooling energy use of the monitored buildings. Examination of daily cooling energy use and peak cooling power revealed some discrepancies between the simulated estimates and measured data. We found that simulations significantly underestimated savings and load reductions. It is uncertain whether this underestimation is caused by the failure of the program to simulate the cooling energy use of the modeled building, or by our failure to accurately describe the building through model input. However, the large discrepancies between measured and simulated results for the simple school bungalows suggest that the DOE-2.1E program may truly underpredict cooling energy savings from albedo modification by as much as twofold.

Acknowledgements

This work was jointly supported by the California Institute for Energy Efficiency (CIEE) and the Sacramento Municipal Utility District (SMUD) through the US Department of Energy, under contract DE-AC0376SF00098.

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098