Measured Savings in Air Conditioning from Shade Trees and White Surfaces

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In support of the Sacramento Municipal Utility District's (SMUD) shade tree program, we have conducted a monitoring project to investigate the potential air-conditioning energy savings of shade trees and white surfaces. This paper discusses the measured savings in air-conditioning electricity use which resulted from painting roofs white and planting shade trees for six houses and a school bungalow in Sacramento CA. The measurement period was late August through early October 1991. The data have not been corrected for variations in solar radiation. For the shade tree cases, much of the savings would disappear if such corrections were made.

Preliminary data indicate that painting the roof of one of the houses white eliminated the air-conditioning energy use, a savings of about 12 kWh/day in energy and 2.3 kW in peak power. Painting the roof and one wall of a school bungalow white reduced its air-conditioning energy use by over 50%. Shading the west windows, south windows, and the air-conditioner condenser units of two of the houses with trees appear to have lowered cooling electricity use by 10 to 40%.

Introduction

We have been studying how to mitigate the heat island effect in U.S. cities, by increasing urban vegetation and albedo (albedo is hemispheric reflectivity integrated over the solar spectrum of wavelengths). Estimates of potential summer peak and total energy savings from heat island mitigation have been made for single-family residences in Sacramento, using the DOE-2 building simulation model. The results indicate that shading homes (windows, walls, and roofs) with large trees can save as much as 34% of their peak cooling demand on a hot summer day (Huang et al. 1987; Huang et al. 1990)[1].

An extensive tree-planting and white-surfacing program in Sacramento (reaching 250,000 unshaded houses) would yield residential cooling savings of about 600 peak MW. These energy savings can be delivered with little cost. In many cases, white surfaces incur no incremental costs if incorporated in routine maintenance; whereas young trees cost about $10 each. Including purchase, planting, and watering costs, the present-valued cost per saved peak kW of these measures would be under $150 per kW in Sacramento (ignoring the many other benefits of more trees, in terms of urban amenity, aesthetics, and outdoor comfort) (SMUD 1991).

The simulations of heat island mitigation measures provide a common basis for comparison of the measures and their potential energy and power savings. However, some important elements, related to actual building operation and both macro- and microclimate variations, are not easy to evaluate using simulations alone. In order to understand the realistic savings potential for each heat-island mitigation measure, before starting large-scale implementation, it is necessary to carry out field experiments to identify unforeseen problems and measure and document actual savings.

Measured energy savings from urban trees and white surfaces are scarce. One previous experimental case study, related to the impact of vegetation, that we know of is that of Parker (1981) in Florida. In that experiment, Parker measured the cooling energy consumption of a mobile building before and after adding trees and shrubs, and found electricity savings of up to 50%. Meier (1991) provides a review of other related or similar work. On the other hand, no significant measured data are available on the effects of white surfaces on cooling energy use. But measured data on the effects of albedo on surface temperatures are available (Taha et al. 1992). The objective of this on-going project is to closely monitor both of these effects in a few buildings in Sacramento.

This paper documents the early efforts of the monitoring task and provides savings results from the first year of the project. In the following sections we will discuss the process of selecting monitoring sites, describe the overall characteristics of each site, and define the monitoring objectives for each one of them. To standardize the processes of instrumenting the buildings and collecting the data, we developed a generalized monitoring protocol and used it to prepare a detailed monitoring plan for each site. The paper also discusses some of the preliminary monitoring results.

Site Selection, Descriptions, and Modifications

Site Selection

During the early stages of this project, we sent out questionnaires and inquiry forms to several homeowners in the Sacramento area. The forms were sent out to a list of people who had previously participated in other monitoring projects by this and other groups. In addition, some of the forms were sent out to SMUD employees. Each questionnaire requested information on building characteristics, occupancy schedules, and system characteristics and operation, as well as general information on site and surroundings' albedo and vegetation density. The questionnaires also contained a request for consent to instrument the buildings.

We were planning to select candidate sites based on the responses given in the questionnaires and to narrow down the list to a few sites. However, the initial number of respondents was not large (~15) and additional factors further reduced this number. Many of those who initially expressed interest in participating did not respond in the final screening stages. We were left with 7 buildings (one school and 6 houses) that we decided to monitor.

Site Description

Table 1 summarizes the overall characteristics of the participant buildings. Site 1 was located in a relatively new residential area and was typical of new construction. Since it was well shaded and located next to a similar but unshaded house (Site 8), we decided to use Site 1 as a control station. Site 8 was a mirror image of Site 1 and adjacent to it. It had no vegetation cover and accordingly, we decided to use it as a vegetation case. Site 2, located in the older area of Sacramento, was selected as an albedo case because the roof was dark and all the exterior walls (and portions of the roof) were heavily shaded by dense vegetation. Also, the owner allowed us to permanently re-coat his roof with a white elastomeric coating (rubber-like paint). Site 5 was well shaded on the south side but could accommodate two small trees on the unshaded east side. Site 6 was located in a new residential area that had a low tree cover. The house itself had little vegetation, particularly on the west side. We decided to position two trees to shade the west windows and partially shade the condenser unit. Also, the roof was highly insulated, thus establishing another reason for monitoring this site as a vegetation case. Thus Sites 5 and 6 were monitored for vegetation effects. Site 7 was also monitored for the effects of vegetation. Two small trees were placed on the southwest side of the house to shade two small windows. Finally, at the school, Site B, we monitored two bungalows for the impacts of albedo modification. The bungalows were adjacent to each other (~0.5 m gap between them) and had similar exposure, dimensions, occupancy, cooling systems, and other characteristics.

Albedo Modifications

One of the school bungalows at Site B, was painted twice (with different colors) to test the effects of albedo modification on surface temperature and air conditioner electricity use. On 8-9-91, we started logging data for the "base case" configuration. Based on our measurements, the metallic roof had an albedo of 0.34 and an estimated emissivity of about 0.3 (both albedo and emissivity can range from 0 to 1). The original walls had an albedo of ~0.30. On 8-21-91, we started logging data again, after the roof and the southeast wall were painted dark brown (the actual painting took place on 8-19). Our measurements indicated an albedo of 0.08 for the brown paint with an emissivity of ~0.95. Finally, on 8-30-91, we began logging data after the roof and the southeast wall were painted white (actual painting took place on 8-28). Our albedo readings indicated a value of 0.68 (emissivity was similar to that of the brown paint, i.e., 0.95).

We started collecting data from Site 2 on 8-22-91. The base case albedo for the grey-painted rolled composition roof was 0.18 over the living area and 0.30 over the garage (not conditioned). After painting with a reflective white paint, our measurements indicated albedos of 0.77 over the living area and 0.81 over the garage. A yellowish hue over the living areas (resulting from fallen leaves) was the reason behind the lower albedo values. Data logging with the white roof started on 9-13-91.

Tree Modifications

Tree modifications were performed with trees in movable containers placed adjacent to walls and windows. At the time of positioning (9-24-91), these trees had a leaf cover of about 50%. Although these trees can grow to 9 m tall by about 9 m across, their sizes at the time of monitoring were very small (~3 m tall by ~1.5 m across). Their impacts on energy use would be much larger once they grew to full size.

Table 1. Site and Building Characteristics

Site→ Case→ Building Type→	Site 1 (control) house	Site 2 (albedo) house	Site 5 (veg.) house	Site 6 (veg.) house	Site 7 (veg.) house	Site 8 (veg.) house	Site B (albedo) school
Site							
Site veg.[1]	mod.	heavy	mod.	low	mod.-low	low	low
Local veg.	mod.-low	mod.-heavy	mod.-low	low	mod.	mod.-low	low
Albedo*	low	low	low	mod.-low	low	low	mod.-low
Local albedo	mod.	mod.-high	mod.-high	mod.	mod.-low	mod.	mod.
Building							
Floor area (ft^2)[2]	1000	1825	1500	1200	1450	900	960
No. of stories	1	1	1	1	1	1	1
Roof material	comp. shingle	rolled comp.	comp. shingle	asph. shingle	comp. shake	comp. shingle	corrug. metal
Wall material	stucco/brick	plywood	wood siding	stucco/siding	stucco	stucco	plywood siding
Roof insulation	R-19	R-11	R-19	R-30	R-19	R-19	R-19
Wall insulation	R-11	R-8	R-11	R-11	R-11	R-11	R-11
Windows	2-pane	1-pane	2-pane	2-pane	2-pane	2-pane	2-pane
Foundation	slab	crawl	slab	slab	slab	slab	crawl
A/C (BTUH)	HP 24000	A/C 40000	HP 29000	A/C 38000	A/C 36000	HP 24000	HP 34600
Heater (BTUH)	HP 21000	Furn 90000	HP 29000	Furn 60000	Furn 42000	HP 21000	HP 50000
Schedules							
No. of occupants	1	2	2	4	6	1	0 to ~20
Weekday schedule	0 (700-1830)	0 (700-1830)	0 (530-2000)	0 (800-1700)	?	0 (800-1700)	~20 (800-1700)
Weekend schedule	0 (vary)	2 (all)	1 (all)	vary	?	vary	0 (all)
Thermostat							
Heating (°F)	68	68	70	68	68	70	68
Cooling (°F)	72	80	80	80	78	82	78
Modification	None	Roof coated	Added 2 trees	Added 3 trees	Added 2 trees	Added 6 trees	Roof coated

1. *Pre-monitoring conditions.*
2. *Excluding garage*

Abbreviations: comp. = composition, asph. = asphalt, corrug. = corrugated, wknd. = weekend, veg. = vegetation, mod. = moderate

Site 5 was well shaded on the south side (even the north side was well-shaded). On the west side there was only one small window, but on the east side there were two bedroom windows that we shaded with two of the trees described above. These trees were removed at the end of the data-collection period as they blocked the narrow walkway on the east side of the building.

Site 6 had no trees on the west-facing side. We shaded two west-facing windows and partially shaded the condenser unit (also located on the west side of the house). An additional tree was placed to shade one bedroom window on the south.

Site 7 had few trees. In fact, the windows facing southwest, northwest, and northeast were all unshaded. There was a tall tree on the south side of the building, but it was too distant to cast any shadows on these windows. We positioned two small trees so that the southwest windows were shaded.

Site 8 had a very low tree cover (the lowest among all sites considered in this study). It had a translucent patio cover on the southwest corner that did not block much solar radiation. A large tree (6 m across, 8 m tall) was planted on the southwest corner of the building on 9-17-91. Because the planting truck could not get close enough, the tree was planted relatively far (~5 m) from the southwest corner. We estimate that this tree would cast a shadow on the wall starting at about 3pm. In addition to this permanent tree, 7 other small ones (as described above) were placed along the south wall to shade the windows and portions of the wall and the condenser unit.

Experiment Design

Monitoring Protocols

Prior to the start of monitoring for this project, we developed detailed experiment design protocols for each site (Akbari et. al. 1991). While the specifics of each site dictated variations in the experiment protocols, the essential features were the same. The monitoring protocol for each site addressed issues related to measurement goals; data product and output; experimental design approach; data analysis tools and procedures; and data accuracy, quality control, verification, and format.

The study required the measurement of numerous variables at each test site. To facilitate an orderly procedure for these measurements and to ensure data quality, we developed methods for using and interfacing with sensors. Depending upon the requirements at a given test site, we employed a variety of sensors to measure the necessary variables: thermocouples (for indoor and outdoor air temperature, surface temperature, and sub-surface soil temperature), hygrometers (for relative humidity), cup anemometers (for wind speed), pyranometers (for albedo), spectral pyranometers (for solar radiation), gypsum-block soil moisture sensors, and current transducers (for air-conditioner energy use).

Calibrations

Two methods of calibration were employed. First, we conducted a test bench calibration. After the test bench calibration, sets of instruments were kept together as units. The units were positioned on test benches in an open outdoor area such that all sensors were exposed to the same atmospheric conditions. One of these units was identified as the control unit. The results from the sensors from other units were then plotted versus the results from the control unit sensors. In this way, sensors were internally calibrated to a control set of sensors.

After the end of the project, the sensors were recalibrated to make sure no drift had occurred. Each combination of sensors, wires, connections, and a data-logger made a set of components that we kept together at the calibration site and then at the monitoring sites. The components of each set were identified by their serial numbers. Each of the pre- and post-calibration periods lasted for one week.

Results and Analysis

In this section, we discuss results from the initial analysis of some of the measured data. For each site, the cooling electricity use is examined as a function of outdoor temperature (means and maxima), indoor temperatures, and indoor/outdoor temperature differences. The analysis is carried out for pre-retrofit (base case) and post-retrofit (albedo or vegetation modification) conditions. The results are presented for both daily and hourly time scales.

There are a few points one should keep in mind. First, the amount of cooling electricity we measured was actually the amount consumed by the condenser unit (in split systems). In these cases, another 200 - 300 W should be added to account for the effects of the air-handler and fan energy use. Second, in Sites 5, 6, 7, and 8, where vegetation modifications were performed, the trees were small, and their effects were limited to shading (no wind or evapotranspirative cooling effects). Thus, this is the minimum beneficial effect trees can have. Finally, there are concerns that, because of the length of the monitoring period, solar intensity became generally lower during the post-retrofit monitoring period. Therefore, cooling energy savings could be overestimated, since part of the difference could have been caused by milder weather conditions and reduced insolation. As we will show later, the post-retrofit period was not cooler than the pre-retrofit period, but the intensity of solar radiation was generally lower.

Albedo Cases

Since this study was developed in support of SMUD's tree planting program, only two albedo cases were investigated. These cases, however, provided some of the more significant results. These results are presented below.

Site 2. Data from this site were available from 8/22 through 9/10 for pre-modification conditions, and from 9/16 through 10/20 for post-modification conditions. There were missing data for 4 days in the "pre" period and one day in the "post" period. Figure 1a shows daily cooling electricity use plotted against the maximum daily temperature for both pre- and post-retrofit (albedos of 0.18 and 0.77) periods. In effect, increasing the albedo of the roof cancelled all the cooling energy use in that building. The reason there is cooling energy use even after whitening the roof is that the thermostat setting was lowered from 25.5°C down to ~23.5°C (78 to 75°F) for a few days. But practically speaking, the cooling load disappeared after the application of a high-albedo paint on the roof.

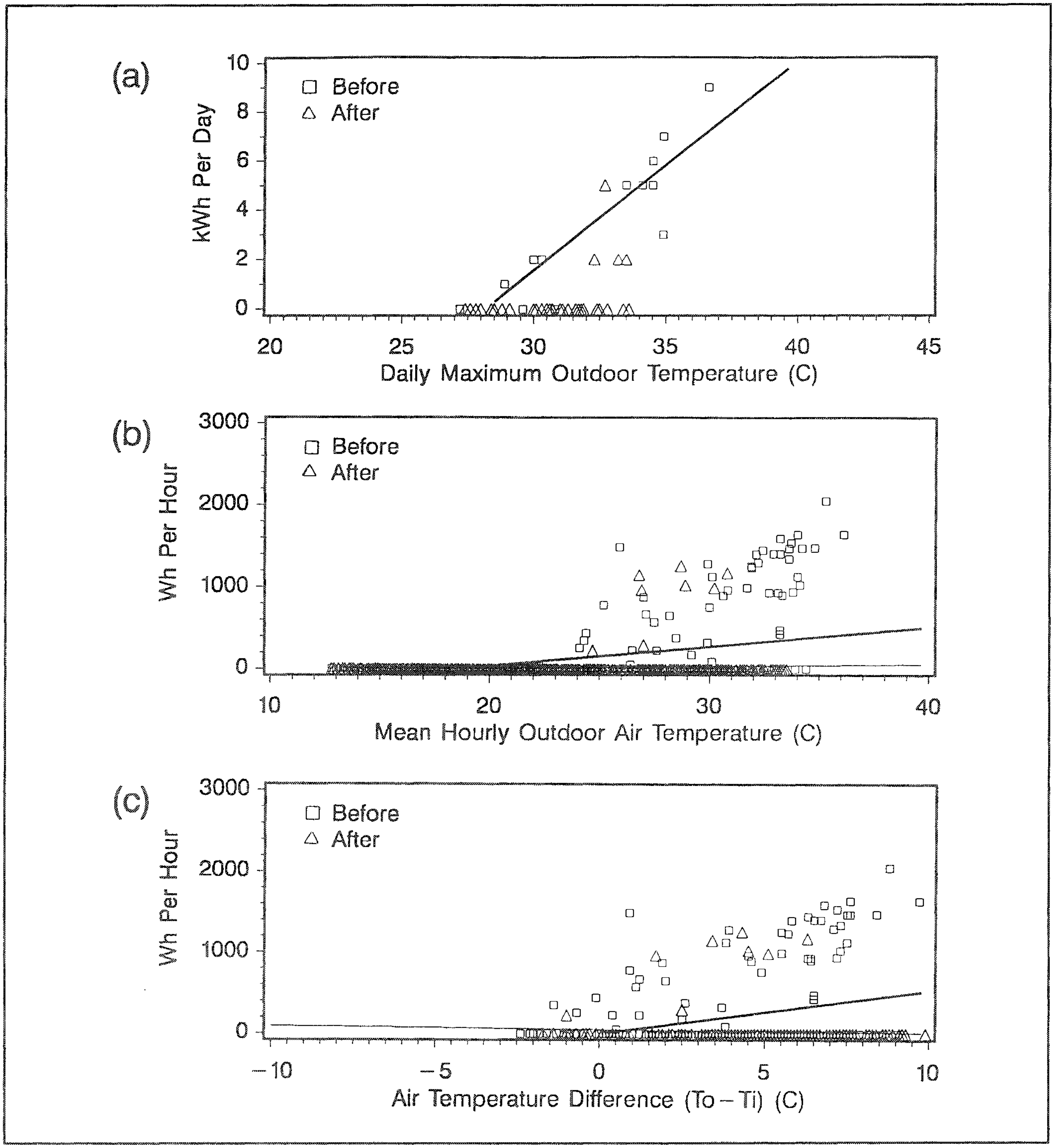

Figure 1. Site 2 (albedo case): (a) Daily energy use plotted vs. daily maximum outdoor air temperature; and hourly energy use plotted vs. (b) mean hourly outdoor air temperature and (c) vs. the outside-inside air temperature difference. The thick lines in these plots are best linear fits to the pre-retrofit (before) data. The thin lines are best linear fits to the post-retrofit (after) data.

The intensity of solar radiation was generally lower during the "post" period; across the 45 day monitoring period, daily total solar radiation decreased from 7.2 to 4 kWh day^{-1}. How much of an effect this decrease had on the reduction in cooling energy use cannot be determined from measured data because most of the data points corresponding to the "post" period have no cooling energy use.

In Figure 1b, average cooling energy use is plotted versus the mean hourly outdoor air temperature. The large amount of energy savings is clear. In Figure 1c, the same energy use data is plotted against the hourly difference between outdoor and indoor air temperatures (To-Ti). The sloping of the scatter is now more obvious, and indicates that there was need for cooling when the outdoor temperature was in the range of 0-9°C (0 to 16°F) higher than the indoor temperature. As in the case with daily data, a certain amount of correction for solar intensity is necessary at the hourly level, too.

The most intriguing factor about this site is its pronounced microclimate. This, coupled with the near-total blockage of window solar gain by trees, produced a house with a cooling load dominated by solar insolation on the roof. In other words, the disappearance of the cooling load resulted because the roof was the only significant source of cooling load. When this point is taken into consideration, it is not surprising that painting the roof resulted in the total elimination of cooling load.

Site B. The test bungalow underwent two modifications during the monitoring period. First its roof and southeast wall were coated with a brown paint and the building was monitored in that state for about one week. Then, the roof and the southeast wall of the test bungalow were coated white, and monitored for 35 days. Table 2 gives values for albedo (α) and emissivity (ϵ) of walls and roof of the test bungalow throughout the monitoring period.

Table 2. Albedo and Emissivity of the Test Bungalow at the School Site

Monitoring Period	Roof α/ε	SE Wall α/ε	Other Walls α/ε
A	0.34/0.30	0.30/0.95	0.30/0.95
B	0.08/0.95	0.08/0.95	0.30/0.95
C & D	0.68/0.95	0.68/0.95	0.30/0.95

Period A corresponds to the base case configuration, Period B corresponds to the time interval during which the test unit had a brown roof and southeast wall. Periods C and D correspond to the time interval during which the roof and the wall of the test unit were coated white. During Periods A, B, and C, the bungalow was unoccupied; during Period D the bungalow was occupied. Due to late start of the monitoring project and since the school was starting in early September, the monitoring periods A, B, and C were fairly short. Here we only discuss data for Periods B and C, when the bungalow was painted white from the dark brown color.

Figure 2a shows data for the bungalow during Periods B and C. We can see that increasing the albedo from 0.08 (brown) to 0.68 (white) had a significant impact on cooling energy use. While cooling with the low albedo case started at an outdoor air temperature of 22°C (72°F), cooling in the case with white coating started at an outdoor air temperature of 31°C (88°F).

Figure 2b shows similar information, except that the data points with zero energy use were dropped. We can see that while cooling needs in the low albedo case encompass a To-Ti range from -3°C to +11°C (-5 to 20°F), the cooling needs in the case with high albedo were confined to a To-Ti range of +4°C to +12°C (7 to 22°F). Note that, in these correlations, there was no need to adjust for solar radiation as Periods B and C were short and Period C was immediately following Period B, so that there was no significant decrease in solar radiation over these intervals (total daily irradiance during Periods B and C was ~7 kWh day^{-1}.

Vegetation Cases

It should be emphasized that the trees used in this study were extremely small. This fact, combined with the uncertainty regarding the impact of variations in solar intensity lead us to conclude that the results for all of the vegetation cases are of questionable significance. Thus, the results presented below should be viewed as being preliminary.

Site 5. This site was first monitored from 9/6 through 19/16, and then two trees were placed on the east side, and the building was monitored again from 9/25 through 10/20. Because of the existing shading and since the trees were placed on the east side (which has a relatively small impact on heat gain), we expected little difference in energy use between the base and the modified cases. Figure 3a shows that there was not much difference between the two cases on a daily basis. At 38°C (100°F), the measured difference amounts to only ~7%. If a correction for solar radiation is performed, there may be minimal or no difference in cooling energy use.

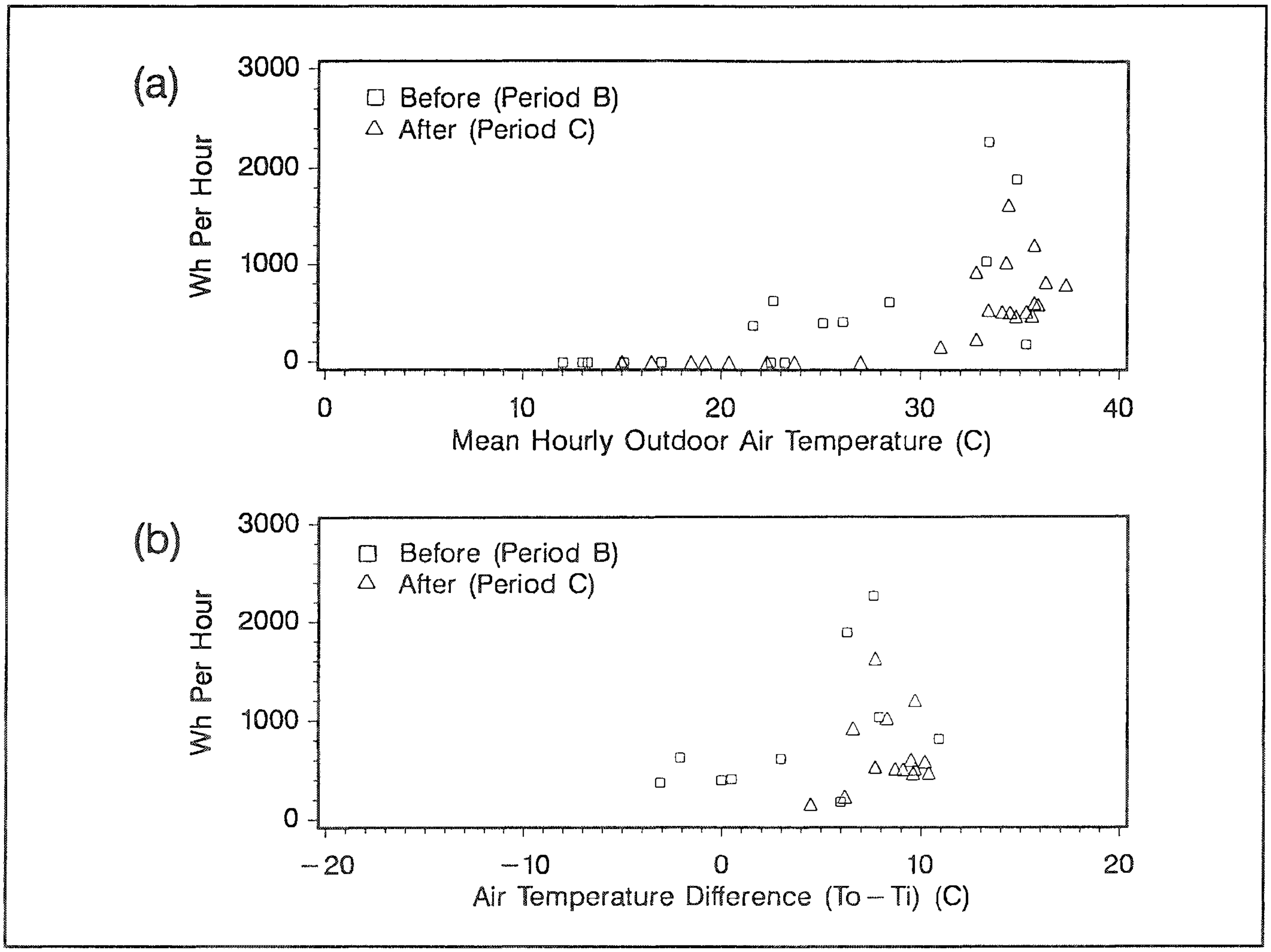

Figure 2. School Site (albedo case): Hourly energy use plotted vs. (a) the mean hourly outdoor air temperature and (b) vs. the outside-inside air temperature difference.

Site 6. Data for this site were available from 8/21 through 9/22 for "pre" conditions and from 9/25 through 10/20 for "post" conditions. There were six missing days in the pre-monitoring period and seven missing days in the post-monitoring period. In the post-retrofit period, two trees were placed on the west side and one tree on the south. The condenser unit was also partially shaded by one of the west trees.

Figure 3b shows daily energy use data plotted versus the maximum daily temperature at Site 6. At 38°C (100°F), there is a difference of 4.75 kWh day^{-1} (about 40%) in cooling electricity use resulting from the shading effect of trees. Across 40 days of monitoring, the daily total solar radiation dropped from 7 kWh day^{-1} down to ~4 kWh day^{-1}. The impact of lower insolation on cooling electricity use is estimated with the help of DOE-2 simulations to be about 10 - 20%.

Site 7. Data from this site were available from 9/3 through 9/22 for the pre-retrofit and from 9/25 through 10/17 for the post-retrofit conditions. There were a few hours of missing data in both pre- and post-retrofit monitoring periods. Figure 3c shows daily data for Site 7. Again, at 38°C (100°F) outdoor air temperature, the difference in cooling electricity use between pre- and post-retrofit periods is ~3 kWh day^{-1} or about 32%.

Site 8. We positioned several trees along the south wall, so as to shade the windows and portions of the wall. Figure 3d represents some of the daily data from that site. At 38°C (100°F), there is a cooling electricity use difference of ~2.5 kWh day^{-1}, which amounts to a reduction of 12%.

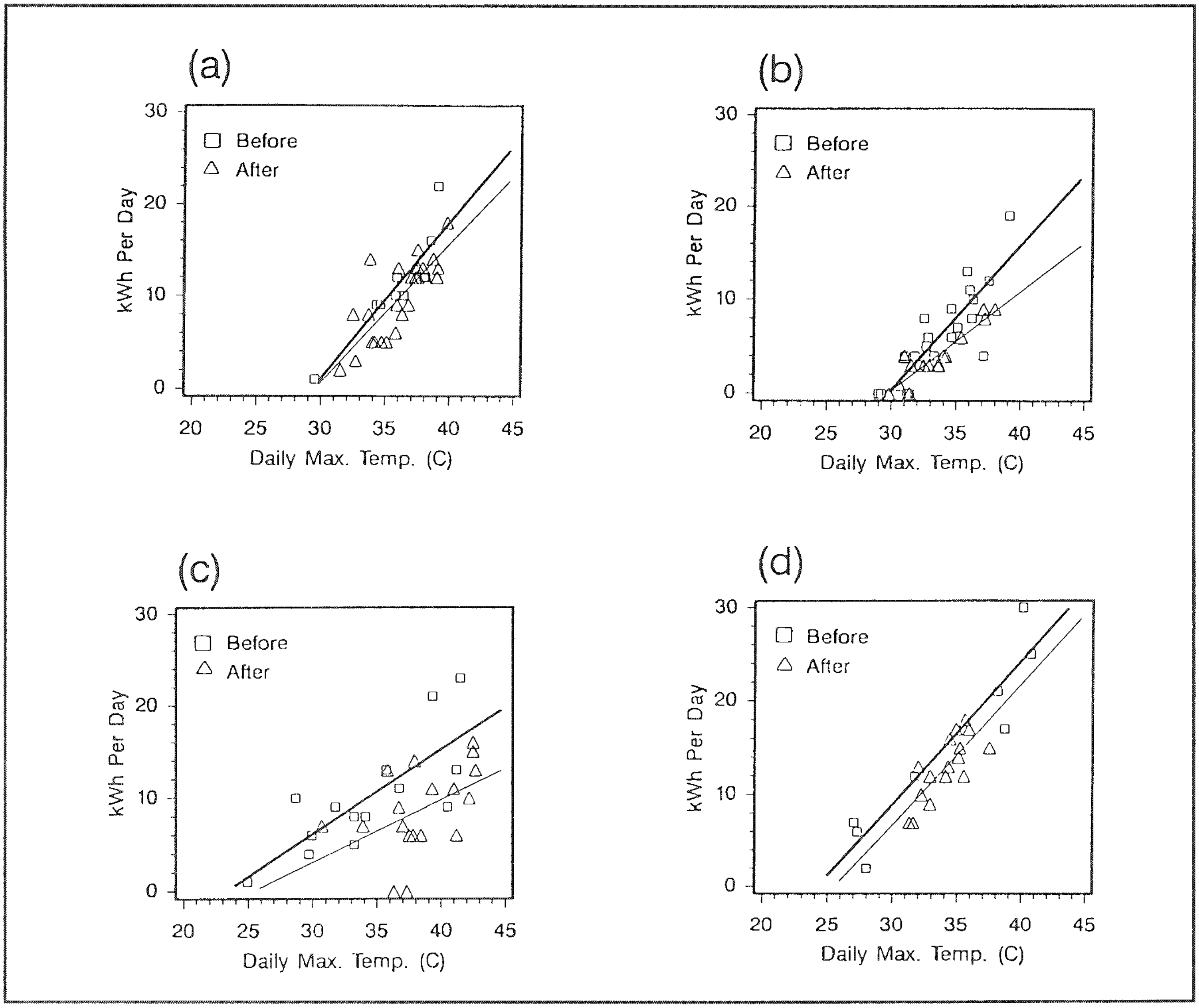

Figure 3. Site 5 (vegetation case): Daily energy use plotted vs. the daily maximum outdoor air temperature for sites 5 (a), 6 (b), 7 (c), and 8 (d). The thick lines in these plots are best linear fits to the pre-retrofit (before) data. The thin lines are best linear fits to the post-retrofit (after) data.

Conclusion

The purpose of this study was to quantify the potential of high-albedo materials and vegetation for reducing cooling energy use in buildings. The analysis of measured data indicates that albedo modifications had significant impacts on cooling energy use, whereas the small trees had a measurable impact only in two of the four vegetation sites.

In one house, recoating the dark roof with a high-albedo coating resulted in almost 100% reduction in cooling energy use. Air conditioning energy use reductions of 50% were achieved when the roof and southeast wall of a school bungalow were painted white from a dark brown color.

In the vegetation sites, savings were generally lower than in the albedo cases. In one house, the addition of two trees on the west and one tree on the south resulted in reducing cooling energy use by ~40%, whereas the addition of two southwest trees to another home reduced its use by ~30%. The other two cases showed smaller effects. The addition of two trees on the east side of a well-shaded house reduced its cooling energy use by

~10%, and the addition of six trees on the south side of a completely unshaded home reduced its cooling energy use by only ~10%. As was pointed out in the text, a large portion of the cooling energy reductions for the vegetation sites may be the result of reduced solar insolation over the course of the study.

In addition to internal loads, schedules, and envelope characteristics, the reason some sites had larger energy use impacts than others might be the fact that the local microclimate was different from one location to another. For example, Site 2 was in a cooler environment, heavily shaded, and therefore, this might have helped save 100% of cooling energy use when the roof was coated with a high-albedo paint. Site 8, on the other hand, was in a warmer part of Sacramento, and that might explain why only 10% of cooling energy was saved by planting six trees on its south side.

This project demonstrated promising potential in cooling energy savings from high-albedo surfaces and shade trees. The tests were limited to the direct effect (direct reduction of incoming solar radiation). Also, in the vegetation sites, the effects of trees were limited to shading only. Trees would have resulted in larger savings in cooling energy use had they been bigger and denser since in addition to their shade they would be able to cool the ambient air by evapotranspiration and reduce infiltration by slowing the wind in the vicinity of buildings. The trees that were used in this project were too small to exert a significant drag on the wind or to evaporate enough water to cool the ambient air. We plan to carry out larger scale studies of the indirect effects of vegetation and albedo, which, in our preliminary computer simulations, seem to be more significant than the direct effects.

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Endnotes

1. Even more promising results were obtained by simulating a change in the overall albedo of the city, from an existing ~15-20% to a "whitewashed" 40% (Taha et al. 1988). Under such conditions, the peak cooling demand dropped by ~40-50% in Sacramento. The overall combined effects of trees and white-surfaces suggest savings of about 50% in residential cooling peak demand in Sacramento (Taha et al. 1988; Akbari et al. 1990).

Disclaimer

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