**Title**
Summer Heat Islands, Urban Trees, and White Surfaces

**Authors**
Akbari, H.
Rosenfeld, A.H.
Taha, H.

**Publication Date**
1990

LBL-28308

# SUMMER HEAT ISLANDS, URBAN TREES, AND WHITE SURFACES

H. Akbari, A. H. Rosenfeld, and H. Taha

Energy Analysis Program
Center for Building Science
Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

January 1990

---

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building System Division of the U. S. Department of Energy under contract No. DE-AC0376SF00098. This work was in part funded by a grant from the University-Wide Energy Research Group, University of California-Berkeley.

# SUMMER HEAT ISLANDS, URBAN TREES, AND WHITE SURFACES

**H. Akbari, Ph.D.**

**A.H. Rosenfeld, Ph.D.**
*Member ASHRAE*

**H. Taha**
*Member ASHRAE*

## ABSTRACT

*Temperature trends for the last 100 years in several U.S. cities were analyzed. Since ≈1940 there has been a steady overall increase in urban temperatures. Summer monthly averages have increased by 0.25-1°F per decade (≈1°F for larger cities like Los Angeles and 0.25°F for smaller cities). There is no evidence that this rise is moderating, and of course global greenhouse warming will add a comparable rise. Typical electric demand of cities increases by 1% to 2% of the peak for each °F, and most major cities are now ≈5°F warmer than they were in the early 1900s. Hence, we estimate that about 5% to 10% of the current urban electric demand is spent to cool buildings just to compensate for the heat island effect. For example, downtown Los Angeles is now 5°F hotter than in 1940 and so the L.A. basin demand is up by 1500 MW, worth $150,000 per hour on a hot afternoon (the equivalent national bill is ≈$1M/hour). In major cities, smog episodes are absent below about 70°F, but they become unacceptable by 90°F, so a rise of 10°F because of past and future heat island effects is very significant.*

*There are some strategies that can alleviate the heat island effect. Computer simulations and field studies have quantified the potential of trees and lighter surfaces for reducing summer heat islands. Results indicate that the cost of saved energy and avoided $CO_2$, through greening and whitening of urban areas, is less than 1¢/kWh and 2¢/kg of carbon, respectively.*

## INTRODUCTION

Cities are getting warmer than their suburban and rural surroundings (Karl et al. 1988; Kukla et al. 1986), and this long-term warming is responsible for an increase of 1% to 2% in cooling loads (with respect to the peak) for each °F raise. As temperature rises, so does the severity of smog and the production of other airborne pollutants.

Before mechanical air conditioning, people cooled their homes by planting trees around them and painting the walls and roofs white. The disappearance of such simple practices in many urban areas contributes to summer "heat islands" with typical daily average intensities of 3° to 5°C. However, there are ways to mitigate this negative effect on both micro- and meso-scales (Landsberg 1978; Thurow, 1983).

Urban trees and light-colored surfaces are effective and inexpensive measures to reduce heat islands and create summer oases. Trees can improve the urban climate by shading, wind-shielding, and evapotranspiration and thus reduce summer cooling energy use in buildings at about 1% of the capital cost of the avoided power plants and air-conditioning equipment. Light colors decrease surface absorption of short-wave radiation, thereby reducing surface temperatures and convective heating of near-surface air. On the urban scale, this results in cooler cities. External surfaces of buildings can be painted white (or a light color) and streets and parking lots resurfaced with white sand (which is necessary anyway), thereby reducing cooling energy needs at relatively low costs.

In addition to saving energy, urban trees and light-colored surfaces are the most cost-effective ways to slow the growth of atmospheric $CO_2$. By reducing the need to burn fossil fuels for generating electricity, urban trees are many times more efficient at limiting atmospheric $CO_2$ than is rural forestation.

Our calculations indicate that heat island mitigation strategies such as urban trees and light-colored surfaces can save 0.5 quad per year at a cost of less than 1¢/kWh and decrease $CO_2$ emissions by about 17 million tons of carbon per year.

## HEAT ISLAND EFFECTS AND CONSEQUENCES

### Long-Term Urban Temperature Trends

Temperature data for the analysis were obtained from the Carbon Dioxide Information Analysis Center (CDIAC 1987) and Goodridge (1987,1989). The data have been adjusted for station moves (relocation), change of height, time of observation bias, change in type of instruments, and discontinuity in record (Karl et al. 1986, 1987). They have not been corrected for urban growth (population) effects.

For example, Los Angeles is a large metropolis with a mild to warm climate. Figure 1a depicts the annual temperature highs between 1877 and 1984. It clearly indicates that downtown Los Angeles was

---

**H. Akbari** is a staff scientist at Lawrence Berkeley Laboratory, **A.H. Rosenfeld** is a professor of physics at the University of California and director of the Center for Building Science, and **H. Taha** is a Ph.D. candidate at the University of California. All are members of the Heat Island Project at the Applied Science Division, Lawrence Berkeley Laboratory, Berkeley, CA.

cooling at a rate of 0.05°F/yr up to 1930 and then started a steady warming of 0.13°F/yr (1.3°F/decade) afterwards. In other words, downtown Los Angeles's annual high temperatures are now ≈6°F higher than they were in 1940. Figure 1b shows the post-'40s warming trend in further detail. One can see that average temperature slopes of the summer months are in the range of 0.11 to 0.13 (±.02)°F/yr. Table 1 summarizes some related statistics:

**TABLE 1**
**Summary Statistics for the Monthly Average Temperature Trends ($\varepsilon$ is standard error of the slope, and $\alpha$ is significance).**

| Month | Fit | $r^2$ | $\varepsilon$ | $\alpha$ |
|---|---|---|---|---|
| June | T=65.71(1940)+0.1307°/yr | 0.346 | 0.027 | 0.00 |
| July | T=70.93(1940)+0.1142°/yr | 0.346 | 0.023 | 0.00 |
| August | T=71.47(1940)+0.1173°/yr | 0.389 | 0.022 | 0.00 |
| September | T=70.46(1940)+0.1108°/yr | 0.278 | 0.026 | 0.00 |

Figure 2 depicts the long-term trend in annual mean temperatures in Washington, DC, between 1871 and 1987. One can see that since 1900 there has been a steady rise of 0.5°F/decade and that the total rise over 80 years is about 4°F. Contrary to Los Angeles, whose temperatures were all urban (Figure 1), Washington, DC's urban stations moved to airport locations in 1942.[1]

The data indicate that this recent warming trend is typical of most U.S. metropolitan areas. As an example, consider some California cities. Figure 3 (Goodridge 1989) shows that before 1940, the average urban-rural temperature differences for 31 urban and 31 rural stations in California were always negative, i.e., cities were cooler than their surroundings (both annual and 10-year averages show this). We speculate that this is a result of oasis effects in the relatively more vegetated city centers. After 1940, when built-up areas took over the vegetated ones, the urban centers became as warm as or warmer than the suburbs, and the trend becomes quite obvious after 1965, with a slope of about 0.7°F/decade. The heat island effect has thus become dominant in these urban areas.

Goodridge (1989) shows that San Diego, Los Angeles, San Francisco, and Sacramento have warming trends exceeding 0.4°F/decade. Our data support his findings and indicate that the August warming trends in San Diego, CA, and San Bernardino, CA, are, respectively, 0.8°F/decade and 0.6°F/decade. They also indicate that the maximum temperatures in Davis and Pasadena, CA, have increased by ≈0.8 and ≈0.9°F, respectively.

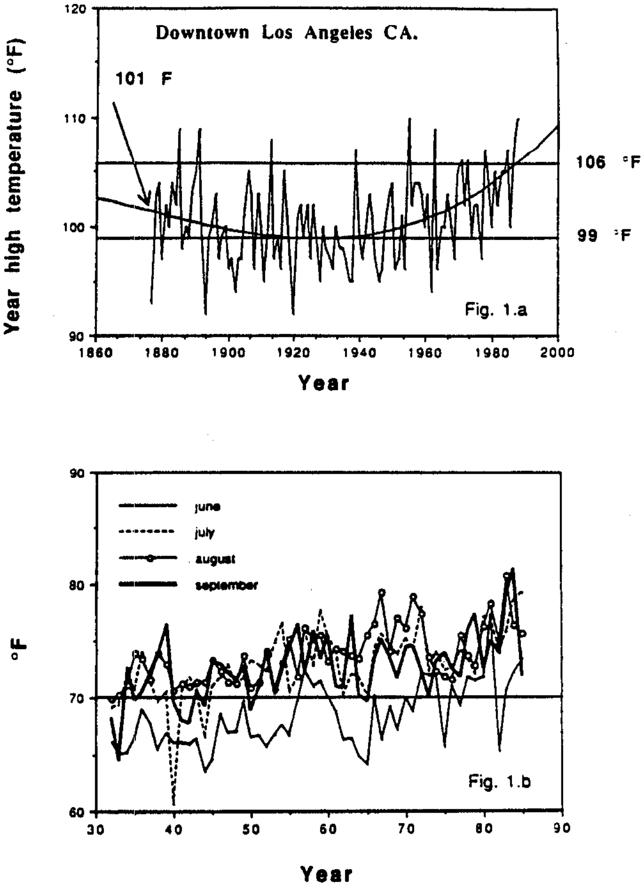


***Figure 1*** *Long-term annual high temperatures (a), and monthly averages (b) in Los Angeles, CA*

## Heat Islands and Cooling Loads

Figures 4a and b depict the dependence of system-wide utility load on dry-bulb temperature for the portion of the city of Los Angeles served by the Los Angeles Department of Water and Power (LADWP). In Figure 4a, the 4 p.m. load is plotted against the 4 p.m. temperature for 365 days in 1986.[2] One can distinguish some weekend scatter, base load scatter, and temperature-dependent cooling load. The upper boundary of the peak demand "envelope" slopes at ≈72 MW/°F (2%/°F). In Figure 4b, the same procedure is repeated by plotting peak load (at 4 p.m.) vs. average daily temperature for 365 days in 1986; the slope is 75 MW/°F, about 2%/°F of the peak. Recalling that the city of Los Angeles has warmed by ≈5°F since 1940 (Figure 1), one can see that we have incurred an increase of 375 MW or 10% of the current peak load.

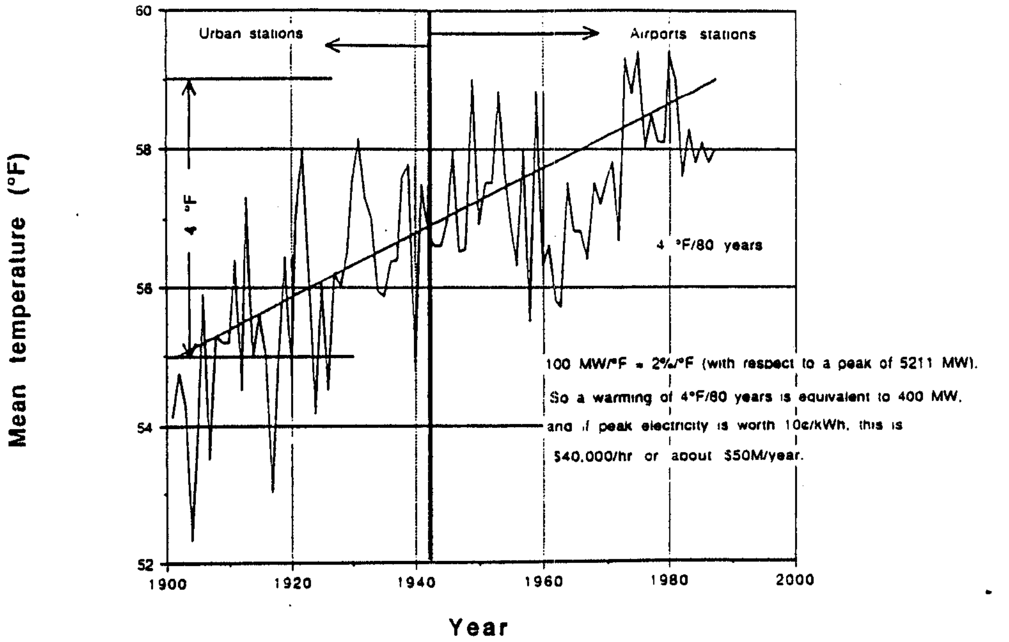
In Figure 5, a similar plot is constructed for a southern California utility (SCE)[3] whereby the 4 p.m. loads are plotted against the daily average temperatures for 365 days in 1986. Although representative temperatures for the SCE service area were available, we decided to plot the SCE load data against the LADWP temperatures, so

---

[1] Up to 1942, the Washington data are for urban weather stations, but after 1942, the stations moved to airports. Figure 2 thus depicts data from different locations. So while urban heat island information is needed, the last 40 years provide mostly airport data (adjusted or unadjusted) that may underestimate the urban effects, because cities warm up faster than their suburbs where airports are usually located. This is not only the case with Washington, DC, but also with most major cities in the U.S. The authors are not aware, at this time, of any continuous urban temperature data base for the last 100 years (except for Los Angeles and San Francisco, CA), and we believe that monitoring of this kind should be undertaken, if city-wide energy use is to be better understood and mitigation strategies properly applied.

[2] We chose 1986 because weather and load data were already available.

[3] The system area surrounds Los Angeles but does not include the city itself, which is served by LADWP.



100 MW/°F = 2%/°F (with respect to a peak of 5211 MW). So a warming of 4°F/80 years is equivalent to 400 MW, and if peak electricity is worth 10¢/kWh, this is $40,000/hr or about $50M/year.

**Figure 2** *Annual mean temperatures in Washington, DC (1871-1987). Data source: Mayberry, E. Potomac Electric Power Company, Washington, DC.*

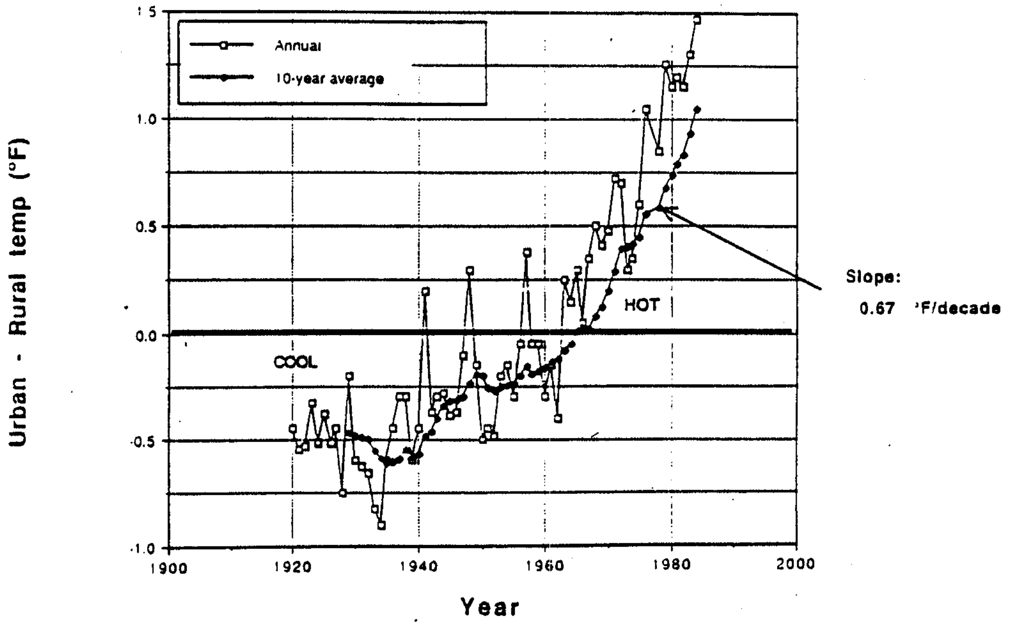


**Figure 3** *Urban-rural temperature differences in California. Based on 31 urban and 31 rural stations. Data Source: Goodrige (1989)*

we can consistently use them[4] for comparison with the long-term trend shown in Figure 1.

Figure 5 shows an envelope's upper boundary slopes at 225 MW/°F, or about 1.6%/°F. If we add this to the LADWP slope (75 MW/°F), the total reaches 300 MW/°F, and for a 5°F rise since 1940, that means ≈1.5 GW of heat island-dependent load. If peak electricity is worth 10¢/kWh, then this represents $150,000/°F for each hour. For Washington, DC (Figure 2), the slope is 100 MW/°F (2%/°F of the 5200 MW peak). So for an increase of 4°F over 80 years, this is an additional 400 MW costing ≈$40,000/hr. There are about 1300 hours of air-conditioning in Wahington, DC, resulting in ≈$50M annually. We estimate that the hourly cost of all the heat islands in the U.S. is of an order of magnitude of $1 million.

---

[4] To study peak load/temperature dependence, an appropriate method is to use 4 p.m. (peak) temperatures over the period of interest, as was the case in Figure 4a. But hourly data are not always available for long-term periods, i.e., the last 100 years, and only daily or monthly averages can be found. The use of the average temperature is thus justified, and we have shown that in Figure 4b. We saw that there was no major change in the slope, compared to Figure 4a. When the SCE load was plotted against LADWP temperatures (Figure 5), it resulted in a similar pattern. We will use temperature averages in our analysis of load/temperature data for other locations, as well.

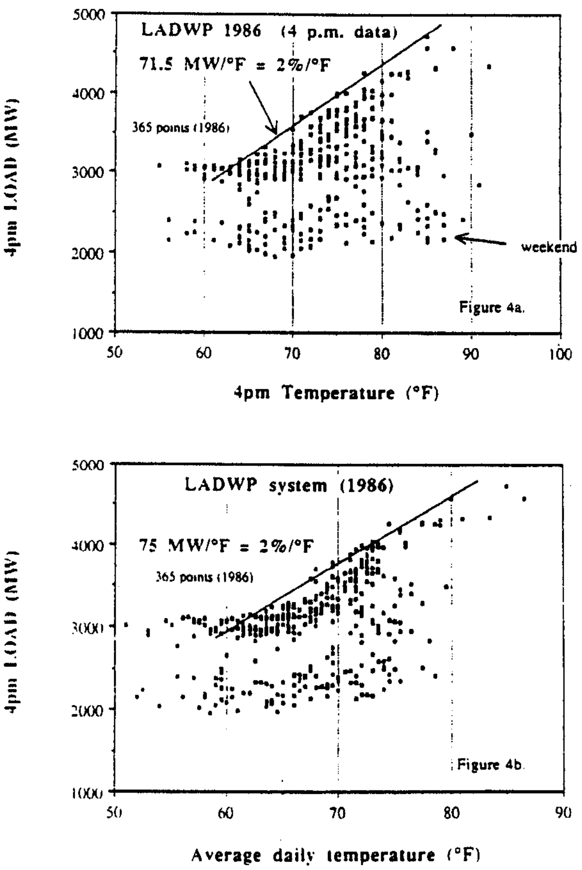


***Figure 4*** *Load vs. temperature in downtown Los Angeles (1986)*

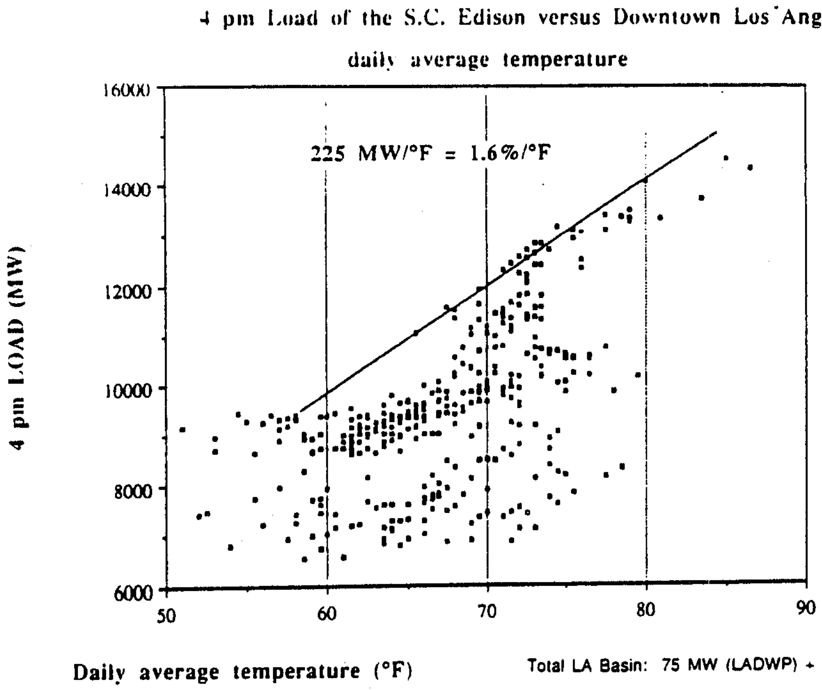
## Heat Islands and Smog

Not only do summer heat islands increase system-wide cooling loads, but they also increase the amount of smog, brought on by higher urban temperatures. For example, Figure 6 shows the daily maxima in ozone ($O_3$) levels for Los Angeles. Below 74°F, smog never exceeds the National Atmospheric Air Quality Standard (NAAQS), but by 94°F, smog levels are too high (≈26 pphm). Restated, smog is very sensitive to this 20°F increase of which one-fourth is already attributable to the heat island effect. Argento (1988) reports similar results for 13 cities throughout the state of Texas.

## HEAT ISLAND MITIGATION

Light-colored urban surfaces and trees are proven and inexpensive measures to reduce heat islands and create summer oases. The effects of modifying the urban environment by planting trees and increasing albedos are best quantified in terms of direct and indirect contributions. The direct effect of planting trees around a building or painting the building surfaces with a light color is to alter the energy balance and cooling requirements of that particular building. However, when trees are planted and albedos are modified throughout an entire city, the energy balance of the whole city is modified, producing city-wide changes in climate. Phenomena associated with the city-wide changes in climate are referred to as indirect effects, because they indirectly affect the energy use in an individual building.

An important reason for making a distinction between direct and indirect effects is that, while direct



Total LA Basin: 75 MW (LADWP) + 225 MW (SCE) = 300 MW
300 MW * 5 °F = 1500 MW, worth ~ $150,000 per hour

***Figure 5*** *Load vs. temperature for the SCE system (1986)*

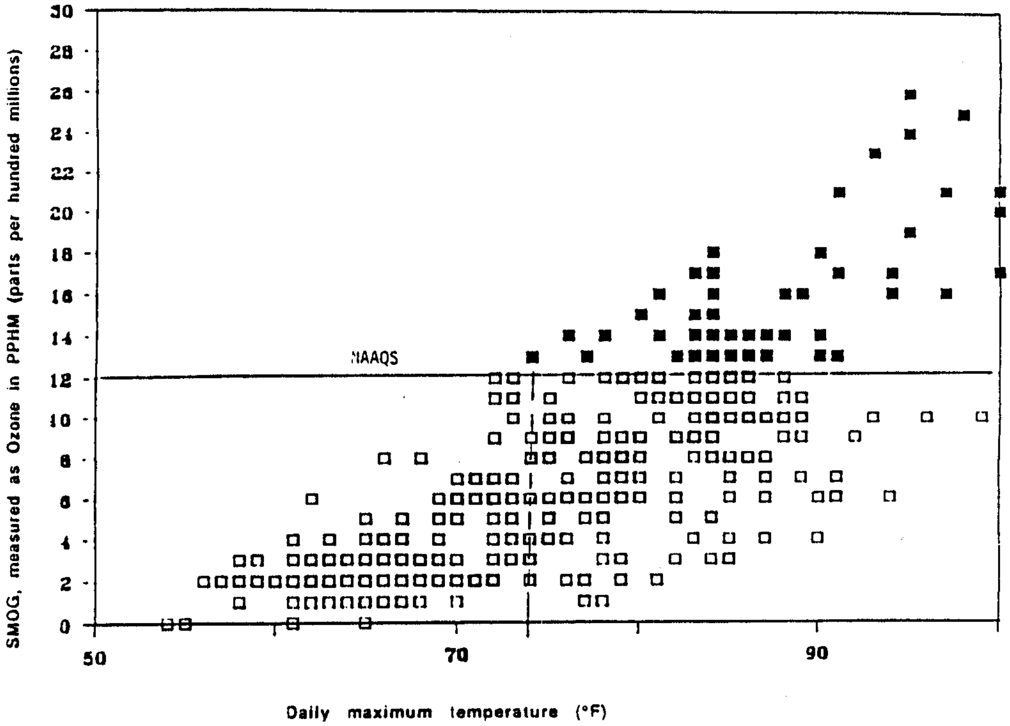


*Figure 6 Ozone level vs. temperature in Los Angeles, CA (1985)*

effects are well recognized and accounted for in present models of building energy use, indirect effects have received much less recognition. Methods of accounting for indirect effects have not been as well developed and remain comparatively less certain. Understanding these effects and incorporating them into accounts of building energy use is the focus of our current research. It is worth noting that the phenomenon of summer urban heat islands is itself the consequence of indirect effects of the built environment. We are proposing to use the same principles to cool hot cities.

The issue of direct and indirect effects also enters into our discussion of atmospheric $CO_2$. Planting trees has the direct effect of reducing atmospheric $CO_2$ because each individual tree directly sequesters carbon from the atmosphere through photosynthesis. However, planting trees in cities also has an indirect effect on $CO_2$. By reducing the demand for cooling energy, urban trees indirectly reduce emission of $CO_2$ from power plants. As will be seen, the amount of $CO_2$ avoided via the indirect effect is considerably greater than the amount sequestered directly.

## Urban Trees

Case studies have documented dramatic differences in cooling energy use between houses on landscaped and unlandscaped sites. Parker (1981) measured cooling savings resulting from well-planned landscaping and found that properly located trees and shrubs reduced daily air-conditioning electricity use by as much as 50%.

Trees affect energy use in buildings through direct processes such as (1) reducing solar heat gain through windows, walls, and roofs by shading, (2) reducing the radiant heat gain from surroundings by shading and view factor reduction; and (3) reducing infiltration by shielding a particular building from wind. Deciduous trees are beneficial because they allow solar gain in buildings during wintertime.

On the other hand, the indirect effects of trees include (1) reducing the rate of outside air infiltration by increasing surface roughness and decreasing urban wind speeds and (2) reducing the heat gain of buildings by lowering ambient air temperatures through evapotranspiration (the evaporation of water from soil-vegetation systems). On hot summer days, trees act as natural "evaporative coolers," using up to 100 gallons of water a day each, thus lowering the ambient temperature. A significant increase in urban trees leads to increased evapotranspiration, thus producing an "oasis effect" and significantly lowering urban ambient temperatures. Buildings in these cooler environments will require less cooling power and energy. The effect of evapotranspiration is minimal in winter because of lower ambient temperatures and the absence of leaves on deciduous trees.

## Urban Albedo

The energy balance of a building or an entire city depends on the net solar radiation at its surface. To describe the relative amounts of reflected vs. absorbed radiation, the term "albedo" is used. An albedo of 1.0 corresponds to a surface that completely reflects, while

### TABLE 2
### Simulated Direct Savings in Cooling Energy and Peak Power Resulting from Planting Trees and Whitewashing Buildings§

| Location | 1973 Houses (leaky and low insulation) Savings Base | (Δ%) | 1980 Houses (tight and high insulation) Savings Base | (Δ%) |
|---|---|---|---|---|
| Chicago, IL | 1400 ft² | | 2000 ft² | |
| Peak kW | 3.60 | 23.6 | 3.20 | 29.1 |
| Annual kWh | 2584.0 | 19.9 | 1888.0 | 21.6 |
| Miami, FL | 1400 ft² | | 1600 ft² | |
| Peak kW | 5.42 | 25.3 | 3.29 | 23.4 |
| Annual kWh | 13623.0 | 22.5 | 8730.0 | 16.5 |
| Minneapolis, MN | 1400 ft² | | 2000 ft² | |
| Peak kW | 3.14 | 27.1 | 2.65 | 31.7 |
| Annual kWh | 1916.0 | 20.2 | 1325.0 | 22.6 |
| Phoenix, AZ | 1400 ft² | | 1600ft² | |
| Peak kW | 7.56 | 26.2 | 5.18 | 31.1 |
| Annual kWh | 13117.0 | 19.8 | 7789.0 | 17.3 |
| Pittsburgh, PA | 1600 ft² | | 1600ft² | |
| Peak kW | 3.50 | 24.9 | 2.36 | 23.3 |
| Annual kWh | 1821.0 | 23.3 | 1177.0 | 20.1 |
| Sacramento, CA | 1400 ft² | | 1600ft² | |
| Peak kW | 5.40 | 25.4 | 3.85 | 26.0 |
| Annual kWh | 3767.0 | 28.3 | 2372.0 | 23.8 |
| Washington, DC | 2000 ft² | | 2200 ft² | |
| Peak kW | 5.80 | 30.3 | 3.98 | 29.4 |
| Annual kWh | 4358.0 | 22.7 | 2790.0 | 20.0 |
| Average | | | | |
| Peak kW | | 26.3 | | 28.0 |
| Annual kWh | | 21.9 | | 18.6 |

§ Tree cover was increased by 30% with respect to the base case, whereas albedo was increased from 30% to 70%. We have used these estimates for calculating the national savings.

an albedo of 0.0 refers to one that completely absorbs all incident solar radiation. The albedo of an individual building can be modified to achieve direct savings: a lighter building reflects more solar radiation and therefore stays cooler. The albedo of an entire city can be modified to achieve indirect savings by lowering urban temperatures.

Most buildings and cities have albedos in the range of 0.20 to 0.35. Traditional cities of white-washed buildings found in hot areas have albedos in the range of 0.30 to 0.45 (Taha et al. 1988). Reflective roof membranes and popular "solar control" glazings of commercial buildings both have albedos of up to 0.8. There is a practical constraint in the maximum achievable urban albedo if this strategy is used in conjunction with increased urban vegetation, since a dense urban tree canopy will cover a large amount of the surface area (the albedo of green trees is ≈0.25). We have estimated an upper limit of 0.40 for the albedo of a highly vegetated city with light-colored surfaces.

## Energy Savings

Table 2 shows the simulated direct savings in cooling energy and peak power resulting from the direct effects of increased urban tree cover and albedo. The results are shown for both the 1973 housing stocks and newer 1980 prototypical houses. The 1973 stock is representative of leaky and poorly insulated housing, while the 1980 homes are tight and well insulated. The savings are calculated for an increase in tree cover of 30% (three trees per house) and an increase in a building's albedo from 30% to 70% over that of a base case.

### TABLE 3
### Simulated Indirect Savings in Cooling Energy Use and Peak Cooling Power for Single-Story 1980-Prototype Houses§

| Location | Urban canopy density increased by 3 trees/house[1] Percent energy savings | Albedo of house and surrounding increased[2] Percent energy savings |
|---|---|---|
| Sacramento, CA | | |
| Peak kW | 23 | 21 |
| Annual kWh | 37 | 45[3] |
| Phoenix, AZ | | |
| Peak kW | 12 | — |
| Annual kWh | 27 | — |
| Lake Charles, LA | | |
| Peak kW | 15 | — |
| Annual kWh | 31 | — |

§ Canopy savings are annual figures. Albedo savings are for the period from July 9 to July 12 only. (All entries are indirect effects.)

[1] Data from Huang et al. (1987). Assumes an increase of three trees per house.

[2] Data estimated from Taha et al. (1988). Assumes an increase from 0.25 to 0.40 in the albedo of the surroundings.

[3] Canopy savings are annual savings. Albedo savings for the period from July 9 to July 12.

Table 3 shows the simulated indirect savings in cooling energy and peak power. For the cities modeled, the effect of an additional three trees per building results in approximately 30% savings in annual cooling energy and approximately 15% to 20% annual savings in peak cooling power. The indirect effects of albedo were quantified for Sacramento, CA, for only four days in July. Simulations showed that increasing the albedo of the surroundings from 0.25 to 0.40 reduced the cooling energy by 45% and peak power by 21%. This suggests that for residential buildings the potential savings from albedo and vegetation are roughly equivalent.

We have comparatively few simulations of indirect effects. Since our urban climate models are still under development, we conservatively interpret these results as maximum effects. When extrapolating to determine national savings (Table 4), we typically assume smaller effects.

Table 4 shows savings of primary energy use for air conditioning in the U.S. The total residential electricity use for air conditioning (room and central) is about 100 billion kWh or 1.2 quads of primary energy per year (Akbari et al. 1988). In the U.S. in 1987, commercial buildings used 670 billion kWh of electricity (EIA 1987) of which approximately 20% was used for cooling, corresponding to about 130 billion kWh or 1.5 quads of source energy per year. Together, residential and commercial cooling uses 2.7 quads of source energy per year, worth \$20 to \$25 billion.[5]

In our calculations, we have assumed that tree planting and albedo modification can be applied to

---

[5] Most residential electricity is still sold at an average price of ≈7.5¢/kWh, but air-conditioning power is mainly on-peak and the cost of new peak power is closer to 10¢/kWh.

**TABLE 4**
**Annual Cooling Energy Savings and Reductions in Released Carbon from Heat Island Mitigation Using Trees and White Surfaces [§,1]**

| | Residential | | | Small Commercial | | | Large Commercial | | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (%) | Energy ($10^{15}$ Btu) | Carbon (M Tons) | (%) | Energy ($10^{15}$ Btu) | Carbon (M Tons) | (%) | Energy ($10^{15}$ Btu) | Carbon (M Tons) | Energy ($10^{15}$ Btu) | Carbon (M Tons) |
| Cooling Energy Use | | 1.2 | 36 | | 0.75 | 24 | | 0.75 | 24 | 2.7 | 84 |
| Heat Island Portion[2] | 15 | 0.18 | 5 | 10 | 0.08 | 2 | 3 | 0.02 | 1 | 0.27 | 8 |
| Direct Savings | 10[3] | 0.12 | 4 | 4[4] | 0.03 | 1 | 0 | 0.0 | 0 | 0.15 | 5 |
| Indirect Savings | 20 | 0.23 | 8 | 12 | 0.09 | 3 | 5[5] | 0.04 | 1 | 0.36 | 12 |
| Total Savings | 30 | 0.35 | 12 | 16 | 0.12 | 4 | 5 | 0.03 | 1 | 0.51 | 17 |

[§] We assumed 100 million trees, white-colored homes, streets, and parking lots.
[1] Production of carbon (as $CO_2$) from a peak power plant assumes 11,600 Btu/kWh sold, and ≈14,500 Btu/lb of carbon.
[2] We assumed that the overall heat island effect on the cooling energy use is 10%. We estimate that the effect of heat islands to be largest (15%) on residential, moderate (10%) on small commercial, and small (3%) on large commercial buildings.
[3] Residential. We assumed 3 trees (plus light surfaces) for 50% of our 50 million air-conditioned homes, so 75 million trees (plus light surfaces).
[4] Small Commercial. We assumed 30% coverage by trees (25 million more trees).
[5] Large Commercial. We assumed no additional trees.

only 50% of the 51 million air-conditioned houses in the U.S. Tree density may already be high (especially in older cities) and increasing tree cover and/or albedo may not be acceptable to all municipalities, and some areas may not have a significant cooling load. We have also assumed that half of the commercial building stock of 4 million buildings is small enough to be directly affected by shading and albedo increase.

The analysis shows that the direct effect of planting three trees per house and changing the building albedo from 30% to 70% is equivalent to an average of 20% cooling energy savings (see Table 2). Applying this to the 25 million available houses, using 75 million trees, would result in energy savings of 0.12 quad. The corresponding direct savings due to the planting of a 30% tree cover around small commercial buildings is about 8% (Akbari et al. 1987). When this is applied to 50% of the 2 million small commercial buildings, using another 25 million trees, this would save an additional 0.03 quad. Conservatively, a direct savings of 0.15 quad would be achieved if 100 million trees were planted.

Data presented in Table 3 suggest that the indirect effects of tree planting and albedo modification alone can save at least 20% of the 1.2 quad of residential cooling energy use (thus 0.23 quad). Because small commercial buildings are less sensitive to outdoor temperature than houses, we expect indirect savings of only about 12% of the 0.75 quad of small commercial cooling energy use (thus 0.09 quad). By reducing urban temperatures, these measures also decrease cooling energy use in large commercial buildings by increasing system efficiency and economizer operating hours. We estimate this would save an additional 5% or 0.04 quad.

### $CO_2$ Savings

Carbon, produced in the form of $CO_2$ from electricity generation, varies from about 0.5 lb carbon/kWh for natural-gas-fired power plants to about 1 lb carbon/kWh for coal-fired power plants. Because cooling energy is almost always used during periods of peak demand (except in the case of thermal storage), the electric utility must meet this demand using a combination of coal-, oil-, and gas-fired power plants. The fraction of each fuel type used varies greatly, depending on the region of the country, and can vary from all coal in some parts of the East to all oil and gas in Texas. However, the national average is approximately half coal and half oil and gas (DOE 1988). This results in an average emission of 0.8 lb carbon/kWh generated for peak power.

About half the savings from the combination of direct and indirect effects shown in Table 4 would result from planting 100 million urban trees. This savings of 0.25 quads (22 billion kWh) corresponds to a savings of 9 million tons of carbon. A fast-growing forest tree sequesters carbon at the rate of ≈13 lb carbon per year. Therefore, 100 million trees could directly sequester 0.65 million tons of carbon, or only one-fifteenth of the energy saved through their reduction in cooling energy use. To directly sequester the amount of carbon saved by the planting of 100 million urban trees would require planting 1.5 billion forest trees corresponding to 1.5 million hectares of forest (by comparison, the total area of Connecticut is about 1.3 million hectares).

### THE COST OF HEAT ISLAND MITIGATION MEASURES

Table 5 gives the cost-effectiveness, energy savings, and carbon reduction of urban trees/light surfaces compared to other conservation and generation strategies. All energy conservation measures that reduce fossil fuel use also reduce carbon emissions. For example, the trend to more efficient electric appliances yields a cost of conserved energy (CCE) of about 2¢/kWh, equivalent to a cost of conserved carbon (CCC) of

### TABLE 5
### Cost-Effectiveness, Energy Savings, and Carbon Reduction of Urban Trees/Light Surfaces Compared to Other Conservation and Generation Strategies§

| Strategy | CCE[1] (¢/kWh) | CCC[1] (¢/lb C) | ΔE (Quad/yr) | ΔC (M Tons/yr) |
|---|---|---|---|---|
| Conservation | | | | |
| (Direct + Indirect Effect) | | | | |
| Urban Trees/ | | | | |
| Light Surfaces | 0.2-1.0 | 0.25-1.25 | 0.5 | 17 |
| (direct $CO_2$ sequestered) | | | | (0.65) |
| Efficient Electric | | | | |
| Appliances[2] | 2 | 2.5 | 0.6 | 21 |
| Efficient Cars[3] | 4.2<br>(50¢/gal) | 8.3 | 2.8 | 60 |
| New Generation | | | | |
| Coal Power | 8 | Base Case | — | Base Case |
| Nuclear Power | 114 | — | 60 | |

§ (Source: Akbari et al. 1988)

[1] CCE is Cost of Conserved Energy and CCC is Cost of Conserved Carbon.

[2] Improved standards as defined by National Appliance Energy Conservation Act (NAECA).

[3] Improved car efficiency from 26 mpg to 36 mpg.

### TABLE 6
### Elements of a Multi-Year Research Program for Control of Summer Heat Islands

(1) Quantify the heat island effect
  - —gather, benchmark, develop, and test heat island simulation models
  - —collect data and make experimental measurements to validate the models
  - —evaluate other ways of obtaining heat island data (e.g. satellite and aircraft data)
  - —integrate all simulated and measured data into a single data base
  - —develop simplified tools to extract heat island data for major urban areas in the U. S. from the integrated data base

(2) Verify the mitigation savings
  - —model the peak power and energy savings of the heat island mitigation measures
  - —design and develop wind-tunnel and full-scale experiments to compare and improve simulation results
  - —perform field monitoring of energy savings to verify estimated savings

(3) Develop implementation guidelines
  - —evaluate the cost-benefits of heat island mitigation measures and compare savings in energy, equipment, and avoided generation to the costs of implementation
  - —develop implementation strategies and guidelines

(4) Quantify the heat island effect on pollution and global warming
  - —develop algorithms to correct for heat island contamination of temperature data used to estimate the severity of global warming
  - —estimate the fossil energy saved by the mitigation measures and hence the delay in global warming
  - —measure the relation between heat islands, smog, and creation of smog feedstocks

2.5¢/lb carbon. Another conservation strategy is to improve efficiency in automobiles. The cost of conserved carbon in going from a 26 mpg to a 36 mpg automobile is 10¢/lb carbon. Both these measures are effective, but they are much more expensive than urban trees and light-colored cities.

Urban trees and light surfaces have a CCE of about 0.2 to 10¢/kWh and a CCC of about 0.3 to 13¢/lb of carbon. This is as much as 10 times less expensive than either of the alternative strategies just cited. The point of the comparison is not to discredit the other conservation strategies but to suggest that planting urban trees and modifying urban albedos seems attractive and definitely worth investigating.

There are still many things to learn about summer heat islands. A multi-year effort in research, modeling, and data gathering is required to further investigate the energy-saving potentials and ways for controlling summer heat islands. Table 6 shows some elements of a multi-year research program, including quantifying the heat island effect, verifying the mitigation savings, developing implementation guidelines, and quantifying the heat island effect on pollution and global warming.

## ACKNOWLEDGMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building System Division of the U.S. Department of Energy, under contract No. DE-AC0376SF00098. This work was in part funded by a grant from the University-Wide Energy Research Group, University of California - Berkeley.

## REFERENCES

Akbari, H.; Taha, H.; Martien, P.; and Huang, J. 1987. "Strategies for reducing urban heat islands: savings, conflicts, and city's role." *Proceedings of the First National Conference on Energy Efficient Cooling*, San Jose CA, Oct. 21-22.

Akbari, H.; Huang, J.; Martien, P.; Rainer, L.; Rosenfeld, A.; and Taha, H. 1988. "The impact of summer heat islands on cooling energy consumption and $CO_2$ emissions." *Proceedings of ACEEE 1988 Summer Study on Energy Efficiency in Buildings*, Vol 5, pp. 11–23, Asilomar CA (Aug.).

Argento, V.K. 1988. "Ozone nonattainment policy vs. the facts of life." *Chemical Engineering Progress*, Dec., pp. 50–54.

CDIAC. 1987. "CDIAC numeric data collection." Environmental Science Division, Oak Ridge National Laboratory, Report NDP-019.

DOE. 1988. "Technical support document for the analysis of efficiency standards on refrigerators, refrigerator-freezers, freezers, small gas furnaces, and television sets." Lawrence Berkeley Laboratory draft report.

EIA. 1987. *Monthly energy review.* DOE/EIA-0035(87/09).

Goodridge, J. 1987. "Population and temperature trends in California." *Proceedings of the Pacific Climate Workshop*, Pacific Grove, CA, March 22–26.

Goodridge, J. 1989. "Air temperature trends in California, 1916 to 1987." J. Goodridge, 31 Rondo Ct., Chico, CA 95928.

Huang, Y.J.; Akbari, H.; Taha, H.; and Rosenfeld, A. 1987. "The potential of vegetation in reducing summer cooling loads in residential buildings." *Journal of Climate and Applied Meteorology*, Vol. 26, No.9, pp. 1103–1116.

Karl, T.R.; Williams, C.N., Jr.; Young, P.M.; and Wendland, W.M. 1986. "A model to estimate the time of observation bias associated with monthly maximum, minimum, and mean temperatures for the United States." *Journal of Climate and Applied Meteorology*, Vol. 25, pp. 145–160.

Karl, T.R., and Williams, N.C. 1987. "Data adjustments and edits to the U.S. historical climate network." National Climatic Data Center, Federal Building, Asheville, NC 28801.

Karl, T.R.; Diaz, H.F.; and Kukla, G. 1988. "Urbanization: its detection and effects in the United States climate record." *Journal of Climate*, Vol. 1, pp. 1099–1123.

Kukla, G.; Gavin, J.; and Karl, T.R. 1986. "Urban warming." *Journal of Climate and Applied Meteorology*, Vol. 25, pp. 1265–1270.

Landsberg, H.E. 1978. "Planning for the climate realities of arid regions." *Urban Planning for Arid Zones: American experience and Directions*, ed. Gideon Golany. New York: John Wiley & Sons.

Parker, J. 1981. "Uses of landscaping for energy conservation." Department of Physical Sciences, Florida International University, Miami. Sponsored by the Governor's Energy Office of Florida.

Taha, H.; Akbari, H.; Rosenfeld, A.; and Huang, J. 1988. "Residential cooling loads and the urban heat island: the effects of albedo." *Building and Environment*, Vol. 23, No. 4, pp. 271–283.