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# COOL SURFACES AND SHADE TREES TO REDUCE ENERGY USE AND IMPROVE AIR QUALITY IN URBAN AREAS

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**Abstract**—Elevated summertime temperatures in urban 'heat islands' increase cooling-energy use and accelerate the formation of urban smog. Except in the city's core areas, summer heat islands are created mainly by the lack of vegetation and by the high solar radiation absorptance by urban surfaces. Analysis of temperature trends for the last 100 years in several large U.S. cities indicate that, since ~1940, temperatures in urban areas have increased by about 0.5–3.0°C. Typically, electricity demand in cities increases by 2–4% for each 1°C increase in temperature. Hence, we estimate that 5–10% of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.0°C in urban temperatures. Downtown Los Angeles (L.A.), for example, is now 2.5°C warmer than in 1920, leading to an increase in electricity demand of 1500 MW. In L.A., smoggy episodes are absent below about 21°C, but smog becomes unacceptable by 32°C. Because of the heat-island effects, a rise in temperature can have significant impacts. Urban trees and high-albedo surfaces can offset or reverse the heat-island effect. Mitigation of urban heat islands can potentially reduce national energy use in air conditioning by 20% and save over $10B per year in energy use and improvement in urban air quality. The albedo of a city may be increased at minimal cost if high-albedo surfaces are chosen to replace darker materials during routine maintenance of roofs and roads. Incentive programs, product labeling, and standards could promote the use of high-albedo materials for buildings and roads. Similar incentive-based programs need to be developed for urban trees. Published by Elsevier Science Ltd.

## 1. INTRODUCTION

Modern urban areas have typically darker surfaces and less vegetation than their surroundings. These differences affect climate, energy use, and habitability of cities. At the building scale, dark roofs heat up more and, thus, raise the summertime cooling demands of buildings. Collectively, dark surfaces and reduced vegetation warm the air over urban areas, leading to the creation of urban 'heat islands'. On a clear summer afternoon, the air temperature in a typical city is as much as 2.5°C higher than in the surrounding rural areas. We have found that peak urban electric demand rises by 2–4% for each 1°C rise in daily maximum temperature above a threshold of 15 to 20°C. Thus, the additional air-conditioning use caused by this urban air temperature increase is responsible for 5–10% of urban peak electric demand, at a direct cost of several billion dollars annually.

In California, Goodridge (1987, 1989) showed 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. After 1940, when built-up areas began to replace vegetation, the urban centers became as warm or warmer than the suburbs, and the warming trend became quite obvious, so that, from 1965 to 1989, urban temperatures have increased by about 1°C.

Regardless of whether or not there is a temperature difference from rural conditions, data suggest that temperatures in cities are increasing. Fig. 1 depicts the summertime monthly maximum and minimum temperatures between 1877 and 1997 in downtown Los Angeles. It clearly indicates that the maximum temperatures at downtown Los Angeles are now about 2.5°C higher than they were in 1920. The minimum temperatures are about 4°C higher than they were in 1880. In Washington, DC, temperatures increased by about 2°C between 1871 and 1987. The data indicate that this recent warming trend is typical of most U.S. metropolitan areas, and exacerbates demand for energy.

Akbari et al. (1992) have found that peak urban electric demand in six American cities (Los Angeles, CA; Washington, DC; Phoenix, AZ; Tucson, AZ; and Colorado Springs, CO) rises by 2–4% for each 1°C rise in daily maximum temperature above a threshold of 15 to 20°C (the case of Los Angeles is shown in Fig. 2). For the Los Angeles Basin, it is estimated that the heat

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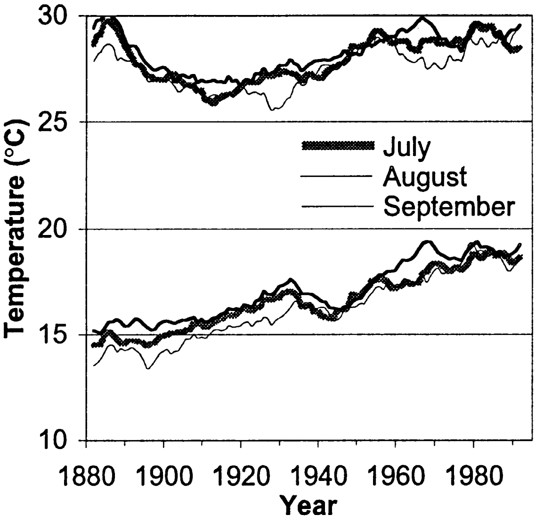


Fig. 1. Ten-year running average summertime monthly maximum and minimum temperatures in Los Angeles, California (1877–1997). The ten-year running average is calculated as the average temperature of the previous four years, the current year, and the next five years. Note that the maximum temperatures have increased by about 2.5°C since 1920.

island increases power consumption by about 1–1.5GW, costing the rate-payers over $100 million per year. Nationwide, the additional air-conditioning use caused by urban air temperature increase is responsible for 5–10% of urban peak electric demand, at a direct cost of several billion dollars annually.

Not only do summer heat islands increase system-wide cooling loads, but they also increase smog production because of higher urban air temperatures (Taha *et al.*, 1994). For example,

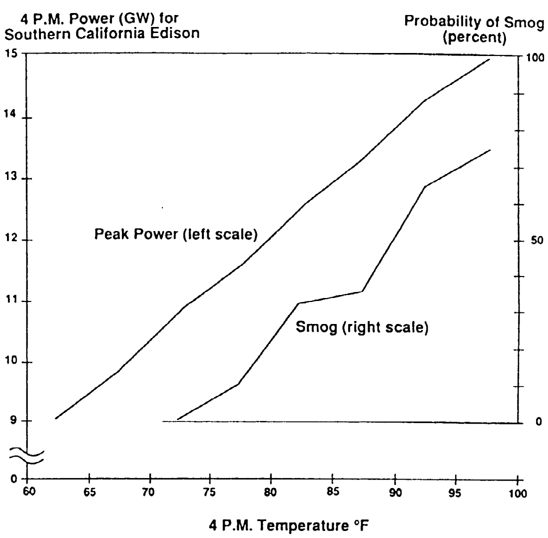


Fig. 2. Ozone levels and peak power for Southern California Edison versus 4 p.m. temperature in Los Angeles, California. (Source: Akbari *et al.*, 1990).

Fig. 2 also shows the probability of smoggy days in Los Angeles, as measured by ozone concentration vs. temperature. At maximum daily temperatures below 22°C, the maximum concentration of ozone is below the California standard of 90 parts per billion (ppb); at temperatures above 35°C, practically all days are smoggy.

## 2. HEAT ISLAND MITIGATION

Use of high-albedo[1] urban surfaces and the planting of urban trees are inexpensive measures that can reduce summertime temperatures. The effects of modifying the urban environment by planting trees and increasing albedo are best quantified in terms of ‘direct’ and ‘indirect’ contributions. The direct effect of planting trees around a building or using reflective materials on roofs or walls is to alter the energy balance and cooling requirements of that particular building. However, when trees are planted and albedo is modified throughout an entire city, the energy balance of the whole city is modified, producing city-wide changes in climate. Phenomena associated with city-wide changes in climate are referred to as indirect effects, because they indirectly affect the energy use in an individual building. Direct effects give immediate benefits to the building that applies them. Indirect effects achieve benefits only with widespread deployment.

There is an important distinction between direct and indirect effects: while direct effects are recognized and accounted for in present models of building-energy use, indirect effects are appreciated far less. Accounting for indirect effects is more difficult and the results are comparatively less certain. Understanding these effects and incorporating them into accounts of energy use and air quality is the focus of our current research. It is worth noting that the phenomenon of summer urban heat islands is itself an indirect effect of urbanization.

The issue of direct and indirect effects also enters into our discussion of atmospheric pollutants. 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

[1]When sunlight hits an opaque surface, some of the energy is reflected (this fraction is called the albedo = a), and the rest is absorbed (the absorbed fraction is 1 − a). Low-a surfaces of course become much hotter than high-a surfaces.

on $CO_2$. By reducing the demand for cooling energy, urban trees indirectly reduce emission of $CO_2$ from power plants. Akbari *et al.* (1990) showed that the amount of $CO_2$ avoided via the indirect effect is considerably greater than the amount sequestered directly. Similarly, trees directly trap ozone precursors (by dry-deposition), a direct effect, and indirectly reduce the emission of these precursors from power plants (Taha, 1996).

## 3. TOOLS FOR ANALYSIS

Fig. 3 depicts the overall methodology used in analyzing the impact of heat-island mitigation measures on energy use and urban air pollution. The DOE-2 building-energy simulation program is used to calculate the energy use and energy savings in buildings. To calculate the direct effects, prototypical buildings are simulated with dark- and light-colored roofs, and with and without shade trees. Typical weather data for each climate region of interest are used in these calculations. To calculate the indirect effects, the typical weather data input to DOE-2 are first modified to account for changes in the urban climate. The prototypical buildings are then simulated with the modified weather data to estimate savings in heating and cooling energy consumption.

To understand the impacts of large-scale increases in albedo and vegetation on urban climate and ozone air quality, mesoscale meteorological and photochemical models are used. For example, Taha *et al.* (1995) and Taha (1996, 1997) used the Colorado State University Mesoscale Model (CSUMM) to simulate the Los Angels Basin's meteorology and its sensitivity to changes in surface properties. The Urban Airshed Model (UAM) was used to simulate the impacts of the changes in meteorology and emissions on ozone air quality. The CSUMM and the UAM essentially solve a set of coupled governing equations representing the conservation of mass (continuity), potential temperature (heat), momentum, water vapor, and chemical species continuity to obtain for prognostic meteorological fields and pollutant species concentrations.

The CSUMM is a hydrostatic, primitive-equation, three-dimensional Eulerian model that was originally developed by Pielke (1974). The model is incompressible (uses incompressibility assumption to simplify the equation for conservation of mass), and employs a terrain-following coordinate system. It uses a first order closure scheme in treating sub-grid scale terms of the governing differential equations. The model's domain is about 10 km high with an underlying soil layer that is about 50 cm deep. The CSUMM generates three-dimensional fields of prognostic variables as well as a boundary layer height profile that can be input to the UAM.

The UAM is a three-dimensional, Eulerian, photochemical model that is capable of simulating inert and chemically reactive atmospheric pollutants. It has been recommended by the U. S. Environmental Protection Agency (EPA) for ozone air quality modeling studies of urban areas (EPA, 1986). The UAM simulates the advection, diffusion, transformation, emission, and deposition of pollutants. It treats about 30 chemical species and uses the carbon bond CB-IV mechanism (Gery *et al.*, 1988). The UAM accounts for

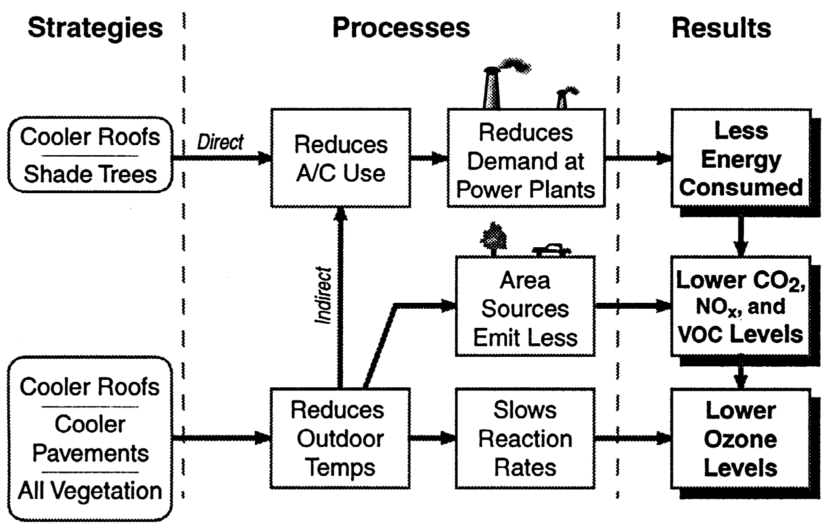


Fig. 3. Methodology to analyze the impact of shade trees, cool roofs, and cool pavements on energy use and air quality (smog).

emissions from area and point sources, elevated stacks, mobile and stationary sources, and vegetation (biogenic emissions). For a detailed discussion of the use and adaptation of these models and the study of the impact of the heat island mitigation strategies in L.A. Basin, see Taha (1996, 1997).

Examples of outputs from these simulations are shown in Figs. 4 and 5. Fig. 4 shows the predicted reduction in air temperature in Los Angeles at 2 p.m. on August 27 as a result of increasing the urban albedo and vegetation cover by moderate amounts (average increases of 7%). Fig. 5 shows corresponding changes in ozone concentrations. Because of the combined effects of local emissions, meteorology, surface properties, and topography, ozone concentrations increase in some areas and decrease in others. The net effect, however, is a decrease in ozone concentrations. The simulations also predict a reduction in population-weighted exceedance exposure to ozone (above the California and National Ambient Air Quality Standards) of 10–20% (Taha, 1996). This reduction, for some smog scenarios, is comparable to ozone reductions obtained by replacing all gasoline on-road motor vehicles with electric cars.

## 4. COOL ROOFS

At the building scale, a dark roof is heated by the sun and, thus, directly raises the summertime cooling demand of the building beneath it. For highly absorptive (low-albedo) roofs, the difference between the surface and ambient air temperatures may be as high as 50°C, while for less absorptive (high-albedo) surfaces with similar insulative properties, such as roofs covered with a white coating, the difference is only about 10°C (Berdahl and Bretz, 1997). For this reason, 'cool' surfaces (which absorb little 'insolation') can be effective in reducing cooling-energy use. Highly absorptive surfaces contribute to the heating of the air, and thus indirectly increase the cooling demand of (in principle) all buildings. Cool surfaces incur no additional cost if color changes are incorporated into routine re-roofing and resurfacing schedules (Bretz *et al*., 1997 and Rosenfeld *et al*., 1992).

Most high-albedo surfaces are light colored, although selective surfaces that reflect a large portion of the infrared solar radiation but absorb some visible light may be dark colored and yet have relatively high albedos (Berdahl and Bretz, 1997).

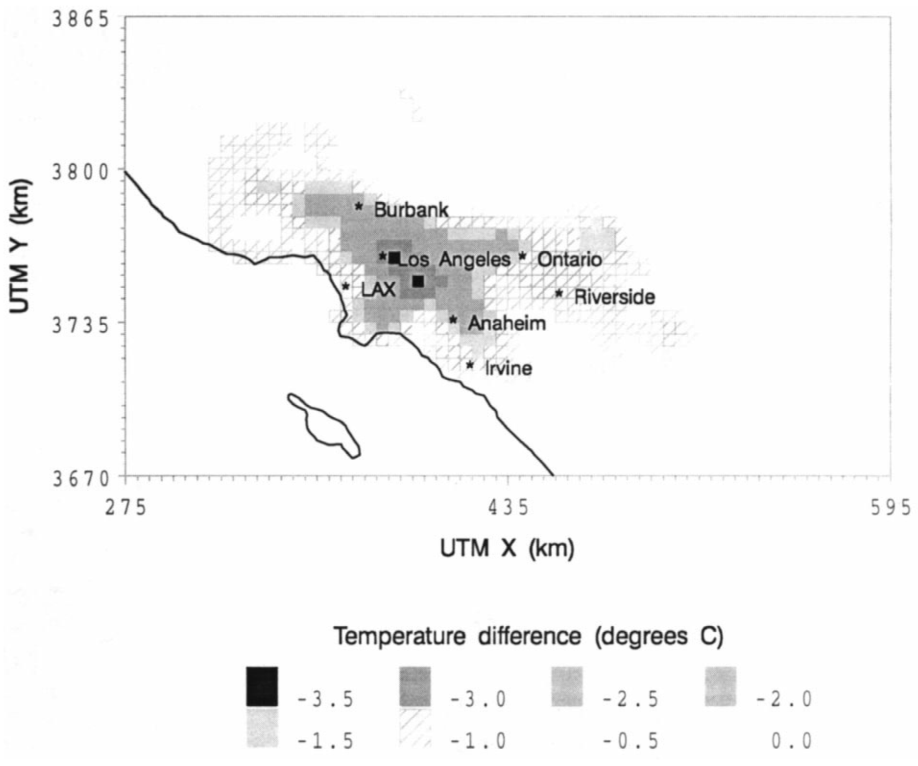


Fig. 4. Temperature difference (from the base case) for a case with increased surface albedo and urban forest. The temperature difference is at 2 p.m. on a late-August day in Los Angeles.

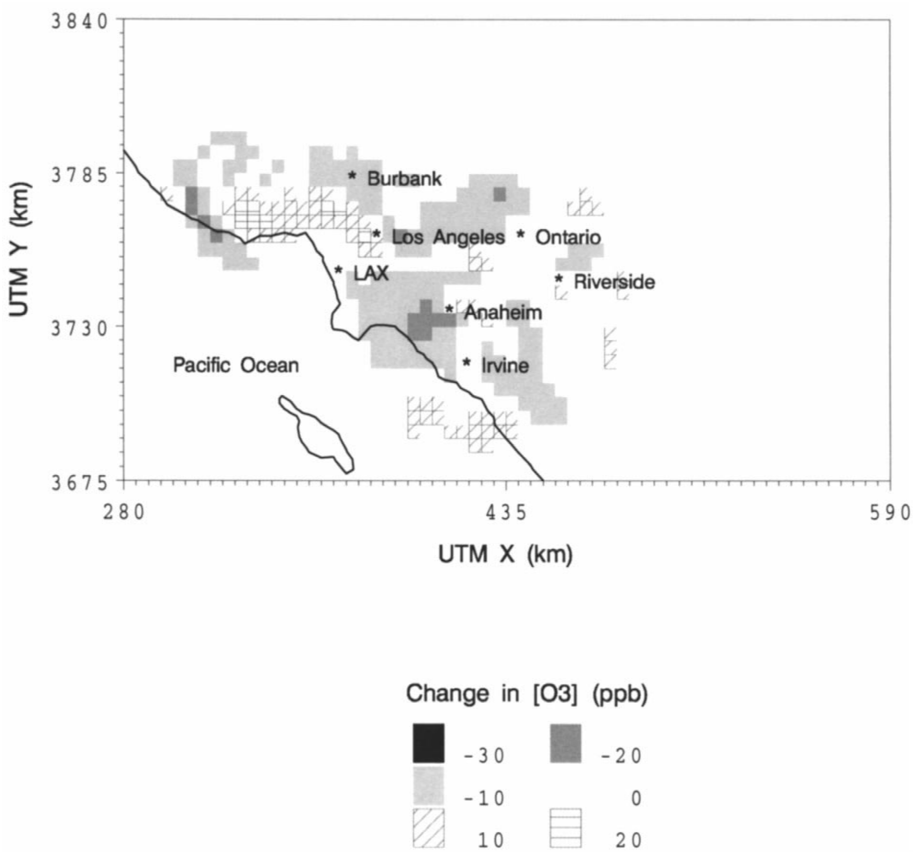


Fig. 5. Ozone concentrations difference (from the base case) for a case with increased surface albedo and urban forest. The difference is shown for 2 p.m. on a late-August day in Los Angeles.

### *4.1. Energy and smog benefits of cool roofs*

*4.1.1. Direct energy savings*. There is a sizable body of measured data documenting the direct energy-saving effects of light-colored roofs. In the summers of 1991 and 1992, Akbari *et al*. (1993, 1997) monitored peak power and cooling-energy savings from high-albedo coatings on one house and two school bungalows in Sacramento, California. They 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/day (80% of base-case use), and peak demand reductions of 0.6 kW (about 25% of base-case demand). In the school bungalows, cooling-energy was reduced by 3.1 kWh/day (35% of base-case use), and peak demand by 0.6 kW (about 20% of base-case demand). (It is important to note that altering the albedo starts to pay for itself immediately through the direct effect.) The buildings were also modeled with the DOE-2.1E simulation program. Akbari *et al.* (1993) and Gartland *et al.* (1996) report that the simulations underestimated the cooling-energy savings and peak-power reductions by as much as twofold.

Parker *et al.* (1995) monitored nine homes in Florida before and after applying high-albedo coatings to their roofs. Air-conditioning energy use was reduced by 10–43%, with average savings of 7.4 kWh/day (savings of 19%). Peak demand between 5 and 6 p.m. was reduced by 0.2–1.0 kW, with an average reduction of 0.4 kW (savings of 22%). The amount of energy savings roughly inversely correlated with the amount of ceiling insulation and the location of the duct system: large savings in poorly insulated homes and those with the duct systems in the attic space, and smaller savings in well insulated homes.

Akbari *et al.* (1998) and Konopacki *et al.* (1998) monitored the impacts of light-colored roofs on cooling-energy use of three commercial buildings in northern California. Increasing the reflectance of the roofs from an initial albedo of about 0.20 to 0.60 dropped the roof temperature on hot summer afternoons by about 25°C. Summertime, standard-weekday, average daily air-conditioning savings were 18% in a medical office building, 13% in a second medical office building, and 2% in a drug store. In another demonstration project in Florida, Parker *et al.* (1998) measured cooling electricity savings resulting from the application of light-colored roofing in a small strip mall; they reported savings of about 20 to 40%. The Sacramento Municipal Utility District (SMUD) reports similar savings, measured in about ten commercial buildings in Sacramento (Hildebrandt *et al*., 1998).

Computer simulations are used to obtain estimates of year-round effects for a variety of building types and climates. A recent study made quantitative estimates of peak demand and annual cooling-electricity use and savings that would result from increasing the reflectivity of the roofs (Konopacki *et al*., 1997). The estimates of annual net savings in cooling electricity are adjusted for the penalty of increased wintertime heating-energy use. The analysis is based on simulation of building-energy use, using the DOE-2 building-energy simulation program. The study specified 11 prototypical buildings: single-family residential (old and new), office (old and new), retail store (old and new), school (primary and secondary), health care (hospital and nursing home), and grocery store. Most prototypes were simulated with two heating systems: gas furnace and heat pumps. DOE-2 simulations were performed for the prototypical buildings, with light and dark roofs, in a variety of climates, to obtain estimates of the energy use for air conditioning and heating. Weather data for 11 U.S. Metropolitan Statistical Areas (MSAs) were used: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York City, Philadelphia, Phoenix, and Washington, DC/Baltimore. Cooling-energy savings and heating-energy penalties were then obtained from the difference in the simulated energy use of the prototype buildings with light- and dark-colored roofs.

The study also estimated how much energy and money could be saved if all the roofs of existing building stocks in large metropolitan areas were changed from dark to light. This was done by scaling the simulated energy savings of the individual prototype buildings by the amount of air-conditioned space immediately beneath all roofs in an entire MSA. For this purpose, we used data on the stock of commercial and residential buildings in each MSA, the saturation of heating and cooling systems, the current roof reflectivities, and the local costs of electricity and gas.

Results for the 11 metropolitan areas are summarized in Tables 1 and 2. Sum totals for all 11 MSAs were: electricity savings, 2.6 tera-watt hours (TWh) (200 kilowatt hours per 100 $m^2$ roof area of air-conditioned buildings); heating energy penalty, 6.9 TBtu (5 therms per 100 $m^2$);[2] net savings in energy bills, $194 M ($15 per 100 $m^2$); and savings in peak demand 1.7 gigawatt (GW) (135 W per 100 $m^2$). Six building types account for over 90% of the annual electricity and net energy savings: old residences accounted for more than 55%, new residences for about 15%, and four other building types (old/new offices and

[2]One therm is 100,000 Btu.

Table 1. Estimates of metropolitan-scale annual cooling electricity savings (GWh), net energy savings ($M), peak demand electricity savings (MW), and annual natural gas penalty (GBtu) resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas

| Metropolitan area | Residential | | | | Commercial | | | | Commercial and residential | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elec (GWh) | Gas (GBtu) | Net (M$) | Peak (MW) | Elec (GWh) | Gas (GBtu) | Net (M$) | Peak (MW) | Elec (GWh) | Gas (GBtu) | Net (M$) | Peak (MW) |
| Atlanta | 125 | 349 | 8 | 83 | 22 | 55 | 1 | 14 | 147 | 404 | 9 | 97 |
| Chicago | 100 | 988 | 6 | 89 | 84 | 535 | 4 | 56 | 183 | 1523 | 10 | 145 |
| Los Angeles | 210 | 471 | 18 | 218 | 209 | 154 | 18 | 102 | 419 | 625 | 35 | 320 |
| Dallas/Ft Worth | 241 | 479 | 16 | 175 | 71 | 113 | 4 | 36 | 312 | 592 | 20 | 211 |
| Houston | 243 | 284 | 21 | 127 | 79 | 62 | 6 | 30 | 322 | 347 | 27 | 156 |
| Miami/Ft Lauderdale | 221 | 4 | 18 | 115 | 35 | 3 | 2 | 11 | 256 | 7 | 20 | 125 |
| New Orleans | 84 | 107 | 6 | 27 | 33 | 28 | 3 | 16 | 117 | 135 | 9 | 42 |
| New York | 35 | 331 | 3 | 56 | 131 | 540 | 13 | 95 | 166 | 871 | 16 | 151 |
| Philadelphia | 44 | 954 | − 1 | 108 | 47 | 292 | 4 | 49 | 91 | 1246 | 3 | 157 |
| Phoenix | 299 | 74 | 32 | 106 | 58 | 31 | 5 | 18 | 357 | 105 | 37 | 123 |
| DC/Baltimore | 182 | 845 | 6 | 183 | 45 | 184 | 2 | 31 | 227 | 1029 | 8 | 214 |
| Total | 1784 | 4886 | 133 | 1287 | 814 | 1997 | 62 | 458 | 2597 | 6884 | 194 | 1741 |

Table 2. Estimates of savings or penalties per 100 $m^2$ of roof area of air-conditioned buildings resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas: annual cooling electricity savings (kWh), net energy savings ($), peak demand electricity savings (W), and annual natural gas penalty (therms)

| Metropolitan area | Residential | | | | Commercial and residential | | | | Commercial | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elec (kWh) | Gas (therms) | Net ($) | Peak (W) | Elec (kWh) | Gas (therms) | Net ($) | Peak (W) | Elec (kWh) | Gas (therms) | Net ($) | Peak (W) |
| Atlanta | 153 | 4 | 10 | 102 | 239 | 6 | 11 | 152 | 162 | 4 | 10 | 107 |
| Chicago | 131 | 13 | 8 | 116 | 228 | 15 | 11 | 152 | 162 | 13 | 9 | 128 |
| Los Angeles | 182 | 4 | 16 | 189 | 350 | 3 | 30 | 171 | 239 | 4 | 20 | 183 |
| Dallas/Ft Worth | 166 | 3 | 11 | 121 | 224 | 4 | 13 | 114 | 176 | 3 | 11 | 119 |
| Houston | 198 | 2 | 17 | 103 | 261 | 2 | 20 | 99 | 211 | 2 | 18 | 102 |
| Miami/Ft Lauderdale | 259 | 0 | 21 | 135 | 340 | 0 | 19 | 107 | 267 | 0 | 21 | 131 |
| New Orleans | 199 | 3 | 14 | 64 | 287 | 2 | 26 | 139 | 218 | 3 | 17 | 78 |
| New York | 104 | 10 | 9 | 166 | 211 | 9 | 21 | 153 | 173 | 9 | 17 | 158 |
| Philadelphia | 81 | 18 | − 2 | 199 | 232 | 14 | 20 | 241 | 122 | 17 | 4 | 211 |
| Phoenix | 314 | 1 | 34 | 111 | 409 | 2 | 35 | 127 | 327 | 1 | 34 | 113 |
| DC/Baltimore | 137 | 6 | 5 | 138 | 221 | 9 | 10 | 152 | 148 | 7 | 5 | 140 |

old/new retail stores) together accounted for about 25%.

The results for the 11 MSAs were extrapolated to estimate the savings in the entire United States. The study estimates that, nationally, light-colored roofing could produce savings of about 10 TWh/year (about 3.0% of the national cooling-electricity use in residential and commercial buildings), an increase in natural gas use by 26 GBtu/year (1.6%), a decrease in peak electrical demand of 7 GW (2.5%) (equivalent to 14 power plants each with a capacity of 0.5 GW), and a decrease in net annual energy bills for the rate-payers of $750M.

*4.1.2. Indirect energy and smog benefits*. Using the Los Angeles Basin as a case study, Taha (1996, 1997) examined the impacts of using cool surfaces (cool roofs and pavements) on urban air temperature and, thus, on cooling-energy use and smog. If higher albedo surfaces are thoroughly applied, an urban heat island can be limited or reversed at negligible expense. In these simulations, Taha estimates that about 50% of the urbanized area in the L.A. Basin is covered by roofs and roads, the albedos of which can realistically be raised by 0.30 when they undergo normal repairs. This results in a 2°C cooling at 3 p.m. during an August episode. This summertime temperature reduction has a significant effect on further reducing building cooling-energy use. The annual savings in L.A. are estimated at $21M (Rosenfeld *et al*., 1998).

Taha has also simulated the impact of urban-wide cooling in Los Angeles on smog; the results show a significant reduction in ozone concentration. The simulations predict a reduction of 10–20% in population-weighted smog (ozone). In L.A., where smog is especially serious, the potential savings were valued at $104M/year (Rosenfeld *et al*., 1998).

### *4.2. Other benefits of cool roofs*

Another benefit of a light-colored roof is a potential increase in its useful life. The diurnal temperature fluctuation and concomitant expansion and contraction of a light-colored roof is smaller than that of a dark one. Also, the degradation of materials due to absorption of ultraviolet light is a temperature-dependent process. For these reasons, cooler roofs may last longer than hot roofs of the same material.

### *4.3. Potential problems with cool roofs*

Several possible problems may arise from the use of reflective roofing materials (Bretz and Akbari, 1994, 1997). A drastic increase in the overall albedo of the many roofs in a city has the potential to create glare and visual discomfort if not kept to a reasonable level. Besides being unpleasant, extreme glare could possibly increase the incidence of traffic accidents. Fortunately, the glare for flat roofs is not a major problem for those who are at street level. For sloped roofs, the problem of glare should be studied in detail before proceeding with a full-scale implementation of this measure.

In addition, many types of building materials, such as tar roofing, are not well adapted to painting. Although such materials could be specially designed to have a higher albedo, this would be at a greater expense than painting. Additionally, to maintain a high albedo, roofs may need to be recoated or rewashed on a regular basis. The cost of a regular maintenance program could be significant.

A possible conflict of great concern is the fact that building owners and architects like to have the choice as to what color to select for their rooftops. This is particularly a concern for sloped roofs.

### *4.4. Cost of cool roofs*

Increasing the overall albedo of roofs is an attractive way of reducing the net radiative heat gains through the roof, and, hence, reducing building cooling loads. To change the albedo, the rooftops of buildings may be painted or covered with a new material. Since most roofs have regular maintenance schedules or need to be re-roofed or recoated periodically, the change in albedo should be done then to minimize the costs.

High-albedo alternatives to conventional roofing materials are usually available, often at little or no additional cost. For example, a built-up roof typically has a coating or a protective layer of mineral granules or gravel. Under such conditions, it is expected that choosing a reflective material at the time of installation should not add to the cost of the roof. Also, roofing shingles are available in a variety of colors, including white, at the same price. The incremental price premium for choosing a white rather than a black single-ply membrane roofing material is less than 10%. Cool roofing materials that require an initial investment may turn out to be more attractive in terms of life-cycle cost than conventional dark alternatives. Usually, the lower life-cycle cost results from longer roof life and/or energy savings.

## 5. URBAN TREES

The benefits of trees can also be divided into direct and indirect effects: shading of buildings and ambient cooling (urban forest). Shade trees intercept sunlight before it warms a building. The urban forest cools the air by evapotranspiration. Trees also decrease the wind speed under their canopy and shield buildings from cold winter breezes. Urban shade trees offer significant benefits by both reducing building air-conditioning, lowering air temperature, and thus improving urban air quality by reducing smog. Over the life of a tree, the savings associated with these benefits vary by climate region and can be up to $200 per tree. The cost of planting trees and maintaining them can vary from $10 to $500 per tree. Tree-planting programs can be designed to be low cost, so they can offer savings to communities that plant trees. We are considering here trees that shade buildings. Placing trees in order to shade air-conditioning equipment would also likely be beneficial.

### *5.1. Energy and smog benefits of shade trees*

*5.1.1. Direct energy savings.* Data on measured energy savings from urban trees are scarce. In one experiment, Parker (1981) measured the cooling-energy consumption of a temporary building in Florida before and after adding trees and shrubs and found cooling-electricity savings of up to 50%. In the summer of 1992, Akbari *et al.* (1997) monitored peak-power and cooling-energy savings from shade trees in two houses in Sacramento, California. The collected data included air-conditioning electricity use, indoor and outdoor dry-bulb temperatures and humidities, roof and ceiling surface temperatures, inside and outside wall temperatures, insolation, and wind speed and direction. The shading and microclimate effects of the trees at the two monitored houses yielded seasonal cooling-energy savings of 30%, corresponding to average savings of 3.6 and 4.8 kWh/day. Peak-demand savings for the same houses were 0.6 and 0.8 kW (about 27% savings in one house and 42% in the other).

A few other studies have focused on the wind-shielding effect of trees. DeWalle *et al.* (1983) used mobile homes to measure the windbreaking effects of trees on energy use. In a follow-up experiment, Heisler (1989) measured the effect of trees on wind and solar radiation in a residential neighborhood. Huang *et al.* (1990) used the data provided by Heisler (1989) and simulated the impact of shading and wind reduction on residential buildings' heating- and cooling-energy use. Their simulations indicated that a reduction in infiltration because of trees would save heating-energy use. However, in climates with cooling-energy demand, the impact of windbreak on cooling is fairly small compared to the shading effects of trees and, depending on climate, it could decrease or increase cooling-energy use. In cold climates, the wind-shielding effect of trees can substantially reduce heat-energy use in buildings. Akbari and Taha (1992) simulated the wind-shielding impact of trees on heating-energy use in four Canadian cities. For several prototypical residential buildings, they estimated heating-energy savings in the range of 10 to 15%.

In a recent study, Taha *et al.* (1996) simulated the meteorological impact of large-scale tree-planting programs in ten U.S. metropolitan areas: Atlanta, GA; Chicago, IL; Dallas, TX; Houston, TX; Los Angeles, CA; Miami, FL; New York,

Table 3. Number of additional trees planted in each metropolitan area and their simulated effects in reducing the ambient temperature. (Source: Taha *et al.*, 1996)

| Location | Millions of addional trees in the simulation domain | Millions of additional trees in the metropolitan area | Max air temperature reduction in the hottest simulation cell (°C) |
|---|---|---|---|
| Atlanta | 3.0 | 1.5 | 1.7 |
| Chicago | 12 | 5.0 | 1.4 |
| Los Angeles | 11 | 5.0 | 3.0 |
| Fort Worth | 5.6 | 2.8 | 1.6 |
| Houston | 5.7 | 2.7 | 1.4 |
| Miami | 3.3 | 1.3 | 1.0 |
| New York City | 20 | 4.0 | 2.0 |
| Philadelphia | 18 | 3.8 | 1.8 |
| Phoenix | 2.8 | 1.4 | 1.4 |
| Washington, DC | 11 | 3.0 | 1.9 |

NY; Philadelphia, PA; Phoenix, AZ; and Washington, DC). Table 3 shows the number of added trees simulated in each city and impact on air temperature. The number of trees in each grid cell varied from the low hundreds to the high tens of thousands. The DOE-2 building simulation program was then used to estimate the direct and indirect impacts of trees on saving cooling-energy use for two building prototypes: a single-family residence and an office. The calculations accounted for a potential increase in winter heating-energy use. Table 4 shows that, in most hot cities, shading a building can save annually \$5 to \$25 per 100 $m^2$ of roof area of residential and commercial buildings. Savings in residential building are higher than in commercial buildings.

*5.1.2. Indirect energy and smog benefits*. Taha *et al*. (1996) estimated the impact on ambient temperature resulting from a large-scale tree-planting program in the selected ten cities. They used a three-dimensional meteorological model to simulate the potential impact of trees on ambient temperature for each region. The mesoscale simulations showed that, on average, trees can cool down cities by about 0.3 to 1°C at 2 p.m.; in some simulation cells, the temperature was decreased by up to 3°C (see Table 3). The corresponding air-conditioning savings resulting from ambient cooling by trees in hot climates ranges from \$5 to \$10 per year per 100 $m^2$ of roof area of residential and commercial buildings. Indirect effects are smaller than direct shading, and, moreover, require that the entire city be planted.

Based on the results of Taha *et al.* (1996), Rosenfeld *et al.* (1998) estimated the potential benefits of trees, specifically in the Los Angeles Basin. The study assumed planting 11M trees according to the following plan: three shade trees (each with a canopy cross section of 50 $m^2$) per air-conditioned house, for a total of 5.4M trees; about one shade tree for each 250 $m^2$ of non-residential roof area for a total of 1M trees; 4.6M trees to shade non-air-conditioned homes or to be planted along streets, in parks, and in other public spaces. The results of that analysis are shown in Table 5. Note that about two-thirds of the savings in L.A. result from the reduction in smog concentration resulting from meteorological changes due to the evapotranspiration of trees. It has also been suggested that trees improve air quality by dry-depositing $NO_x$, $O_3$, and PM10 particulates.

Table 4. DOE-2 simulated HVAC annual energy savings from trees. Three trees per house and per office are assumed. All savings are \$/100 $m^2$. (Source: Taha *et al.*, 1996)

| Location | Old residence | | New residence | | Old office | | New office | |
|---|---|---|---|---|---|---|---|---|
| | Direct | Indirect | Indirect | Direct | Indirect | Direct | Indirect | Direct |
| Atlanta | 5 | 2 | 3 | 1 | 3 | 2 | 2 | 2 |
| Chicago | 3 | 2 | 1 | 0.5 | 1 | 1 | 2 | 1 |
| Los Angeles | 12 | 8 | 7 | 5 | 6 | 12 | 4 | 10 |
| Fort Worth | 6 | 6 | 5 | 4 | 4 | 5 | 2 | 4 |
| Houston | 10 | 6 | 6 | 4 | 3 | 5 | 3 | 3 |
| Miami | 9 | 3 | 6 | 3 | 3 | 2 | 2 | 2 |
| New York City | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 2 |
| Philadelphia | − 5 | 0 | − 7 | 0 | 2 | 1 | 1 | 1 |
| Phoenix | 27 | 8 | 16 | 5 | 9 | 5 | 6 | 4 |
| Washington, DC | 3 | 2 | 1 | 1 | 3 | 1 | 2 | 1 |

Table 5. Energy savings, ozone reduction, and avoided peak power resulting from use of urban trees in the Los Angeles Basin (Source: Rosenfeld *et al.*, 1998)

| | Benefits | Direct | Indirect | Smog | Total |
|---|---|---|---|---|---|
| 1 | Cost savings from trees (M$/year) | 58 | 35 | 180 | 273 |
| 2 | Δ Peak power (GW) | 0.6 | 0.3 | | 0.9 |
| 3 | Present value per tree ($) | 68 | 24 | 123 | 211 |

Rosenfeld *et al.* (1998) estimate that 11M trees in L.A. will reduce PM10 by less than 0.1%, worth only $7M, which is disappointingly smaller than the benefits of $180M from smog reduction.

The present value (PV) of savings is calculated to find out how much a homeowner can afford to pay for shade trees. Rosenfeld *et al.* (1998) estimate that, on this basis, the direct savings to a home owner who plants three shade trees would have a present value of about $200 per home ($68/tree). The present value of indirect savings was smaller, about $72/home ($24/tree). The PV of smog savings was about $120/tree. Total PV of all benefits from trees was then $210/tree.

Reducing smog by citywide cooling can be considered equivalent to reducing the formation of smog precursors at constant temperature. We estimate that shade trees will reduce the maximum smog concentration by 5%. Using the ozone 'isopleths' (such as Milford's),[3] a 5% reduction in smog is equivalent to reducing precursors by approximately 12%, i.e., reducing $NO_x$ in L.A. by 175 tons/day, a very significant drop and 25 times more than the 4 tons/day through reduced power-plant emissions.

## 5.2. Other benefits of shade trees

There are other benefits associated with urban trees. Some of these include improvement in the quality of life, increased value of properties, decreased rain run-off water and, hence, a protection against floods (McPherson *et al.*, 1994). Trees also directly sequester atmospheric carbon dioxide, but Rosenfeld *et al.* (1998) estimate that the direct sequestration of carbon dioxide is less than one-fourth of the emission reduction resulting from savings in cooling-energy use. These other benefits of trees are not considered in the cost benefit analysis shown in this paper.

## 5.3. Potential problems with shade trees

There are some potential problems associated with trees. Some trees emit volatile organic compounds (VOCs) that exacerbate the smog problem. Obviously, selection of low-emitting trees should be considered in a large-scale tree-planting program. Benjamin *et al.* (1996) have prepared a list of several hundred tree species with their average emission rates.

In dry climates and areas with a serious water shortage, drought-resistant trees are recommended. Some trees need significant maintenance that may entail high cost over the life of the trees. Tree roots can damage underground pipes, pavements and foundations. Proper design is needed to minimize these effects. Also, trees are a fuel source for fire; selection of appropriate tree species and planting them strategically to minimize the fire hazard should be an integral component of a tree-planting program.

## 5.4. Cost of trees

The cost of a citywide tree-planting program depends on the type of program offered and the types of trees recommended. At the low end, a promotional planting of trees 5–10 feet high costs about $10 per tree, whereas a professional tree-planting program using fairly large trees could amount to $150 to $470 a tree (McPherson *et al.*, 1994). McPherson has collected data on the cost of tree planting and maintenance from several cities. The cost elements include planting, pruning, removal of dead trees, stump removal, waste disposal, infrastructure repair, litigation and liability, inspection, and program administration. The data provide details of the cost for trees located in parks, yards, along streets, highways, and houses. The present value of all of these life-cycle costs (including planting) is $300 to $500 per tree. Over 90% of the cost is associated with professional planting, pruning, and tree and stump removal. On the other hand, a program administered by the Sacramento Municipal Utility District (SMUD) and Sacramento Tree Founda-

[3] Milford *et al.* (1989) have carried out detailed calculations analyzing the changes in the maximum ozone concentration reached in Los Angeles vs. initial concentration of $NO_x$ and VOCs (volatile organic compounds). They presented their calculations in the form of 'isopleths' of equal maximum smog concentration for various levels of $NO_x$ and VOCs concentration (typically shown as a percent reduction of emissions) for a typical summer episode.

tion in 1992–1996 planted 20-foot tall trees at an average cost of $45 per tree. This only includes the cost of a tree and its planting; it does not include pruning, removal of dead trees, and stump. With this wide range of costs associated with trees, in our opinion, tree costs should be justified by other amenities they provide beyond air-conditioning and smog benefits. The best programs are then probably the information programs that provide data on energy and smog savings of trees to the communities and home owners that have decided to plant trees for other reasons.

Even trees planted along streets and in parks where they do not offer direct shade to air-conditioned buildings exert an ambient cooling effect sufficient to have a substantial impact on smog reduction. Simulations for Los Angeles indicate that trees account for net savings (energy and smog savings) of about $270M annual benefit, of which, $58M comes from their contribution to shading (Table 5).

At another level, our calculations suggest that urban trees play a major role in sequestering $CO_2$ and thereby delaying global warming. Rosenfeld *et al.* (1998) showed that a tree planted in Los Angeles avoids the combustion of 18 kg of carbon annually, even though it sequesters only 4.5 kg (as it would if growing in a forest). In that sense, one shade tree in Los Angeles is equivalent to four forest trees.

## 6. COOL PAVEMENTS

The practice of widespread paving of city streets with asphalt began only within the past hundred years. The advantages of this smooth and all-weather surface for the movement of bicycles and automobiles is obvious, but some of the associated problems are perhaps not so well appreciated. One consequence of covering streets with dark asphalt surfaces is the increased heating of the city by sunlight. A dark surface absorbs light, and, therefore, it gets warmer. The pavements in turn heat the air and help create the ‘urban heat island’. If urban surfaces were lighter in color, more of the incoming light would be reflected back into space and the surfaces and the air would be cooler. This tends to reduce the need for air conditioning.

Urban pavements are made predominantly of asphalt concrete. In this discussion, we will not deal with the common alternative, cement concrete, and the ongoing debate as to whether it is preferable because of its longer life-time. The questions we address are whether there are ways to reduce the heating of cities caused by asphalt concrete and whether this can be economical and practical.

In Fig. 6, we show some measurements of the effect of albedo on pavement temperature. The data clearly indicate that significant modification of the pavement temperature can be achieved: a

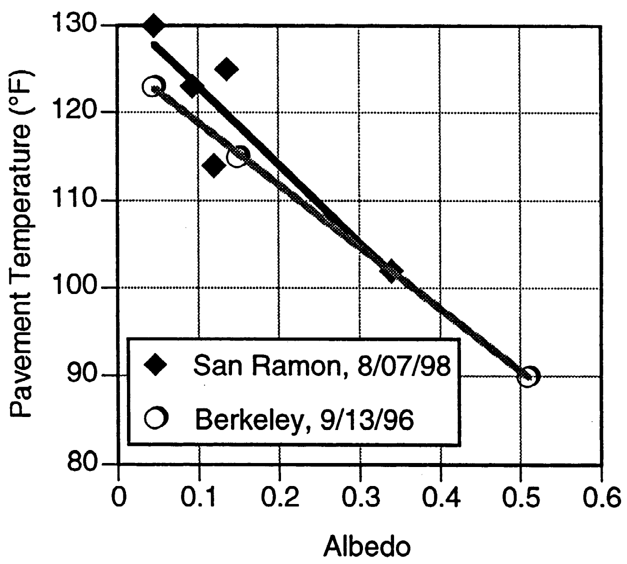


Fig. 6. Dependence of pavement surface temperature on albedo. Data were taken at about 3 p.m. in Berkeley, California, on new, old, and light-color coated asphalt pavements. The data from San Ramon, California, were taken at about 3 p.m. on four asphalt concrete and one cement concrete (albedo = 0.35) pavements.

10°C decrease in temperature for a 0.25 increase in albedo.

### *6.1. Energy and smog benefits of cool pavements*

An estimate of the benefits can be deduced by first finding the temperature decrease that would result if a city were resurfaced with more reflective paving materials. Cool pavements provide only indirect effects through lowered ambient temperatures. Lower temperature has two effects: (1) reduced demand for electricity for air conditioning and (2) decreased production of smog (ozone). Rosenfeld *et al*. (1998) estimated the cost savings of reduced demand for electricity and of the externalities of lower ozone concentrations in the Los Angeles Basin.

*6.1.1. Electric power savings in Los Angeles*. Simulations for Los Angeles indicate that a reasonable change in the albedo of the city could cause a noticeable decrease in temperature. Taha (1997) predicted a 1.5°C decrease in temperature of the downtown area.[4] The lower temperatures in the city are calculated for the condition that all roads and roofs are improved. From the meteorological simulations of 3 days in each season, the temperature changes for every day in a typical year were estimated for Burbank, typical of the hottest one-third of L.A. The energy consumptions of typical buildings were then simulated for the original weather and also for the modified weather. The differences are the annual energy changes due to the decrease in ambient temperature. The result is a city-wide annual saving of about $71M (million), due to combined albedo and vegetation changes. The kWh savings attributable to the pavement are $15M/year, or $0.012/m$^2$ year. Analysis of the hourly demand indicates that cooler pavements could save an estimated 100 MW of peak power in L.A. Fewer power plants, required to handle the growth of peak load, need be built if cooler pavements are installed, saving money, resources, and pollution.

*6.1.2. Smog savings in Los Angeles*. The simulations of the effects of higher albedo on smog formation indicate that an albedo change of 0.3 throughout the developed 25% of the city would yield a 12% decrease in the population-weighted ozone exceedance of the California air-quality standard (Taha, 1997). It has been estimated (Hall *et al*., 1992) that L.A. people would be willing to pay about $10 billion per year to avoid the medical costs and lost work time due to air pollution. The greater part of pollution is particulates, but the ozone contribution averages about $3 billion/year. Assuming a proportional relationship of the cost with the amount of smog exceedance, the cooler-surfaced city would save 12% of $3 billion/year, or $360M/year. As above, we attribute about 21% of the saving to pavements. Thus, smog improvement from altering the albedo of all 1250 km$^2$ of pavements by 0.25 saves about $76M/year. Per unit area, this is worth about $0.06/m$^2$ per year.

### *6.2. Other benefits of cool pavements*

*6.2.1. Increased life expectancy of pavements*. It has long been known that the temperature of a pavement affects its performance (Yoder and Witzak, 1975). This has been emphasized by the new system of binder specification advocated by the Strategic Highway Research Program (SHRP). Beginning in 1987, this program led pavement experts to carry out the task of researching and then recommending the best methods of making asphalt concrete pavements. A result of this study was the issuance of specifications for the asphalt binder. The temperature range that the pavement will endure is a primary consideration (Cominsky *et al*., 1994). The performance grade (PG) is specified by two temperatures: (1) the average 7-day maximum temperature that the pavement will likely encounter, and (2) the minimum temperature the pavement will likely attain. Note, importantly, that it is the pavement temperature and not the air temperature that is considered. There is a rule of thumb in the industry, the 'rule of 90', that, when the sum of the absolute values of these temperatures is greater than 90°C, some kind of modification of the asphalt will be needed; this adds to the cost. For example, if a binder is specified as PG 58-22, it is intended to function between 58 and $-22$°C. The sum of the absolute values, $58 + |-22| = 80$. An ordinary grade of asphalt will suffice; its cost is about $125 per ton. If, however, the pavement must function between 76 and $-16$°C, or PG 76-16, the sum $76 + |-16| = 92$, a modified asphalt is recommended. This higher grade costs about $165 per ton (Bally, 1998), a 30% increase in price.

As an example of a temperature-dependent

[4]The model assumes that all roofs (1250 km$^2$) have albedo increased by 0.35, from about 0.15 to 0.5, and all pavements (1250 km$^2$) have albedo increased from about 0.1 to 0.35.

source of pavement failure, we consider 'tertiary creep'. Pavements gradually accumulate permanent distortions as tires roll over them repeatedly. 'Tertiary creep' refers to the phenomenon of the accelerated rate of distortion after many such repetitions. This signals gross failure of the pavement. Cominsky *et al.* (1994) gave evidence that cooler pavements can have a significantly higher resistance to tertiary creep and, thus, can last much longer. Using Cominsky's data, we estimate that a 10°C decrease in pavement temperature can result in a 25-fold increase in its life expectancy against this type of failure, a factor so large that we suspect it is an overestimate.

*6.2.2. Improved visibility*. Reflectivity of pavements is also a safety factor in visibility at night and in wet weather, affecting the demand for streets' electric lighting. Street lighting is more effective if pavements are more reflective, which can lead to greater safety; or, alternatively, less lighting could be used to obtain the same visibility. These benefits have not yet been monetized.

### *6.3. Potential problems with cool pavements*

A practical drawback of high reflectivity is glare, but this does not appear to be a problem. We suggest a change in resurfacing using not black asphalt, with an albedo of about 0.05–0.12, but the application of a product with an albedo of about 0.35, similar to that of cement concrete. The experiment to test whether this will be a problem has already been performed: every day, millions of people drive on cement concrete roads, and we rarely hear of accidents caused by glare, or of people even complaining about the glare on such roads. Thus, every reader of this paper likely knows the answer from experience.

There is also a concern that, after some time, light-colored pavement will darken because of dirt. This tends to be true, but again, experience with cement concrete roads suggests that the light color of the pavement persists after long usage. Most drivers can see the difference in reflection between an asphalt and a cement concrete road when they drive over them, even when the roads are old. More studies are needed to quantify the effect of aging.

The use of chip seals is a promising method of resurfacing that achieves lighter color. (Chip sealing is the pressing on of aggregate into soft binder, as a resurfacing technique (Asphalt Institute, 1989).) Although this is popular in many districts, some have reservations about the use of chip seals in cul de sacs, where tires are turned hard and loosen the aggregate. Aggregate is sometimes thrown by tires, but, when installed properly, this seems to be rare.

### *6.4. Cost of cool pavements*

It is clear that cooler pavements will have energy, environmental and engineering benefits. The issue is then whether there are ways to construct pavements that are feasible, economical, and cooler. The economic question is whether or not the savings generated by a cool pavement over its lifetime are greater than its extra cost. Properly, one should distinguish between initial cost and lifetime costs (including maintenance, repair time, and length of service of the road). Often the initial cost is decisive, so we will consider only that cost here.

*6.4.1. Thick pavements*. A typical asphalt concrete contains about 7% of asphalt by weight, or about 17% by volume; the remainder is rock aggregate, except for a few percent of voids. The cost of ordinary asphalt (1998 prices) is about \$125 per ton, and the price of aggregate is about \$20 per ton, exclusive of transportation costs. Thus, in one ton of mixed asphalt concrete, the cost of materials only is about \$28/ton, of which about \$9 is in the binder and \$19 is in the aggregate. For a pavement about 10 cm thick (4 inches), with a density of 2.1 ton/m$^3$, the cost of the binder alone is about \$2 per m$^2$ and aggregate costs about \$4.2 per m$^2$.

Experimentally, the albedo of a fresh asphalt concrete pavement is about 0.05 (Pomerantz *et al.*, 1997) because the relatively small amount of black asphalt coats the lighter colored aggregate. As an asphalt concrete pavement is worn down and the aggregate is revealed, we observed an albedo increase to about 0.15 for ordinary aggregate. If it were made with a reflective aggregate, we could expect the long-term albedo to approach that of the aggregate.

How much money might such a reflective pavement save? Using the assumptions for Los Angeles, a cooler pavement would generate a stream of savings of \$0.07/m$^2$ per year for the lifetime of the road, about 20 years. At a real interest rate of 3% per year, this has a present value about 15 times the current saving (Rosenfeld *et al.*, 1998). Thus, the potential savings are worth \$1.1/m$^2$ at present. This saving would allow for purchase of a binder, instead of \$2/m$^2$, costing \$3/m$^2$, or 50% more expensive. Or, one could buy aggregate; instead of spending \$4.2/m$^2$, one can now afford \$5.2/m$^2$ (a 20% more expensive, whiter, aggregate). It is doubtful that such modest increases in costs can buy much whiter pavements.

In the special case of a climate in which the pavement is subjected to such wide temperature swings that the 'rule of 90' is violated, the cost of binder is increased by about 30%, if SHRP recommendations are followed. For a 10 cm thick new road, the cost of ordinary asphalt is $2/m$^2$ and higher grade asphalt costs $2.60/m$^2$. Instead of buying the higher grade binder, one could apply a chip seal, which costs about $0.60/m$^2$. Chip seals comprise a binder onto which aggregate is pressed. The aggregate is visible from the outset, and, if it is reflective, the pavement stays cooler. It might be sufficiently cool that it is unnecessary to use the higher grade binder. For example, the data of Fig. 6 show that a 0.25 increase in albedo can reduce the pavement temperature by 10°C. This suggests that the maximum temperature specification for the pavements might be reduced by 10°C. A lower grade of binder might then be acceptable. The reduced cost of the binder cancels the cost of the chip seal, and one enjoys the cooling benefit at no extra cost.

Thus, for thick pavements, the energy and smog savings may not pay for whiter roads. However, if the lighter-colored road leads to substantially longer lifetime, the initial higher cost may be offset by lifetime savings. An example of this is to be seen when a higher grade binder is replaceable by a white surface. This must be evaluated according to the demands on the road and the climate.

*6.4.2. Thin pavements*. At some times in its life, a pavement needs to be maintained, i.e., resurfaced. This offers an opportunity to get cooler pavements economically. Good maintenance practice calls for resurfacing a new road after about 10 years (Dunn, 1996) and the lifetime of resurfacing is only about 5 years. Hence, within 10 years, all the asphalt concrete surfaces in a city can be made light-colored. As part of this regular maintenance, any additional cost of the whiter material will be minimized. Note also that because the lifetime of the resurfacing is only about 5 years, the present value of the savings is five-times greater than the annual savings. Thus, for LA, the present value is about $0.36/m$^2$ ($0.03/ft$^2$). Can a pavement be resurfaced with a light color at an added cost less than this saving?

For resurfacing, there are the options of a black topping, such as a slurry seal, or a lighter-colored surface, achieved by using a chip seal. The costs of both of these are about the same, $0.60/m$^2$ (Means, 1996). For a chip seal, about half the materials cost is aggregate and half is the binder. If special light-colored aggregate is used in the chip seal, there will be an extra cost. For example, if the aggregate costs 50% more, instead of $0.30/m$^2$ it will cost $0.45/m$^2$, and the price of the chip seal will rise by $0.15/m$^2$. If the energy, environmental and durability benefits over the lifetime of the resurfacing exceed $0.15/m$^2$, the cooler pavement pays for itself. Again, this depends on local circumstances: the climate and smog conditions vs. the cost of light-colored aggregate. For Los Angeles, we have estimated that energy and environmental savings alone are about $0.36/m$^2$ (present value over the lifetime of 5 years for a resurfacing), and, thus, one could afford to pay twice the usual price for aggregate and still have no net increase in cost. Lifetime benefits would also accrue in addition to energy and smog benefits.

## 7. CONCLUSIONS

Cool surfaces (cool roofs and cool pavements) and urban trees can have a substantial effect on urban air temperature and, hence, can reduce cooling-energy use and smog. We estimate that about 20% of the national cooling demand can be avoided through a large-scale implementation of heat-island mitigation measures. This amounts to 40 TWh/year savings, worth over $4B per year by 2015, in cooling-electricity savings alone. Once the benefits of smog reduction are accounted for, the total savings could add up to over $10B per year.

Achieving these potential savings is conditional on receiving the necessary federal, state, and local community support. Scattered programs for planting trees and increasing surface albedo already exist, but to start an effective and comprehensive campaign would require an aggressive agenda. We have started to collaborate with the American Society for Testing of Materials (ASTM) and the industry, to create test procedures, ratings, and labels for cool materials. We have also initiated plans to incorporate cool roofs and trees into the Building Energy Performance Standards of ASHRAE (American Society of Heating Refrigeration, and Airconditioning Engineers), California Title 24, and the California South Coast's Air Quality Management Plans. We also plan to demonstrate savings in selected 'Cool Communities', including federal facilities, particularly military bases. A related effort involves expanding the Los Angeles Basin's Regional Clean Air Incentive Market (RECLAIM) $NO_x$-credit trading market to include air temperature reduction by cool surfaces. The South Coast Air Quality Management District and the EPA now recognize that air temperature is as much a cause of smog as $NO_x$ or volatile organic compounds, so that cool surfaces and shade trees should be monetized on RECLAIM along with $NO_x$. Finally, EPA is considering mechanisms that would allow inclusion of cool surface and trees in State Implementation Plans (SIPs) for ozone compliance.

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## REFERENCES

Akbari H., Gartland L. and Konopacki S. (1998) Measured energy savings of light-colored roofs: results from three California demonstration sites. In *Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings* Vol. 3, p. 1.

Akbari, H., Davis, S., Dorsano, S., Huang, J. and Winnett, S. (1992). *Cooling Our Communities: A Guidebook on Tree Planting Light-Colored Surfacing*. U.S. Environmental Protection Agency, Office of Policy Analysis, Climate Change Division

Akbari H., Rosenfeld A. and Taha H. (1990) Summer heat islands, urban trees, and white surfaces. *ASHRAE Trans*. **96**(1). American Society of Heating, Refrigeration, and Air Conditioning Engineers, Atlanta, Georgia.

Akbari H., Bretz S., Taha H., Kurn D. and Hanford J. (1997) Peak power and cooling energy savings of high-albedo roofs. *Energy and Buildings-Special Issue on Urban Heat Islands and Cool Communities* **25**(2), 117–126.

Akbari H., Bretz S. E., Hanford J. W., Kurn D. M., Fishman B. L., Taha H. G. and Bos W. (1993) *Monitoring Peak Power and Cooling-energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results*, Lawrence Berkeley Laboratory Report LBL-34411, Berkeley, CA.

Akbari H. and Taha H. (1992) The Impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities. *Energy, the International Journal* **17**(2), 141–149.

Asphalt-Institute (1989). *The Asphalt Handbook,* The Asphalt Institute, Lexington, KT.

Bally, M., 1998. Private communication on the prices for Superpave grades of asphalt charged by Koch Performance Asphalt Co. in Nevada.

Benjamin M. T., Sudol M., Bloch L. and Winer A. M. (1996) Low-emitting urban forests: A taxonomic methodology for assigning isoprene and monoterpene emission rates. *Atmospheric Environment* **30**(9), 1437–1452.

Berdahl P. and Bretz S. (1997) Preliminary survey of the solar reflectance of cool roofing materials. *Energy and Buildings Special Issue on Urban Heat Islands and Cool Communities* **25**(2), 149–158.

Bretz S., Akbari H. and Rosenfeld A. (1997) Practical issues for using high-albedo materials to mitigate urban heat islands. *Atmospheric Environment* **32**(1), 95–101.

Bretz S. and Akbari H. (1997) Long-term performance of high-albedo roof coatings. *Energy and Buildings Special Issue on Urban Heat Islands and Cool Communities* **25**(2), 159–167.

Bretz S. and Akbari H. (1994) Durability of high-albedo roof coatings. In *Proceedings of the ACEEE* 1994 *Summer Study on Energy Efficiency in Buildings*, Vol. 9, p. 65.

Cominsky R. J., Huber G. A., Kennedy T. W. and Anderson M. (1994). *The Superpave Mix Design Manual for New Construction and Overlays*. *SHRP-A-407,* National Research Council, Washington, DC.

DeWalle D. R., Heisler G. M. and Jacobs R. E. (1983) Forest home sites influence heating and cooling energy. *Journal of Forestry* **81**(2), 84–87.

Dunn B. H. (1996) What you need to know about slurry seal. *Better Roads* **March**, 21–25.

EPA (1986). *Guideline on Air Quality Models (Revised),* U.S. Environmental Protection Agency EPA-450/2-78-027R.

Gartland L. M., Konopacki S. J., Akbari H. (1996) Modeling the effects of reflective roofing. In *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings*, Vol. 4, p. 117.

Gery M. W., Whitten G. Z. and Kills J. P. (1988) *Development and Testing of the CBM-IV for Urban Abd Regional Modeling*. Report EPA-600/3/88-012. U.S. EPA, Research Triangle, North Carolina. ANL No. 058719, Argonne National Laboratory, Argonne, IL.

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

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

Hall J. V., Winer A. M., Kleinman M. T., Lurmann F. M., Brajer V. and Colome S. D. (1992) Valuing the health benefits of clean air. *Science* **255**, 812–817.

Heisler G. M. (1989). In *Effects of Trees On Wind and Solar Radiation in Residential Neighborhoods, Final Report On Site Design and Microclimate Research, Anl No. 058719,* Argonne National Laboratory, Argonne, IL.

Hildebrandt E., Bos W. and Moore R. (1998) Assessing the impacts of white roofs on building cooling loads: a comparison of results from three different methods. *ASHRAE Trans*. **104**(1). Proceedings of the American Society of Heating, Refrigeration, and Air Conditioning Engineers, Atlanta, Georgia (January).

Huang Y. J., Akbari H. and Taha H. (1990) The wind-shielding and shading effects of trees on residential heating and cooling requirements. *ASHRAE Trans*. **96**(1). Proceedings of the American Society of Heating, Refrigeration, and Air conditioning Engineers, Atlanta, Georgia (February).

Konopacki, S., Akbari, H., Gartland, L. and Rainer, L. (1998). Demonstration of Energy Savings of Cool Roofs. Lawrence Berkeley National Laboratory Report LBNL-40673, Berkeley, CA

Konopacki, S., Akbari, H., Gabersek, S., Pomerantz, M. and Gartland, L. (1997) Cooling Energy Saving Potentials of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. Lawrence Berkeley National Laboratory Report LBL-39433, Berkeley, CA

McPherson, E.G., Nowak, D.J. and Rowntree, R.A. (1994). Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project, Forest Service, U.S. Dept. of Agriculture. NE-186.

Means R. S. (1996). *Site and Landscape Costs*, R.S. Means Company, Inc, Kingston, MA.

Milford J. B., Armistead G. R. and McRae G. J. (1989) A new approach to photochemical pollution control: implications of spatial patterns in pollutant responses to reduction in nitrogen oxides and reactive organic emissions. *Environmental Science and Technology* **23**, 1290–1301.

Parker D. S., Sherwin J. R. and Sonne J. K. (1998) Measured performance of reflective roofing systems in Florida commercial buildings. *ASHRAE Trans*. **104**(1). American Society of Heating, Refrigeration, and Air Conditioning Engineers, Atlanta, Georgia (January).

Parker D. S., Barkaszi S. F., Jr., Chandra S. and Beal D. J. (1995) Measured cooling energy savings from reflective roofing systems in Florida: field and laboratory research results, *Proceeding of the Thermal Performance of the Exterior Envelopes of Buildings VI*, December 4–8, 1995, Clearwater, FL.

Parker J. H. (1981). *Use of Landscaping For Energy Conservation*, Department of Physical Sciences, Florida International University, Miami, FL.

Pielke R. (1974) A three-dimensional numerical model of the sea breeze over South Florida. *Monthly Weather Review* **102**, 115–139.

Pomerantz M., Akbari H. Chen A., Taha H. and Rosenfeld A. H. (1997) Paving Materials for Heat Island Mitigation, Lawrence Berkeley National Laboratory Report LBNL-38074. Berkeley, CA.

Rosenfeld A. H., Romm J. J., Akbari H. and Pomerantz M. (1998) Cool communities: strategies for heat islands mitigation and smog reduction. *Energy and Buildings* **28**, 51–62.

Rosenfeld A., Akbari H., Taha H. and Bretz S. (1992) Implementation of light-colored surfaces: profits for utilities and labels for paints. In *Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings*, Vol. 9, p. 141.

Taha H. (1996) Modeling the impacts of increased urban vegetation on the ozone air quality in the South Coast Air Basin. *Atmospheric Environment* **30**(20), 3423–3430.

Taha H. (1997) Modeling the impacts of large-scale albedo changes on ozone air quality in the South Coast Air Basin. *Atmospheric Environment* **31**(11), 1667–1676.

Taha H., Douglas S. and Haney J. (1994) The UAM sensitivity analysis: the August 26–28 1987 oxidant episode. In *Analysis of Energy Efficiency and Air Quality in the South Coast Air Basin-Phase II*, Taha H. et al. (Ed.), Lawrence Berkeley Laboratory Report LBL-35728, Berkeley, CA, Chapter 1.

Taha H., Douglas S., Haney J., Winer A., Benjamin M., Hall D., Hall J., Liu X. and Fishman B. (1995) *Modeling the Ozone Air Quality Impacts of Increased Albedo and Urban Forest in the South Coast Air Basin*, Lawrence Berkeley Laboratory Report LBL-37316, Berkeley, CA.

Taha H., Konopacki S. and Gabersek S. (1996) *Modeling the Meteorological and Energy Effects of Urban Heat Islands and their Mitigation: A 10-Region Study*, Lawrence Berkeley Laboratory Report LBL-38667, Berkeley, CA.

Yoder E. J. and Witzak M. W. (1975). *Principles of Pavement Design*, Wiley, New York.