Potentials of urban heat island mitigation

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ABSTRACT

Urban areas tend to have higher air temperatures than their rural surroundings as a result of gradual surface modifications that include replacing the natural vegetation with buildings and roads. The term "Urban Heat Island" describes this phenomenon. The surfaces of buildings and pavements absorb solar radiation and become extremely hot, which in turn warm the surrounding air. Cities that have been "paved over" do not receive the benefit of the natural cooling effect of vegetation. As the air temperature rises, so does the demand for air-conditioning (a/c). This leads to higher emissions from power plants, as well as increased smog formation as a result of warmer temperatures. In the United States, we have found that this increase in air temperature is responsible for 5–10% of urban peak electric demand for *a/c* use, and as much as 20% of population-weighted smog concentrations in urban areas.

Simple ways to cool the cities are the use of reflective surfaces (rooftops and pavements) and planting of urban vegetation. On a large scale, the evapotranspiration from vegetation and increased reflection of incoming solar radiation by reflective surfaces will cool a community a few degrees in the summer. As an example, computer simulations for Los Angeles, CA show that resurfacing about two-third of the pavements and rooftops with reflective surfaces and planting three trees per house can cool down LA by an average of 2–3K. This reduction in air temperature will reduce urban smog exposure in the LA basin by roughly the same amount as removing the basin entire on-road vehicle exhaust. Heat island mitigation is an effective air pollution control strategy, more than paying for itself in cooling energy cost savings. We estimate that the cooling energy savings in U.S. from cool surfaces and shade trees, when fully implemented, is about $5 billion per year (about $100 per air-conditioned house).

1. INTRODUCTION

Across the world, urban temperatures have increased faster than temperatures in rural areas. For example, from 1930 to 1990, downtown Los Angeles recorded a growth of 0.5 degrees C per decade (Akbari et al., 2001). Every degree increase adds about 500 megawatts (MW) to the air conditioning load in the Los Angeles Basin (Akbari et al., 2001). Similar increases are taxing the ability of developing countries to meet urban electricity demand, while increasing global GHG emissions. Local air pollution (e.g., particulates, volatile organics, and nitrogen oxides, which are precursors to ozone formation) are already a problem in most cities in developing countries. Higher temperatures mean increased ozone formation, with accompanying health impacts. LBNL has conducted research on both the electricity and air pollution effects of higher temperatures, and devised methods to reduce both effects. We have tested reflective coatings on building roofs and pavements, and tree-planting schemes, to demonstrate potential cost-effective reductions of energy use—between 10 and 40 percent. Among energy-efficiency solutions, cool roofs and cool pavements are ideally suited to hot climates that prevail in much of the developing world. Cool (light-colored) pavements also increase night-time visibility and pavement durability.

Urban areas have typically darker surfaces

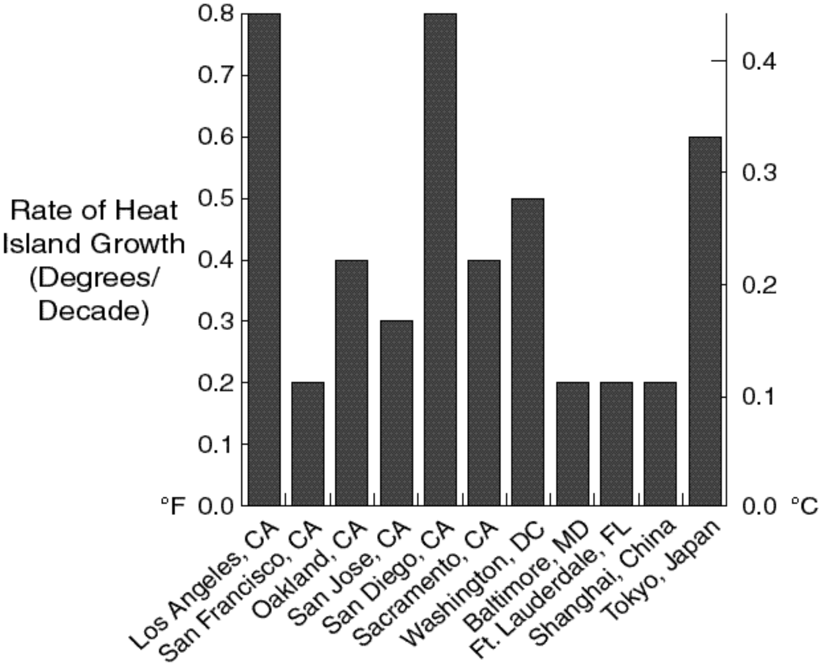

Figure 1: Increasing urban temperature trends over the last 3–8 decades in selected cities.

and less vegetation than their surroundings (HIG, 2005). 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 2.5K higher than in the surrounding rural areas. Research shows that peak urban electric demand rises by 2–4% for each 1K rise in daily maximum temperature above a threshold of 15–20°C. Thus, the additional air-conditioning use caused by this urban air temperature increase is responsible for 5–10% of urban peak electric demand.

In California, Goodridge (1987, 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. After 1940, when built-up areas began to replace vegetation, the urban centers became as warm or warmer than the suburbs. From 1965 to 1989, urban temperatures increased by about 1K.

Regardless of whether there is an urban-rural temperature difference, data suggest that temperatures in cities are increasing. For example, the maximum temperatures in downtown Los Angeles are now about 2.5K higher than they were in 1930. The minimum temperatures are about 4K higher than they were in 1880 (Akbari et al., 2001). In Washington, DC, temperatures increased by about 2K 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. Limited available data also show this increasing trend in urban temperatures in major cities of other countries (Fig. 1).

Not only do summer heat islands increase system-wide cooling loads, they also increase smog production because of higher urban air temperatures (Taha et al., 1994). Smog is created by photochemical reactions of pollutants in the air; and these reactions are more likely to intensify at higher temperatures. For example, in Los Angeles, for every 1°C the temperature rise above 22°C, incident of smog increases by 5%.

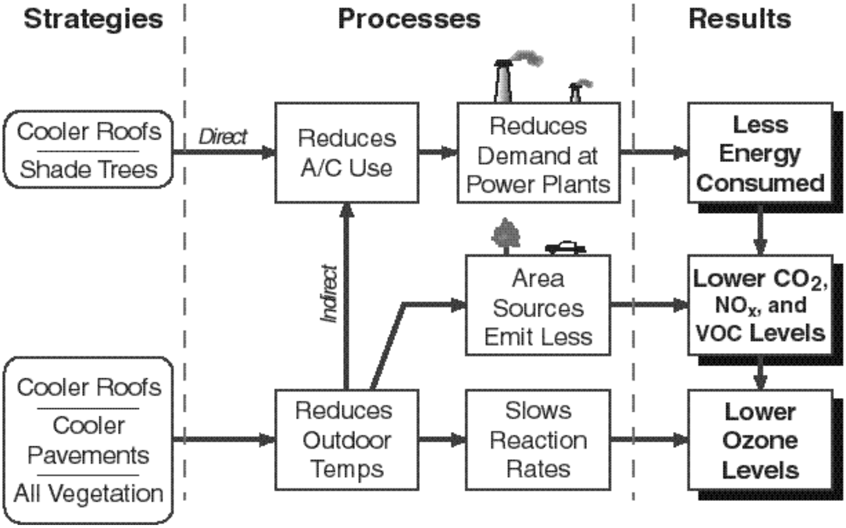

Figure 2: Methodology for energy and air-quality.

2. HEAT ISLANDS MITIGATION TECHNOLOGIES

Use of high-albedo[*] urban surfaces and 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.

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 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 process in which ozone is directly absorbed by tree leaves), and indirectly reduce the emission of these precursors from power plants (by reducing combustion of fossil fuels and hence reducing NOx emissions from power plants) (Taha, 1996).

Over the past two decades, LBNL has been studying the energy savings and air-quality benefits of heat-island mitigation measures. The approaches used for analysis included direct measurements of the energy savings for cool roofs and shade trees, simulations of direct and indirect energy savings of the mitigation measures (cool roofs, cool pavements, and vegetation), and meteorological and air-quality simulations of the mitigation measures. Figure 2 depicts the overall methodology used in analyzing

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[*] When sunlight hits an opaque surface, some of the sunlight 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.

Table 1: Comparison of measured summertime air-conditioning daily energy savings from application of reflective roofs. $\Delta\rho$ is change in roof reflectivity, RB is radiant barrier, duct is the location of air-conditioning ducts, and R-val is roof insulation in Km^2/W.

Location	Building type	Roof area [m^2]	Roof system			Savings [$Wh/m^2/day$]
			R-val	duct	$\Delta\rho$	
California						
Davis	Medical Office	2,945	1.4	Interior	0.36	68
Gilroy	Medical Office	2,211	3.3	Plenum	0.35	39
San Jose	Retail Store	3,056	RB	Plenum	0.44	4.3
Sacramento	School Bungalow	89	3.3	Ceiling	0.60	47
Sacramento	Office	2,285	3.3	Plenum	0.40	14
Sacramento	Museum	455	0	Interior	0.40	20
Sacramento	Hospice	557	1.9	Attic	0.40	11
Sacramento	Retail Store	1600	RB	None	0.61	72
San Marcus	Elementary School	570	5.3	None	0.54	45
Reedley	Cold Storage Facility					
	Cold storage	4900	5.1	None	0.61	69
	Fruit conditioning	1300	4.4	None	0.33	
	Packing area	3400	1.7	None	0.33	Nil (open to outdoor)
Florida						
Cocoa Beach	Strip Mall	1,161	1.9	Plenum	0.46	7.5
Cocoa Beach	School	929	3.3	Plenum	0.46	43
Georgia						
Atlanta	Education	1,115	1.9	Plenum	N/A	75
Nevada						
Battle Mountain	Regeneration	14.9	3.2	None	0.45	31
Carlin	Regeneration	14.9	3.2	None	0.45	39
Texas						
Austin	Retail Store	9,300	2.1	Plenum	0.70	39

the impact of heat-island mitigation measures on energy use and urban air pollution.

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 (Taha et al., 1997). For example, Taha et al., (1995) and Taha (1996, 1997) used the Colorado State University Mesoscale Model (CSUMM) to simulate the Los Angeles Basin's meteorology and its sensitivity to changes in surface properties. More recently, we have utilized the PSU/NCAR mesoscale model (known as MM5) to simulate the meteorology. The Urban Airshed Model (UAM) was used to simulate the impact of the changes in meteorology and emissions on ozone air quality. The CSUMM, MM5, and the UAM essentially solve a set of coupled governing conservation equations representing the conservation of mass (continuity), potential temperature (heat), momentum, water vapor, and chemical species continuity to obtain prognostic meteorological fields and pollutant species concentrations.

2.1 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 50K, while for less absorptive (high-albedo) surfaces with similar insulative properties, such as roofs covered with a white coating, the difference is only about 10K (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. In most applications, cool roofs 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 roofing materials are light colored, although selective surfaces that reflect a large portion of the infrared solar radiation but absorb some visible light can be dark colored and yet have relatively high albedos (Levinson et al., 2005a,b; Berdahl and Bretz, 1997).

2.1.1 Energy and Smog Benefits of Cool Roofs

Direct Energy Savings

Several field studies have documented measured energy savings that result from increasing roof solar reflectance (see Table 1). Akbari et al., (1997) reported monitored cooling-energy savings of 46% and peak power savings of 20% achieved by increasing the roof reflectance of two identical portable classrooms in Sacramento, California. Konopacki et al., (1998) documented measured energy savings of 12–18% in two commercial buildings in California. Konopacki and Akbari (2001) documented measured energy savings of 12% in a large retail store in Austin, Texas. Akbari (2003) documented energy savings of 31–39 Wh/m^2/day in two small commercial buildings with very high internal loads, by coating roofs with a white elastomer with a reflectivity of 0.70. Parker et al., (1998) measured an average of 19% energy savings in eleven Florida residences by applying reflective coatings on roofs. Parker et al., (1997) also monitored seven retail stores in a strip mall in Florida before and after applying a high-albedo coating to the roof and measured a 25% drop in seasonal cooling energy use. Hildebrandt et al., (1998) observed daily energy savings of 17%, 26%, and 39% in an office, a museum and a hospice, respectively, retrofitted with high-albedo roofs in Sacramento. Akridge, (1998) reported energy savings of 28% for a school building in Georgia which had an unpainted galvanized roof that was coated with white acrylic. Boutwell and Salinas, (1986) showed that an office building in southern Mississippi saved 22% after the application of a high-reflectance coating. Simpson and McPherson (1997) measured energy savings in the range of 5–28% in several quarter-scale models in Tucson AZ.

In addition to these building monitoring studies, computer simulations of cooling energy savings from increased roof albedo have been documented in residential and commercial buildings by many studies, including Konopacki and Akbari, (1998), Akbari et al., (1998a), Parker et al., (1998), and Gartland et al., (1996). Konopacki et al., (1997) estimated the direct energy savings potential from high-albedo roofs in eleven U.S. metropolitan areas. The results showed that four major building types account for over 90% of the annual electricity and monetary savings: pre-1980 residences (55%), post-1980 residences (15%), and office buildings and retail stores together (25%). Furthermore, these four building types account for 93% of the total air-conditioned roof area. Regional savings were found to be a function of three factors: energy savings in the air-conditioned residential and commercial building stock; the percentage of buildings that were air-conditioned; and the aggregate regional roof area. Metropolitan-wide annual savings from the application of cool roofs on residential and commercial buildings were as much as $37M for Phoenix and $35M in Los Angeles and as low as $3M in the heating-dominated climate of Philadelphia. Analysis of the scale of urban energy savings potential was further refined for five cities: Baton Rouge, LA; Chicago, IL; Houston, TX; Sacramento, CA; and Salt Lake City, UT by Konopacki and Akbari, (2002, 2000).

The results for the 11 Metropolitan Statistical Areas (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/yr (about 3.0% of the national cooling-electricity use in residential and commercial buildings), an increase in natural gas use by 26 GBtu/yr (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.

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. 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 2K 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 Los Angeles are estimated at $21M (Rosenfeld et al., 1998).

We have 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).

2.1.2 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 resulting from the absorption of ultra-violet light is a temperature-dependent process. For these reasons, cooler roofs may last longer than hot roofs of the same material.

2.1.3 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. 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 entail 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.

2.1.4 Cost of Cool Roofs

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. In 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.

2.2 Cool Pavements

The practice of widespread paving of city streets with asphalt began only within the past century. The advantages of this smooth and all-weather surface for the movement of bicycles and automobiles are 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. The pavements in turn heat the air. LBNL has conducted studies to measure the effect of albedo on pavement temperature. The data clearly indicate that significant modification of the pavement surface temperature can be achieved: a 10K decrease in temperature for a 0.25 increase in albedo. 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. Pomerantz et al., (1997) present an overview of cool paving materials for urban heat island mitigation.

2.2.1 Energy and Smog Benefits of Cool Pavements

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.

Simulations for Los Angeles (L.A.) basin indicate that a reasonable change in the albedo of the city could cause a noticeable decrease in temperature. Taha, (1997) predicted a 1.5K decrease in temperature of the downtown area. The lower temperatures in the city are calculated based on the assumption that all roads and roofs are improved. From the meteorological simulations of three days in each season, the temperature changes for every day in a typical year were estimated for Burbank, typical of the hottest 1/3 of L.A. basin. 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, due to combined albedo and vegetation changes. The kWh savings attributable to the pavement are \$15M/yr, or \$0.012/m^2-yr. Analysis of the hourly demand indicates that cooler pavements could save an estimated 100 MW of peak power in L.A.

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 residents of L.A. 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/yr. Assuming a proportional relationship of the cost with the amount of smog exceedance, the cooler-surfaced city would save 12% of \$3 billion/yr, or \$360M/yr. As above, we attribute about 21% of the saving to pavements. Rosenfeld et al. (1998) value the benefits from smog improvement by altering the albedo of all 1250km^2 of pavements by 0.25 saves about \$76M/year (about \$0.06/m^2 per year).

2.2.2 Other Benefits of Cool 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 which 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.

Reflectivity of pavements is also a safety factor in visibility at night and in wet weather, affecting the demand for electric street 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.

2.2.3 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.

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.

2.2.4 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 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.

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. 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 is about \$2 per m^2 and aggregate costs about \$4.2 per m^2.

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. The present value of potential savings at a real discount rate of 3% is \$1.1/m^2. This saving would allow for purchase of a binder costing \$3/m^2, instead of \$2/m^2—or 50% more. Alternatively, 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.

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.

For 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.

2.3 Shade trees and urban vegetation

Akbari, (2002) provides an overview of benefits and cost associated with planting urban trees. 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 and 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.

2.3.1 Energy and Smog Benefits of Shade Trees

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).

DeWalle et al., (1983), Heisler, (1989), and Huang et al., (1990) have focused on measuring and simulating the wind-shielding effects of tree on heating- and cooling-energy use. Their analysis 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 reduce heat-energy use in buildings. However, using strategically placed deciduous trees can decrease winter heating penalties. 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 10–15%.

Taha et al. (1996) simulated the meteorological impact of large-scale tree-planting programs in 10 U.S. metropolitan areas: Atlanta GA, Chicago IL, Dallas TX, Houston TX, Los Angeles CA, Miami FL, New York NY, Philadelphia PA, Phoenix AZ, and Washington, DC. 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, and showed that in most hot cities, shading a building can save annually \$5 to \$25 per $100m^2$ of roof area of residential and commercial buildings.

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 10 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 0.3K to 1K at 2 pm.; in some simulation cells the temperature was decreased by up to 3K. The corresponding air-conditioning savings resulting from ambient cooling by trees in hot climates ranges from \$5 to \$10 per year per $100m^2$ of roof area of residential and commercial buildings. Indirect effects are smaller than the direct effects of shading, and, moreover, require that the entire city be planted.

Rosenfeld et al., (1998) studied the potential benefits of planting 11M trees in the Los Angeles Basin. They estimate an annual total savings of \$270 million from direct and indirect energy savings and smog benefit; about 2/3 of the savings resulted from the reduction in smog concentration resulting from meteorological changes due to the evapotranspiration of trees. It also has been suggested that trees improve air quality by dry-depositing NO_X, O_3, and PM10 particulates. Rosenfeld et al. (1998) estimate that 11M trees in LA 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 homeowner 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 thus \$210/tree.

2.3.2 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 CO_2 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.

2.3.3 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 rate.

In dry climates and areas with a serious water shortage, drought-resistant trees are recommended. Some trees need significant maintenance that may entail high costs 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.

2.3.4 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 $150–470 a tree (McPherson, 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, in yards, and along streets, highways, and houses. The present value of all these life-cycle costs (including planting) is $300–500 per tree. Over 90% of the cost is associated with professional planting, pruning, tree and stump removal. On the other hand, a program administered by the Sacramento Municipal Utility District (SMUD) and Sacramento Tree Foundation 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 removal of stumps. 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 probably the information programs that provide data on energy and smog savings of trees to the communities and homeowners that are considering planting trees for other reasons.

3. 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 are collaborating with the American Society for Testing of Materials (ASTM), the Cool Roof Rating Council (CRRC), and the industry, to create test procedures, ratings, and labels for cool materials. The cool roofs criteria and standards are incorporated 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. Many field projects have demonstrated the energy benefits of cool roofs and shade trees. The South Coast Air Quality Management District and the United States Environmental Protection Agency (EPA) now recognize that air temperature is as much a cause of smog as NO_X or volatile organic compounds. In 1992, the EPA published a milestone guideline for tree planting and light-colored surfacing (Akbari et al., 1992). Many countries have joined efforts in developing heat-island-reduction programs to improve urban air quality. The efforts in Japan are of notable interest.

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