Opportunities for Saving Energy and Improving Air Quality in Urban Heat Islands

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1. Introduction and Background on Urban Heat Island

World energy use is the main contributor to atmospheric CO_2. In 2002, about 7.0 giga metric tons of carbon (GtC) were emitted internationally by combustion of gas, liquid, and solid fuels (CDIAC, 2006), 2 to 5 times the amount contributed by deforestation (Brown *et al.*, 1988). The share of atmospheric carbon emissions for the United States from fossil fuel combustion was 1.6 GtC. Increasing use of fossil fuel and deforestation together have raised atmospheric CO_2 concentration some 25% over the last 150 years. According to global climate models and preliminary measurements, these changes in the composition of the atmosphere have already begun raising the Earth's average temperature. If current energy trends continue, these changes could drastically alter the Earth's temperature, with unknown but potentially catastrophic physical and political consequences. During the last three decades, increased energy awareness has led to conservation efforts and leveling of energy consumption in the industrialized countries. An important byproduct of this reduced energy use is the lowering of CO_2 emissions.

Of all electricity generated in the United States, about one-sixth is used to air-condition buildings. The air-conditioning use is about 400 tera-watt-hours (TWh), equivalent to about 80 million metric tons of carbon (MtC) emissions, and translating to about $40 billion (B) per year. Of this $40 B/year, about half is used in cities that have pronounced "heat islands." The contribution of the urban heat island to the air-conditioning demand has increased over the last 40 years and it is currently at about 10%. Metropolitan areas in the United States (e.g., Los Angeles, Phoenix, Houston, Atlanta, and New York City) have typically pronounced heat islands that warrant special attention by anyone concerned with broad-scale energy efficiency (HIG, 2006).

The ambient air is primarily heated through three processes: direct absorption of solar radiation, convection of heat from hot surfaces, and man-made heat (exhaust from cars, buildings, etc.). Air is fairly transparent to light─the direct absorption of solar radiation in atmospheric air only raises the air temperature by a small amount. Typically about 90% of solar radiation reaches the Earth’s surface and then is either absorbed or reflected. The absorbed radiation on the surface increases the surface temperature. And in turn the hot surfaces heat the air. This convective heating is responsible for the majority of the diurnal temperature range. The contribution of man-made heat (e.g., air conditioning, cars) is very small, compared to the heating of air by hot surfaces, except for the downtown high-rise areas.

Modern urban areas have darker surfaces or lower “effective” albedo[1] and relatively less vegetation than their more natural surroundings, which affects urban climate, energy use, and thermal environmental conditions. Dark roofs, for example, heat up more than their more reflective counterparts and thus raise the summertime cooling demands of buildings. Collectively, on a neighborhood scale, dark surfaces and reduced vegetation warm the air over urban areas, contributing to urban heat islands. **Figure 1** shows a sketch of a typical summer afternoon urban heat island. On a clear summer afternoon, the air temperature in a typical city can be as much as 2.5 Kelvin (K) higher than surrounding rural areas.[2] In hot cities, peak urban electric demand in the U.S. rises by 2-4% for each 1 K rise in daily maximum temperature above ambient air temperatures of 15-20°C.

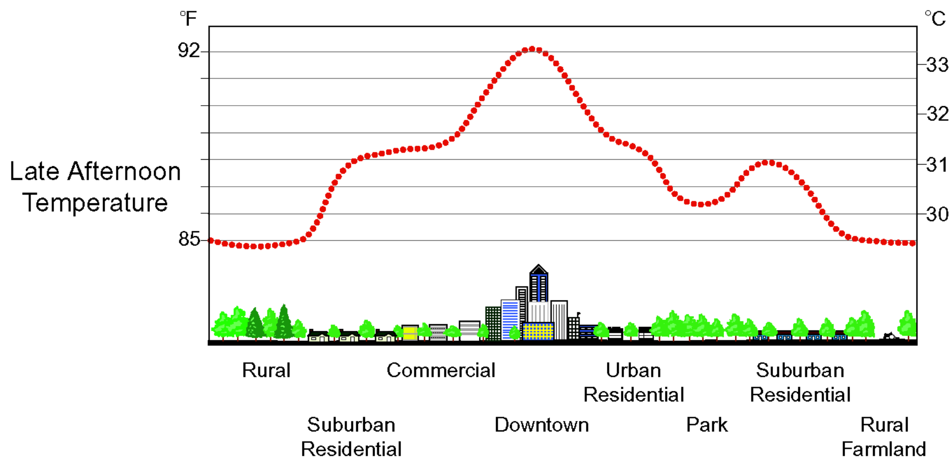


Figure 1. *Sketch of a hypothetical urban heat-island profile.*

Temperatures in cities are generally increasing. An analysis of summertime monthly maximum and minimum temperatures between 1877-1997 in downtown Los Angeles clearly indicated that maximum temperatures are now about 2.5 K higher than in 1920 (Akbari *et al.*, 2001a; see **Figure 2** and **Figure 3**). Minimum temperatures are about 4 K higher than in 1880. A California study analyzing the average urban-rural temperature differences for 31 urban and 31 rural stations from 1965-1989 showed that urban temperatures have increased by about 1 K (Goodrich, 1987, 1989; see **Figure 4**). This trend in increasing temperatures in urban areas is typical of most U.S. metropolitan areas and observed in many other cities across the world (Akbari *et al*., 1992; see **Figure 5**). Santamouris (2006) has also reviewed the existing heat island data in Europe and noted the increasing trends in summertime temperatures in many European cities. Summertime urban heat islands can exacerbate demand for cooling energy. Note that this is above and beyond what is believed to be the global warming trend. Since most people live in cities, they would experience the effects of both global warming *and* urban heat islands.

[1] When sunlight (including ultraviolet, visible, and near-infrared light) 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.

[2] The nighttime heat island is typically greater than the daytime summer heat island. The nighttime heat island is caused by the differential in cooling between the rural and urban areas during the early evening hours and its magnitude is typically largest in winter.

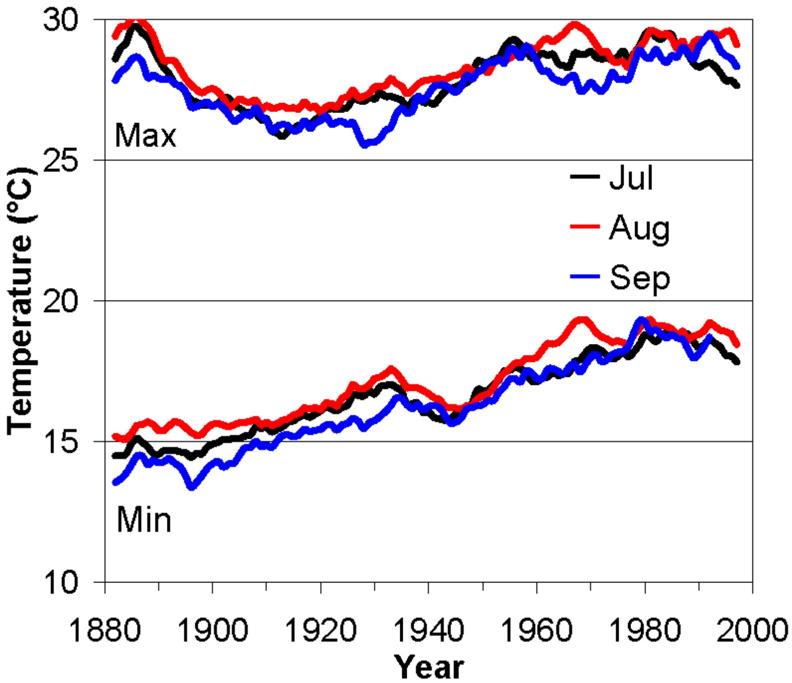


Figure 2. Ten-year running average summertime monthly maximum and minimum temperatures in Los Angeles, California (1877-2004). The ten-year running average is calculated as the average temperature of the previous 4 years, the current year, and the next 5 years. Note that the maximum temperatures have increased about 2.5 K since 1920. During the same period, the minimum temperature is also increased by about 3 K. (Source: Akbari et al., 2001a; updated data)

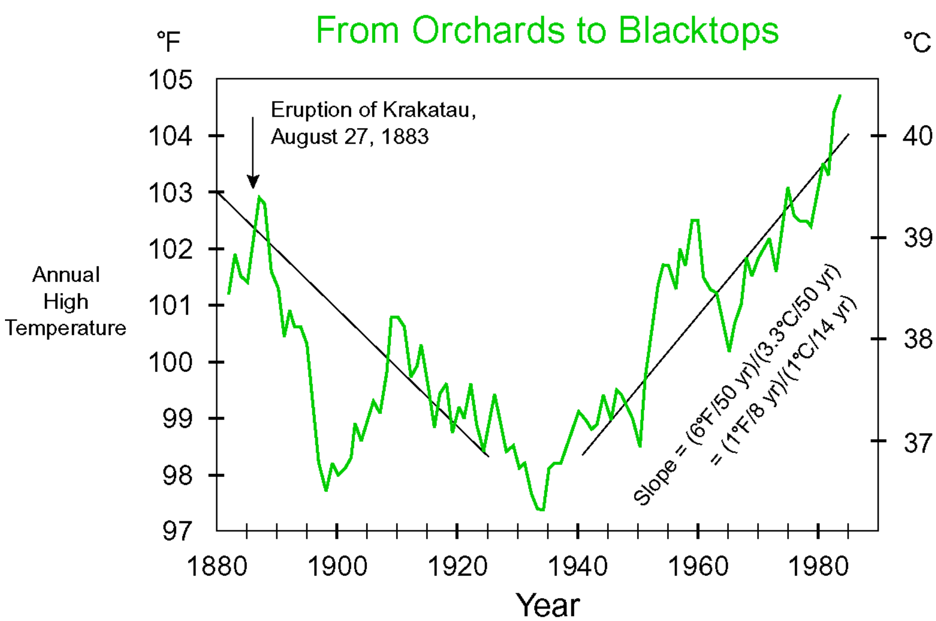


Figure 3. Ten-year running-average maximum annual temperatures in Los Angeles, California (1877-1997). The ten-year running average is calculated as the average temperature of the previous 4 years, the current year, and the next 5 years.

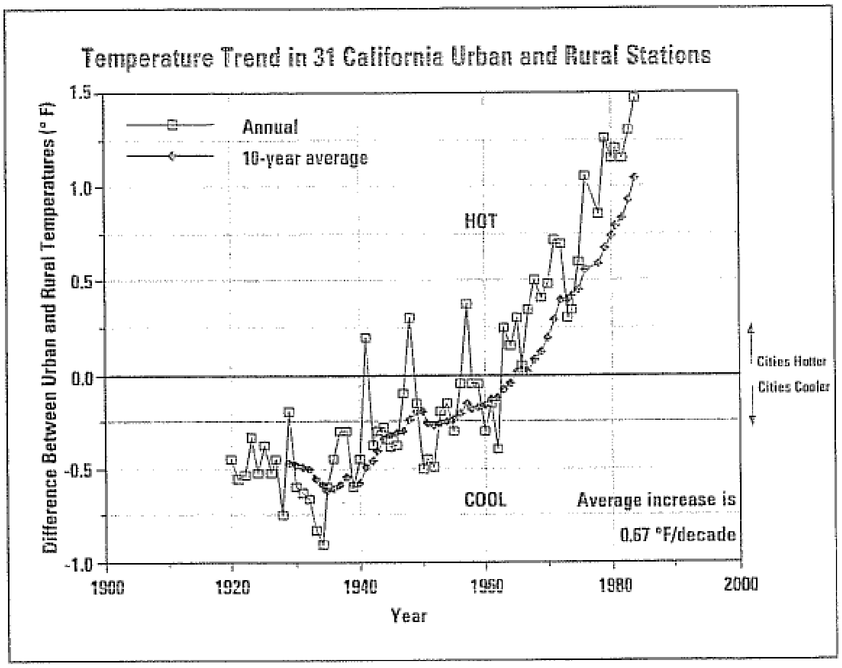


Figure 4. *Warming trend in California Urban areas. Since 1940, the temperature difference between urban and rural meteorological stations has shown an increase of about 0.67 F per decade. Note that during 1920-1960, cities were actually cooler than suburban areas, probably because of relatively more vegetation in urban areas. (Source: Akbari* et al., *1990, based on data from Goodrich, 1989).*

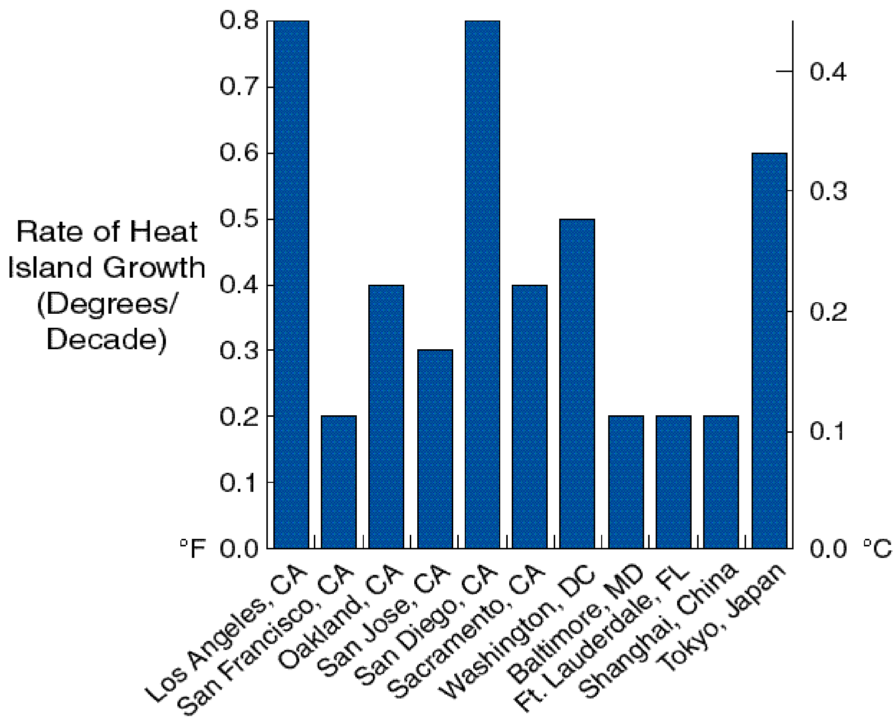


Figure 5. *Trend of Increasing urban temperature over the last 3–8 decades in selected cities. (Source: Akbari* et al., *1992.)*

Increasing urban ambient temperatures results in increased system-wide electricity use. In the Los Angeles Basin, the heat-island-induced increase in power consumption of 1-1.5 GW can cost rate-payers $100 million per year (see **Figure 6**). In the United States, additional air-conditioning use from increased urban air temperature comprises 5-10% of urban peak electric demand at a direct cost of several billion dollars per year. Since cooling-demand on hot summer days is the cause of peak demand for electricity, the electric utilities have installed additional capacity to compensate for the heat-island effects.

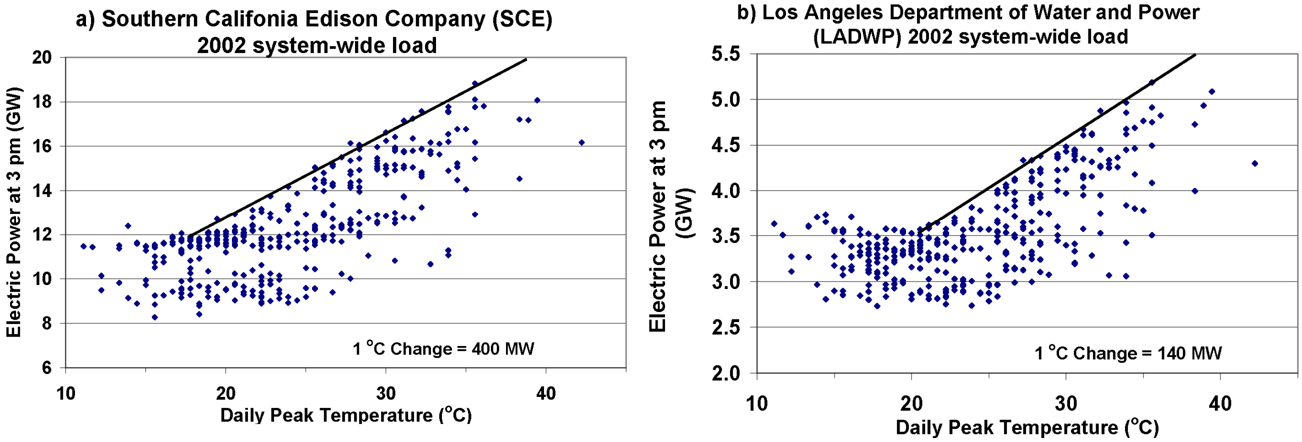


Figure 6. *Daily peak utility electric power demand vs. daily peak air temperature. The increased summertime temperatures cause increased cooling requirements. In Los Angeles Basin (primarily served by Southern California Edison and Los Angeles Department of Water and Power), we estimate that about 1-1.5 GW of power are used to compensate the heat island effect. This increased power adds about $100,000 per hour ($100 million a year) during summer days to the utility customers' electricity bills.*

Besides increasing system-wide cooling loads, summer heat islands increase smog production. Smog production is a highly temperature-sensitive process. In the Los Angeles Basin, at daily maximum temperatures below 22°C, maximum ozone concentration is typically below the California standard [90 parts per billion (ppb)]; at above 32°C, practically all days are smoggy (see **Figure 7**).

The relationship between the urban heat islands and pollution has also been studied in several European cities. Sarrat et al., (2006) have shown that urban heat island has an important effect on the primary and secondary regional pollutant (NOx and ozone) in Paris metropolitan area. Stathopoulou et al., (2006) collected air temperature and ozone concentration data from several stations in the greater Athens area and found a strong positive correlation between daytime air temperature and ozone concentration.

Summer heat islands increase citizens discomfort and heat wave related mortalities. According to the U.S. Centers for Disease Control and Prevention (CDC, 2006), over the past 20 years, more Americans were killed by heat than by hurricanes, lightning, tornadoes, floods, and earthquakes combined. Within a five-day period, the 1995 Chicago heat wave killed between 525 and 726 people, depending on the method used for determining which deaths were attributable to the high temperatures. In the heat wave of 1980, some 1,250 Americans died. A heat wave in summer of 2003 in India killed at least 1,200 people. Most tragic is the death of between 10,000 to 15,000 people who died in France's scorching heat wave in August 2003. Many of the victims were elderly people living in poorly designed houses or apartments that were not air-conditioned.

In France, the heat wave brought temperatures of up to 40°C in the first two weeks of August 2003 in a country where air-conditioning is rare. Although high temperatures may attributed to be the immediate cause of the higher mortality rates, the lack of preparation to face the high temperatures is the real cause for these "natural" disasters. In regions where higher summer temperatures are prevalent (Mediterranean, North Africa, and Middle East), incidents of such disasters are far lower.

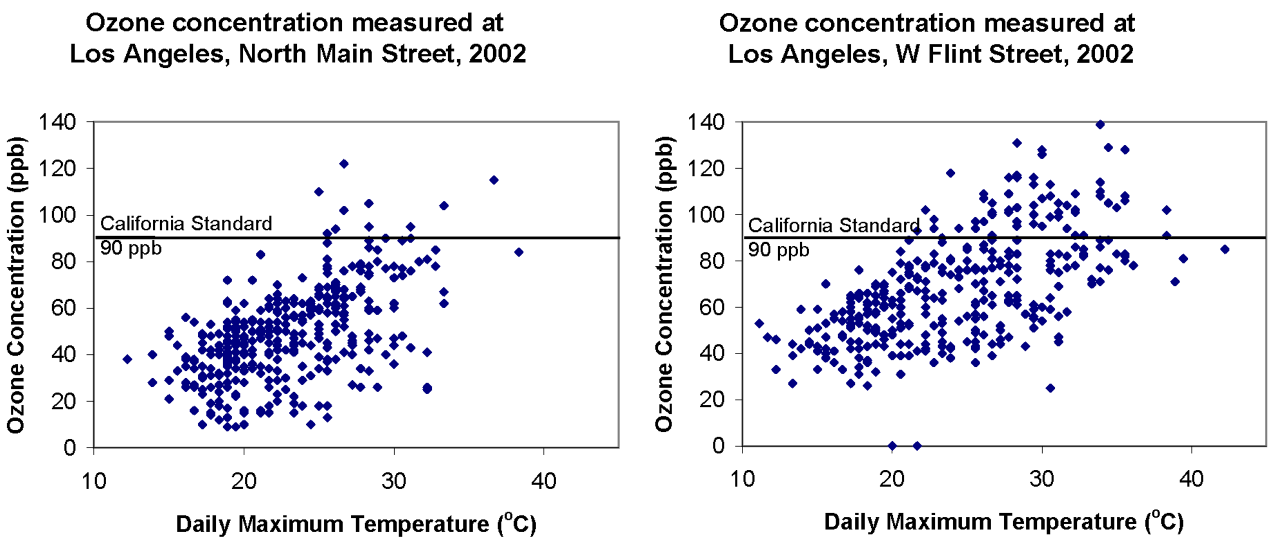


Figure 7. Daily maximum ozone concentration vs. daily maximum temperature in two locations at Los Angeles. The impact of the heat island is also seen in smog. The formation of smog is highly sensitive to temperatures; the higher the temperature, the higher the formation and, hence, the concentration of smog. In Los Angeles at temperatures below 22°C, the concentration of smog (measured as ozone) is below the California standard. At temperatures of about 32°C practically all days are smoggy. Cooling the city by about 3°C would have a dramatic impact on smog concentration.

It is important to note that heat island is a direct result of urbanization that creates an urban fabric consisting mostly of roofs, paved surfaces (roads, drive ways, parking lots), and less vegetation (trees, lawns, bushes, shrubs). Understanding and quantifying the fabric of a city is an important first step in analyzing and designing implementation programs to mitigate urban heat islands. Of particular importance is the fraction of each surface-type within an area. An accurate characterization of the urban surfaces will also allow a better estimate of the potential for increasing surface albedo (roofs, pavements) and urban vegetation. This would in turn provide more accurate modeling of the impact of heat-island reduction measures on ambient cooling and urban ozone air quality.

In four studies, Akbari *et al.* (1999a), Akbari and Rose (2001a,b) and Rose *et al.* (2003) characterized the fabric of Sacramento CA, Salt Lake City UT, Chicago IL, and Houston TX, using high-resolution aerial digital orthophotos covering selected areas in each city (see **Figure 8** for an example of high-resolution orthophotos). Four major land-use types were examined: commercial, industrial, transportation, and residential. These orthophotos were analyzed to estimate the fraction of each major land use type (defined as urban fabric) and to estimate the land-use land-cover (LULC) in each city (see **Figure 9** and **Figure 10**). Although there were differences among the fabrics of these four metropolitan areas, some significant similarities were found.

Table 1 shows the LULC for the four metropolitan areas based on USGS data. Of approximately 800 km^2 of urban area in Sacramento, about 49% was residential; in Salt Lake City about 59% of the 620 km^2; in Chicago about 53% of 2,520 km^2, and in Houston about 56% of 3,430 km^2. The fraction of industrial, transportation, and mixed urban land-uses in these four cities varied only by a few percent.

For the entire metropolitan area, the percentage of the total roof areas, as seen from above the canopy was about 19% in the Sacramento and Salt Lake City metropolitan areas, 25% in Chicago metropolitan area, and 21% in Greater Houston (Akbari *et al.*, 1999a; Akbari and Rose 2001a,b; Rose *et al.*, 2003; see **Table 2**). The percentage of paved areas ranged from 29% to 39%, vegetated areas 29% to 41%, and other areas 10%-40%. Under the canopy, the roof area ranged from 20% to 25%, paved surfaces 29% to 45%, vegetated areas 20% to 37%, and other areas 9% to 15%.

In residential areas, the percentage of the total roof areas, as seen from above the canopy, ranged from 19% to 26%, paved surfaces 25%-26%, vegetated areas 39%-49%, and others 4%-16%. Under the canopy, roof area ranged from 20% to 27%, paved surfaces 24% to 32%, vegetated areas 33% to 47%, and other areas 6% to 17%.

Other researchers involved in the analysis of urban climate have tried to quantitatively characterize the surface-type composition of various urban areas. Myrup and Morgan (1972) conducted such work was the analysis of the urban fabric in Sacramento. They applied the strategy of examining the land-use data in progressively smaller segments of macro-scale (representative areas of Sacramento), meso-scale (individual communities), micro-scale (land-use ordinance zones), and basic-scale (city blocks). The data they used included USGS photos, parks and recreation plans, city engineering roadways, and detailed aerial photos. Their analysis covered 195 km^2 of urban areas. The percentages of the land-use areas were calculated as follows: residential 35.5%, commercial 7.2%, industrial 13.5%, streets and freeways 17.0%, institutional 3.2%, and open space and recreational 23.6%. They found the average residential area to be composed of about 22% streets, 23% roofs, 22% other impervious surfaces, and 33% green areas. Overall, they found a composition of 14% streets, 22% roofs, 22% other impervious surfaces, 36% green areas, and 3% water surfaces. They defined "other impervious surfaces" to include highway shoulder strips, airport runways, and parking lots. Streets included curbs and sidewalks.

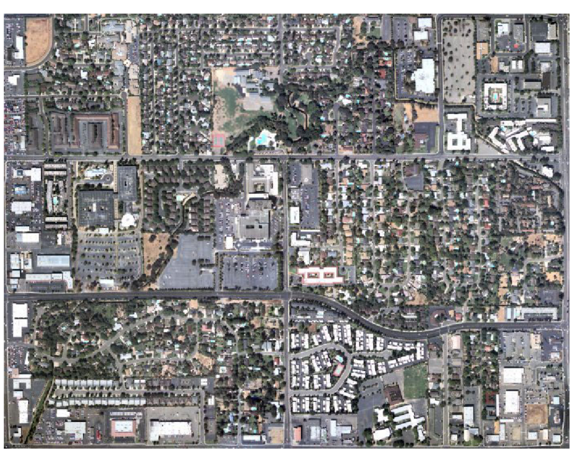


Figure 8. Orthophoto of a typical mixed urban area in Sacramento, CA.

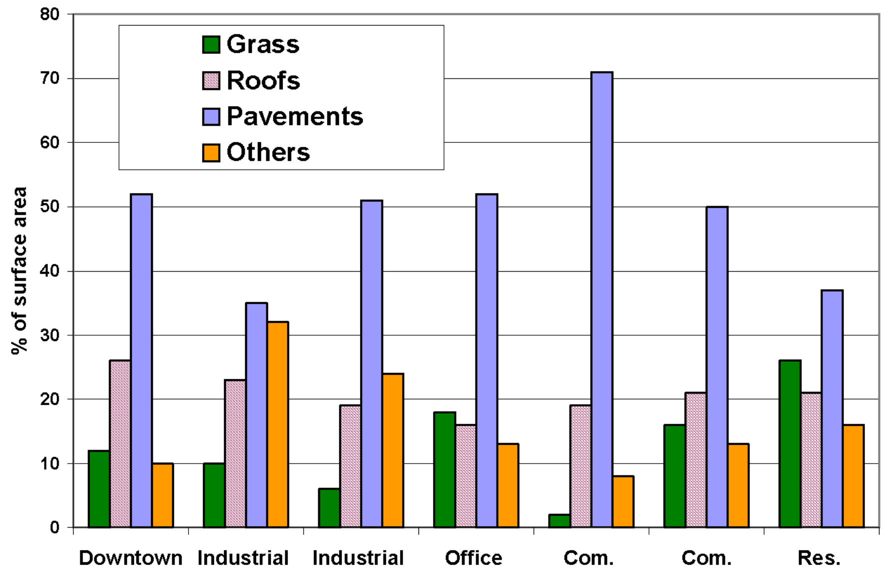


Figure 9. Urban fabric of several residential and commercial areas in Sacramento California. Note that in all areas paved surfaces and roofs together comprise more than 55% of the developed areas.

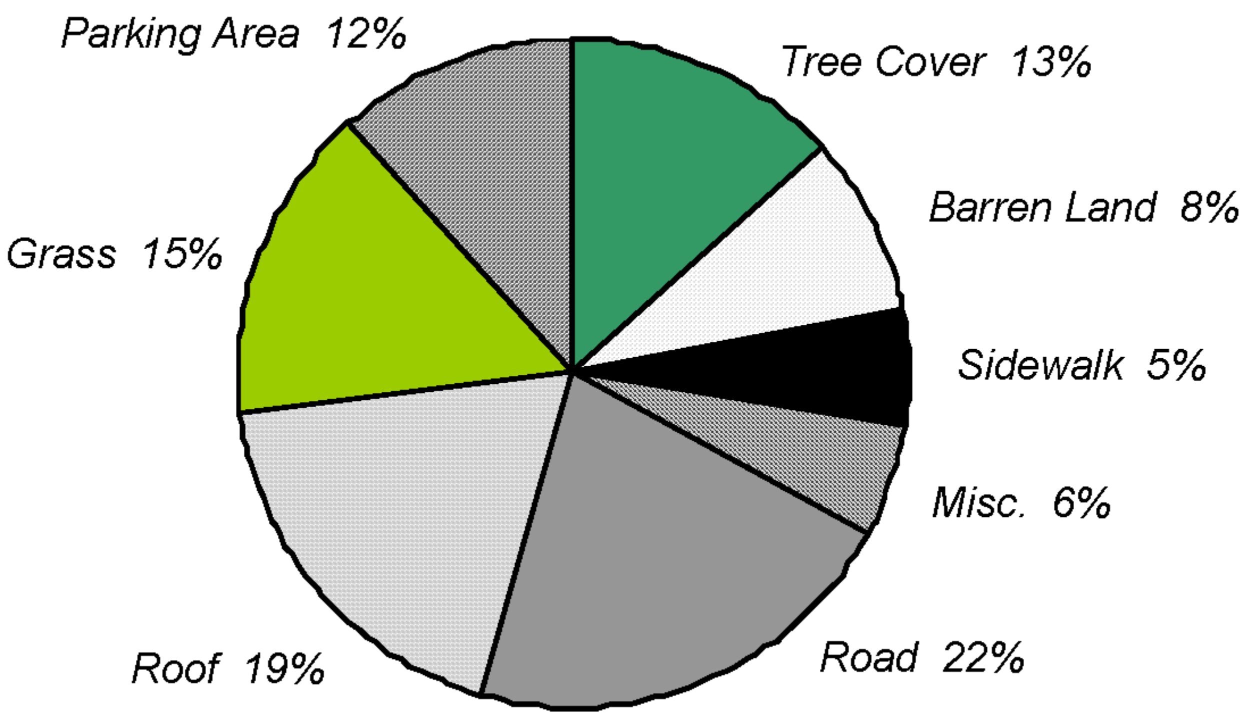


Figure 10. *The Land Use/Land Cover (LULC)* percentages *for* Sacramento, CA...

Table 1. USGS land use/land cover (LULC) percentages for four cities: Sacramento CA, Salt Lake City UT, Chicago IL, and Houston TX.

	Sacramento	**Salt Lake City**	**Chicago**	**Houston**
Total Metropolitan Area (km^2)	809	624	2521	3433
LULC (%)				
Residential	49.3	59.1	53.5	56.1
Commercial/Service	17.1	15.0	19.2	5.1
Industrial	7.2	4.9	11.5	9.3
Transportation/Communication	11.4	9.8	7.7	2.9
Industrial and Commercial	0.3	0.0	0.1	4.8
Mixed Urban or Built-up Land	5.2	1.9	0.4	3.5
Other Mixed Urban or Built-up Land	9.5	9.4	7.6	18.3

Table 2. The Land Use/Land Cover (LULC) percentages (%) for four cities: Sacramento CA, Salt Lake City UT, Chicago IL, and Houston TX.

City	**Vegetation**	**Roofs**	**Pavements**	**Other**
Above-the-canopy				
Metropolitan Salt Lake City	40.9	19.0	30.3	9.7
Metropolitan Sacramento	28.6	18.7	38.5	14.3
Metropolitan Chicago	30.5	24.8	33.7	11.0
Greater Houston	38.6	21.4	29.0	10.9
Residential Salt Lake City	46.6	19.7	25.3	8.5
Residential Sacramento	39.2	19.4	25.6	15.8
Residential Chicago	44.3	25.9	25.7	4.1
Residential Houston	48.9	20.5	24.7	6.0
Under-the-canopy				
Metropolitan Salt Lake City	33.3	21.9	36.4	8.5
Metropolitan Sacramento	20.3	19.7	44.5	15.4
Metropolitan Chicago	26.7	24.8	37.1	11.4
Greater Houston	37.1	21.3	29.2	12.4
Residential Salt Lake City	38.6	23.9	31.6	6.0
Residential Sacramento	32.8	19.8	30.6	16.8
Residential Chicago	35.8	26.9	29.2	8.1
Residential Houston	47.4	21.1	23.9	7.6

2. Heat Islands Mitigation Technologies

Possible technologies used in lowering the summertime ambient temperatures and increasing comfort include use of light colored materials on roofs and walls; trees and vegetation to shade buildings, walkways, and streets; and using light-colored paving materials for streets, parking lots, driveways, and sidewalks. Santamouris (2001) provides a thorough description of building and pavement construction materials that have been historically used as a countermeasure for urban heat islands. Also Doulos et al. (2004) have measured and compared the thermal performance of 93 commonly used construction materials in Greece.

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" effects. 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 of roofs and pavements is increased throughout an entire community, the energy balance of the whole community is modified, producing community-wide changes in climate. Phenomena associated with community-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.

When dark roofs are heated by the sun, they directly raise the demand for cooling for the buildings beneath those roofs. For highly absorptive (low-albedo) roofs, the surface/ambient air-temperatures difference may reach 50 K, while for less absorptive (high-albedo) surfaces with similar insulative properties (e.g. white-coated roofs), the difference can be only about 10 K. Clearly, a cool roof reduces cooling energy requirements of its own building,

Hot roofs also heat the outside ambient air, thus indirectly increasing cooling demand of neighboring buildings. We have simulated the effect of urban-wide application of reflective roofs on cooling-energy use and smog in many metropolitan areas (Taha *et al.*, 2001; 2000; 1995). We estimate roof albedos can realistically be raised by 0.30 on average, resulting in a 1-2.5 K cooling at 3pm (on a sunny August day). This temperature reduction reduces building cooling-energy use even further. Other benefits of light-colored roofs include a potential increase in the roofs useful life.

The beneficial effects of trees are both direct in shading of buildings and indirect in cooling the ambient air (urban forest). Trees can intercept sunlight before it warms buildings and cool the air by evapotranspiration. In winter, trees can shield buildings from cold winds. Urban shade trees offer significant benefits by reducing building air-conditioning, and lowering air temperature, thus improving urban air quality (reducing smog). Savings associated with these benefits vary by climate and region and, over a tree's life, can reach up to $200/tree. The cost of planting and maintaining trees can vary from $10-500/tree. Tree-planting programs can be low-cost, offering savings to tree-planting communities. The choice of tree species is also important. Low-emitting drought-resistance trees are typically recommended.

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 reduces the emission of these precursors from power plants─by reducing combustion of fossil fuels and hence reducing NOx emissions from power plants (Taha, 1996).

There are other important benefits associated with urban trees. These include improvement in environmental quality, increased property values, and decreased run-off which lead to flood protection.

Urban pavements are made predominantly of asphalt concrete. The advantages of this smooth and all-weather surface type for vehicles are obvious, but some associated problems are perhaps not so well appreciated. Sunlight on dark asphalt surfaces produce increased heating. An air-temperature increase, in turn, increases cooling-energy use in buildings, and can accelerate smog formation. The albedo of fresh asphalt concrete pavement is about 0.05: 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, albedo increases to about 0.10 to 0.15 (the value of ordinary aggregates). If a reflective aggregate is used, the long-term albedo can be higher.

Unlike cool roofs and urban trees, cool pavements provide only indirect effects in terms of urban cooling energy use, i.e., through lowered ambient temperatures. Lower temperatures have two effects: 1) reduced demand for electricity for air conditioning and 2) decreased rate of smog production (ozone). Savings from reduced electricity demand and from the externalities of lower ozone concentrations can be significant.

Furthermore, the temperature of a pavement affects its structural performance; cooler pavements last longer in hot climates. Reflectivity of pavements can improve visibility at night and can reduce electric street-lighting demand. Street lighting is more effective if pavements are more reflective, increasing safety as a result. Despite concerns that, in time, dirt will darken light-colored pavements, experience with cement concrete roads suggests that the light color of the pavement can actually persist after long usage.

We estimate that by full implementation of the above mitigation measures (cool roofs, shade trees, and cool pavements) the cooling demand in the U.S. can be *decreased by 20%*. This equals to about 40 TWh/year in savings, worth over $4B per year by 2015 in cooling-electricity savings alone. If smog reduction benefits are included, savings could total to over $10B/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 the initiation of an effective and comprehensive campaign would require an aggressive agenda.

Over the past two decades, scientists at the Lawrence Berkeley National Laboratory (LBNL) have 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 11** depicts the overall methodology used in analyzing the impact of heat-island mitigation measures on energy use and urban air pollution.

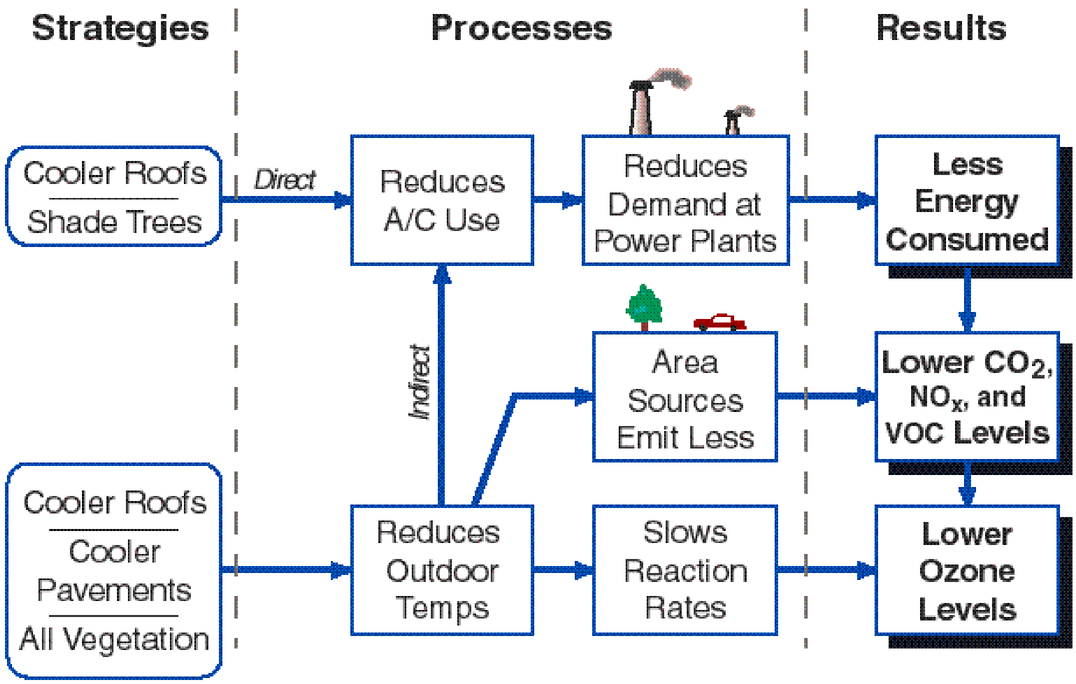


Figure 11. Methodology for energy and air-quality analysis.

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 (Berdahl and Bretz, 1997; see **Figure 12**). For this reason, "cool" surfaces (which absorb little solar radiation) 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).

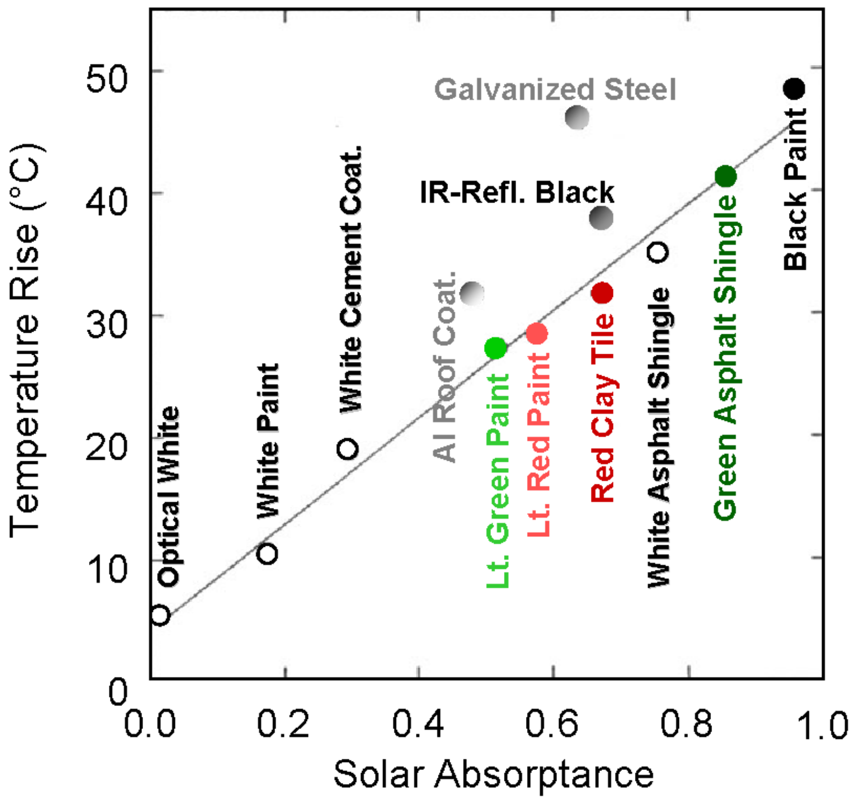


Figure 12. Temperature rise (surface temperature minus air temperature) of various roofing materials measured at peak solar conditions. All samples were insulated on the back and the measurements were made at low wind speed.

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, Smog, and other Benefits of Cool Roofs

Direct Energy Savings

Field studies in California and Florida have demonstrated cooling-energy savings in excess of 20% upon raising the solar reflectance of a roof to 0.6 from a prior value of 0.1–0.2 (Konopacki and Akbari, 2001; Konopacki *et al.*, 1998; Parker *et al.*, 2002) (see **Table 3**). Energy savings are particularly pronounced in older houses that have little or no attic insulation, especially if the attic contains the air distribution ducts. Akbari *et al.* (1997a) observed 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. In a large retail store in Austin, Texas, Konopacki and Akbari (2001) documented measured energy savings of 12%. 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.* (1998b) measured an average of 19% energy savings in eleven Florida residences by applying reflective coatings on their roofs. Parker *et al.* (1997, 1998b) 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 after an unpainted galvanized roof 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.

Cool roofs also significantly reduce buildings' peak electric demand in summer (Akbari *et al.*, 1997a; Levinson *et al.*, 2005c).

More recently, Akbari *et al.* (2005) monitored the effects of cool roofs on energy use and environmental parameters in six California buildings at three different sites: a retail store in Sacramento; an elementary school in San Marcos (near San Diego); and a 4-building cold storage facility in Reedley (near Fresno). The latter included a cold storage building, a conditioning and fruit-palletizing area, a conditioned packing area, and two unconditioned packing areas. Results showed that installing a cool roof reduced the daily peak roof surface temperature of each building by 33-42K. In the retail store building in Sacramento, for the monitored period of 8 August to 30 September 2002, the estimated savings in average air conditioning energy use was about 72 Wh/m^2/day (52%). In the school building in San Marcos, for the monitored period of 8 July to 20 August 2002, the estimated savings in average air conditioning energy use was about 42-48 Wh/m^2/day (17-18%). In the cold storage facility in Reedley, for the monitored period of 11 July to 14 September 2002, and 11 July to 18 August 2003, the estimated savings in average chiller energy use was about 57-81 Wh/m^2/day (3-4%). Using the measured data and calibrated simulations, Akbari *et al*. extrapolated the results and estimated savings for similar buildings installing cool roofs in retrofit applications for all California climate zones.

In addition to these building monitoring studies, computer simulations of cooling energy savings from increased roof albedo in residential and commercial buildings have been documented by many studies, including Konopacki and Akbari (1998), Akbari *et al*. (1998), Parker *et al*. (1998b), 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 (see **Figure 13**). The results showed that four major building types account for over 90% of the annual electricity and monetary savings in the U.S.: 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 low as $3M in the heating-dominated climate of Philadelphia and as much as $37M for Phoenix and $35M in Los Angeles.

Table 3. Comparison of measured summertime air-conditioning daily energy savings from application of reflective roofs. Δρ is change in roof reflectivity, RB is radiant barrier, duct is the location of air-conditioning ducts, and R-value is roof insulation in Km^2/W. Source: Akbari et al. (2005).

Location	Building type	Roof area	Roof system			Savings
		[m^2]	R-value	duct	Δρ	[$Wh/m^2/day$]
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 results for the 11 Metropolitan Statistical Areas (MSAs) were extrapolated to estimate the savings in the entire United States. At 8¢/kWh, the value of U.S. potential nationwide net commercial and residential energy savings (cooling savings minus heating penalties) exceeds $750 million per year (Akbari *et al.*, 1999). The study estimates that, nation-wide, 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 (heating) use by 26 GBtu/yr (1.6%), and a decrease in peak electrical demand of 7 GW (2.5%) (equivalent to 14 power plants each with a capacity of 0.5 GW).

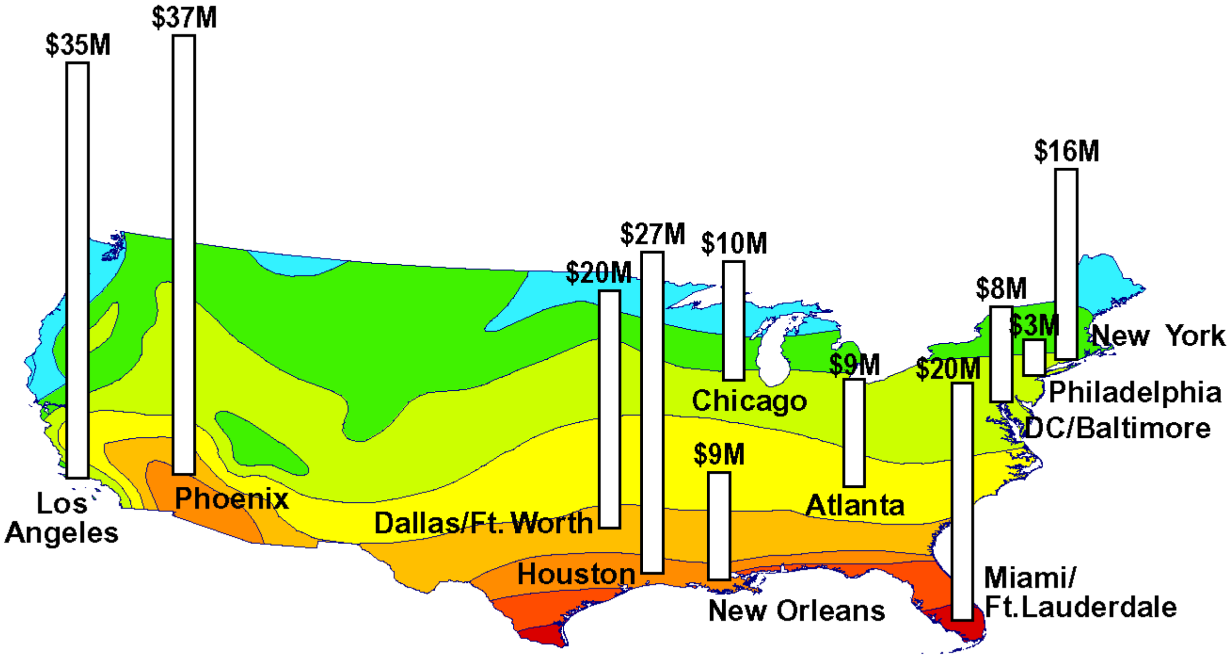


Figure 13. *Estimated energy-saving potentials of light-colored roofs in 11 U.S. metropolitan areas. About 10 residential and commercial building prototypes in each area are simulated. Both savings in cooling and penalties in heating are considered. The estimated saving potentials is about $175M (1997 energy prices) per year for the 11 cities. Extrapolated national energy savings is about $0.75B per year. (Source: Konopacki* et al., *1997)*

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, 2000a, 200b). The study included the direct and indirect effects of both cool roofs and trees. The direct saving potentials for cool roofs in these five metropolitan areas ranged from $8-38 M (see **Table 4** and its caption for details).

Indirect Energy and Smog Benefits

Indirect effects require that a large fraction of the urban area be modified to produce a change in the local climate. To date, results have been attained only by computer simulations. 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 2 K 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).

Table 4. Metropolitan-wide estimates of annual energy savings, peak power avoided, and annual carbon emissions reduction from Heat-Island Reduction strategies for residential and commercial buildings in Baton Rouge, Chicago, Houston, Sacramento and Salt Lake City.

Metropolitan Area and HIR Strategy	Annual Energy [M$]	Annual Electricity [GWh]	Annual Electricity [M$]	Annual Natural Gas [Mtherm]	Annual Natural Gas [M$]	Peak Power [MW]	Annual Carbon [ktC]
Baton Rouge							
Base Case	114.8	1,275	92.8	30.7	21.9	858	257
Savings							
Direct shade trees	5.2	94	6.9	(2.4)	(1.7)	62	12
Direct high albedo	8.0	120	8.7	(1.0)	(0.7)	60	19
Indirect	2.3	39	2.8	(0.7)	(0.5)	13	6
Combined	*15.5*	*253*	*18.4*	*(4.1)*	*(2.9)*	*135*	*36*
Chicago							
Base case	879.4	3,505	293.4	804.3	586.0	3,456	1,749
Savings							
Direct shade trees	13.5	293	25.0	(15.6)	(11.4)	128	26
Direct high albedo	10.9	224	18.9	(11.0)	(8.1)	237	21
Indirect	5.4	65	5.6	(0.3)	(0.2)	33	10
Combined	*29.8*	*582*	*49.5*	*(26.9)*	*(19.7)*	*398*	*58*
Houston							
Base case	696.6	7,230	572.0	169.7	124.7	5,158	1,453
Savings							
Direct shade trees	27.8	421	34.3	(8.8)	(6.5)	247	58
Direct high albedo	38.3	523	42.0	(5.0)	(3.7)	269	80
Indirect	15.6	236	19.1	(4.7)	(3.5)	218	33
Combined	*81.8*	*1,181*	*95.4*	*(18.5)*	*(13.6)*	*734*	*170*
Sacramento							
Base case	296.2	2,238	185.9	162.2	110.3	2,454	608
Savings							
Direct shade trees	9.8	247	20.6	(15.8)	(10.7)	180	18
Direct high albedo	14.6	220	18.3	(5.5)	(3.8)	163	29
Indirect	5.9	114	9.5	(5.3)	(3.6)	106	11
Combined	*30.3*	*581*	*48.4*	*(26.6)*	*(18.1)*	*449*	*59*
Salt Lake City							
Base case	67.0	511	31.4	70.8	35.6	488	188
Savings							
Direct shade tree	1.1	52	3.3	(4.2)	(2.2)	33	3
Direct high albedo	1.8	45	2.8	(2.0)	(1.0)	32	5
Indirect	0.8	25	1.6	(1.6)	(0.8)	20	2
Combined	*3.7*	*122*	*7.7*	*(7.8)*	*(4.0)*	*85*	*9*

a) Metropolitan-wide annual energy savings [M$ = Million$], annual electricity savings [M$ and GWh = Giga Watt-hour], annual natural gas deficit [M$ and Mtherm = Million therms], peak power avoided [MW = Mega Watt] and annual carbon emissions reduction [kt = thousand tons].

b) The methodology consisted of the following: [1] define prototypical building characteristics in detail for old and new construction, [2] simulate annual energy use and peak power demand using the DOE-2.1E model, [3] determine direct and indirect energy benefits from high-albedo surfaces (roofs and pavements) and trees, [4] identify the total roof area of air-conditioned buildings in each city, and [5] calculate the metropolitan-wide impact of HIR strategies.

c) Base energy expenditures and peak power demand are calculated for buildings without shade trees and with a dark roof (albedo 0.2). Direct savings are determined for buildings with eight shade trees (retail: four) and a high-albedo roof (residential 0.5 and commercial 0.6), and indirect savings include the impact of reduced air temperature from urban reforestation and high-albedo surfaces.

d) The conversion from GWh to carbon corresponds to the U.S. mix of electricity. 1997 regional electricity and gas cost are used in the calculations. In 1995, DOE/EIA-0383(97) (EIA, 1997). EIA (1997) shows that 3000 TWh sold emitted 500 MtC (million metric tons of carbon); thus, 1 GWh emits 167tC. The estimated carbon emission from combustion of natural gas is 1.447 kgC/therm.

Taha (1997) also simulated the impact of urban-wide cooling in Los Angeles on smog— predicting 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) (see **Table 5**). Table 5 also shows the present value (PV) of all future savings associated with installation of cool roofs. The present value (PV) of future savings from the installation of cool roofs is calculated using

$$PV = a\frac{1-(1+d)^{-n}}{d}$$

Where

a = annual savings ($),

d = real discount rate (3%),

n = life of the savings from cool roofs, in years.

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

	Benefits	Direct	Indirect	Smog	Total
1	Cost savings from cool roofs (M$/yr)	46	21	104	171
2	Δ Peak power (GW)	0.4	0.2		0.6
3	Present value per 100 m^2 of roof area ($)	153	25	125	303

In a more recent study, Akbari and Konopacki (2005) developed summary tables (sorted by heating- and cooling-degree-days) to estimate the potential of Heat-Island Reduction (HIR) strategies (i.e., solar-reflective roofs, shade trees, reflective pavements, and urban vegetation) to reduce cooling-energy use in buildings. The tables provide estimates of savings for both direct effect and indirect effect (see **Table 6** for summary of their results). The estimated savings in Table 6 includes both direct and indirect effects of cool roofs, cool pavements, and shade trees. About 50% of the savings are the direct savings from the application of cool roofs. The estimated indirect savings from the combined effects of cool roofs, shade trees, and cool pavements are about 25%. The study does not address the smog benefits from HIR.

<u>Other Benefits of Cool Roofs</u>

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.

2.1.2. 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. Besides being unpleasant, extreme glare could possibly increase the incidence of traffic accidents. Fortunately, the glare from roofs is not a major problem for those who are at street level.

Table 6. Estimated ranges of annual basecase (electricity use, gas use, and peak demand) and savings from heat-island reduction measures across all climate regions.

Prototype Building	Electricity (kWh/100m^2)		Gas (Therm/100m^2)		Peak Power (kW/100m^2)	
	Base Use	Savings	Base Use	Penalties	Base Use	Savings
Residential						
Pre-1980 Gas-Heated	1600 - 11000	400 - 1200	0 - 1000	0 - 50	3.1 - 4.0	0.4 - 0.6
Pre-1980 Electrically-heated	8500 - 20000	100 - 1200			3.1 - 4.0	0.4 - 0.6
1980$^+$ Gas-Heated	700 - 7000	150 - 700	0 - 500	0 - 20	1.7 –3.3	0.2 - 0.4
1980$^+$ Electrically-heated	5000 - 9000	50 - 600			1.7 - 3.3	0.2 - 0.4
Office						
Pre-1980 Gas-Heated	7000 - 18700	1200 - 1400	0 - 500	0 - 20	6.3 – 8.4	0.5 – 1.0
Pre-1980 Electrically-heated	12600 - 18700	1100 - 1300			6.3 – 8.4	0.5 – 1.0
1980$^+$ Gas-Heated	3500 - 10800	500 - 600	0 - 300	0 - 10	3.5 – 4.6	0.2 – 0.5
1980$^+$ Electrically-heated	5700 - 10800	300 - 600			3.5 – 4.6	0.2 – 0.5
Retail Store						
Pre-1980 Gas-Heated	8200 – 15700	1400 - 1500	0 - 200	0 - 10	4.5 – 5.7	0.4 – 0.7
Pre-1980 Electrically-heated	10700 - 17200	1300 -1700			4.1 – 5.7	0.4 – 0.7
1980$^+$ Gas-Heated	3100 - 8900	500 - 700	0 - 60	0 - 6	2.2 – 2.8	0.2 – 0.3
1980$^+$ Electrically-heated	4000 - 8900	300 - 700			2.2 – 2.8	0.2 – 0.3

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. The roofing industry has responded to this concern by developing and marketing cool-colored materials for roofs (see section Cool Colored Roofing Materials).

2.1.3. 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 at those times 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 non-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.

2.1.4. Cool-Colored Roofing Materials

Suitable cool *white* materials are available for most products, with the notable exception of asphalt shingles; cooler *colored* (nonwhite) materials are needed for all types of roofing, especially in the residential market. Coatings colored with conventional pigments tend to absorb the invisible "near-infrared" (NIR) radiation that bears more than half of the power in sunlight (see **Figure 14**). Replacing conventional pigments with "cool" pigments that absorb less NIR radiation can yield colored coatings that look the same to the eye but have higher solar reflectance. These cool coatings lower roof surface temperature, reducing the need for cooling energy in conditioned buildings and making unconditioned buildings more comfortable.

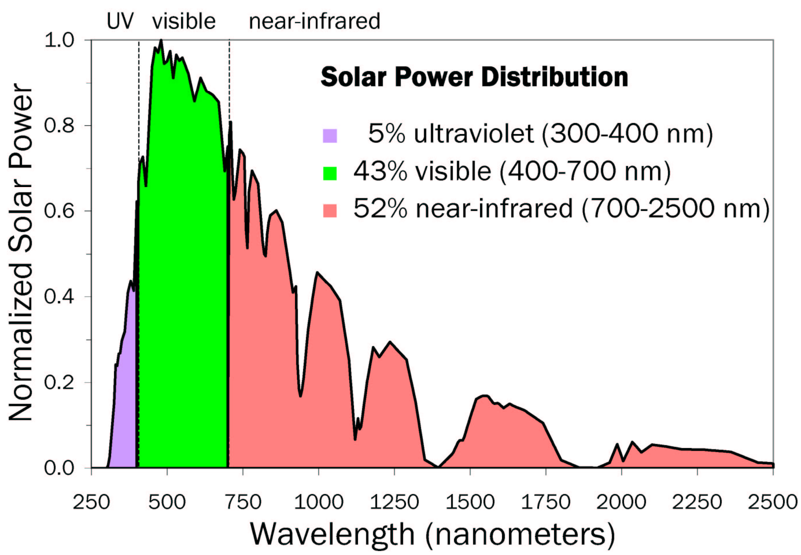


Figure 14. Peak-normalized solar spectral power; over half of all solar power arrives as invisible, "near-infrared" radiation.

According to *Western Roofing Insulation and Siding* magazine (2002), the total value of the 2002 projected residential roofing market in 14 western U.S. states (AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY) was about $3.6 billion (B). We estimate that 40% ($1.4B) of that amount was spent in California. The lion's share of residential roofing expenditure was for fiberglass shingle, which accounted for $1.7B, or 47% of sales. Concrete and clay roof tiles made up $0.95B (27%), while wood, metal, and slate roofing collectively represented another $0.55B (15%). The value of all other roofing projects was about $0.41B (11%). We estimate that the roofing market area distribution was 54–58% fiberglass shingle, 8-10% concrete tile, 8–10% clay tile, 7% metal, 3% wood shake, and 3% slate (**Table 7**).

Suitable cool *white* materials are available for most roofing products, with the notable exception (prior to March 2005[3]) of asphalt shingles. Cool nonwhite materials are needed for all types of roofing. Industry researchers have developed complex inorganic color pigments that are dark in color but highly reflective in the near infrared (NIR) portion of the solar spectrum. The high near-infrared reflectance of coatings formulated with these and other "cool" pigments—e.g., chromium oxide green, cobalt blue, phthalocyanine blue, Hansa yellow—can be exploited to

[3] In March 2005, a major manufacturer of roofing shingles in California announced availability of cool colored shingles in four popular colors.

manufacture roofing materials that reflect more sunlight than conventionally pigmented roofing products.

Table 7. Projected residential roofing market in the U.S. western region surveyed by Western Roofing and Siding Magazine *(2002). The 14 states included in the U.S. western region are AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY.*

Roofing Type	Market share by $		Estimated market share by roofing area
	$B	%	%
Fiberglass Shingle	1.70	47.2	53.6-57.5
Concrete Tile	0.50	13.8	8.4-10.4
Clay Tile	0.45	12.6	7.7-9.5
Wood Shingle/Shake	0.17	4.7	2.9-3.6
Metal/Architectural	0.21	5.9	6.7-7.2
Slate	0.17	4.7	2.9-3.6
Other	0.13	3.6	4.1-4.4
SBC Modified	0.08	2.1	2.4-2.6
APP Modified	0.07	1.9	2.2-2.3
Metal/Structural	0.07	1.9	2.2-2.3
Cementitious	0.04	1.1	1.2-1.3
Organic Shingles	0.02	0.5	0.6
Total	**3.60**	**100**	**100**

Cool-colored roofing materials are expected to penetrate the roofing market within the next few years. Preliminary analysis suggests that they may cost up to $1/m^2 more than conventionally colored roofing materials. However, this would raise the total cost of a new roof (material plus labor) by only 2-5%.

A U.S. consortium (Cool Team) of two national research laboratories and 12 companies that manufacture roofing materials, including shingles, roofing granules, clay tiles, concrete tiles, tile coatings, metal panels, metal coatings, and pigments are collaborating to expedite manufacturing of cool-colored roofing materials (Akbari *et al*., 2006). The iterative development of cool colored materials has included selection of cool pigments, choice of base coats for the two-layer applications (discussed later in this paper), and identification of pigments to avoid.

Creating Cool Nonwhite Coatings

In order to determine how to optimize the solar reflectance of a pigmented coating matching a particular color, and how the performance of cool-colored roofing products compares to those of a standard materials, the Cool Team (a) has identified and characterized the optical properties of over 100 pigmented coatings; (b) created a database of pigment characteristics; and (c) developed a model to maximize the solar reflectance of roofing materials for a choice of visible color.

The LBNL Cool Team measured the spectral reflectance *r* and transmittance *t* of a thin coating containing single pigment or binary mix of pigments (Levinson *et al.*, 2005a,b). These spectral, or wavelength-dependent, properties of the pigmented coating were measured at 441 evenly spaced wavelengths spanning the solar spectrum (300 – 2,500 nanometers). Then, using a modified version of the Kebelka-Monk's two-flux model, each sample was characterized by its computed spectral absorption coefficient, *K*, and backscattering coefficient, *S*. A cool color is defined by a large absorption coefficient *K* in parts of the visible spectral range, to permit the attainment of desired colors, and a small *K* in the near infrared (NIR). For cool colors, the *S* is small (or large) in the visible spectral range for formulating dark (or light) colors, and large in the NIR.

Inspection of the film's spectral absorptance (calculated as 1-*r*-*t*) reveals whether a pigmented coating is cool (has low NIR absorptance) or hot (has high NIR absorptance). The spectral reflectance and transmittance measurements were also used to compute spectral rates of light absorption and backscattering (reflection) per unit depth of film. The spectral reflectance of a coating colored with a mixture of pigments can then be estimated from the spectral absorption and backscattering rates of its components. The results of these measurements and analyses are summarized in a database detailing the optical properties of the characterized pigmented coatings (Figure **15**).

Creating Cool Nonwhite Roofing Products

Roofing shingles, tiles, and metal panels comprise more than 90% (by roof area) of the residential roofing market in the United States. The Cool Team has evaluated the best ways to increase the solar reflectance of these products and to produce cool roofing materials. As the direct result of this collaborative effort, manufactures of roofing materials have introduced cool shingles, clay tiles, concrete tiles, metal roofs, and concrete tile coatings.

In addition to using NIR-reflective pigments in manufacturing of cool roofing materials, application of novel engineering techniques can further enhance economically the solar reflectance of colored roofing materials. Cool-colored pigments are partly transparent to NIR light; thus, any NIR light not reflected by the cool pigment is transmitted to the underneath layer, where it can be absorbed. To increase the solar reflectance of colored materials with cool pigments, a reflective undercoating can be used. This method is referred as a two-layered technique.

Figure 16 demonstrates the application of the two-layered technique to manufacture cool colored materials. A thin layer of dioxazine purple (14–27 µm) is applied on four substrates: (a) aluminum foil (~ 25 µm), (b) opaque white paint (~1000 µm), (c) non-opaque white paint (~ 25 µm), and (d) opaque black paint (~ 25 µm). It appears to the eye (and is confirmed by the visible reflectance spectrum), that the color of the material is black even when applied to an opaque white or aluminum foil substrate. However, the solar reflectance of these samples exceed 0.4; its solar reflectance over a black substrate is only 0.05.

[R03] Red Iron Oxide (iii)

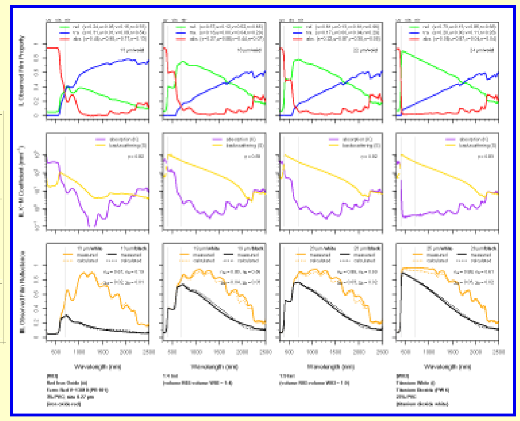
Paint Code	**R03**
Paint Name	Red Iron Oxide (iii)
Pigment Name	Ferro Red V-13810 (PR 101)
Color Family	Red/Orange
Color Subfamily	iron oxide red
Mean Particle Size (microns)	0.27
Dry Film PVC	3%
Pigment Datasheet	available
Paint Datasheet	unavailable
LBNL Commentary	available

Masstone and Mixtures with White (Tints)

[R03] Red Iron Oxide (iii) +
[W03] Titanium White (i)

image over white				
image over black				
spectral datafile	R03 masstone	R03 tint 1:4	R03 tint 1:9	W03 masstone

guide to reading spectral datafiles



Mixtures with Nonwhite Colors

[R03] Red Iron Oxide (iii) +
[B16] Iron Titanium Brown Spinel (i)

image over white			
image over black			
spectral datafile	R03 masstone	R03+B16 mixture 1:1	B16 masstone

guide to reading spectral datafiles

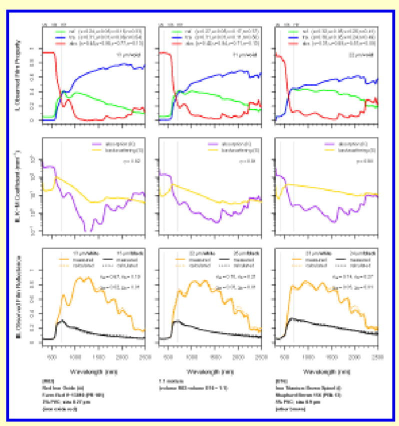


Figure 15. Description of an iron oxide red pigment in the Lawrence Berkeley National Lab pigment database.

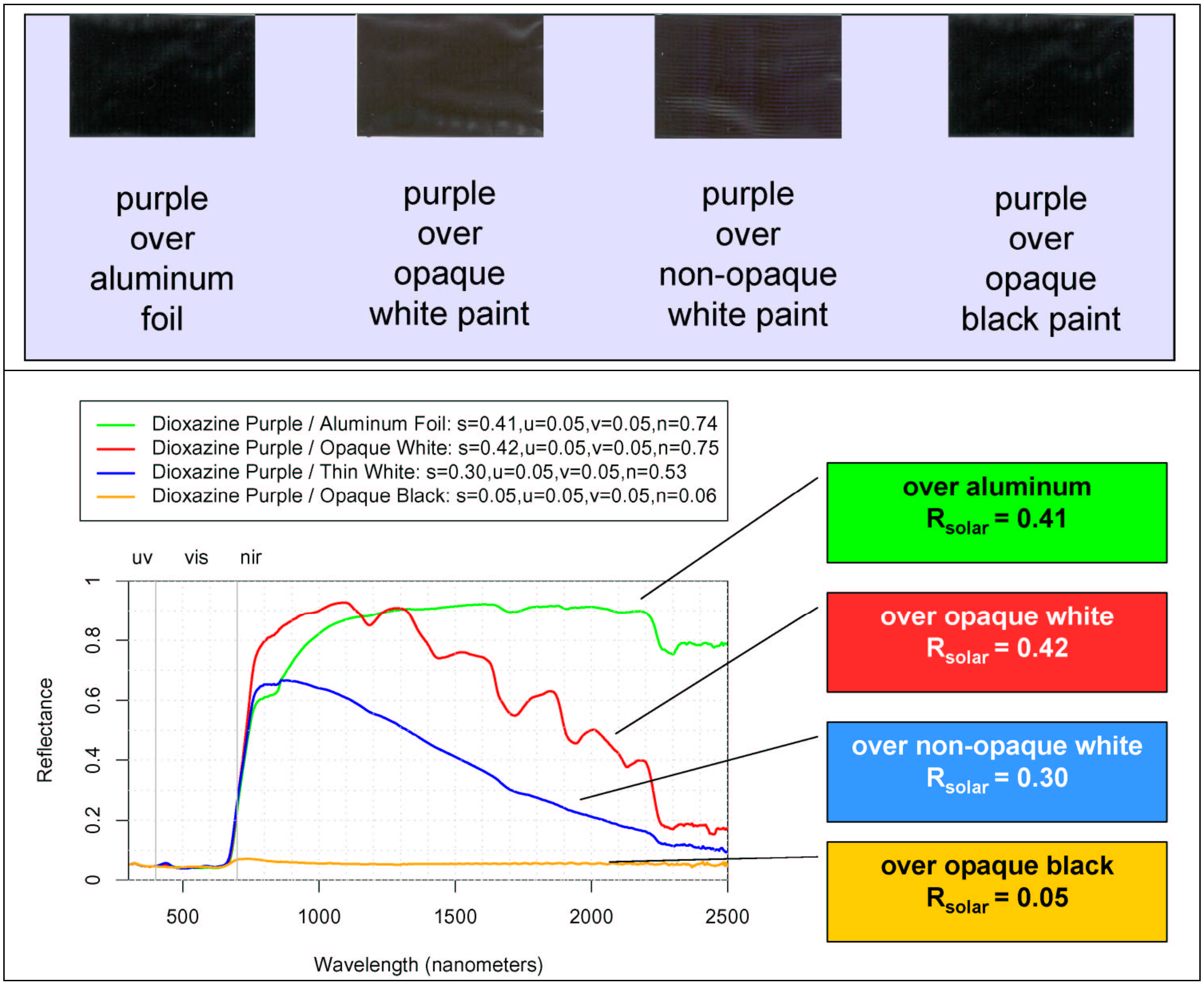


Figure 16. Application of the two-layered technique to manufacture cool colored materials.

Cool Colored Shingles

The solar reflectance of a new shingle, by design, is dominated by the solar reflectance of its granules, which cover over 97% of its surface. Manufacturers use granules coated with titanium dioxide (TiO_2) rutile white to produce white (or grey) shingles. Because a thin TiO_2-pigmented coating is reflective but not opaque in the NIR, multiple layers are needed to obtain high solar reflectance. This technique has been used to produce "super-white" (meaning truly white, rather than gray) granulated shingles with solar reflectances exceeding 0.5 (see **Figure 17**).

Although white roofing materials are popular in some areas (e.g., Greece, Bermuda; see **Figure 18**), many consumers aesthetically prefer non-white roofs. Manufacturers have also tried to produce colored granules with high solar reflectance by using nonwhite pigments with high NIR reflectance. To increase the solar reflectance of colored granules with cool pigments, multiple color layers, a reflective undercoating, and/or reflective aggregate should be used. Obviously, each additional coating increases the cost of production.

Several cool shingles have been developed in 2004 and 2005. **Figure 19** shows examples of prototype cool shingles and compares their solar reflectances with those of the standard colors. Also, in 2005, a major manufacturer of roofing shingles in California announced availability of cool colored shingles in four popular colors.

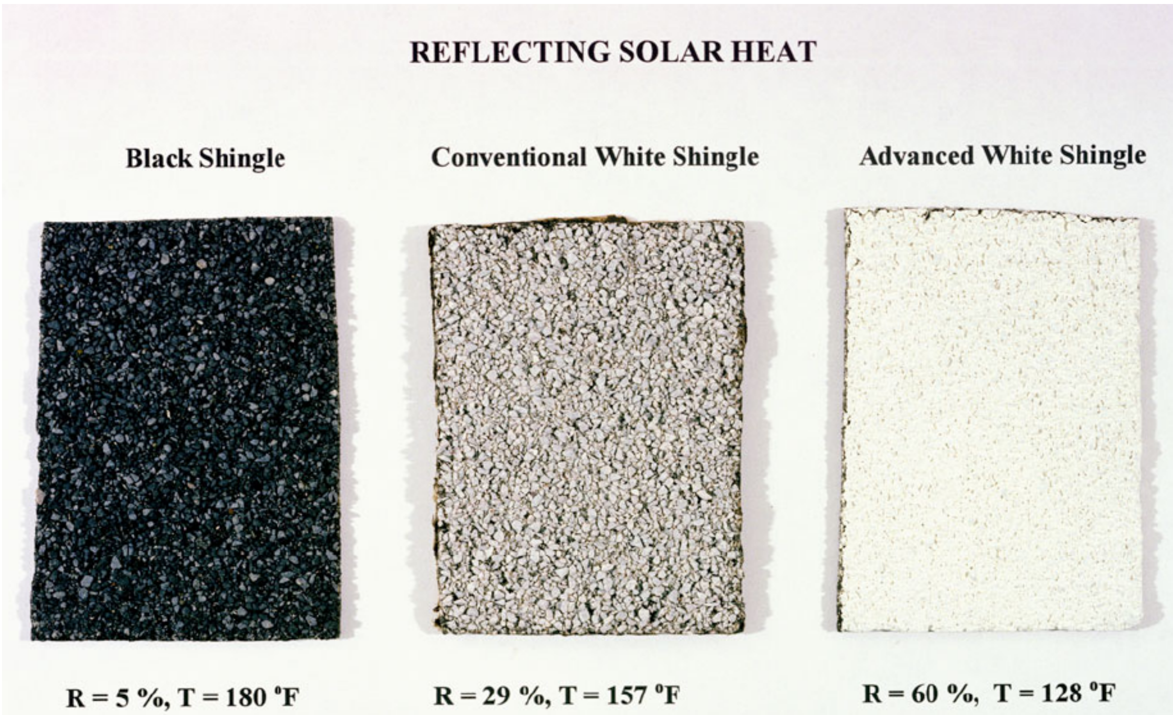


Figure 17. Development of super white shingles.

Bermuda Santorini (Greece)

Figure 18. White roofs and walls are used in Bermuda and Santorini (Greece).

Figure 19. Examples of prototype cool shingles.

Cool Colored Tiles and Tile Coatings

Clay and concrete tiles are used in many areas around the world. In the U.S., clay and concrete tiles are especially popular in the hot-climate regions. There are three ways to improve the solar reflectance of colored tiles: (1) use clay or concrete with low concentrations of light-absorbing impurities, such as iron oxides and elemental carbon; (2) color the tile with cool pigments contained in a surface coating or mixed integrally; and/or (3) include an NIR-reflective (e.g., white) sublayer beneath an NIR-transmitting colored topcoat. Although all these options are in principle easy to implement, they may require changes in the current production techniques that may add to cost of the finished products. Colorants can be included throughout the body of the tile, or used in a surface coating. Both methods need to be addressed.

The American Rooftile Coating Company has developed a palette of cool nonwhite coatings for concrete tiles. Each of the cool colored coatings shown in **Figure 20** has a solar reflectance better than 0.40. The solar reflectance of each cool coating exceeds that of a color-matched, conventionally pigmented coating by 0.15 (terracotta) to 0.37 (black). MCA-Tile manufactures clay tiles in many colors (glazed and unglazed) with solar reflectance greater than 0.4 (see **Table 8**).

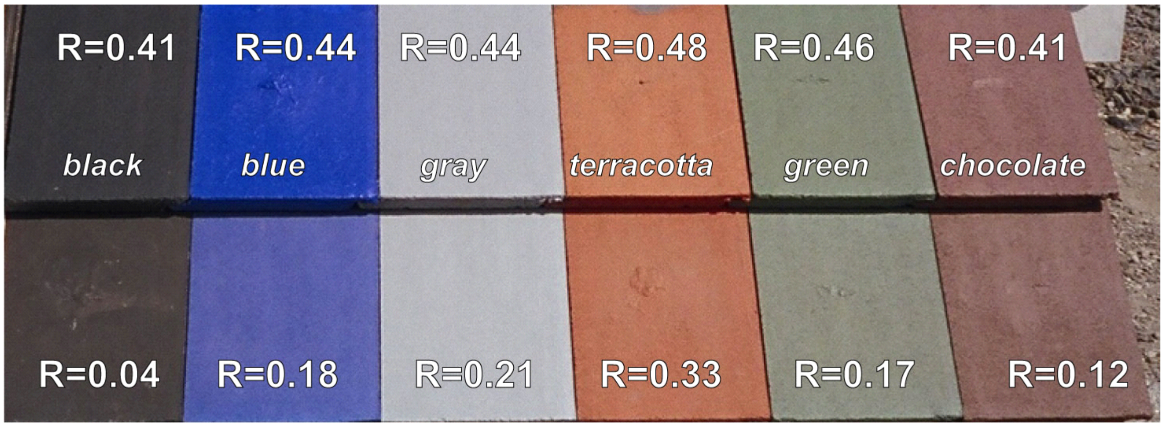


Figure 20. Palette of color-matched cool (top row) and conventional (bottom row) roof-tile coatings developed by industrial partner American Rooftile Coatings. Shown on each coated tile is its solar reflectance, R.

Synnefa *et al.* (2006a&b) have also measured the solar spectral reflectance of 10 prototype cool colored coatings, developed at the National and Kapodistrian University of Athens. These coatings are developed to be used as measures to reduce the summertime cooling energy use in buildings and to reduce summertime urban temperatures.

Cool Colored Metal Panels

Metal roofing materials are installed on a small (but growing) fraction of the U.S. residential roofs. Historically metal roofs have had only about 3% of the residential market. However, the architectural appeal, flexibility, and durability, due in part to the cool-colored pigments, has steadily increased the sales of painted metal roofing, and as of 2002 its sales volume has increased to 8.9% of the residential market, making it the fastest growing residential roofing product (F.W. Dodge 2005). Metal roofs are available in many colors and can simulate the shape and form of many other roofing materials (see **Figure 21**). Application of cool-colored pigments in metal roofing materials may require the fewest number of changes (and in many cases no changes) to the existing production processes. In fact, cool pigments have been incorporated into paint systems used for metal roofing since 2002. For example, the BASF Industrial Coatings line of cool coatings for metal includes over 20 cool-colored products (**Figure 22**). As in the cases of tile and asphalt shingle, cool pigments can be applied to metal via a single or double-layered technique. If the metal substrate is highly reflective, a single-layered technique may suffice. The coatings for metal shingles are thin, durable polymer materials. These thin layers use materials efficiently, but limit the maximum amount of pigment present. However, the metal substrate can provide some NIR reflectance if the coating is transparent in the NIR. Several manufactures have developed cool colored metal roof products.

Cool nonwhite coatings have been enthusiastically adopted by premium coil coaters and metal roofing manufacturers. Metal panels and clay tiles were the first types of roofing to be produced in cool colors. BASF Industrial Coatings (Southfield, MI) has launched a line of cool colored siliconized-polyester coatings that is quickly replacing their conventional siliconized-polyester coatings. Steelscape Inc. (Kalama, WA) has recently introduced a cool polyvinylidene fluoride (PVDF) coating for the metal building industry. Custom-Bilt Metals (Chino, CA) has switched more than 250 of its metal roofing products to cool colors. The Cool Team is currently testing a cool-colored metal roof on a demonstration house in Sacramento.

Table 8. Sample cool colored clay tiles and their solar reflectances (Source: http://www.MCA-Tile.com).

Model	Color	Initial solar reflectance	Solar reflectance after 3 years
Weathered Green Blend		0.43	0.49
Natural Red		0.43	0.38
Brick Red		0.42	0.40
White Buff		0.68	0.56
Tobacco		0.43	0.41
Peach Buff		0.61	0.48
Regency Blue		0.38	0.34
Light Cactus Green		0.51	0.52

*Figure 21. Simulated roofing products made from metal: (**a**) Advanta Shingles, (**b**) Bermuda Shakes, (**c**) Castle Top, (**d**) Dutch Seam Panel, (**e**) Granutile, (**f**) Perma Shakes, (**g**) Scan Roof Tile, (**h**) Snap Seam Tile, (**i**) Techo Tile, (**j**) Verona Tile, (**k**) Oxford Shingles, and (**l**) Timbercreek Shakes. Products **a-j** are manufactured by ATAS International, Inc., while products k and l are manufactured by Classic Products, Inc. (Photos courtesy of ATAS International and Classic Products).*

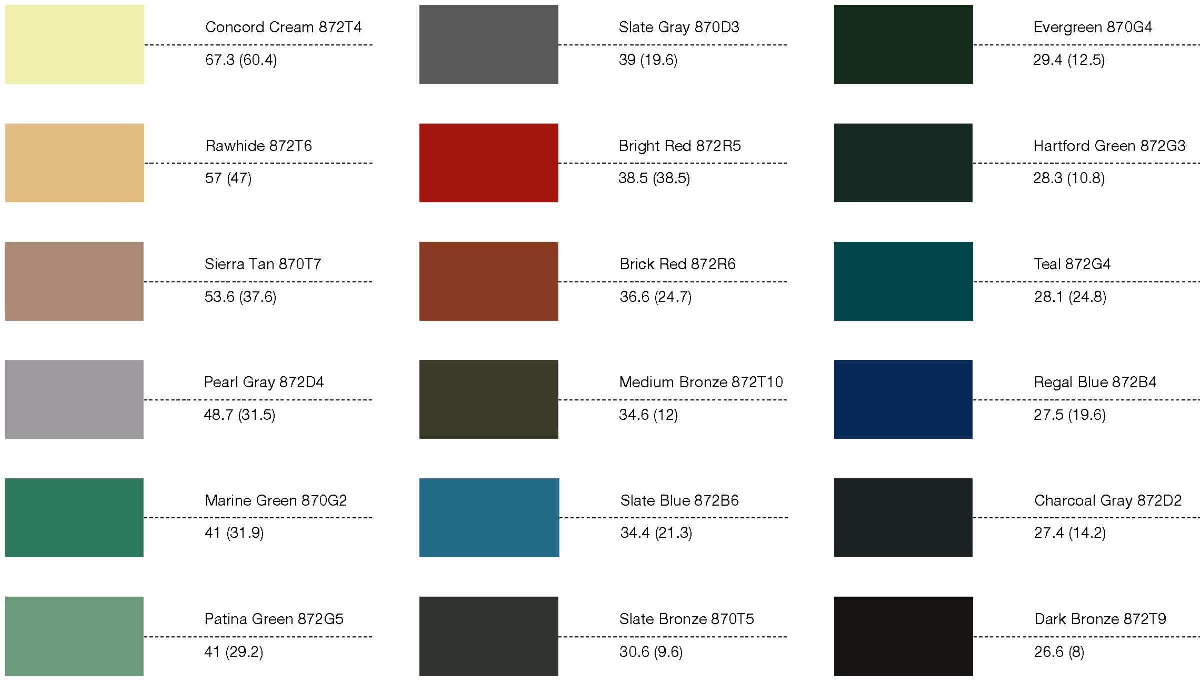


Figure 22. Some of the cool colored coatings for metal roofing products available from BASF Industrial Coatings. To the right of each color swatch is shown the solar reflectance of the cool formulation, followed (in parentheses) by the solar reflectance of a color-matched standard formulation. (Source: http://www.basf.com/pdfs/ULTRA-Cool.pdf).

<u>Durability of Cool Nonwhite Coatings</u>

The durability of cool materials has been tested in weatherometers after being exposed to 5,000 hours of xenon-arc light and to about 10,000 hours of fluorescent light. **Figure 23** compares the total color change and reduction in gloss of cool roofing colored metals and standard colored metals exposed to accelerated fluorescent UV light. In almost all cases cool materials have performed better than standard materials.

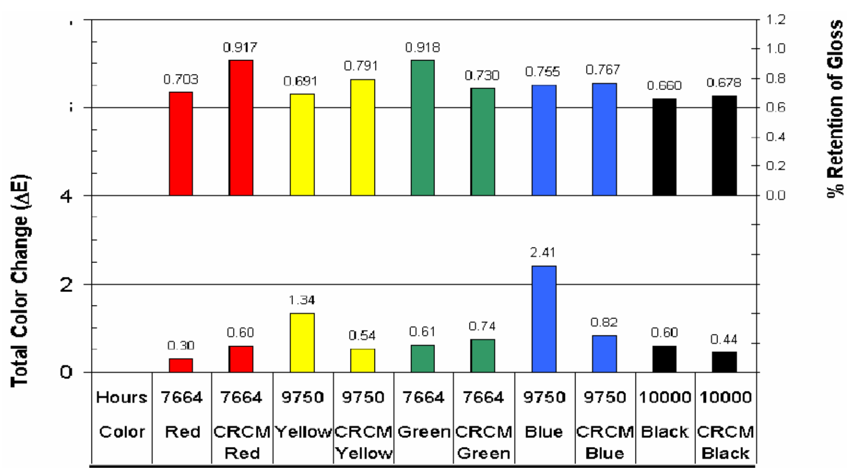


Figure 23. Fade resistance and gloss retention of painted metals (data courtesy of BASF).

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 readily noticed. One consequence of streets covered with dark asphalt surfaces is the pavements heat the air, increasing temperature of the city. Measured data clearly indicate that changing the pavement albedo has a significant effect on the pavement surface temperature. 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.

Urban pavements are made predominantly of asphalt concrete that is dark in color. The challenge is to develop cool pavements that are economical and practical.

In **Figure 24**, we show some measurements of the effect of albedo on pavement temperature. The data clearly indicates that significant modification of the pavement temperature can be achieved: a 10 K decrease in temperature for a 0.25 increase in albedo.

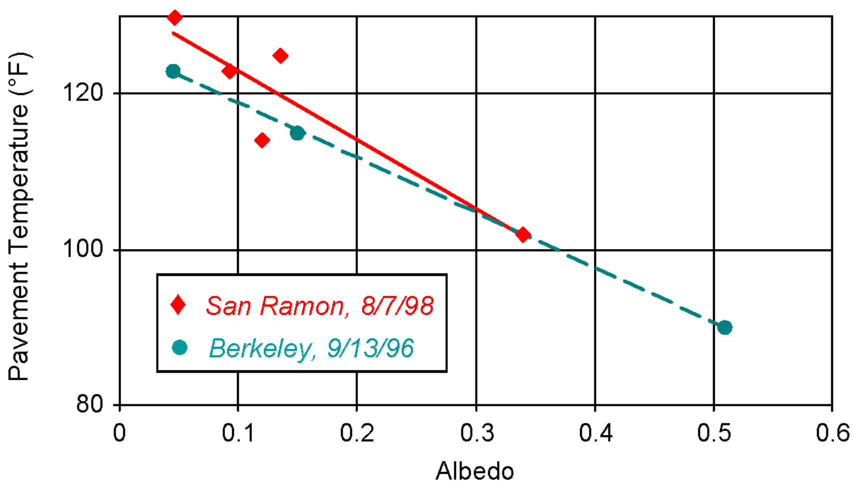


Figure 24. The dependence of pavement surface temperature on albedo. Data in Berkeley, California were taken at about 3 pm, on new, old, and light-color coated asphalt pavements. The data from San Ramon, California were taken at about 3 pm on four asphalt concrete and one cement concrete (albedo = 0.35)

2.2.1. Energy and Smog Benefits of Cool Pavements

Cool pavements affect energy use and air quality through lowered ambient temperatures. Lower temperature has two important 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). The estimated annual cost to the residents of L.A. because of air quality related medical costs and lost work time is about $10 B (Hall *et al*., 1992). The greater part of pollution is particulates, but the ozone contribution averages about $3 B/yr. Assuming a proportional relationship of the cost with the amount of smog exceedance, the cooler-surfaced city would save 12% of $3 B/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 1250 km^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 & 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 (Monismith *et al*., 1994). 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. Instead of black asphalt, with an albedo of about 0.05–0.12, we suggest 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. 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 cool pavements that are feasible and economical. 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.

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 per 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 0.10 - 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.

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, the present value of potential savings estimated at \$1.1/m^2. 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).

In the special case of a climate in which the pavement is subjected to wide temperature swings then additional savings accrue because higher quality binders may be avoided. Note, importantly, and logically, that it is the *pavement* temperature and not the *air* temperature that is considered in specifying a binder. If an asphalt pavement may be exposed to large temperature variations over the year, the binder must be specially formulated to handle the expansion, contraction and viscosity changes between the maximum and minimum temperatures. There is a rule of thumb in the industry, "Rule of 90", that when the difference of these temperatures is greater than 90 °C, some kind of modification of the asphalt will be needed; this adds to the cost. The Rule of 90 arises because ordinary asphalt has difficulty in performing over wide temperature ranges. Additives, such as polymers, are needed to attain performance over a wide range. For example, if a binder is specified as PG 58-22, it is intended to function between 58 C and minus 22 C. The difference, 58 - (-22) = 80. An ordinary grade of asphalt binder will suffice; its cost is about \$125 per ton. If, however, the pavement temperature varies between 76 C and -16 C, or PG 76-16, the difference 76 - (-16) = 92. An enhanced binder is recommended at a price of about \$165 per ton (Bally 1998); a 30% increase in price. It may be possible to stay within the Rule of 90 and avoid the increased cost of binder if the pavement albedo is increased and the pavement does not get as hot. 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 Figure 24 show that a 0.25 increase in albedo can reduce the pavement temperature by 10 K. This suggests that the maximum temperature specification for the pavements might be reduced by 10 K, which means 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 directly for whiter roads. If, however, the lighter-colored road leads to substantially longer lifetime, the initial higher cost is offset by lifetime savings. An example of this is to be seen when a higher grade binder is replaceable by a whiter surface.

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 within 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 5 times greater than the annual savings. Thus, for LA, the present value is about $0.36/m^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 2006). 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.

2.2.5. Cool Pavement Materials

As stated earlier, most urban paved surfaces are either made of asphalt concrete (commonly referred to as *asphalt pavements*) or cement concrete (known as *concrete pavements*). Installing new pavements typically requires grading of the terrain and a new base course of rock. The thickness of this base and its preparation will depend on the anticipated traffic. The topmost (wearing) course, which is relatively independent of the base, is the important part for the albedo of the pavement. A pavement is typically maintained (repaired and resurfaced several times) throughout its life. The maintenance usually involves resurfacing the topmost layer of pavement. This makes routine maintenance an ideal time for introducing light-color surfaces to roads. The following is a brief description of various technologies used in pavement industry.

New Pavements

There are three main types of new pavements: asphalt concrete, cement concrete, and porous paver. In general, a pavement consists of a binder (asphalt, tar, or Portland cement) and aggregate (stones of various sizes down to sand). The function of the binder is to glue the aggregate together. The aggregate provides the strength, friction and resistance to wear, and the binder keeps the stones from dispersing under the forces of the traffic and weather.

Asphalt concrete in new pavements. Asphalt or bituminous materials are the most common binders of road surfaces (Asphalt-Institute, 1989). The relative amount of asphalt and aggregate is about 1 part in 10 (typically about 7% asphalt by weight, or 17% by volume). This type of pavement is properly called "asphalt concrete", suggestive of its composite nature. The fact that about 80% of roads now in service are made of asphalt concrete is a result of its relatively low initial cost and ease of repair.

Asphalt is derived from petroleum. It is often the residue after lighter components, such as gasoline and kerosene, are fractionated from crude oil. As such, it varies in composition depending on the reservoir of origin and on the fractionating process to which it is subjected. Compared to the Portland cement concrete, bituminous concrete is more flexible. This has the advantage that the wearing surface tends to conform to any movements of the subgrade with less cracking, but too much softness can lead to spreading or rutting of the road. In particular, asphalt concrete softens more than Portland cement concrete at typical temperatures that roads attain.

Cement concrete in new pavements. Cement concrete consists of an inorganic binder, or *cement*, which, after being mixed with water, can harden and hold together stony aggregate. The raw material of the cement contains *lime* (CaO), which is derived from *limestone* (calcium carbonates, $CaCO_3$) or oyster shells.

Portland cement contains *clay,* which has iron oxides, silica, and alumina in it. The approximate composition (by weight %) of Portland cement is (Leighou, 1942) lime (60%), silica (20%), alumina (5%), iron oxide (3%), magnesia (2%), and other (10%). Depending on the composition of the starting materials, a suitable mixture of them is ground together. (E.g., limestone contains 52% lime and 3% silica, but slag contains 42% lime and 34% silica, so the amount of clay (57% silica) to be added would differ between limestone and slag based cements to get a final silica content of 20%.)

Concrete paving is the choice for very heavy traffic loads because the material does not deform as much as asphalt. In dry climates, for example, concrete is chosen when the traffic exceeds 70,000 cars per day. In wet climates, where the softer undersurface requires a stiffer road, concrete is preferred for traffic of 40,000 per day (Smart, 1994). However, the higher initial cost of concrete and the difficulty of modifying the surface favors the application of asphalt to roads that carry traffic in low volume and low weight, such as in residential areas and parking lots.

Cement is darkened by the presence of iron oxide, which can be reduced to get a whiter cement by using kaolin. Adding titanium dioxide makes cement whiter, but manganese oxide, present in slag, makes it browner. Measurements and literature searches (Taha, Sailor *et al*., 1992), give fresh cement concrete a solar reflectance of 0.35 - 0.40. As cement concrete ages it tends to get darker because of dirt, and the solar reflectance tends toward 0.25 - 0.30. Contrarily, asphalt concrete tends to get lighter as it ages, because the black asphalt wears away to reveal the lighter aggregate.

It is possible to produce concrete with visible reflectivity approaching 68% by using whiter cements and aggregates (Lehigh-Cement, 1994)[4]. The cement is white because the starting materials are selected to have low concentrations of colored minerals, such as iron oxides. White aggregates, such as white sand, and some limestones are available, at a cost premium of 10-20%.

Porous and grass pavers for new pavements. Porous pavements are defined as pavements that deliberately allow water to pass through them. Permeability has the advantages of permitting rain water to be stored in the earth and reducing the problems of flooding. A road surface made of grass has the added desirable qualities that the grass evapotranspires and thus cools the air above it, as well as being decorative. However, a grassy field as a parking lot or access road is soft when it is wet and is easily rutted permanently. These defects can be alleviated by enclosing the soil in a lattice structure that provides lateral containment. The lattice structure thus serves as a binder for the soil or gravel. We refer to such porous pavements as "grass pavement". All grass pavements must have sufficient water year round, which, makes it ill-suited for dry climates.

Grass pavers are best suited for occasional use where perhaps one or two cars a day traverse it (e.g., parking for employees, sports facilities, overflow), or as fire lanes, because grass cannot survive frequent traffic. The lattices supporting the grass pavers are made either of concrete or plastic. **Figure 25** shows two plastic grasscrete lattices and a picture of a grasscrete surface designed for car parking.

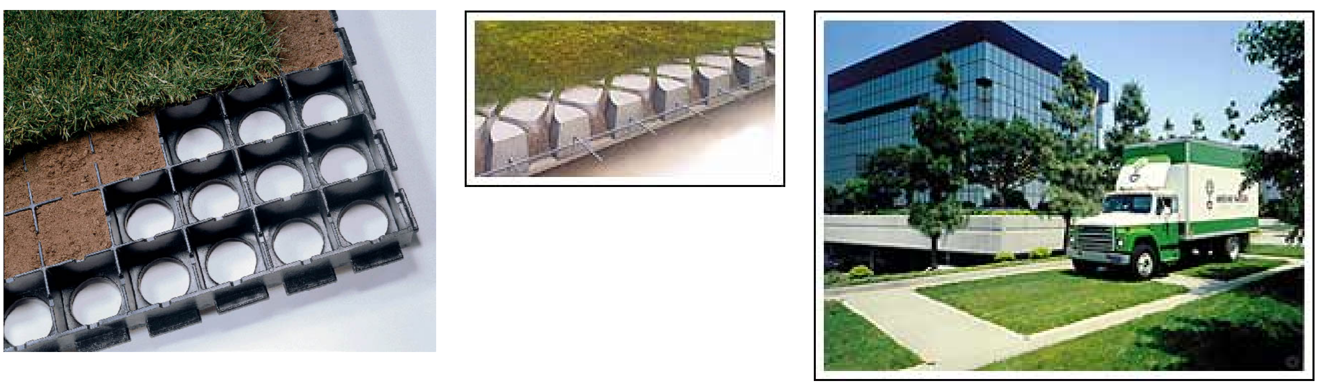


Figure 25. Grasscrete lattices and a picture of a grasscrete application.

Another type of porous pavement is formed of asphalt or cement concrete (Brown, 1996) or which is loosely packed so that water can percolate through it. To construct a permeable pavement entirely of asphalt or cement concrete, the aggregate is chosen to be a single size, usually about 9.5 mm (3/8”). (so-called "open-graded" aggregates.) In the absence of fine aggregates and sand, the stones pack so loosely that there are channels through which moderate flows of water can filter (Asphalt-Institute, 1974). This porous pavement is usually placed over a solid pavement for strength, and is domed such that the water leaks out the sides of the roadway. Blockage of the pores by dirt, and fractures by freeze-thaw cycles may be problems. The porous surface has a safety advantage of avoiding standing water that can lead to aquaplaning by fast-moving vehicles. Another appealing benefit is that these surfaces tend to suppress tire noise (Hugues and Heritier, 1995; Lefebvre and Marzin, 1995). Runoff of rain water is reduced if it can percolate into the ground, relieving demand on a city’s street drainage system. **Figure 26** shows examples of asphalt concrete and cement concrete porous pavements.

[4]White cement is available, for example, from Lehigh Portland Cement Co., Allentown, PA 18195

Figure 26. Porous pavements.

Tree-resin modified emulsions. "RoadOyl", a relatively new binder, is tan colored because it is derived from pine tree pitch and resin (Loustalot *et al.*, 1995). When it is mixed with stone or sand, it produces a light colored pavement. In the emulsified form it is water soluble, applied without heating and thus is particularly convenient to apply where access to large equipment is limited. After drying and setting it is water insoluble. It is comparable in strength to asphalt concrete in laboratory tests, but has not yet been extensively tested on city streets. RoadOyl comprises about 6% by weight of the finished pavement. It is manufactured by Road Products Corp. of Knoxville, TN.

Coal-tar resins. In the South Eastern U.S., near coal mining regions, coal - tar resins are used in a manner similar to asphalt binder. Because it is not applied much nation-wide, and it is black, we shall not discuss it any further here.

<u>Resurfacing of pavements</u>

Asphaltic coatings. Asphalt and asphalt based materials are the most common for repair and resurfacing of roads (Raza, 1995). Asphalt adheres well to both older asphalt and to cement concrete. For large jobs, conventional hot-mix asphalt concrete at least an inch thick is commonly used.

Keeping asphalt in a fluid state is accomplished by having oil-fired heaters onboard the spreaders. For small repair jobs, room temperature bituminous binders have been developed. One such binder is asphalt dissolved in kerosene or creosote. This is called a "cutback" asphalt. The solvent evaporates over a "curing" time, after which the asphalt is hard. The emission of the organic solvents, however, has adverse effects on the environment, so the cutback asphalts have been superseded by water-soluble asphalt emulsions (AEMA, 1995). Here the bitumen is ground to small particles and chemically treated with an emulsifier so that it remains in suspension in water. The emulsifier is chosen anionic or cationic to facilitate the wetting of the particular mineral aggregates that are mixed with the emulsion. After the spreading of the emulsion and aggregate, the water separates ("breaks") and evaporates harmlessly. The asphalt coats and binds the aggregate to form an asphalt concrete. Asphalt emulsions cost from 15% to 100% more than bulk asphalt (Reed, 1997; Raza, 1995; Means, 2006). Emulsions have drying times of as little as a few hours, resulting in minimal disruption of traffic. A newer type of binder is formed by adding polymers to asphalt emulsions─this is called "micro-surfacing".

There are two general approaches to the resurfacing of existing pavements (Hunter, 1994). In both cases the new surface is a composite of binder and aggregate; the difference is whether these components are mixed after or before the binder is spread on the old surface. In a “chip” seal application, the binder is spread first, the aggregate is dropped on top of it, and *then* pressed into the binder. Otherwise, the aggregate and binder are premixed and then spread. The mixing is often done onboard the spreader vehicle just before the mixture is applied to the pavement. The premixed pavements are known as "overlays", "slurry coats", "microsurfaces", "seal coats", or "fog coats" depending on the binder and the size of aggregate.

Chip seal. The binder in a chip seal is usually a fast-drying emulsified asphalt. As soon as possible after the binder is spread, the aggregate is dropped and rolled into the binder. The typical surface is about 6 mm (1/4") thick, which is determined by the diameter of the largest aggregate. When the chip seal is used to resurface an existing pavement it is sometimes referred to as a "seal coat", which may be confused with the same word applied to a slurry coat containing fine aggregate(AEMA, 1995). When the chip seal is applied to a stony or soil surface, it may be referred to as a "surface treatment" (AEMA, 1995).

Chip seals are usually applied to low-use roads, such as in rural areas. The rough aggregate on the surface is problematic in residential areas where children play, and loose aggregate thrown by car tires may pose another danger. The color of the surface is strongly influenced by the color of the aggregate. When white limestone is used, where it is abundant, a quite white surface results. **Figure 27** shows a picture of a chip seal application and contrasts its solar reflectance to that of an asphalt pavement.

Figure 27. Photo of a chip seal application (lower part of the picture) and asphalt pavement (upper part) in San Jose, CA. Note the lighter color (higher solar reflectance) of the chip seal surface.

Hot-mix overlays. For roads needing considerable repair or that must support large stresses, such as near stop signs where acceleration and turning are frequent, a sturdy repair can be done with a hot mix containing aggregate from 9.5 – 12.5 mm (3/8" - 1/2") in maximum diameters.

Slurries. For surfaces with medium need of repair and that carry considerable traffic, resurfacing may be done with a mixture of asphalt emulsion and aggregate. The size of the aggregate and the formulation of the emulsion are determined by the expected traffic and the climate. The typical aggregate is about 6 mm (1/4") maximum diameter (ISSA, 1991). **Figure 28** show the machinery for slurry seal coating and the finished surface.

Figure 28. Machinery for slurry seal application and finished surface.

Microsurfacing. When polymers are added to slurry binders the product is called "microsurfacing" (Raza, 1994a,b). The polymer confers greater resistance to wear. In addition, it becomes possible to apply a layer in multistone thicknesses─it can be more than 1.5 times thicker than the largest aggregate. It can be used for layers down to 7.5 mm (0.3").

Seal coat or sand coat. It consists of a mixture of emulsified asphalt and sand. Sometimes cement and other materials are added to the mix, but the aggregate particles must be smaller in diameter than about 0.04". The preliminary preparation of the surface is relatively simple. Deposits of grease and oil must be removed or sealed over. Otherwise, the surface must be thoroughly cleaned of loose dirt or paving particles. The surface is then dampened with water, and the slurry is applied in a smooth coat. It is recommended that two coats be applied.

The color of the material is basically gray, and is normally made darker by the addition of carbon black. Even when the carbon black is omitted, the gray surface has an albedo of 0.05. To lighten the color, rutile (titanium dioxide, TiO_2) powder can be added. This increases albedo to 0.10 with *no* loss of structural quality. An emulsion designed to rejuvenate asphalt, Reclamite (Erickson, 1989) is coated with sand. Thus a lighter color is achievable if white sand is used.

Fog coat. A thin layer of diluted asphalt emulsion is spread on existing pavement. It can be used as a protective layer, but also to change color. The typical amount of asphalt applied is about $0.06l/m^2$ (0.03 gal/yd^2) (AEMA, 1995). This results in a coating of about 0.13 mm(0.005") thick. The cost of the labor would dominate the total cost because the amount of material is so small.

Petroleum resin coatings. A petroleum product that is not an asphalt is manufactured by Neville

Chemical Co., Pittsburgh, PA, and sold as "Pavebrite®" (Willockl, 1995). Similar products are distributed in Europe by the French Shell Oil, as "Mexphalte C" and by Total as "LSC" (Liants Synthetiques Clairs). These are synthetic resins derived from lighter fractions of petroleum, and chemically modified. The pure material is tan in color, but coloring additives can achieve bright colors. The color of the aggregates must be chosen to not interfere with the desired color, as well as to provide the required mechanical strength. The aggregates are fine graded, meaning they all pass through a # 8 mesh (about 2.5 mm=0.1") screen. This is necessary in order to prevent the color of the aggregate from becoming significant as the pavement wears, if one desires that the color pavement stay the color of the binder. For the purposes of a whiter road, a white binder could be mixed with white rocks of any desired sizes. The mechanical properties of the paving is reported to be at least as good as comparable asphaltic pavings.

The typical use in the U.S. has been for pavements at least 12.5 mm (1/2") thick. In Holland there is some experience in using the binder in slurries. A ton occupies about 0.42 m^3 (15 ft^3). When used for a 12.5 mm (1/2") pavement, it requires one ton to make 34 m^2.

Tree resin coatings. A resinous material derived from pine trees, known as RoadOyl®, is used for roads and dust-suppression. In Marshall stability tests, it is reported to perform at least as well as asphalt (SSC, 1995). It has not yet been completely evaluated as a slurry binder.

Cement concrete coatings ("white-topping"). Layers of concrete as thin as 5 cm (2") have been used for resurfacing roads. The procedure is still somewhat experimental and the long-term behavior and proper practice are still under study. **Figure 29** shows the schematic of a "white-topping" and its application on covering a portion of a street.

Acrylics. These are synthetic polymers which can be highly colored. They are expensive, and are thus far have been used mostly for special applications such as tennis courts. Reed and Graham, Inc., San Jose CA, has produced experimental materials based on acrylics mixed with pigments, that proved to have acceptable structural strength as a roadway (Lungren and Goldman, 1996), and solar reflectivities of about 50% (Berdahl and Wang, 1996).

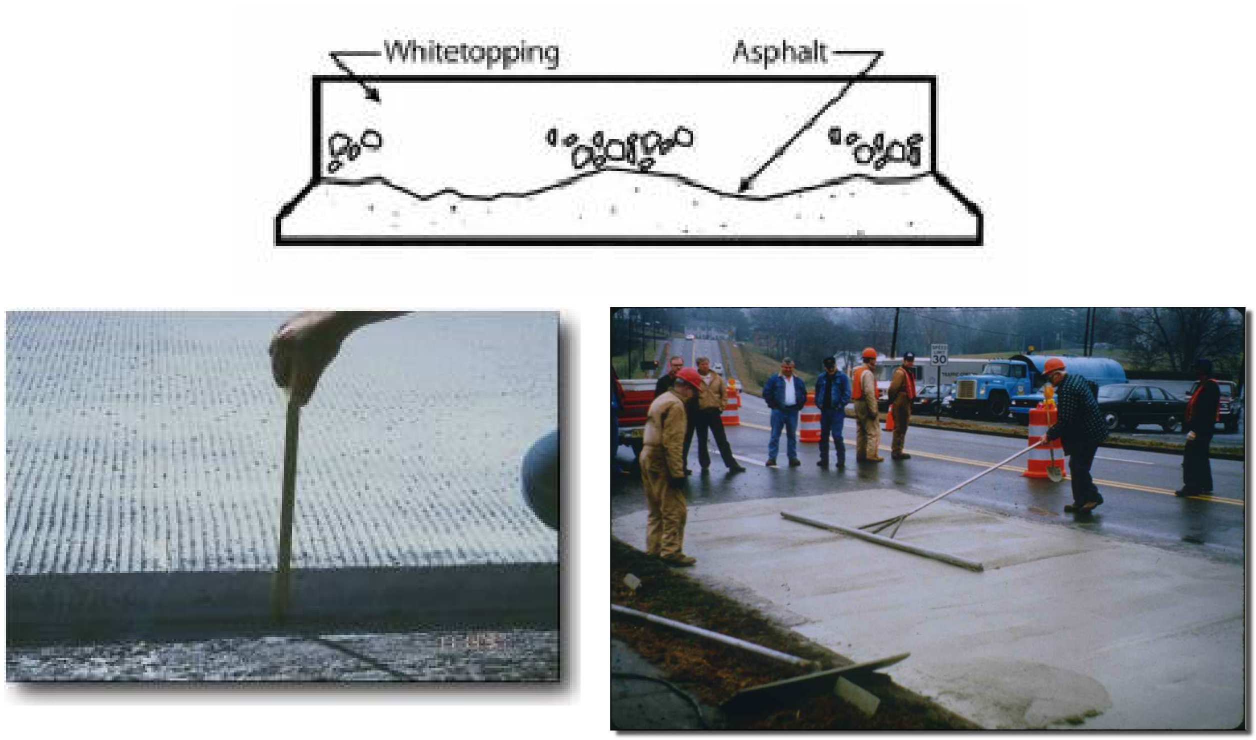


Figure 29. Schematic of a "white-topping" and application pictures.

2.3 Shade Trees and Urban Vegetation

Urban shade trees offer significant benefits by both reducing building air conditioning and lowering air temperature, thus improving urban air quality by reducing smog. Shade trees intercept sunlight before it warms a building. Trees also decrease the wind speed under their canopy and shield buildings from cold winter breezes. Akbari (2002) provides an overview of benefits and cost associated with planting urban trees. In a comprehensive study for Chicago IL, McPherson *et al.* (1994) provides a good review of the impact of an urban forest on the urban ecosystem.

In addition to their obvious aesthetic value, urban trees can modify the climate of a city and provide better urban thermal comfort in hot climates. A significant increase in the number of trees can moderate the intensity of the urban heat island by altering the heat balance of the entire city (**Figure 11**).

Trees affect energy use in buildings through both direct and indirect processes. The direct effects are: (1) reducing solar heat gain through windows, walls, and roofs by shading, and (2) reducing the radiant heat gain from the surroundings by shading. The indirect effects include: (3) reducing the outside air infiltration rate by lowering ambient wind speeds, (4) reducing the heat gain into the buildings by lowering ambient temperatures through *evapotranspiration* in summer, and (5) in hot and humid climates, increasing the latent air-conditioning load by adding moisture to the air through evapotranspiration (Huang *et al*., 1987).

<u>Shading</u>

During the summer, properly placed and scaled trees around a building can block unwanted solar radiation from striking the building, reducing its cooling-energy use. In cold climates, shading of buildings can also increase the wintertime heating-energy use. Deciduous trees are particularly beneficial since they allow solar gain in buildings during the winter while blocking it during the summer. The shade cast by trees also reduces glare and blocks the diffuse light reflected from the sky and surrounding surfaces (thereby altering the heat exchange between the building and its surroundings), providing natural insulation during both hot and cold weather. During the day, tree shading also reduces heat gain in buildings by reducing the surface temperatures of the surroundings. At night, trees block the heat flow from the building to the cooler sky and surroundings.

<u>Wind shielding (shelterbelts)</u>

Trees act as windbreaks that lower the ambient wind speed, which can lower a building’s cooling-energy use depending on its physical characteristics. In certain climates, tree shelterbelts are used to block hot and dust-laden winds. In addition to energy-saving potentials, this will improve comfort conditions outdoors within the city.

<u>Evaporative cooling</u>

The term *evapotranspiration* refers to the evaporation of water from vegetation and surrounding soils. On hot summer days, a tree can act as a natural “evaporative cooler” using up to 100 gallons of water a day and thus lowering the ambient temperature (Kramer and Kozlowski, 1960). Evapotranspiration is most effective in the summer because of the presence of leaves on deciduous trees and the higher ambient temperatures.

Increased evapotranspiration during the summer from a significant increase in urban trees can produce an "oasis effect" in which the urban ambient temperatures are significantly lowered.

Though in some cases the amount of latent cooling (i.e., humidity removal) might be slightly increased on the whole, buildings in such cooler environments will consume less cooling power and energy.

2.3.1. Energy and Smog Benefits of Shade Trees

Direct Energy Savings

Data on measured energy savings from urban trees is scarce. Case studies (Laechelt and Williams, 1976; Buffington, 1979; Akbari *et al.*, 1997b; Parker, 1981) have documented dramatic differences in cooling-energy use between houses on landscaped and unlandscaped sites. Akbari *et al.* (1997b) conducted a "flip-flop" experiment to measure the impact of shade trees on two houses in Sacramento. The experiment was carried out in three segments: (1) monitoring the cooling-energy use of both houses to characterize a base case energy use of the houses, (2) installing eight large and eight small shade trees at one of the sites for a period of four weeks, and then (3) moving the trees from one site to the other. The experiment documented seasonal cooling-energy savings of about 30% (about 4 kilowatt-hour per day, kWh/day). The estimated peak electricity saving was about 0.7 kW. In Florida, Parker (1981) measured the cooling-energy savings from well-planned landscaping and found that properly located trees and shrubs around a mobile trailer reduced the daily air-conditioning electricity use by as much as 50%.

In computer simulation studies, Konopacki and Akbari (2000a, 2000b, 2002) investigated the energy-saving potential of urban trees in five U.S. cities: Baton Rouge LA, Chicago IL, Houston TX, Sacramento CA, and Salt Lake City UT. The analysis included both *direct* (shading) and *indirect* (evapotranspiration) effects. The study considered planting an average of four shade trees per house, each with a top view cross section of 50 m^2, and estimated net annual dollar savings in energy expenditure of \$5.2M, \$13.5M, \$27.8M, \$9.8M, and \$1.1M for Baton Rouge, Chicago, Houston, Sacramento, and Salt Lake City, respectively.

In another computer study, Taha *et al*. (1996) analyzed the 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 NY, Philadelphia PA, Phoenix AZ, and Washington DC. Both direct and indirect effects on air-conditioning energy use were addressed, using the DOE-2 building simulation program for energy calculations and a mesoscale simulation model for meteorological calculations. The energy analysis focused on residential and small commercial (small office) buildings (**Table 9**). For most hot cities, the estimated total (direct and indirect) annual energy savings were \$10 to \$35 per 100 m^2 of a single-story residential and commercial buildings.

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 analyses 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. In cold climates, the wind-shielding effect of trees can 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 10–15%.

Table 9. DOE-2 simulated HVAC annual energy savings from trees. Three trees per house and per office are assumed. All savings are $/100m². (Source: Taha et al., 1996).

Location	Old Residence		New Residence		Old Office		New Office	
	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
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

Heisler (1990a) has measured the impact of trees in reducing ambient wind. Akbari and Taha (1992) used Heisler's data and analyzed the impact of wind reduction on heating- and cooling-energy use of typical houses in cold climates. Simulations indicated that in cold climates, a 30% uniform increase in urban tree cover can reduce winter heating bills in urban areas by about 10% and in rural areas by 20%. Savings in urban areas can almost be doubled if evergreen trees are planted strategically on the north side of buildings so that the buildings can be better protected from the cold north winter wind.

Heisler (1986 and 1990b) has investigated the effect of tree placement around a house on heating- and cooling-energy use. Trees planted on the east and west sides of a building shade the walls and windows from sunlight in the morning and afternoon. Depending on wall construction, the impact of morning heating may be seen in the late morning and early afternoon hours. Similarly, the impact of afternoon heating of the west walls may be seen in evening hours. Akbari *et al.* (1993) performed parametric simulations on the impact of tree locations on heating- and cooling-energy use and found that savings can vary from 2% to over 7%; cooling-energy savings were higher for trees shading the west walls and windows.

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 simulated cells the temperature was decreased as much as 3K (see **Table 10**). The estimated 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 the direct effects of shading, and, moreover, require that the entire city be planted.

Table 10. Number of additional trees planted in each metropolitan area and their simulated effects in reducing the ambient temperature. Note that the simulated area is much larger than the metropolitan area.

Location	# of additional trees in the simulation domain (M)	# of additional trees in the metropolitan area (M)	Max air temperature reduction in the hottest simulation cell (K)
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

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 were from the reduction in smog concentration resulting from meteorological changes due to the evapotranspiration of trees (see **Table 11**). Peak demand savings was estimated to be 0.9 GW.

Table 11. Energy savings, ozone reduction, and avoided peak power resulting from the addition of 11 million of urban trees in the Los Angeles Basin (Source: Rosenfeld et al., 1998).

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

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) assumed the planting of small shade trees that would take about 10-15 years to reach maturity. Savings from trees before they reach maturity was neglected and the PV of all future savings was calculated to be $7.5 for each $1 saved annually. On this basis, the direct savings to a homeowner who plants three shade trees would have a PV of about $200 per home ($68/tree). The PV 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.

Urban trees affect air pollution through two major processes: (1) cooling of the ambient temperature and hence slowing the process of smog formation, and (2) dry deposition by which the airborne pollutants (both gaseous and particles) can be removed from the air. Trees directly remove pollutant gases (CO, NO_x, O_3, and SO_2) predominantly through leaf stomata (Smith, 1984; Fowler, 1985). Nowak (1994a) performed an analysis of pollutant removal by the urban forest in Chicago and concluded that through dry deposition trees on the average remove about

0.002% (0.34 $g/m^2/yr$) of CO, 0.8% (1.24 $g/m^2/yr$) of NO_2, 0.3% (1.09 $g/m^2/yr$) of SO_2, 0.3% (3.07 $g/m^2/yr$) of O_3, and 0.4% (2.83 $g/m^2/yr$) PM10 pollutants from the air.

Simulations performed by Taha *et al*. (1997) for Los Angeles indicated that on a daily basis 1% of the mass of ozone in the mixed layer would be scavenged by planting an additional 11M trees (dry-deposited). In addition to this amount of ozone being scavenged directly from the atmosphere, there is 0.6% less ozone formation in the mixed layer due to the fact that vegetation also scavenges NO_2, an ozone precursor. The total effect of increased deposition by the additional vegetation is thus to decrease atmospheric ozone in the mixed layer by 1.6%.

Taha *et al.* (2000) refined their analysis and studied the effects of urban vegetation (and other heat-island reduction technologies─reflective roofs and pavements) on ozone air quality for Baton Rouge, Salt Lake City, and Sacramento. The meteorological simulations indicated a reduction in daytime ambient temperature on the order of 1-2 K. In Baton Rouge, the simulated reduction of 0.8 K in the afternoon ambient temperature leads to a 4-5 ppb (part per billion) reduction in ozone concentration. For Salt Lake City, the afternoon temperature and ozone reductions were 2 K and 3-4 ppb. And in Sacramento the reductions were 1.2K and 10 ppb (about 7% of the peak ozone concentration of 139 ppb). Note that the reported reductions in ambient and ozone concentration have resulted from the combined effect of urban vegetation and reflective roofs and pavements. Preliminary simulations indicated that in dry climates such as Sacramento and Salt Lake City, the contribution of urban vegetation and reflective surfaces to ambient air temperature and ozone reduction is about the same. In humid climates such as Baton Rouge, increasing the reflectivity of surfaces is more effective in reducing ambient temperature and ozone than adding to the urban vegetation.

It is also suggested that trees improve air quality by dry-depositing NO_x, O_3, and PM10. Rosenfeld *et al.* (1998) estimated that 11M trees in LA will reduce PM10 by less than 0.1% through dry deposition, worth about $7 M per year.

Shade trees, by reducing peak power by 0.9 GW, save about 0.5 g of NO_x per kWh avoided from power plants in the Basin. Simulations have found that 4 tons of NO_x per day are avoided, about 1/3% of the base case.

2.3.2. Other Benefits of Shade Trees

There are other benefits associated with urban shade 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.

Data for the rate of carbon sequestration by urban trees are scarce; most data is given in the units of tons per year of carbon per hectare of forested land. However, Nowak (1994b) has performed an analysis of carbon sequestration by individual trees as a function of tree diameter measured at breast height (dbh). He estimates that an average tree with a dbh of 31-46 cm (about 50 m^2 in crown area) sequesters carbon at a rate of 19 kg/year. The rate of carbon sequestration for several species of trees can be estimated, using data by Frelich (1992) on the age, the dbh, crown area, and height for 12 species of trees around Twin Cities, MN. Using this data, the volume of the wet biomass of the trunk can be estimated by assuming a cone-shape tree with a base area with the given diameter and height. The total volume of the tree accounting for main branches and roots is approximately 1.5 the volume of the tree trunk. The weight of the biomass can be estimated by multiplying the volume by a density of 900 kg/m^3. The weight of the dry mass is estimated at 50% of the wet mass and the amount of carbon is estimated to be 50% of the dry mass. The calculation yields an average of about 4.5 kg/year over the life of a tree until its crown has grown to about 50 m^2 (**Table 12**). Data indicate that as trees grow, the rate of sequestration increases. The average sequestration rate for a 50-m^2 tree was estimated at about 11 kg/year.

This calculation suggests that urban trees play a major role in sequestering CO_2—thereby delaying global warming. Rosenfeld *et al.* (1998) estimated that a tree planted in Los Angeles avoids the combustion of 18 kg of carbon annually, and according to our calculations an average shade tree sequesters about 4.5-11 kg/yr (as it would if growing in a forest). In that sense, one shade tree in Los Angeles is equivalent to 3-5 forest trees.

Table 12. Annual carbon sequestration by individual trees. Each tree is assumed to have a crown area 50 m^2. dbh = Diameter of tree at breast height; H = Tree height. (Source: Frelich, 1992)

Tree type	Age	dbh (cm)	H (m)	Average C sequestered (kg/yr)	C sequestrated at maturity* (kg/yr)
Norway Maple	30	33.0	10.1	3.2	9.9
Sugar Maple	29	29.5	11.2	2.9	7.8
Hackberry	25	27.4	10.3	2.7	8.5
American and Little-leaved Linden	33	41.4	11.5	5.3	13.8
Black Walnut	32	31.0	11.2	3.0	8.0
Green Ash	26	30.2	11.7	3.6	10.8
Robusta and Siouxland Hybrid	33	52.1	20.5	14.9	29.6
Kentucky Coffee Tree	40	31.0	9.9	2.1	3.6
Red Maple	24	27.4	10.2	2.8	8.9
White Pine	34	34.5	13.6	4.2	15.2
Blackhills (white) Spruce	60	37.6	15.9	3.3	7.7
Blue Spruce	60	49.3	18.9	6.7	12.8
Average				4.6	11.4
Average excluding Robusta/Siouxland				3.6	9.7

* Maturity is defined when the tree has a crown area of 50 m^2.

2.3.3. Potential Problems with Shade Trees

There are some potential problems associated with trees. Trees can contribute to smog problems by emitting volatile organic compounds (VOCs) that exacerbate the smog problem. The photochemical reaction of VOCs and NOx produces smog (O_3). 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. Unfortunately, this results in very little evapotranspiration and thus very little ambient cooling. Some trees need significant maintenance that may entail high costs over the life span 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 with a height of 1.5-3 m 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 provides details of the cost for trees located in parks, yards, streets, highway, and houses. The present value of all these life-cycle costs (including planting) is $300 to $500 per tree. Over 90% of the cost is associated with professional planting, pruning, tree and stump removal. On the other hand, a tree-planting program administered by the Sacramento Municipal Utility District (SMUD) and Sacramento Tree Foundation in 1992-1996 planted trees 6 m in height at an average (low) cost of $45 per tree. This figure includes only the cost of a tree and its planting; it does not include pruning, removal of dead trees, and stump removal. Tree costs can also be justified by other amenities they provide beyond air-conditioning and smog reduction. The low-cost programs are then probably the information programs that provide data on the energy and smog savings that trees offer to the communities and homeowners who have decided to plant trees for other reasons.

Two primary factors to be considered in designing a large-scale urban tree program is the potential room (space available) for planting trees, and the types of programs that utilize and employ the wide participation of the population. We recently studied the fabric (fraction of different land-uses) of Sacramento by statistically analyzing high-resolution aerial color photographs of the city, taken at 0.30-m resolution (Akbari *et al.*, 1999; see *Figure* 10**)**. On average, tree cover comprises about 13% of the entire Sacramento metropolitan area. Assuming that trees can be planted in areas to cover barren land (8%) and grass (15%), tree cover in Sacramento would increase to 36%. The design of a large-scale urban tree program should take advantage of this type of data to plan the program accurately for each neighborhood.

3. Analysis Tools

Figure 11 depicts the overall methodology used in analyzing the impact of heat-island mitigation measures on energy use and urban air pollution. Hourly building energy simulation models (such as DOE-2) are used to calculate the energy use and energy savings in buildings.[5] 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 the hourly simulation model 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.

Factors affecting the energy balance in urban areas include urban geometry, surface properties, and release of anthropogenic heat. The extent and intensities of urban heat islands depend strongly on temporal aspects (diurnal and seasonal) of the weather and synoptic conditions. They also depend on other factors such as the location, topography, size of the city and its population density (Oke, 1987; 1988).

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, 2001) used the Colorado State University Mesoscale Model (CSUMM) and the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) MM5 to simulate the meteorology of several urban areas and its sensitivity to changes in surface properties. The Urban Airshed Model (UAM) and the California Institute of Technology (CIT) air shed model were used to simulate the impact of the changes in meteorology and emissions on ozone air quality. The CSUMM, MM5, CIT, 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 governing equations are summarized below:

(1) $\partial \rho / \partial t = -(\nabla \cdot \rho \mathbf{V})$ Conservation of Mass

(2) $\partial \theta / \partial t = -\mathbf{V} \cdot \nabla \theta + S_\theta$ Conservation of Energy

(3) $\partial \mathbf{V} / \partial t = -\mathbf{V} \cdot \nabla \mathbf{V} - \frac{1}{\rho} \nabla p - g\,\mathbf{k} - 2\,\mathbf{\Omega} \times \mathbf{V}$ Conservation of Momentum

(4) $\partial q / \partial t = -\mathbf{V} \cdot \nabla q + S_q$ Conservation of Moisture

(5) $\partial C_i / \partial t + \nabla \cdot \mathbf{V} C_i) = \nabla \cdot (\mathbf{K} \nabla C_i) + R_i + S_i + D_i$ Conservation of Species

[5] DOE-2 is an hourly simulation program that simulates the heating and cooling energy demand of the building. DOE-2 input include building and heating, ventilation, and air conditioning characteristic data, operating schedules, occupancy and hourly weather data (BESG, 1990).

Where

ρ = density of the air

V = wind velocity vector

θ = potential temperature,

S_θ = source or sink term for potential temperature

p = pressure

g = gravitational acceleration

k = unit vector in vertical direction

Ω = earth angular velocity

q = specific humidity

S_q = source or sink term for humidity

C_i = concentration of species i

K = turbulent diffusion coefficient

R_i = reaction rate for species i

S_i = source rate for species i

D_i = sink (or deposition) rate for species i.

The CSUMM is a hydrostatic, primitive-equation, three-dimensional Eulerian model 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 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 air quality models.

The MM5 is a state-of-science, non-hydrostatic, three-dimensional (Eulerian) primitive equation model that is gaining wide acceptance in the scientific and regulatory communities in the U.S. The MM5 has been used by researchers, meteorologists, and scientists in numerous applications including: weather forecasting; air pollution forecasting; frontogenesis, thunderstorms; hurricanes; urbanscale phenomena, such as urban heat islands and related convective circulations; land-sea breeze circulations; and topographically-induced flows. Though utilized worldwide, the MM5 is mostly used in the United States in both research and forecast/operational modes. The modeling system is comprised of several components collectively referred to as the MM5. The model has been under continuous development since the late 70s and is based on an original formulation (Anthes and Warner, 1978; Anthes *et al.*, 1987) that was developed and maintained by the Pennsylvania State University in collaboration with the National Center for Atmospheric Research. More recently, the model has undergone significant changes and improvements (Dudhia, 1993; Grell *et al.*, 1994).

The UAM and CIT are three-dimensional, Eulerian, photochemical models that are capable of simulating inert and chemically-reactive atmospheric pollutants. These models are used in various urban air shed areas to study the effects of air quality improvement technologies. The UAM and CIT simulate the advection, diffusion, transformation, emission, and deposition of pollutants. They treat about 30 chemical species and uses the carbon bond CB-IV mechanism (Gery *et al.*, 1988). The models account for 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 the L.A. Basin, see Taha (1996, 1997).

Examples of outputs from these simulations are shown in **Figure 30** and **Figure 31**. Figure 30 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%). Figure 31 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.

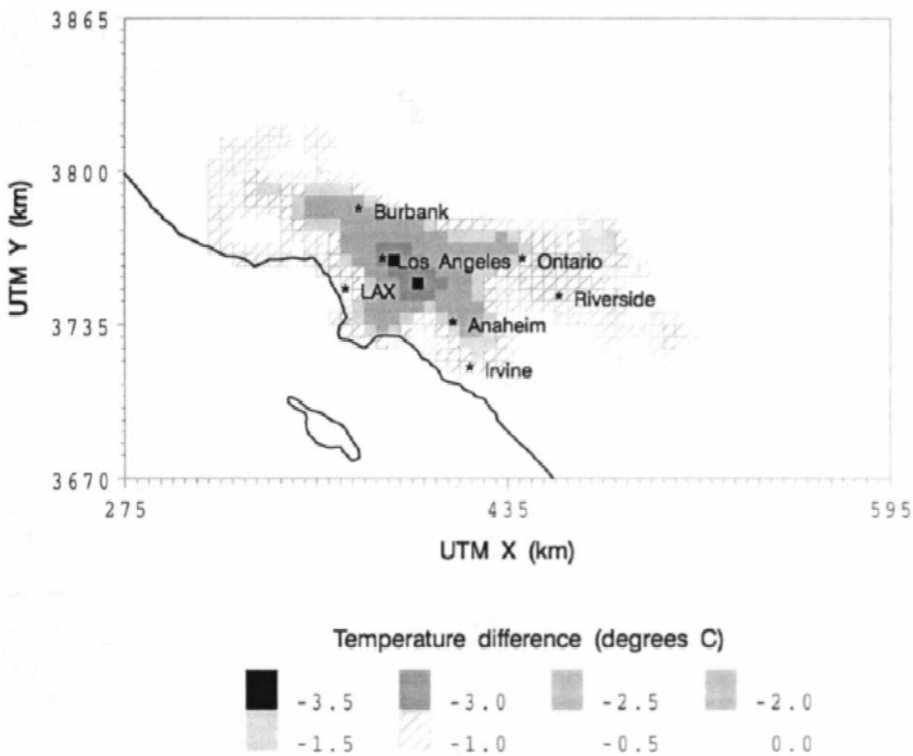


Figure 30. Temperature difference (from the base case) for a case with increased surface albedo and urban forest. The temperature difference is at 2 pm on a late-August day in Los Angeles.

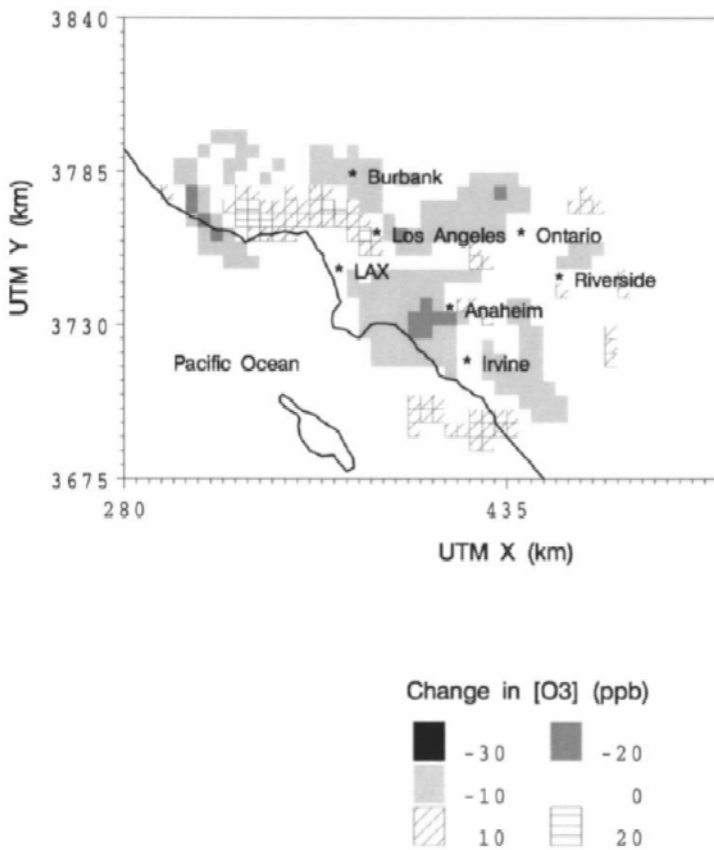


Figure 31. Ozone concentrations difference (from the base case) for a case with increased surface albedo and urban forest. The difference is shown for 2 pm on a late-August day in Los Angeles.

4. Summary and Conclusions

Most urban areas are warmer than their surrounding rural areas. The temperature difference between urban and rural areas is commonly referred to as urban heat islands. With the rapid expansion of cities in the last five decades, heat islands are growing and are affecting the world's ever-increasing urban population. Increasing urban ambient temperatures raise building cooling energy use, worsen the urban air quality, and reduce citizens' comfort. 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. In the United States, it is estimated 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 governmental 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 a more aggressive agenda. Much of the fundamental work to promote heat-island mitigation measures are already in place. The American Society for Testing of Materials (ASTM) has developed standards for measurement of solar reflectance of roofing and pavement materials. The Cool Roof Rating Council (CRRC) has been organized to measure, rate, and label the solar reflectance and thermal emittance of roofing materials. Many industrial leaders have introduced cool roofing materials on the market. In contrast, the development of cost-effective solutions for cool pavement has been very slow. 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 building code, 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 quite notable interest.

Trees can potentially reduce energy consumption in a city and improve air quality and comfort. These potential savings are clearly a function of climate: in hot climates, deciduous trees shading a building can save cooling-energy use, in cold climates, evergreen trees shielding the building from the cold winter wind can save heating-energy use. Trees also improve urban air quality by lowering the ambient temperature and hence reducing the formation of urban smog, and by dry deposition to absorb directly gaseous pollutants and PM10 from the air. Low-emitting trees should be considered in designing a tree-planting program, so that volatile organic compounds emitting trees would not undermine our efforts. Finally, a major cost of a tree-planting program is that associated with planting and maintaining by tree professionals. The cost of water consumption of trees in most climates is small compared to planting and maintenance costs. It is quite possible to design a low-cost tree-planting program that utilizes and employs the full voluntary participation of the population.

Pavements cover a surprisingly large fraction of a city's surface and typically are among the darkest and hottest surfaces. There are well-accepted methods of creating lighter-colored pavements, such as chip-seals using whiter aggregate. The difficulty in implementing cooler pavements is in taking a long-term and city-wide view of the situation. Most often, the decision about pavements is made on the basis of initial cost, without regard for the shortened lifetime of hot pavements or the heat-island effects. When these are taken into account, as in the study by Ting *et al*. (2001) the life-time costs of cooler pavements may be lower for many kinds of roads.

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