Title
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As modern urban areas have grown, there has been a corresponding growth in darker surfaces and a decline in vegetation, affecting urban climate, energy use, and habitability. Dark roofs heat up more and thus raise the summertime cooling demands of buildings, collectively with reduced vegetation, warming the air over urban areas and creating “heat islands.” On a clear summer afternoon, the air temperature in a typical city can be as much as 2.5ºC (4.5ºF) higher than in surrounding rural areas. (The peak heat island effect occurs during cold winter evenings and is caused primarily by the rapid cooling of the rural areas—the thermal storage of pavements and dark-roofed buildings is much greater than greenery.) Peak urban electric demand rises by 2 to 4 percent for each 1ºC (1.8ºF) rise in daily maximum temperature above 15 to 20ºC (59 to 68ºF), so the additional air-conditioning use caused by higher urban air temperature is responsible for 5 to 10 percent of urban peak electric demand, costing U.S. ratepayers several billion dollars annually.

Temperatures in cities are increasing. Figure I depicts summertime monthly maximum and minimum temperatures between 1877 and 1997 in downtown Los Angeles, clearly indicating that these maximum temperatures are now about 2.5ºC (4.5ºF) higher than in 1920. Minimum temperatures are about 4ºC (7.2ºF) higher than in 1880. In California from 1965 to 1989, the average urban-rural temperature differences, measured at thirty-one pairs of urban and rural stations, have increased by about 1ºC (1.8ºF). In Washington, D.C., temperatures rose 2ºC (3.6ºF) between 1871 and 1987. This recent warming trend is typical of most U.S. metropolitan areas and exacerbates demand for energy. In Los Angeles, we estimate a heat-island induced increase in power consumption of 1 to 1.5 GW, costing ratepayers $100 million per year.

Besides increasing systemwide cooling loads, summer heat islands increase smog production. Smog production is a highly temperature-sensitive process. At maximum daily temperatures below 22ºC (71.6ºF), maximum ozone concentration in Los Angeles is below the California standard of 90 parts per billion. At 35ºC (95ºF), practically all days in Los Angeles are smoggy (see Figure 2).

HEAT ISLAND MITIGATION

When sunlight hits an opaque surface, some energy is reflected (this fraction is known at the albedo or reflectivity); the rest is absorbed. Use of high-albedo urban surfaces and planting urban trees are inexpensive measures that reduce summertime temperatures. The effects of planting trees and increasing albedo are both direct and indirect. Planting trees around a building or using reflective materials on roofs or walls has a direct effect: altering the energy balance/cooling requirements of that building. Planting trees and modifying albedo throughout the city has an indirect effect: citywide climate modification. By reducing air temperature, the air conditioning requirements of all buildings are reduced. Planting trees also sequesters atmospheric carbon through photosynthesis. Figure 3 depicts the overall process that impacts energy use and air quality within an urban area.

COOL ROOFS

When dark roofs are heated by the sun, they directly raise summertime building cooling demand. For highly absorptive (low-albedo) roofs, the surface/ambient air temperature difference may be 50ºC (90ºF), while for less absorptive (high-albedo) surfaces with similar insulative properties (e.g., white-coated roofs), the difference is only about IOºC (18ºF), which means that "cool" surfaces can effectively reduce cooling-energy use. For example, a high-albedo roof coating on a house in Sacramento, California, yielded seasonal savings of 2.2 kWh/day (80% of base-case use), and peak-demand reductions of 0.6 kW (about 25% of base-case demand). Field studies of nine homes in Florida before and after applying high-albedo coatings to their roofs 'elded an air-conditioning energy-use reduction of 10 to 43 percent, saving on average 7.4 kWh/day (19º/o). The peak-demand reduction at 5:00 P.m. was 0.2 to 1.0 kW, an average of 0.4 kW (22%).

Researchers have simulated the impact of the urbanwide application of reflective roofs on cooling-energy use and smog in the Los Angeles Basin. They estimate that roof albedos can realistically be raised by 0.30 on average, resulting in a 2ºC (3.6ºF) cooling at 3:00 P.m. on a sunny August day. This temperature reduction significantly reduces building cooling-energy use further. The annual electricity savings in Los Angeles are worth an estimated $21 million. Cooling the air also results in a 10 to 20 percent reduction in population-weighted exposure to smog.

Other benefits of light-colored roofs include a potential increase in their useful life. The daily temperature fluctuation and concomitant expansion/contraction of a light-colored roof is less than that of a dark one. Also, materials degradation because of absorption of ultra-violet light is temperature-dependent. Thus, cooler roofs may last longer than hot roofs of the same material. Cool roofs incur no additional cost if color changes are incorporated into routine reroofing and resurfacing schedules.

URBAN TREES

The beneficial effects of trees are also both direct and indirect: shading of buildings and ambient cooling. Their shade intercepts sunlight before it warms buildings, and their evapotranspiration cools the air. In winter, trees shield buildings from cold winds. Urban shade trees offer significant benefits by reducing building air conditioning, lowering air temperature, and thus improving urban air quality (reducing smog). Over a tree's life, savings associated with these benefits vary by climate region and can be up to $200 per tree. The cost of planting and maintaining trees can vary from $10 to $500 per tree. Tree planting programs can be low-cost, offering a good return on investments for communities.

Data on energy savings from urban trees are rare but impressive. In one experiment, the cooling-energy consumption of a temporary building in Florida was cut by up to 50 percent after adding trees and shrubs. Cooling-energy savings from shade trees in two houses in Sacramento were about 30 percent, corresponding to average savings of 3.6 to 4.8 kWh/day.

Simulations of the meteorological and energy impact of large-scale tree-planting programs in ten U.S. metropolitan areas show that on average trees can cool cities by about 0.30ºC to 1.OOC (0.5ºF to 1.80ºF) at 2:00 P.m. The corresponding annual air-conditioning savings from ambient cooling by trees in hot climates range from $5 to $10 per 10OM^2 Of roof area of residential and commercial buildings. Indirect effects are smaller than direct shading, and, moreover, require that the entire city be planted. There are other benefits associated with urban trees. These include improvement in life quality; increased property values; and decreased rain run-off and hence flood protection. Trees also directly sequester atmospheric $C0_2$, but the direct sequestration Of $C0_2$ is less than one-fourth of the emission reduction from savings in cooling-energy use.

COOL PAVEMENTS

Urban pavements are made predominantly of asphalt concrete. The advantages of this smooth and all-weather surface for vehicles are obvious, but some associated problems are perhaps not so well appreciated. Dark asphalt surfaces produce increased heating by sunlight. Experimentally, the albedo of a fresh asphalt concrete pavement is only 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 0.15 for ordinary aggregate. If a reflective aggregate is used, the longterm albedo can approach that of the aggregate.

The benefits of cool pavements can be estimated by first finding the temperature decrease resulting from resurfacing a city with more reflective paving materials. Cool pavements provide only indirect effects through lowered ambient temperatures. Lower temperature has two effects: (1) reduced demand for electricity for air conditioning and (2) decreased smog production.

Furthermore, the temperature of a pavement affects its performance: cooler pavements last longer. Reflectivity of pavements is also a safety factor in visibility at night and in wet weather, reducing electric street-lighting demand. Street lighting is more effective if pavements are more reflective, increasing safety. In reply to concerns that in time dirt will darken light-colored pavements, experience with cement concrete roads suggests that the light color of the pavement persists after long usage.

SUMMARY

Cool surfaces (cool roofs and cool pavements) and urban trees can reduce urban air temperature and hence can reduce cooling-energy use and smog. A thorough analysis for Los Angeles (see Table 1) showed that a full implementation of heat island mitigation measures can achieve savings of more than $500 million per year. Extrapolating those results, we estimate that national cooling demand can be decreased by 20 percent. This equals 40 TWyear savings, worth over $4 billion a year by 2015 in cooling-electricity savings alone. If smog reduction benefits are included, savings could total to over $10 billion a year.

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See also: Air Conditioning; Air Pollution; Atmosphere; Climatic Effects; District Heating and Cooling; Domestic Energy Use; Efficiency of Energy Use; Energy Economics; Environmental Economics; Environmental Problems and Energy Use; Geography and Energy Use.

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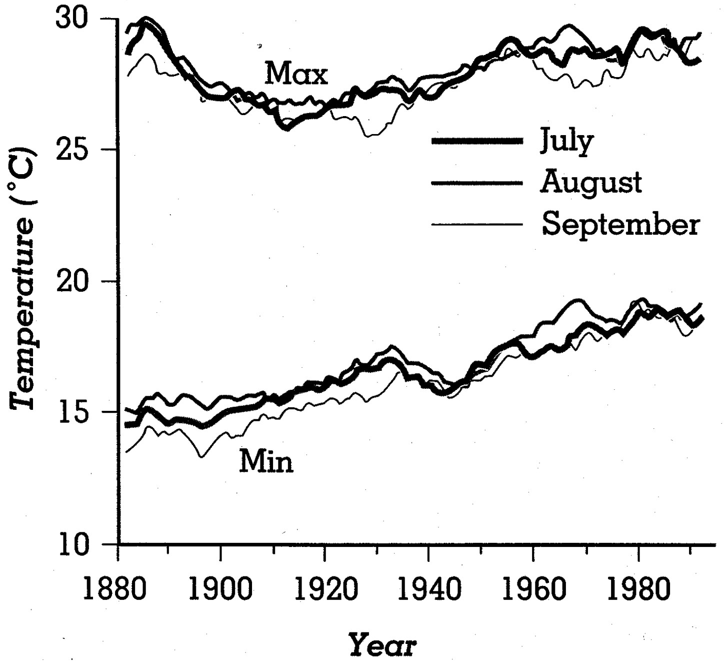

Figure 1.
Ten-year running average summertime monthly maximum and minimum temperatures in Los Angeles, California (1877–1997). The average is calculated as the average temperature of the previous four years, the current year, and the next five years. Note that the maximum temperatures have increased about 2.5°C (4.5°F) since 1920.

	Measures			
Benefits	***Cooler roofs***	***Trees***	***Cooler pvmnts***	***Totals***
1. Direct				
a A/C energy savings (M$/yr)	**46**	**58**	**0**	**104**
b Δ *Peak power (GW)*	*0.4*	*0.6*	*0*	*1.0*
c Present value ($)	153	64	0	
2. Indirect				
a A/C energy savings of 3°C cooler air (M$/yr)	**21**	**35**	**15**	**71**
b Δ *Peak power (GW)*	*0.2*	*0.3*	*0.1*	*0.6*
c Present value ($)	25	24	18	
3. Smog				
a 12% ozone reduction (M$/yr)	**104**	**180**	**76**	**360**
b Present value ($)	125	123	91	
4. Total				
a All above benefits (M$/yr)	**171**	**273**	**91**	**535**
b *Total* Δ *peak power (GW)*	*0.6*	*0.9*	*0.1*	*1.6*
c Total present value ($)	303	211	109	

Table 1.

Energy, Ozone Benefits, and Avoided Peak Power of Cooler Roofs, Pavements, and Trees in Los Angeles Basin

NOTE: The present value and surcost data for surfaces are calculated for 100 m^2 of roof or pavement area, and for one tree.

SOURCE: Rosenfeld et al., 1998.

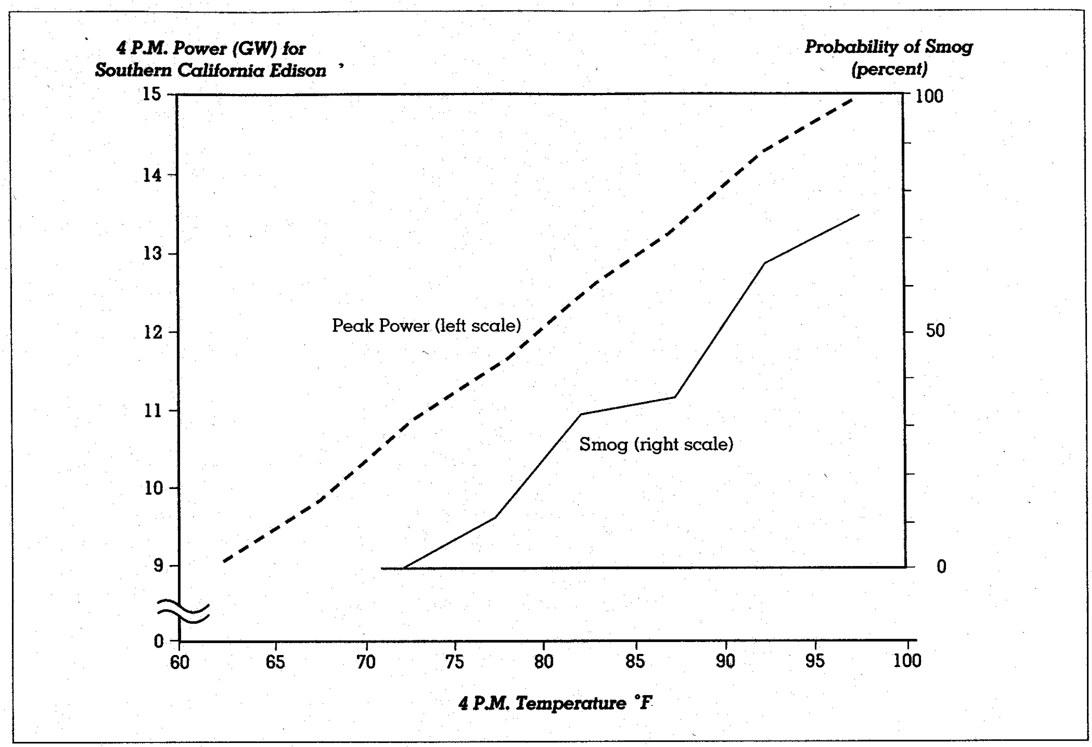

Figure 2.
Ozone levels and peak power for Southern California Edison versus 4 P.M. temperature in Los Angeles as a predictor of smog.

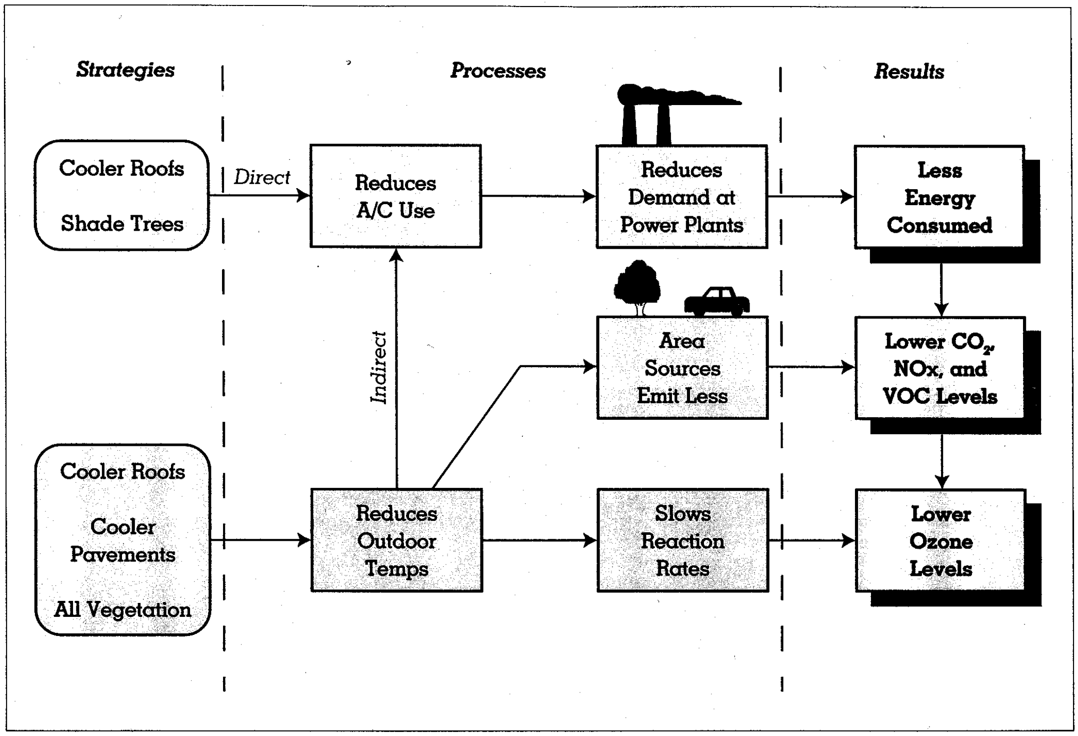

Figure 3.
Methodology to analyze the impact of shade trees, cool roofs, and cool pavements on energy use and air quality (smog).