THE IMPACT OF SUMMER HEAT ISLANDS ON COOLING ENERGY CONSUMPTION AND CO_2 EMISSIONS

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ABSTRACT

It has been well documented that summer heat islands increase the demand for air conditioning. Several studies have suggested developing guidelines to mitigate this negative effect, on both micro- and meso-scales. Reducing summer heat islands saves cooling energy, reduces peak demand, and reduces the emission of CO_2 from electric power plants. This paper summarizes some of our efforts to **quantify** the effects of techniques to reduce heat islands. In particular, we summarize simulations we have made on the effects of planting trees and switching to light colored surfaces in cities. Our results indicate that these techniques effectively reduce building cooling loads and peak power in selected U.S. cities, and are the cheapest way to save energy and reduce CO_2 emissions.

This paper compares the economics of technologies to mitigate summer heat islands with other types of conservation measures. We estimate the cost of energy conserved by planting trees and recoating surfaces on a national level and compare it with the cost of energy conserved by increasing efficiencies in electrical appliances and cars. Early results indicate that the cost of energy saved by controlling heat islands is less than 1¢/kWh, more attractive than efficient electric appliances (~2¢/kWh), and far more attractive than new electric supplies (~10¢/kWh). In transportation, the cost of conserving a gallon of gasoline, though far more attractive than buying gasoline at current prices, is again more expensive than controlling heat islands. By accounting for the carbon content of the fuels used for power generation and transportation, we restate these comparisons in terms of cents per avoided pound of carbon emitted as CO_2. Our results show that the cost of avoided CO_2 from planting trees/increasing albedo is about 0.3-1.3¢/lb. of carbon; for buying efficient electric appliances, 2.5¢/lb. of carbon; and for efficient cars, 10¢/lb. of carbon.

KEYWORDS: Air Conditioning, Cooling, Energy Conservation, Environment, Global CO_2 Control, Heat Islands, Modeling, Peak Power Demand, Commercial, Residential, Shading, Albedo, Policy, Vegetation, Evapotranspiration

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INTRODUCTION

Long before mechanical air conditioning, people cooled their homes in the summer by surrounding them with trees and painting the walls and roofs white. The lack of such practices in many urban areas contributes to summer "heat islands" with a typical daily average intensity of 3-5 °C. Several studies have suggested developing guidelines to mitigate this negative effect, on both micro- and meso-scales (Landsberg, 1978; Thurow, 1983).

In this paper, we discuss the use of urban trees and light-colored surfaces as cheap, city-wide energy conservation strategies. Trees improve the urban climate and, by shading, evapotranspiration, and wind shielding, reduce summer cooling energy use in buildings at only about 1% of the cost of the avoided power plants and air-conditioning equipment. Using light-colored paints and surfacing the asphalt of streets and parking lots with light-color sand are equally effective means to reduce summer air conditioning electricity use.

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

World energy use is the main contributor to atmospheric CO_2. In 1987, the people of the world burned some 300 quadrillion Btus ('quads') of fuel, releasing 5.4 billion tons of carbon into the atmosphere, 2 to 5 times the amount contributed by deforestation (Brown et al., 1988). Increasing use of fossil fuel and deforestation together have raised atmospheric CO_2 concentration some 24% over the last 150 years. According to models of global climate 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. Since the first OPEC embargo in 1973 and the oil price shocks in 1979, increased energy awareness have led to conservation efforts and leveling of energy consumption in the industrialized countries. U.S. energy use remained at 74 quads/year from 1973 to 1986, although it grew by 1.7 quads in 1987 (Rosenfeld, 1987). An important byproduct of this reduced energy use is a lowering of CO_2 emissions.

Although we are not yet to the point of offering specific guidelines, our preliminary calculations indicate that heat island mitigation strategies such as urban trees and light-colored surfaces are attractive conservation measures that can save 0.5 quad per year with a payback time of 0.3 to 1.8 years, and decrease CO_2 emissions by about 20 million tons of carbon per year.

DIRECT AND INDIRECT EFFECTS OF MODIFYING THE URBAN ENVIRONMENT

The effects of modifying the urban environment, planting trees and increasing albedos, are best quantified in terms of direct and indirect contributions. The **direct** effect of planting trees around a building or painting its surfaces a light color is to alter the energy balance and cooling requirements of that particular building. However, when trees are planted and albedos modified throughout an entire city, the energy balance of the whole city is modified, producing city-wide changes in climate. Phenomena associated with the city-wide changes are referred to as **indirect** effects. The energy use of an individual building is indirectly affected by the changes made throughout the city.

An important reason for making the distinction between direct and indirect effects is that while direct effects are well recognized and can be well accounted for in present models of building energy use, indirect effects have received much less recognition. Methods of accounting for indirect effects have not been as well developed and remain comparatively much less certain. Understanding these effects and incorporating them into accounts of building use is the focus of our current research. It is worth noting that the phenomenon of summer urban heat islands is itself the consequence of inadvertent indirect effects of the built environment. We are proposing using the same principles to create cooler cities.

The issue of direct and indirect effects also enters into our discussions of atmospheric CO_2. Planting trees has a direct effect of reducing atmospheric CO_2 because each individual tree, during its lifetime, directly sequesters carbon from the atmosphere. However, planting trees in cities also has a secondary (indirect) effect on CO_2. By reducing the demand for cooling energy, urban trees indirectly reduce emission of CO_2 from power plants. As we shall discuss, the amount of CO_2 avoided through the secondary effects of trees is considerably greater than the amount sequestered directly.

URBAN TREES AS AN ENERGY CONSERVATION STRATEGY

In addition to their aesthetic value, urban trees can modify the climate of a city and reduce building cooling energy use. Individually, urban trees act as shading and wind-shielding elements modifying the conditions around an adjacent building. Significant increases in the number of urban trees can alter the heat balance of the entire city, moderating the intensity of the urban heat island.

Case studies (Laechelt and Williams, 1976; Buffington, 1979) have documented dramatic differences in cooling energy use between houses on landscaped and unlandscaped sites. In particular, researchers at Florida International University (Parker, 1981) measured cooling savings resulting from well planned landscaping and found that properly located trees and shrubs reduced daily air conditioning electricity use by as much as 50%.

Trees affect energy use in buildings through direct processes such as (1) reducing solar heat gain through windows, walls, and roofs by shading, (2) reducing the radiant heat gain from surroundings by shading, and (3) reducing infiltration by protecting a particular building. When properly placed around a building, trees can prevent unwanted solar radiation from striking the building and reduce its cooling energy use. Deciduous trees are particularly beneficial because they allow solar gain in buildings during the winter and block it during the summer. Acting as wind breaks, trees also lower wind speeds, which may reduce or increase a building's cooling energy use depending on outdoor conditions.

The indirect effects include (1) reducing the outside air infiltration rate by increasing the city surface roughness and lowering ambient wind speeds, (2) reducing the heat gain into the buildings by lowering summer ambient temperatures through **evapotranspiration** (the evaporation of water from vegetation), and (3) in some cases, increasing latent air conditioning load by adding moisture to the air through evapotranspiration. 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. The effect of evapotranspiration is minimal in winter because of lower ambient temperatures and the absence of leaves on deciduous trees. A significant increase in urban trees, increasing evapotranspiration during the summer, can produce an "oasis effect" and significantly lower urban ambient temperatures. Buildings in cooler environments will consume less cooling power and energy, although, in some cases, the amount of latent cooling, i.e. humidity removal, might be slightly increased.

ALBEDO AS AN ENERGY CONSERVATION STRATEGY

The energy balance of a building or an entire city depends on the net radiation reflected from its surface. To describe this dependence, one uses the property **albedo**. Whereas the reflectance of a surface depends on the frequency of the radiation incident upon it, albedo refers to the reflectivity of a surface averaged over the entire solar spectrum. An albedo of 1.0 corresponds to a surface that completely reflects, while an albedo of 0.0 refers to one that completely absorbs all incident radiation. The albedo of an individual building can be modified to achieve direct savings: a lighter building reflects more solar radiation and stays cooler. The albedo of an entire city can be modified to achieve indirect savings by changing city-wide temperatures.

In nature, albedos of different surfaces range from extremes of 0.90 (reflective white) to 0.05 (dark black). Most buildings and cities have albedos in the range of 0.20-0.35, although these values can differ depending on characteristics of the surfaces. Traditional cities of white-washed buildings found in hot climates have albedos in the range of 0.30-0.45 (Taha et al., 1988). Reflective roof membranes and the popular "solar control" glazings of commercial buildings both have albedos of up to 0.8. There is a practical constraint in the maximum achievable urban albedo if this strategy is used in conjunction with increased urban vegetation, since a dense urban tree canopy will cover a large amount of the surface area (the albedo of trees is ~0.25). We have estimated an upper limit of 0.40 for the albedo of a highly-vegetated city with light-colored surfaces.

In practice, using albedo as an energy conservation strategy requires a good understanding of the local climate. In a given location, one needs to be concerned with the impact of albedo on both cooling and heating energy use. Although in general, an effective strategy is to increase the albedo in hot climates to decrease cooling loads, and to decrease the albedo in cold climates to reduce heating loads.

ENERGY SAVINGS

In previous papers (Akbari et al., 1986; Huang et al., 1987; Taha et al., 1988), we analyzed the potential energy and power savings resulting from the use of urban trees and albedo. An analysis of savings was made for both direct and indirect contributions for a number of U.S. cities.

Direct effects were modeled using DOE-2.1C, a computer model for building energy analysis. The effect of trees was modeled by increasing building shade and reducing local wind speeds. To simulate a 30% increase in cover, three trees (one south, two west) were added around each house. The effect of varying foliage density of deciduous trees was accounted for. The reduction in wind speed within the canopy was simulated based on tree cover, where we used an empirical formula derived for vegetated suburban houses in Davis, CA (McGinn, 1982). Although in these studies wind was modeled as an indirect effect, the distinction between direct and indirect effects of wind is inexact, and, for convenience, in this paper we have assumed it to be a direct effect only. The direct effect of albedo was modeled by changing the absorptivity of the building shell, thus affecting the external surface temperature and the conductive heat gain.

The ability of DOE-2.1C to accurately model the direct effects of shading, absorptivity, and infiltration is well recognized. We believe the simulations we have done to be accurate representations of effects nation-wide. However, modeling city-wide climate variations due to trees and albedo is less certain. Our quantifications of indirect effect are preliminary and our methods deserve further discussion.

Indirect effects were simulated using models of urban climate which quantified the impact of trees on wind speed, temperature, and humidity (Huang et al., 1987) and the impact of albedo on ambient dry bulb temperature (Taha et al., 1988). The modifications in ambient conditions were input to DOE-2.1C to simulate the modified building energy and power consumption.

To simulate the effects of evapotranspiration, the amount of water released to the atmosphere was first computed based on meteorological conditions and canopy characteristics. The water vapor was then mixed in an atmospheric volume determined by the dimensions of the city and the time-varying mixing height above it. The depression in dry-bulb temperature and increase in specific humidity were obtained assuming uniform mixing of the water vapor within the volume.

The indirect effects of albedo were simulated with a one-dimensional model of the urban boundary layer, where the energy balance state at the urban surface accounted for representative values of surface albedo. The albedo values used were obtained from spatially averaging the albedos of the major surface components in the urban area. The indirect effect of trees was to reduce the ambient temperature and increase the local humidity. Temperature reduction was beneficial, while the increase in humidity added to the cooling loads of buildings. The combination of these effects was fully accounted for in the building energy analysis. In the warm cities we have selected, the indirect effect of increasing albedo was to reduce the urban ambient temperature, so that the building was actually simulated in a cooler microclimate.

Since the indirect effects of albedo modifications were simulated one-dimensionally, our calculations implicitly assumed that the increased albedo would affect the urban temperature but not the radiative budget at the building site (Taha et al., 1988). In other words, the geometry of reflection is not accounted for, nor does the reflected radiation have any effect on surrounding windows or surfaces. Although higher albedos could increase the net heat gain through fenestration because of the increase in reflected radiation, this is not accounted for in our model. In the real world, some design considerations would be necessary to avoid this problem. The re-orientation of windows as well as the careful design of shades would be important. Urban trees could be so located as to block the reflected energy from neighboring buildings. If only the roof surfaces of the houses were whitewashed, the problems of glare and increased heat gain through windows would not exist at all. Finally, we should note that the indirect effects of trees (evapotranspiration) and albedo (temperature depression) have so far been simulated independently. There is now no account for feedback effects which could be significant, since trees may decrease the local albedo and the lower temperature (resulting from higher albedos) may in turn decrease evapotranspiration. This combination of these effects will be accounted for in the near future.

Table I gives the incremental savings in cooling energy and peak power resulting from the direct effects of increased urban tree cover and albedo. The results are shown for both the 1973 housing stocks and newer 1980 houses. The 1973 stock is representative of leaky and poorly insulated housing, while the 1980 homes are tight and well insulated. The 'Base' column in each case represents the base case for a building with normal albedo (30%) and no surrounding trees. The 'Trees' column gives the effects of a 30% increase in tree cover (3 trees) and is broken down into effects of increased shading alone, wind reduction alone, and combined wind and shading effects. It can be seen that by reducing heat gain, shading always reduces cooling loads. The effects of wind reduction, on the other hand, can be beneficial or detrimental depending on outdoor conditions. In the 1973 houses, with relatively high infiltration and conductive heat gains, ventilation is useful in removing the built-up indoor heat. Therefore, reducing wind speed would result in increased cooling energy and power. In the better insulated 1980 houses, infiltration is proportionally significant than conduction, therefore reducing wind speed reduces the cooling peak power. But similar to the 1973 stock, reducing wind speed increases the cooling hours. The 'Albedo' column shows the direct effect of increasing the house albedo to 70%. This is the effect of albedo alone, and it is positive in all the cases. Finally, the 'Combined' column gives the effect of combining the higher albedo with a 30% increase in tree cover. All entries other than those in the 'Base' column represent percent savings.

We are uncomfortable with the surprisingly large negative impacts of wind reduction on cooling energy consumption. Reducing wind affects building cooling energy use by 1) increasing the building envelope's surface temperature (hence increasing the conductive gains), 2) reducing infiltration, and 3) changing the ventilation schedules currently used in our simulations. We are investigating the negative contribution of these three factors. At this time, we believe that the ventilation schedules, which are to some degree arbitrary and can be easily modified, has the largest negative impact on the cooling energy consumption. However, for estimating the conservation potential of trees, we have used the current conservative savings as shown in **Table I.**

Table I. **Direct savings in cooling energy and peak power resulting from planting trees and whitewashing buildings.** All columns, except the bases, are in percent (Δ%) relative to basecases. Symbols "s", "w", and "a" stand for shading, wind, and albedo, respectively. The tree cover was increased by 30% with respect to the base case, whereas albedo was increased from 30% to 70%. Note the large negative impact of wind reduction (column "w") that is mainly the result of our modeling of ventilative cooling. We have kept these conservative estimates for calculating the national savings. For further discussion, see the text.

Location	1973 Houses (leaky and low-insulation)						1980 Houses (tight and high-insulation)					
		Trees			Albedo	Combined		Trees			Albedo	Combined
	Base	s (Δ%)	w (Δ%)	s+w (Δ%)	a (Δ%)	a+s+w (Δ%)	Base	s (Δ%)	w (Δ%)	s+w (Δ%)	a (Δ%)	a+s+w (Δ%)
Chicago IL	1400 ft^2						2000 ft^2					
Peak kW	3.60	19.4	-2.5	16.9	5.8	23.6	3.20	21.0	2.8	23.8	5.3	29.1
Annual kWh	2584.0	29.7	-26.6	3.11	14.8	19.9	1888.0	30.9	-22.8	8.1	12.8	21.6
Miami FL	1400 ft^2						1600 ft^2					
Peak kW	5.42	7.0	-9.2	-2.2	20.5	25.3	3.29	14.0	3.0	17.0	6.3	23.4
Annual kWh	13623.0	15.8	-19.3	-3.5	18.6	22.5	8730.0	14.8	-5.6	9.2	7.4	16.5
Minneapolis MN	1400 ft^2						2000 ft^2					
Peak kW	3.14	23.9	-1.9	22.0	3.5	27.1	2.65	29.1	0.0	29.11	4.1	31.7
Annual kWh	1916.0	27.3	-18.9	8.4	11.3	20.2	1325.0	36.6	-22.1	14.5	11.1	22.6
Phoenix AZ	1400 ft^2						1600 ft^2					
Peak kW	7.56	12.6	2.7	15.3	7.8	26.2	5.18	11.4	11.2	22.6	5.8	31.1
Annual kWh	13117.0	15.9	-12.0	3.9	12.9	19.8	7789.0	15.0	-8.9	6.1	8.9	17.3
Pittsburgh PA	1600 ft^2						1600 ft^2					
Peak kW	3.50	26.8	-12.2	14.6	13.7	24.9	2.36	27.5	-9.7	17.8	9.3	23.3
Annual kWh	1821.0	34.0	-35.5	-1.5	19.1	23.3	1177.0	33.1	-28.8	4.3	12.0	20.1
Sacramento CA	1400 ft^2						1600 ft^2					
Peak kW	5.40	19.7	-10.1	9.6	13.3	25.4	3.85	16.7	0.2	16.9	7.5	26.0
Annual kWh	3767.0	34.6	-36.8	-2.2	22.3	28.3	2372.0	29.3	-21.5	7.8	11.5	23.8
Washington DC	2000 ft^2						2200 ft^2					
Peak kW	5.80	17.4	1.7	19.1	10.5	30.3	3.98	19.1	6.0	25.1	6.7	29.4
Annual kWh	4358.0	25.7	-21.8	3.9	16.4	22.7	2790.0	26.6	-15.5	11.1	10.6	20.0
Average												
Peak kW						26.3						28.0
Annual kWh						21.9						18.6

Table II summarizes our earlier work of indirect savings of cooling energy and peak power. These data represent percent savings in addition to savings which result from direct effects. For the cities modeled, the effect of an additional 3 trees results in approximately 30% savings in annual cooling energy and approximately 15-20% annual savings in peak cooling power. The indirect effects of albedo were quantified for Sacramento, CA for only four days in July. During these days, simulations showed that by increasing the albedo of the surroundings from 0.25 to 0.40, the cooling energy was reduced by 45% and peak power by 21%, suggesting that for a residential building the potential savings from albedo and vegetation are roughly equivalent.

Table II. **Indirect savings** in cooling energy use and peak cooling power for single story prototype houses. Canopy savings are annual figures. Albedo savings are for the period from July 9 to July 12 only. (All entries are indirect effects, additional to direct effects)

	Urban canopy density increased by 3 trees/house*	Albedo of house and surrounding increased**
Location	Percent energy savings	Percent energy savings
Sacramento CA		
Annual kWh	37	45†
Peak kW	23	21
Phoenix AZ		
Annual kWh	27	--
Peak kW	12	--
Lake Charles LA		
Annual kWh	31	--
Peak kW	15	--
Los Angeles CA (LAX)‡		
Annual kWh	~0	--
Peak kW	32	--

* Data from Huang et al., 1987. Assumes an increase of 3 trees per house.

** Data estimated from Taha et al., 1988. Assumes an increase from 0.25 to 0.40 in the albedo of the surroundings.

† Canopy savings are annual savings. Albedo savings for the period from July 9 to July 12.

‡ LAX is on the Pacific Ocean.

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

QUANTIFICATION OF NATIONAL ENERGY SAVINGS

Total Cooling Energy Use In the U.S.

Of the 86 million households in the U.S., 51 million have air conditioners (room and central) which use an average of 2000 kWh per year (EIA, 1984); so total usage is about 100 billion kWh or 1.2 quads of source energy per year. In the U.S. in 1987 commercial buildings used 670 billion kWh of electricity (EIA, 1987), of which, approximately 20% was used for cooling. This corresponds to a total cooling energy use of about 130 billion kWh or 1.5 quads of source energy per year. Together, residential and commercial cooling uses 2.7 quads of source energy per year, which is worth at least $23 billion[1].

Direct Savings

We will assume that tree planting and albedo modification can be applied to 50% of the 51 million air conditioned houses. These measures cannot be applied to all houses with air conditioners since tree density may already be high (especially in older cities). Increase in tree cover and/or albedo modification may also not be acceptable by all municipalities, and some areas may not have a significant cooling load. We will also assume that half of the commercial building stock of 4 million buildings is small enough to be directly affected by shading and albedo modification.

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

Indirect Savings (Heat Island Effects)

Our preliminary results quantifying indirect effects (See **Table II**) suggest that tree planting and albedo modification save at least 20% of residential cooling energy use (0.23 quad). Because small commercial buildings are less sensitive to outdoor temperature than residential houses we expect only a 12% savings in small commercial cooling energy use (0.09 quad) due to indirect effects. By reducing temperatures throughout the city, these measures also decrease cooling energy use in large commercial buildings by increasing system efficiency and economizer operating hours. We estimate this would save 5% or an additional 0.04 quad. **Table III** summarizes the estimated savings due to direct and indirect effects on residential and commercial cooling.

CARBON DIOXIDE AND CONSERVATION

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

About half of the savings from the combination of the direct and indirect effects shown in **Table III** would result from the planting of 100 million urban trees. This savings of 0.25 quads (22 billion kWh) corresponds to a savings of 9 million tons of carbon. Since forest trees sequester carbon at the rate of ~6.5 tons per hectare (Brown et al., 1988) and there are ~1000 trees per hectare, each tree directly sequesters ~13 lb. carbon per year. Therefore, 100 million trees will directly sequester 0.65 million tons of carbon, or one fifteenth of that saved through their reduction in cooling energy use. Another way of looking at this is that to directly sequester the amount of carbon saved by the planting of 100 million urban trees would require the planting of 1.5 billion forest trees corresponding to 1.5 million hectares of forest (Total area of Connecticut is about 1.3 million hectares.)

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

Table III. **Yearly savings** (by 100 million trees) of primary energy used for air conditioning in the U.S. and consequent reductions in released carbon*.

	Residential **			Small Commercial †			Large Commercial ‡			Total	
	(%)	Energy (10^{15} Btu)	Carbon (M Tons)	(%)	Energy (10^{15} Btu)	Carbon (M Tons)	(%)	Energy (10^{15} Btu)	Carbon (M Tons)	Energy (10^{15} Btu)	Carbon (M Tons)
Direct Savings	10	0.12	4	4	0.03	1	0	0.0	0	0.15	5
Indirect Savings	20	0.23	8	12	0.09	3	5	0.04	1	0.36	12
Total	30	0.35	12	16	0.12	4	5	0.03	1	0.51	18

* Production of carbon (as CO_2) from a peak power plant assumes 11,600 Btu/kWh sold, and ~14,500 Btu/lb. of carbon.
** **Residential.** US annual residential cooling electricity use is ~100 BkWh/yr, corresponding to 1.2 quads. We assumed 3 trees (plus light surfaces) for 50% of our 50 million air conditioned homes, so 75 million trees (plus light surfaces).
† **Small Commercial.** US uses 65 BkWh (= 0.75 quad). We assumed 30% coverage by trees (25 million more trees).
‡ **Large Commercial.** US uses 65 BkWh (= 0.75 quad). We assumed no additional trees.

THE COST OF CONSERVED ENERGY AND CARBON

Since all energy conservation measures that reduce fossil fuel use also reduce carbon emissions, the savings shown in **Table III** should be compared to other conservation strategies in terms of economic attractiveness (**Table IV**). For example, the trend to more efficient electric appliances yields a cost of conserved energy (CCE) of about 2¢ per kWh saved. Using the value of 0.8 lb. of carbon (in the form of CO_2) for each kWh generated calculated in the previous section, we can compute the cost of conserved carbon (CCC) from more efficient electric appliances at 2.5¢/lb. C. Another conservation strategy is improving efficiency in automobiles. The cost of conserved carbon in going from an automobile that gets 26 mpg to one that gets 36 mpg is 10¢/lb. C. Both these measures are effective and proven, but they are much more expensive than urban trees and light-colored cities.

Table IV shows that increased tree planting and white surfaces have an approximate CCE of about 0.2 - 1.0¢/kWh, and an approximate CCC of about 0.3 - 1.3¢/lb. of C. This is as much as ten times cheaper than either of the examples mentioned above. The point of the comparison is not to discredit the other conservation strategies, which are effective and proven, but to suggest that planting urban trees and modifying urban albedos seems attractive, and definitely worth investigating.

Table IV. Cost effectiveness, energy savings, and carbon savings of urban trees/light surfaces, efficient electric appliances, and efficient cars.

Measure	CCE* (¢/kWh) or (¢/gal)	Payback Time (yr)	CCC* (¢/lb C)	Implemented Fraction (%)	ΔUEC* by 2000 (%)	ΔE (Quad/yr)	ΔC (M Tons/yr)	Cost of Program* ($B)
Urban Trees/ Light Surfaces**	0.2-1.0	0.3-1.8	0.3-1.3	50	19	0.51	18	0.5-2.5
Efficient Electric Appliances†	2	3	2.5	100	17	0.6	21	10
Efficient Cars‡	50	2.5	10	100	38	2.8	50	50

*** Headings Defined**
a) CCE is Cost of Conserved Energy, CCC is Cost of Conserved Carbon, and UEC is Unit Energy Consumption.
b) Program cost is the nation-wide cost for implementing the measure.

**** Urban Trees/Light Surfaces**
a) To estimate the CCE and CCC, we assumed that 100 M trees (Table III) cost $5-25 each (including their water consumption for two years) for a total cost of $B 0.5 to 2.5. The real interest rate is assumed 7%. We would plant 3 seedlings per air conditioned house, and it takes about 10 years for seedling to yield adequate shade.
b) In calculating CCC, we assumed that electricity is produced from peak power plants at 1 kWh = 11,600 Btu = ~ 0.8 lb of carbon.
c) ΔUEC for air conditioning is the sum of direct and indirect effects of urban trees/white surfaces for both residential and commercial sectors.

† Appliances
All entries for this row are based on information provided by H. S. Geller, "Energy and Economical Savings from National Appliance Energy Standards," ACEEE, March 1987.

‡ Cars
The entries for this row are based M. Ross article "Road Vehicles and Petroleum Use in the US to Year 2000," ACEEE, draft, Aug. 1987.
a) The fleet average is assumed to improve from 26 to 36 mpg.
b) The CCE for improving the efficiency of cars from 26 to 36 mpg is estimated to be 50¢/gal.
c) The CCC assumes 5 lb of carbon in a gallon of gasoline.
d) Today, at 18.6 mpg, we use 6.63 Mbod of transportation gasoline. The 26 mpg standard will reduce this 6.63 to 4.75 Mbod. Further gain from 26 to 36 mpg will reduce 4.75 to 3.42, saving of 1.33 Mbod, corresponding to 2.8 Quads.
e) Program cost is based on 125 million cars and light trucks at an additional cost of $400 each.

IMPLEMENTATION

Tree Planting

An estimate of the costs for a large-scale urban tree planting program can be derived by examining a recent experience in Los Angeles, CA. A vigorous tree-planting program was undertaken by Los Angeles in 1983 to beautify the city by planting a million trees before the 1984 Olympic games. This effort was spearheaded by the Tree People (Tree People, 1983). A large lumber company supplied 600,000 drought-resistant seedling pines in containers, which were distributed by a fast food chain restaurant, along with postcards to be returned when the seedlings were planted. Schools and neighborhood groups also planted trees, and undertook to water them for the first two years, after which they can survive on their own. Later in the program, distributors gave out more coniferous and deciduous, smog and drought tolerant native tree species.

The weak point of the project was its follow-up. Although more than a million seedlings and trees were distributed or planted, it is not known what fraction survived. The strong point of the project was its low cost. Less than $1 million was spent, mainly for printing and advertising, which translates to a cost per seedling of only $1. In this paper, we assume, conservatively, that a seedling or a young tree can be planted and brought to maturity in a city for $5 to $25.

There are already millions of urban trees, and there is much literature on urban forestry, e.g. annual Proceedings of the US National Urban Forestry Conferences (American Forestry Association, 1986), publications of the International Society of Arboriculture, and various books (Miller, 1988; Harris, 1983; Johnson et al., 1982; Grey and Deneke, 1978). In addition to the planting costs, there are potential problems associated with increased numbers of urban trees. Akbari et al. (1987) discuss some potential conflicts between a tree campaign and urban infrastructure.

A careful selection of species and the determination of a safe proximity to buildings, power lines, and so forth can largely eliminate many common problems. Attention to soil type when planting trees next to existing structures will help avoid problems associated with the roots causing changes in moisture content of shrinkable clay soils, resulting in foundation movement and possible structural damage to buildings.

In addition to the above concerns, attention must be paid to the costs for planting, watering, and maintaining trees. In arid environments, there may be a direct conflict between planting trees to reduce energy consumption and the lack or cost of water. It may be possible to overcome this conflict to some extent by using drought-tolerant species that are well adapted to the environment. However, trees that evaporate less water will provide less evaporative cooling.

Another issue to be considered is whether it is physically possible or desirable to increase the number of trees in cities to cover an additional 10% to 25% of the urban area. The answer depends on how heavily forested the city is, how dry the climate is, and where in the city the trees are to be planted. We can estimate the feasibility of an urban tree planting program using results from an analysis of the physical characteristics of the city in question.

Albedo Modification

There are a number of ways to modify a city's albedo: when it is time to repaint or reroof or resurface asphalt, lighter colors can be substituted for the existing color of buildings, reflective rooftops can be used, and white sand can be rolled onto the top of asphalt. Since many urban surfaces need to be recoated eventually, the cost of these methods may be less than the cost of planting and maintaining trees and, in contrast to planting new trees, altering the urban albedo starts to pay for itself immediately.

Changing the albedo of a city does not have to create major conflicts. Cities with white-washed buildings have been acceptable to many countries (e.g. Greece, Middle Eastern countries) throughout history. Also, highly reflective glass buildings are commonly regarded as beautiful. Of course building owners and architects like to have choices of colors for their buildings. An essential element in any undertaking to modify the urban albedo should be an ongoing dialogue with the public to obtain their input and cooperation.

Economics of Implementation

The cost of trees/white surfaces is quite small (~$15-75/home once compared to $100/year for air conditioning). Nevertheless, there are questions about how to apportion costs. Businesses and city residents both benefit from a more comfortable environment and from lower summer cooling costs. Utilities benefit from reduced peak power demand, which translates into the construction of fewer new power plants. Cities benefit from an improved local climate because environment is an important consideration for people and businesses deciding where to locate.

A practical and no-cost method of increasing the city albedo is to encourage the use of lighter colors at the time of repainting or reroofing buildings, or resurfacing top asphalts. The cost of planting and maintaining trees in large quantities is low. Since many home owners like to plant trees anyway, all that is needed is a little encouragement and some information on what kind of trees and where to plant them for the most energy savings benefits.

CONCLUSION

During 10 years of high oil prices, conservation kept U. S. energy use constant and resulted in a 10-year leveling of national CO_2 production. Now energy consumption is rising again.

To continue what has been proven to be effective, we propose planting trees and using lighter colored surfaces in cities wherever there is a significant demand for air conditioned buildings. These simple measures are based on design principles that were only recently abandoned with the advent of cheap, abundant air conditioning. The ideas are essentially these: plant a couple of trees on the south and one on the west side of the building to provide shade and evaporative cooling; increase the reflectance of the building and its surroundings so that the building will absorb less radiant energy.

The savings in cooling energy that can be achieved via shading and increased surface reflectivity, or albedo modification, are well recognized. Our preliminary studies suggest that such measures, have a direct effect of reducing the need for residential building cooling by as much as 30%.

Because the direct savings from shading and albedo modification are fairly well recognized, the research of the Heat Island Project at LBL has been primarily on the indirect effects of these measures. Indirect effects are changes in the city microclimate that may eliminate current summer urban heat islands. Eliminating summer heat islands not only further increases the amount of energy saved in the residential sector, but by reducing ambient air temperatures, reduces commercial cooling energy requirements as well.

The same measures offer an extremely inexpensive way to reduce carbon emissions. Although all trees directly sequester carbon, planting an urban tree could produce direct saving of power plant emissions that is equivalent to many times the yearly amount of carbon sequestered by a tree in the forest. The indirect savings achieved by reducing summer heat islands more than doubles the savings of the direct effects of these measures.

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