ELSEVIER

Energy and Buildings 28 (1998) 51–62

ENERGY AND BUILDINGS

Cool communities: strategies for heat island mitigation and smog reduction [1]

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Accepted 24 October 1997

Abstract

Adopting our 'cool communities' strategies of reroofing and repaving in lighter colors and planting shade trees can effect substantial energy savings, directly and indirectly. In our target city of Los Angeles, annual residential air-conditioning (A/C) bills can be reduced directly by about US$100 M and, because these strategies serve to cool the air in the Los Angeles basin and reduce smog exceedance levels by about 10%, an additional savings of US$70 M in indirect cooling and US$360 M in smog-reduction benefits—a total savings of about US$1/2 B per year—is possible. Trees are most effective if they shade buildings, but the savings are significant even if they merely cool the air by evapotranspiration. In Los Angeles, avoided peak power for air conditioning can reach about 1.5 GW (more than 15% of the city's air conditioning). Generalized to the entire US, we estimate that 25 GW can be avoided with potential annual benefits of about US$5 B by the year 2015. Recent steps taken by cities in the warm half of US towards adoption of cool communities include (1) incorporation of cool roofs in the revised ASHRAE building standards S90.1 and (2) inclusion of cool surfaces and shade trees as tradeable smog-offset credits in Los Angeles. Other step underway include (1) plans by the US Environmental Protection Agency (EPA) to approve heat island mitigation measures in the state implementation plan to comply with ozone standards and (2) plans for ratings and labeling of cool surfaces.

Keywords: Heat islands; Cool communities; Savings; Implementation; Policy; Smog; Ozone; Incentives; Cool roofs; Pavements; Trees; Energy; Utilities; Air conditioning; Residential buildings; Commercial buildings; South Coast USA; Simulation

1. Introduction

In the United States, of all electricity generated about one-sixth (translating to about US$40 B/year) is used to air-condition buildings. Of this US$40 B/year, about half is used in cities classified as 'heat islands' where the air conditioning demand has risen 10% within the last 40 years. These 'heat islands', which are numerous in the United States (Los Angeles, Phoenix, Houston, Atlanta, New York City, among others) warrant special attention by anyone concerned with broad-scale energy efficiency.

The cool communities strategy presented here is two-tiered: not only does it assure cost savings to individual homeowners and commercial consumers, but it reduces energy consumption citywide. It also serves to reduce smog, important in those regions such as our demonstration city of Los Angeles where air pollution is a significant health problem. Recent data on L.A. smog (ozone—O_3) reveal that the ozone concentration begins to exceed the National Ambient Air Quality Standard (NAAQS) of 120 parts per billion by volume (ppbv) when the daily maximum temperature hits about 22°C—and O_3 often reaches 240 ppbv around 32°C. In other words, ozone goes from acceptable to terrible in just 10 to 15°C. Within that small range, this man-made heat island has contributed 3°C.

Here, clearly, the issue goes beyond energy and utility cost savings and becomes a serious public health concern. In dollars, the medical cost attributable to poor air quality in Los Angeles , which includes the cost of worker absenteeism, has been estimated at US$10 B/year. Of this amount, approximately US$7 B is related to the impact of particulates in the air and the rest to ozone [2]. Small problems, crop damage and devaluation of real estate [3] (neither of which we are

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[1] A summary of this paper was presented at the 1996 Summer Study on Energy Efficiency in Buildings sponsored by the American Council for an Energy Efficient Economy [1].

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0378-7788/98/$19.00
PII S0378-7788(97)00063-7

including in our calculations) represent indirect costs that some believe to account for US$1 B annually. Although here we are focusing on Los Angeles, where smog levels are notoriously high, the strategies described are broadly applicable.

The essential components of a cool communities approach involve promoting wide-scale planting of shade trees and a concomitant shift from dark-colored roofing and paving materials to lighter colors. A recent special issue of Energy and Buildings on Urban Heat Islands discusses these cool communities strategies in detail [Vol. 25, No. 2]. The cooling effect of shade trees is largely due to the phenomenon of 'evapotranspiration'. Using lighter colors in roofing and paving materials means that the reflection from incoming solar radiation is higher and thus heat absorption is lower. According to Goodridge [4,5], most California cities cooled down about 1°C when irrigation was introduced but, in the sixties, with urban development, vegetation gave way to asphalt pavement and buildings with dark roofs and these cities once again heated up. In Los Angeles, a city that has grown tremendously in the last several decades, data show that the city has been warming since 1950 at the rate of 1°C every 15 years.

As a prime candidate for our cool communities strategy, we have concentrated our efforts on Los Angeles. After we have fully discussed the potential impact of implementing a cool communities strategy in Los Angeles, we will address some of the policy and procedural prerequisites (labels, building code modifications, the Los Angeles 'cap and trade' market) that need to be in place if such a strategy is to be successfully implemented. We then generalize our findings to what might be possible on a nationwide basis by the year 2015.

2. Methodology

In calculating the potential energy savings and ancillary benefits that might accrue were our cool communities strategy to be adopted in the Los Angeles basin, we took into account the direct energy savings, the indirect energy savings, and the potential impact on air pollution, specifically smog. (In some climates, switching from a dark-colored roof to a white or light-colored roof, and/or adding shade trees, may result in a heating penalty in winter. Our analysis accounts for this penalty, which is small in the warm climates where we advocate a 'cool communities' strategy.) The basic assumptions used in our calculations are as follows.

(1) Of 5 M homes in the Los Angeles basin, we assumed that the coastal houses are not air conditioned and that only about 1.8 M of the inland houses are air conditioned.

(2) We estimated a roof area per house of 200 m^2, a total of 1000 km^2 of roofs, and another 250 km^2 of commercial-building roofs that can benefit from light-colored roofs and shade trees. We estimated the potential increase in the solar reflectivity of the roofs to be about 0.35 (on a scale of 0 to 1). In addition, we calculated another 1250 km^2 of paved surfaces where solar reflectivity could be increased to about 0.25. Hence, based on a total of 2500 km^2 surface area, our modifications stand to effect an average increase in solar reflectivity of 0.3. Given that the total populated area of L.A. is about 10,000 km^2, our calculations apply to 25% of the urban map of the city. Accordingly, the overall urban solar reflectivity stands to increase by 0.075.

(3) We assumed that all 5 M houses would change to lighter-color roofs, the air-conditioned houses benefiting directly from cooler roofs and the non-air-conditioned houses largely contributing to the general cooling of the Los Angeles basin, thus indirectly lowering the cooling demand of air-conditioned houses and the smog concentration in the basin.

(4) To estimate the cooling potential of vegetation, we 'planted' 11 M trees according to the following plan: three shade trees (each with a canopy cross section of 50 m^2) per air-conditioned house, for a total of 5.4 M trees; about one shade tree for each 250 m^2 of non-residential roof area for a total of 1 M trees; 4.6 M trees to shade non-air-conditioned homes or to be planted along streets, in parks, and in other public spaces.

The calculations based on these assumptions are presented in Table 1.

2.1. Direct savings

For the first part of our calculations, we used the DOE-2 program to simulate two inland (air-conditioned) prototype houses: those built before the enactment of California Title 24 in 1978 (55% or 1.0 M) and those built after (45% or 0.8 M) [8]. (Title 24, mandated increases in the energy efficiency of new residential and commercial buildings.) We estimated the direct savings from installing cool roofs and planting shade trees, using the DOE-2 building energy simulation program. For air-conditioned buildings, we used Burbank weather data as representative. To get citywide savings, we multiplied savings for each home by the number of residences likely to benefit.

Light-colored roofs and shade trees also have a major impact on the energy used for air conditioning in commercial buildings. For purposes of this study, we did not simulate all commercial buildings in L.A. that would potentially benefit from cool roofs and shade trees. Instead, we used the results of a detailed study conducted for Sacramento where the number of cooling degree days (cdd) is similar to that of Burbank [9]. That study finds a total energy savings for commercial buildings equivalent to 25% of residential savings. Hence, to estimate the direct savings of light-colored roofs and shade trees for all building categories, we multiplied residential savings by a factor of 1.25. The same approach was taken below to estimate indirect energy savings in commercial buildings.

2.2. Indirect energy savings

In the second part of our calculations, we estimated the indirect energy savings by first using Taha's meteorological

Table 1
Physical inputs used to calculate the impact of cool communities measures on building energy use and smog concentration in Los Angeles, including outputs of the meteorological and smog models

I. Physical Inputs:

Cool surfaces	Area (km^2)	Δa	Trees	Area (km^2)	Number (M)
Roofs	1250	0.35	Total shading[c]	320	6.4
5 M homes[a]	1000		Residences	270	5.4
Non-residential building	250		Non-residential building	50	1
Pavement	1250	0.25	Non-shading	230	4.6
Total	2500[b]	0.3	Total trees	550	11

II. Outputs of the meteorological model:
Cooling (population-averaged at 2 P.M.): ΔT (combined) = 3.0°C, ΔT (albedo only) = 1.5°C, ΔT (trees only) = 1.5°C

III. Outputs of the smog model:
Reduction of the ozone concentration exceeding 90 ppbv = 12%. This 12% is for the 'combined' simulation, averaged over population and over 8 h
Albedo only, or trees only, each contribute 50% of the 12%

Source: Taha [6,7].
Albedo change is denoted by Δa, temperature by T, and million by M.
[a] Roof area of a typical home assumed to be 200 m^2.
[b] Input to meteorological model: 1250 km^2 of roofs whose albedo has been increased (at time of reroofing) by 0.35 (e.g., from green with $a = 0.15$, to white shingle or white flat roof, weathered for a few years to $a = 0.5$). In the same run, we simulated the resurfacing of 1250 km^2 of pavements, switching from $a = 0.05$ (asphalt) to $a = 0.30$ (cement or light-colored asphalt concrete).
[c] Assumes planting of 11 M trees and giving them 10–15 years to grow to maturity. Fully grown, the canopy of a tree is taken to have a cross section of 50 m^2.

model [6,7] to calculate the amount of ambient cooling from an increase in solar reflectivity of roof and pavement surfaces and planting of 11 M new shade trees. Taha's model calculates a different cooling for each hour of the day in about 400 'developed cells' (i.e., urbanized areas, each cell 25 km^2); these 400 cells together account for almost the entire population of the basin. To estimate the savings in air conditioning usage, we combined the cooling in these 400 cells to arrive at a single population-averaged hourly cooling that reaches a maximum of 3°C at about 2 P.M., when the temperature itself is at its maximum. These simulations model the cooling derived from 'albedo only,' 'trees only,' and both combined. The cooling for 'albedo only' turns out to equal that of 'trees only,' and is additive; thus, we generally refer to the combined result but attribute half the savings to each strategy. The results are shown in Table 1, line II.

After simulating the cooling of ambient air, we used the DOE-2 simulation to estimate the indirect savings for the prototype homes. The lower temperatures found in the meteorological simulation for a typical day in each season are used to modify the yearly weather tape, and these data were then used as inputs to DOE-2 simulations to recalculate the air-conditioning usage of the homes. When subtracted from the usage in base-case weather, we found the indirect savings due to '3°C cooler air.'

2.3. Smog savings

In the third and final part of our calculations, we estimated the potential for smog (ozone) reduction, and its benefits in dollars, using the airshed simulation model [10,11]. In the first run, the base-case inputs used represented the temperatures recorded during a smog episode in August 1988. In a second run, the inputs represent the temperature outputs of the meteorological model described above. The differences between these two simulations give the spatial distribution of ozone reduction, spotty because the now-cooler city reduces the upwelling of heated air, thus allowing the smog precursors to concentrate in a smaller volume and actually increase the ozone level in certain cells. This reduced upwelling cancels about half the gain one might hope for by simply looking at the temperature dependence of the rates of reaction involved in ozone formation.

Considerable uncertainty attaches to how to measure the cost of poor air quality to public health. For the most part, people seem not to be bothered by low concentrations of ozone, say below 50 ppbv. The NAAQS is 120 ppbv, but will soon be lowered; the California standard is already down to 90 ppbv. Air quality is usually measured as its 'exceedance' above one of these two standards, and, of course, the higher the threshold, the higher the percentage reduction in ozone and the more effective the strategy appears to be. Taha's paper on the modeling gives the percent reduction above several different thresholds, but here we take one relatively stringent standard: the exceedance above 90 ppbv, population-weighted and averaged over 8 h. On this basis, our strategies reduced exceedance by 12%. This result is entered in Table 1, line III. We assume that a 12% average reduction in smog will save us 12% in the US\$3 B annual smog cost—i.e., medical costs and time lost from work—or US\$360 M/year.

In apportioning how much of the benefits we calculated could be attributed to the three separate strategies (trees, roofs, and pavements), we found 50% of the temperature decrease (and thus 50% of smog reduction) arises from tree

Table 2
Simulation of annual cooling and heating costs of prototype homes in Burbank, CA

		Old residence		New residence	
		US$/year	% of A/C base case	US$/year	% of A/C base case
1	Base case A/C	156	100%	96	100%
2	Base case heat	184		90	
Direct savings (net) due to					
3	Roofs: $\Delta a = 0.35$	24	15%	16	17%
4	Shade from trees	18[a]	12%	18[a]	17%
5	3°C cooler air	36	23%	26	27%
6	Total savings	78	50%	60	61%
		kW	% of A/C base case	kW	% of A/C base case
7	Peak power base case	2.62	100%	1.84	100%
8	ΔPeak power, $\Delta a = 0.35$	0.64	24%	0.62	33%

The net air-conditioning savings are calculated assuming a cooler roof ($\Delta a = 0.35$) and the shade from three mature trees, each with a canopy cross section of 50 m^2.

[a] Roof area of a typical home assumed to be 200 m^2.

planting. The remaining 50% was proportionally attributed to albedo changes resulting from light-colored roofs (0.35) and pavements (0.25), which translate to 29% of the benefits from light-colored roofs and 21% from light-colored pavements. Although trees also serve to absorb particulates[5], and reduce peak power demand[6] and hence NO_x and O_3, these benefits are too small to include in our calculations.

3. Savings calculated, Los Angeles

3.1. Direct energy savings

The results of our DOE-2 simulations for both old (pre-1978) and new (post-1978) homes are shown in Table 2, rows 3 and 4. Net savings in annual energy bills were calculated by subtracting the slight increase in the winter bill for gas heat from the savings gained in air conditioning. Specifically, for old residences, the net direct saving of US$24/year attributable to light-colored roofs is the difference between the savings in cooling costs (US$37/year) and the penalty in heating costs (US$13/year)[7]. This method of calculating net savings was checked experimentally by LBNL [8] and by the Florida Solar Energy Center [13]. Simulations have always underestimated the experimentally observed savings from cool roofs.

Extrapolating these direct energy savings attributable to roofs and shade trees from the Burbank area to all of L.A., as shown in Table 3, produces a savings of about US$46 M annually for roofs and US$58 M annually for trees.

3.2. Indirect energy savings

The prototype homes used for this study were simulated with DOE-2 using a modified weather tape (cooler by 3°C at 2 P.M. in August). The reduction in air conditioning for individual buildings is shown in Table 2. Carrying this result over Table 3, row II, shows the total savings for the Los Angeles basin of US$71 M/year. Table 3 also shows a peak demand savings of 0.6 GW from white surfaces and trees[8].

3.3. Smog reduction and biogenic emissions

Our meteorological simulations indicate that the smog reduction is equally attributable to the contributions from trees (evapotranspiration) and light-colored surfaces (both roofs and pavements), as shown in Table 3. We should emphasize that our smog simulations assume that the trees do not have any biogenic emissions. Indeed, along with other

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[5] McPherson et al. [12] estimate that 50 M trees in a 3350 km^2 study area around Chicago decreased particulates (PM10) by 0.4%. Our scenario adds only 11 M trees to a larger populated area (10,000 km^2); these trees will reduce PM10 by less than 0.1%. With an estimated annual health cost from particulates of about US$7 B, a 0.1% reduction would be worth only US$7 M, which is disappointingly smaller than the smog benefits of US$360 M.

[6] Even though peak power will drop by 1.5 GW, and some peak power is generated (and produces NO_x) within the basin, Taha calculates that decreased NO_x will reduce smog by only about 1%.

[7] It may seem surprising that the A/C advantage is 24% (US$37 from a base case of US$156) while the heating penalty is only 7% (US$13 from the base case of US$184). The explanation is that the daily solar gain on a horizontal surface drops by about a factor of 8 between midsummer and midwinter because (1) days are shorter in winter, (2) the sun angle is lower, and (3) winters are cloudier. Each of these factors reduces solar gain to 1/2; $(1/2)^3 = 1/8$. This factor of 8 decouples the winter and summer solar gain of roofs. Despite an increase in heating, the higher cost of electricity (for cooling) vs. gas (for heating) favors the reduction of air conditioning.

[8] As a check on the computed value of peak power avoided by the decrease in temperature, we compared it with the actual temperature-dependent demand for electricity in L.A.. Data from the utilities supplying the L.A. basin, (Southern California Edison and Los Angeles Department of Water and Power) give the electricity demand as a function of temperature at every hour of the day. These data show a distinct increase in demand when the temperature exceeds 21°C (70°F), but the rate of increase depends on the time of day [14]. Using the slope of the demand vs. temperature curves at about 2 P.M., [(ΔPeak power)ΔT] = 320 MW/°C, we can find the decrease in peak-power demand if the temperature were lowered by $\Delta T = 3$°C at 2 P.M. to be 0.96 GW, a result that is in satisfactory agreement with our computed estimate of 0.6 GW.

Table 3
Energy savings, ozone reduction, and avoided peak power from use of cool communities strategies (Los Angeles basin)

Benefits	Measures			
	Cooler roofs	Trees	Cooler pavements	Total[a]
I. Direct[b]				
1. A/C energy savings from cooler roofs or shade (US$ M/year)	46	58	0	104
2. ΔPeak power (GW)	0.4	0.6	0	1.0
3. Present value (US$)[c]	153	68	0	
II. Indirect[d]				
1. A/C energy savings from 3°C cooler air (US$ M/year)	21	35	15	71
2. ΔPeak power (GW)	0.2	0.3	0.1	0.6
3. Present value (US$)[c]	25	24	6 or 18[e]	
III. Smog				
1. 12% ozone reduction (US$ M/year)	104	180	76	360
2. Present value (US$)[c]	125	123	30 or 90[e]	
IV. Total				
1. All above benefits (US$ M/year)	171	273	91	535
2. Total Δ peak power (GW)	0.6	0.8	0.1	1.6
3. Total present value (US$)[c]	303	211	36 or 108[e]	
V. Surcost (US$)[c]	<25	See Section 4.2	<30	

[a] For comparisons, the annual base case L.A. A/C bill is approximately US$500 M and annual O_3 cost is about US$3 B.

[b] To estimate the L.A.-wide direct and indirect effects, we use the data in multiplied by the number of buildings of each type (old residences, new residences, non-residences). We assumed that, of the 1.8 M residences with A/C, the relative number of old residences, new residences and non-residential buildings corresponds to that of Sacramento, CA. These numbers are 55% pre-Title 24 (1 M 'old' residences), 45% post-Title 24 (0.8 M 'new' residences, energy-efficient construction), and that non-residential savings are about 25% of the residential savings [9].

[c] The present values and surcosts for surfaces are calculated for 100 m^2 of roof or pavement area, and for one tree.

[d] The indirect savings are calculated assuming all 11 M trees are planted and all 2500 km^2 roofs and pavements in the L.A. basin are modified, although only the air-conditioned buildings benefit from cooler air.

[e] See footnote 12. The entries differ threefold depending on whether we chose a PV multiplier of 5 or 15.

landscaping considerations, this factor should be a criterion for choosing trees before implementing a large-scale tree-planting program (see Section 6.2).

Table 3, row IV lists the total annual benefits: roofs (US$171 M), trees (US$273 M) and pavements (US$91 M). These savings amount to about US$535 M/year, assuming all roofs have their albedos raised by 0.35 and pavement albedos by 0.25, and that the 11 M shade trees are mature.

3.4. *Smog precursor (NO_x and equivalent) reduction*

3.4.1. *NO_x measured in tons/day*

On a summer day in Los Angeles some 1350 tons of NO_x (oxides of nitrogen) and 1500 tons of volatile organic compounds (VOCs) react to form ozone. In this section we compare the small NO_x reduction from reduced air conditioning, and the large 'equivalent' NO_x reduction from lowering smog levels, with this 1350 tons/day base case.

First we calculate the small NO_x savings from the 1.6 GW of avoided airconditioning peak power electricity use. Marginal peak power is LA is generated by peaking plants in the Basin which emit 0.5 kg of NO_x per MWh. Hall and Hall [16] ran our hourly demand reduction through the ELFIN model and found that the daily avoided NO_x is 7 tons/day, i.e., only 1/2% of the basecase 1350 tons/day.Next we calculate the 50 times larger "equivalent" NO_x avoided by cooling LA up to 3 °C. Reducing smog by citywide cooling can be considered equivalent to reducing the formation of smog precursors at constant temperature. Taha [6,7] estimates that shade trees and light-colored surfaces will reduce maximum smog concentration by 10%. Using the ozone 'isopleths' (such as Milford's[9]), a 10% reduction in smog is equivalent to reducing precursors by about 25%, i.e., reducing NO_x by 350 tons/day, a very significant drop and 50 times more than the 7 tons/day through reduced power plant emissions.

3.4.2. *NO_x traded in dollars*

Los Angeles has a smog offset trading marked called RECLAIM, discussed in Section 5.1. A typical RECLAIM trading price for NO_x is $3000/ton[10]. To covert this offset cost to ¢/kWh of peak power, we multiply by 0.5 kg/MWH to get 0.15 ¢/kWh, which is only 2% of the price of residential electricity. This shows that the main motivation for saving air conditioning energy use is to save the cost of the power, not to avoid the related emissions.

But the 350 tons/day of avoided "equivalent" NO_x is indeed valuable, in fact worth $1M/day. To convert this to a yearly value, we note that there are about 100 smoggy days

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[9] Milford et al. [15] have carried out detailed calculations analyzing the changes in the maximum ozone concentration reached in Los Angeles vs. concentration of NO_x and VOCs. They presented their calculations in the form of 'isopleths' of equal maximum smog concentration for various levels of NO_x and VOCs concentration (typically shown as a percent reduction of emissions) for a typical summer episode.

[10] The 1994 SCAQMD Air Quality Management Plan quotes this price for measure CMB-05–clean stationary fuels.

in LA, so, at \$1M/day the value becomes \$100M/year. This in turn can be compared with the \$360M annual avoided health cost in Table 3, line III.1. We conclude that current RECLAIM trading prices do not yet fully reflect our estimates of the health costs of ozone, but they are of the right order of magnitude.

4. Cost/benefit analysis of individual buildings

4.1. Present value of savings

In addition to the potential large-scale benefits of citywide cooling are the benefits to individual homeowners, shown in Table 3 as 'present values', which are given for each energy-saving strategy.

The present value (PV) of future savings are calculated using

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

where, a = annual savings (US\$), d = real discount rate, n = service life of the conservation measure, in years.

The PV for a new roof, for example, is calculated by assuming a service life of 20 years and a discount rate of 3%[11]. These inputs yield a PV of US\$15 for each US\$1 saved annually. The benefits from shade trees are delayed because they will be only half-grown in 10 years. Accordingly, we estimate that the PV of savings from trees would be worth only half of that of the roofs, i.e., US\$7.5 for each US\$1 saved annually. On this basis, the direct savings to the owner of a home with 200 m^2 of old roof who installs a cooler roof and plants three shade trees will have a PV of about US\$500/home. The PV of indirect savings are smaller, about US\$100/home.

The PV of smog savings are calculated in two steps. We first convert the L.A.-wide annual savings (Table 3, row III.1) to annual savings per 100 m^2 of roofs or pavements, or per tree. The resulting annual savings are then multiplied by the PV multiplier (7.5 for trees, 15 for roofs, and 5 for pavements[12]) to estimate the PVs.

The total PV per home is greater than US\$1000. The PV is needed to calculate not only how much a homeowner can afford to pay for cool roofs and shade trees, but also the value of smog reduction. Starting in 1998, the PV of a cool surface is relevant to 'market transformation' programs to be offered by utilities or other electricity providers, as discussed in Section 5.2.

4.2. Cost premiums of reflective roofs, pavements, and trees

The appropriate time for building owners, homeowners, and communities to make the switch to cool surfaces is when their roofs or pavements need maintenance or replacement (typically every 20 years for residential shingles, 5–10 years for a flat roof, 5–10 years for a parking lot or road). At that time, the recommended replacements will cost little extra. Our base-case calculations are for current conditions, but our 3°C cooler results represent savings possible in 15–20 years, by that time all surfaces will have been redone and trees will be mature. The extra cost of manufacturing white instead of brown or green roofing shingles is estimated by the producers to be less than US\$22/100 m^2 (about 2¢/ft^2) of roofs. The extra cost at retail will be decided by the market. Although white (compared to dark) roofing membranes have a one-time surcost of about US\$100/100 m^2, they yield a continuing savings of US\$65 per 100 m^2 per year. Our conservative estimate is that an average roofing surcost is less than US\$25/100 m^2 of residential roof, as shown in Table 3.

For pavements there are more options to consider. According to Pomerantz et al. [17], the most economical way to make cool pavements is to lay a thin cool coating over the existing dark surface. (We address only first costs, not lifetime costs of pavements.) The additional cost of materials for a topping 6 mm (1/4 in.) thick, ΔP in US\$/100 m^2, can be shown to be

$$\Delta P=1.45\Delta A+29.4\Delta B, \qquad (2)$$

where ΔA is the additional cost (in US\$/ton) of white aggregate and ΔB is the additional cost of white or clear binder (in US\$/gal). The price of whiter aggregates depends on the shipping costs from their special quarries. In Texas, where limestone is common, this white aggregate is used routinely at no extra cost whereas in the of San Francisco Bay Area, the extra cost is about US\$20/ton. Using this figure as a representative value and using asphalt as the binder, $\Delta B=0$, we find an additional cost of ΔP = US\$29/100 m^2. Because aggregate is about 80% by volume of the pavement, just switching to white aggregate will give the desired life-cycle increase in solar reflectivity of 0.25[13]. Based on 100 m^2, the US\$29 cost premium is less than the PV of US\$36 and much less than US\$108 (Table 3, line IV.3).

The cost of a citywide tree-planting program depends on the type of program offered and the type of tree recommended. At the low end, a promotional tree planting of trees 5–10 ft high cost about US\$10 per tree, whereas a profes-

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[11] Economists often choose a discount rate, d, equal to the current prime rate, or something close thereto. But here, we chose a lower value of 3%/year 'real' (i.e., in constant dollars after inflation) as adopted by the California Energy Commission for energy-efficient buildings and other long-range investments designed to save fossil fuel for future generations.

[12] The estimate of a PV multiplier for pavements is based on new materials (i.e., aggregates). The current practice of the industry is to recycle the old aggregates by scraping off the surface of the pavements and recycling it. In that case, the useful life of the aggregates is increased at least by a factor of 5 which will result in an increase in the PV multiplier to 15.

[13] Pomerantz et al. [17] discuss another approach, which, at present, does not seem to be economically feasible. They suggest a clear or a white binder, chemically similar to asphalt, that costs an additional US\$7/gal, or a completed pavement cost of an additional US\$190/100 m^2. It is also important to note that light-colored binder must be replaced every 5 to 10 years, while light-colored aggregates can be left in place or scraped off and recycled.

sional tree-planting program using fairly large trees could amount to US$150 to US$470 per tree (Ref. [12], p. 118). A program administered by the Sacramento Municipal Utility District and Sacramento Tree Foundation in 1992–1996 planted 20-foot tall trees at an average cost of US$45 per tree. McPherson et al. [12] also associate significant costs to issues related to tree maintenance such as pruning, removal of dead trees, removal of stump of dead trees, repair of damages to infrastructure, and program administration. The PV of all these life-cycle costs (including planting) is US$300 to US$500 per tree. With this wide range of costs associated with trees, in our opinion, tree costs should be justified with other amenities they provide beyond air conditioning and smog, so we do not quote any surcost.

Even trees planted along streets and in parks where they do not offer direct shade to air-conditioned buildings exert a cooling effect sufficient to have a substantial impact on smog reduction. As shown in Table 3, trees account for about half the total benefits achieved and, of their US$270 M annual benefit, only US$58 M comes from their contribution to shading. (These conclusions may not hold for more humid climates.) At another level, these calculations suggest that urban trees play a major role in sequestering CO_2 and thereby delaying the global warming. Appendix A shows that a tree planted in Los Angeles avoids the combustion of 15 kg of carbon annually, even though it sequesters only 4.5 kg (as it would if growing in a forest). In that sense, one shade tree in Los Angeles is equivalent to three forest trees.

5. Financial and institutional sources of support

We doubt that the direct savings noted in Table 3 are enough, in themselves, to induce a building owner to re-roof in lighter colors and to plant shade trees. The annual benefits of US$535 M possible after 15–20 years of re-roofing, planting, and re-paving will be realized only if we can mobilize institutions to champion them. Fortunately for our Cool Communities strategy, 1996–97 saw the advent of two sources of funding capable of transforming the market for cool surfaces and shade trees. These two sources are RECLAIM/ASC (Section 5.1) and market transformation funds under California Assembly Bill AB 1890 (Section 5.2). In addition, the US Environmental Protection Agency (EPA) is considering mechanisms that would allow inclusion of cool surfaces and shade trees in 'SIPs' (State Implementation Plans for ozone compliance, Section 5.3).

5.1. SCAQMD and RECLAIM/ASC

The REgional CLean Air Incentive Market (RECLAIM) is a market incentive program, established in 1993, that covers the largest stationary sources in the south coast basin. Allowable levels of NO_x and SO_x emissions for these sources have been capped, and will be lowered by 8% each year. Under the program, covered sources are allowed to choose between reducing their own emissions by the required amount, or buying 'extra' reductions achieved by other covered sources (or use a combination of both).

Area source credits (ASC) were created in 1997 by Rule 2506 to extend the emissions trading approach to a wider base of non-mobile area sources [18]. The types of activities that may earn area source credits are also much broader than those allowed under the RECLAIM program. The two credit markets are temporarily separate, but it is planned to merge the two currencies of credit into a common 'universal' credit in 1998. Rule 2506 defined a set of eligibility criteria defining the types of activities that could quality for area source credits. Cool roofs and shade trees are potentially eligible for this trading scheme once a quantification methodology that translates the temperature reductions into equivalent NO_x and VOC reductions has been developed and approved. DOE and LBNL plan to work with AQMD to develop such a quantification methodology.

We illustrate 'equivalent NO_x' using the same numbers we used in Section 3.4. Our modeling gives a midday cooling of 3°C and a corresponding 10% reduction in peak O_3 concentration (corresponding to a 12% reduction in exceedance over 90 ppb). But the base case (unmodified temperature) for the same airshed ozone-formation model shows that to reduce O_3 by 10%, the precursors, NO_x and VOCs must be reduced by about 25%. The 'equivalence' at unmodified temperature is then that a 10% reduction in O_3 is equivalent to a 25% reduction in NO_x and VOCs. But half the 10% reduction in O_3 arises from 2500 km^2 of lighter surfaces and half from 11 M shade trees, so we can apportion the 25% reduction in NO_x to each km^2 of surface and to each millions of trees.

Before committing to specific equivalence numbers, SCAQMD decided to verify the LBNL numbers through an independent contractor, and in September 1997 that work was still under way [14]. But LBNL plans to work with SCAQMD and other cap-and-trade markets as they form to establish NO_x equivalence for local climate and smog conditions.

5.2. Market transformation for energy efficiency via California AB 1890

During the 1990s and through 1997, California utilities have been spending approximately US$200 M/year on programs to improve energy efficiency on the customer's side of the meter; these are called demand side management (DSM) programs. Utilities have done this partly out of goodwill, but mainly because of the strong incentives offered under a 'collaborative process' with the Public Utilities Commission, which now makes it more profitable for a utility to sell efficiency ('negawatts') than raw energy ('megawatts') [19].

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[14] K.T. Tran, V.A. Mirabella, Meteorological and Photochemical Modeling of Large-scale Albedo Changes in the South Coast Air Basin, Applied Modeling, Woodland Hills, CA, 1997, unpublished report.

But in 1998 California electric utilities will be 're-regulated' to make them more competitive and, soon, the DSM incentive rates will disappear. Instead, the California Legislature has passed AB 1890, which adds a 3% 'public benefit' fee to all electricity sold in the state [20]. This 3% will raise about US$500 M/year of which US$220 M will be available for DSM and 'market transformation' programs run by utilities or other providers. Under AB 1890, a utility (or other provider) can request funding, including a profit margin, to introduce cooler roofs through technical assistance, loans (repaid out of customer savings), and bulk purchases, etc.

5.3. State implementation plans to comply with ozone standards

About 100 M Americans already live in metropolitan areas that exceed current ozone standards. After EPA tightened the standards in 1997, more than 50% of Americans live in cities that will be out of compliance for ozone and particulates (PM 2.5 μ). Accordingly, some 30 states must submit to EPA long-range SIPs. As noted earlier, EPA is considering the role that could be played by cool surfaces and shade trees.[15] DOE/LBNL plan to collaborate with EPA and state official to help them draft these measures, whose numerical value, naturally, will vary from one region to another.

5.4. Cooler pavements

So far we have discussed mainly cool roofs and shade trees that promise direct energy bill savings to interest a building owner. But it may be harder to introduce cool pavements and trees that do not shade buildings. Cities and counties might consider requiring them, based on three other advantages. (1) Cities and counties can sell the credits on the RECLAIM/ASC market and apply for AB 1890 funds. (2) Concrete pavement (in contrast to asphalt) has a higher first cost but outlives asphalt and has a lower life-cycle cost. (Iowa already requires concrete.) (3) Most of our colleagues (and Shell Oil-Paris) believe that cooler roads will last 20–50% longer because of reduced daily thermal cycling, reduced ultraviolet damage to the cooler (hence, stiffer) binder, and better ability of the cooler binder to spread the load of truck tires. We intend to check these anecdotal suggestions by modeling and measuring the service life of roofs and pavements in term of temperature dependence. The benefits of cooler pavements may be greater than we have indicated here.

6. Infrastructure requirements for implementing cool communities strategies

There are many preconditions to creating a mass market for using cooler materials and for planting appropriate trees. The issues involved are discussed below as they apply to: cool materials, shade trees, and demonstration strategies.

6.1. Cool roofing/pavement materials

6.1.1. Product testing and rating

Currently, the energy performance of roof and pavement materials is not regularly tested or reported by product manufacturers. While there are some highly-reflective products on the market, consumers are unable to differentiate among available products to determine which would yield the greatest energy savings. There are industry approved test methods to measure solar reflectance (albedo), and American Society for Testing Materials (ASTM) is currently defining a new rating called solar reflectance index (SRI) to serve as a guide to the relative roof and pavement temperatures under midday summer sun. The SRI shows where the surface temperature falls between black and white, and when measured in the field, can account for impaired reflectivity after weathering.

If product manufacturers were to adopt a system to routinely measure and report the optical radiative properties of their materials (solar reflectance and thermal emittance), then consumers could more easily incorporate energy performance into their purchasing decision. This type of product information could be reported on a physical product label, or in a centralized product database. LBNL has developed a preliminary database of cool materials that have been tested. It could easily be modified to include tested data on additional products. The database is available on the worldwide web: http://eande.lbl.gov/heatisland.

6.1.2. Incorporating cool roofs into new buildings

Most states have energy efficiency building codes for new residential and commercial buildings. These codes specify a maximum 'energy budget' or performance threshold that a building must meet in order to be constructed in that state. These codes typically allow architects and builders to choose the optimal combination of energy-saving technologies that will meet the performance threshold. While a cool roof will reduce a building's annual energy use, most state codes do not allow architects or builders to take any credit for this feature in estimating the energy performance of a planned building. As a result, builders have no incentive to include a cool roof in a new building design. Recently, however, the American Society for Heating Refrigeration and Air-conditioning Engineers (ASHRAE) adopted language that would give credit for reflective roofs in Standard 90.1, New Commercial Buildings. The consensus-based national model codes developed by ASHRAE often serve as the basis for building codes adopted by States. This new move by ASHRAE to recognize the impact of cool roofs in commercial buildings is an important step. ASHRAE's 90.2 committee for residential buildings is considering a similar revision.

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[15] Both SCAQMD and 'BAAQMD' (San Francisco Bay Area Air Quality Management District) list cool surfaces and shade trees as control measures (SCAQMD Control Measure CM#94MISC-01 [21] and BAAQMD has proposed measure CMF9 [22]).

6.2. Shade trees

6.2.1. Low-emitting trees

Trees emit reactive organic gases (ROGs) which, as mentioned earlier, are precursors to smog [7]. The rates of emission among varieties varies over a range of 1000:1; the more pungent the smell of the tree (e.g., Eucalyptus) the more likely it is to spell trouble. The biogenic emissions of many varieties of trees have been measured by several researchers [23,24], and California varieties are being studied at UCLA [25]. (As suggested earlier, biogenic penalties are not accounted for here and must be factored into any program.)

6.2.2. Building performance standards

Organizations that set standards have been reluctant to give energy credit for shade trees on the basis that trees may never be planted as planned, or may die and not be replaced. It may be difficult to modify ASHRAE standards to give credit for shade trees, but local city or county governments in smog-plagued areas could implement local codes or ordinances that require planting of shade trees as part of a regional strategy to reduce ozone levels. Local Air Quality Districts could consider including the smog benefits of such tree planting ordinances in their SIPs for smog compliance.

6.3. Demonstrations

DOE, DOD, and LBNL are cooperating with the non-profit group American Forests to demonstrate air-conditioning energy savings by planting shade trees and installing light-colored surfaces at DOD facilities in hot climates and selected 'cool communities.' Currently, with EPA sponsorship, LBNL (in collaboration with the Florida Solar Energy Center) has set up five cool-roof demonstration sites in California and Florida. The demonstration buildings include a retail drug store, two medical centers, and two strip malls. These demonstrations are intended to show case the benefits of the light-colored roofs to the public. Three of these demonstration sites (the California buildings) are equipped with an information kiosk, where the public can obtain both general information about light-colored roofing materials and real-time data on the energy-saving impacts of the light-colored roof on the demonstration buildings.

7. Comparison of cool communities strategies with two existing strategies for smog reduction

As part of this study, we conducted preliminary simulations comparing the impact on smog of cool surfaces and shade trees with all the other traditional smog-reduction strategies. Here, we restrict our comparison to the new cleaner-burning gasoline, and to the current California proposals for 10% ZEVs (zero-emission vehicles, i.e., all-electric) or LEVs (low-emission vehicles, i.e., 'hybrids'). Compared to the 12% smog reduction from heat island mitigation, our estimates, albeit crude, indicate that the cleaner-burning gasoline will reduce ozone by about 5%, and that 10% ZEVs/LEVs will reduce ozone by only another 2–4%. Of course these strategies have other virtues: cleaner burning gasoline will produce less SO_x and 10% electric and hybrid cars will cut particulates from cars by 10%. As we mentioned earlier, particulates are a worse threat to health than is smog, and cooling the L.A. basin does nothing to reduce particulates, nor do more trees help appreciably in this respect. The specific comparisons are noted below.

7.1. Cleaner-burning gasoline

Cleaner-burning gasoline was introduced in 1996. It should reduce smog precursors from cars by 15% (equivalent to removing 1.5 M cars from the basin). Cars are blamed for more than half the smog precursors, so one might hope for more than a 7.5% reduction in smog. Because ozone is not linearly related to its precursors, we may not do quite as well as 7.5%. For example, two air-quality modeling groups estimate the reduction of O_3, assuming all the motor vehicles are removed from the L.A. airshed [7,26] and from Chicago [27]. Although their results are preliminary and the smog-reduction figures are not uniformly stated (we use population-weighted, 8-h exceedance above 90 ppbv; other groups use just the reduction in the highest daily peak), nevertheless, a plausible range of O_3 reduction amounts to 20–40% and is unlikely to exceed 50%. If cleaner-burning gasoline further reduces this 20–40% by 15%, we can expect a reduction of about 5%, as mentioned above.

7.2. Electric and hybrid cars

According to present California plans, electric car sales are to start at 2% and quickly rise to 10%. Given that the present fleet turns over only every 10–15 years, it will take about 15 years for the fraction of electric cars to approach 10% of the fleet. If removing all cars reduces ozone by 20–40%, then the 10% electric cars or hybrids will not do much better than another 2–4%.

8. Generalization of our cool communities strategies from Los Angeles to the entire United States in 2015

In a recent study, we performed detailed calculations to estimate the direct impact of light-colored roofs in eleven metropolitan areas, and we extrapolated the results to the entire country [28]. The 11 US metropolitan areas include: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York City, Philadelphia, Phoenix, and Washington, D.C./Baltimore. Using the DOE-2 building simulation code, we calculated HVAC annual electricity and net energy savings, peak demand electricity savings, and annual natural gas penalty from light-colored roofs. We calculated energy use for the following

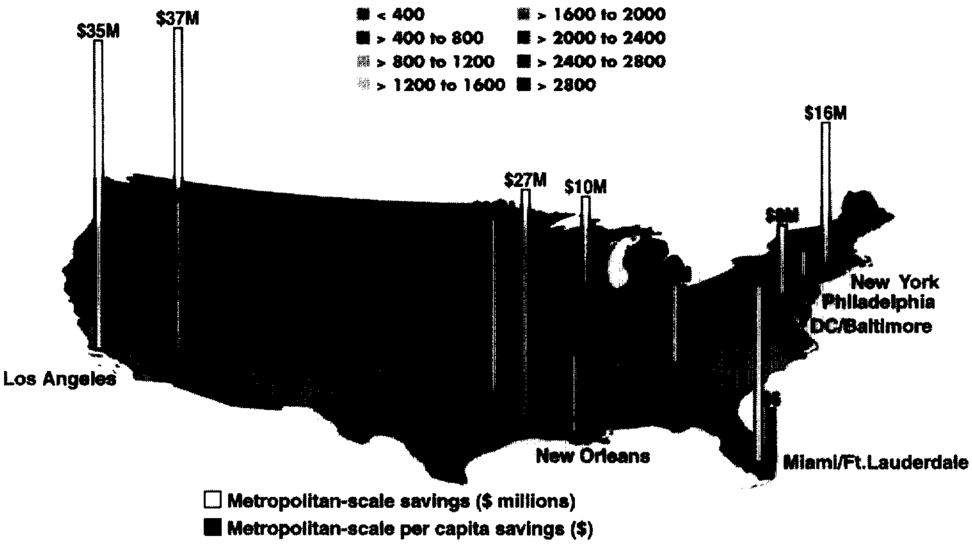

Fig. 1. Annual Net Cooling Energy Savings for 11 Metropolitan Areas. The contour map shows simulated annual hours for a typical house. (Source: Konopacki et al. [28].)

Table 4
Potential impact of 10% reduced air conditioning on electricity usage, electricity cost, and CO_2 levels in the US by the year 2015: comparison of EIA base case and our projected savings by cool communities strategies

	Air conditioning in 2015		All electricity uses in 1995
	Base case	Projected savings	
1. Electric use (B kW h)	400	40	3000
2. Electricity cost (US$B)	40	4	200
3. CO_2 (MtC)	70	7	500

For perspective, the right-hand column shows all electric use today.
For air conditioning, we assume 1 kW h of peak power costs 10¢/kW h.
For 'all electricity,' including off-peak, we quote actual costs. One MtC = 1 million metric tons of carbon. For the US mix of generated power, about 0.167 kg of C (as CO_2) is released for each kilowatt hour of electricity sold.

prototype buildings: single-family residences (old and new), offices (old and new), retail stores (old and new), schools (primary and secondary), hospitals, nursing homes, and grocery stores. Energy savings were then scaled by factoring in local energy prices, HVAC equipment saturations, observed distribution of local roof albedos, and available roof area, to estimate net savings in metropolitan-wide energy use. The results for these 11 metropolitan areas are shown in Fig. 1.

The savings for the 11 metropolitan areas were extrapolated to arrive at an estimate of national savings. The results showed a direct savings of about 3% in electricity use for cooling. According to the L.A. calculations, the direct effect of cool roofs is only about 26% of the total direct and indirect savings possible for light-colored surfaces (roofs and pavements) and trees. Scaling up the national savings from direct effects of light-colored roofs (3%) to include all cool community measures (to account for direct and indirect effect of cool surfaces and shade trees), we obtain a savings of about 11%; we round this off to a 10% savings to estimate the national impact.

Table 4 shows the nationwide A/C savings possible in 2015 assuming this 10% reduction below the Energy Information Agency's (EIA) assumed base case [29]. The avoided 40 B kW h/year is the typical product of 8 large (1-GW) power plants, each one costing about US$1B or more.

9. Summary and conclusions

Our analysis indicates that we can reduce the L.A. heat island by as much as 3°C. Cooler roof and paving surfaces and 11 M more shade trees should reduce ozone exceedance by 12% in Los Angeles and by slightly less in other smoggy cities. This 12% improvement exceeds that estimated for cleaner-burning gasoline and dramatically exceeds our estimates for reductions from electric or hybrid vehicles. The combined direct and indirect effect of the cool communities strategies can potentially reduce air-conditioning use in a Los Angeles home by half and save about 10% of A/C use of a one-story office building. The total direct and indirect annual savings in the L.A. basin, including that attributable to smog reduction, is estimated at US$0.5 B per year. The corresponding national A/C saving is about 10%.

Significant steps towards implementation were taken in 1997. These steps (as well as future steps needed) are discussed in Section 5 and Section 6.

Acknowledgements

This work was supported by the US DOE and the US Environmental Protection Agency under Contract No. DE-AC0376SF00098. We wish to thank Stephen J. Konopacki for the DOE-2 simulations, Dr. Haider Taha for his climate and smog simulations. Allan Chen and Laurel Cook editorial advice. Dr. Alan Lloyd, former chief scientist, and Henry Hogo, Julia Lester, and Joe Cassmassi at South Coast Air Quality Management District, have over the years provided data for our meteorological and urban airshed modeling, along with advice and helpful criticism.

Appendix A

Avoiding CO_2 and delaying global warming: urban trees vs. forest trees

Remedies offered to counter the threat of global warming typically include (1) abating the combustion of fossil fuel and deforestation, and (2) reforestation, thus extracting CO_2 from the atmosphere and sequestering carbon in biomass. While our strategies satisfy both of these goals, our calculations reveal that using trees to shade buildings serves to prevent carbon (C) from being burned much more than it serves to directly sequester carbon.

Our purpose here is to compare the amounts of CO_2 emission avoided by a tree (conserving electricity used for air conditioning) with the amount of C sequestered in that tree. The results, shown in Table A, col. C, show that it is about three times more effective in terms of CO_2 emissions to plant an urban tree to shade a building and to cool a community than it is to plant it in a forest.

In Table A, we consider the intermediate case of an older residence (built before Title 24 took effect in 1975) whose savings fall in the middle (50% more than for a new home, but only 1/5 the savings from an office building). We converted part of Table A (for a shade tree in L.A.) from dollars-avoided to carbon-avoided (= 15 kg/year) and compared it with the carbon directly sequestered in a growing tree (= 4.5 kg/year). Of course, it is less expensive to grow a tree in a forest than in a city, but not necessarily US$9/year cheaper (see Table A, col. A), even ignoring another US$16/year benefit from smog reduction.

Today, companies and foundations concerned with greenhouse gases are planting trees in the US and in rainforests [30–32]. We strongly urge that the SCAQMD and the Los Angeles utilities work to attract some of these tree programs and to allow RECLAIM/Area source credits.

The inputs to Table A are set in boldface; the conversions among US$ (for A/C electricity saved), kW h (saved), and avoided carbon are explained below. The direct saving from shade trees (row 1, col. A) is US$6/year per tree (see Table 2, row 3), which includes the winter penalty. The savings from evapotranspiration of trees are obtained by dividing the annual US$35 M indirect savings of trees (Table 3, row II) by 11 M, i.e., US$3.2/year per tree. The energy saved is derived from the price of electricity, US$0.10/kW h. The amount of C released as CO_2 by the production of 1 kW h of electrical energy, adjusted for transmission and distribution losses, is 0.167 kg C/kW h [29].

For savings attributable to sequestration of C (row 2, col. C), we consulted Dr. McPherson, of the US Forest Service in Davis, California. He suggested that our 20-year-old shade tree would contain about 90 kg of sequestered carbon (above and below ground). Thus, the 20-year average sequestering rate is 4.5 kg/year, which is only about 30% of the 15 kg/year C avoided by a shade tree.

Table A: impact of single shade tree on reduction of air conditioning usage and atmospheric CO_2 vs. comparable reduction from carbon sequestration of the tree

	A US$/year saved per tree	B kW h/year avoided per tree	C Reduction in kg C/year
Total A/C savings	**9**	92	15
Shade	**6**	60	10
Evapotranspiration	**3.2**	32	5
Carbon sequestration	0.1 (n/a)	n/a	**4.5**

The conversion from kW h (col. B) to carbon (col. C) is for the US mix of electricity. In 1995, DOE/EIA/AEO-96 (Ref. [29]) shows that 3000 TW h sold emitted 500 MtC, so 1 kW h emits 0.167 kg C.

Appendix B

List of acronyms

ASHRAE	American Society for Heating Refrigeration and Air-conditioning Engineers
ASTM	American Society for Testing Materials
BAAQMD	San Francisco Bay Area Air Quality Management District
CABO	Council of American Building Officials
CEC	California Energy Commission
DOE	US Department of Energy
DOD	US Department of Defense
DSM	Demand Side Management
EPA	US Environmental Protection Agency
LEV	Low-emission vehicles
NAAQS	National Ambient Air Quality Standard
PV	Present value
RECLAIM	REgional CLean Air Incentive Market
SCAQMD	South Coast Air Quality Management District
SIP	State Implementation Plans for ozone compliance
SRI	Solar reflectance index
ZEV	Zero-emission vehicles
ppbv	parts per billion by volume

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