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A simple tool for estimating city-wide annual electrical energy savings from cooler surfaces

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ABSTRACT

We present a simple method to estimate the maximum possible electrical energy saving that might be achieved by increasing the albedo of surfaces in a large city. We restrict this to the "indirect effect", the cooling of outside air that lessens the demand for air conditioning (AC). Given the power demand of the electric utilities and data about the city, we can use a single linear equation to estimate the maximum savings. For example, the result for an albedo change of 0.2 of pavements in a typical warm city in California, such as Sacramento, is that the saving is less than about 2 kWh per m^2 per year. This may help decision makers choose which heat island mitigation techniques are economical from an energy-saving perspective.

Keywords: Urban heat island mitigation; Electrical energy saving; pavements; Albedo; Cool surface

Introduction

The fact that cities are warmer than their rural surrounds is well established (US EPA, 2015). In hot cities, this excess heating exacerbates the demand for air conditioning (AC) with the resulting environmental penalties of additional energy consumption and air pollution. To counter these costly consequences, the causes of the excess heating need to be addressed. One of the causes that has been identified is dark surfaces of pavements and roofs. Surfaces are dark because they absorb visible light. Dark surfaces thus absorb sunlight and become warm. Air passing over such surfaces is heated more than if the surfaces were lighter-colored and cooler. There has been extensive effort and success in making cooler roofs. The research on cooler pavements has been reviewed recently (Santamouris, 2013). Most research asked the question, can cooler surfaces be made? In this paper we take the viewpoint of the potential consumers of this research (public-works decision makers) who may ask the question, how much electrical energy (which translates to money) can it save?

We wish to provide a tool that requires the input of few, accurate and readily available data about the city that is contemplating cooler surfaces. The output should be a useful estimate of the potential savings. We aim to estimate an upper limit to the saving in annual energy that a cooler surface may offer. With this information a decision can be made about whether a proposed mitigation strategy may be cost effective and should be pursued.

Previously, calculations of the energy savings due to cooler air have been performed by a modeling or "bottom-up" approach: starting with simulations of the AC energy used by a distribution of buildings in the weather of a typical year. A simulation is then made of the effect of higher-albedo surfaces on the outside air temperature of the city during a year. The modified weather is used to recalculate the AC energy use of the buildings. The difference of the energy

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simulations is the electrical energy saving. For example, when this method was applied to the Los Angeles Basin, an increase in albedo of 0.25 in an area of pavement of 1250 $km^2 = 1.25 \times 10^9$ m^2 was predicted to achieve savings of electricity worth US $15M/y (and ozone reduction valued at US $76M/y) (Rosenfeld et al 1998). Another example of this approach is the extensive work of Akbari and Konopacki (Akbari and Konopacki, 2005).

In this paper we propose a "top-down" method, using input data for the entire city. Starting with the system-wide power demand (i.e. rate of electricity use for all purposes) we extract the maximum demand for AC power, and calculate the maximum dependence of the AC power on temperature. We then estimate the maximum change in temperature that a change in albedo might cause. We again use properties of the entire city: the maximum diurnal temperature swings, the areas of modified surfaces, and the original and raised albedos of modified surfaces. Combining the maximum temperature dependence of the AC demand with the maximum temperature change caused by the albedo change, we estimate maximum change in AC energy use in the entire city in a year. The results are simple one-line equations. This will allow decision-makers to quickly estimate the maximum energy savings and then compare to the costs of a proposed modification.

Methodology and assumptions

We wish to estimate an upper limit to the savings that may result from lowering the outside air temperature by making surfaces cooler, finally resulting in less AC energy being consumed. We refer mostly to pavements. The method should also be applicable to roof surfaces when adjustments are made for the differing thermal resistances and thermal emittances, and the facts that pavements are closer to people but are shaded more.

We shall be concerned only with how much AC energy is saved because buildings are now in a slightly cooler environment. This has been called the "indirect effect". We ignore the AC energy saved in air-conditioned buildings that result from less heat flowing into their top story due to having cooler roofs (the "direct effect" that is widely studied elsewhere). We also ignore the effect of the sunlight reflected from pavements that is absorbed by the walls and through the windows of buildings and thus increases the AC demand. This is an additional kind of direct effect that might be called a "reflection effect". This could either increase or decrease building cooling loads, depending on the extent to which increased day lighting can displace the need for artificial lighting. We thus present a simple method for estimating the maximum energy saved in the entire city in a year as a result of lowering outside-air temperature. Conveniently, this will depend on readily obtained data of the city: the hourly electricity demand and the number of cooling hours in a year. Of course, it also depends on the change in the outside air temperature.

To estimate the maximum decrease in outside air temperature when an area of surface has its albedo increased, we recall an earlier simple "top-down" method (Pomerantz et al. 2000). There it is shown that the temperature decrease also depends on properties of the entire city such as maximum diurnal air-temperature swings and areas modified. (While the surfaces heat the air, in the indirect effect it is the air temperatures that affect the AC. Thus, the only temperatures mentioned henceforth are the air temperatures.) The method assumes that the city area is big enough so that the air temperature is significantly determined by the albedo within its own area. Wind from the outside the city can only reduce the effect of albedo changes. By ignoring the wind we obtain the maximum effect of the albedo changes, which is our goal. We review below

this method for estimating the maximum air temperature decrease. This computation completes the estimation of the maximum energy savings in the city in a year.

Multiplying the annual AC energy saving by the price of electricity and dividing by the area of surface modified, we then obtain the annual monetary saving per unit area of surface modified. If the extra cost for a high albedo surface is much greater than this saving, the pavement is uneconomical from the energy-saving viewpoint. This is one of several factors that may help decide whether to go forward with a project. We now present some details.

Estimate the electrical energy savings due to cooler temperatures

We start with the definition of power as energy delivered per unit time. If the hourly mean air temperature T_i changes by ΔT_i, the hourly mean AC power demand in the entire city changes by $\Delta P_i = (dP/dT)_i \cdot \Delta T_i$, where subscript *i* indexes the hour of the year. Here *P* refers only to the power used for AC, and ΔT_i refers to the changes in air temperature due to changes in surface albedos. We will show below simple ways to estimate these quantities. The AC energy saved in hour *i* is

$$\Delta E_i = \Delta P_i \cdot \tau \ . \qquad (1)$$

where fixed interval τ = 1 h.

To find the annual AC energy savings, ΔE_a, we sum over all the hours in a year during which the AC is on

$$\Delta E_a = \sum_i^{+} \left[\left(\frac{dP}{dT} \right)_i \cdot \Delta T_i \cdot \tau \right] \qquad (2)$$

where ΔT_i is the air temperature change in that hour that is caused by the change in albedo. The + superscript indicates that the sum is taken only over those hours during which the AC is operating. $(dP/dT)_i$ and ΔT_i vary with the hour of year, so that the sum is difficult to evaluate in general. However, because we are seeking the maximum energy savings, we will use maximum average values of $(dP/dT)_i$ and ΔT_i. (We explain in the Appendix what we mean by "maximum" and that they occur on days of high temperatures.) To estimate the AC power demand we need data of utility system power vs time on otherwise similar days with and without need for AC. Such data of system power vs time are often difficult to obtain from utility companies. Depending on the availability of the data on system power vs time, we present two approaches.

1. **Maximum energy saving if system power demand data vs time is available**

To find the maximum energy saving, we apply Eq. (2) but insert the maximum values, $(dP/dT)_{max}$ and dT_{max}. We explain below how to find these maximum values from city-wide data. Because they are constants, we take them out of the sum. Because we apply maximum values for these constants, this will surely overestimate the sum. Then Eq. (2) reduces to the simple relationship:

$$\Delta E_a < \left\{ \left(\frac{dP}{dT} \right)_{\max} \cdot \Delta T_{\max} \right\} \cdot \sum_i [\tau]^+ \qquad (3)$$

The remaining sum is the annual hours of AC operation. This can be approximated by the total hours during which the air temperature is above a reference (or base) temperature, T_0. By choosing a low reference temperature we can be sure that we exceed the likely hours of operation. We choose the conventional T_0 = 18 ºC (65 ºF); in fact, this reference temperature gives an overestimate of the hours of operation because few air conditioners turn on at this temperature. Let CH18C ("cooling hours to base 18 ºC") represent the annual hours during which T > 18°C. Because $\sum_i [\tau]^+ \leq$ CH18C,

$$\Delta E_a < \left\{ \left(\frac{dP}{dT} \right)_{\max} \cdot \Delta T_{\max} \right\} \cdot \text{CH18C} \quad . \qquad (4)$$

We now give an example of how we obtain $(dP/dT)_{\max}$ if the hourly power demand of a utility system is known. By the courtesy of the Sacramento Municipal Utility District (SMUD) power company, we obtained the hourly electrical power demand data for their entire system for the year 2012. We graph in Fig. 1 the system demand as a function of time during two specific days, one hot and one mild. To obtain the maximum dP/dT we chose a hot day of the year, 8 Aug 2012, when the outside air temperature reached 37 ºC (99 ºF). However, this system demand contains both AC and other electrical uses (we refer to the non-AC load as the "base load"). To isolate the maximum AC load we compare with the load on a mild day that has no AC but is as similar to 8 Aug as possible. Such a day is 2 May 2012. These days are equally spaced about the summer solstice (the daylight is the same), and both are Wednesdays. The base uses should be as nearly equal as possible. Fortunately, on 2 May the temperature peaked at only 21 ºC (69 ºF) so there was virtually no AC. Thus the 2 May data represent the base system load. The striking difference in loads between the two curves in Fig. 1 is what we wish to reduce by lowering the air temperature. We refer to this difference as the 'AC component' or 'AC load' or 'AC demand'.

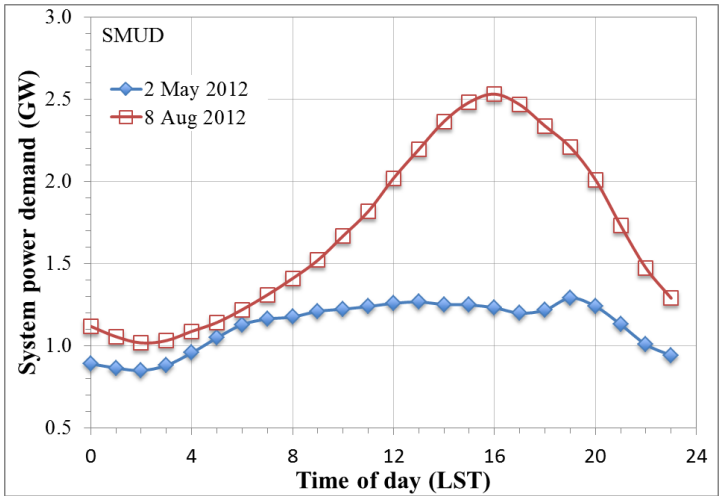

Figure 1. Hourly power demands on the SMUD system on 8 Aug 2012 and 2 May 2012.

To extract the AC component of the total 8 Aug load, we subtract the 2 May load. We plot this difference in power demand, the maximum AC demand, vs time in Fig. 2. Also in Fig. 2 we plot the air temperatures on 8 Aug 2012.[1] The similarity of the shapes of the curves suggests correlation between the AC demand and the air temperature.

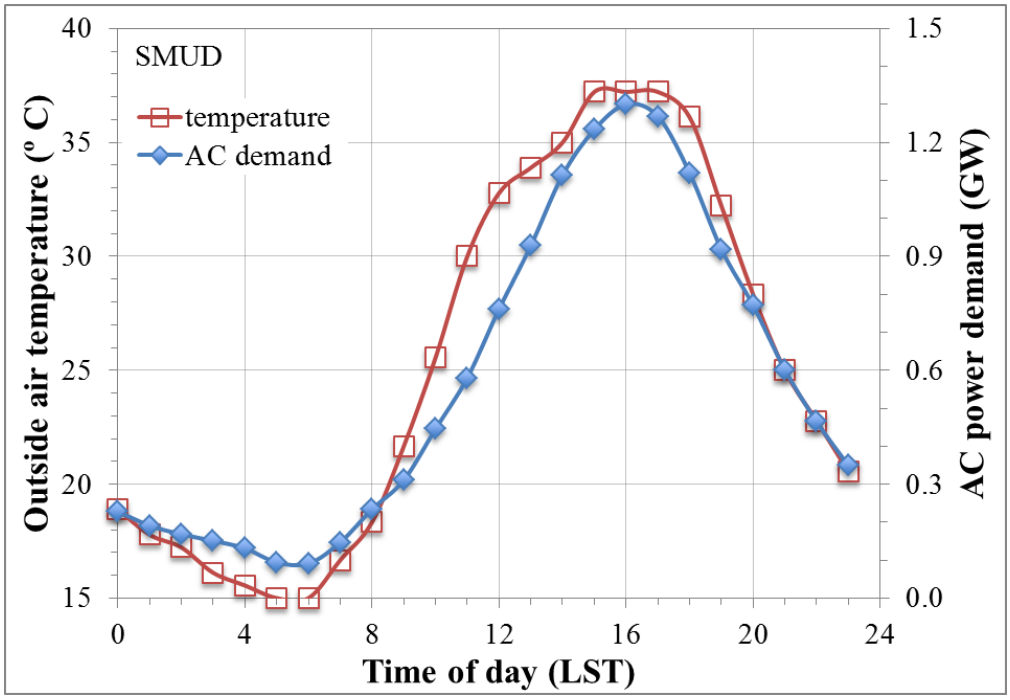

Figure 2. Air temperature and estimated SMUD AC power demand on 8 Aug 2012.

To quantify the correlation, we graph in Fig. 3 the AC power demand vs the air temperatures. The linear fit to the data for temperatures above 18 ºC has a coefficient of determination $R^2 = 0.93$. *The slope of the line is the desired quantity* $dP/dT = 0.053$ *GW/ºC (= 0.029 GW/ºF) for SMUD.*

[1] Establishing the exact meaning of the "time" of some parameter is troublesome because there is no uniform reporting standard. Hours are reported variously as "1 - 24" or "0 - 23", often without stating when they start. The most clear is "hh:mm". It is often unclear whether the parameter value is exactly at that time or some average before or after the stated time. We correct for standard time vs. daylight time. In California, weather data are reported in standard time, but the utilities' demand data are sometimes in daylight time. Our goal is to correlate energy demand with temperature. We thus align the peaks of demand with the peaks in temperature by shifting the data when necessary. For the SMUD data in Figs. 2 and 3, the temperature data have been shifted later by one hour.

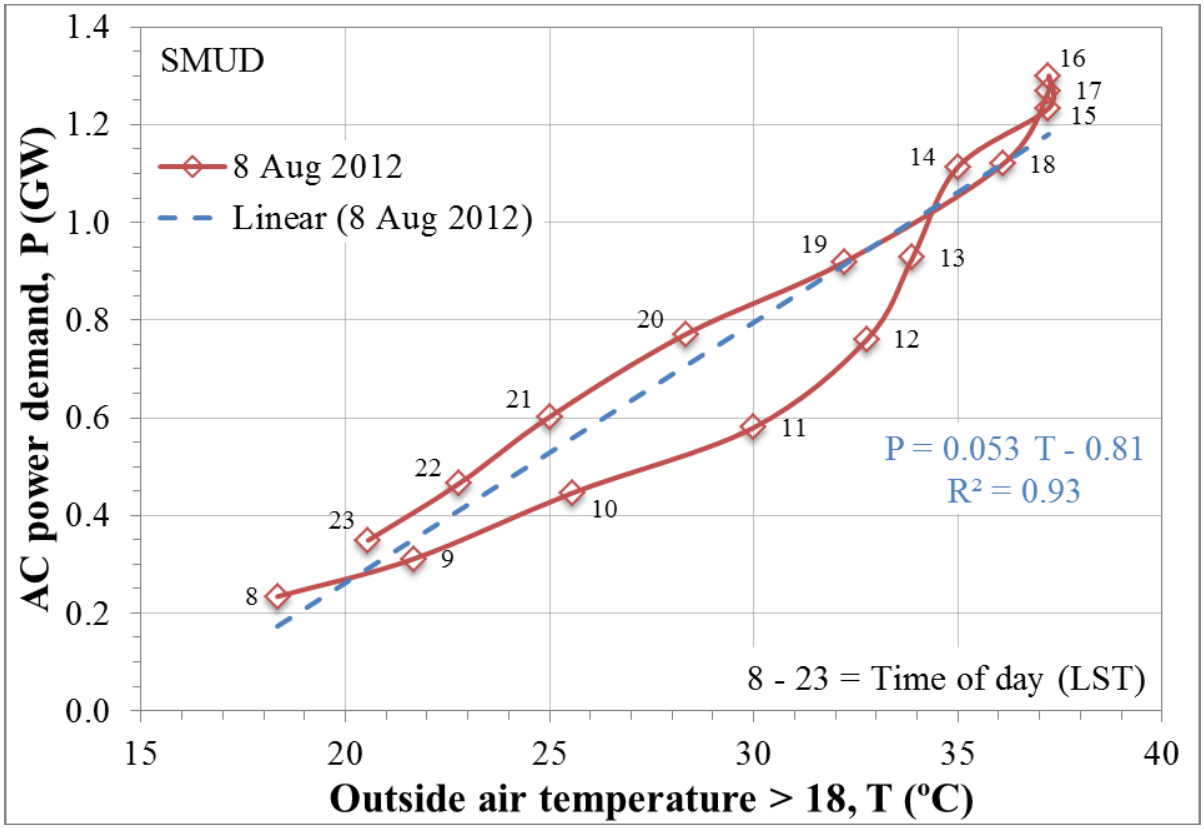

Figure 3. SMUD AC power demand (P) versus outside air temperature (T) > 18°C for 8 Aug 2012.

SMUD is actually a somewhat complicated case. The entire service area of SMUD has a population of about 1.5M (SMUD 2014) which includes the City of Sacramento and several smaller towns and farm areas. The City alone has about 0.5M people (United States Census Bureau 2014). Because the city is more urbanized than the other parts of the service area, we assume that the demand by the City alone is more than its fraction of the population of the entire service area. We make the considerable overestimate that the City of Sacramento uses 2/3 of the total demand on SMUD. Correspondingly, we take the slope of *P* vs *T* for the City to be 2/3 of 0.053 GW/ºC or 0.035 GW/ºC. This is the value entered in Table 1 for the City of Sacramento.

We have applied this analysis to several warm cities in California for which we have obtained complete annual power demand data. There are a number of cities that have their own electric utility companies that provide power only within the city boundaries. This obviates the complications of SMUD and makes the calculations simpler and more accurate. These include Burbank, Glendale, Los Angeles, and Pasadena. The input data and the results are shown in Table 1. Note that despite the large range of city sizes, there is one characteristic parameter that is relatively constant, D_{max}. This will be explained in the next section. It hints at an important regularity in the electrical energy demands for cooling.

Utility - year (major city)	**'Maximum' slope, $(dP/dT)_{max}$ (GW/ ºC)**	**Base demand, P_b (GW)**	**Normalized slope parameter, D_{max} ($ºC^{-1}$)**	**Annual CH18C (h/y)**	**Max diurnal temperature swing, $T_{d,max}$ (ºC)**	**Service area, A (km^2)**
Burbank Water and Power (BWP) - 2012 (Burbank)	0.0081	0.14	0.057	3000	16	45
Glendale Water and Power (GWP) – 2012 (Glendale)	0.0089	0.14	0.064	3000	16	79
Pasadena Water & Power - 2012 (Pasadena)	0.0083	0.14	0.058	3000	16	59
Riverside Public Utility (RPU) - 2012 (Riverside)	0.015	0.25	0.060	3000	16	211
Sacramento Municipal Utility District (SMUD) - 2012 (Sacramento)	0.053	1.2	0.044	2600	17	NA
Los Angeles Department of Water and Power (LADWP) - 2012 (Los Angeles)	0.13	3.3	0.039	2600	7	1250
San Diego Gas and Electric (SDGE) - 2013 (San Diego)	0.09	2.5	0.036	3800	7	NA
City of Sacramento (*approx.*)	0.035	0.8	0.044	2600	17	250

Table 1. Data for various utilities and cities in California.

2. Estimating maximum energy saving if system power demand vs time is not available

Even if complete system power data as a function of time are not available, $(dP/dT)_{max}$ can be estimated. Clearly $(dP/dT)_{max}$ depends on the number of customers (reflected in the total demand) on the electrical utility company. We thus normalize $(dP/dT)_{max}$ by dividing it by the base (non-AC) power demand, denoted by P_b. P_b is determined, for Sacramento as an example, from the data of 2 May 2012 in Fig. 1 to be P_b = 1.2 GW. We define the normalized

slope parameter D_{max} by $(dP/dT)_{max}/P_b = S\,D_{max}$. The meaning of D_{max} is simply that, when multiplied by 100, it is the maximum percentage change in the base power per unit change in temperature. S represents the saturation of AC (or prevalence or fraction of buildings with AC) in the city. ($S \approx 1$ in hot cities like Phoenix, AZ, and $S \approx 0$ in Fairbanks, Alaska.) We are concerned with hot cities for which $S \approx 1$; for cooler cities the savings will be less. To estimate the maximum energy savings, we take $S = 1$. Substituting $(dP/dT)_{max} \approx D_{max}\,P_b$ in formula 3 we get

$$\Delta E_a < D_{max} \cdot P_b \cdot \Delta T_{max} \cdot \sum_i [\tau]^+ \qquad (5)$$

Again, because CH18C is greater than the sum in (5) we can substitute CH18C for it. This will also overestimate the savings. The result is

$$\Delta E_a < D_{max} \cdot P_b \cdot \Delta T_{max} \cdot \mathrm{CH18C} \qquad (6)$$

This formula may be further simplified if the parameter D_{max} is independent of the city. To check the hypothesis of the constancy of D_{max}, we determined D_{max} for several other warm cities in California. The results, shown in the fourth column of Table 1, confirm that it is approximately constant. $D_{max} \leq 0.05 \pm 0.01$ / ºC in all the cases we know. The EPA Heat Island website quotes other research that suggests that the change in demand is ≤ 3 % per ºC. (US EPA, 2015) Because we are seeking maximum values of the energy saving, we will use the value of 6% / ºC for California.

One may expect variations caused by the climates and relative efficiencies in various jurisdictions. Thus, for cities for which system load as a function of time is not available, we propose to use

$$\Delta E_a < D_{max} \cdot [P_b] \cdot [\mathrm{CH18C}\ ] \cdot [\Delta T_{max}] \qquad (7)$$

with D_{max} = 0.06/ ºC = 0.03/ ºF for the cases we have examined in California; other places may differ. This means, for temperatures above 18 ºC, the maximum decrease in power demand is less than 6% of the base power for each decrease of air temperature by 1 ºC.

The quantities in [ ] brackets in formula 7 are specific to the city of interest. P_b is obtained from power companies. CH18C is found from weather data (Olsen et al. 2014). Thus all the relevant parameters are easily available with good accuracy, except for the maximum change in air temperature due to albedo change, ΔT_{max}. We show how to estimate this change in air temperature in the next section of this report.

Estimate air temperature reduction due to reflective surfaces

We estimate the order of magnitude of the effect of change in surface albedo on air temperature using a simplified method. Our approach is based on the physical fact that the daily swings in air temperatures are caused by the transfer of heat from the solid surfaces to the air, not the direct absorption of sunlight by the air. In an earlier paper (Pomerantz 2000) we derived the effect on air temperature caused by reducing the solar absorptance of a surface to a lower value,

$\alpha_{j,\mathrm{L}}$, from a higher value, $\alpha_{j,\mathrm{H}}$. (Solar absorptance α = (1 – albedo); j refers to the type of surface – pavements, roofs, vegetated – and L and H indicate the low and high solar absorptance values of the modified surface). Briefly, the calculation is based on the approximation that the contribution of a surface to the air temperature is proportional to the absorptance and the area of the surface. These linear dependences were verified recently by modeling studies. (Li, Bou-Zeid, and Oppenheimer, 2014.) A surface of type j contributes an amount T_j to the total daily (diurnal) air temperature rise between the daily low temperature and the daily high, $T_\mathrm{d} = T_\mathrm{high} - T_\mathrm{low}$, such that

$$\frac{T_j}{T_\mathrm{d}} = \frac{\alpha_j \cdot A_j}{\sum \alpha_k \cdot A_k} \tag{8a}$$

The sum is over all the different surfaces, k, in the city, each having an absorptance α_k and area A_k. If the absorptance of surface j is changed from a high value $\alpha_{j,\mathrm{H}}$ to a lower value $\alpha_{j,\mathrm{L}}$, and we define absorptance change as $\Delta\alpha_j = (\alpha_{j,\mathrm{L}} - \alpha_{j,\mathrm{H}})$, the fractional contribution of the surface j to T_d changes by

$$\frac{\Delta T_j}{T_\mathrm{d}} = \frac{\Delta\alpha_j \cdot A_j}{\sum \alpha_k \cdot A_k} \tag{8b}$$

Defining the city-wide area-weighted average absorptance, $<\alpha>$, by $<\alpha> A = \sum \alpha_k \cdot A_k$, where A = area of the entire city, we obtain

$$\Delta T_{j,\max} \approx \left\{ \frac{A_j}{A} \cdot \left\lceil \frac{\Delta\alpha_j}{<\alpha>} \right\rceil \right\} \cdot T_{\mathrm{d,max}} \tag{9}$$

In Eq. 9 we have neglected the change in $<\alpha>$ due to the change in α_j of the j^{th} fraction of surface; this is a second order effect. We have also substituted the maximum diurnal temperature change, $T_{\mathrm{d,max}}$, in order to obtain the maximum air temperature change due to surface j, $\Delta T_{j,\max}$.

Eq. 9 simply says that the total change in air temperature is apportioned to the heated surfaces according to how hot they get and what fraction of the total area they are. With the goal of getting the maximum electrical energy saving, we applied the maximum diurnal temperature swing. We make the approximation that in sunlight the differences between the temperatures of surfaces and the outside air temperatures depend only on the albedos of the surfaces.[2] A second implicit approximation is that the diurnal temperature cycle in local air temperatures is caused by the heating of the solid surfaces in the area of interest (i.e., neglect wind from outlying areas). Wind from the outside can only decrease the effect of albedo changes, so the estimate in Eq. 9 is a maximum change, as desired. Note that Eq. 9 also relies on the additivity of the effects of the various surfaces of the city. Taha's (2008) simulations have demonstrated that the rise in air temperature is the sum of the effects of the impermeable surfaces and trees.

[2] It is imprecise because it neglects differences in thermal emittance and thermal conductance among the materials of the surfaces. Pavements have higher thermal conductivities than roofs so that they are cooler than roofs of the same albedos. However pavements may have a larger effect than roofs because the heat from roofs rises and may not affect people as much as pavements do. Thus the effects of thermal conduction and height act to offset each other. We estimate that the assumption of equal effects of roofs and pavements may introduce errors of as much as 30%.

Eq. 9, as simple as it is, gives close agreement with full meteorological simulations of the effect of albedo changes. As an example, take an albedo change of 0.2 ($\alpha_{j,\mathrm{L}} = 0.7$, $\alpha_{j,\mathrm{H}} = 0.9$) and typical values for pavements in a large city: $A_j / A = 1/3$, $<\alpha> = 0.8$ and $T_{\mathrm{d,max}} = 14$ ºC (25ºF). (Pavement fraction from Akbari, et. al, 1999) Eq. 9 then predicts that the cooler pavement will produce a maximum air temperature change, $\Delta T_{\mathrm{j,max}} \approx$ -1.2 ºC (-2.1ºF). This is indeed at the high end of the range of simulated air temperature decreases, as reported in the literature (Santamouris, 2013, Table 2; Taha 2013, Fig. 4).

Estimates of the energy savings per unit area and final formulas

Here we collect the results of the previous sections.

In case 1, when hourly data for system power are known, we combine formulas 4 (energy saving) and 9 (the maximum change in air temperature) to obtain the upper bound of the annual change in the AC energy:

$$\Delta E_{\mathrm{a}} < \left(\frac{dP}{dT}\right)_{\max} \cdot \mathrm{CH18C} \cdot \left(\frac{A_j}{A}\right) \cdot \left[\frac{\Delta\alpha_j}{<\alpha>}\right] \cdot T_{\mathrm{d,max}} \qquad (10)$$

In case 2, where hourly load data are not available, we combine formulas 7 (energy savings) with 9 (the maximum change in air temperature) to obtain

$$\Delta E_{\mathrm{a}} < (0.06\ /\ ^{\circ}\mathrm{C}) \cdot P_{\mathrm{b}} \cdot \mathrm{CH18C} \cdot \left\{\frac{A_j}{A} \cdot \left[\frac{\Delta\alpha_j}{<\alpha>}\right] \cdot T_{\mathrm{d,max}}\right\} \qquad (11)$$

where we have substituted the empirically determined value $D_{\max} < 0.06$ / ºC for moderately hot cities in California.

More relevant is the cooling energy cost savings compared to the premium cost associated with cool pavement implementation. Although the construction cost will depend on the method used and local costs, we can estimate the maximum annual savings per unit area. To calculate the annual savings per area, we simply divide formulas (10) and (11) by the area that is modified, A_j, to get

$$\frac{\Delta E_{\mathrm{a}}}{A_j} < \left(\frac{dP}{dT}\right)_{\max} \cdot \frac{CH\ 18\,C}{A} \cdot \left[\frac{\Delta\alpha_j}{<\alpha>}\right] \cdot T_{\mathrm{d,max}} \qquad (12)$$

$$\frac{\Delta E_{\mathrm{a}}}{A_j} < (0.06\ /\ ^{\circ}\mathrm{C}) \cdot \left[\frac{P_{\mathrm{b}}}{A}\right] \cdot \mathrm{CH18C} \cdot \left[\frac{\Delta\alpha_j}{<\alpha>}\right] \cdot T_{\mathrm{d,max}} \qquad (13)$$

These have the advantage that the area of the city, A, is an easily obtained datum; the less-easily obtained 'area of pavement' does not appear. (United States Census Bureau 2014) Note that all the parameters in formulas (12) and (13) that characterize the albedo change and power demand should be accessible to decision makers. Answers are obtained by simple multiplication and division. But the complication is to find the P_{b} of the corresponding area of the city (as distinct from the total load in the utility service area which may encompass more than the city, but is usually the best data available). Utility service areas are often not commensurate with political boundaries.

Results

As examples of the application of formulas 12 and 13, we take a change of the albedo of pavements from 0.1 to 0.3 (change of absorptance $\Delta\alpha$ = - 0.2) and average absorptance $< \alpha >$ = 0.8. We apply this to several cities and utility companies and present the results in Table 2.

Energy savings

Applying the first method, formula 12, in which hourly load data are known for the entire urbanized service area, we estimate the maximum AC energy savings of the power companies of Burbank, Glendale, Pasadena, Riverside, Sacramento and Los Angeles. For Sacramento, for example, using the values in Table 1, formula 12 predicts that the annual cooling energy saved per square meter of modified pavement is $\Delta E_a / A_j$ < 1.6 kWh/y·m^2. The results for all the cities are presented in Table 2, column 2.

City or county (Utility)	**Max energy saving per year and square meter, $\Delta E_a/A_j$ (kWh / y·m^2) by formula 12.**	**Max energy saving per year and square meter, $\Delta E_a/A_j$ (kWh / y·m^2) by formula 13.**	**Max monetary saving from energy saving ($ / y·m^2)**
Burbank (BWP)	2.0	2.2	1.6
Glendale (GWP)	1.2	1.3	1
Pasadena (PWP)	1.6	1.7	1.3
Riverside (RPU)	0.9	0.9	0.6
Sacramento (SMUD) (approx.)	1.6	2.1	1.1
Los Angeles county (LADWP)	0.8	0.7	0.4

Table 2. Maximum possible annual electrical energy and cooling cost savings resulting from an increase in pavement albedo of 0.2 (change of absorptance = - 0.2) for various cities and their utility companies in California.

To test the second method, formula 13, we apply it to the same power companies (pretending that we do not have all the hourly data). Thus, we substitute in formula 13 the appropriate values listed in Table 1. We present the results in the third column of Table 2. There is agreement with the first method to within a factor of 2 in the worst case. The important result is that the maximum possible savings are < 2kWh/ y·m^2 in both methods. To get a feeling for the magnitude of this energy saving, a kWh is about the energy a microwave oven uses in an hour.

Monetary savings

The cost of a kWh of electrical energy varies with the utility company. We consider here some examples of California utilities. In addition, in recent years the concept of "Time-of-Use" (TOU) is being applied to the cost of energy. This is the idea that the cost of energy increases during times of high demand. In the case of electrical energy, the cost may be greater for a

number of reasons including: the cost of building power plants that are unused most of the year, less efficient plants are turned on to meet peak demand, energy may be transmitted from more distant sources, effects of pollution may be greater. Also, the peak demand and the TOU cost will vary with the climate. The energy avoided by reducing AC demand occurs at the times of peak electricity demand so that TOU pricing is relevant. We use TOU prices kindly provided by Energy and Environmental Economics group, who are preparing such information for the California Energy Commission (Price and Cutter 2014). Results for several cities are listed in column 4 of Table 2. They are obtained simply by multiplying the energy savings in column 2 by the corresponding TOU price. (Price and Cutter 2014)

As examples: for the City of Sacramento, the average TOU cost over the cooling season is estimated at US \$0.67/kWh. Thus the saving is < US \$1.1/y·m^2. The saving accrue over the lifetime of the pavement. The order of magnitude of pavement lifetimes is ten years. Over a 10-year lifetime, the AC energy saving is worth < US \$10 /m². For LADWP, which is in a slightly cooler climate zone, the cooling-season average TOU cost is about US \$0.45/kWh. This gives a maximum monetary saving of < US \$0.36/y·m^2. Over a 10-year lifetime, the energy saving is < US \$3/m².

To compare with the savings per area calculated with a modeling or "bottom-up" approach, we refer to the study of the Los Angeles Basin (Rosenfeld et al. 1998). Annual electrical energy cost saving due to cooler pavements was estimated at \$15M/y, but TOU pricing was not applied in that report. A price of about US \$0.10/kWh was used. Adjusted for differences in assumed parameters ($\Delta\alpha$ = - 0.25 in Rosenfeld, et al, $\Delta\alpha$ = - 0.20 chosen here), the savings would be about \$12M/y. The pavement in the LA Basin comprised an area of 1250 km^2 = 1.25×10^9 m^2 in that study. Thus, the annual electrical energy monetary saving per square meter was about \$0.01/y·m^2. This result is consistent with the top-down approach that, using a cost of \$0.10/kWh, predicts a saving of less than \$0.08/y·m^2.

Discussion and Conclusions

Using few, available and reliable data about a city, this method offers a quick estimate of the maximum electrical energy savings due to the indirect effect of cooler surfaces in large cities. All the approximations made tend to maximize the estimated savings. We have ignored several effects that lessen the benefits of cooler surfaces. For example, if winds come from the outside they will blow away and lessen the effect of the city's albedos. We ignored the reflection effect of additional sunlight striking buildings after reflection from the higher albedo pavements. We also ignored the penalty that more heating will be needed in winter. We also neglected that a pavement that starts with an albedo of 0.3 is likely to get dirty and have its albedo decline over its lifetime. Thus, our estimate of the maximum benefit is an even greater overestimate. If one wanted a closer estimate of the energy saving, the coefficient D_{max} could be divided in half, to account for the smaller slopes (dP/dT) at the more common lower temperatures. (See the Appendix for explanation.) It is likely that the benefits will be greatest for the hottest places, such as desert cities like Phoenix, Arizona. This will be accounted for by the parameters of the city, such as D_{max}, (dP/dT), CH18C and $T_{d,max}$. For relatively cooler places, such as Sacramento and the Los Angeles Basin, the annual electrical energy savings are less than 2 kWh/m², worth less than about \$1/m² at an energy price of US \$0.50/kWh. If there are paving options that have the same cost, it would be preferable to choose the higher-albedo option. There may be other benefits, such as reduced air pollution, that may be more valuable than the energy savings; that is outside the scope of this method.

This simple method may help decision-makers evaluate the economic benefits of higher-albedo surfaces as a means of reducing the demand for electricity. The cost premium associated with high albedo pavements should be compared to the economic value of all benefits, including electricity savings, peak power demand reduction, and air quality improvement.

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Appendix– the ‘maximum’ slopes and temperature changes

We clarify here what we mean by the “maximum” slopes and temperature changes. It is reasonable that, as the temperature rises above some base temperature, air conditioners stay on longer, and more air conditioners turn on, so that there is a non-linearly increasing AC demand. To see if this expectation is reflected in real data, examples from SMUD (Sacramento, CA) are shown in Fig. A.1. These show the slopes on progressively warmer days. When the highest T was 26 ºC, the slope dP/dT = 0.021 GW/ºC. When the high temperature was 31 ºC, dP/dT was 0.026 GW/ºC. As seen in Fig. 3, when the peak T was 37 ºC, dP/dT = 0.053 GW/ºC. Clearly, the average slope on a hot day is thus higher than on a cooler day. We refer to these high average slopes as “maximum slopes”. The use of the slopes from high-temperature days even for relatively cooler days insures that the maximum energy saving is estimated.

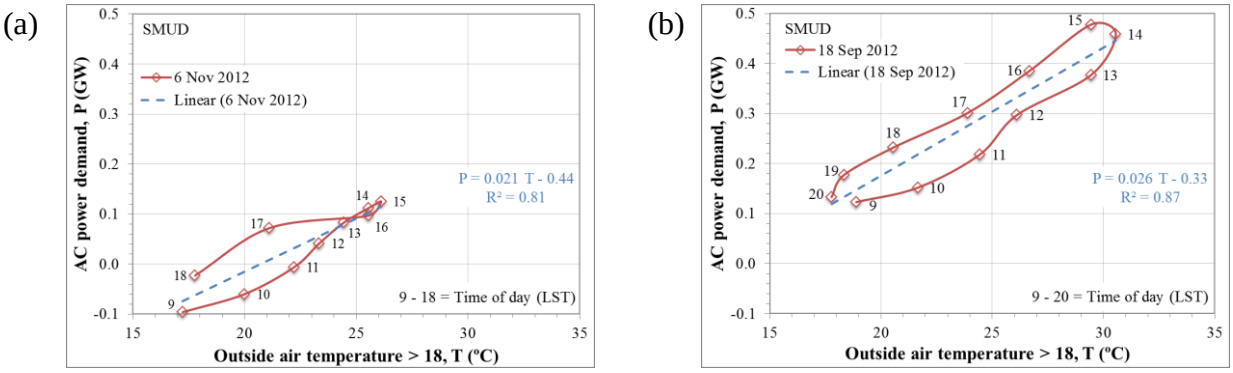

Figure A.1 AC hourly demand on the SMUD electrical system on progressively warmer days for (a) 6 Nov 2012 and (b) 18 Sep 2012. The average slope of the curves, dP/dT, increases from the cooler to the warmer day. A still higher T is shown in Fig. 3; on that hot day the average slope is the largest of all.

Likewise for the “maximum” temperature changes, we find from Eq. (9) an estimate of the largest temperature change that might be induced by albedo change. This occurs at the peak of the daily temperature. At other times the change in temperature is less. This is observed in simulations (Li, Bou-Zeid and Oppenheimer 2014, Fig. 7). Thus, the use of the maximum change in temperature for all hours of AC operation maximizes the estimate of electrical energy change.