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Are Cooler Surfaces a Cost-Effect Mitigation of Urban Heat Islands?

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ABSTRACT

Much research has gone into technologies to mitigate urban heat islands by making urban surfaces cooler by increasing their albedos. To be practical, the benefit of the technology must be greater than its cost. This report provides simple methods for quantifying the maxima of some benefits that albedo increases may provide. The method used is an extension of an earlier paper that estimated the maximum possible electrical energy saving achievable in an entire city in a year by a change of albedo of its surfaces. The present report estimates the maximum amounts and monetary savings of avoided CO_2 emissions and the decreases in peak power demands. As examples, for several warm cities in California, a 0.2 increase in albedo of pavements is found to reduce CO_2 emissions by < 1 kg per m^2 per year. At the current price of CO_2 reduction in California, the monetary saving is < US$ 0.01 per year per m^2 modified. The resulting maximum peak-power reductions are estimated to be < 7% of the base power of the city. The magnitudes of the savings are such that decision-makers should choose carefully which urban heat island mitigation techniques are cost effective.

Key Words: Urban Heat Island mitigation; maximum electrical saving; carbon dioxide avoided; peak power reduction; city-wide annual; cost effective

1. INTRODUCTION

The urban heat island (UHI) effect is a cause of concern because of the additional energy consumption and air pollution that it causes. (Akbari, et al, 2015) One way in which the air is heated is by contact with surfaces heated by the sun. Thus, an obvious way to try to cool the air is to make the surfaces more reflective of sunlight, e.g., make them whiter. Much effort has been expended in finding techniques that achieve higher albedos of city surfaces and to quantify the benefits. A major practical question, however, is whether the mitigation technique costs more than the benefit it produces. To be useful to decision-makers, the answer should be as direct and clear as possible. Earlier, a simple method was presented that can provide an estimate of the maximum cooling energy saving in an entire city in a year, caused by lowering the outside air temperature. (Pomerantz, Rosado & Levinson, 2015) It provides, in simple linear formulas, direct connections between the change in surface albedo and the maximum electrical energy saving. The parameters in the formulas characterize the entire city: hourly power demand, daily (diurnal) temperature swing, and annual hours of cooling. This is a "top-down" approach, as distinct from the "bottom-up" method of simulating individual buildings, and summing over the city in a simulated changed weather. (Rosenfeld, et al, 1998) Neither method addresses the benefits of cooler air regarding comfort, health, or global cooling. (An entirely different effect that is sometimes erroneously conflated with the UHI is the energy saving for an individual air-conditioned building that results from making its surfaces cooler; this is not considered here.)

In the present paper, the "top-down" method is applied to more cities than previously, and is extended to estimate the maximum CO_2 avoided and peak power reductions. Results for several warm cities in California, USA, are presented. A pattern becomes evident from which more general inferences can be drawn. The decision whether to implement a mitigation-measure depends on the local cost vs the local benefit.

2. Methodology

A method of estimating the maximum electrical energy savings caused by cooler surfaces was presented in an earlier paper (Pomerantz, et al, 2015). In brief, the method starts with the total power demand of an entire city (i.e. rate of electricity use for all purposes). From this is extracted the demand for air conditioning (AC) power on a hot day. Then the maximum dependence of the AC power on air temperature is derived. Next, the maximum change in air temperature that a change in albedo might cause is estimated. Again the properties of the entire city are inputs: the maximum diurnal temperature swings, the areas of modified surfaces, and the original and raised albedos of modified surfaces. Combining the maximum air temperature dependence of the AC demand with the maximum air temperature change caused by the albedo change, gives an estimate of the maximum change in AC energy demand in the entire city in a year. The results are simple one-line equations whose answers are compatible with the bottom-up approach, but are much simpler to apply.

There are thus two steps: 1) find the maximum change in AC energy due to a change in the air temperature and 2) find the maximum reduction of the city's air temperature due to an increase in the albedo of a surface of type *j* (such as pavements), $\Delta T_{j,\max}$.

It was shown that these can be estimated by Equations 1 and 2 below. The change in AC energy used in the entire city in a year, ΔE_{a} , is

$$\Delta E_a < \left(\frac{dP}{dT}\right)_{max} \cdot \Delta T_{j,max} \cdot CH\,18\,C\,(1)$$

where $(\mathrm{d}P/\mathrm{d}T)_{\max}$ is the maximum change in city-wide demand for AC power, P, due to a change in air temperature, T, and $CH18C$ is the number of cooling hours in a year (the number of hours in the year that the city has temperatures above the reference temperature 18 °C = 65 °F).

The $\Delta T_{j,\max}$ was shown (Pomerantz et al, 2000) to be

$$¿\alpha > ¿ \cdot T_{d,max}\,(2)$$
$$\Delta T_{j,max} < \frac{A_j}{A} \cdot \frac{\Delta \alpha_j}{¿}$$

Where A_{j} = city-wide area of surface of type *j* (such as pavements), A = area of the entire city, $\Delta\alpha_{j}$ is the reduction in solar absorptance of the surface of type *j* (solar absorptance = 1 – albedo), $<\alpha>$ = average solar absorptance of the entire city, and $T_{d,\max}$ = the maximum diurnal temperature swing (maximum difference of daily high – daily low temperatures). For the typical conditions considered here (A_{j}/A = 0.3, $\Delta\alpha_{j}/<\alpha>$= 0.2/0.8, $T_{d,\max}$ = 16 °C), this formula predicts $\Delta T_{j,\max}$ < 1.2 °C. This is in the range of predictions by numerous meteorological simulations that give values that cluster around 1 °C, but vary from 0 °C to 5 °C for similar conditions. (Santamouris, 2013; Taha, 2013; Santamouris, 2014)

Combining Eqs. 1 and 2, and dividing both sided by A_j, the area modified, the annual electrical energy saving per unit area modified is

$$\frac{\Delta E_a}{A_j} < \left(\frac{dP}{dT}\right)_{max} \cdot CH\,18\,C \cdot \left(\frac{1}{A}\right) \cdot ¿ \quad \frac{\Delta\alpha_j}{¿} \; ¿ \; ¿\alpha>¿ \qquad (3)$$

In order to get the maximum effect, the maximum values of all the parameters in Eq. 3 are deduced from appropriate data. Also, the chosen examples are warm cities whose temperatures are most controlled by their own surfaces. These are cities that are far from cool water, are large enough in area and are not in windy places. It is necessary to know how much power each of these cities demand. Fortunately, there are several cities in California that have their own electrical utility companies that serve only within known city boundaries. Cities that fit all these criteria and are quite warm in summer include Anaheim, Burbank, Glendale, Pasadena and Riverside. These are all in the Los Angeles basin. Cities that fit some of the criteria are Los Angeles and Sacramento. (Company names and years of data are given in an Appendix). For all the individual cities, actual data of the power demand as a function of temperature are used to obtain the crucial factor $(\mathrm{d}P/\mathrm{d}T)_{\max}$.

3. RESULTS

The magnitudes of the maxima of savings of electrical energy, the CO_2 avoided and the peak power reduction that would result from a change in surface albedo are readily obtained. Several warm cities in the Los Angeles basin and Sacramento, in California, are taken as examples. Assumed are reasonably high increases of the albedo of pavements, from 0.1 to 0.3 (reducing absorptance, □□ = 0.2) and city-average absorptance <□> = 0.8. Typical high values of $T_{\mathrm{d,max}}$ = 16 °C and $CH18C$ = 3000 hr/year are taken for all the cities.

3.1. Maximum energy savings and its monetary value

City-specific data required for Eq. 3 are presented in the second and third columns of Table 1. These are the maximum changes of AC power demand vs temperature, extracted from local utility company data, shown in the second column. The service areas for each utility are given in the third column. Results derived from Eq. (3), the maximum electrical energy savings per year per m^2 of pavement modified, are listed in column 4. The maximum monetary savings of energy is obtained by multiplying the energy saving by the price of energy (fifth column). (The time-of-use (TOU) price of electrical energy in these cities in the hottest time of year averages about \$ 0.70 /kWh. All monetary units are US\$. The table uses more specific prices.) It can be seen that the maximum savings are about \$ 1 / $yr{\cdot}m^2$. Because of all the overestimates used in the analysis, the actual savings are likely 1/10 as large, or about \$ 0.10 / $yr{\cdot}m^2$. (Pomerantz, et al 2015) This is the electrical energy monetary benefit that should be compared to the price of modifying the pavement.

Table 1. Data and results for several cities in California.

City (or county)	'Maximum' slope, $(\mathrm{d}P/\mathrm{d}T)_{\max}$ (GW / °C)	Service area A (km²)	Max energy saving per year and square meter, (kWh / $y{\cdot}m^2$)	Max monetary saving from energy (US\$ / $y{\cdot}m^2$)	Max CO_2 avoided (kg / $y{\cdot}m^2$)	Max monetary saving from CO_2 avoided (US\$ / $y{\cdot}m^2$)	Max peak power decrease (GW)
Anaheim	0.0107	129	0.9	0.6	0.5	0.005	0.015
Burbank	0.0081	45	2.0	1.6	1.0	0.01	0.012
Glendale	0.0089	79	1.2	1	0.7	0.007	0.013
Pasadena	0.0083	59	1.6	1.3	0.9	0.009	0.013
Riverside	0.015	211	0.9	0.6	0.5	0.005	0.023
Sacramento (approx.)	0.018	250	0.8	0.6	0.4	0.004	0.027
Los Angeles (county)	0.13	1250	1.2	0.9	0.7	0.007	0.20

3.2. Maximum CO_2 avoided and its monetary value

Because less electrical energy is needed, less CO_2 will be emitted from power plants. It is simple to calculate this avoided CO_2 by applying the "emission factor" (the amount of CO_2 emitted during the generation of a unit of electrical energy). This factor is designated by "e". The current emission factor in California, e < 0.5 kg CO_2 / kWh. (US EPA eGrid, 2016) Thus, the avoided CO_2 per year per unit area of modified surface is

$$\Delta CO_2 < e\,(\Delta E_a/\eta A_j) \qquad (4)$$

The factor η, the efficiency of generation and transmission of the grid, accounts for the fact that the energy generated is a factor $1/\eta$ greater than the energy delivered; $\eta \approx 0.9$. For the example of $\Delta\alpha = 0.2$, the results for various cities are shown in the sixth column in Table 1. These give reductions < 1 kgCO_2/y·m^2. Multiplying this by the current price of CO_2 emission of about \$10/10^3 kg = \$0.01 / kg, yields a monetary saving due to avoided emission of < \$0.01 / y·m^2. (cf seventh column of Table 1). Thus, the maximum avoided CO_2 is a fraction of a kg per m^2 in a year, with a monetary value less than a penny. The emission factors in the USA vary between 0.7 to 3 times the California value, with an average about twice that of California; an average emission factor would yield a saving of less than two pennies a year per m^2.

3.3 Maximum peak power reduction

We can easily estimate the magnitude of the "peak-shaving", the change in peak power as a result of cooler surfaces, ΔP_p. This is simply $\Delta P_p = (\mathrm{d}P/\mathrm{d}T)_{max}\,\Delta T_{j,\,max}$. A good estimate is obtained by multiplying $(\mathrm{d}P/\mathrm{d}T)_{max}$, the second column of Table 1, by an estimate of the highest temperature decrease the modified surfaces may cause, $\Delta T_{j,\,max}$ < 1.2 °C. The results are shown in the eighth column of Table 1. For comparison, a typical coal-fired power plant can generate 0.5 GW.

The peak reduction can also be expressed as a percentage of the base power of the utility. The US EPA quotes a result that on hot days the power demand increases by 3 % per °C. (US EPA HI website, 2016) Our analysis of the power demands in warm cities in California estimates a maximum change of < 6% per °C (Pomerantz, et al, 2015). Thus, a decrease $\Delta T_{j,\,max}$ < 1.2 °C would give a maximum decrease in peak power of about < 7 %.

4. Conclusions

This report gives a method for estimating the maxima of some benefits that may accrue due to cooler surfaces. The electrical energy savings and avoided CO_2 emissions in a year are evaluated for several warm cities in California. The values obtained are maxima because maximal parameters are applied in the formulas and several effects that would lessen the benefits, including wind from outside the cities and winter penalties, are ignored. The example of an increase of pavement albedo of 0.2 results in electrical energy savings of considerably less than about 2 kWh in a year per m^2 modified. The monetary value in California is proportionately less than \$1 per year per m^2. The accompanying avoided CO_2 emission is less than 1 kg CO_2 / year per m^2 modified. The current California value of this avoided CO_2 is less than a \$0.01 a year per m^2 modified. The peak power may be reduced by less than 7 %. These are overestimates probably by about a factor of ten.

Thus, in the cases studied here, measures to reduce the UHI by increasing albedo save very little money. Clearly, any extra costs of mitigation measures must be very low, practically zero, to justify them on economic grounds. These costs depend on the prices of local labor and materials and thus vary with locality.

Most of the emphasis in the study of the UHI has been on techniques to achieve mitigation. The costs of the mitigation, compared to the values of the benefits, have tended to be neglected. The method presented here can be applied to other cities in different climates and different cost structures. Whether these benefits are "large" or "small", whether they are worth doing, depends on the relative costs of implementing them. To be of practical value to society, the costs of heat island mitigation measures need to be compared to their benefits.

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REFERENCES

Akbari, H., C. Cartalis, D. Kolokotsa, A. Muscio, A. L. Pisello, F. Rossi, M. Santamouris, A. Synnefa, N. H. Wong, M. Zinzi (2015) "Local climate change and urban heat island mitigation techniques - The state of the art", *Journal Of Civil Engineering And Management* , **22**, 1-16 . DOI:10.3846/13923730.2015.1111934,

Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. (2000). "The effect of pavement temperatures on air temperatures in large cities" Berkeley, CA, *Lawrence Berkeley National Laboratory*, paper LBNL - 43442. http://eetd.lbl.gov/sites/all/files/2000_pomerantz_et_al_effect_of_pavement_temp_on_air_temp_in_large_cities.pdf

Pomerantz, M., P. J. Rosado and R. Levinson (2015), "A simple tool for estimating city-wide annual electrical energy savings from cooler surfaces", *Urban Climate*, **14, Part 2**, 315–325. doi:10.1016/j.uclim.2015.05.007

Rosenfeld, A. H., H. Akbari, J. J. Romm, and M. Pomerantz. (1998). "Cool communities: strategies for heat island mitigation and smog reduction." *Energy and Buildings*, 51-62.

Santamouris, M. (2013) "Using cool pavements as a mitigation strategy to fight urban heat island - a review of the actual developments." *Renewable and Sustainable Energy Reviews* **26,** 224-40. Cf. Table 2.

Santamouris, M. (2014) "Cooling The Cities – A Review Of Reflective And Green Roof Mitigation Technologies To Fight Heat Island And Improve Comfort In Urban Environments", *Solar Energy* **103**, 682-703. Doi:10.1016/J.Solener.2012.07.003. Cf. Table 1.

Taha, H., (2013) "Meteorological, emissions and air-quality modeling of heat-island mitigation: recent findings for California, USA." *International Journal of Low-Carbon Technologies* doi:10.1093/ijlct/ctt010. Cf. Fig. 4.

US EPA eGrid website http://www.epa.gov/sites/production/files/2015-10/documents/egrid2012_ghgoutputrates_0.pdf , accessed 10 Feb. 2016.

US EPA Heat Island website http://www.epa.gov/heat-islands/heat-island-impacts accessed 10 Feb. 2016.

APPENDIX: THE ELECTRICAL UTILITY COMPANIES WHOSE DATA WERE USED:

The utility companies cited below provided data on their hourly power demand, or made it available on the internet. The work reported here could not have been done without the kind cooperation of these utility companies. The cities and companies and the years of the data are: Anaheim (Anaheim Public Utility, 2013), Burbank (Burbank Water and Power, 2012), Glendale (Glendale Water and Power, 2012), Pasadena (Pasadena Water and Power, 2012), Riverside (Riverside Public Utility, 2012), Sacramento (Sacramento Municipal Utility District, 2012), Los Angeles county (Los Angeles Department of Water and Power, 2012).