THE IMPACT OF REFLECTIVITY AND EMISSIVITY OF ROOFS ON BUILDING COOLING AND HEATING ENERGY USE

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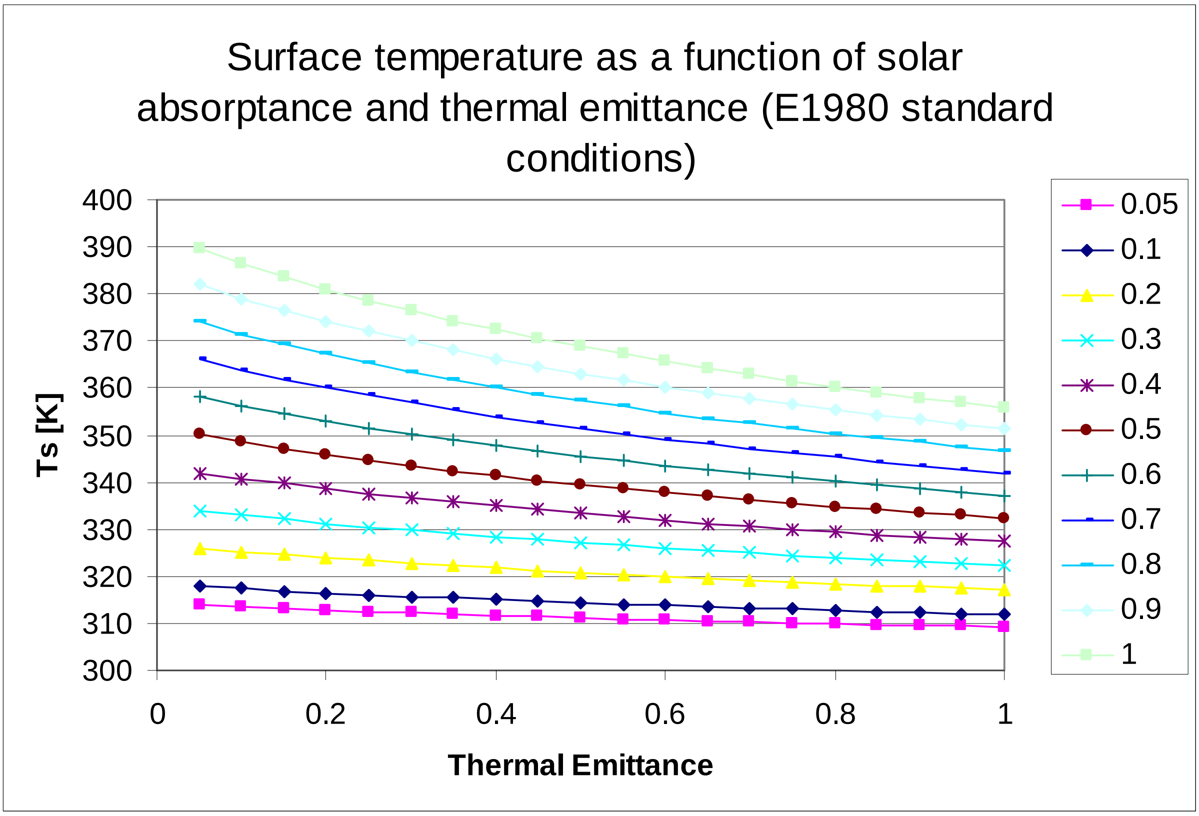
1. Surface Temperature

The laws of physics dictate that metallic materials (materials with low thermal emittance) get hot under the sun. This is a fact and it is not subject to arguments (and does not change no matter who says what). As it is seen in the attached Figure 1, for a material with a solar absorptance of 0.75, the steady state temperature of the surface can vary from 368 K (for thermal emittance of 0.10) to 346 K (for thermal emittance of 0.90). For reference comparison, the temperature of a non-metallic black surface with 0.95 absorptivity is only 355K; 13 K cooler than a metallic surface with solar absorptance of 0.75 and thermal emittance of 0.10! In fact, the solar reflectance of such a metallic surface has to be at least 0.40 for the surface to have the same temperature as the hot black surface. [Of course this is known to everybody and there is even a play on the topic by Tennessee Williams.]



2. The effect of surface temperature on cooling and heating energy use

Sometimes last year, I recall sending EPA the only paper I knew that had analyzed the effect of the solar reflectance and thermal emittance (Akbari and Konopacki 1998) on the buildings heating and cooling energy use. The paper is a peer-reviewed one. The analysis is based on DOE-2 simulations of prototypical offices and residences. All the results are very conservative in nature.

The paper concluded that in all US climates for all building that require both heating and cooling, a building with roofing material with high solar reflectance and high thermal emittance has the minimum net annual energy expenditure. For buildings that do not have cooling but significant heating, having a roof with low thermal emittance can have a 2% reduction in heating energy use. The analysis did not include the effect of the snow on the roofs which tends to reduce the winter time penalties of higher solar reflectance and winter time benefits of lower thermal emittance.

The results are also very intuitive noting that the winter time penalties of higher solar reflectance and benefits of lower thermal emittance is only diminished with the fact that (a) days are shorter in the winter, (b) sun angle is lower in the winter, (c) winter heating tends to occur in early morning and evening hours (when there is no significant sunlight), (d) wintertime sky in cold climates are typically cloudy, (e) ...

I hope that this provides the ample evidence for making requirements for minimum thermal emittance of EnergyStar roofs.

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Thermal VII Thermal Performance of the Exterior Envelopes of Buildings VII, Miami, 1998.

THE IMPACT OF REFLECTIVITY AND EMISSIVITY OF ROOFS ON BUILDING COOLING AND HEATING ENERGY USE

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ABSTRACT

Dark roofs are heated by the summer sun and thus raise the summertime cooling demand of buildings. For highly absorptive roofs, the difference between the surface and ambient air temperatures may be as high as 50°C (90°F), while for less absorptive (high-albedo) roofs, such as white coatings, the difference is only about 10°C. Measured data and computer simulations have demonstrated the impact of roof albedo in saving cooling energy use in buildings. Savings are both a function of climate and the amount of roof insulation. The cooling energy savings for reflective roofs are highest in hot climates. A reflective roof may also lead to a higher heating energy use. Clearly, reflective roofs are not recommended for cold climates where there is no need to cool the buildings. Simulations also indicate that roof emissivity can have a substantial effect on both heating and cooling energy use. In cold climates, a low-emissivity roof can add resistance to the passage of heat flow out of the building and result in savings in heating energy use. In cooling dominant climates, a low-emissivity roof will lead to a higher roof temperature and, hence, a higher cooling load from the roof.

In this paper we summarize the result of computer simulations and analyze the impact of roof albedo and emissivity on heating and cooling energy use. The simulations are performed for 11 representative climates throughout the country. Several residential and commercial prototypical buildings are considered for these simulations. In hot climates, changing the roof emissivity from 0.9 (emissivity of most non-metallic surfaces) to 0.25 (emissivity of fresh and shiny metallic surfaces) can result in a net 10% increase in annual utility bills. In colder climates, the heating energy savings approximately cancel out the cooling energy penalties from decreasing the roof emissivity. In very cold climates with no summertime cooling, the heating energy savings resulting from decreasing the roof emissivity can be up to 3%.

INTRODUCTION

Use of dark roofs affects energy use in buildings and the urban climate. At the building scale, dark roofs are heated by the summer sun and thus raise the summertime cooling demand. For highly absorptive (low-albedo[1]) roofs, the difference between the surface and ambient air temperatures may be as high as 50°C (90°F), while for less absorptive (high-albedo) surfaces with similar insulative properties, such as roofs covered with a white coating, the difference is only about 10°C (Berdahl and Bretz 1997). For this reason, "cool" surfaces (which absorb little "insolation") can be effective in reducing cooling energy use. Cool surfaces incur no additional cost if color changes are incorporated into routine re-roofing and resurfacing schedules (Bretz et al. 1997 and Rosenfeld et al. 1992).

Experiments in California and Florida have measured cooling energy savings in the range of 10 to 50% (ranging from \$10 to \$100 per year per 100 m^2) in several residential and small commercial buildings. The savings, of course, are strong functions of the thermal integrity of a building and of climate conditions. Akbari et al. (1993, 1997) measured peak power and cooling-energy savings from high-albedo coatings at one house and two school bungalows in Sacramento, California. Applying a high-albedo coating to one house resulted in seasonal savings of 2.2 kWh/day (80% of base case use), and peak demand reductions of 0.6 kW (about 25% of base case demand). In the school bungalows, cooling-energy was reduced 3.1 kWh/day (35% of base case use), and peak demand by 0.6 kW (about 20% of base case demand). Parker et al. (1998a) monitored nine homes in Florida before and after applying high-albedo coatings to their roofs. Air-conditioning energy use was reduced by 10% - 43%, with an average savings of 7.4 kWh/day (19% of low-albedo use). Peak demand between 5 and 6 PM was reduced by 0.2 - 1.0 kW, with an average reduction of 0.4 kW (22% of low-albedo demand). Energy savings were generally inversely correlated with the amount of ceiling insulation and duct system location: large savings in poorly insulated homes and those with the duct systems in the attic space, and smaller savings in well insulated homes.

The focus of more recent studies has been on commercial buildings. Konopacki et al. (1998) report measured cooling energy savings of 2-18% in two medical offices and one retail building. The saving have been achieved by changing the solar reflectivity of the roof from 0.20 to 0.60. Parker et al. (1997, 1998b) have measured electricity savings of about 20% to 40% from light-colored roofs in a small strip mall in Florida. The Sacramento Municipal Utility District (SMUD) reports similar savings measured in about 10 commercial buildings in Sacramento (Hildebrandt et al. 1998).

Darker surfaces also warm the air over urban areas more quickly, leading to the creation of summer urban "heat islands" (Fishman et al. 1994) Cooler roofs potentially reduce the summertime air temperature and hence indirectly reduce cooling energy use by an additional 5%-10%. In addition, in cities with air quality problems, lowering the ambient temperature reduces the episode of smoggy days. Rosenfeld et al. (1995, 1996 and 1998) and Taha (1997) have quantified the indirect impact of cool roofs on energy use and smog.

Thermal emissivity is another property of the roof surface that affects the building heating and cooling energy use. In theory, the higher the emissivity the higher the radiative heat transfer from the roof to the sky. On summer days, roofs with high emissivity are desirable since they stay cool and reduce heat gain through the roof. In cold climates, during the winter nights, roofs with low-emissivity are more desirable since they add a resistance to the passage of heat loss through the roof.

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[1] When sunlight hits a surface, some of the energy is reflected (this fraction is called the albedo = a) and the rest is absorbed (the absorbed fraction is 1-a). Low-a surfaces of course become much hotter than high-a surfaces.

In this paper we summarize the results of computer simulations analyzing the impact of roof albedo and emissivity on heating and cooling energy use. We first present simulation results for 11 US metropolitan areas summarizing the impact of roof reflectivity. The estimates for these 11 metropolitan areas are extrapolated to the entire country; we predict savings of about $0.75 billion per year. Then we perform simulations to quantify the impact of roof emissivity. The simulations are performed for 11 climate regions in the U.S. Two small office buildings (old and new) and two homes (old and new) are considered for these simulations. Finally, we briefly discuss policy and implementation issues such as rating and ASHRAE standards.

THE IMPACT OF REFLECTANCE

In a recent study, we have made quantitative estimates of the impact of reflective roofs on peak demand and annual cooling electricity use of buildings (Konopacki et al. 1997). Both cooling energy savings and possible heating energy penalties were estimated. The net energy savings were adjusted for the increased wintertime energy use.

The analysis was carried out in two steps. First, we simulated the impact of roof reflectivity on cooling and heating energy use of several prototypical buildings, using the DOE-2.1E building energy simulation program. We specified 11 prototypical buildings that would provide the highest potential savings: single-family residential (old and new), office (old and new), retail store (old and new), school (primary and secondary), health (hospital and nursing home), and grocery store. The prototypical buildings were simulated with two heating systems: gas furnace and heat pumps. The 11 U.S. Metropolitan Statistical Areas (MSAs) included: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York City, Philadelphia, Phoenix, and Washington DC/Baltimore.

In all simulations, we assumed a basecase roof reflectivity of 0.25 and emissivity of 0.9 for both residential and commercial buildings. The basecase reflectivity was determined after a detailed analysis of aerial photographs in three cities of Atlanta, Washington, DC and Philadelphia (Konopacki et al. 1997). The modified reflectivities were selected based on the analysis of existing database (Bretz and Akbari 1997). The reflectivity of the modified residential buildings (mostly sloped) was selected to be 0.55. For commercial buildings that are characterized mostly by flat and low-sloped roofs, the reflectivity of the modified roofs was selected to be 0.70. The emissivity of the modified roofs for both commercial and residential buildings was 0.9.

Second, we estimated the quantity of energy and money that could be saved if the current building roof stock had changed from dark to light. This was done by scaling the simulated energy savings of the prototype buildings by the amount of air conditioned space immediately beneath roofs in an entire MSA. For this purpose, data in each MSA on the stock of commercial and residential buildings, the saturation of heating and cooling systems, the current roof reflectivities, and the local costs of electricity and gas were used.

Table 1 shows the results of the analysis for the 11 metropolitan areas. Table 2 normalizes the savings and deficits data per 100-m^2 of roof areas. For the 11 metropolitan area, total potential electricity savings is estimated at 2.6 tera-watt hours (TWh) (200 kilowatt hours per 100m^2 roof area of air-conditioned buildings). The natural gas deficit is estimated at 6.9 TBtu (5 therms per 100m^2). The net savings in energy bills is $194 M ($15 per 100m^2). The use of reflective roofs also potentially saves about 1.7 gigawatt (GW) in peak power demand (135 W per 100m^2). Residential buildings accounted for over two-thirds of electricity savings and about 74% of net savings in utility bills. In fact, six building types accounted for about 90% of the annual electricity and net energy savings: old residences accounted for more than 55%, new residences about 15%, and four other building types (old/new offices and old/new retail stores) together about 25%.

Net savings were also a strong function of climate. In the residential sector (the average of new and old residences), the net savings range from a negative \$2 to \$34 per 100m^2 of roof area. Basically, the colder the climate, the less the savings. Excluding Philadelphia (where there was a net deficit of \$2/100m^2), savings of \$5/100m^2 to \$34/100m^2 were estimated. For a 200-m^2 house, the net savings are estimated to be about \$10 to \$68 per year. For commercial buildings, the net savings are even more attractive and range from \$10/100m^2 to \$35/100m^2. Assuming an average 20 years roof life and a 3% real interest rate, the present value of the savings is about \$75 to \$525 per a 100-m^2 of roof area. These savings especially in hot climates are very significant, given that the reflectivity of most roofs can be increased at a very small incremental cost when a new roof is installed.

Konopacki et al. (1997) extrapolated the results of the 11 metropolitan areas and estimated the savings in the entire United States. Nationally, light-colored roofing could produce annual savings of \$750M per year by reducing the utility bills in residential and commercial buildings. The electricity savings were about 10 TWh/yr (about 3% of the national cooling electricity use in residential and commercial buildings), and the peak power savings were about 7 GW (2.5%) (equivalent to 14 power plants each with a capacity of 0.5 GW). The increase in natural gas use for heating was estimated to be about 26 TBtu/yr (1.6%).

THE IMPACT OF EMISSIVITY

The surface temperature of a roof is a strong function of both absorptivity and emissivity. For a roof surface exposed to the sun, the steady-state surface temperature is obtained by

$$(1 - a)I = \varepsilon\sigma(T_s^4 - T_{sky}^4) + h_c(T_s - T_a) + U(T_s - T_{in}) \quad (1)$$

where,

a = solar reflectivity

I = solar flux, Wm^{-2}

ε = thermal emissivity

σ = Stefan Boltzmann constant, 5.6685×10^{-8} $Wm^{-2}K^{-4}$

T_s = steady-state surface temperature, K

T_{sky} = sky apparent radiative temperature, K

h_c = convective coefficient, $Wm^{-2}K^{-1}$

T_a = air temperature, K

T_{in} = inside temperature, K

U = overall roof heat transfer coefficient, $Wm^{-2}K^{-1}$.

A close inspection of Eq. 1. reveals the following points:

During hot summer days, the lower the roof emissivity the higher the surface temperature, and hence an increased heat conduction into the building. In airconditioned buildings, this would lead to a higher cooling energy use.

During moderate days in summer, spring and fall, when the outside air temperature is below inside temperature but building air conditioning is operating, the lower the roof emissivity, the higher the surface temperature, and hence a decreased heat loss from the roof of the building. This would lead to a higher cooling energy use.

During the winter when heating is required, the lower the emissivity, the lower the heat loss from the roof of the building. This would lead into a lower heating energy use.

For extreme climate conditions where either the cooling or the heating load is dominant, the choice of emissivity is clear: roofs with high emissivity for cooling dominant climates and roofs with low emissivity for heating dominant climates. For those climates that have both heating and cooling the choice is not that obvious.

In order to analyze the impact of roof emissivity on heating and cooling energy use of a building we performed DOE-2 parametric simulations. DOE-2 performs an hourly calculation of steady-state roof surface temperature based on Eq 1. The calculations are based on a linear approximation of the long-wave radiation term in Eq. 1. Furthermore DOE-2 adds two levels of hourly details to Eq.1. (1) It calculates the apparent hourly sky temperature based on the moisture content of the air and the amount of cloud cover; the higher the cloud cover and the moisture content, the closer the sky temperature to the ambient air temperature. (2) In calculating the hourly convection coefficient, DOE-2 accounts for the wind speed.

We selected four building prototypes (old and new construction residence, and old and new small office building) and performed DOE-2 simulations in 11 climate regions. The prototypes selected were those used by Konopacki et al. (1997) to estimate the potential cooling energy savings from the application of reflective roofs.[2]

The parametrics include a set of three values for the roof reflectivity (a = 0.8, 0.5, and 0.2) and a set of three values for the roof emissivity (ε = 0.9, 0.5, and 0.25). The selected ranges of reflectivities and emissivities cover a wide range of roofing materials in the market. For reflectivity and emissivity values outside the selected range, the heating and cooling energy impacts can be accurately estimated using a linear extrapolation. Both heating and cooling energy use were simulated. The total utility costs and savings were calculated using the local electricity and gas prices. Tables 3a,b and 4a,b show the results for the residential and office buildings.

In hot climates such as Phoenix, the net utility bills in the old residential building increased \$0.30-0.70/m^2 (\$0.03-0.07/ft^2) when the emissivity was decreased from 0.9 to 0.25. Obviously, the impact of emissivity was higher when the roof was highly absorptive (i.e. a= 0.2). In cold climates, such as Philadelphia and Chicago, the net utility bills in the old residential building were fairly insensitive to roof emissivity; the net increase in cooling electricity use by decreasing the emissivity was

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[2] In simulations performed by Konopacki et al. (1997), the system for each prototype was first sized assuming a dark-colored roof. Then, the same system size was used to calculate the heating and cooling energy use and savings for the modified roofs. In the simulations carried out for this study, we allowed DOE-2 to size the appropriate systems for both initial and modified roofs. The impact of this automatic sizing is to slightly overpredict both heating and cooling energy savings because of the emissivity and albedo modifications.

cancelled by the decrease in heating gas use. The same observation is made by inspecting the results for the old office building.

As was the case with roof reflectivity, the impact of roof emissivity in new construction with more roof insulation, in absolute terms, was lower than old construction with less insulation. In new residential buildings in hot climates the net utility bills increased \$0.20-0.40/m^2 (\$0.02-0.04/ft^2) when the emissivity was decreased from 0.9 to 0.25. In cold climates, the net utility bills in the residential building were again insensitive to roof emissivity.

ISSUES WITH LIGHT-COLORED ROOFS

Increasing the overall albedo of roofs is an attractive way to reduce the net radiative heat gains through the roof and hence, reduce building cooling loads. To change the albedo, the rooftops of buildings may be coated or covered with a new material. Since most roofs have regular maintenance or need to be re-roofed or recoated periodically, the change of the albedo should be done then. It is important to note that altering the albedo starts to pay for itself immediately.

However, several possible conflicts may arise. These include the potential to create glare and visual discomfort; incompatibility of roofing materials to changing their reflectivity (many types of building materials, such as tar roofing, are not well adapted to coating); and a possible concern that the building owners and architects like to have the choice as to what color to select for their rooftops. These issues are viewed differently in buildings with flat roofs and sloped roofs. Bretz et al. (1997) review these potential conflicts and suggest solutions.

Another issue of great concern is the longevity of roof reflectivity. Many light-colored materials may initially have a high reflectivity. However, as they age their reflectivity degrades significantly. We have conducted field studies to examine the degradation in roof reflectivity, focusing on reflective coatings, concluding that most of the albedo degradation of the coatings occurred within the first year of application, an average decrease of 0.15 in albedo (Bretz and Akbari 1997). After the first year, the degradation slowed significantly. The overall degradation in roof reflectivity did not exceed 0.20, even for several samples that were in the field over 6 years. This same result has been observed by Byerley and Christian (1994). They report a decrease in albedo of 0.21 in 3.5 years.[3] Also, in most cases, washing the coatings restored 90%-100% of the initial roof albedo. Since, dirt accumulates fairly quickly on the roof, the benefit from washing a roof is short lived. A similar experiment is currently being carried out at Oak Ridge National Laboratory; the objective of the experiment is to compare the field performance of several coatings in the outdoor test facilities at ORNL (Petrie et al. 1998).

It has been stated that in hot and humid climates, cold roofs may experience condensation problems. During the day, the roof and attic do not heat up enough to drive off the possible condensed moisture of the previous night. This may have a negative impact on the lifespan of the roof.

[3] Byerly and Christian (1994) measured albedo through a different technique other than ASTM E 903 that may not produce the same results for all materials at all conditions. Also, in their study, they did not quote albedo measurements before and after washing. However, they indicated that by washing the surface "the appearance did not return to the bright-white associated with the new application."

CURRENT ACTVITIES OF INTEREST

ASTM standards for measuring roof reflectivity and emissivity

In 1994, a group of industry representatives, including several ASTM members, from the public and private sectors attended two workshops on cool construction materials. The group formed the National Committee for the Planning of the Cool Construction Materials Program. One of the major tasks in this National Plan was to develop performance data and standard procedures for evaluation of cool construction materials. An ASTM subcommittee was formed as the vehicle to develop standard practices for measuring and rating of cool construction materials (Akbari et al. 1996).

The ASTM subcommittee has determined that two radiative properties (solar reflectivity and thermal emissivity) need to be measured in both the laboratory and the field. In response to lack of standards for field measurements of solar reflectivity, the subcommittee has drafted a test method for measuring solar reflectivity of horizontal and low-sloped surfaces (ASTM 1998a). The subcommittee believes that two existing ASTM standards "E 903 - Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres" and "E 408 - Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques" meet the needs for laboratory measurement of these properties (ASTM 1998b,c).

Another activity of the subcommittee includes developing a Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Surfaces. It is the objective of this standard to define a Solar Reflectance Index (SRI) which defines the relative steady-state temperature of a surface with respect to the standard white (SRI = 100) and standard black (SRI = 0) under the standard solar and ambient conditions.

Database for cool materials

We are working with the coating, roofing, and pavement industries, and with federal and private laboratories to generate a database of cool materials. An early draft of such a database can be found on the Internet page: http:HeatIsland.LBL.gov

Building energy performance standards

With our new understanding of the importance of cool roofs, we are working with ASHRAE, CABO (Council of American Building Officials), and with the CEC (California Energy Commission, which drafts California's Title 24 building standards), to have the next generation of their standards give credit for cool roofs. ASHRAE Standard Committee 90.1, has recently voted to give credit for roof albedo (See Akbari et al. 1998).

Field demonstration of cool roofs

Projects are currently underway in Florida (carried out by Florida Solar Energy Center) and in California to demonstrate the field performance of cool roofs (Konopacki et al. 1998, and Parker et al. 1997, 1998b).

Weathering of roof coatings

Oak Ridge National Laboratory (ORNL) is currently involved in a project to test the long-term performance of 24 different roof coatings (ranging from asphalt emulsions to white latex coatings) at their test facilities.

CONCLUSION

Experiments on individual buildings have shown that coating roofs white reduces air conditioning energy use between 10 and 50% (corresponding to savings ranging from $10 to $100 per year per 100 m^2), depending on the thickness of insulation under the roof. Nationwide, it is estimated that about $0.75B per year can be saved by widespread implementation of light-colored roofs. For energy saving purposes, reflective roofs should be primarily considered for air-conditioned buildings. Clearly, in warm climates, reflective roofs provide greater opportunities for energy savings than in cold climates.

Thermal emissivity of roofs can have an effect on both heating and cooling energy use. In cold climates, a low-emissivity roof can add resistance to passage of heat flow out of the building and result in savings in heating energy use. In cooling dominant climates, a low-emissivity roof will lead to a higher roof temperature and, hence, a higher cooling load from the roof. In hot climates, changing the roof emissivity from 0.9 (emissivity of most non-metallic surfaces) to 0.25 (emissivity of fresh and shiny metallic surfaces) can result in a net 10% increase in annual utility bills. In colder climates, the heating energy savings approximately cancel out the cooling energy penalties from decreasing the roof emissivity. In very cold climates with no summertime cooling, the heating energy savings resulting from decreasing the roof emissivity can be up to 3%.

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Table 1. Estimates of metropolitan-scale annual cooling electricity savings (GWh), net energy savings ($M), peak demand electricity savings (MW), and annual natural gas deficit (GBtu) resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas.

Metropolitan Areas	Residential				Commercial				Commercial and Residential			
	Elec (GWh)	Gas (GBtu)	Net (M$)	Peak (MW)	Elec (GWh)	Gas (GBtu)	Net (M$)	Peak (MW)	Elec (GWh)	Gas (GBtu)	Net (M$)	Peak (MW)
Atlanta	125	349	8	83	22	55	1	14	147	404	9	97
Chicago	100	988	6	89	84	535	4	56	183	1523	10	145
Los Angeles	210	471	18	218	209	154	18	102	419	625	35	320
Dallas / Ft Worth	241	479	16	175	71	113	4	36	312	592	20	211
Houston	243	284	21	127	79	62	6	30	322	347	27	156
Miami / Ft Lauderdale	221	4	18	115	35	3	2	11	256	7	20	125
New Orleans	84	107	6	27	33	28	3	16	117	135	9	42
New York	35	331	3	56	131	540	13	95	166	871	16	151
Philadelphia	44	954	-1	108	47	292	4	49	91	1246	3	157
Phoenix	299	74	32	106	58	31	5	18	357	105	37	123
DC / Baltimore	182	845	6	183	45	184	2	31	227	1029	8	214
Total	**1784**	**4886**	**133**	**1287**	**814**	**1997**	**62**	**458**	**2597**	**6884**	**194**	**1741**

Table 2. Estimates of savings or penalties per 100 m^2 of roof area of air-conditioned buildings resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas: annual cooling electricity savings (kWh), net energy savings ($), peak demand electricity savings (W), and annual natural gas deficit (therms)

Metropolitan Area	Residential				Commercial				Commercial and Residential			
	Elec (kWh)	Gas (therms)	Net ($)	Peak (W)	Elec (kWh)	Gas (therms)	Net ($)	Peak (W)	Elec (kWh)	Gas (therms)	Net ($)	Peak (W)
Atlanta	153	4	10	102	239	6	11	152	162	4	10	107
Chicago	131	13	8	116	228	15	11	152	162	13	9	128
Los Angeles	182	4	16	189	350	3	30	171	239	4	20	183
Dallas / Ft Worth	166	3	11	121	224	4	13	114	176	3	11	119
Houston	198	2	17	103	261	2	20	99	211	2	18	102
Miami / Ft Lauderdale	259	0	21	135	340	0	19	107	267	0	21	131
New Orleans	199	3	14	64	287	2	26	139	218	3	17	78
New York	104	10	9	166	211	9	21	153	173	9	17	158
Philadelphia	81	18	-2	199	232	14	20	241	122	17	4	211
Phoenix	314	1	34	111	409	2	35	127	327	1	34	113
DC / Baltimore	137	6	5	138	221	9	10	152	148	7	5	140

Table 3a -- Old Residence. Simulated impact of roof reflectivity and emissivity on building heating and cooling energy use.

location	albedo = 0.8			albedo = 0.5			albedo = 0.2		
	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25
Atlanta									
Elec (kWh/m^2)	16.5	17.2	17.7	18.8	19.9	21.0	21.0	22.5	23.9
Gas ($kBtu/m^2$)	300.7	293.9	288.3	293.2	285.7	279.8	286.9	279.9	274.8
Total ($\$/m^2$)	3.33	3.34	3.34	3.46	3.49	3.54	3.59	3.66	3.73
Chicago									
Elec (kWh/m^2)	12.1	12.5	12.8	13.4	14.1	14.6	14.8	15.6	16.3
Gas ($kBtu/m^2$)	749.0	738.3	730.9	735.5	724.7	715.2	723.5	710.7	700.4
Total ($\$/m^2$)	5.48	5.46	5.46	5.55	5.57	5.57	5.63	5.66	5.68
Los Angeles									
Elec (kWh/m^2)	9.3	10.1	10.7	11.6	12.9	14.0	13.8	15.6	17.2
Gas ($kBtu/m^2$)	117.2	110.3	103.9	113.0	105.7	98.3	109.0	101.5	94.8
Total ($\$/m^2$)	1.64	1.67	1.70	1.84	1.91	1.98	2.03	2.16	2.27
Fort Worth									
Elec (kWh/m^2)	32.1	32.8	33.4	34.5	35.7	36.6	36.9	38.4	39.7
Gas ($kBtu/m^2$)	234.7	230.2	226.8	231.5	227.0	223.6	228.9	224.2	220.7
Total ($\$/m^2$)	3.85	3.88	3.91	4.02	4.09	4.14	4.19	4.28	4.36
Houston									
Elec (kWh/m^2)	26.2	27.1	27.9	29.0	30.4	31.5	31.7	33.5	35.1
Gas ($kBtu/m^2$)	134.8	131.0	127.8	131.9	128.0	124.9	129.7	125.7	122.4
Total ($\$/m^2$)	3.23	3.30	3.35	3.47	3.58	3.67	3.71	3.86	3.98
Miami									
Elec (kWh/m^2)	47.0	48.3	49.5	50.8	52.8	54.5	54.4	57.0	60.2
Gas ($kBtu/m^2$)	11.1	10.4	10.0	11.0	10.3	9.8	10.9	10.2	9.8
Total ($\$/m^2$)	3.91	4.02	4.11	4.22	4.38	4.51	4.52	4.72	4.97
New Orleans									
Elec (kWh/m^2)	21.8	22.8	23.6	24.7	26.3	27.7	27.6	29.7	31.7
Gas ($kBtu/m^2$)	115.9	111.8	108.5	113.1	109.1	105.8	110.8	106.5	103.3
Total ($\$/m^2$)	2.43	2.48	2.53	2.64	2.74	2.84	2.86	2.99	3.14
New York City									
Elec (kWh/m^2)	11.1	11.4	11.6	12.1	12.6	13.0	13.1	13.9	14.4
Gas ($kBtu/m^2$)	630.2	622.6	616.8	620.3	611.8	605.2	611.1	601.7	595.4
Total ($\$/m^2$)	6.88	6.86	6.86	6.97	6.97	6.99	7.05	7.09	7.14

location	albedo = 0.8			albedo = 0.5			albedo = 0.2		
	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25
Philadelphia									
Elec (kWh/m^2)	11.7	12.1	12.4	13.1	13.8	14.4	14.5	15.4	16.3
Gas (kBtu/m^2)	566.0	556.4	548.7	553.3	543.0	536.0	544.4	534.9	527.0
Total ($/$m^2$)	5.34	5.33	5.32	5.44	5.46	5.49	5.56	5.61	5.67
Phoenix									
Elec (kWh/m^2)	49.2	51.0	52.8	54.2	57.2	59.8	58.9	62.8	66.2
Gas (kBtu/m^2)	98.8	93.8	89.3	97.0	91.9	87.6	95.7	90.5	86.0
Total ($/$m^2$)	5.97	6.13	6.29	6.50	6.78	7.03	6.99	7.37	7.71
Washington DC									
Elec (kWh/m^2)	15.2	15.8	16.4	17.3	18.2	18.8	19.1	20.2	21.3
Gas (kBtu/m^2)	464.3	455.4	448.1	454.3	444.5	438.0	447.6	439.4	433.5
Total ($/$m^2$)	4.95	4.92	4.90	5.02	5.00	4.99	5.09	5.10	5.13

* Results of DOE-2 simulations for an old construction 143 m^2 (1540 ft^2) residence with R-11 roof insulation and an electric cooling and gas heating system. We have used local electricity and gas rates to calculate the total cooling and heating cost.

Table 3b -- New Residence. Simulated impact of roof reflectivity and emissivity on building heating and cooling energy use.

location	albedo = 0.8			albedo = 0.5			albedo = 0.2		
	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25
Atlanta									
Elec (kWh/m^2)	12.0	12.4	12.8	13.3	13.9	14.4	14.4	15.3	16.1
Gas ($kBtu/m^2$)	184.1	180.2	177.0	179.8	175.6	172.8	177.0	173.7	170.6
Total ($\$/m^2$)	2.19	2.19	2.20	2.26	2.28	2.30	2.33	2.37	2.41
Chicago									
Elec (kWh/m^2)	8.3	8.5	8.7	9.0	9.4	9.6	9.7	10.2	10.6
Gas ($kBtu/m^2$)	500.2	494.5	489.9	492.0	485.5	480.3	484.4	477.1	471.1
Total ($\$/m^2$)	3.68	3.67	3.67	3.72	3.72	3.72	3.75	3.76	3.78
Los Angeles									
Elec (kWh/m^2)	6.3	6.7	7.1	7.5	8.1	8.7	8.6	9.5	10.3
Gas ($kBtu/m^2$)	56.3	53.5	50.2	54.4	51.0	47.7	52.7	49.1	46.0
Total ($\$/m^2$)	0.97	0.99	1.00	1.07	1.11	1.15	1.17	1.23	1.29
Fort Worth									
Elec (kWh/m^2)	22.5	23.0	23.3	23.9	24.5	25.0	25.1	26.0	26.6
Gas ($kBtu/m^2$)	140.7	138.1	136.1	138.7	136.2	134.2	137.1	134.5	132.6
Total ($\$/m^2$)	2.57	2.58	2.60	2.66	2.69	2.72	2.74	2.79	2.83
Houston									
Elec (kWh/m^2)	18.1	18.6	19.1	19.6	20.4	21.0	21.1	22.1	23.0
Gas ($kBtu/m^2$)	78.1	76.0	74.3	76.5	74.3	72.5	75.2	73.0	71.2
Total ($\$/m^2$)	2.15	2.18	2.21	2.28	2.33	2.39	2.40	2.48	2.56
Miami									
Elec (kWh/m^2)	35.1	35.8	36.5	37.1	38.2	39.2	39.1	40.5	41.8
Gas ($kBtu/m^2$)	4.5	4.2	4.0	4.3	4.1	4.0	4.3	4.1	3.9
Total ($\$/m^2$)	2.89	2.94	3.00	3.05	3.14	3.21	3.21	3.32	3.43
New Orleans									
Elec (kWh/m^2)	15.0	15.6	16.4	17.0	17.8	18.6	18.5	19.8	20.8
Gas ($kBtu/m^2$)	64.9	62.8	61.0	63.2	61.0	59.1	61.8	59.6	57.8
Total ($\$/m^2$)	1.58	1.61	1.67	1.73	1.78	1.83	1.84	1.93	1.99
New York City									
Elec (kWh/m^2)	7.8	8.0	8.1	8.4	8.7	8.9	8.9	9.3	9.6
Gas ($kBtu/m^2$)	422.4	417.9	414.5	416.5	411.4	407.5	411.0	405.2	402.1
Total ($\$/m^2$)	4.67	4.66	4.66	4.71	4.72	4.72	4.76	4.77	4.80

Philadelphia									
Elec (kWh/m^2)	8.1	8.4	8.6	8.9	9.3	9.6	9.7	10.2	10.6
Gas (kBtu/m^2)	369.6	363.9	359.9	363.9	358.5	354.3	359.4	353.4	348.7
Total (\$/m^2)	3.56	3.55	3.55	3.62	3.63	3.64	3.69	3.71	3.73
Phoenix									
Elec (kWh/m^2)	33.2	34.3	35.2	36.0	37.5	38.8	38.4	40.5	42.3
Gas (kBtu/m^2)	48.8	46.2	44.0	47.9	45.5	43.5	47.3	44.9	42.6
Total (\$/m^2)	3.91	4.00	4.08	4.19	4.34	4.47	4.45	4.65	4.84
Washington DC									
Elec (kWh/m^2)	10.8	11.1	11.4	11.8	12.4	12.8	12.9	13.5	14.1
Gas (kBtu/m^2)	299.6	294.4	290.1	293.7	288.7	284.8	290.5	285.4	281.2
Total (\$/m^2)	3.27	3.24	3.23	3.29	3.29	3.29	3.34	3.34	3.35

* Results of DOE-2 simulations for a new construction 143 m^2 (1540 ft^2) residence with R-19 roof insulation and an electric cooling and gas heating system. We have used local electricity and gas rates to calculate the total cooling and heating cost.

Table 4a -- Old Small Office. Simulated impact of roof reflectivity and emissivity on building heating and cooling energy use.

location	albedo = 0.8			albedo = 0.5			albedo = 0.2		
	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25
Atlanta									
Elec (kWh/m^2)	39.8	40.8	41.6	43.1	44.7	46.2	46.3	48.5	50.5
Gas (kBtu/m^2)	110.1	106.1	102.8	104.3	99.9	96.4	99.3	94.5	90.7
Total ($/$m^2$)	3.59	3.63	3.68	3.80	3.89	3.98	4.00	4.13	4.26
Chicago									
Elec (kWh/m^2)	31.0	31.5	32.1	33.0	33.7	34.5	34.8	36.0	37.3
Gas (kBtu/m^2)	350.8	345.1	340.9	342.0	335.6	330.6	333.9	326.6	320.9
Total ($/$m^2$)	4.39	4.41	4.44	4.51	4.55	4.58	4.62	4.69	4.77
Los Angeles									
Elec (kWh/m^2)	36.4	37.8	39.1	40.2	42.2	44.1	43.6	46.4	48.9
Gas (kBtu/m^2)	12.7	10.8	9.2	10.3	8.6	7.0	8.6	7.0	5.7
Total ($/$m^2$)	3.32	3.43	3.53	3.64	3.81	3.97	3.93	4.17	4.39
Fort Worth									
Elec (kWh/m^2)	58.2	59.1	59.7	61.3	62.8	64.0	64.4	66.4	67.7
Gas (kBtu/m^2)	77.5	74.7	72.3	73.2	69.8	67.2	69.2	65.5	62.6
Total ($/$m^2$)	4.07	4.11	4.14	4.25	4.33	4.39	4.42	4.53	4.61
Houston									
Elec (kWh/m^2)	56.5	57.7	58.6	60.0	61.9	63.3	63.5	65.9	68.0
Gas (kBtu/m^2)	33.6	31.9	30.3	31.2	29.2	27.7	29.0	27.0	25.3
Total ($/$m^2$)	4.44	4.52	4.59	4.70	4.83	4.93	4.96	5.13	5.28
Miami									
Elec (kWh/m^2)	82.6	83.9	85.1	86.9	88.9	90.2	90.9	93.3	95.7
Gas (kBtu/m^2)	0.7	0.7	0.4	0.7	0.4	0.4	0.4	0.4	0.4
Total ($/$m^2$)	5.62	5.71	5.79	5.91	6.05	6.14	6.18	6.34	6.51
New Orleans									
Elec (kWh/m^2)	53.2	54.5	55.6	57.1	59.1	61.0	60.8	63.6	66.0
Gas (kBtu/m^2)	32.7	31.0	29.4	30.1	27.9	26.4	27.7	25.5	23.7
Total ($/$m^2$)	4.64	4.74	4.83	4.95	5.11	5.26	5.26	5.48	5.67
New York City									
Elec (kWh/m^2)	29.5	30.1	30.6	31.4	32.4	33.1	33.3	34.6	35.5
Gas (kBtu/m^2)	294.1	289.7	286.4	288.4	283.1	279.4	282.5	276.8	272.4
Total ($/$m^2$)	5.54	5.58	5.63	5.75	5.84	5.90	5.95	6.07	6.16

Philadelphia									
Elec (kWh/m^2)	32.3	33.1	33.7	35.0	36.1	37.1	37.4	39.0	40.4
Gas (kBtu/m^2)	256.1	250.2	245.6	247.6	240.5	235.0	239.2	231.5	225.2
Total ($/$m^2$)	5.35	5.41	5.45	5.61	5.70	5.79	5.85	5.99	6.12
Phoenix									
Elec (kWh/m^2)	73.2	75.2	76.9	78.7	81.6	84.2	83.6	87.7	91.3
Gas (kBtu/m^2)	13.6	11.6	10.3	11.4	9.7	8.1	9.9	7.9	6.6
Total ($/$m^2$)	6.81	6.97	7.13	7.30	7.56	7.79	7.74	8.10	8.44
Washington DC									
Elec (kWh/m^2)	37.1	38.0	38.7	40.0	41.3	42.5	42.6	44.4	46.3
Gas (kBtu/m^2)	202.8	196.8	192.4	195.3	188.5	183.2	188.0	180.6	174.4
Total ($/$m^2$)	3.81	3.84	3.87	3.97	4.02	4.08	4.12	4.20	4.30

* Results of DOE-2 simulations for a old construction 455 m^2 (4900 ft^2) office with R-11 roof insulation and an electric cooling and gas heating system. We have used local electricity and gas rates to calculate the total cooling and heating cost.

Table 4b -- New Small Office. Simulated impact of roof reflectivity and emissivity on building heating and cooling energy use.

location	albedo = 0.8			albedo = 0.5			albedo = 0.2		
	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25
Atlanta									
Elec (kWh/m^2)	31.7	32.2	32.6	33.3	34.3	35.0	35.1	36.3	37.3
Gas ($kBtu/m^2$)	62.0	60.0	58.4	59.3	57.1	55.4	56.9	54.5	52.5
Total ($\$/m^2$)	2.70	2.73	2.75	2.81	2.87	2.91	2.93	3.00	3.07
Chicago									
Elec (kWh/m^2)	24.5	24.8	25.1	25.5	26.1	26.5	26.6	27.3	27.9
Gas ($kBtu/m^2$)	234.6	231.3	228.7	229.3	225.6	222.3	224.5	219.9	216.6
Total ($\$/m^2$)	3.26	3.27	3.28	3.32	3.34	3.36	3.38	3.41	3.44
Los Angeles									
Elec (kWh/m^2)	29.5	30.3	31.0	31.6	32.8	33.8	33.5	35.0	36.3
Gas ($kBtu/m^2$)	3.1	2.6	2.2	2.6	2.0	1.8	2.0	1.8	1.3
Total ($\$/m^2$)	2.65	2.71	2.77	2.83	2.93	3.02	2.99	3.12	3.24
Fort Worth									
Elec (kWh/m^2)	44.7	45.0	45.5	46.2	47.1	47.8	48.0	49.2	50.2
Gas ($kBtu/m^2$)	40.0	38.4	37.3	37.8	36.0	34.7	35.8	33.8	32.3
Total ($\$/m^2$)	3.04	3.05	3.08	3.12	3.17	3.21	3.23	3.30	3.36
Houston									
Elec (kWh/m^2)	43.4	44.1	44.7	45.4	46.4	47.2	47.2	48.7	49.8
Gas ($kBtu/m^2$)	16.0	15.2	14.5	14.9	14.1	13.4	14.1	13.0	12.3
Total ($\$/m^2$)	3.37	3.42	3.46	3.52	3.59	3.65	3.65	3.76	3.84
Miami									
Elec (kWh/m^2)	63.6	64.4	64.9	65.8	66.9	67.9	68.0	69.5	70.5
Gas ($kBtu/m^2$)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total ($\$/m^2$)	4.32	4.38	4.42	4.48	4.55	4.62	4.63	4.73	4.79
New Orleans									
Elec (kWh/m^2)	41.3	42.0	42.7	43.5	44.5	45.6	45.5	47.0	48.4
Gas ($kBtu/m^2$)	15.6	14.7	14.1	14.5	13.4	12.7	13.4	12.3	11.6
Total ($\$/m^2$)	3.55	3.61	3.66	3.73	3.81	3.90	3.89	4.01	4.13
New York City									
Elec (kWh/m^2)	23.5	23.8	24.0	24.5	25.0	25.5	25.6	26.3	26.8
Gas ($kBtu/m^2$)	198.1	195.3	193.3	194.4	191.3	188.9	190.9	187.4	184.7
Total ($\$/m^2$)	4.19	4.20	4.22	4.30	4.34	4.38	4.41	4.47	4.53

location	albedo = 0.8			albedo = 0.5			albedo = 0.2		
	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25	ε = 0.9	ε = 0.5	ε = 0.25
Philadelphia									
Elec (kWh/m^2)	25.9	26.1	26.4	27.0	27.7	28.3	28.4	29.3	30.0
Gas (kBtu/m^2)	163.4	159.9	157.1	158.4	154.2	150.9	153.3	148.7	145.0
Total ($/$m^2$)	4.04	4.03	4.06	4.14	4.19	4.24	4.27	4.35	4.41
Phoenix									
Elec (kWh/m^2)	54.5	55.6	56.5	57.5	59.1	60.4	60.1	62.2	64.4
Gas (kBtu/m^2)	3.7	3.1	2.6	3.1	2.4	2.0	2.6	2.0	1.5
Total ($/$m^2$)	5.03	5.13	5.21	5.30	5.45	5.57	5.54	5.73	5.93
Washington DC									
Elec (kWh/m^2)	29.2	29.7	30.0	30.8	31.5	32.0	32.2	33.2	34.0
Gas (kBtu/m^2)	123.4	120.2	117.3	119.1	115.1	112.0	114.9	110.5	107.0
Total ($/$m^2$)	2.79	2.80	2.81	2.88	2.90	2.92	2.95	3.00	3.04

* Results of DOE-2 simulations for a new construction 455 m^2 (4900 ft^2) office with R-19 roof insulation and an electric cooling and gas heating system. We have used local electricity and gas rates to calculate the total cooling and heating cost.