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Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions

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Abstract

The impact from using cool roof coatings on the cooling and heating loads and the indoor thermal comfort conditions of residential buildings for various climatic conditions is estimated. The energy cooling loads and peak cooling demands are estimated for different values of roof solar reflectance and roof *U*-value. The results show that increasing the roof solar reflectance reduces cooling loads by 18–93% and peak cooling demand in air-conditioned buildings by 11–27%. The indoor thermal comfort conditions were improved by decreasing the hours of discomfort by 9–100% and the maximum temperatures in non air-conditioned residential buildings by 1.2–3.3 °C. These reductions were found to be more important for poorly or non-insulated buildings. For the locations studied, the heating penalty (0.2–17 kWh/m^2 year) was less important than the cooling load reduction (9–48 kWh/m^2 year). The application of cool roof coatings is an effective, minimal cost and easy to use technique that contributes to the energy efficiency and the thermal comfort of buildings.

Keywords: Roof solar reflectance; Cooling energy savings; Indoor temperature; Roof *U*-value; Passive cooling

1. Introduction

In most countries, energy use in the building sector represents about one third of the total energy consumption. The contribution of building sector electricity use to that of the total electricity use of the country is even higher. In 2003, nearly 60% of total net electricity consumption in the OECD (Organisation for Economic Co-operation and Development) economies was in the building sector both residential and commercial, each representing about half of this electricity consumption [1]. In developing countries the residential building sector accounts for more than half of the electricity consumption [2]. Furthermore, the robust economic growth in many of the non-OECD countries is expected to boost residential demand for electricity, supporting a major transformation in living standards as electric lighting, air-conditioning and other appliances, and new technologies become available to an increasing share of the world's population [3]. Energy consumption for residential cooling shows an increasing trend worldwide and is, therefore, of primary concern not only for countries that are characterized by hot climatic conditions but also for cities suffering from the heat island effect. Urban heat islands with daytime average air temperatures 2–5 °C higher than the surrounding rural areas are present in many cities around the world. In Athens, Greece, according to climatic measurements performed at 30 urban and suburban stations during the summer of 1997, the daily heat island intensity under the canopy was found to be close to 10 °C [4–7]. Apart from the thermal discomfort, heat islands are an energy efficiency concern because increased air temperatures, raise air-conditioning loads in buildings, in turn raising energy consumption, peak electricity demand and energy prices [8–10]. According to the International Energy Administration (IEA 2005), from 1978 to 1997 the electricity use for residential air-conditioning in the US rose from 3.27×10^{17} to 4.43×10^{17} J and nearly 75% of all households had air-conditioners. In the OECD countries, electricity demand for residential space cooling has increased by 13% from 1990 to

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2000 [1]. Furthermore, the total demand for air-conditioners, at an international level, has increased by 6.8% during the period of 1999–2002 [11]. This extensive use of air-conditioning apart from being an energy efficiency concern is also an economic concern. Increasing electricity demand for cooling also increases peak electricity utility loads which forces utilities to burn more fossil, increasing energy costs and pollution levels. In addition, problems with indoor air quality related to the use of air-conditioners are of serious concern [7,8].

To decrease the demand for air-conditioning use, cool materials have gained a lot of interest during the past few years [12–14]. Cool materials are characterized by high solar reflectance (SR) and high thermal emittance values [15]. A number of white or light colored materials are currently commercially available for rooftops having high solar reflectance values ranging from 0.4 to 0.85. The thermal emissivity of these materials was measured to be about 0.9. For peak solar conditions (about 1000 W/m^2), for an insulated surface, and under a low wind condition, the temperature of a black surface with solar reflectance of 0.05 is about 50 °C higher than ambient air temperature. For a white surface with solar reflectance of 0.8, the temperature rise is about 10 °C. Surface temperature measurements demonstrated that a cool coating can reduce a concrete tile's surface temperature by 7.5 °C and it can be 15 °C cooler than a silver grey coating [16,17]. Furthermore, new cool colored materials that are highly reflective in the near infrared, are being developed for the cases where the aesthetics of darker colors is preferred [18,19]. The maximum difference between the solar reflectance of a cool and conventional color matched coating was found to be 0.22 with a corresponding surface temperature difference of 10.2 °C [18]. Another study reports that the solar reflectance of commercially available products has increased to 0.30–0.45 from 0.05–0.25 [19].

Increasing the solar reflectance lowers a surface's temperature since solar radiation is reflected rather than absorbed. In turn this decreases the heat penetrating into the building. During the summer, this results in lower cooling loads if it is an air-conditioned building, or in more comfortable thermal conditions if the building is not air-conditioned. The large-scale use of cool materials in an urban area leads also to indirect energy savings due to the increased solar reflectance that contributes to the reduction of the air temperature because of surface heat balance at the urban level. The indirect benefits arise from this ambient cooling of a city or neighborhood that will in turn decrease the need for air-conditioning [20,21].

Many experiments have been undertaken demonstrating the effectiveness of cool roofs in reducing cooling-energy use in residential buildings. Akbari et al. [22] measured cooling energy savings of about 2.2 kWh/day from changing the roof albedo of a residence in Sacramento, California from 0.18 to 0.73. Reductions in total and peak air-conditioning load of approximately 5% were measured for two identical white (SR $\approx$ 0.75) compared to gray (SR $\approx$ 0.30) and silver (SR $\approx$ 0.50) roofed scale model buildings in Tucson Arizona [23]. In another study [24], the average seasonal electricity savings resulting from application of highly reflective roofs on 11 residences in Florida was found to be 19%. In addition to field studies, computer simulations of cooling energy savings from an increased roof albedo have been documented for residential buildings. A simulation study performed for two mild and hot climates, showed that as the absorbtance varies from 1 to 0, the total energy load decreases by 32% and 47%, respectively for not insulated buildings and by 26% and 32% for insulated buildings [25]. The study concluded that the absorptance of a flat roof has an important effect on heating and cooling loads and the introduction of light colors especially on the roof decreases the total load. A comparative analysis that was conducted for new residential buildings in various cities in the U.S. showed that a residence with a cool roof could utilize a lower level of insulation than one with a dark roof with zero net change in the annual energy bill [26]. A study on the energy efficient envelope design for high-rise apartments in Hong Kong showed that a 30% reduction in solar absorptance can achieve 12% saving in annual required cooling energy [27]. Using cool roofing colored materials it was demonstrated that increasing the roofs reflectance from 0.08 to 0.3 and 0.5 decreases the consumed energy by 15% and 30%, respectively in Miami and Dallas [28] Cheng and Givoni [29] studied the effect of color on indoor temperatures in hot humid climates. They experimented with test cells and reported that for lightweight construction, the maximum air temperature inside the black cell was higher by about 12 °C than that of the white cell. Additionally the air temperature inside the white cell was only 2–3 °C higher than the outdoor.

This study aims to evaluate by means of simulation the potential energy savings and the impact on thermal comfort from the use of cool roof coatings in residential buildings in various climatic conditions worldwide. A parametric analysis is also carried out in order to estimate the impact of solar reflectance and insulation on cooling and heating loads as well as peak cooling loads.

2. Description of methodology

In order to estimate the effect of the use of cool and cool colored materials on the residential energy load, simulations were performed for 27 cities around the world representing different climatic conditions, including Mediterranean, humid continental, subtropical arid, desert conditions, etc. Table 1 gives the latitude and the longitude of the selected cities. TRNSYS thermal simulation software [30] was used for the simulations. The calculations were performed with an hourly time step. The meteorological data were taken from the METEONORM [31] database.

The base case building used in the simulation is a single story, flat roof house with a roof area of 100 m^2. It is non-directional, in the sense that its length and width are equal (10 m). Its height is assumed to be 3 m. Each wall has a glazing of 4 m^2 (13.3% of the wall area), a *U*-value of 5.8 W/m^2 K and it is well shaded (external shading factor 0.7). The *U*-value of the walls was considered to be 2.2 W/m^2 K and the *U*-value of the roof equal to 0.84 W/m^2 K. Infiltration and ventilation rates were both set equal to 0.8 ach. Regarding internal gains, the

Table 1
The latitude and longitude of the selected stations for the simulations

Station	Latitude (°)	Longitude (°)
Abu Dhabi, UEA	24.3	−54.58
Alexandria, Egypt	31.14	−30.35
Ankara, Turkey	39.42	−33.07
Athens, Greece	38	−23.37
Baghdad, Lebanon	33.14	−44.31
Barcelona, Spain	41.32	−2.1
Beijing, China	39.48	−117.02
Cairo, Egypt	30.12	−31.24
Casablanca, Moroco	33.29	7.33
Chania, Greece	35.29	−24.07
Damascus, Syria	33.31	−36.47
Johannesburg, South Africa	−26.17	−27.5
Karachi, Pakistan	25.03	−66
Los Angeles, USA	33.56	118.11
Miami, USA	25.59	80.04
Mexico City, Mexico	19.19	99.09
New Delhi, India	28.16	−77.21
New York, USA	40.47	73.58
Nice, France	43.4	−7.12
Palermo, Italy	38.04	−13.38
Riyadh, Saudi Arabia	24.5	−46.43
Rome, Italy	42.11	−12.8
Sevilla, Spain	37.22	5.58
Sydney, Australia	−33.46	−151.22
Teheran, Iran	35.33	−51.58
Thessaloniki, Greece	40.13	−22.58
Tokyo, Japan	35.34	−139.51

heat input per person was considered according to ISO7730, while for the artificial lighting and any other equipment it was assumed that 50% of the input is contributed to the place as convective heat and the 50% as radiative.

This building type may not necessarily be representative of the typical house in all the tested locations. However, the purpose is to report the cooling energy savings and potential wintertime penalties from changing the roof's solar reflectance comparatively for various climatic conditions.

The thermostat set point temperatures for cooling and heating was set to 26 and 21 °C respectively. Three different values of roof solar reflectance were simulated based on the experimental results for the cool and cool colored materials described above. For the base case the solar reflectance was considered to be 0.2. The increased values of solar reflectance due to the use of cool coatings were (a) a moderate 0.6 and (b) an extreme value of 0.85. It should be mentioned that the reflectance of a roof may change over time from aging, weathering, and soiling. Regular cleaning can mitigate the effects of soiling. LBNL suggests that the aged solar reflectance of a roof can decrease by as much as 0.15, mostly within the first year of service [15].

The infrared emittance was considered to be 0.9. Furthermore, for estimating the effect of cool coatings on thermal comfort conditions in the building, the above simulations were repeated but for the building running under free floating conditions.

To present representative results, five cases were chosen (a) Abu Dhabi where there is no heating load, (b) New Delhi where the cooling load is significantly more important than the heating load, (c) Casablanca where the heating load is almost half compared with the cooling load, (d) Damascus where cooling and heating loads are almost equal and (e) Tokyo that is heating load dominated.

For these five representative cases a parametric analysis was carried out including calculation of cooling loads for different values of roof solar reflectance ranging from 0.05 to 0.85 and for four values of roof *U*-value: $U_1 = 3.24\ \mathrm{W/m^2\,K}$, $U_2 = 2.7\ \mathrm{W/m^2\,K}$, $U_3 = 0.84\ \mathrm{W/m^2\,K}$ and $U_4 = 0.39\ \mathrm{W/m^2\,K}$ (representing roof *R*-values of 1.8, 2.1, 6.8 and 14.6 h ft^2 F/Btu). Furthermore, the effects on peak cooling loads of building were also calculated.

3. Analysis of the results

3.1. Estimating the impact from changing the roof solar reflectance on energy loads and thermal comfort for various climatic conditions

The cooling loads were calculated for the reference case (SRroof = 0.2) and the two increased solar reflectance scenarios representing buildings using cool roofing materials. The results (corresponding to a roof *U*-value of 0.84 W/m^2 K) are presented in Table 2. It should be pointed out that the values mentioned in this part of the study depend on the building characteristics and therefore are only indicative. As expected increasing roof reflectance results in reduced summer cooling loads. The decrease in the cooling loads for an increase in roof solar reflectance by 0.4 varies between 6.8 and 29 kWh/m^2 and for a higher increase by 0.65 between 8.4 and 48 kWh/m^2. As it can be seen from the table, buildings in places having a small reduction in their cooling load from the increase in their roof solar reflectance are characterized by small cooling loads but their corresponding % relative decrease in cooling load is higher. For example, a 65% relative decrease in cooling load for Mexico City corresponds to cooling load reduction of 6.8 kWh/m^2 and small values of base case and increased case cooling loads equal to 9 and 2.2 kWh/m^2, respectively.

In an effort to estimate also the heating penalty from increasing solar reflectance cooling loads were also calculated. Fig. 1, depicts the changes in cooling and heating loads resulting from an increase in roof solar reflectance of 0.65. The figure shows that the potential savings are greater in cooling season dominated climates. For the building chosen and the climates examined in this study, even in the cases where heating loads are more important than cooling loads, the decrease in cooling loads always exceeded the increase in heating load (except for the case of Mexico City) although in some cases this distinction was small. We can therefore conclude that increasing the solar reflectance of a roof is typically more beneficial in hot climates where cooling load dominates most of the year.

In order to evaluate the effect of climate on thermal comfort conditions inside the building the number of hours that the indoor temperature exceeds 27 and 29 °C were

Table 2
The calculated cooling loads for the base case (roof solar reflectance equal to 0.2) and the two increased albedo cases (ΔSR1 = 0.4 and ΔSR2 = 0.65) and the corresponding % decrease in cooling loads between the base case and the two scenarios

Place	Cooling load (kWh/m^2)			% Decrease in cooling load between base case and case 1	% Decrease in cooling load between base case and case 2
	Base case (SR = 0.2)	Increased albedo case 1 (SR = 0.6)	Increased albedo case 2 (SR = 0.85)		
Athens	58.0	43.3	34.6	25	40
Thessaloniki	46.8	34.5	27.2	26	42
Chania	62.7	47.4	38.5	24	39
Sevilla	54.9	41.7	33.8	24	38
Barcelona	30.1	20.3	14.9	33	51
Palermo	40.1	27.0	19.9	33	50
Rome	37.1	25.9	19.5	30	47
Nice	27.1	16.7	11.1	38	59
Abu Dhabi	265.4	236.0	217.0	11	18
Baghdad	144.3	125.8	114.1	13	21
Riyadh	179.1	154.8	139.5	14	22
Damascus	61.0	46.8	38.4	23	37
New Delhi	158.9	136.8	122.7	14	23
Beijing	47.6	35.6	28.6	25	40
Tokyo	36.5	26.2	20.4	28	44
Teheran	80.2	65.5	56.3	18	30
Karachi	158.5	131.3	114.3	17	28
Ankara	35.4	24.2	17.9	32	49
LA	32.4	19.9	13.3	39	59
New York	34.9	24.7	18.9	29	46
Miami	117.7	92.4	76.7	22	35
Mexico City	9.0	2.2	0.6	75	93
Casablanca	43.9	28.7	20.2	35	54
Cairo	104.5	84.6	72.4	19	31
Alexandria	75.1	57.2	46.6	24	38
Johannesburg	38.0	21.7	13.2	43	65
Sydney	37.7	24.3	16.8	35	55

calculated. These two threshold temperatures were chosen based on the ASHRAE standard 55-1992 [32] on thermal comfort conditions. According this standard the acceptable temperature range for summer conditions is 23.3–27.7 °C. The first value is close to the upper limit of this range and the second one a little higher. The calculated hours of discomfort for the conventional building and the two buildings using cool coatings (SR1 = 0.6 and SR2 = 0.85), for the two threshold values are presented in Table 3. It is evident that increasing the roof solar reflectance reduces the hours of discomfort for both threshold temperatures. This reduction is a function of the climatic conditions. Increasing the solar reflectance by 0.4 reduces the hours of discomfort by as much as 75% for a threshold value of 27 °C although for some cases this reduction is a lot smaller. Increasing the solar reflectance by 0.65 further decreases the number of discomfort hours. For a threshold temperature value of 29 °C, the indoor thermal conditions are further improved. The reduction of the hours of discomfort varies between 5% and 97% for a roof solar reflectance of 0.6 and between 9% and 100% for a solar reflectance of 0.85.

Table 4 gives the calculated maximum indoor temperatures for the conventional house and the two cases of increased roof solar reflectance. For the first scenario the maximum temperature decrease varies between 0.8 and 2 °C and for the second between 1.2 and 3.7 °C. It can be concluded that the use of cool roofing materials can contribute to the improvement of indoor thermal comfort conditions by decreasing the hours of discomfort and the maximum temperatures.

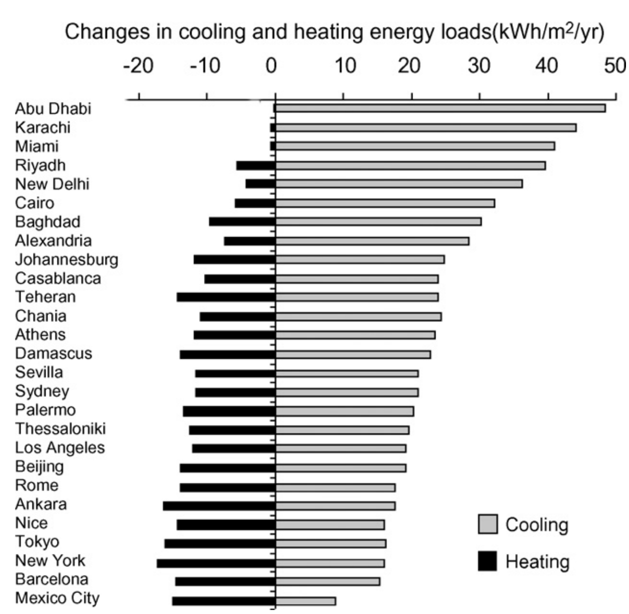

Fig. 1. Climate effect on cooling and heating load changes for a change in roof solar reflectance of 0.65.

Table 3
The calculated number of hours with the indoor temperature exceeding 27 and 29 °C

Place	Hours above a threshold indoor temperature (27 °C)					Hours above a threshold indoor temperature (29 °C)				
	Base case	ΔSR 0.4	ΔSR 0.65	Reduction of discomfort hours (%)	Reduction of discomfort hours (%)	Base case	ΔSR 0.4	ΔSR 0.65	Reduction of discomfort hours (%)	Reduction of discomfort hours (%)
Athens	3254	2729	2352	16	28	2445	1889	1482	23	39
Thessaloniki	3816	3192	2735	16	28	2839	2072	1527	27	46
Chania	1857	1293	961	30	48	1073	632	371	41	65
Sevilla	2210	1934	1739	12	21	1271	940	749	26	41
Barcelona	4422	4156	3978	6	10	3994	3702	3492	7	13
Palermo	2006	1500	1186	25	41	1331	858	560	36	58
Rome	2359	1950	1637	17	31	1733	1211	902	30	48
Nice	4532	4139	3793	9	16	3831	3199	2676	16	30
Abu Dhabi	2300	1485	1007	35	56	1234	613	309	50	75
Baghdad	2942	2435	2133	17	27	2235	1742	1334	22	40
Riyadh	2900	2376	2082	18	28	2120	1603	1283	24	39
Damascus	2565	1576	985	39	62	1393	617	270	56	81
New Delhi	7028	6505	6144	7	13	6097	5509	5077	10	17
Beijing	2256	1475	1017	35	55	1224	629	401	49	67
Tokyo	615	152	30	75	95	125	4	0	97	100
Teheran	6125	5371	4839	12	21	4803	4032	3457	16	28
Karachi	5768	5535	5382	4	7	5299	5033	4831	5	9
Ankara	1934	1307	876	32	55	1093	593	338	46	69
LA	2007	1630	1354	19	33	1456	1055	791	28	46
New York	2659	2063	1601	22	40	1746	1084	715	38	59
Miami	5739	5441	5229	5	9	5240	4911	4659	6	11
Mexico City	2266	1766	1414	22	38	1566	1057	717	33	54
Casablanca	3109	2687	2377	14	24	2474	1989	1591	20	36
Cairo	2384	1762	1250	26	48	1509	892	545	41	64
Alexandria	3440	3140	2883	9	16	2974	2582	2345	13	21
Johannesburg	2642	2229	1940	16	27	2050	1538	1226	25	40
Sydney	2190	1758	1436	20	34	1491	1046	800	30	46

3.2. Parametric analysis for estimating the impact of U-value and roof solar reflectance on energy savings

For the five representative climates selected, the net energy savings, i.e. the cooling savings minus the heating penalty, were calculated for four different roof *U*-values. Although subtracting heating load increase from cooling load reduction is not entirely correct given the fact that the systems used for cooling and heating are usually different, this calculation helps demonstrate the impact of the roof *U*-value on the savings from changing the roof solar reflectance by 0.4 (Fig. 2). It is evident that the *U*-value and thus the amount of insulation of the roof is a very important factor that affects the energy savings resulting from changing the roof reflectance. Furthermore as it can be observed in Fig. 2, the net energy savings are not a linear function of the *U*-value of the roof. The roof's surface temperature will change if its reflectance changes. However if the *U*-value is small (the roof is well insulated) the heat transfer between the surface of the roof and the interior of the building is small and the impact on the energy use is not important. Increasing reflectance would be more beneficial regarding the reduction of energy savings and energy costs for lower or no roof

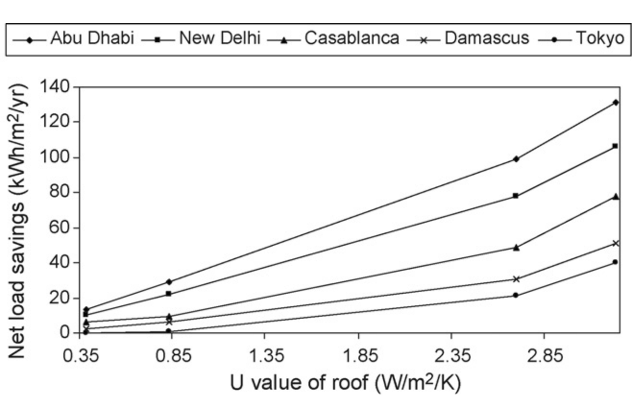

Fig. 2. The effect of *U*-value on the net energy savings resulting from changing the roof reflectance by 0.4.

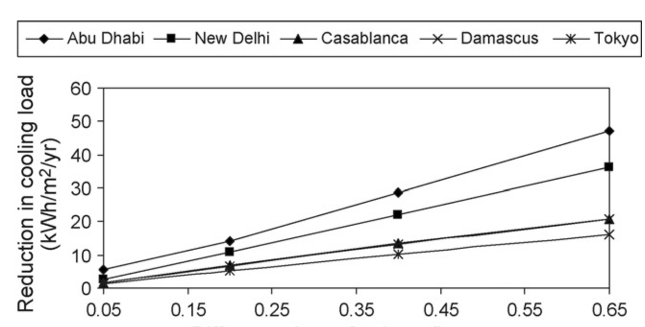

Fig. 3. The impact of roof solar reflectance changes on cooling load reduction for a roof *U*-value equal to 0.84.

Table 4
The calculated maximum indoor temperature for the base case and the increased roof solar reflectance cases

Place	Maximum indoor temperature (°C)			Decrease in maximum indoor temperature (°C)	
	Base case	ΔSR 0.4	ΔSR 0.65	ΔSR 0.4	ΔSR 0.65
Athens	39.6	37.9	36.7	1.8	2.9
Thessaloniki	37.9	36.4	35.4	1.5	2.5
Chania	35.6	34.1	33.1	1.6	2.5
Sevilla	35.7	34.9	34.5	0.8	1.2
Barcelona	47.3	45.5	44.3	1.8	3.0
Palermo	36.6	35.0	33.9	1.6	2.7
Rome	40.1	38.3	37.1	1.8	3.0
Nice	39.9	38.3	37.3	1.6	2.6
Abu Dhabi	36.1	34.4	33.2	1.8	2.9
Baghdad	39.1	37.2	36.0	1.9	3.1
Riyadh	37.5	35.9	34.8	1.6	2.7
Damascus	35.0	33.4	32.3	1.6	2.7
New Delhi	44.4	42.5	41.2	2.0	3.3
Beijing	37.2	35.4	34.2	1.8	3.0
Tokyo	31.2	29.5	28.4	1.6	2.7
Teheran	40.7	38.9	37.6	1.9	3.1
Karachi	44.4	42.7	41.6	1.7	2.8
Ankara	37.1	35.2	34.0	1.9	3.2
LA	37.7	35.5	34.5	2.1	3.1
New York	37.1	35.4	34.3	1.7	2.8
Miami	46.2	44.3	43.0	2.0	3.2
Mexico City	36.8	35.2	34.3	1.6	2.5
Casablanca	39.7	37.8	36.7	1.9	3.0
Cairo	36.6	34.6	33.3	2.0	3.3
Alexandria	43.3	41.5	40.3	1.8	3.0
Johannesburg	39.2	37.5	36.4	1.7	2.8
Sydney	39.1	37.5	36.4	1.6	2.7

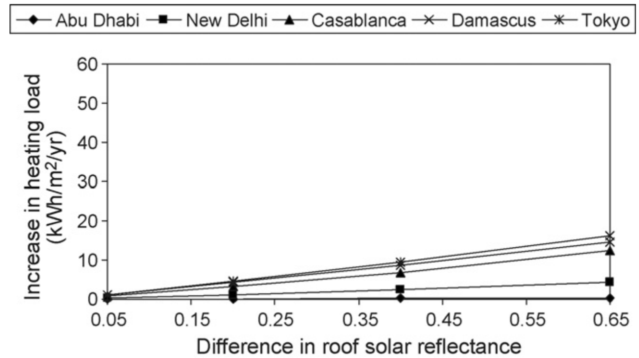

Fig. 4. The impact of roof solar reflectance changes on heating load increase for a roof U-value equal to 0.84.

insulation levels. This observation is quite important considering the fact the majority of the old residential buildings is poorly or not at all insulated. It should be pointed out though that in cooling dominated climates the reduction in energy savings can be significant even for higher levels of roof insulation (Fig. 2).

The cooling and heating loads for different values of roof solar reflectance ranging from 0.2 to 0.85 were calculated. The cooling load reduction and the heating load increase as a function of the difference in roof solar reflectance for a roof U-value equal to 0.84 are shown in Figs. 3 and 4. As expected, larger increases in roof solar reflectance correspond to larger increases in cooling load reduction and heating load increase. Furthermore, it is evident that an equal increase in solar reflectance produces greater reduction in cooling load for hotter climates. This differentiation between climates becomes more important for larger changes in solar reflectance. For example,

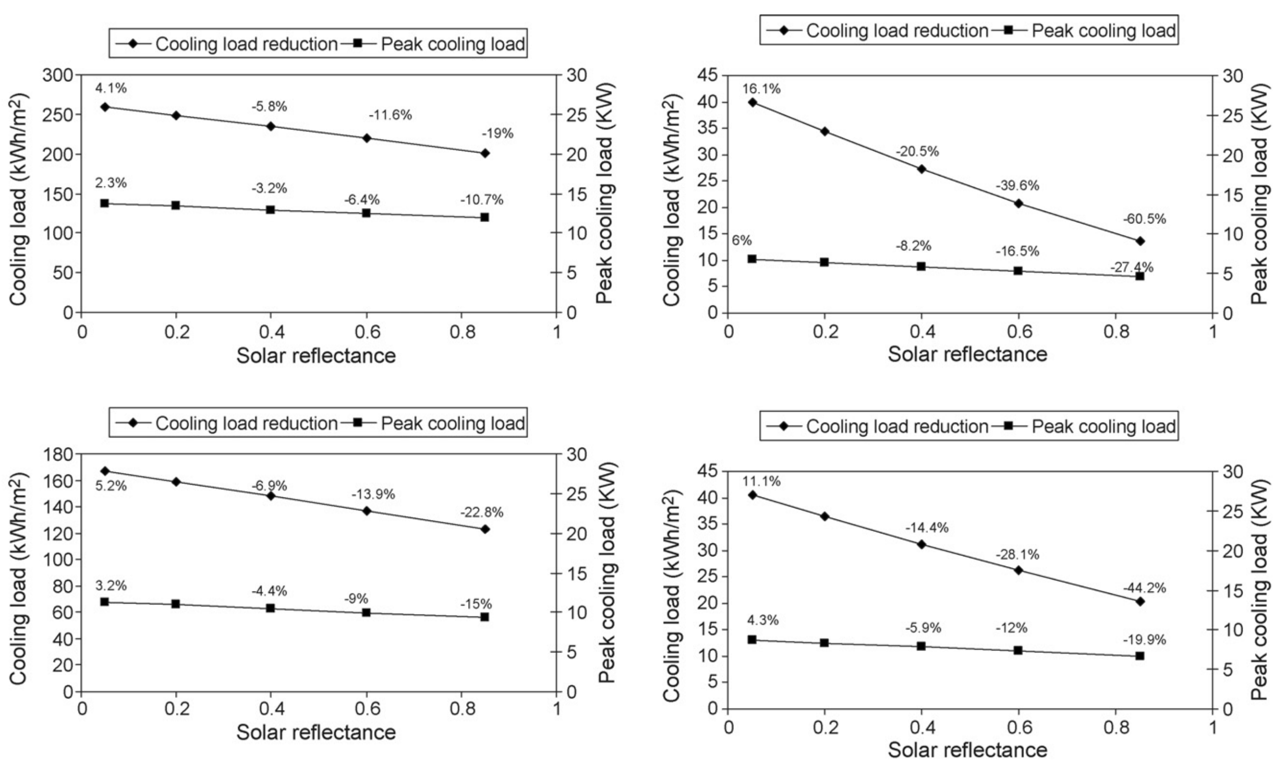

Fig. 5. The calculated cooling load and peak cooling load for various values of solar reflectance, for the five cases.

an increase in roof solar reflectance by 0.05 produces reductions in cooling loads that range between 1.34–5.7 kWh/m^2 for all five cases, increasing the solar reflectance by 0.65 produces reductions in cooling loads that now range between 16.1–47.2 kWh/m^2. The same applies for heating loads where an equal increase in solar reflectance produces greater increase in heating load for colder climates, although this effect is not as important as in cooling load reduction. Finally, as it is shown in Figs. 3 and 4, the effect of increasing the roof's solar reflectance has a more significant impact on cooling loads reduction than on heating loads increase for the climates studied. Increasing the solar reflectance of the roof by 0.65 yields a cooling load reduction that ranges between 16.1–47.2 kWh/m^2 for the five cases, while the corresponding increase in heating loads ranges only between 0.4–16.2 kWh/m^2. This observation is quite important because it points out that using cool materials could also be beneficial for climates that have heating loads that are comparable to cooling loads, depending of course on the corresponding costs.

Fig. 5 depicts the annual cooling load and the peak-cooling load for various values of solar reflectance ranging from 0.05 to 0.85 and for the five cases. The calculations correspond to a roof *U*-value of 0.84 W/m^2 K. It was found the percentage saving in cooling load is greater than the peak-cooling load saving from equal changes of roof solar reflectance. More specifically increasing the solar reflectance by 0.65 from a base case of 0.2, can achieve savings in cooling load that vary between 19% and 65% while the corresponding savings in peak cooling load vary between 10.7% and 27% according to the specific climatic conditions.

The annual reduction in cooling load was found to be linear function ($R^2 = 1$) of changes in roof solar reflectance for each location and for each roof *U*-value considered as it is shown in Fig. 6 for the case of Damascus. For the calculations the base case roof albedo was considered equal to 0.2. This observation is very important because it allows for energy savings presented here to be adjusted for applications where the base case and modified roof top albedo are different from the assumptions of this study. It can also be used in order to calculate the cooling savings loads corresponding to the aged roof reflectance. For this reason the calculated values of the annual cooling load reduction for various changes in roof solar reflectance are given in Table 5, for the four studied levels of roof *U*-values and the five selected locations.

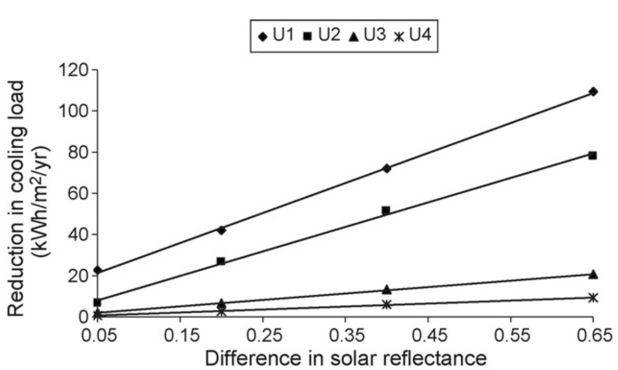

Fig. 6. The calculated reduction in cooling from changing the roof solar reflectance, for the four different *U*-values.

Table 5
Calculated annual cooling load reduction (kWh/m^2) for various changes in roof solar reflectance

ΔSR	Roof *U*-value (W/m^2 K)			
	3.24	2.7	0.84	0.39
Abu Dhabi				
0.05	16.3	33.2	5.6	1.6
0.2	65.4	49.3	14.3	6.6
0.4	131.4	99.1	28.8	13.4
0.65	213.3	160.7	47.2	22.1
New Delhi				
0.05	13.6	26.9	2.7	1.3
0.2	54	39.1	11	5.1
0.4	106.4	77.7	22.1	10.2
0.65	169.2	124.5	36.2	16.9
Casablanca				
0.05	12.2	22.1	1.8	0.7
0.2	47.3	32.7	7.1	2.9
0.4	89.3	61.1	13.6	5.6
0.65	130.1	89.4	20.8	8.9
Damascus				
0.05	22.5	6.7	1.7	0.7
0.2	37.5	26.4	6.7	2.9
0.4	71.7	51.2	13.3	5.8
0.65	109.0	78.3	20.7	9.2
Tokyo				
0.05	8.6	6.0	1.3	0.6
0.2	33.4	58.6	5.3	2.2
0.4	63.8	23.2	10.3	4.4
0.65	95.0	66.1	16.1	7.1

4. Conclusions

This study arises from the need to put forward passive solutions for reducing energy use for cooling and improve indoor thermal conditions in residential buildings. A simulation study was carried out aiming to assess the impact of using cool coatings on roofs on the energy loads and indoor thermal comfort conditions in residential buildings for various climatic conditions. It was found that an increase in roof solar reflectance by 0.65 resulting from the application of a cool coating, reduces cooling loads by 8–48 kWh/m^2, the hours of discomfort by 9–100% and the maximum temperature by 1.2–3.7 °C, depending on the climatic conditions. Additionally, a parametric analysis that was performed showed that two main factors affecting the energy savings resulting from using cool coatings in residential buildings was the climate and the *U*-value of the roof. It was demonstrated that the heating penalty (0.2–17 kWh/m^2 year) is less important compared to the cooling load reduction (9–48 kWh/m^2 year) for the climates studied and that increasing the reflectance of the roof would be more beneficial regarding the reduction of energy savings and energy costs for lower or no roof insulation levels, as is the case for most old construction buildings. Regarding peak cooling loads it was shown that increasing the solar reflectance by 0.65

from a base case of 0.2, can achieve savings that vary between 10.7% and 27% according to the specific climatic conditions. It should be mentioned that in order to estimate the energy use and savings, the types of systems used for cooling and heating as well as the energy prices (Euros/kWh) for the systems used should be taken into account. Finally the annual reduction in cooling load was found to be linear function of changes in roof solar reflectance for each location and for each roof *U*-value considered.

The use of cool coatings is an inexpensive and passive solution that can contribute to the reduction of cooling loads in air-conditioned buildings and the improvement of indoor thermal comfort conditions by decreasing the hours of discomfort and the maximum temperatures in non air-conditioned residential buildings. The results of this study can contribute to the promotion of the use of cool materials as well as the adoption of high albedo measures in building energy codes and urban planning regulations.

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References

[1] Energy Information Administration (EIA), International Energy Annual, 2003, http://www.eia.doe.gov/iea/.
[2] Organisation for Economic Cooperation and Development, Energy Statistics of OECD Countries (http://www.oecd.org/).
[3] Energy Information Administration, International Energy Outlook 2006: Chapter 2: Energy Consumption by End-Use Sector, http://www.eia.doe.gov/oiaf/ieo/world.html.
[4] M. Santamouris, Heat island research in Europe—the state of the art, Advances Building Energy Research 1, in press.
[5] G. Mihalakakou, H. Flocas, M. Santamouris, C. Helmis, The impact of synoptic scale atmospheric circulation on the urban heat island effect over Athens, Greece, Journal of Applied Meteorology 41 (5) (2002) 519–527.
[6] I. Livada, M. Santamouris, K. Niachou, N. Papanikolaou, G. Mihalakakou, The thermal island effect in the extrended region of Athens, Theoretical Applied Climatology 71 (2002) 219–230.
[7] M. Santamouris (Ed.), Energy and Climate in the Urban Built Environment, James and James Science Publishers, London, 2001.
[8] H. Akbari, S. Davis, S. Dorsano, J. Huang, S. Winert, Cooling our Communities—A Guidebook on Tree Planting and White Colored Surfacing, US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division, 1992.
[9] M. Santamouris, N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, D.N. Assimakopoulos, On the impact of urban climate on the energy consumption of buildings, Energy and Buildings 70 (2001) 201–216.
[10] S. Hassid, M. Santamouris, N. Papanikolaou, A. Linardi, N. Klitsikas, C. Georgakis, D.N. Assimakopoulos, The effect of the Athens heat island on air conditioning load, Energy and Buildings 32 (2000) 131–141.
[11] Japan Refrigeration and Air conditioning Industry Association, Estimates of World Demand for Air Conditioners, 2000–2008, http://www.jraia.or.jp.
[12] A.H. Rosenfeld, J.J. Romm, H. Akbari, M. Pomerantz, Cool communities: strategies for heat islands mitigation and smog reduction, Energy and Buildings 28 (1998) 51–62.
[13] A.H. Rosenfeld, H. Akbari, J.J. Romm, M. Pomerantz, Cool communities: strategies for heat island mitigation and smog reduction, Energy and Buildings 28 (1) (1995) 51–62.
[14] H. Akbari, M. Pomerantz, H. Taha, Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas, 2001.
[15] S. Bretz, H. Akbari, Long-term performance of high albedo roof coatings, Energy and Buildings 25 (1997) 159–167.
[16] P. Berdahl, S.E. Bretz, Preliminary survey of the solar reflectance of cool roofing materials, Energy and Buildings 25 (1997) 149–215.
[17] A. Synnefa, M. Santamouris, I. Livada, A study of the thermal performance of reflective coatings for the urban environment, Solar Energy 80 (2006) 968–981.
[18] A. Synnefa, M. Santamouris, K. Apostolakis, On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy, in press.
[19] H. Akbari, P. Berdahl, A. Desjarlais, N. Jenkins, R. Levinson, W. Miller, A. Rosenfeld, C. Scruton, S. Wiel, Cool colored materials for roofs, in: ACEEE Summer Study on Energy Efficiency in Buildings, Proceedings of American Council for an Energy Efficient Economy, Asilomar Conference Center in Pacific Grove, CA, August, 2004.
[20] A.H. Rosenfeld, H. Akbari, M. Pomerantz, H. Taha, J.J. Romm, Policies to reduce heat islands: magnitudes of benefits and incentives to achieve them, in: Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, vol. 9, 1996.
[21] H. Taha, S. Konopacki, S. Gabersek, Impacts of large scale surface modifications on meteorological conditions and energy use: a 10-region modeling study, Theoretical and Applied Climatology 62 (1999) 175–185.
[22] H. Akbari, S. Bretz, D. Kurn, J. Hanford, Peak power and cooling energy savings of high-albedo roofs, Energy and Buildings 25 (1997) 117–126.
[23] J.R. Simpson, E.G. McPherson, The effects of roof albedo modification on cooling loads of scale model residences in Tucson Arizona, Energy and Buildings 25 (1997) 127–137.
[24] D. Parker, J. Huang, S. Konopacki, L. Gartland, J. Sherwin, L. Gu, Measured and simulated performance of reflective roofing systems in residential buildings, ASHRAE Transactions 104 (1) (1998) 963–975.
[25] A. Shariah, B. Shalabi, A. Rousan, B. Tashtoush, Effects of absorptance of external surfaces on heating and cooling loads of residential buildings in Jordan, Energy Conversion and Management 39 (1998) 273–284.
[26] S. Konopacki, H. Akbari, Simulated Impact of Roof Surface Solar Absorptance, Attic and Duct Insulation on Cooling and Heating Energy in Single Family New Residential Buildings. LBNL Report 41834, Berkeley, CA, 1998.
[27] C.K. Cheung, R.J. Fuller, M.B. Luther, Energy efficient envelope design for high rise apartments, Energy and Buildings 37 (1) (2005) 37–48.
[28] W.A. Miller, A.O. Desjarlais, H. Akbari, R. Levinson, P. Berdahl, R.G. Scichili, Special IR reflective pigments make a dark roof reflect almost like a white roof, in: Thermal Performance of the Exterior Envelopes of Buildings, IX, in Progress for Proceedings of ASHRAE THERM IX, Clearwater, FL, 2004.
[29] V. Cheng, B. Givoni, Effect of envelope color and thermal mass on indoor temperatures in hot humid climate, Solar Energy 78 (2005) 528–534.
[30] TRNSYS (Version 15), A Transient System Simulator Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA.
[31] METEONORM, Global Meteorological Database for Solar Energy and Applied Climatology, Swiss Federal Institute of Technology, Zurich, Switzerland.
[32] ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy.