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The Impacts of Cool Colored Roofs and Solar Reflectance Index of Material in Reducing Building Cooling Energy Use

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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. One simple and effective way to mitigate urban heat islands, and their negative impacts on cooling energy consumption is to use high-albedo materials on major urban surfaces such as rooftops, streets, sidewalks and etc. Roofs that have high solar reflectance and high thermal emittance stay cool in the sun. A roof with lower thermal emittance but exceptionally high solar reflectance can also stay cool in the sun. Measured data and computer simulations have demonstrated the impact of roof albedo on saving cooling energy use in buildings. Cool roofs can also lower the citywide ambient air temperature in summer, slow ozone formation and increase human comfort. This study is based on library research and data analysis; in this the paper summarized the results of investigations and analyzed the impact of roof albedo and emissivity on heating and cooling energy use. Results indicatethat raising the solar reflectance of a roof from a typical value of 0.1–0.2 to an achievable 0.6 can reduce cooling-energy use in buildings by more than 20%. The existing results clearly show that the mitigation and cooling potential of cool roofs is very significant and can highly contribute to decrease temperature of the urban environment.

Keywords: *Cool roofs, Solar Reflectance, Thermal Emittance, High-albedo Materials, Roof Shapes, Cooling Energy Savings*

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1. Introduction:

Modern urban areas have typically darker surfaces and less vegetation than their surroundings. These differences affect climate, energy use, and habitability of cities.

At the building scale, dark roofs heat up more and, thus, raise the summer-time cooling demands of buildings. Collectively, dark surfaces and reduced vegetation warm the air over urban areas, leading to the creation of urban `heat islands'.

A high solar reflectance or albedo[1] is the most important characteristic of a cool roof as it helps to reflect sunlight and heat away from a building, reducing roof temperatures (Fig. (1)) (US. EPA 2005).

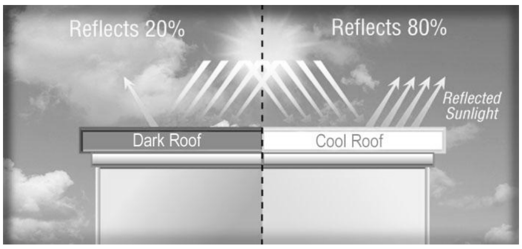

Figure (1). Solar reflectance in dark and cool surfaces.

Cooler roofs potentially reduce the summertime air temperature and, hence, indirectly reduce cooling energy use by an additional 5% to 10% (Akbari, Pomerantz and Taha 2001).

Roofs that have high solar reflectance (high ability to reflect sunlight: spectrum 0.3–2.5μm) and high thermal emittance (high ability to emit thermal radiation: spectrum 4–80μm) stay cool in the sun(Akbari and Levinson 2008). Coatings colored with conventional pigments tend to absorb the invisible "near-infrared" (NIR) radiation that bears more than half of the power in sunlight (Fig. (2)) (Akbari et al. 2004).

Replacing conventional pigments with "cool" pigments that absorb less NIR radiation can yield similarly colored coatings with higher solar reflectance(Akbariet al. 2004). For highly absorptive roofs, the difference between the surface and ambient air temperatures may be as high as 50°C (90°F), while/or less absorptive (high-albedo) roofs, such as white coatings, the difference is only about 10°C(Akbari and Konopacki 1998). 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.

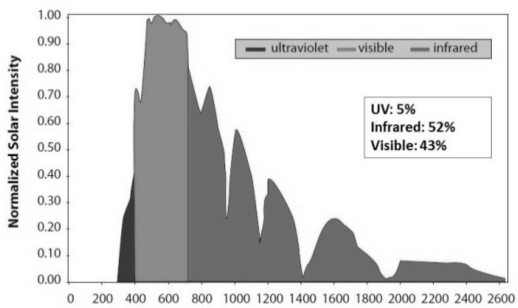

Figure (2). Peak-normalized solar spectral power; over half of all solar power arrives as invisible, "near-infrared" radiation.

On a typical summer afternoon, a cool-colored roof that reflects 35% of sunlight will stay about 12°C (22°F) cooler than a traditional roof that looks the same but reflects only 10% of sunlight(LBL 1998).

The cooling energy savings for reflective roofs are highest in hot climates. 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 fact, each 1°C (1.8°F) of urban air temperature reduction may result

1. Albedo, or reflection coefficient, derived from Latin albedo "whiteness" (or reflected sunlight) in turn from albus "white", is the diffuse reflectivity or reflecting power of a surface. High Albedo Roofs minimize the absorption of summer heat, thereby reducing air conditioning costs, These roofs, sometimes called reflective or cool roofs.

in savings of 2-3% of the system-wide electric utility load in most major mid-latitude cities. In hot climates, changing the roof emissivity from 0.9 (emissivity of most nonmetallic surfaces) to 0.25 (emissivity a/fresh and shiny metallic surfaces) can result in a net 10% increase in annual utility bills. In very cold climates with no summertime cooling, the heating energy savings resulting from decreasing the roof emissivity can be up to 3% (Akbari and Konopacki 1998, Taha, Sailor and Akbari 1992).

Typically, electricity demand in cities increases by 2–4% for each 18C increase in temperature. Hence, we estimate that 5–10% of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.08C in urban temperatures (Akbari, Pomerantz and Taha 2001).

Evaluation of the heat island mitigation potential of cool roofs in a city is a quite new scientific subject. Taha also conducted a modeling study that analyzed the mesoscale meteorological and ozone air quality impacts of large-scale increases in surface albedo in southern California. With extreme increases in albedo, peak concentrations at 3 p.m. decreased by as much as 7%, i.e. from 220 down to 205 ppb (parts per billion) while the total ozone mass in the mixed layer decreased by up to 640 metric tons (4.7%). In reference to air quality, domain-wide population-weighted exceedance exposure to ozone decreased by as much as 16% during peak afternoon hours and by up to 10% during the daytime (Gago et al. 2013). 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 by 3.1 kWh/day (35% of base-case use), and peak demand by 0.6 kW (about 20% of base-case demand). (It is important to note that altering the albedo starts to pay for itself immediately through the direct effect.) (Akbari, Pomerantz and Taha 2001).

Parker et al. (1995) 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 average savings of 7.4 kWh/day (savings of 19%). Peak demand between 5 and 6 p.m. was reduced by 0.2–1.0 kW, with an average reduction of 0.4 k (savings of 22%) (Parker et al. 1995).

The objective of the present paper is to review, in a critical way, the available scientific information on the mitigation potential of reflective roofs (cool roofs). Also, to combine and analyze the existing theoretical and experimental data, compare and homogenize the results and if possible, to provide general conclusions and suggestions.

2. Research Method:

This study based on library research and data analysis; in this paper we summarize the results of Investigations and analyze the impact of roof albedo and emissivity on heating and cooling energy use. The existing results clearly show that the mitigation and cooling potential of cool roofs is very significant and can highly contribute to decrease temperature on the urban environment.This study was carried out to review and summarize this research area through an investigation of the most important feature of material roofing in reducing building cooling energy use.

This paper systematically reviews recent research on the effects of various planning strategies to counteract or mitigate the cooling energy use in buildings and urban environment. The main objective of such strategies is to reduce energy consumption in cities as well as greenhouse gas emissions into the atmosphere. The methodology used for this systematic review work is described, and consists of the following steps:

1- Definitions and Terms

2- Benefits and Penalties

3- Building-scale Effects

4- The Impact of Reflectance and Emissivity

5- Urban-scale Effects

6- Energy Savings and Cost of Cool Roofs

7- Standards and Codes of Cool Roofs

8- Cool-Roof Provisions in other Standard and Programmes

9- Shape and Type of Cool Roof

10- Cool Materials

3. Definitions and Terms:

Solar Reflectance (SR):

Solar Reflectance is a parameter between 0 (dark surface) and 1 (cool surface) which the fraction of the incident solar energy which is reflected by the surface in question. This is the reflectance in the visual part of the solar spectrum, wavelengths of 400 to 700 nanometers. A good white coating with a solar reflectance of 0.8 typically has a visible reflectance of about 0.9 (LBL 1998).

Table (1). Suggested color-reflectivity classification for opaque building materials and selected albedo values [ASTM E1980, ASTM International Standard].

Reflectivity code	Albedo	Color code	Albedo
Reflective	0.90	Reflective	0.60-0.75
Very light	0.75	White	0.50-0.60
Light	0.65	Grey-dark grey	0.30-0.50
Medium	0.45	Green, Red, Brown	0.20-0.30
Dark	0.25	Dark brown to blue	0.10-0.20
Very dark	0.10	Dark blue to black	0.80-0.90

Thermal Emittance (TE):

Thermal Emittance is a parameter between 0 and 1 which measures the ability of a warm or hot material to shed some of its heat in the form of infrared radiation. The wavelength range for this radiant energy is roughly 5 to 40 micrometers (LBL 1998).

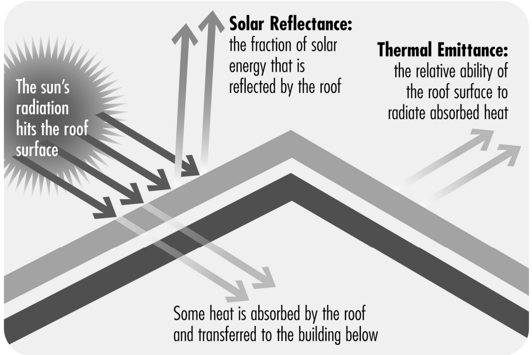

Figure (3). Solar reflectance and thermal emittance are the two radioactive properties to consider when selecting a cool roof. (Image courtesy of the Cool Roof Rating Council).

Solar Reflectance Index (SRI):

The Solar Reflectance Index (SRI.) is a measure of the roof's ability to reject solar heat, as shown by a small temperature rise. It is defined so that a standard black (reflectance 0.05, emittance 0.90) is 0 and a standard white (reflectance 0.80, emittance 0.90) is 100. For example, the standard black has a temperature rise of 90°F (50°C) in full sun, and the standard white has a temperature rise of 14.6°F (8.1°C).

The solar reflectance index (SRI) is a composite value calculated using the equations in ASTM E1980[1], "Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces." For a given set of environmental conditions, SRI is based on a surface's solar reflectance and thermal emittance (LBL 1998, Marceau and VanGeem 2008).

1- ASTM International, known until 2001 as the American Society for Testing and Materials (ASTM), is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.

Table (2). Solar Reflectance and Thermal Emittance for Building Materials [Based on data from Wechsler and Glaser (1966)].

Material	SR	TE
Concrete	0.30	0.94
Red brick	0.30	0.90
Wood (freshly planed)	0.40	0.90
White paper	0.75	0.95
Tar paper	0.05	0.93
White plaster	0.93	0.91
Bright galvanized iron	0.35	0.13
Bright aluminum foil	0.85	0.04
White pigment	0.85	0.96
Grey pigment	0.03	0.87
Green pigment	0.73	0.95
White paint on Al	0.80	0.91
Black paint on Al	0.04	0.88
Aluminum paint	0.80	0.40
Water	0.05	0.95
Ice	0.69	0.90
Gravel	0.72	0.28
Dry, plowed ground	0.10	0.80
Sand	0.24	0.76
Vegetated fields	0.10	0.76
Forests	0.10	0.85

4. Benefits and Penalties

Substituting a cool roof for a warm roof reduces conduction of heat into the building, convection of heat into the outside air, and thermal radiation of heat into the atmosphere. This benefits our buildings, our cities, and our planet.

Prescribing the use of cool roofs in building energy efficiency standards promotes the cost-effective use of cool roofs to save energy, reduce peak-power demand and improve air quality. Another option is to credit, rather than prescribe, the use of cool roofs.

This can allow more flexibility in building design, permitting the use of less energy-efficient components (e.g. larger windows) in a building that has energy-saving cool roofs. Such credits are energy neutral, but may still decrease peak-power demand and improve air quality. They may also reduce the initial cost of the building.

1- Benefits:

- Cooler outside air.
- Fewer power plant emissions.
- Better air quality (Reduced air pollution and greenhouse gas emissions).
- Slowed climate change.
- Energy and cost savings (Reduced energy use).
- Improved human health and comfort.
- Reduced electrical grid strain.

2- Penalties:

- Increased need for heating in winter.
- Glare.
- Negative impact on the life span of the roof (US. EPA 2005).

Computer simulations are used to obtain estimates of year-round effects for a variety of building types and climates. A recent study made quantitative estimates of peak demand and annual cooling-electricity use and savings that would result from increasing the reflectivity of the roofs.

The estimates of annual net savings in cooling electricity are adjusted for the penalty of increased wintertime heating energy use (Akbari, Pomerantz and Taha 2001).

5. Building-scale Effects

At the building scale, a dark roof is heated by the sun and, thus, directly raises the summertime cooling demand of the building beneath it.

For highly absorptive (low-albedo) roofs, the difference between the surface and ambient air temperatures may be as high as 50°C, while for less absorptive (high-albedo) surfaces with similar insulate properties, such as roofs covered with a white coating, the difference is only about 10°C (Akbari and Konopacki 1998). For this reason, `cool' surfaces (which absorb little `insolation') can be effective in reducing cooling energy use.

For example; direct and indirect effects of albedo modifications on cooling energy use in a residential building, Sacramento CA, July 9-12.

Solar reflectance (SR) and thermal emittance (TE) are the buildings albedo, respectively and the last row represents the cooling energy hours during that period. Table 3 summarizes the results for a house in Sacramento CA, for the period between July 9 and July 12 (Taha, Sailor and Akbari 1992, Griggs, Sharp and MacDonald 1989).

Table (3). Direct and indirect effects of SR modifications on cooling energy use in a residential building, Sacramento CA, July 9-12.

	Basecase	**Direct savings**	**Direct+Indirect savings**
Building	SR= 0.30	SR= 0.90	SR= 0.90
kWh/day	25	19%	62%
Peak kw	7.07	14%	35%
Cool.hours/day	14	7%	44%

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 Monitored nine homes in Florida before and after applying high-albedo coatings to their roofs. Air-conditioning energy use was reduced by 10% to 43%, with an average savings of 7.4 kWh/day (19% of low-albedo use) (Akbari and Konopacki 1998). The direct effect of lowering the albedo and removing the surrounding vegetation of a surface and is to increase its solar heat gain and thus its surface temperature. If the surface is the roof or wall of a building, the increased heat gain directly increases the cooling energy use and peak cooling demand of the building. Fig. 4 and 5 shows the midday temperatures of various horizontal surfaces exposed to sunlight (Akbari, Levinson and Rainer 2005).

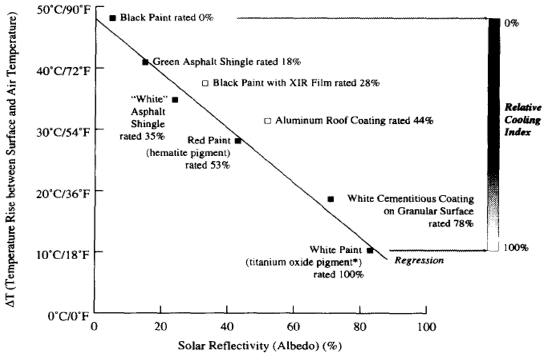

Figure (4). The difference between surface and air temperatures vs. solar reflectivity of paints and roofing materials facing the sun.

For highly absorptive (low-albedo) surfaces, the difference between the surface and ambient air temperature, (ΔT_{s-a}) may be as high as 50 °C (100 °F), while for less absorptive (high-albedo) surfaces, such as white paint, (ΔT_{s-a}) is about 10 °C. For this reason, shade trees (which reduce the insolation on a surface) and cool surfaces (which absorb little of the incident insolation) are effective means of direct cooling and reducing energy use (Akbari, Levinson and Rainer 2005, LBL 2005).

Highly absorptive surfaces contribute to the heating of the air, and thus indirectly increase the cooling demand of (in principle) all buildings. Cool surfaces incur no additional cost if color changes are incorporated into routine re-roofing and re-surfacing schedules.

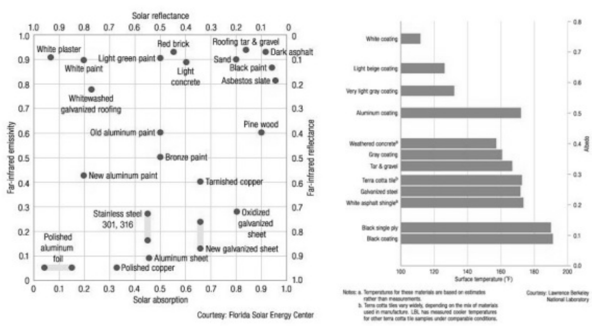

Figure (5). Surface temperature and albedo of common roofing materials and paints.

Through direct shading and evapotran spiration, trees reduce summer cooling energy use in buildings at about 1% of the capital cost of avoided power plants plus air-conditioning equipment (Akbari, Rosenfeld and Taha 1990).
Cool surfaces are more effective than trees, and cost little if color changes are incorporated into routine maintenance schedules.
Also, the results from light-colored surfaces are immediate, while it may be ten or more years before a tree is large enough to produce significant energy savings (Akbari, Rosenfeld and Taha 1989).

5.1. The Impact of Reflectance

A cool roof with high solar reflectance; transfers less heat to the building below, so the building stays cooler and uses less energy for air conditioning.
In a recent study, LBNL[1]research team have made quantitative estimates of the impact of reflective roofs on peak demand and annual cooling electricity use of buildings. Both cooling energy savings and possible heating energy penalties were estimated. The net energy savings were adjusted for the increased wintertime energy use.
In all simulations, they assumed a base-case roof reflectivity of 0.25 and emissivity of 0.9 for both residential and commercial buildings.

- The modified reflectivities were selected based on the analysis of the existing database. The reflectivity of the modified residential buildings (mostly sloped) was selected to be 0.55.
- For the commercial buildings that are characterized mostly with flat and low-sloped roofs, the reflectivity of the modified roofs was selected to be 0.70.

1- Lawrence Berkeley National Laboratory; Lawrence Berkeley National Laboratory (Berkeley Lab) is a Department of Energy (DOE) Office of Science lab managed by University of California.

The emissivity of the modified roofs for both commercial and residential buildings was 0.9 (Akbari and Konopacki 1998).

Table (4). The Impact of modified reflectivities.

Modified (SR)	Basecase (SR)	Buildings
SR= 0.55	SR= 0.25 TE= 0.90	Residential Building
SR= 0.70	SR= 0.25 TE= 0.90	commercial Building

Result: light-colored roofing could produce annual savings of $750 M per year by reducing the utility bills in residential and commercial buildings.
The electricity savings was about 10 TWh/yr (about 3% of the national cooling electricity use in residential and commercial buildings), and the peak power savings was about 7 GW (2.5%) (equivalent to fourteen 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%) (Akbari and Konopacki 1998).

5.2. 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 (Akbari and Konopacki 1998):

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

- SR= solar reflectance
- I= solar flux, $W.m^{-2}$.
- TE= thermal emittance.
- σ = Stefan Boltzmann constant, $5.670373(21) \times 10^{-8}$ $W.m^{-2}.K^{-4}$.
- T_s= steady-state surface temperature, K.
- T_{sky}= sky apparent radioactive temperature, K.
- h_c= convective coefficient, $W.m^{-2}.K^{-1}$.
- T_a= air temperature, K.

- T_{in}= inside temperature, K.
- U= overall roof heat transfer coefficient, $W.m^{-2}.K^{-1}$.

Analyticalformulas:

Summer: During hot summer days, the lower the roof emissivity, the higher the surface temperature, and hence an increased heat conduction into the building. In air-conditioned (A/C) buildings, this would lead to a higher cooling energy use.

(Notice::Increase: Decrease)

↑ ↓

Table (5). Analytical formulas in summer.

cooling energy consumption	Heat conduction	$T_{surface}$	TE	Summer
↑	↑	↑	↓	A/C buildings

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 to a lower heating energy use.

Table (6). Analytical formulas in winter.

heating energy consumption	Heat conduction	$T_{surface}$	TE	Winter
↓	↓	↓	↓	A/C buildings

Notice: 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.

Example: In residential buildings in hot climates (Phoenix, U.S), the net utility bills increased 20 ¢/m2 to 40 ¢/m2 when the emissivity was decreased from 0.9 to 0.25 (Akbari and Konopacki 1998), (Akbari, Levinson and Rainer 2005).

In cold climates (Philadelphia and Chicago, U.S), the net utility bills in the residential building were again insensitive to roof emissivity (Akbari and Konopacki 1998, Akbari, Levinson and Rainer 2005).

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.

6. Urban-scale Effects:

When a region of dry, low-albedo, unshaded surfaces (i.e. a city) is exposed to sunlight, the surfaces become very hot, and in turn warm the air throughout the region. This climatic effect is quite substantial (Akbari, Levinson and Rainer 2005).

The implications of lower ambient temperatures and the use of cool roofs on urban scale include:

1- A decrease in some photochemical reaction rates.
2- A decrease in air pollutant emissions.
3- Human comfort and health.
4- Improve air and water quality.
5- A decrease in evaporative losses of organic compounds from mobile and stationary sources.
6- A decreased need for cooling energy, generating capacity, and, thus, emissions from power plants (LBL 1998, Quattrochi and Ridd 1994, SOS 1995).

In big cities, a cool roof transfers less heat to the building below, so the building stays cooler and uses less energy for air conditioning.

But cool roofs deflect some desired heat gain during the winter. In general, though, cool roofs result in net energy savings, especially in areas where electricity prices are high.

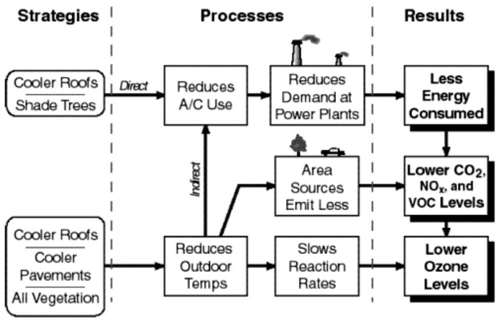

Figure (6). Methodology to analyze the impact of cool roofs, shadetrees, and cool pavements on energy use and air quality (Akbari, Pomerantz and Taha 2001).

7. Energy Savings and Cost of Cool Roofs

7.1. Energy Savings of Cool Roofs:

Reflective roofing is an effective summertime energy saver in warm and sunny climates. It has been demonstrated to save up to 40% of the energy needed to cool a building during the summer months (Gartland, Konopacki and Akbari 1996). Buildings without air conditioning can reduce their indoor temperatures and improve occupant comfort during the summer if highly reflective roofing materials are used.

But there are questions about the tradeoff between summer energy savings and extra wintertime energy use due to reduced heat collection by the roof.

These questions are being answered by simulating buildings in various climates using the DOE-2 program (version 2.1E) (Gartland, Konopacki and Akbari 1996).

Butunfortunatelyin our country(Iran) usingcool surfaces ina wide range and with the aim ofoptimizing theenergy consumption; has not beenconsidered bydesignersand investors. Undoubted; data and information on energy-saving and cost estimate is not available.

During hot summer months in united statescountries, cool roofs reduce the need for cooling in air conditioned buildings, which saves energy and money.

The use of highly reflective materials on roof surfaces has been measured to save between 10 and 50% of the energy used for summer cooling in tests performed in California and Florida.

Sacramento (school bungalows):

In the study of school bungalows in Sacramento, the measured cooling energy savings due to changing the roof color from brown to white was 4.6 kWh/day on average. In the school bungalows, cooling-energy was reduced by 3.1 kWh/day (35% of base-case use), and peak demand by 0.6 kW (about 20% of base-case demand). 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).

California (commercial buildings):

1- Monitored the impacts of light-colored roofs on cooling-energy use of three commercial buildings in northern California. Increasing the reflectance of the roofs from an initial albedo of about 0.20 to 0.60 dropped the roof temperature on hot summer afternoons by about 25°C. Summertime, standard-weekday, average daily air conditioning savings were 18% in a medical office building, 13% in a second medical office building, and 2% in a drug store (Akbari, Pomerantz and Taha 2001, Konopacki, et al. 1998).

2- In the school building in San Marcos, for the monitored period of 8 July–20 August 2002, the estimated savings in average air conditioning energy use was about 42–48 Wh/m2/day (17–18%). On hot days, when the afternoon temperature exceeded 32°C, the measured savings in average peak demand for hours 10 a.m.–4 p.m. was about 5 W/m2 of conditioned area (Akbari, Levinson and Rainer 2005).

The buildings were also modeled with the DOE-2.1E simulation program.

The results for the 11 MSAs were extrapolated to estimate the savings in the entire United States. Weather data for 11 U.S.[4] Metropolitan Statistical Areas (MSAs) were used (Akbari, Pomerantz and Taha 2001).

- Result of case studies:

The study estimates that, nationally, light-colored roofing could produce savings of about:

- 10 TWh/ year (about 3.0% of the national cooling-electricity use in residential and commercial buildings).
- An decrease in natural gas use by 26 GBtu/year (1.6%).
- A decrease in peak electrical demand of 7 GW (2.5%; equivalent to 14 power plants each with a capacity of 0.5 GW).
- A decrease in net annual energy bills for the rate-payers of $750M.

Table (7). Estimates of metropolitan-scale annual cool in energy savingsin11MetropolitanStatisticalAreas (Akbari, Pomerantz and Taha 2001).

Metropolitan area	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

Cooling-energy savings and heating-energy penalties were then obtained from the difference in the simulated energy use of the prototype buildings with light- and dark-colored roofs.

Cool roofs on residential buildings yielded measured summertime cooling energy savings and peak-power demand reductions that ranged from negligible to 80 per cent (Akbari and Levinson 2008).

7.2. Cost of Cool Roofs

Increasing the overall albedo of roofs is an attractive way of reducing the net radiative heat gains through the roof, and, hence, reducing building cooling loads. To change the albedo, the rooftops of buildings may be painted or covered with a new material.

Since most roofs have regular maintenance schedules or need to be re-roofed or recoated periodically, the change in albedo should be done then to minimize the costs.

High-albedo alternatives to conventional roofing materials are usually available, often at little or no additional cost.

For example, a built-up roof typically has a coating or a protective layer of mineral granules or gravel. Under such conditions, it is expected that choosing a reflective material at the time of installation should not add to the cost of the roof.

The incremental price premium for choosing a white rather than a black single-

ply membrane roofing material is less than 10% (Akbari, Pomerantz and Taha 2001).
Cool roofs on non-residential buildings typically yielded measured summertime daily cooling energy savings and peak-power demand reductions of 10 to 30 per cent, though values have been as low as 2 per cent and as high as 40 per cent.
Generally; Cool surfaces (cool roofs and cool pavements) and urban trees can have a substantial effect on urban air temperature and, hence, can reduce cooling-energy use and smog (Akbari, Rosenfeld and Taha 1990). We estimate that about 20% of the national cooling demand can be avoided through a large-scale implementation of heat-island mitigation measures. This amounts to 40 TWh/year savings, worth over $4B per year by 2015, in cooling-electricity savings alone (Akbari, Pomerantz and Taha 2001, Akbari and Taha 1992).

8. Standards and Codes of Cool Roofs

Provisions for cool roofs in energy efficiency standards can promote the building-and climate-appropriate use of cool roofing technologies. Cool-roof requirements are designed to reduce building energy use, while energy-neutral cool-roof credits permit the use of less energy-efficient components (e.g. larger windows) in a building that has energy-saving cool roofs. Both types of measures can reduce the life-cycle cost of a building (initial cost plus lifetime energy cost).

Since 1999, several widely used building energy efficiency standards, including:
1- ASHRAE 90.1.
2- ASHRAE 90.2.
3- The International Energy Conservation Code (IECC).
4- ASTM E1980-11 (Standard for calculating solar reflectance index of roofs).
5- California's Title 24 (building code) and etc. have adopted cool-roof credits or requirements.

It is difficult for a building owner to assess the influence of roof properties on the lifetime cost of heating and cooling energy, which depends upon:
- climate- and building-specific hourly uses of heating and cooling energy.
- hourly valuations of energy.
- the time value (discounting) of money.
- the service life of the roof.

Building owners may also be unaware of the societal benefits of cool roofs, such as lower peak-power demand and lower outdoor air temperatures (improving comfort and slowing the formation of smog).
Hence, without cool-roof standards, owners will tend to choose roofs that minimize initial construction cost, rather than the aggregate cost of construction and lifetime energy consumption.

8.1. Development of standard:

8.1.1. ASHRAE: In 1999, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) first credited cool roofs on non-residential and high-rise residential buildings in ASHRAE Standard 90.1-1999 and In 2004, ASHRAE Standard 90.2-2004 (Akbari and Levinson 2008).
- ASHRAE 90.1: Energy standards for buildings "except low-rise" residential buildings.
- ASHRAE 90.2: Energy efficient design of "low-rise" residential buildings.
- ASHRAE standards 90.1-2004 (new commercial buildings) and 90.2-2007 (new residential buildings) offer credits for installing roofs with high solar reflectance (Ashrae 2004, Ashrae 2007).

8.1.2. California's Title 24: In January 2001, the state of California followed the

ASHRAE approach by crediting in its "Title 24" Energy Efficiency Standards for Residential and Non-Residential Buildings the use of cool roofing products on non-residential buildings with low-sloped roofs (CEC, 2001) (Akbari and Levinson 2008).

California's current (year 2005) 'Title 24' building energy-efficiency standards prescribe a minimum initial solar reflectance of 0.70 and a minimum initial thermal emittance of 0.75 for low-sloped roofs on nonresidential buildings, with somewhat lower thermal emittance requirements for roofs of especially high solar reflectance. The current Title 24 standards also offer performance credits for the use of cool products on other types of roofs (CEC 2005).

8.1.3. IECC: The 2012 International Energy Conservation Code (IECC) section 801.2 allows commercial buildings to comply with the 2003 IECC by satisfying the requirements of ASHRAE Standard 90.1, which, in turn, offers cool-roof credits. Table 404.5.2(1) assigns to the roof on the reference residential building a solar absorptance of 0.75 (solar reflectance of 0.25) and a thermal emittance of 0.90, while the roof on the proposed building is assigned its proposed values of solar absorptance and thermal emittance(IECC 2012).

8.1.4. ASTM E1980: 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 ASTM subcommittee has determined that two radiative properties (solar reflectivity and thermal emissivity) need to be measured in both the laboratory and the field.

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 1980) (Akbari and Konopacki 1998).

It is the objective of this standard to define a solar reflectance index (SRI) that 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 (Akbari and Konopacki 1998), (IECC 2012).

One way to measure how "cool" a roof can be is by calculating its Solar Reflectance Index (SRI). This index is calculated following ASTM Standard E1980-11 using a roof product's solar reflectance and thermal emittance values (Blau and Budinski 1999). The SRI calculation can also be used to estimate the surface temperature of the roof product under prescribed conditions. High SRI values indicate "cooler" roofing products (LBL 1998).

9. Database for Solar Reflectance Index Calculator

Solar Reflectance Index Calculator, ASTM Designation; E 1980-01: http://web.ornl.gov/sci/roofs%2Bwalls/calculators/sreflect/index.htm.

10. Cool-Roof Provisions in other Standard and Programmers

Many World countries and US states have adopted building energy efficiency codes from ASHRAE Standard 90.1 or the International Energy Conservation Code (IECC).

Cool-roof requirements have also been developed by several voluntary energy-efficiency programmes, including:

1- The US Environmental Protection Agency (EPA) Energy Star label.

2- The Leadership in Energy and Environmental Design (LEED); Green Building Rating System.

3- CRRC (Cool Roof Rating Council).
4- Green Globes.
5- The cool-roof rebate programmes offered by the state of California and its utilities.
6- CABO (Council of American Building Officials).
7- CEC (California Energy Commission).

Table (8). Cool-Roof Provisions in other Standard and Programmes (Energy Star, CRRC, LEED, Green Globes and etc.).

COOL ROOF GRANTS PROGRAM

Building Type	Initial Reflectance		Rebate (per square foot)	
	Low Slope[1]	Medium Slope[2]		Soy–base coating
Residential	≥ 0.65	≥ 0.25	\$0.50	\$0.70
Commercial	≥ 0.65	≥ 0.25	\$0.55	\$0.75
Industrial	≥ 0.65	≥ 0.25	\$0.60	\$0.80

RATING AND CERTIFICATION REQUIREMENTS

	Steep Sloped Building Roof slope > 2:12	Low Sloped Building Roof slope ≤ 2:12
ENERGY STAR®	Initial Solar Reflectance ≥0.25 3 year Solar Reflectance ≥0.15	Initial Solar Reflectance ≥0.65 3 year Solar Reflectance ≥0.50
CRRC®	Solar Reflectance ≥ 0.20 Thermal Emittance ≥ 0.7	Solar Reflectance ≥ 0.70 Thermal Emittance ≥ 0.75
LEED®	SRI ≥ 29	SRI ≥ 78
Green Globes	SRI ≥ 29	SRI ≥ 78

11. Shape of Cool Roof:

Late summer afternoon temperatures in cities are 2°F to 10°F (1.5°C–6°C) higher than in surrounding areas. Only about 1% of that increase is from heat generated directly by vehicles and equipment, according to Lawrence Berkeley National Laboratory (LBNL) research. The rest is from solar-heated surfaces. Those higher temperatures decrease comfort, increase air-conditioning costs, and exacerbate health problems, because ozone (a component of smog) is created when pollutants, such as nitrogen oxides and volatile organic compounds, heat up. A temperature drop of 3°F–4°F (2°C) can reduce smog by 10%–20%, according to LBNL (LBL 1998).

A cool roof is one that strongly reflects sunlight and also cools itself by efficiently emitting radiation to its surroundings. The two basic characteristics that determine the "coolness" of a roof are solar reflectance (SR) and thermal emittance (TE). Both properties are rated on a scale from 0 to 1, where 1 is the most reflective or emissive.

Reflective, light colored “cool” roofs can not only help reduce cooling costs, but can also have a positive environmental impact by reducing the urban heat island effect (LBL 1998).

Shape and form of roof is a significant impact in reducing solar reflectance and thermal emittance emission.

Solar reflectance index (SRI) in flat roof more from steep roof and dome roof. As a result, the solar reflectance and thermal emittance on the flat roofs, is higher. Therefore, during hot summer months, flat roofs with cool coatings reduce the need for cooling in air conditioned buildings, which saves energy and money.

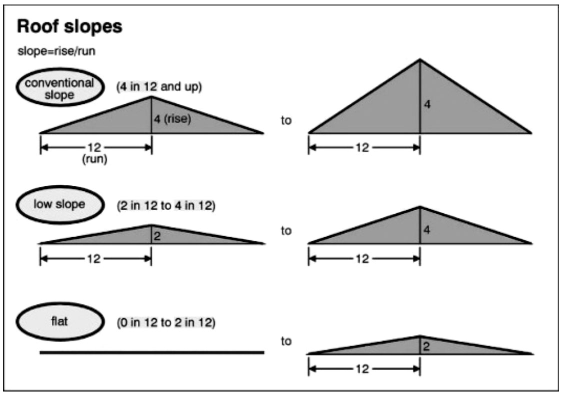

Figure (8). Shape of Cool Roof (Flat, Low Slope and Steep Slope).

12. Types of Cool Roofs:

Cool roofs for commercial and industrial buildings fall into one of three categories: roofs made from inherently cool roofing materials, roofs made of materials that have been coated with a solar reflective coating, or green planted roofs (Campra, et al. 2008), (Akbari, Matthews and Seto 2012).

- Inherently Cool roofs **(Thermoplastic White Vinyl):**

White vinyl roofs, which are inherently reflective, achieve some of the highest reflectance and emittance measurements of which roofing materials are capable; solar reflectance (SR): 70-80% (Akbari, Levinson and Rainer 2005, Campra, et al. 2008).

Department of Energy USA - Cool Roof Rating Council (CRRC) - Lawrence Berkeley Lab; Case Study: Use white vinyl roofing membranes:

- Reducing the average temperature: 24°C.
- Save energy: 11%.
- Demand reduction of cooling systems: 14%.

- Coated Cool roofs:

An existing roof can be made reflective by applying a solar reflective coating to its surface; with reflective coatings, polymers, pigments and aluminum flakes (Akbari, et al. 2004).

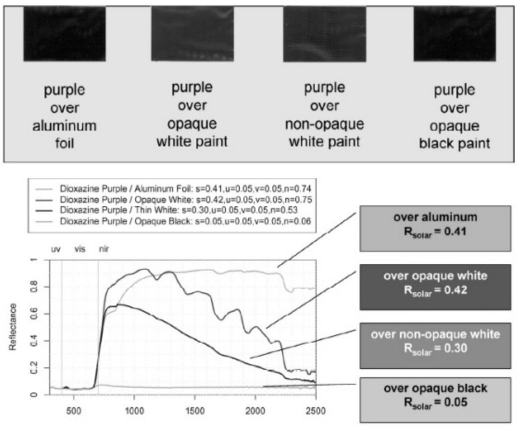

Figure (9). Layering pigments and reduce energy consumption.

- Green roofs:

Green roofs provide a thermal mass layer which helps reduce the flow of heat into a building. The solar reflectance of green roofs varies depending on the plant types (generally 30-50%). Because of the lower solar reflectance, green roofs reflect less sunlight and absorb more solar heat than white roofs. The absorbed heat in the green roofs is trapped by the greenhouse effect and then cooled by evapotranspiration (Akbari, Pomerantz and Taha 2001, Akbari, Rosenfeld and Taha 1990).

Figure (10) On a typical day, ChicagoCity Hall, green roofs; temperature differencewiththe neighboringrooftops: 40°C.

13. Cool Materials:

The 'cool materials' or Highly reflective are a cost effective, environmentally friendly and passive technique that contributes to achieving energy efficiency in buildings by lowering energy demand for cooling and improving the urban microclimate by lowering surface and air temperatures. Cool materials are characterized by:

(a) High solar reflectance (SR).

(b) High thermal (infrared) emittance (TE) (Santamouris, Synnefa and Karlessi 2011).

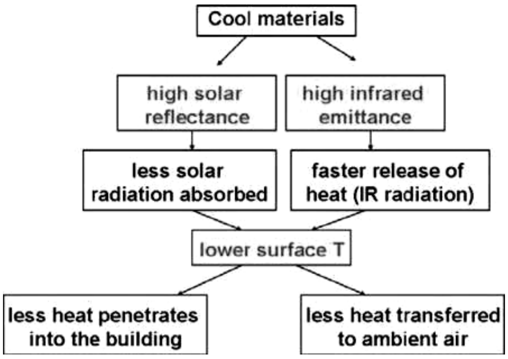

Figure (11). The basic principles of cool materials.

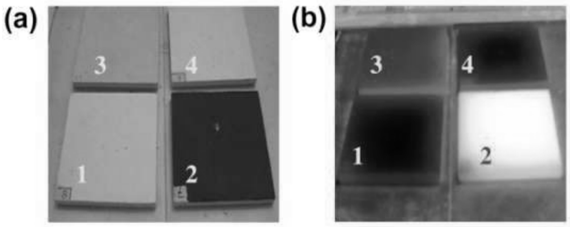

Figure (12). Visible (a) and infrared (b) images of four concrete tiles painted with cool white coatings (1 and 4), a black coating (2) and an unpainted off-white (3) one. The difference in solar reflectance translates into a significant difference in surface temperatures (Santamouris, Synnefa and Karlessi 2011).

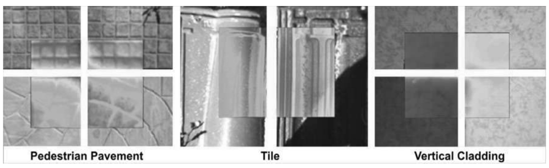

Figure (13). Examples of the images recorded by the IR camera (SRI) (Alchapar, Correa and Cantón 2014).

Solar reflectance and thermal emittance of materials and conventional and cool roof coverings have been studied by many researchers and reported in several databases such as US Cool Roof Rating Council, Energy Star Roof Products program, EU Project Cool Roofs and LBNL (Lawrence Berkeley National Laboratory) cool roofing materials database (Kültür and Türkeri 2012).

13.1. Example for Cool Materials (Case Study)

The building located in Oss, Netherlands has a surface area of 1685 m2 and 7.58 m height. The specific dwelling houses the production unit and storage of a chemical company and was constructed in October 1997 (Mastrapostoli, et al. 2014).

Figure (14). The roof before and after cool material application.

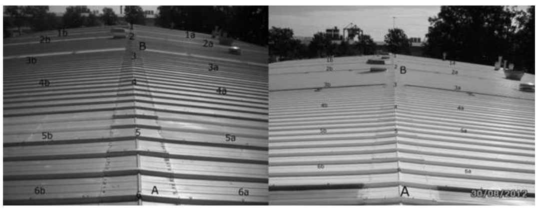

Figure (15). Visual and thermal images of the roof before the cool material application (1st phase).

Figure (16). Visual and thermal images of the roof after the cool material application (2nd phase).

Sensor no	T (°C)	1st phase		2nd phase	
		24/7/2012	25/7/2012	29/8/2012	30/8/2012
1	T_{max}	35.8	36.8	29.6	27.0
	T_{min}	21.6	23.2	22.9	21.2
2	T_{max}	33.8	31.0	28.5	25.5
	T_{min}	21.5	22.4	22.0	21.0
3	T_{max}	35.5	36.6	28.8	26.8
	T_{min}	21.7	22.4	22.2	21.0
4	T_{max}	33.3	34.3	29.0	25.4
	T_{min}	21.9	22.4	22.1	21.1
5	T_{max}	38.4	39.4	30.6	28.9
	T_{min}	21.7	22.3	22.3	21.0

Figure (17). Maximum and minimum indoor temperatures for all sensors during 1st and 2nd phase of the field testing (Mastrapostoli, et al. 2014).

14. Conclusions

Heat island refers to the temperature increase in urban areas compared to rural settings, intensifying the cooling energy consumption of buildings. Roofs constitute a major part in urban areas, hence cool roof coverings contribute to mitigate heat island.

Cool surfaces (cool roofs and cool pavements) can have a substantial effect on urban air temperature and, hence, can reduce cooling-energy use and smog. 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), depending on the thickness of insulation under the roof.

Raising the albedo of urban surfaces and increasing urban vegetation are easy ways to conserve energy, save money and probably to reduce air pollution. Experiments have shown 20-40% direct energy savings by increasing the albedo of a single building, and computer simulation indicates that the indirect effects of wide-scale albedo changes will nearly double the direct savings.The resulting decrease in outside air temperature can slow urban smog formation and improve human health and outdoor comfort. Reduced thermal stress may also increase the lifetime of cool roofs, lessening maintenance and waste.

Some other benefits include: Reducing utility bills associated with air conditioning, Increasing occupant comfort and avoid installing an air conditioner where there isn’t already one, Decreasing the size and prolong the life of your air conditioning system, Lowering roof maintenance costs and extend roof life, avoiding re-roofing costs and reducing solid waste, Assist your home in meeting building codes, Mitigate your community's Urban Heat Island Effect, Maintain aesthetics with a roof that performs and looks good, receive utility rebates (in some locations), indirect benefits.

cool roofs decrease urban air temperatures and thus slow the formation of ground level ozone. Ozone, the primary component of smog, can aggravate respiratory illness and can act as a greenhouse gas.

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تأثیر رنگ سرد سقف و شاخص بازتاب خورشیدی مواد بر کاهش مصرف انرژی خنک‌کننده ساختمان

پریسا قبادی[1]

چکیده

استفاده از بام‌های با پوشش تیره اثر قابل توجهی در میزان مصرف انرژی ساختمان‌ها و آب و هوای مناطق شهری دارد. در مقیاس تک بنا، بام‌های با پوشش تیره رنگ توسط تابش خورشید تابستان گرم می شوند که نتیجه آن افزایش تقاضای مصرف انرژی سرمایشی در فصل تابستان می باشد. یکی از راه‌های ساده و موثر جهت کاهش تشکیل جزایر حرارتی شهری، و اثرات منفی آن در مصرف انرژی سرمایشی؛ استفاده از مواد با ضریب بازتاب بالا در سطوح شهری از قبیل پشت بام‌ها، خیابان‌ها، پیاده‌روها و غیره می باشد. به این دلیل که بام‌های با ضریب بازتاب (SR) و نشر حرارتی (TE) بالا می توانند در برابر تابش آفتاب خنک بمانند. همچنین بام‌های با ضریب نشر حرارتی پایین و ضریب بازتاب خورشیدی بالا قادرند در برابر تابش خورشیدی نیز خنک باشند. بنابراین داده‌های اندازه‌گیری شده و شبیه سازی‌های کامپیوتری تاثیر استفاده از بام‌های سرد (Cool Roof) را در صرفه جویی مصرف انرژی سرمایشی ساختمان‌ها را به وضوح نشان می دهند. علاوه بر این بام‌های سرد می توانند کاهش درجه حرارت محیط سراسر شهر در فصل تابستان، کاهش تشکیل ازون و افزایش آسایش انسانی را به همراه داشته باشند. این پژوهش براساس مطالعات کتابخانه ای و تجزیه تحلیل و استنتاج منطقی از داده‌ها صورت گرفته است؛ در این تحقیق خلاصه ای از نتایج تحقیقات صورت گرفته در این زمینه ارائه می شود و اثرات بازتاب و نشر حرارتی بام‌ها بر مصرف انرژی سرمایشی و گرمایشی مورد تحلیل قرار می گیرد. نتایج نشان می دهد که افزایش بازتاب خورشیدی بام از یک مقدار معمولی ۰/۲–۰/۱ به مقدار ۰/۶، می تواند مصرف انرژی سرمایشی ساختمان را بیش از ۲۰٪ کاهش دهد. نتایج موجود به وضوح نشان می دهد که پتانسیل سرمایشی بام‌های سرد بسیار قابل توجه است و می تواند کمک مهمی به کاهش درجه حرارت محیط‌های شهری داشته باشد.

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