Title

Global Cooling: Policies to Cool the World and Offset Global Warming from CO2 Using Reflective Roofs and Pavements

Permalink

Author

Akbari, Hashem

Publication Date

2009-09-25

Global Cooling: Policies to Cool the World and Offset Global Warming from CO_2 Using Reflective Roofs and Pavements

Hashem Akbari[1] and Ronnen Levinson, Heat Island Group,*
Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Arthur Rosenfeld, California Energy Commission, Sacramento, CA, USA
Matthew Elliot, California Environmental Associates, San Francisco, CA, USA
**Corresponding author email: HAkbari@ENCS.Concordia.ca*

ABSTRACT

Increasing the solar reflectance of the urban surface reduce its solar heat gain, lowers its temperatures, and decreases its outflow of thermal infrared radiation into the atmosphere. This process of "negative radiative forcing" can help counter the effects of global warming. In addition, cool roofs reduce cooling-energy use in air conditioned buildings and increase comfort in unconditioned buildings; and cool roofs and cool pavements mitigate summer urban heat islands, improving outdoor air quality and comfort. Installing cool roofs and cool pavements in cities worldwide is a compelling win-win-win activity that can be undertaken immediately, outside of international negotiations to cap CO_2 emissions. We propose an international campaign to use solar reflective materials when roofs and pavements are built or resurfaced in temperate and tropical regions.

Introduction

As the threat of climate change becomes more pronounced, a number of scientists have proposed supplementing the full range of mitigation efforts with geo-engineering (manipulation of the Earth's environment) to quickly respond to this threat (AMS 2009). Many proposed geo-engineering techniques are novel and unproven. One simple technology has been in practice for thousands of years: changing the solar reflectance (albedo) of the built surface. "Cool roofs" and "cool pavements" should be among the first geo-engineering techniques used to combat global warming.

Increasing the solar reflectance of the urban surface reduces its solar heat gain, lowers its temperatures, and decreases its outflow of thermal infrared radiation into the atmosphere. This process of "negative radiative forcing" effectively counters global warming. Most existing flat roofs are dark and reflect only 10 to 20% of sunlight. Akbari et al. (2008) have shown that resurfacing conventional dark roofs with a cool white material that has a long-term solar reflectance of 0.60 or more increases its solar reflectance by at least 0.40. Retrofitting 100 m^2 of roof has an effect on radiative forcing equivalent to a one-time offset of 10 tonnes of CO_2. Given that CO_2 is currently traded in Europe at \$20/tonne, the value of this change could be worth up to \$200.

---

[1] Present Address: Department of Buildings, Civil and Environmental Engineering, Concordia University, Montreal, Canada. Tel: 514-848-2424 x3201.

In addition to reflecting light back into the atmosphere, it is well established that cool roofs reduce energy use in air conditioned buildings and increase comfort in unconditioned buildings (Akbari et al. 2005, 2001; Levinson et al. 2005). Similarly, the widespread application of cool roofs and cool pavements helps to mitigate summer urban heat islands, thereby reducing the overall air conditioning load and improving outdoor air quality and comfort (Akbari et al. 2001).

As a result of the low cost premium, substantial energy saving, and the lack of aesthetic conflict, it is fairly easy to persuade or require the owners of buildings to select white materials for flat roofs, and in California this has been required for non-residential buildings since 2005. However, the demand for white sloped roofs is limited in North America for aesthetic reasons. California has compromised by requiring only "cool colored" surfaces for sloped roofs, starting in January 2010. The use of cool-colored roofs increases solar reflectance by about 0.20, yielding the equivalent of a one-time CO_2 offset of 5 t per 100 m^2, or about half that achieved with white surfaces. The solar reflectance of pavement can be raised on average by about 0.15, the equivalent of a 4 t reduction in CO_2 per 100 m^2.

Over 50% of the world population now lives in urban areas, and by 2040 that fraction is expected to reach 70% (UN 2009). Using fine-resolution orthophotos, Akbari and Rose (2008) have estimated roof and pavement surface area fractions in four U.S. cities. Roof area fractions varied from 20% for less dense cities to 25% for more dense cities; pavement area fractions varied from 29% to 44%. Many metropolitan urban areas around the world are less vegetated than typical U.S. cities. In our calculations, we use average roof and pavement area fractions of 25% and 35%, respectively. We estimate that permanently retrofitting urban roofs and pavements in the tropical and temperate regions of the world with solar-reflective materials would have an effect on global radiative forcing equivalent to a one-time offset of 44 Gt of emitted CO_2, worth \$880 billion at \$20/tonne (Akbari et al. 2008).

How can the reader visualize this one time offset of 44 Gt of CO_2? If the average car emits 4 t of CO_2 each year, permanently increasing the solar reflectance of urban roofs and pavements worldwide would be the equivalent of avoiding 11 billion car-years of emissions, or taking the world's 600 million cars off the road for 18 years. Aggressively pursuing a strategy of cooling urban surfaces could delay some of the effects of climate change, during which time society can take further measures to reduce greenhouse gas emissions and improve our ability to adapt.

We propose an international "cool cities" campaign to use solar reflective materials when roofs and pavements are built or resurfaced in temperate and tropical regions. This paper discusses local, state, national, and international policies and programs for implementation of cool roofs and cool pavements.

Cool Strategies and Policies

The technology, policies, and public acceptance of cool roofs are far more advanced than those of cool pavements. The cool roofs policies are typically presented in the form of building standards, public awareness information programs, and rebate and incentives programs. Such policies have not been implemented for cool pavements. An aggressive international program to install cool roof and cool pavements can potentially increase the solar reflectance of majority of roof and paves surfaces within a 20-year period.

Cool Roofs

Cool Roof Standards, Building Codes, Rating, and Labelling in U.S.

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.

Since 1999, several widely used building energy-efficiency standards, including ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California's Title 24 have adopted cool-roof credits or requirements. Akbari and Levinson (2008) have summarized these standards. The techniques used to develop the ASHRAE and Title 24 cool-roof provisions can be used as models to address cool roofs in building energy-efficiency standards worldwide.

Building energy-efficiency standards typically specify both mandatory and prescriptive requirements. Mandatory requirements, such as practices for the proper installation of insulation, must be implemented in all buildings subject to the standard. A prescriptive requirement typically specifies the characteristics or performance of a single component of the building (e.g., the thermal resistance of duct insulation) or of a group of components (e.g., the thermal transmittance of a roof assembly).

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 reduce peak power demand and improve air quality. They may also reduce the first cost of the building. The following is a list of cool roof standards, building codes, rating, and labelling in the U.S.

- **ASHRAE Standard 90.1-2007** prescribes cool materials for low-sloped roofs on nonresidential buildings in some U.S. climates.

- **ASHRAE Standards 90.1-2004 and 90.1-2001** offer credits for cool materials for low-sloped roofs on nonresidential buildings in some U.S. climates.

- **ASHRAE Standard 90.2-2004** offers credits for cool materials for all roofs on residential buildings in some U.S. climate zones.

- The **2008 California Title 24 Standards** prescribe cool materials for roofs on residential and nonresidential buildings in some California climate zones.

- The **2005 California Title 24 Standards** prescribe cool materials for low-sloped roofs on nonresidential buildings in all California climate zones (but one coastal region) and offers credits for steep-sloped roofs on residential and nonresidential buildings in all California climate zones.

- The **2003 International Energy Conservation Code** allows commercial buildings to comply by satisfying the requirements of ASHRAE Standard 90.1, which at the time that IECC 2003 was written offered cool-roof credits.

- The **Chicago, IL** Energy Conservation Code prescribes a minimum solar reflectance and thermal emittance for low-sloped roofs.

- The **2004 Florida Building Code** prescribes cool materials for all roofs on non residential buildings that are essentially the same as those in ASHRAE Standard 90.1-2004.

- **Hawaii.** In 2001, 2002, and 2005, respectively, the counties of Honolulu, Kauai, and Maui adopted cool-roof credits for commercial and high-rise residential buildings based on ASHRAE Standard 90.1-1999.

- **U.S. EPA ENERGY STAR™ Label.** The U.S. EPA currently requires that low-sloped roofing products have initial and three-year-aged solar reflectances not less than 0.65 and 0.50, respectively. Steep-sloped roofing products must have initial and three-year-aged solar reflectances not less than 0.25 and 0.15, respectively.

- **LEED Green Building Rating System.** The Leadership in Energy and Environmental Design (LEED) Green Building Rating System assigns one rating point for the use of a cool roof in its Sustainable Sites Credit.

- **Cool Roof Rating Council.** The Cool Roof Rating Council was established in 1998 to "develop accurate and credible methods for evaluating and labeling the solar reflectance and thermal emittance (radiative properties) of roofing products and to disseminate the information to all interested parties."

California: Cool Roofs and Climate Targets

In California and many other states, cool roofs are an accepted measure to reduce air conditioning load (Akbari and Levinson 2008), thus decreasing electric bills and CO_2 emissions. However, to date, none of these codes have taken account of the effect that cool roofs and pavements have in reducing radiative forcing. Noting that, on average, existing urban surfaces can be changed to cool surfaces over a 15-year period, this effect is several times larger than the CO_2 emissions avoided through reduced electric load over this 15 year period.

Most roofs are replaced every 10 to 25 years (residential roofs every 20 to 30 years, non-residential roofs every 10 to 20 years), while most paved surfaces are resurfaced approximately every 10 years. By our calculations, an aggressive 15-year state-wide campaign to implement cool roofs and pavements in California would effectively be the equivalent of reducing California emissions by 31 Mt CO_2/year for 15 years. This is 18% of the annual target established by California Assembly Bill (AB 32). AB32 requires that by 2020 the state's greenhouse gas emissions be reduced to 1990 levels, a roughly 25% reduction under business-as-usual estimates. Such a campaign would involve requiring that all new roofs on new construction and existing buildings be white (or at least cool-colored) (an average increase of 0.25 in roof solar reflectance), and that resurfaced pavements utilize top layers of light-colored materials (an average increase of 0.15 in pavement solar reflectance).

Akbari et al. (2008) estimate the worldwide cooling potential of white roofs and cool pavements in all major tropical and temperate cities (about 1% of Earth's land area) is equivalent to offsetting roughly 44 Gt CO_2 emissions. This in turn would be equivalent to avoiding a year's worth of global CO_2 emissions.

Table 1 summarizes the results for California. Total California urban areas are estimated at 16,000 km^2 (4% of the total California area of 410,000 km^2). The estimated roof and paved surface areas are 4,000 km^2 and 5,600 km^2, respectively. We use the equivalency that increasing the solar reflectance of a m^2 of an urban surface by 0.01 yields a negative radiative forcing equivalent to offsetting 2.55 kg of CO_2 emissions. Assuming average increases of 0.25 and 0.15 in the solar reflectances of roofs and pavements, respectively, the equivalent CO_2 offset in California is estimated at 470 Mt.

In addition to cooling the Earth, cool roofs also reduce air-conditioning (AC) electricity use. In California, we estimate that 1/3 of residential and 2/3 of non-residential buildings are air conditioned. Assuming a modest average air-conditioning savings of about 3 kWh/year per m^2 of conditioned roof area, the AC savings in California is estimated at 6 TWh/year. The CO_2 emission reduction is estimated at 3 Mt/year (see Table 2). Although this 3 Mt CO_2/year is an attractive measure for AB32, we note that it is only 1/10th of the albedo-equivalence of 31 Mt CO_2/year.

In Figure 1 we compare to the goals of AB32 the potentials of equivalent CO_2 savings (negative radiative forcing) and actual CO_2 savings (emission reductions) from installing cool roofs and cool pavements. AB32 targets a 175 Mt/year reduction in CO_2 emissions by 2020, relative to 2010. If we assume linear progress from 2010 to 2020 in the implementation of the AB32 measures, the total CO_2 savings targeted by AB32 during this period is 875 Mt. Assuming an average of 31 MtCO_2-equivalent savings per year from cool roofs and cool pavements, in California this would produce an additional equivalent savings of 310 Mt during the same 10 years, continuing at the same rate of 31 Mt CO_2/year until 2025. After all the target urban surfaces are made reflective, this equivalent savings drops to zero in 2026. Only the cool-roof AC savings of 3 Mt CO_2/year would continue after 2026.

Cool Roofs in Other Countries

Cool Roof Energy Saving Potentials. Cool roofs offer significant cooling energy savings in buildings with air conditioning and improve comfort in buildings without air conditioning. Akbari et al. (2005) have calculated the effect of cool roofs on the annual cooling energy use of a prototypical house for most cooling-dominant cities around the world. The savings estimates are based on an increase in roof solar reflectance to 0.3 (typical cool roof) from 0.1 (typical hot roof).

Table 3 shows cooling degree days based on 18°C (CDD18) and potential cooling energy savings in kWh per year for a house with a roof area of 100 m^2. The savings can be linearly adjusted for houses with larger or smaller roof areas. They also can be linearly scaled for a smaller or greater change in the roof's solar reflectance. The savings range from approximately 170 kWh/year for mild climates to over 700 kWh/year for very hot climates. At US$0.10/kWh, the economical value of cooling energy savings ranges from US$0.25-1.00/year per m^2 of roof area. Assuming a 20 year life for a roof and a discount rate of 3%, the present value of the 20 year savings will be $3.70 to $14.90 per m^2 of roof area. In most countries, these savings may equal or exceed the cost premium (if any) for the cool roof. For houses that are not air conditioned, cool-colored roofing materials offer comfort, typically at very reasonable costs. Assuming an emission rate of 750 g CO_2 per kWh of electricity savings, the annual CO_2 savings ranges from 1.9 – 7.5 kg/m^2 of roof area.

We have also calculated the effect of cool roofs on the annual cooling energy use of a prototypical office building for the same cooling-dominant cities around the world. The prototype may not necessarily be representative of the stock of office buildings in all countries.

Table 4 shows potential cooling energy savings in kWh per year for a house with 100 m^2 of roof area. The savings range from approximately 500 kWh/year for mild climates to over 1000 kWh/year for very hot climates. At $0.10/kWh electricity price, the savings range from $0.50-1.00 per m^2 of roof area. Assuming a 20 year life for a roof and a discount rate of 3%, the present value of the 20 year savings will be $7.40 to $14.90 per m^2 of roof area. In most countries, these savings may equal or exceed the cost premium (if any) for the cool roof. For offices that are not air conditioned, white roofing materials offer comfort, typically at very reasonable costs. The annual CO_2 savings ranges from 3.8 – 7.5 kg/m^2 of roof area.

Cool Roofs Codes and Standards. In much of the world, the design, construction, and materials used for residential and commercial buildings are guided by building codes. Building codes are an obvious leverage point for promoting cool roofs. The bulk of the codes are dedicated to ensuring the integrity of the building from a health and safety perspective, but the codes also cover matters relating to energy use, and have, in recent years, become increasingly inclusive of requirements that save energy in buildings as long such measures are cost competitive. Because building codes are focused on the energy savings potential of individual buildings, they do not consider the climate benefits of cool roofs or the micro□climate benefits of reducing the heat island effect. As a result, building codes inherently undervalue cool roofs within the suite of efficiency options (e.g., insulation, efficient windows, radiant barriers).

The process for updates, degree of centralization, and level of enforcement of building codes vary greatly by country. For example, in China, there is a single national code with three climate zones. In India, there is a single national code, but it is voluntary. In the European Union (EU), building codes are decentralized, determined at the country level. The variation in building codes creates a range of different possible strategies for the promotion of cool roofs.

Because of large population and significant growth in infra-structure, China and India may present the greatest near-term opportunities for effective promotion of cool roofs through building codes. India particularly offers great promises as its population density, growth in buildings, and tropical climate zones make it a high potential region for cool roofs. Further, the Indian government’s interest in climate mitigation/adaptation is considerable and the playing field is shifting rapidly towards greater capacity for energy efficiency implementation of all kinds.

The European Union (particularly its southern countries that require significant summertime cooling) also offer significant opportunities. In February 2009, the EU Cool Roof Council (EU-CRC) organized its first meeting to promote and provide support for installation of cool roofs in Europe.

Brazil with its large population and mostly hot climate also offers significant opportunities. The “One Degree Less” movement (ODL 2009), pioneered in Brazil, has adopted cool roofs and heat island mitigation as its first practical program to combat global warming. However, in Brazil the lack of building codes can create challenging conditions.

Other developed (e.g., Australia) and developing countries in Middle East and Africa offer significant opportunities for installing white roofs to save energy and cool the globe. Many traditional (but ignored) architectural practices use passive technologies (including white roofs and walls) for improving indoor comfort in buildings.

Cool Pavements

Akbari et al. (2008) reviewed the literature for the solar reflectance of many standard and reflective paved surfaces including paving materials such as chip seal, slurry coating, and light-color coating. They report that the solar reflectance of freshly installed asphalt pavement is about 0.05. Aged asphalt pavements have a solar reflectance of 0.10 - 0.18, depending on the type of aggregate used in the asphalt mix. A light-color (low carbon content) concrete can have an initial solar reflectance of 0.35 - 0.40 that will age to about 0.25 - 0.30. They recommend using cool pavement materials in the urban area to increase the solar reflectance of paved surfaced by about 0.15.

Current pavement construction standards do not account for the solar reflectance of pavements. However, the maximum temperature of a pavement and the diurnal range of pavement temperature is an important consideration in design of a pavement. Laboratory tests have demonstrated that cooler pavements have a longer life time (Pomerantz and Akbari 1998; Pomerantz et al. 1997).

LEED Green Building Rating System. The Leadership in Energy and Environmental Design (LEED) Green Building Rating System assigns one rating point for the use of cool pavements in its Sustainable Sites Credit. LEED Version 2.2 (2005) uses Solar Reflectance Index (SRI), rather than solar reflectance, thermal emittance, or Energy-Star™ compliance, to qualify a cool pavement. SRI is a relative index of the steady-state temperature of a roof's surface on a typical summer afternoon (ASTM 1980). LEED requires a cool pavement to have a minimum SRI 29.

International CO_2 Market

The value of a global cooling strategy in carbon equivalent terms is over $800 billion, based on $20/tonne CO_2 (Akbari et al. 2008). Tapping into the carbon market in order to finance the implementation of a global cooling strategy is one potential strategy that could help pay for retrofits and a wider roll□out of cool roofs and pavements. This market-based approach would circumvent the slower timeline of updating and changing building code, but would depend on the ability to sell albedo-based offsets into the carbon market.

Existing CO_2 markets do not allow trading of CO_2-equivalent offsets for geo-engineering technologies, such as cool cities, that directly cool the earth and slow the rate of global warming. The CO_2 market is currently based on measures that directly reduce the CO_2 emissions. Generally, these markets have at least four criteria for such CO_2 reduction measures; they must be real, permanent, verifiable, and additional.

Real. Albedo-based CO_2 offsets do not represent a "real" reduction in greenhouse gas emissions: instead, they are best expressed as an equivalent reduction in GHG emissions, based on a real reduction in overall radiative forcing. To qualify for the offset market, the standards of the voluntary market and compliance markets would need to be modified to account for the offset potentials of increasing urban albedo. This would require working with scientific and legislative bodies to recognize and offer credits for the effect of increasing urban albedo.

Permanent. One of the major requirements of offsets is that they have permanent, rather than temporary effects. In order to make the cooling effects of increasing urban albedo permanent, programs would need to be set to ensure that roofs and pavements are kept reflective in perpetuity. The value of installing a 100 m^2 of white roof replacing a dark roof at current rate of \$20 per tonne of CO_2 is estimated at \$200. Assuming a discount rate of 3%, the annual value is \$6. Further assuming a 20 year life for a roof, the 20 year PV will be \$89 per 100 m^2 of roof area (this does not account for the air conditioning energy savings or improvement in comfort in a building). Innovative programs could be designed to maintain the reflectance of the roof with these savings.

Verifiable. In the offset market, carbon credits need to be able to be verified. The Clean Development Mechanism (CDM), California Climate Action Registry (CCAR) and other registries have developed protocols for different types of offsets in order to estimate, measure, monitor, and verify the offsets. Such protocols do not currently exist for albedo□based offsets. We need to develop reliable monitoring techniques to ensure the permanency of the albedo offset.

Additional. Offsets require a baseline in order to calculate the benefit. In other words, we need a means to estimate what the world would have looked like without the offset, or to demonstrate that the albedo changes would not have occurred without the offset payment. With respect to cool roofs and cool pavements, one could estimate the average reflectivity of roofing and paving materials in a particular region and use that as a baseline, though methodologies and protocols would need to be developed and agreed upon. However, baselines are not static. They are informed by technical, financial, and cultural barriers, which change over time. Often, offset providers use “common practice” as a rule of thumb.

An International Cool Cities Campaign

We propose to organize the hundred largest cities in the temperate and tropical regions of the world to develop city-specific implementation programs to install cool roofing and pavement materials. We have contacted a few such large cities and obtained their initial acceptance to join the 100 Cool Cities program. These cities include New York (USA), Taipei (Taiwan), São Paulo (Brazil), Delhi (India), Hyderabad (India), Los Angeles (USA), Osaka (Japan), and Tokyo (Japan). We are in the process of contacting many other cities in all five continents. The 100 Cool Cities program will

- Develop an international collaborative research and implementation program to regionally analyze the effect of cool city technologies in major metropolitan areas of the world; assist the stakeholders in developing countries to develop customized and regional technologies and programs using the support of local industries; and develop an international center with regional offices in many cities around the world.

- Conduct basic and applied research in developing, demonstrating, and with the help of industry, manufacturing advanced building envelope and pavement materials; and investigate the effect of alternative and complementary technologies (e.g., solar thermal collectors and photovoltaics) in developing effective cool cities programs.

- Develop advanced techniques to monitor the implementation programs, using remotely sensed satellite and aerial orthophotography; collect and analyze data on the actual effectiveness of the implementation programs; and develop an on-line database for use by various stakeholders.

- Work with regional and national air quality monitoring and control agencies to analyze the effect of cool cities (including urban vegetation) on air quality; work with IPCC and other international climate change research and analysis bodies to develop regional equivalencies between cool cities measures and CO_2 emission reduction; work with international agencies to incorporate the effect of cool cities in the CO_2 emission market exchange.

This program will utilize resources from many countries around the world. The initial collaborative countries include the U.S., Canada, member countries of the European Union (France, England, Spain, Italy, Germany, Greece), Jordan, Egypt, Kuwait, Qatar, India, China, Japan, Brazil, Singapore, and Australia.

Conclusions

Using cool roofs and cool pavements in urban areas, on average, can increase the mean albedo of an urban area by about 0.1. We estimate that increasing the albedo of urban roofs and paved surfaces worldwide will induce a negative radiative forcing equivalent to offsetting 44 Gt of emitted CO_2.

Converting to cool urban surfaces does not address the underlying problem of global warming. Global warming is primarily caused from the increase in the concentration of greenhouse gases (GHG) and absorbing particles in the atmosphere (IPCC 2009). We emphasize that problem of global warming must be resolved by developing and implementing a complete portfolio of measures to reduce GHG emissions. In addition to directly cooling the globe, cool urban surfaces, particularly cool roofs, yields significant air conditioning energy savings and hence a reduction in GHG emissions.

We propose an international campaign to cool our urban areas and the world by using solar reflective materials when roofs and pavements are initially built or resurfaced in temperate and tropical regions. There are sufficiently compelling financial incentives for cities and countries to take these steps now, irrespective of the outcomes from ongoing international negotiations around climate mitigation priorities.

Acknowledgements

This work was supported by the California Energy Commission (CEC) through its Public Interest Energy Research Program (PIER), and by the Assistant Secretary for Energy Efficiency and Renewable Energy at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231. The authors wish to acknowledge the support and guidance from staff of the

California Energy Commission Project manager, Guido Franco; and PIER Energy-Related Environmental Research manager, Linda Spiegel.

References

Akbari, H., S. Menon, and A. Rosenfeld. 2008. "Global Cooling: Increasing World-wide Urban Albedos to Offset CO_2," *Climatic Change*, DOI 10.1007/s10584-008-9515-9.

Akbari, H. and R. Levinson. 2008. Evolution of cool roof standards in the United States. *Advances in Building Energy Research* 2, 1-32.

Akbari, H. and L.S. Rose. 2008. "Urban Surfaces and Heat Island Mitigation Potentials," In press, *J. Human-Environment System*, 11(2), pp. 85-101.

Akbari, H., R. Levinson, W. Miller, and P. Berdahl. 2005. "Cool Colored Roofs to Save Energy and Improve Air Quality." Proceedings of the 1st International Passive and Low Energy Cooling for the Built Environment, Palenc 2005, Vol 1, Page 89, 19-21 May 2005, Santorini, Greece.

Akbari, H. R.M. Levinson, and L. Rainer. 2005. "Monitoring the Energy-Use Effects of Cool Roofs on California Commercial Buildings," Energy and Buildings, 37(10): 1007-1016.

Akbari, H., M. Pomerantz, and H. Taha. 2001. "Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas," *Solar Energy*, **70**(3): 295-310.

AMS. 2009. Geo-engineering the Climate System: A Policy Statement of the American Meteorological Society. Online at http://www.ametsoc.org/policy/2009geoengineeringclimate_amsstatement.html .

ASTM. 1998. ASTM E 1980-98: Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces. In Annual Book of ASTM Standards, Vol. 04.12. Philadelphia, PA: American Society for Testing and Materials.

IPCC. 2009. Various reports by Intergovernmental Panel on Climate Change. http://www.ipcc.ch

Levinson, R., H. Akbari, S. Konopacki, and S. Bretz. 2005. "Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements," Energy Policy, 33 (2): 151-170.

ODL. 2009. One Degree Less. http://www.onedegreeless.org .

Pomerantz, M. and H. Akbari. 1998. "Cooler Paving Materials for Heat Island Mitigation," Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 9, p. 135, Pacific Grove, CA.

Pomerantz, M., H. Akbari, A. Chen, H. Taha, and A. H. Rosenfeld, 1997. "Paving Materials for Heat Island Mitigation," Lawrence Berkeley National Laboratory Report LBL-38074, Berkeley, CA.

UN. 2009. United Nation population division. Online at http://www.un.org/esa/population/unpop.htm .

Table 1. CO_2 offset equivalence of increasing the albedo of roofs and paved surfaces in all California urban areas.

Row	Item	Value
1.	Area of California	$410x10^9$ m^2
2.	Estimated California dense urban areas (about 4%)	$16x10^9$ m^2
3.	Roof area (25% of urban area) [a]	$4x10^9$ m^2
4.	Paved surface area (35% of urban area)	$5.6x10^9$ m^2
5.	*Emitted* CO_2 offset for increasing roof albedo by 0.25 (Akbari et al 2008)	-64 kg CO_2/m^2 of roof
6.	Potential emitted CO_2equivalent reduction of cool roofs [Row 3 x Row 5]	260 Mt CO_2
7.	*Emitted* CO_2 offset for increasing pavement albedo by 0.15 (Akbari et al 2008)	-38 kg CO_2/m^2 of pavement
8.	Potential emitted CO_2 equivalent reduction of cool pavements [Row 4 x Row 7]	210 Mt CO_2
9.	Total potential emitted CO_2 equivalent reduction of cool roofs and cool pavements [Row 6 + Row 8] [one-time only, not annual]	470 Mt CO_2
10.	Time to resurfaces all roofs and pavements	15 years
11.	Annual CO_2 equivalent emission reduction for cool roofs and cool pavements [Row 9 / Row 10]	31 Mt CO_2/yr
12.	AB32 target for CO_2 reduction in 2020	175 Mt CO_2/yr
13.	Estimated total CO_2 reductions from AB32 from 2010 to 2020	875 Mt CO_2
14.	Current California yearly CO_2 equivalent emissions	470 Mt CO_2/yr

Note: We carry out the following calculations as an independent check for the total roof area in California. CEC estimates that the stock of existing houses in California is 12.5 M. Assuming that each house has a roof area of about 150 m^2, the total residential area is estimated at 1.9 billion m^2. Accounting for the roof area of nonresidential buildings (approximately the same as the total residential roofs), we estimate a total of 3.8 billion m^2 (3800 km^2) roof area in California. This checks with Row 3.

Table 2. CO_2 avoided by reducing cooling load by installing cool roofs on residential and non-residential buildings.

Row	Item	Value
1.	Total residential and non-residential roof area	$4x10^9$ m^2
2.	Fraction all buildings that are air conditioned	0.5
3.	Average air conditioning savings	3 kWh/m^2 yr
4.	CO_2 emission per kWh electricity generation	0.5 kg CO_2/kWh
5.	Annual avoided CO_2 emissions (Row 1 x Row 2 x Row 3 x Row 4)	3 Mt CO_2/yr

Note: The CO_2 emission reduction is a rough estimate accounting for both reduced summertime emissions reduction and wintertime penalties.

Table 3. Annual cooling energy savings (kWh) by installing a cool roof (increasing roof's solar reflectance by 0.20) for a typical 100 m^2 house.

Country	City	CDD18	Savings	Country	City	CDD18	Savings
Albania	Tirana	715	208	Morocco	Rabat-Sale	606	187
Algeria	Alger/Dar-El-Beida	899	244	Mozambique	Maputo	2,085	477
Argentina	Buenos Aires/Ezeiza	693	203	Pakistan	Karachi Airport	3,136	683
Australia	Sydney/K Smith	678	201	Panama	Howard AFB	3,638	782
Bahamas	Nassau	2,511	561	Paraguay	Asuncion/Stroessner	2,218	503
Bermuda	St Georges/Kindley	1,802	421	Peru	Lima-Callao/Chavez	906	245
Bolivia	Trinidad	2,879	633	Philippines	Manila Airport	3,438	743
Brazil	Belo Horizonte	1,702	402	Puerto Rico	San Juan/Isla Verde	3,369	729
	Brasilia	1,353	333	Saudi Arabia	Dhahran	3,340	723
	Rio de Janeiro	2,360	531		Medina	3,691	793
	Sao Paulo	1,187	301		Riyadh	3,304	717
Brunei	Brunei Airport	3,516	758	Senegal	Dakar/Yoff	2,445	548
China	Beijing (Peking)	840	233	Singapore	Singapore/Changi	3,647	784
	Shanghai/Hongqiao	1,129	289	Spain	Barcelona	533	172
Cuba	Havana/Casa Blanca	2,700	598		Madrid	886	241
Cyprus	Akrotiri	1,139	291	Syria	Damascus Airport	1,074	278
Dominican Republic	Santo Domingo	3,053	667	Taiwan	Taipei	2,204	500
Egypt	Aswan	3,187	693	Tajikistan	Dusanbe	1,081	280
	Cairo	1,833	427	Tanzania	Dar es Salaam	2,922	641
France	Nice	545	175	Thailand	Bangkok	3,962	846
Greece	Athenai/Hellenikon	1,030	270		Chiang Mau	3,140	684
Hong Kong	Royal Observatory	2,136	487	Tunisia	Tunis/El Aouina	1,102	284
India	Bombay/Santa Cruz	3,386	733	Turkey	Istanbul/Yesilkoy	567	179
	Calcutta/Dum Dum	3,211	698	Turkmenistan	Ashkhabad	1,442	351
	New Delhi/Safdarjung	2,881	633	United States	Phoenix	2,579	574
Indonesia	Djakarta/Halimperda	3,390	733		Burbank/Hollywood	920	248
Italy	Palermo/Punta Raisi	1,058	275		Sacramento	743	213
	Roma/Fiumicino	621	189		Washington/National	930	250
Jamaica	Kingston/Manley	3,656	785		Miami	2,516	561
	Montego Bay/Sangster	3,112	679		Atlanta	1,104	284
Japan	Kyoto	1,084	280		Honolulu, Oahu	2,651	588
	Osaka	1,180	299		New Orleans/Moisant	1,627	387
	Tokyo	938	251		Memphis	1,324	327
Jordan	Amman	1,063	276		Dallas-Ft Worth	1,519	366
Kenya	Nairobi Airport	566	179	Uruguay	Montevideo/Carrasco	595	184
Korea	Seoul	746	214	Venezuela	Caracas/Maiquetia	3,331	722
Libya	Tripoli/Idris	1,686	399	Vietnam	Saigon (Ho Chi Minh)	3,745	803
Madagascar	Antananarivo/Ivato	701	205	Zimbabwe	Harare Airport	775	219
Malaysia	Kuala Lumpur	3,475	750				
Mexico	Chihuahua	1,058	275				
	Mexico City	245	115				
	Acapulco/Alvarez	3,623	779				

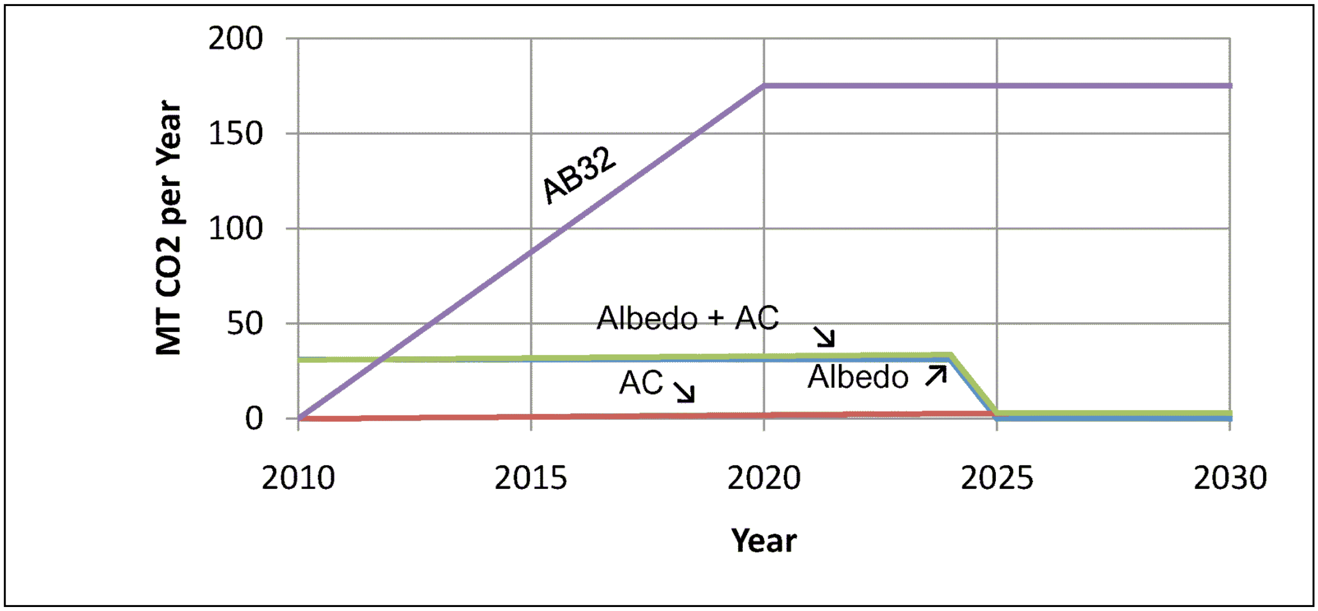
CDD18 is cooling-degree-days base on 18 °C.

Table 4. Annual cooling energy savings (kWh) per 100 m^2 of roof area by installing a cool roof (increasing roof's solar reflectance by 0.40) for a typical office building.

Country	City	CDD18	Savings	Country	City	CDD18	Savings
Albania	Tirana	715	603	Morocco	Rabat-Sale	606	586
Algeria	Alger/Dar-El-Beida	899	633	Mozambique	Maputo	2,085	825
Argentina	Buenos Aires/Ezeiza	693	600	Pakistan	Karachi Airport	3,136	995
Australia	Sydney/K Smith	678	597	Panama	Howard AFB	3,638	1076
Bahamas	Nassau	2,511	894	Paraguay	Asuncion/Stroessner	2,218	847
Bermuda	St Georges/Kindley	1,802	779	Peru	Lima-Callao/Chavez	906	634
Bolivia	Trinidad	2,879	953	Philippines	Manila Airport	3,438	1044
Brazil	Belo Horizonte	1,702	763	Puerto Rico	San Juan/Isla Verde	3,369	1033
	Brasilia	1,353	707	Saudi Arabia	Dhahran	3,340	1028
	Rio de Janeiro	2,360	870		Medina	3,691	1085
	Sao Paulo	1,187	680		Riyadh	3,304	1022
Brunei	Brunei Airport	3,516	1056	Senegal	Dakar/Yoff	2,445	883
China	Beijing (Peking)	840	624	Singapore	Singapore/Changi	3,647	1078
	Shanghai/Hongqiao	1,129	670	Spain	Barcelona	533	574
Cuba	Havana/Casa Blanca	2,700	925		Madrid	886	631
Cyprus	Akrotiri	1,139	672	Syria	Damascus Airport	1,074	662
Dominican Republic	Santo Domingo	3,053	982	Taiwan	Taipei	2,204	844
Egypt	Aswan	3,187	1003	Tajikistan	Dusanbe	1,081	663
	Cairo	1,833	784	Tanzania	Dar es Salaam	2,922	960
France	Nice	545	576	Thailand	Bangkok	3,962	1129
Greece	Athenai/Hellenikon	1,030	654		Chiang Mau	3,140	996
Hong Kong	Royal Observatory	2,136	833	Tunisia	Tunis/El Aouina	1,102	666
India	Bombay/Santa Cruz	3,386	1035	Turkey	Istanbul/Yesilkoy	567	580
	Calcutta/Dum Dum	3,211	1007	Turkmenistan	Ashkhabad	1,442	721
	New Delhi/Safdarjung	2,881	954	United States	Phoenix	2,579	905
Indonesia	Djakarta/Halimperda	3,390	1036		Burbank/Hollywood	920	637
Italy	Palermo/Punta Raisi	1,058	659		Sacramento	743	608
	Roma/Fiumicino	621	588		Washington/National	930	638
Jamaica	Kingston/Manley	3,656	1079		Miami	2,516	895
	Montego Bay/Sangster	3,112	991		Atlanta	1,104	666
Japan	Kyoto	1,084	663		Honolulu, Oahu	2,651	917
	Osaka	1,180	679		New Orleans/Moisant	1,627	751
	Tokyo	938	640		Memphis	1,324	702
Jordan	Amman	1,063	660		Dallas-Ft Worth	1,519	734
Kenya	Nairobi Airport	566	579	Uruguay	Montevideo/Carrasco	595	584
Korea	Seoul	746	608	Venezuela	Caracas/Maiquetia	3,331	1027
Libya	Tripoli/Idris	1,686	761	Vietnam	Saigon (Ho Chi Minh)	3,745	1094
Madagascar	Antananarivo/Ivato	701	601	Zimbabwe	Harare Airport	775	613
Malaysia	Kuala Lumpur	3,475	1050				
Mexico	Chihuahua	1,058	659				
	Mexico City	245	527				
	Acapulco/Alvarez	3,623	1074				

CDD18 is cooling-degree-days base on 18 °C.

Figure 1. Comparison of CO_2 saving from AB32 and radiative forcing equivalent from cool urban surfaces.



The ‘albedo’ line is the equivalent CO_2 offset from negative radiative forcing. The lowest line, labeled “AC”, reaching only 3 $MTCO_2$/yr in 2025 is the savings from avoided electricity from reduced cooling load from cool roofs. While important, the annual CO_2 emission reductions from energy savings are 10 times smaller than the annualized equivalent CO_2 offset from negative radiative forcing.