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Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements

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Abstract

Roofs that have high solar reflectance (high ability to reflect sunlight) and high thermal emittance (high ability to radiate heat) tend to stay cool in the sun. The same is true of low-emittance roofs with exceptionally high solar reflectance. Substituting a cool roof for a non-cool roof tends to decrease cooling electricity use, cooling power demand, and cooling-equipment capacity requirements, while slightly increasing heating energy consumption. Cool roofs can also lower citywide ambient air temperature in summer, slowing ozone formation and increasing human comfort.

DOE-2.1E building energy simulations indicate that use of a cool roofing material on a prototypical California nonresidential (NR) building with a low-sloped roof yields average annual cooling energy savings of approximately 3.2 kW h/m^2 (300 kW h/1000 ft^2), average annual natural gas deficits of 5.6 MJ/m^2 (4.9 therm/1000 ft^2), average annual source energy savings of 30 MJ/m^2 (2.6 MBTU/1000 ft^2), and average peak power demand savings of 2.1 W/m^2 (0.19 kW/1000 ft^2). The 15-year net present value (NPV) of energy savings averages \$4.90/m^2 (\$450/1000 ft^2) with time-dependent valuation (TDV), and \$4.00/m^2 (\$370/1000 ft^2) without TDV. When cost savings from downsizing cooling equipment are included, the average total savings (15-year NPV + equipment savings) rises to \$5.90/m^2 (\$550/1000 ft^2) with TDV, and to \$5.00/m^2 (\$470/1000 ft^2) without TDV.

Total savings range from 1.90 to 8.30 \$/m^2 (0.18–0.77 \$/ft^2) with TDV, and from 1.70 to 7.10 \$/m^2 (0.16–0.66 \$/ft^2) without TDV, across California's 16 climate zones. The typical cost premium for a cool roof is 0.00–2.20 \$/m^2 (0.00–0.20 \$/ft^2). Cool roofs with premiums up to \$2.20/m^2 (\$0.20/ft^2) are expected to be cost effective in climate zones 2–16; those with premiums not exceeding \$1.90/m^2 (\$0.18/ft^2) are expected to be also cost effective in climate zone 1. Hence, this study recommends that the year-2005 California building energy efficiency code (Title 24, Part 6 of the California Code of Regulations) for NR buildings with low-sloped roofs include a cool-roof prescriptive requirement in all California climate zones. Buildings with roofs that do not meet prescriptive requirements may comply with the code via an "overall-envelope" approach (non-metal roofs only), or via a performance approach (all roof types).

1. Introduction

Roofs that have high solar reflectance (high ability to reflect sunlight) and high thermal emittance (high ability to radiate heat) tend to stay cool in the sun. The same is true of low-emittance roofs with exceptionally high solar reflectance. Roofs that stay cool in the sun are hereafter denoted "cool roofs."

Low roof temperatures lessen the flow of heat from the roof into the building, reducing the need for electricity for space cooling in conditioned buildings. Since building heat gain through the roof peaks in late afternoon, when summer electricity use is highest, cool roofs can also reduce peak electricity demand. Prior research has indicated that savings are greatest for buildings located in climates with long cooling seasons and short heating seasons, particularly those buildings that have distribution ducts in the plenum, cool-coatable distribution ducts on the roof, and/or low rates of plenum ventilation (Akbari, 1998; Akbari et al., 1999; Konopacki and Akbari, 1998).

Prior studies have measured daily air-conditioning energy savings and peak power demand reduction from the use of cool roofs on nonresidential (NR) buildings in several warm-weather climates, including California, Florida, and Texas. Cool roofs typically yielded measured summertime daily air-conditioning savings

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Table 1
Measured energy savings in six California NR buildings (Konopacki et al., 1998; Hildebrandt et al., 1998)

	Davis medical office	Gilroy medical office	San Jose retail store	Sacramento office	Sacramento museum	Sacramento hospice
Roof						
Area (m^2)	2950	2210	3060	2290	455	557
Type	Built-up	Built-up	Built-up	4-ply with capsheet	Built-up gravel	Composite shingle/flat built-up
Material	Asphalt capsheet with light gray granules	Asphalt capsheet with light gray granules	Asphalt capsheet with tan granules	Asphalt capsheet with light gray granules	Asphalt capsheet with light gray granules	Asphalt capsheet with tan granules
Insulation (m^2 K/W)	1.4 (R-8 rigid)	3.4 (R-19 fiberglass)	Radiant barrier	3.4 (R-19)	None	1.9 (R-11)
Structure	Metal deck	Wood deck	Wood deck	Metal deck	Wood deck	Wood deck
Plenum type	Return plenum	Ventilated plenum	Ventilated plenum	Return plenum	Ventilated plenum	Ventilated plenum
Ceiling type	Tiles	Tiles	Tiles	Tiles	Tiles	Tiles
Pre-coating condition	25% granule loss and bubbling	25% granule loss and cracking	25% granule loss and cracking	25% granule loss and bubbling	25% granule loss and cracking	25% granule loss and cracking
Pre-coating solar reflectance	0.24	0.25	0.16	0.24	0.25	0.16
Post-coating solar reflectance after 1 year	0.60	0.60	0.60	0.60	0.60	0.60
Degraded (weathered) solar reflectance	0.55	0.55	0.55	0.55	0.55	0.55
Supply duct						
Insulation (m^2 K/W)	None	0.81 (R-4.6)	0.35 (R-2)	None	0.81 (R-4.6)	0.35 (R-2)
Location	Conditioned space	Plenum	Plenum	Conditioned space	Plenum	Plenum
Results						
Measured daily A/C energy savings (W h/m^2/day)	67	39	4	23	44	25
Cooling days/year	110	110	165	165	165	165
Degraded annual A/C energy savings (kW h/m^2/yr)	6.4	3.7	0.6	1.3	2.6	2.2
Degraded peak demand reduction (W/m^2)	3.3	2.4	1.6	n/a	n/a	n/a

and peak demand reductions of 10–30%, though values have been as low as 2% and as high as 40% (Table 1) (Konopacki et al., 1998). For example:

- Konopacki et al. (1998) measured summer daily air-conditioning savings of 68, 39, and 4 W h/m^2 (18%, 13%, and 2%) for three California NR buildings—two medical offices in Davis and Gilroy and a retail store in San Jose. Corresponding demand reductions were 3.3, 2.4, and 1.6 W/m^2 (12%, 8%, and 9%). Estimated annualized air-conditioning savings were 6.4, 3.7, and 0.6 kW h/m^2, assuming an aged solar reflectance of 0.55.
- Hildebrandt et al. (1998) measured summer daily air-conditioning savings (annual savings/number of cooling days per year) of 23, 44, and 25 W h/m^2 (17%, 26%, and 39%) in an office, a museum and a hospice in Sacramento, CA. Estimated annualized air-conditioning savings were 1.3, 2.6, and 2.1 kW h/m^2, assuming an aged solar reflectance of 0.55.
- Konopacki and Akbari (2001) estimated summer daily cooling energy savings of 39 W h/m^2 (11%) and peak power reduction of 3.8 W/m^2 (14%) in a large retail store in Austin, TX. Estimated annualized air-conditioning savings were 6.8 kW h/m^2, assuming an aged solar reflectance of 0.55.
- Parker et al. (1998) measured summer daily energy savings of 44 W h/m^2 (25%) and a peak power reduction of 6.0 W/m^2 (30%) for a school building in Florida. Estimated annualized air-conditioning savings were 4.7 kW h/m^2, assuming an aged solar reflectance of 0.55.
- Parker et al. (1997) measured summer daily energy savings of 8 W h/m^2 (25%) and peak power reduction of 0.6 W/m^2 (29%) in seven retail stores within a Florida strip mall. Estimated annualized air-conditioning savings were 0.7 kW h/m^2, assuming an aged solar reflectance of 0.60.

Cool roofs transfer less heat to the outdoor environment than do warm roofs (Taha, 2001). The resulting lower outside air temperatures can slow urban smog formation and increase human health and outdoor comfort. Reduced thermal stress may also increase the lifetime of cool roofs, lessening maintenance and waste (Akbari et al., 2001).

The potential of cool roofs to save cooling electricity has not gone unnoticed. In its revised standards for commercial and residential buildings, the American Society for Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) has included provisions to offer credits in building energy-use budgets for cool roofs in ASHRAE Standard 90.1-2001: energy standards for buildings except low-rise residential buildings (ASHRAE, 2001a) and ASHRAE Standard 90.2-2001: energy-efficient design of low-rise residential buildings (ASHRAE, 2001b). The cool-roof analysis performed in support of these ASHRAE standards is summarized by Akbari et al. (1998, 2000). In January 2001, the state of California followed the ASHRAE approach by adopting provisions to offer credit in its Title 24 building energy code to new commercial buildings with cool roofs (CEC, 2001). Other states and cities (such as Georgia, Florida, and Chicago) have developed codes to encourage the use of cool roofs (BCAP, 2002).

This paper details a proposal to promote the use of cool roofs to reduce cooling energy usage and peak electrical power demand in air-conditioned buildings. The measure would modify the treatment of cool roofs in California's building energy efficiency standards (Title 24, Part 6 of the California Code of Regulations, hereafter denoted as "Title 24") for NR buildings, including but not limited to offices, retail stores, health-care facilities, schools, universities, and high-tech manufacturing facilities. Under the current standards, cool roofs are a compliance option. Under this proposal, cool roofs would be considered a prescriptive requirement for NR buildings with low-sloped roofs (i.e., roofs with a ratio of rise to run not exceeding 2:12). Prescriptive requirements would not change for NR buildings with high-sloped roofs, high-rise residential buildings, low-rise residential buildings, or hotel/motel buildings.

This study addresses the physics, availability, market, marginal cost, durability, environmental impact and interaction with other energy-saving measures of cool roofing technologies, then compares simulated cool-roof energy savings to cool-roof cost premiums to estimate the cost effectiveness of cool roofing in each of California's climate zones.

Note: the terms "code" and "standard" will be used interchangeably to refer to Title 24 requirements.

2. Background: cool roofing technologies

2.1. Physics

The daytime surface temperature of a roof is raised by absorption of solar radiation and lowered by emission of thermal radiation to the sky. Solar heating is proportional to solar absorptance (absorptance of an opaque material = 1 − reflectance), while radiative cooling is proportional to thermal emittance. Hence, other factors (e.g., incident solar radiation, convective cooling, and conductive cooling) being equal, a roof with high solar reflectance and high thermal emittance can stay cooler than a roof with a low solar reflectance and/or low thermal emittance.

A bare, shiny metal (e.g., aluminum foil) may have an emittance as low as 0.03, and a roof coating formed with metal flakes may have a moderate emittance (ca. 0.5). Virtually all other construction materials have high thermal emittance (~0.80–0.95). In North America, 43% of the solar radiation (spectrum 300–2500 nm) arriving at the Earth's surface is visible (400–700 nm); another 52% is near-infrared (700–2500 nm), and 5% is ultraviolet (300–400 nm) (ASTM, 1998b). Since nearly all of this radiation is visible or near-infrared (NIR), a roof with a non-metallic surface and high visible and/or NIR reflectance will be cool. White surfaces are cool because they have high visible reflectance, high NIR reflectance, and high thermal emittance. Ordinary black surfaces are warm because they have low visible and NIR reflectances. (Some novel black coatings have high NIR reflectance, and thus stay cooler than conventional black surfaces.) Shiny metals typically have high visible and NIR reflectances, but low thermal emittances, and thus stay warmer than a non-metallic surface of comparable solar reflectance. For brevity, the terms reflectance (ρ), absorptance (α), and emittance (ε) will be used hereafter to denote solar reflectance, solar absorptance, and thermal emittance, respectively.

A low-emittance (LE) surface can stay as cool as a high-emittance (HE) surface if the LE surface has a significantly higher reflectance. For example, a new bare metal roof with an emittance of 0.20 and a reflectance of 0.79 would under standard conditions (i.e., specified values of insolation, wind speed, air temperature, and sky temperature) have the same surface temperature as a new white roof with an emittance of 0.75 and a reflectance of 0.70. An even higher initial reflectance (in this case, 0.89) would be needed to match the surface temperature of the aged LE roof to that of the aged HE cool roof (see Appendix A). Akbari and Konopacki (1998) have investigated the relative effects of solar reflectance and thermal emittance on the heating- and cooling-energy uses of prototypical office and residential buildings in several climate regions in the US.

2.2. Availability

There are cool and non-cool options available for nearly all low-sloped roofing products (Table 2). For example, a built-up roof can have an initial reflectance of 0.04 if covered with a smooth, black asphalt surface ($\varepsilon = 0.90$), or 0.80 if coated with a smooth, white surface ($\varepsilon = 0.90$). Similarly, a single-ply membrane can have an initial reflectance of 0.04 if black ($\varepsilon = 0.90$), 0.20 if gray ($\varepsilon = 0.90$), or 0.80 if white ($\varepsilon = 0.90$). Low-sloped roofing technologies are described in Table 3.

Western Roofing Insulation and Siding magazine reported that in the year 2001, three products—built-up roofing (BUR), modified bitumen, and single-ply membrane—accounted for 83% of sales dollars (material and labor) in the \$6.0 B (billion), 14-state western US market for low-sloped NR-building roofing (Dodson, 2001). Metal, asphalt shingle, tile, polyurethane foam, liquid applied coatings, and other materials made up the remainder. California represented about 38%—i.e., \$2.3 B—of the western market, which also includes Alaska, Arizona, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Texas, Utah, Washington, and Wyoming.

An earlier study by *Western Roofing Insulation and Siding* (Dodson, 1999) reported that in the year 1999, the values of the western-region NR replacement and new roofing markets were \$4.1 B and \$1.4 B, respectively. Since the 2001 study did not separate replacement roofing from new roofing, the 1999 ratio of \$4.1 B replacement to \$1.4 B new will be used to compare the sizes of the two markets. By this metric, the replacement market is 2.9 times the size of the new construction market.

The National Roofing Contractors Association (NRCA) reported that the year-2000 low-sloped roofing market in the organization's Pacific region—California, Oregon, and Washington—was dominated by BUR, modified bitumen, and single-ply membrane, making up 74% of new-construction sales dollars and 83% of reroofing sales dollars (NRCA, 2000). However, the 2000 NRCA estimate of Pacific-region BUR sales fraction was much higher than the 2001 Western Roofing estimate of BUR sales fraction in the western region (50% vs. 29%), while the reverse was true for modified bitumen (12% vs. 30%). The NRCA's Pacific-region figures are derived from responses from fewer than 50 contractors. Since the Roofing Contactors Association of California reports that there were approximately 5000 active roofing contractors statewide in 2002 (Hoffner, 2002), the NRCA figures may lack statistical validity.

The 2001 Western Roofing and 2000 NRCA market estimates are presented in Table 3. Also shown are estimates of the western-region roof area coverage by product, based on Lawrence Berkeley National Laboratory (LBNL) estimates of typical roofing-product prices. BUR (27%), modified bitumen (26%), and single-ply membrane (22%) cover 75% of the western-region roof area. While manufacturer reports of sales to the California market would have provided better estimates of the fraction of California roofs covered with each product, such data do not appear to be publicly available.

There are over 200 companies manufacturing roofing products in the Unites States. Most manufacturers specialize by type of roofing material. However, firms that manufacture asphalt-based roofing products, such as asphalt shingles, BUR, and/or modified bitumen, may offer all three. Companies that specialize in asphalt-based roofing have the largest sales volumes.

Roofing manufacturers sell most of their roofing products through distributors. The distributors generally contact the manufacturers to obtain materials, although some manufacturers also use representatives to sell products.

Table 2
Cool and non-cool options for low-sloped roofs

Non-cool roof options				*Cool roof options*			
Roof type	Reflectance	Emittance	Cost ($\$/m^2$)	Roof type	Reflectance	Emittance	Cost ($\$/m^2$)
Built-up roof			13–23	Built-up roof			13–23
With dark gravel	0.08–0.15	0.80–0.90		With white gravel	0.30–0.50	0.80–0.90	
With smooth asphalt surface	0.04–0.05	0.85–0.95		With gravel and cementitious coating	0.50–0.70	0.80–0.90	
With aluminum coating	0.25–0.60	0.20–0.50		Smooth surface with white roof coating	0.75–0.85	0.85–0.95	
Single-ply membrane			11–22	Single-ply membrane			11–22
Black (EPDM, CPE, CSPE, PVC)	0.04–0.05	0.85–0.95		White (EPDM, CPE, CSPE, PVC)	0.70–0.78	0.85–0.95	
Gray EPDM	0.15–0.20	0.85–0.95					
Modified bitumen			16–20	Modified bitumen			16–21
With mineral surface capsheet (SBS, APP)	0.10–0.20	0.85–0.95		White coating over a mineral surface (SBS, APP)	0.60–0.75	0.85–0.95	
Metal roof			19–40	Metal roof			19–40
Unpainted, corrugated	0.30–0.50	0.20–0.30		White painted	0.60–0.70	0.80–0.90	
Dark-painted, corrugated	0.05–0.08	0.80–0.90					
Asphalt shingle			12–15	Asphalt shingle			13–16
Black	0.04–0.05	0.80–0.90		White[a]	0.25–0.27	0.80–0.90	
Brown	0.05–0.09	0.80–0.90					
Liquid applied coating			5–8	Liquid applied coating			6–9
Smooth black	0.04–0.05	0.85–0.95		Smooth white	0.70–0.85	0.85–0.95	
				Smooth off-white	0.40–0.60	0.85–0.95	
				Rough white	0.50–0.60	0.85–0.95	
Concrete tile			32–43	Concrete tile			32–43
Red	0.10–0.12	0.85–0.90		White	0.65–0.75	0.85–0.90	
				With off-white coating	0.65–0.75	0.85–0.90	
Clay tile			32–43	Clay tile			32–43
Red	0.20–0.22	0.85–0.90		White	0.65–0.75	0.85–0.90	
Fiber-cement tile			32–43	Fiber-cement tile			32–43
Unpainted	0.18–0.22	0.85–0.90		White	0.65–0.75	0.85–0.90	

Shown are ranges of typical values for initial solar reflectance, initial thermal emittance, and cost.

[a] Asphalt shingles marketed as “white” are gray, and are not particularly cool.

Table 3
NR-building low-sloped roofing technologies and their market shares in three Pacific-region states (NRCA, 2000) and 14 western-region states (Dodson, 2001)

Technology	Description	Cost[a] ($\$/\mathrm{m}^2$)	Pacific[b]		Western[c]	
			New sales (%)	Retrofit sales (%)	Sales (%)	Area[d] (%)
Built-up roof (BUR)	A continuous, semi-flexible multi-ply roof membrane, consisting of plies (layers) of saturated felts, coated felts, fabric, or mats, between which alternate layers of bitumen are applied. Built-up roof membranes are typically surfaced with roof aggregate and bitumen, a liquid-applied coating, or a granule-surfaced cap sheet.	18	46	52	31	27
Modified bitumen	(1) A bitumen modified through the inclusion of one or more polymers (e.g., atactic polypropylene and/or styrene butadiene styrene). (2) Composite sheets consisting of a polymer-modified bitumen often reinforced and sometimes surfaced with various types of mats, films, foils, and mineral granules. It can be classified into two categories: thermoset, and thermoplastic. A thermoset material solidifies or sets irreversibly when heated; this property is usually associated with cross-linking of the molecules induced by heat or radiation. A thermoplastic material softens when heated and hardens when cooled; this process can be repeated provided that the material is not heated above the point at which decomposition occurs.	18	10	15	30	26
Single-ply membrane	A roofing membrane having only one layer of membrane material (either homogeneous or composite) rather than multiple layers. The principal roof covering is usually a single-layer flexible membrane, often of thermoset, thermoplastic, or polymer-modified bituminous compounds. Roofing membranes can be torch-applied or hot-mopped with asphalt during application.	16	18	16	23	22
Metal	Metal roofs can be classified as architectural or structural.	29	2.2	1.7	5.2	2.8
Asphalt shingle	Asphalt is a dark brown to black cementitious material, solid or semisolid, in which the predominant constituents are naturally occurring or petroleum-derived bitumens. It is used as a weatherproofing agent. The term asphalt shingle is generically used for both fiberglass and organic shingles. There are two grades of asphalt shingles: (1) standard, a.k.a. 3-tab; and (2) architectural, a.k.a. laminated or dimensional. Shingles come in various colors.	14	5.8	2.5	3.6	4.2
Tile	Usually made of concrete or clay, tile is a combination of sand, cement, and water; the water fraction depends on the manufacturing process. Fibers may be added (replacing sand) to increase strength and reduce weight. Concrete tiles are either air-cured or auto-claved, whereas clay tiles are kiln-fired. Color is added to the surface of the tile with a slurry coating process, or added to the mixture during the manufacturing process.	38	2.5	3.9	0.3	0.1
Polyurethane foam (SPF)	A foamed plastic material formed by spraying polymeric methyl diisocyanate (PMDI) and a resin to form a rigid, fully adhered, water-resistant, and insulating membrane.	8	0.4	6.3	2.5	5.2
Liquid applied coatings	A liquid surfacing material (acrylic, elastomeric, or asphaltic) for various roof types, especially BUR and metal. Available in different colors; may be divided on the basis of reflectivity into black, aluminum, white, and tinted coatings.	4	3.2	3.3	2.5	9.2
Other	All other roofing materials that are not covered under the categories mentioned above.	11			2.1	3.1

[a] LBNL's numbers for typical material and labor costs are approximate, and are based on phone interviews.

[b] The NRCA's estimates of Pacific-region market distributions may lack statistical validity because fewer than 50 contractors from these three states (CA, OR, and WA) responded to its survey.

[c] California accounts for 38% of the market in the 14 states (AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, TX, UT, WA, and WY) that make up the western region surveyed by Western Roofing magazine.

[d] LBNL's estimates of roof areas fractions are derived from product market shares and costs.

Table 4
Cost premiums for cool varieties of common low-sloped roofing products

Roofing product	Cool variety	Cost premium ($/m^2)
Ballasted BUR	Use white gravel	Up to 0.5
BUR with smooth asphalt coating	Use cementitious or other white coatings	1.1–2.2
BUR with aluminum coating	Use cementitious or other white coatings	1.1–2.2
Single-ply membrane (EPDM, TPO, CSPE, PVC)	Use a white membrane	0.0–0.5
Modified bitumen (SBS, APP)	Use a white coating over the mineral surface	Up to 0.5
Metal roofing (both painted and unpainted)	Use a white or cool-color paint	0.0–0.5
Roof coatings (dark color, asphalt base)	Use a white or cool-color coating	0.0–1.1
Concrete tile	Use a white or cool-color tile	0.0–0.5
Fiber-cement tile	Use a white or cool-color tile	0.5
Red clay tile	Use a cool red tile	1.1

Though more profitable for the manufacturer, factory-direct sales make up a smaller portion of the roofing market than does distribution, and are usually used only for large-quantity purchases. Manufacturers distribute most of their products through local outlets such as independent wholesale distributors and company-owned distribution centers.

From the distributor there are three main channels to the end-user: lumber yards (45–50% of sales), direct sales to large contractors or home builders (40%), and retail establishments such as home improvement centers and hardware stores (10–15%) (Freedonia Group, 1997).

The EPA EnergyStar® roof program lists over 100 Roof Product Partners on its web site (http://yosemite1.epa.gov/estar/consumers.nsf/content/roofbus.htm). The EPA program allows manufacturers to self-certify their products' performance criteria and does not include a minimum emittance requirement for eligible roofing products. However, the web site lists over 250 non-metal roofing products that have an initial solar reflectance of 0.70 or higher.

2.3. Cost premiums

Cool options are available for most types of low-sloped roofing. In estimating cost effectiveness for new construction and for regularly scheduled reroofing, we consider only the incremental initial cost of changing the reflectance of the roof from a low value to a high value. Table 4 lists estimates of typical incremental costs obtained from interviews of manufacturers, contractors, owners, and specifiers.

Additional expenditure would be required if a building owner wished to maintain the cool roof's reflectance at its initial high level (i.e., $\rho \geqslant 0.70$). That additional cost has not been factored into the life cycle cost (LCC) analysis because the simulated energy savings are based on a degraded reflectance (0.55) that assumes no additional maintenance.

2.4. Durability

Roof reflectance may change over time from aging, weathering, and soiling. Regular cleaning can mitigate the effects of soiling. A study monitoring the effects of aging and weathering on 10 California roofs found that the reflectance of cool materials can decrease by as much as 0.15, mostly within the first year of service (Bretz and Akbari, 1997). An ongoing study at LBNL has found similar reflectance degradations for an assortment of single-ply membrane roofs sited around the United States. Once the membranes were cleaned, their reflectances approached those of fresh roofing materials.

Exposure tends to moderately decrease the reflectance of light-colored materials, while moderately increasing the reflectance of dark materials. LBNL's observations suggest that the aged solar reflectance of a roof may be estimated from the relation:

$$\rho_{\text{aged}} = \rho_0 + c(\rho_{\text{initial}} - \rho_0), \quad (1)$$

where constants $\rho_0 = 0.2$ and $c = 0.7$. That is, the change to reflectance with aging is modeled as a 30% reduction in the difference between the initial reflectance and a value of 0.2.[1]

ASHRAE Standard 90.1 (NR buildings) assigns credits to cool roofs with a minimum reflectance of 0.70 (ASHRAE, 2001a). However, the credits are calculated based on an aged reflectance of 0.55 (Akbari et al., 1998), which is consistent with Eq. (1). Like the ASHRAE calculations, the current Title 24 code assigns a degraded reflectance of 0.55 to a cool roof. The energy-savings analysis presented in this study will also use a degraded cool-roof solar reflectance of 0.55.

A cool roof has a lower daytime peak temperature than does a warm roof, reducing the thermal stress that

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[1] An equivalent expression relating aged solar absorptance to initial solar absorptance is $\alpha_{\text{aged}} = \alpha_0 + c(\alpha_{\text{initial}} - \alpha_0)$, where constants $\alpha_0 = 0.8$ and $c = 0.7$. This form is used in the performance approach because the alternative calculation method (ACM) inputs initial absorptance, rather than initial reflectance.

results from diurnal temperature change. This is commonly believed to extend product life. However, potential product-lifetime increases have not been factored into cost-effectiveness calculations because long-term studies of this effect are not available.

2.5. Relationships of cool roofs to other building energy efficiency measures

Cool roofs can reduce needs for roof insulation, ceiling insulation, cooling capacity, air-handling-unit capacity, and plenum ventilation capacity.

- The effect of a cool roof is inversely proportional to the level of insulation. With the current prescriptive requirements, total building energy use is reduced by cool roof installation, and this installation is cost effective (Akbari et al., 1998).
- A cool roof could reduce building cooling load by 1–5 W/m^2, depending on building type, roof insulation, and climate zone. Hence, the cooling unit can potentially be downsized.
- A building's air-handling unit (AHU) is typically designed to accommodate the summer peak cooling load. A lower summer peak cooling load can reduce the size of the AHU and save electricity. The smaller AHU can also operate more efficiently and use less electricity during the heating season.
- Cool roofs reduce the need for plenum ventilation. In many cases, a cool roof can eliminate the need for mechanical attic ventilation.

2.6. Environmental impact

Cool roofs are expected to have both positive and negative environmental impacts. Benefits include increased human comfort, slowed smog formation, carbon-emission reduction, and mitigation of urban heat islands in summer. Waste from disposal of roofs would also decrease if cool roofs last longer than warm roofs. Penalties include slightly higher wintertime heating energy use, degraded wintertime urban air quality, and, in some cases, use of water and detergents to clean roofs.

Cool roofs transfer less heat to the outdoor environment than do warm roofs. The resulting lower air temperatures can slow urban smog formation and increase human comfort both outdoors and in unconditioned buildings. On a clear summer afternoon, the air temperature in a typical North American urbanized area can be about 1–5 °C hotter than that in the surrounding rural area (Taha, 2001). The additional air-conditioning use induced by this urban air temperature elevation is responsible for 5–10% of urban peak electric power demand, at a direct cost of several billion dollars annually. At the community scale, increasing the solar reflectance of roofs can effectively and inexpensively mitigate an urban heat island (Akbari et al., 2001).

Measured data and computer simulations studying the effect of temperature on Los Angeles smog show that lowering the ambient air temperature significantly reduces ozone concentration. The simulations predict a reduction in population-weighted smog (ozone) of 10–12% resulting from a 1.5–2 °C cooling in ambient temperature. Cool roofs could contribute about one-third of this reduction. For some scenarios, a 10–12% reduction in ozone is comparable to that obtained by replacing all gasoline on-road motor vehicles with electric cars (Taha et al., 1997, 1999, 2000; Taha, 2001; Rosenfeld et al., 1995).

Electricity savings and peak-demand reduction yielded by cool roofs can reduce power-plant emissions of NO_x, CO_2, and PM10, especially when peak demand reduction decreases the use of inefficient peak-power plants (CEC, 2000, p. 81).

Cool roofs may last longer than warm roofs because of reduced thermal stress. Thus, if installed in the course of either new construction or regularly scheduled roof replacement—i.e., once every 10–25 years—cool roofs would reduce waste and the need for landfill space.

Cool roofs tend to increase consumption of building heating energy. Of particular concern is the potential for cool roofs to increase gas-furnace emissions into local air districts where winter air pollution may be problematic. That is, if a building is cooled with remotely generated electric power, and heated with locally burned natural gas, installation of a cool roof may yield increased annual local emissions from natural gas combustion even while reducing annual energy consumption.

Small quantities of water and detergent may be used in cases where annual roof cleaning is required to maintain high reflectance. The use of potable water to clean roofs may be detrimental in California's frequent droughts, and the use of detergent may pollute ground water. One contractor interviewed cleans roofs without detergent, using high-pressure water ($5.7\,\ell/m^2$) and baking soda ($2.4\,g/m^2$) to wash the roofs and neutralize acidic pollutants (Lease, 2002).

3. Path for Title 24 code change

3.1. Existing code

Under the express terms adopted as emergency regulations on January 3, 2001, California's Title 24 code, "Building Energy Efficiency Standards for Residential and NR Buildings," defines a cool roof as a "roofing material with high solar reflectance and high emittance (HE) that reduces heat gain through the roof." Title 24 specifies rules for certification and labeling of roofing-product solar reflectance and thermal emittance. Cool roofs are not included in the prescriptive requirements for building envelopes, but roof reflectance is incorporated in the overall-envelope and performance-based approaches.

In the NR-building overall-envelope approach, the roof's solar reflectance is factored into the building heat gain equation via specification of roof solar absorptance. The solar absorptance of a proposed cool roof is set to 0.45 (solar reflectance 0.55), while that of a standard roof is fixed at 0.70 (solar reflectance 0.30).

The residential and NR alternative calculation method (ACM) approval manual for performance-based compliance also assigns reduced solar absorptance (increased solar reflectance) to cool roofs. The proposed cool roof absorptance is 0.45 (reflectance 0.55), while the standard roof absorptance is 0.70 (reflectance 0.30).

Section 118(f) of the Standards sets reflectance and emittance requirements for cool roofs. Clay and concrete tile roofs must have a minimum initial solar reflectance of 0.40 and a minimum thermal emittance of 0.75 to be considered cool, while all other cool roofing products are required to have a minimum initial solar reflectance of 0.70 and a minimum thermal emittance of 0.75.

3.2. Code change proposal

The proposed change adds a prescriptive requirement for NR buildings with low-sloped roofs that establishes a thermal-emittance-dependent minimum initial solar roof reflectance[2] for each of California's 16 climate zones (Fig. 1). A roof with an initial thermal emittance not less than 0.75 qualifies as cool if it has an initial solar reflectance not less than 0.70; a roof with an initial thermal emittance $\varepsilon_{\text{initial}}$ less than 0.75 (e.g., a metallic roof) qualifies as cool if it has an initial solar reflectance not less than $0.70 + 0.34 \times (0.75 - \varepsilon_{\text{initial}})$. The derivation of this thermal-emittance-dependent minimum initial solar roof reflectance is presented in Appendix A.

These prescribed reflectance values are based on an estimated life cycle cost (LCC) analysis for cool roofs. Since definite LCC savings were found in zones 2–16, and LCC savings were found in zone 1 under some circumstances, the same thermal-emittance-dependent minimum initial solar reflectance would be required for all climate zones. By establishing this prescriptive value, overall-envelope and performance approach calculations would result in compliance credits or penalties, depending on the product performance rating relative to the prescriptive requirement.

No changes are made to prescriptive requirements for the solar reflectance and thermal emittance of roofs on NR buildings with other than low-sloped roofs, high-rise residential buildings, low-rise residential buildings, or guest rooms in hotel/motel buildings.

The prescriptive requirements for cool roofing products are revised to allow for LE products that have exceptionally high solar reflectance. An existing provision qualifying moderate-reflectance clay and concrete tiles as cool is restricted to low-rise residential applications and is not affected by this proposal.

The proposed change modifies all three envelope-compliance options, as described below. Revisions will be necessary to the standards, NR manual, NR ACM manual, and compliance forms to reflect the changes. The low-rise residential standards will remain unchanged.

3.2.1. Prescriptive compliance

The proposed change would adopt requirements in each climate region for the thermal-emittance-dependent minimum initial solar reflectance of low-sloped roofs on NR buildings. This would expand the list of prescriptive envelope requirements, since the 2001 revisions to Title 24 do not address cool roofs in the prescriptive compliance approach.

3.2.2. Performance compliance

The 2001 revisions allow the inclusion of cool roofs as a compliance option for credit. The current proposal will use the newly established prescriptive requirements for low-sloped roofs on NR buildings to determine the energy budget for performance compliance calculations, resulting in potential compliance credits or penalties. In addition, the ACM manual will be modified to include an input for emittance for low-sloped roofs on NR buildings.

3.2.3. Overall-envelope approach

Since the overall-envelope approach does not factor in thermal emittance, this approach will apply only to roofs with thermal emittance not less than 0.75 (typically non-metallic), and may not be used for metallic roof surfaces (e.g., bare metal, galvanized steel, or aluminum coating). For low-sloped roofs on NR buildings, the standard heat gain equation will reference the applicable initial solar reflectance from the prescriptive envelope criteria table (Table 1-H in the 2001 Standards), and then degrade it to determine the aged value for the standard-building roof solar reflectance. Currently, the equations use a constant value of 0.45 for solar absorptance (solar reflectance 0.55) and do not address thermal emittance. The proposed heat gain equation will degrade the Cool Roof Rating Council (CRRC)[3] certified values for initial solar reflectance to

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[2] To stay cool, a surface with low thermal emittance requires a higher solar reflectance than does a surface with high thermal emittance. Hence, the minimum initial solar reflectance for cool roof is thermal-emittance dependent.

[3] The Cool Roof Rating Council (http://coolroofs.org) is an independent organization established to provide cool-roof radiative property data.

Fig. 1. Locations of the 16 California climate zones (courtesy Eley Associates).

determine the value for the proposed building's aged solar roof reflectance. Products not rated by CRRC will be assigned a default initial solar reflectance of 0.10.

The text of the proposed code change is available in a longer version of this study (Levinson et al., 2002).

4. Cost effectiveness analysis of code change

Cool-roof cost effectiveness can be estimated by quantifying five parameters: annual decrease in cooling electricity consumption, annual increase in heating electricity and/or gas consumption, net present value (NPV) of net energy savings, cost savings from downsizing cooling equipment, and the cost premium for a cool roof. Cost premiums were based on interviews of manufacturers, contractors, owners, and specifiers, while savings were estimated via computer simulation of building energy use. Four other parameters can yield cool-roof benefits, but were not included in this determination of cost-effectiveness: peak cooling electricity demand reduction (specifically, cost savings and air-quality improvements associated with reduced use of peak-power generation); expenditure decrease from participation in a load curtailment program; expenditure decrease from participation in a reflective-roof rebate program; and savings in material and labor costs from the extended lives of the roof's surface and insulation.

The DOE-2.1E building energy simulation model (BESG, 1990; Winkelmann et al., 1993) was used to estimate for each of California's 16 climate zones the effects of a cool roof on the uses of cooling and heating energy by a prototypical Title 24-compliant building. Simulated savings were shown to be comparable to savings measured for several buildings retrofitted with cool roofs. Finally, the simulated estimates of savings per m^2 of cool roof area were combined with a profile of

California's NR new construction (NRNC) and California Energy Commission (hereafter, simply Commission) projections of annual NRNC area additions to predict statewide savings.

4.1. Methodology

4.1.1. Simulating building energy savings

We constructed a prototypical Title 24 single-floor, 455 m^2 small office building (Table 5) with five cooling/heating zones—one interior zone, and four equal-area perimeter zones (Fig. 2). Title 24 building characteristics (envelope, air-conditioner energy efficiency ratio (EER), interior load and schedules) were obtained from the Commission's 2001 Energy Efficiency Standards Report (CEC, 2001). Each zone is served by an EER10 packaged rooftop air conditioner and a natural-gas furnace. A constant-volume air handler supplies air to each zone through ducts and returns the air through a plenum above a dropped ceiling. The building was assigned the level of roof insulation prescribed by Title 24, which is R-11 (1.9 m^2 K/W) in the southern coastal areas (zones 6–9: Los Angeles Beach, San Diego, Santa Ana, and Los Angeles City) and R-19 (3.4 m^2 K/W) elsewhere. Wall insulation was R-13 (2.3 m^2 K/W), which meets or exceeds Title 24 requirements of R-11 to R-13 (1.9–2.3 m^2 K/W).

The DOE-2.1E simulations estimated annual cooling and ventilation electricity use (kW h/m^2), annual heating natural gas use (MJ/m^2), and peak cooling and ventilation power demand (W/m^2). Cool-roof-induced annual energy and peak power savings were determined by simulating the building twice: once with an aged cool roof (degraded $\rho = 0.55$, $\varepsilon = 0.90$), and once with an aged non-cool roof (degraded $\rho = 0.20$, $\varepsilon = 0.90$). This corresponds to a reflectance difference of $\Delta\rho_0 = 0.35$ with unchanged emittance. Savings are linearly proportional to the change in roof reflectance (Konopacki et al., 1997); hence, savings for some other reflectance difference $\Delta\rho_1$ can be calculated from:

$$\text{Savings}_{\Delta\rho_1} = (\Delta\rho_1/\Delta\rho_0) \times \text{savings}_{\Delta\rho_0}.$$

The simulations were conducted using degraded reflectances (cool 0.55, non-cool 0.20) rather than initial reflectances (cool 0.70, non-cool 0.20) to conservatively estimate savings. Note also that since cool-roof savings are proportional to roof area, rather than to floor area, the simulation results (savings per unit roof area) apply to multi-floor as well as single-floor buildings. (There is essentially no heat transfer between levels of a multi-floor building if each level is conditioned to the same air temperature.)

Annual source energy savings (MJ/m^2) were calculated from annual electricity and natural gas savings using conversion factors of 10.8 source MJ/kW h electricity (33% combined generation and distribution efficiency) and 1 source MJ/MJ natural gas (100% distribution efficiency).

The 15-year NPV of savings (\$/m^2) was calculated with and without time dependent valuation (TDV). A period of 15 years was chosen to be consistent with the typical lifetime of a low-sloped NR building roof (Table 6).

The TDV method assigns 15-year unit values of NPV to electricity (\$/kW h) and natural gas (\$/MJ) that vary with hour of year and climate zone. These hourly multipliers are used to calculate the NPVs of savings achieved in each of the 8760 h in a year. Summing these hourly savings yields the TDV NPV (\$).

The non-TDV method converts annual electricity savings and annual natural gas savings to NPV \$ using NPV multipliers (\$1.37/kW h and \$0.069/MJ) based on 15-year projections of statewide annual average electricity and gas prices. The same multipliers are used in every climate zone (Eley Associates, 2002).

It should be noted that the energy conversion factors and NPV multipliers were specified by the California Energy Commission, and might not be representative of efficiencies and prices outside California.

The average cost per kW of cooling capacity ranges from \$560 to \$660 for a package system, from \$560 to \$670 for a split system, and from \$350 to \$480 for a central (i.e., multi-zone, built-up) system, exclusive of the air handling unit (Somasundaram et al., 2000). Since the air handling unit typically costs about half as much as the rest of a central cooling system, the total cost for a central system ranges from about 525 to 720 \$/kW. Thus, initial cost savings available from downsizing the air conditioning system were conservatively estimated at \$500/kW. Equipment cost savings were added to energy savings to determine total savings.

4.1.2. Projecting statewide energy savings for NRNC and roof replacement

4.1.2.1. New construction. A database of NRNC (RLW, 1999) describes 990 sample California NR buildings, providing each building's floor area, roof area, climate zone, building type, and "case weight" factor indicating how representative the sample building is of California NRNC. The NRNC database defines 17 building types. The 10 types that are expected to be conditioned during the day—grocery store, medical/clinical, office, restaurant, retail and wholesale store, school, theater, hotels/motel, community center, and library—we refer to as "daytime-conditioned." Seven other types—commercial and industrial (C&I) storage (warehouse), general C&I work (factory), other, religious worship/auditorium/convention, unknown, fire/police/jail, and gymnasium—may be conditioned during the day, but are excluded from the estimated statewide cool-roof area because significant fractions of their cooling loads may be incurred during the evening.

Table 5
Characteristics of the prototypical Title 24 single-floor small office building used in DOE-2.1E simulations of cool-roof energy savings (CEC, 2001)

General	Floor area (also roof area)	455 m^2
	Orientation	Non-directional
	North/south	21 m
	East/west	21 m
	Conditioned zones	5
Zones	Perimeter-north	77 m^2
	Perimeter-south	77 m^2
	Perimeter-east	77 m^2
	Perimeter-west	77 m^2
	Core	149 m^2
Roof construction	Built-up with grey mineral capsheet	Base case
	Built-up with white coated mineral capsheet	Cool case
	1.9 cm plywood deck	Low-slope
	Return air plenum (unconditioned)	
	Insulation	1.9 or 3.4 m^2 K/W
	Dropped t-bar ceiling with 1.3 cm acoustical tile	
Roof solar reflectance	Base case	0.20
	Aged cool case	0.55
Roof thermal emittance	Base case	0.90
	Aged cool case	0.90
Wall construction	Brick	
	Wood frame (15%)	
	Insulation (85%)	2.3 m^2 K/W
	1.3 cm drywall	
	Height	2.7 m
Windows	Window-to-wall ratio	0.50
	Double-pane	Clear
	Operable shades	Yes
Foundation	Concrete slab-on-grade	
	Carpet with pad	
Cooling equipment	Packaged rooftop air conditioner	5 (1 unit per zone)
	Capacity	Auto-sized
	EER	10
	COP	2.9
	Set-point	25.6°C
Heating equipment	Natural gas furnace	5 (1 unit per zone)
	Capacity	Auto-sized
	Efficiency	74%
	Set-point	21.1°C
Distribution	Constant-volume forced air system	5 (1 unit per zone)
	Capacity	Auto-sized
	Fan efficiency	1.1 W/(ℓ/s)
	Economizer	Temperature
	Duct leakage	10%
	Duct temperature drop	0.6°C
	Outside air	7 ℓ/s/person
Operation	Weekdays	9a.m.–6p.m.
	Saturday	9a.m.–noon
Interior loads	Infiltration (Title 24 schedule W-23)	0.5 ACH
	Lighting (Title 24 schedule W-25)	13 W/m^2
	Equipment (Title 24 schedule W-24)	16 W/m^2
	Occupants (Title 24 schedule W-26)	25

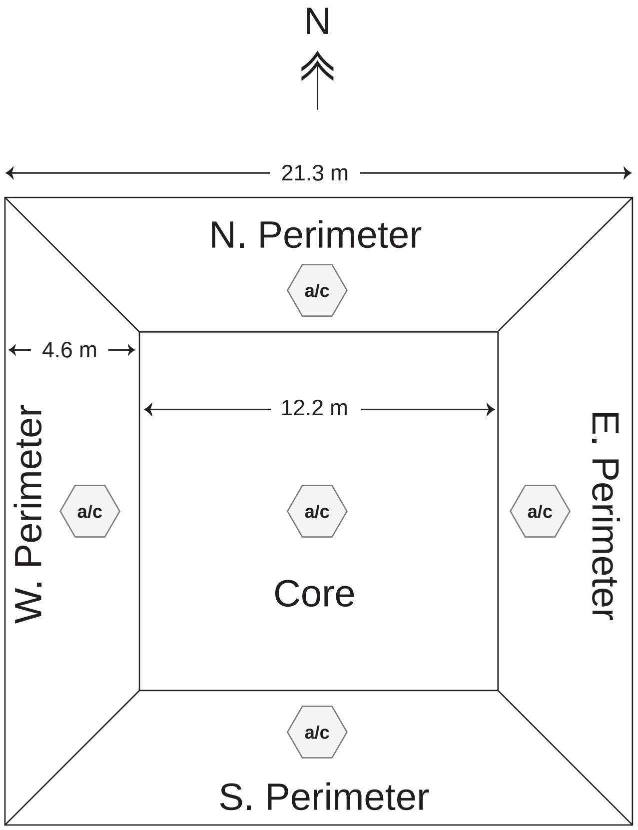

Fig. 2. Top view of the square, five-zone prototypical Title 24 single-floor small office building used in DOE-2.1E simulations of cool-roof energy savings. Each zone has its own rooftop package air-conditioning (a/c) unit.

Table 6
Life expectancies of roofing materials (NRCA, 1998; Lufkin and Pepitone, 1997)

Roofing material	Life expectancy (years)
Wood shingles and shakes	15–30
Tile[a]	50
Sheet metal[b]	20 to 50 +
BUR/asphalt[c]	12–25
BUR/coat and tar[c]	12–30
Single-ply modified bitumen	10–20
Single-ply thermoplastic	10–20
Single-ply thermoset	10–20
Asphalt shingle	15–30
Asphalt overlay	25–35

[a] Depends on quality of tile, thoroughness of design, and climate.

[b] Depends on gauge of metal, quality of coating, thoroughness of design and application.

[c] Depends on materials and drainage; coatings will add to life span.

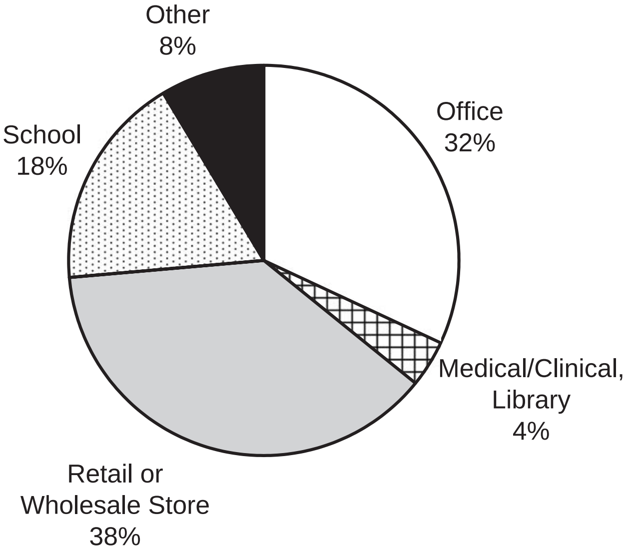

Fig. 3. Contributions by building category to the total roof area of daytime-conditioned NRNC in California, based on a database of 990 representative buildings (RLW, 1999).

We will now consider the effect of applying the savings rate (savings per unit roof area) computed for an office building to other daytime-conditioned NRNC. The database indicates that office buildings contribute 32% of the total roof area of daytime-conditioned NRNC in California. The remaining roof area comes from retail and wholesale stores, 38%; schools, 18%; medical/clinical buildings and libraries, 4%; and other buildings, 8% (Fig. 3). Medical/clinical buildings and libraries are generally similar to office buildings in design and operation, and would be expected to offer comparable savings per unit roof area. Earlier simulations of cool-roof energy savings in Sacramento (Konopacki and Akbari, 2002) and Los Angeles (Konopacki et al., 1997) suggest that the savings rate for retail buildings is approximately twice that for office buildings, primarily because retail buildings operate about 20 h more each week. The savings rate for a school may be lower than that for an office if the school is vacant in summer. If we assume that (a) the savings rate for medical/clinical buildings and libraries is equal to that for office buildings; (b) the savings rate for retail and wholesale stores is twice that for office buildings; and (c) the savings rates for buildings in the school and "other" categories are half those for office buildings, the average savings rate (weighted by roof area) for all daytime conditioned NRNC would be about 25% higher than that for office buildings. Hence, applying to the California NRNC building mix the savings rate computed for an office building will likely yield a conservative estimate of statewide savings.

We denote the total case-weighted roof area of daytime-conditioned sample buildings in climate zone i as $R_{\text{samples},i}$, and the total case-weighted floor area of all 990 sample buildings as F_{samples}. If the rate of savings per unit roof area in climate zone i is S_i, statewide savings per unit floor area can be estimated as

$$\sum_i S_i(R_{\text{samples},i}/F_{\text{samples}}).$$

Over the period 2001–2010, the Commission predicts annual additions to NR floor area ranging from 1430 to 1520 ha (1 ha = 10^4 m^2), averaging 1470 ha (CEC, 2000). We assume as a qualified guess that 80% of the NRNC would be low-sloped (i.e., have a low-sloped roof), and that 80% of the low-sloped NRNC would be built with a non-cool roof. Hence, the total floor area of cool-roofable, low-sloped, daytime-conditioned NRNC is 80% × 80% = 64% of 1470 ha, or 940 ha. This is the state NRNC floor area to which cool-roof savings are applicable, denoted $F_{\text{CA,applicable}}$.

Statewide savings can be estimated from the expression $F_{\text{CA,applicable}} \sum_i S_i(R_{\text{samples},i}/F_{\text{samples}})$.

4.1.2.2. Roof replacement. Although Title 24 NR energy standards apply only to roofs in new construction, the analysis presented in this study applies also to roof replacement. It would tend to underestimate savings in older buildings with less efficient cooling equipment, and/or less roof/ceiling insulation. Savings were not precisely calculated for roof replacements because data regarding the extent of roof replacements by climate zone are not currently available. Assuming that the statewide savings for roof replacements would be roughly proportional to the ratio of replacement ($4.1 B) to new ($1.4 B) roof sales reported by *Western Roofing Siding and Insulation* in 1999 (Dodson, 1999), statewide projected savings from roof replacement would be 2.9 times those from new construction.

4.2. Results

4.2.1. Simulated building energy savings for new construction

Simulated cool-roof savings by climate zone are detailed in Table 7.

Annual electricity savings ranged from 1.24 to 4.45 kW h/m^2 (average 3.20 kW h/m^2).

Annual natural gas deficits ranged from 1.9 to 12.0 MJ/m^2 (average 5.6 MJ/m^2).

Annual source energy savings ranged from 3.4 to 44.3 MJ/m^2 (average 29.5 MJ/m^2).

Peak power demand savings ranged from 1.4 to 2.7 W/m^2 (average 2.1 W/m^2), yielding cooling equipment cost savings of 0.72–1.35 $/m^2 (average $1.01/m^2).

Fifteen-year NPV energy savings ranged from 1.17 to 6.96 $/m^2 (average $4.85/m^2) with TDV, and from 1.02 to 5.78 $/m^2 (average $4.00/m^2) without TDV (Fig. 4).

Total savings (cooling-equipment cost savings + 15-year NPV energy savings) ranged from 1.89 to 8.31 $/m^2 (average $5.87/m^2) with TDV, and from 1.74 to 7.13 $/m^2 (average $5.02/m^2) without TDV (Fig. 5). The value of equipment savings was about 19% that of TDV NPV energy savings, and about 23% that of non-TDV NPV energy savings.

The greatest annual electricity savings (kW h) were found in the southern inland areas (climate zones 13, 14, and 15), which are hot; and on the southern coast (zones

Table 7
Simulated Title 24 cool-roof annual energy, peak demand, cooling equipment cost, and NPV dollar savings (energy only, and total = energy + equipment) for a prototypical Title 24 building in each California climate zone, with and without TDV

Climate zone	Roof *R*-value	Annual energy/m^2			Peak power/m^2		TDV NPV/m^2				Non-TDV NPV/m^2			
		Elect. (kW h)	Gas (MJ)	Source (MJ)	kW	$equip.	$elect.	$gas	$energy	$total	$elect.	$gas	$energy	$total
1	19	1.24	−9.43	3.9	1.43	0.72	1.97	−0.80	1.17	1.89	1.69	−0.67	1.02	1.74
2	19	3.18	−6.70	27.6	2.15	1.08	5.32	−0.55	4.76	5.83	4.36	−0.46	3.90	4.97
3	19	1.98	−5.56	15.8	1.64	0.82	3.61	−0.45	3.16	3.98	2.72	−0.38	2.35	3.16
4	19	2.65	−4.77	23.8	1.94	0.97	4.49	−0.40	4.09	5.06	3.63	−0.33	3.29	4.26
5	19	2.08	−5.34	17.1	1.78	0.89	3.68	−0.45	3.23	4.12	2.85	−0.38	2.48	3.36
6	11	4.18	−4.66	40.5	2.39	1.19	6.80	−0.39	6.42	7.61	5.73	−0.31	5.41	6.61
7	11	3.37	−2.95	33.4	2.69	1.35	5.53	−0.26	5.26	6.61	4.61	−0.22	4.39	5.74
8	11	4.45	−4.20	43.8	2.69	1.35	7.33	−0.37	6.96	8.31	6.08	−0.30	5.78	7.13
9	11	4.33	−5.11	41.6	2.16	1.08	7.07	−0.42	6.65	7.73	5.94	−0.36	5.59	6.67
10	19	3.66	−4.09	35.4	1.92	0.96	5.95	−0.33	5.61	6.57	5.03	−0.28	4.75	5.70
11	19	2.88	−5.56	25.6	1.61	0.81	4.90	−0.47	4.42	5.23	3.96	−0.40	3.56	4.37
12	19	3.08	−6.02	27.2	2.03	1.02	5.23	−0.51	4.71	5.73	4.22	−0.42	3.80	4.82
13	19	3.78	−5.79	35.0	2.07	1.03	6.37	−0.47	5.89	6.92	5.17	−0.40	4.77	5.80
14	19	3.79	−5.34	35.6	2.25	1.12	6.20	−0.43	5.77	6.89	5.20	−0.36	4.84	5.97
15	19	4.09	−1.93	42.3	1.75	0.88	6.45	−0.17	6.28	7.15	5.60	−0.14	5.46	6.33
16	19	2.51	−12.04	15.1	1.93	0.96	4.32	−0.99	3.33	4.29	3.43	−0.84	2.60	3.57
Min.		1.24	−12.04	3.9	1.43	0.72	1.97	−0.99	1.17	1.89	1.69	−0.84	1.02	1.74
Max.		4.45	−1.93	43.8	2.69	1.35	7.33	−0.17	6.96	8.31	6.08	−0.14	5.78	7.13
Avg.		3.20	−5.59	29.0	2.03	1.01	5.33	−0.47	4.86	5.87	4.39	−0.39	4.00	5.01

Savings are computed for each zone's prescribed level of roof insulation, and normalized per m^2 of air-conditioned roof area.

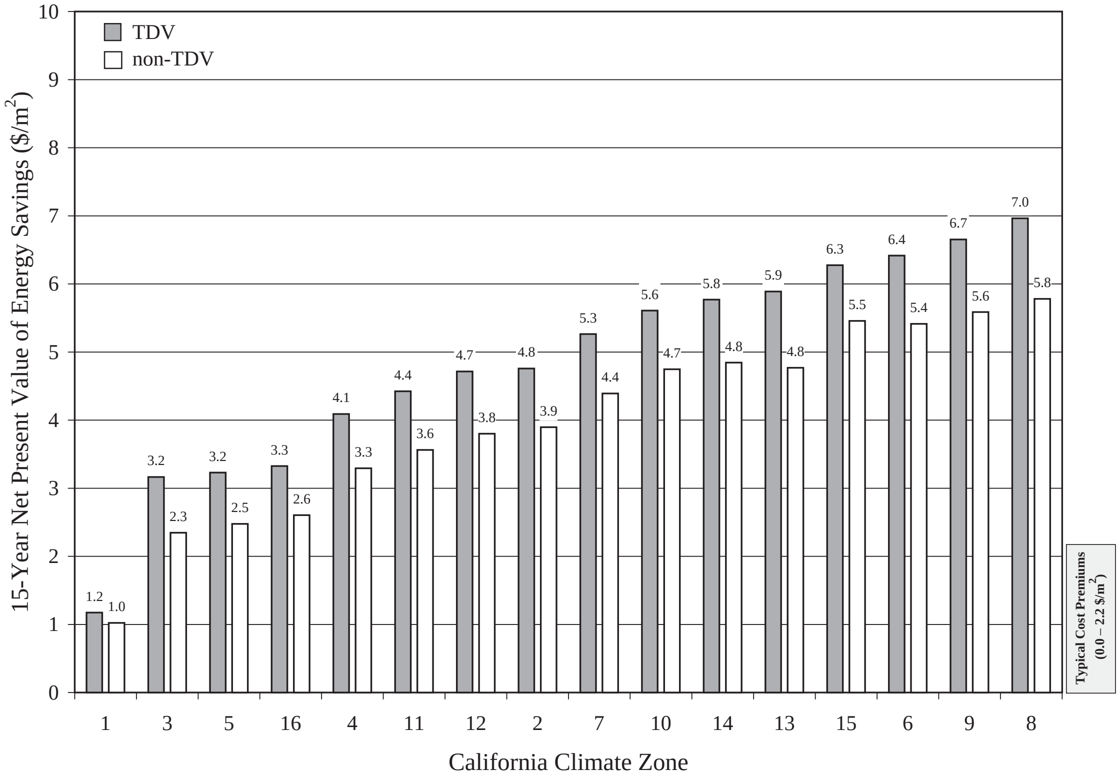

Fig. 4. 15-year NPV of energy savings ($/m²) by California climate zone, simulated for a prototypical Title 24 building with a cool roof. Savings are shown with and without time dependent valuation (TDV).

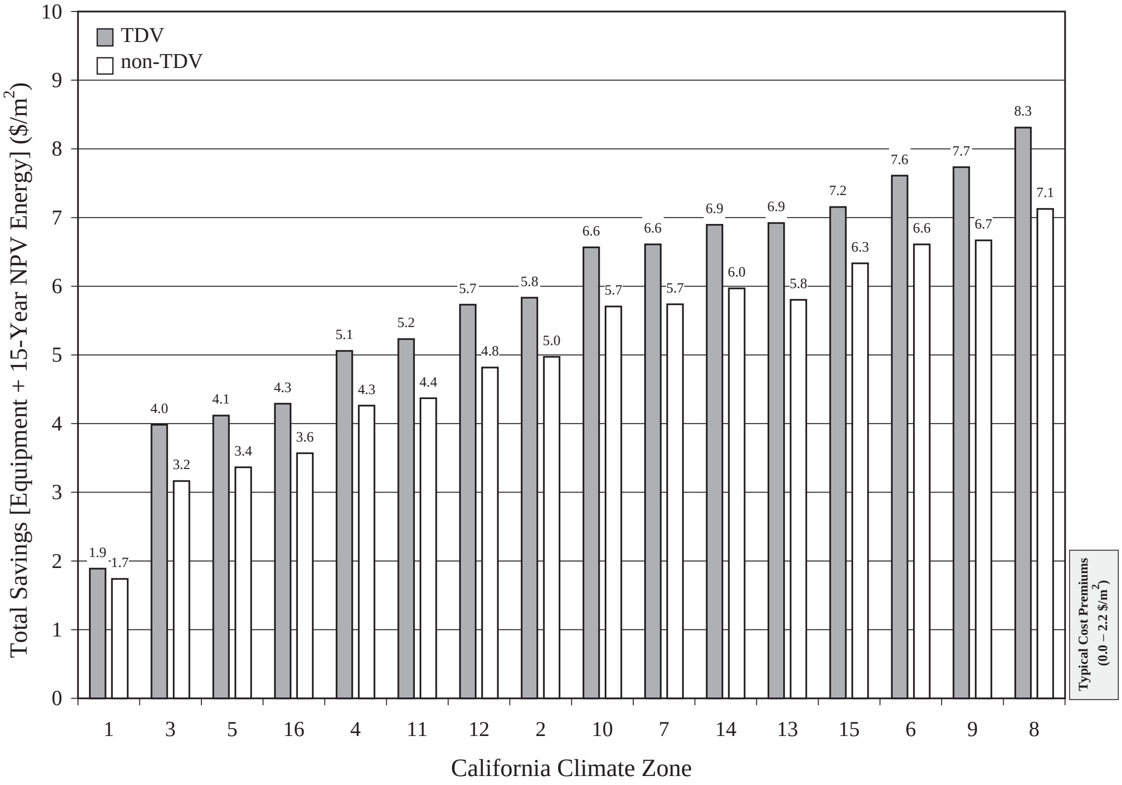

Fig. 5. Total savings (cooling equipment savings + 15-year NPV of energy savings) in $/m² by California climate zone, simulated for a prototypical Title 24 building with a cool roof. Savings are shown with and without time dependent valuation (TDV).

Table 8
Daytime-conditioned NR roof area; also, simulated cool-roof annual energy, peak demand, cooling equipment cost, and NPV savings (energy only, and total = energy + equipment), with and without TDV

Climate zone	ha daytime-conditioned roof area/ha$_{app}$	Annual energy			Peak power		TDV NPV		Non-TDV NPV	
		MW h elect./ha$_{app}$	GJ gas/ha$_{app}$	GJ source/ha$_{app}$	kW/ha$_{app}$	k\$equip./ha$_{app}$	k\$energy/ha$_{app}$	k\$total/ha$_{app}$	k\$energy/ha$_{app}$	k\$total/ha$_{app}$
1	0.001	0.0	−0.1	0.04	0.01	0.01	0.01	0.02	0.01	0.02
2	0.019	0.6	−1.3	5.4	0.4	0.2	0.9	1.1	0.8	1.0
3	0.041	0.8	−2.3	6.5	0.7	0.3	1.3	1.6	1.0	1.3
4	0.051	1.3	−2.4	12.1	1.0	0.5	2.1	2.6	1.7	2.2
5	0.006	0.1	−0.3	1.0	0.1	0.1	0.2	0.2	0.1	0.2
6	0.061	2.6	−2.8	24.7	1.5	0.7	3.9	4.7	3.3	4.0
7	0.036	1.2	−1.1	12.0	1.0	0.5	1.9	2.4	1.6	2.1
8	0.041	1.8	−1.7	17.8	1.1	0.5	2.8	3.4	2.3	2.9
9	0.041	1.8	−2.1	16.9	0.9	0.4	2.7	3.1	2.3	2.7
10	0.046	1.7	−1.9	16.3	0.9	0.4	2.6	3.0	2.2	2.6
11	0.010	0.3	−0.5	2.5	0.2	0.1	0.4	0.5	0.3	0.4
12	0.057	1.8	−3.4	15.5	1.2	0.6	2.7	3.3	2.2	2.7
13	0.019	0.7	−1.1	6.7	0.4	0.2	1.1	1.3	0.9	1.1
14	0.017	0.6	−0.9	6.0	0.4	0.2	1.0	1.2	0.8	1.0
15	0.010	0.4	−0.2	4.3	0.2	0.1	0.6	0.7	0.6	0.6
16	0.001	0.0	−0.1	0.1	0.02	0.01	0.03	0.04	0.02	0.03
Total	0.457	15.8	−22.3	148	9.8	4.9	24.3	29.2	20.1	24.9

Values are shown in each California climate zone, and totaled statewide. Calculations are normalized per applicable hectare (ha$_{app}$) of NR new construction in California, where applicable means having a non-cool, low-sloped roof.

6, 8, and 9), where the prescribed roof insulation level is only R-11 (1.9 m^2 K/W). The smallest savings were found along the north coast (zone 1), along the central coast (zones 3 and 5), and in the mountains (zone 16).

Since the NPV (both TDV and non-TDV) of the annual natural gas deficit was typically small compared to that of the annual electricity savings, the NPV of energy savings was also greatest in the southern inland and southern coastal climate zones.

4.2.2. Statewide projected savings for new construction and roof replacement

4.2.2.1. New construction. The database of 990 sample buildings indicates that there are 0.46 ha of daytime-conditioned roof area per ha of California NRNC floor area (Table 8). Using the average Commission estimate of 1470 ha of annual NRNC, 670 ha of statewide daytime-conditioned roof area are added each year to California's NR building stock, of which 430 ha are low-sloped and not yet cool. This yields the following annual values for statewide NRNC:

- electricity savings of 14.8 GW h;
- natural gas deficit of 21.0 TJ;
- source energy savings of 139 TJ;
- peak power demand savings[4] of 9.2 MW;
- equipment savings of \$4.6 M;
- TDV NPV energy savings of \$22.9 M;
- TDV total savings (equipment + NPV energy) of \$27.5 M;
- non-TDV NPV energy savings of \$18.9 M; and
- non-TDV total savings (equipment + NPV energy) of \$23.5 M (Table 9).

Roof replacement. Statewide replacement of warm roofs by cool roofs is projected to yield (annually):

- electricity savings of 43.0 GW h;
- natural gas deficits of 60.9 TJ;
- source energy savings of 404 TJ;
- peak power demand savings of 26.7 MW;
- equipment savings of \$13.3 M;
- TDV NPV energy savings of \$66.4 M;
- TDV total savings (equipment + NPV energy) of \$79.7 M;
- non-TDV NPV energy savings of \$54.8 M; and
- non-TDV total savings (equipment + NPV energy) of \$68.1 M.

5. Discussion

5.1. Simulated vs. measured building energy savings

The California building studies (Konopacki et al., 1998; Hildebrandt et al., 1998) are detailed in Table 1.

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[4] "Annual" power savings refers to reductions in the annual need for power plant construction.

Table 9
Typical Commission-projected statewide annual NRNC floor area; estimated statewide annual daytime-conditioned NRNC roof area; and simulated statewide cool-roof annual energy, peak demand, cooling equipment cost, and NPV savings (energy only, and total = energy + equipment), with and without TDV

	Floor area (ha)	Daytime-conditioned roof area (ha)	Annual energy			Peak power		TDV NPV		Non-TDV NPV	
			Elect. (GW h)	Gas (TJ)	Source (TJ)	MW	M$ equip.	M$ energy	M$ total	M$ energy	M$ total
All NRNC	1470	670	23.2	−32.8	218	14.4	7.2	35.8	43.0	29.5	36.7
Applicable NRNC	940	430	14.8	−21.0	139	9.2	4.6	22.9	27.5	18.9	23.5

Estimates are shown for all NRNC and for the subset of NRNC to which cool-roof savings is applicable (that having a non-cool, low-sloped roof).

The annualized measured energy savings were within or exceed the range of simulated annual kW h savings, except in the case of the retail store in San Jose. In that exceptional case, the simulation overpredicted measured savings because the building was modeled without an attic radiant barrier that was present in the actual building. In general, differences between simulated and measured savings can be attributed to one or more of the following:

- inadequacy of DOE-2.1E's model of attic radiation exchange;
- actual weather vs. typical weather used in simulations;
- actual building operation vs. Title 24's standard operating assumptions;
- actual roof insulation vs. Title 24's prescriptive requirement;
- actual air-conditioner equipment efficiency vs. Title 24's prescriptive requirements; and
- actual change in solar reflectance vs. 0.35 increase used in simulations.

5.2. Cost effectiveness for new construction

The 15-year NPV of cool-roof energy savings for a Title 24 prototypical new building with an EER10 air conditioner[5] ranged from 1.18 to 7.00 $/m^2 (average $4.84/m^2) with time dependent valuation (TDV), and from 1.08 to 5.81 $/m^2 (average $3.98/m^2) without TDV. Cost savings from downsizing cooling equipment ranged from 7.21 to 13.5 $/m^2 (average $10.1/m^2). Thus, total savings (equipment + energy) ranged from 1.94 to 8.29 $/m^2 (average $5.92/m^2) with TDV, and from 1.72 to 7.10 $/m^2 (average $5.06/m^2) without TDV. With or without TDV, total savings in all climates except zone 1 exceeded $2.15/m^2. Since the typical cost premium for a cool roof is 0.00–2.15 $/m^2, cool roofs are expected to be cost effective in climate zones 2–16. Cool roofing materials with cost premiums not exceeding $1.94/m^2 are expected to be cost effective in climate zone 1.

6. Summary and conclusions

Reviews of low-sloped roofing technologies and the western-state roofing market indicate that cool options are available for nearly all low-sloped roofs, including the three dominant products: BUR, modified bitumen, and single-ply membrane. We qualify roofs as cool if they have a minimum thermal emittance of 0.75 and a minimum solar reflectance of 0.70. A roof with an initial thermal emittance ($\varepsilon_{\text{initial}}$) less than 0.75 can qualify as cool if it has a minimum initial solar reflectance not less than $0.70 + 0.34 \times (0.75 - \varepsilon_{\text{initial}})$. Buildings with roofs that do not meet prescriptive requirements may comply with Title 24 via an "overall-envelope" approach, or via a performance approach. The former applies only to buildings with non-metal roofs, while the latter may be used for all buildings.

Substituting a cool roof for a non-cool roof decreases cooling electricity use, peak cooling power demand, and cooling-equipment capacity requirements, while increasing heating energy consumption. Cool roofs can also lower the ambient air temperature, slowing ozone formation and increasing human comfort. Cool roofs may also last longer than non-cool roofs, reducing solid waste and demand for landfill. The increased need for heating energy may yield a net increase in local emissions if buildings are heated with natural gas and cooled with electricity.

DOE-2.1E building energy simulations indicate that the use of a cool roof on a prototypical California Title-24 NR building with a low-sloped roof yields (to two significant figures) average annual cooling energy savings of 3.2 kW h/m^2, average annual natural gas

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[5] The 2001 Title 24 requirements for air-cooled, electrically operated unitary air conditioners are EER10.3 for units sized 65–135 kBTU/h (19–40 kW), and EER9.7 for units sized 135–240 kBTU/h (40–70 kW). EER10 was chosen as an average. Since cooling electricity use and peak power demand scale inversely with efficiency, values for buildings with more efficient cooling units can be calculated by multiplying the cooling electricity use and peak power demand results in Tables 7–9 by $10/n$, where n is the higher EER.

deficits of 5.6 MJ/m^2, average annual source energy savings of 30 MJ/m^2, and average peak power demand savings of 2.1 W/m^2. The 15-year net present value (NPV) of energy savings averages \$4.90/m^2 with time dependent valuation (TDV), and \$4.00/m^2 without TDV. When cost savings from downsizing cooling equipment are included, the average total savings (15-year NPV + equipment savings) rise to \$5.90/m^2 with TDV, and \$5.00/m^2 without TDV.

Statewide projected annual savings (deficits) for new construction are 15 GW h electricity, (21) TJ natural gas, 140 TJ source energy, 9.2 MW peak power demand (reduction in annual need for power plant construction), and \$4.6 M equipment. With TDV, NPV energy savings are \$23 M, and total savings are \$28 M; without TDV, NPV energy savings are \$19 M, and total savings are \$24 M. For roof replacement, statewide projected annual savings (deficits) are 43 GW h electricity, (61) TJ natural gas, 400 TJ source energy, 27 MW peak power demand (reduction in annual need for power plant construction), and \$13 M equipment. With TDV, NPV energy savings are \$66 M, and total savings are \$80 M; without TDV, NPV energy savings are \$55 M, and total savings are \$62 M.

Total savings ranged from 1.90 to 8.30 \$/m^2 with TDV, and from 1.70 to 7.10 \$/m^2 without TDV, across California's 16 climate zones. The typical cost premium for a cool roof is 0.00–2.20 \$/m^2. Cool roofs with premiums up to \$2.20/m^2 are expected to be cost effective in climate zones 2–16; those with premiums not exceeding \$1.90/m^2 are expected to be also cost effective in climate zone 1. Hence, this study recommends that the year-2005 Title 24 code for NR buildings with low-sloped roofs include a cool-roof prescriptive requirement in all California climate zones.

The analysis and recommendations in this study were directed only at NR buildings with low-sloped roofs. In the future, it might make sense to extend the analysis and propose modifications to California Title 24 energy efficiency standards for all other building types: NR buildings with high-sloped roofs, residential buildings with low-sloped roofs, and residential buildings with high-sloped roofs.

Many California homes equipped with air conditioning are in coastal or transitional climates where mechanical cooling is used only on the hottest days of the year. In such cases, the installation of a cool roof can potentially obviate the need to operate or even install air conditioning. This could make analysis of a residential-building code change proposal of great interest to California.

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Appendix A. Requisite reflectance premium for an LE cool roof

Under typical daytime conditions, an LE roof will be warmer than an HE roof of equal solar reflectance. Thus, an LE cool roof must be more reflective than an HE cool roof to achieve the same steady-state surface temperature.

Consider a roof surface of solar reflectance ρ and thermal emittance ε. Neglecting conduction of heat into the building, the roof's steady-state surface temperature T is determined by equating its solar heat gain to its radiative and convective heat losses:

$$(1-\rho)I = \varepsilon\sigma(T^4 - T_{\mathrm{sky}}^4) + h_{\mathrm{c}}(T - T_{\mathrm{air}}), \tag{A.1}$$

where I is insolation (W m^{-2}), $\sigma = 5.6685 \times 10^{-8}$ W m^{-2} K^{-4} (the Stefan–Boltzmann constant), h_{c} is the convection coefficient (W m^{-2} K^{-1}), T_{sky} is the sky temperature (K), and T_{air} is the air temperature (K). The insolation, convection coefficient, and temperatures of sky and air may be taken from the moderate-wind standard conditions specified by ASTM E 1980-98 ("standard practice for calculating solar reflectance index of horizontal and low-sloped opaque surfaces"): $I = 1000$ W m^{-2}, $h_{\mathrm{c}} = 12$ W m^{-2} K^{-1}, $T_{\mathrm{sky}} = 300$ K, and $T_{\mathrm{air}} = 310$ K (ASTM, 1998a). This energy balance may be solved numerically to determine the roof temperature T.

We now wish to determine the minimum reflectance required of an LE cool roof so that its surface temperature does not exceed that of an HE cool roof; i.e., $T_{\mathrm{LE}} \leqslant T_{\mathrm{HE}}$. Eq. (A.1) can be rearranged to relate reflectance to emittance:

$$\rho = [1 + h_{\mathrm{c}}(T - T_{\mathrm{air}})/I] - [\sigma(T^4 - T_{\mathrm{sky}}^4)/I]\varepsilon. \tag{A.2}$$

When the LE and HE roofs are at the same temperature T_{cool} (i.e., $T_{\mathrm{LE}} = T_{\mathrm{HE}} = T_{\mathrm{cool}}$),

$$\rho_{\mathrm{LE}} - \rho_{\mathrm{HE}} = [\sigma(T_{\mathrm{cool}}^4 - T_{\mathrm{sky}}^4)/I](\varepsilon_{\mathrm{HE}} - \varepsilon_{\mathrm{LE}}). \tag{A.3}$$

Thus, if an LE roof is to stay as cool as an HE roof ($T_{\mathrm{LE}} = T_{\mathrm{HE}} = T_{\mathrm{cool}}$), the reflectance premium $\Delta\rho \equiv$

$\rho_{\mathrm{LE}} - \rho_{\mathrm{HE}}$ required to compensate for the emittance deficit $\Delta\varepsilon \equiv \varepsilon_{\mathrm{HE}} - \varepsilon_{\mathrm{LE}}$ is

$$\Delta\rho = f(T_{\mathrm{cool}})\Delta\varepsilon, \tag{A.4}$$

where

$$f(T_{\mathrm{cool}}) \equiv \sigma(T_{\mathrm{cool}}^4 - T_{\mathrm{sky}}^4)/I. \tag{A.5}$$

If the reflectance premium exceeds that specified by Eq. (A.4), the LE roof will be even cooler than the HE roof.

Since roof reflectance typically changes with age, we need to specify an initial reflectance premium high enough for the aged LE roof to stay as cool as the aged HE cool roof. This requires two steps. First, we calculate an aged reflectance premium $\Delta\rho_{\mathrm{aged}}$ based on the surface temperature of the aged HE cool roof, $T_{\mathrm{cool,aged}}$. Then, we determine the necessary initial reflectance premium, $\Delta\rho_{\mathrm{initial}}$, based on the aged reflectance premium.

We postulate that the relationship between initial and aged roof reflectance is

$$\rho_{\mathrm{aged}} = \rho_0 + c(\rho_{\mathrm{initial}} - \rho_0), \tag{A.6}$$

where constants $\rho_0 = 0.2$ and $c = 0.7$. Rearranging,

$$\rho_{\mathrm{initial}} = \frac{\rho_{\mathrm{aged}} + (c-1)\rho_0}{c}. \tag{A.7}$$

From this we can relate the initial reflectance premium to the aged reflectance premium:

$$\Delta\rho_{\mathrm{initial}} = \frac{\Delta\rho_{\mathrm{aged}}}{c}. \tag{A.8}$$

In the absence of data on the variation of roof emittance with age, we also postulate that roof emittance is constant, so that $\Delta\varepsilon_{\mathrm{initial}} = \Delta\varepsilon_{\mathrm{aged}}$. Thus, the premium in initial solar reflectance required to ensure that an aged LE roof stays as cool as an aged HE roof is

$$\Delta\rho_{\mathrm{initial}} = \frac{1}{c} f(T_{\mathrm{cool,aged}})\Delta\varepsilon_{\mathrm{aged}}. \tag{A.9}$$

A.1. Example 1. New cool roof

Consider a new HE cool roof with solar reflectance $\rho_{\mathrm{HE}} = 0.70$ and thermal emittance $\varepsilon_{\mathrm{HE}} = 0.75$. Its surface temperature will be $T_{\mathrm{cool}} = 324.4\,\mathrm{K}$ (124.3°F), yielding $f(T_{\mathrm{cool}}) = 0.169$. Thus, the minimum solar reflectance required for a new LE cool roof is

$$\begin{aligned}\rho_{\mathrm{LE}} &\geqslant \rho_{\mathrm{HE}} + f(T_{\mathrm{cool}})(\varepsilon_{\mathrm{HE}} - \varepsilon_{\mathrm{LE}}) \\ &\approx 0.70 + 0.17(0.75 - \varepsilon_{\mathrm{LE}}).\end{aligned} \tag{A.10}$$

A new roof with an emittance of 0.20 (e.g., a bare metal roof) would need a minimum solar reflectance of 0.79 to qualify as cool. As a limiting case, the minimum solar reflectance required for a new zero-emittance cool roof would be 0.83.

A.2. Example 2. Aged cool roof

Consider an HE cool roof with initial solar reflectance $\rho_{\mathrm{HE,initial}} = 0.70$ and initial thermal emittance $\varepsilon_{\mathrm{HE,initial}} = 0.75$. We calculate its aged reflectance from Eq. (A.6) as $\rho_{\mathrm{HE,aged}} = 0.55$. The surface temperature of the aged HE roof will be $T_{\mathrm{cool,aged}} = 332.8\,\mathrm{K}$ (139.3°F), yielding $f(T_{\mathrm{cool,aged}}) = 0.236$. Thus, the minimum initial solar reflectance required for a LE cool roof is approximately

$$\begin{aligned}\rho_{\mathrm{LE,initial}} &= \rho_{\mathrm{HE,initial}} + \frac{1}{c} f(T_{\mathrm{cool,aged}})\Delta\varepsilon_{\mathrm{aged}} \\ &\approx 0.70 + 0.34(0.75 - \varepsilon_{\mathrm{LE,initial}}).\end{aligned} \tag{A.11}$$

Here we have assumed that the low and high emittances do not change with age.

A roof with an emittance of 0.20 (e.g., a bare metal roof) would need a minimum initial solar reflectance of 0.89 to qualify as cool. This corresponds to an aged reflectance of 0.68. As a limiting case, the minimum initial solar reflectance required for a zero-emittance cool roof would be 0.95, corresponding to an aged reflectance of 0.72.

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