



Inclusion of Cool Roofs in Nonresidential Title 24 Prescriptive Requirements

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Overview

Description

This proposal would modify the treatment of cool roofs (primarily roofs with high solar reflectance and high thermal emittance) in California's Title-24 standards for non-residential (NR) buildings. Under the current standards, cool roofs are a compliance option. Under this proposal, cool roofs will 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 guest rooms in hotel/motel buildings.

The proposed measure promotes the use of cool roofs to reduce cooling energy usage and peak electrical power demand in air-conditioned buildings regulated by Title 24. Such buildings include but are not limited to offices, retail stores, health care facilities, schools, universities, and high-tech manufacturing facilities. 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 *et al.*, 1999; Konopacki and Akbari, 1998).

Benefits

Roofs that have high thermal emittance (high ability to radiate heat) and high solar reflectance (high ability to reflect sunlight) tend to stay cool in the sun. The same is true of low-emittance roofs with exceptionally high solar reflectance.¹ 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 cooling power demand in conditioned buildings. Since roof temperatures peak in late afternoon, when summer electricity use is highest, cool roofs can also reduce peak electricity demand.

¹ A low-emittance roof with exceptionally high solar reflectance can stay as cool as a white roof. For example, an unaged bare metal roof with a thermal emittance of 0.20 and a solar reflectance of 0.79 would under standard conditions have the same surface temperature as an unaged white roof with a thermal emittance of 0.75 and a solar 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 low-emittance roof to that of the aged high-emittance cool roof (see Appendix, p.32).

Cool roofs transfer less heat to the air than do warm roofs. The resulting lower 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.

Environmental Impact

Cool roofs are expected to have both positive and negative environmental impacts. Benefits include increased human comfort, slowed smog formation, and mitigation of urban heat islands in summer. Waste from disposal of roofs would also decrease. 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.

Environmental Benefits

Cool roofs transfer less heat to the air 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 2 to 9 °F hotter than that in the surrounding rural area. The additional air-conditioning use induced by this urban air temperature elevation is responsible for 5 to 10% of urban peak electric 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).

Air temperature also has a significant influence on the formation of urban smog. Measured data and computer simulations studying the impact of temperature in Los Angeles smog show that a significant reduction in ozone concentration is achieved by lowering the ambient temperature. The simulations predict a reduction in population-weighted smog (ozone) of 10 to 20% resulting from a 3 to 4 °F cooling in ambient temperature. Cool roofs contribute about one-third of this reduction. For some scenarios, a 10 to 20% reduction in ozone is comparable to that obtained by replacing all gasoline on-road motor vehicles with electric cars (Rosenfeld *et al.*, 1995).

Cool roofs may last longer than warm roofs due to reduced thermal stress. Thus, if installed in the course of either new construction or regularly scheduled roof replacement (i.e., once every 10 to 25 years),² cool roofs would reduce waste and the need for landfill.

Environmental Penalties

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 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. One contractor interviewed cleans roofs without detergent, using high-pressure water (140 gal/1000 ft²) and baking soda (0.5 lb/1000 ft²) to wash the roofs and neutralize acidic pollutants (Lease, 2002).

Type of Change

Existing Title 24 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 Non-Residential Buildings," defines a cool roof as a "roofing material with high solar reflectance and high emittance 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 nonresidential-building overall envelope approach, the roof's solar reflectance is factored into the building heat gain equation via specification of roof solar absorptance. (For an opaque surface like that of a roof, absorptance = 1 - reflectance.) 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).

² Although Title 24 regulates only new construction, the analysis presented in this CASE study applies also to roof replacement.

The Residential and Nonresidential 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 tiles 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.

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 reflectance³ for each of California's 16 climate zones (Figure 1, p. 45). These 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 possible LCC savings were found in zone 1, 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 qualify low-emittance 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.

The proposed change modifies all three envelope-compliance options, as described below. Revisions will be necessary to the Standards, Nonresidential Manual, Nonresidential ACM manual, and compliance forms to reflect the changes. The Low-rise Residential Standards will remain unchanged.

³ 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.

Prescriptive Compliance. Adopt requirements in each climate region for the thermal-emittance-dependent minimum initial solar reflectance low-sloped roofs on nonresidential 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.

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 nonresidential 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 nonresidential buildings.

Overall Envelope Approach. Since the overall envelope approach does not factor in thermal emittance, it will apply only to roofs with thermal emittance not less than 0.75 (typically non-metallic). It may not be used for metallic roof surfaces (e.g., bare metal, galvanized steel, or aluminum coating). For low-sloped roofs on nonresidential 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 (CRRRC) certified values for initial solar reflectance to determine the value for the proposed building aged solar roof reflectance. Products not rated by CRRRC will be assigned a default solar initial reflectance of 0.10.

Technology Measures

Measure Availability and Cost

Technologies

The daytime surface temperature of a roof is raised by absorption of solar radiation and lowered by thermal radiation to the sky. Solar heating is proportional to solar absorptance (absorptance = $1 - \text{reflectance}$), 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.

Virtually all construction materials except bare, shiny metals have high thermal emittance.⁴ Since 95% of solar radiation arrives at the earth's surface in the visible and near-infrared (NIR) spectra,⁵ 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. Black surfaces are warm because they have low visible and NIR reflectances.⁶ 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. However, a low-emittance surface can stay as cool as a high-emittance surface if the low-emittance surface has a higher solar reflectance (see Appendix, p. 32). 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.

There are cool and noncool options available for nearly all low-sloped roofing products (Table 1, p. 36). 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 smooth and coated white ($\varepsilon=0.90$). 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 2 (p. 37).

Market

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 \$6.0B, 14-state western U.S. market⁷ for low-sloped commercial-building roofing (Western Roofing, 2001). Metal, asphalt shingle, tile, polyurethane foam, liquid applied coatings, and other materials made up the remainder. California represented about 38% of

⁴ Non-metallic construction materials typically have thermal emittances in the range of 0.80 to 0.95. A bare, shiny metal (e.g., aluminum foil) may have an emittance as low as 0.03, while a roof coating formed with metal flakes may have an intermediate emittance (circa 0.5).

⁵ 43% of the energy in the standard air-mass 1.5 solar spectrum (300-2,500 nm) lies in the visible range (400-700 nm). Another 52% is in the near-infrared (700-2,500 nm), and 5% in the ultraviolet (300-400 nm).

⁶ Some novel black coatings have high NIR reflectance, and thus stay cooler than conventional black surfaces.

⁷ The 14 western states included in this market are Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Texas, Utah, Washington, and Wyoming.

the western market—i.e., \$2.3B. Product shares in the western-region roofing market are not necessarily representative of those in California.

The National Roofing Contractors Association (NRCA) also reported that the year 2000 low-slope roofing market in the 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 re-roofing sales dollars (NRCA, 2000). However, the NRCA estimate of Pacific-region BUR sales was much higher than the Western Roofing estimate of BUR sales in the western region (50% vs. 29%), while the reverse was true for estimates of modified bitumen sales (12% vs. 30%). The NRCA's Pacific-region figures are derived from responses from fewer than 50 contractors, and thus may lack statistical validity.

The Western Roofing and NRCA market estimates are presented in Table 2 (p. 37). 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. By roof area, 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.

Manufacturers

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

Table 3 (p. 40) lists major roofing manufacturers and their primary products.

Distribution

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.

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 to 50% of sales), direct sales to large contractors or home builders (40%), and retail establishments such as home improvement centers and hardware stores (10 to 15%) (Freedonia Group, 1997).

Availability

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. It is likely that some fraction of these manufacturers and their associated products will not meet the performance requirements for cool roofs defined in this proposal, but it is reasonable to assume that many will. Thus, an ample supply of eligible products should be readily available for low-sloped roofs.

Cost

Cool options are available for most types of low-sloped roofing. We propose the use of cool roofs for new construction and for regularly scheduled re-roofing. In estimating cost effectiveness, we consider only the incremental initial cost of changing the reflectance of the roof from a low value to a high value.

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

Material and labor costs for roofing projects vary from one contractor to another. Table 4 (p. 41) lists estimates of incremental costs obtained from interviews of manufacturers, contractors, owners, and specifiers.

Useful Life, Persistence and Maintenance

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, but moderately increase the reflectance of dark materials. LBNL's observations suggest that the aged solar reflectance of a roof may be estimated as

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

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 0.2.⁸

ASHRAE Standard 90.1 (non-residential buildings, section 5.3.1.1) assigns credits to cool roofs with a minimum reflectance of 0.70 (ASHRAE, 2001). However, the credits are calculated based on an aged reflectance of 0.55, which is consistent with Eq. (1) (Akbari *et al.*, 1998c). 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. The revised prescriptive-compliance and overall-envelope approaches use Eq. (1) to calculate degraded solar reflectance from initial solar reflectance.

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

Performance Verification

There are no additional performance verification or commissioning activities required to ensure proper installation and performance of cool roof products.

⁸ 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 ACM inputs initial absorptance, rather than initial reflectance.

Cost Effectiveness

Cost effectiveness can be estimated by quantifying four parameters: annual decrease in cooling electricity consumption, annual increase in heating electricity and/or gas, net present value (NPV) of net energy savings, and the cost premium for a cool roof. Four other parameters can yield cool-roof benefits, but are not included in this determination of cost-effectiveness: peak cooling electricity demand reduction, 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 extended life of roof surface and insulating materials.

This study's simulations of energy savings yielded by an aged, unmaintained cool roof (cool roof $\rho = 0.55$, $\varepsilon = 0.90$; noncool roof $\rho = 0.20$, $\varepsilon = 0.90$) estimate that the 15-year NPV of cool-roof energy savings for a Title-24 prototypical building ranges from \$0.12 to 0.69/ft² (average \$0.48/ft²) with time dependent valuation (TDV), and from \$0.10 to 0.57/ft² (average \$0.40/ft²) without TDV. With or without TDV, savings in all climates except zone 1 exceeded \$0.20/ft². Since the typical cost premium for a cool roof is \$0.00-0.20/ft², cool roofs are expected to be cost effective in climate zones 2 – 16. Cool roofing materials with modest cost premiums (i.e., not exceeding \$0.10/ft²) are expected to be cost effective in climate zone 1.

Analysis Tool

The building energy simulation program DOE-2.1E will be the primary analysis tool to quantify energy savings and peak demand.

The latest version of LBNL's DOE-2.1E is release 114, which adds minor improvements in energy calculation algorithms and can model more complex buildings and systems. DOE-2.1E has multiple merits: it is based on known and published existing algorithms; it has over 20 years of experience and feedback from the simulation community; it can handle many complex zones and systems; and it has been validated for many test cases, lending confidence to its use.

The major disadvantage of DOE-2.1E is that many of its basic algorithms are 20 to 30 years old, and have been surpassed by more accurate modern algorithms. In particular, the radiation exchange algorithms in DOE-2.1E couple the surface temperature to that of the zone air, which makes its estimation of the effect of cool roofs on building energy use too low, particularly for buildings with a plenum space. In a study of school buildings in Sacramento, DOE-2.1E simulations of energy and peak power savings were 37% and 57% below measured values (Akbari, 1993).

Relationship to Other Measures

Cool roofs can reduce need 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. At 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 0.1 – 0.5 W/ft², 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 also reduce the need for plenum ventilation. In many cases, a cool roof can eliminate the need for mechanical attic ventilation.

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Methodology

Overview

The cost effectiveness of cool roofs was estimated by comparing cool-roof cost premiums to cool-roof cost savings. Premiums were based on interviews of manufacturers, contractors, owners, and specifiers, while savings were estimated via computer simulation of building energy use. The DOE-2.1E building energy model was used to estimate for each of California's 16 climate zones the

effects of cool roofs on the use of cooling and heating energy by a prototypical Title-24 compliant building. Simulated savings were then shown to be comparable to savings measured for several buildings retrofitted with cool roofs. Finally, the simulated estimates of savings per 1000 ft² of cool roof area were combined with a profile of California's non-residential new construction (NRNC database) and California Energy Commission projections of annual NRNC square foot additions to predict statewide savings.

Simulated Building Energy Savings

The DOE-2.1E simulations estimated annual cooling and ventilation electricity use (kWh/1000 ft²), annual heating natural gas use (therms/1000 ft²), and peak cooling and ventilation power demand (kW/1000 ft²). Cool-roof-induced annual energy and peak power savings were determined by simulating the building twice: once with a cool roof (aged $\rho = 0.55$, $\varepsilon = 0.90$), and once with a noncool roof (aged $\rho = 0.20$, $\varepsilon = 0.90$). This corresponds to a reflectance difference of $\Delta\rho_0 = 0.35$ with unchanged emittance. Since savings are linearly proportional to the change in roof reflectance (Akbari *et al.*, 1998), savings for some other reflectance difference $\Delta\rho_1$ can be calculated from

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

Each of the five zones in the 4,900 ft² prototype building is served by a packaged rooftop air-conditioner with natural gas heating. The A/C system was modeled with supply air ducts and a return air plenum. The building was assigned the level of roof insulation prescribed by Title-24, which is R-11 in the southern coastal areas (zones 6 through 9: Los Angeles Beach, San Diego, Santa Ana, and Los Angeles City) and R-19 elsewhere. Wall insulation was R-13, which meets or exceeds Title 24 requirements of R-11 to R-13 (Commission, 2001).

Annual source energy savings (source MBTU/1000 ft²) were calculated from annual electricity and natural gas savings using conversion factors of 10.239 source kBTU/kWh (33% combined generation and distribution efficiency) and 100 source kBTU/therm (100% distribution efficiency).

The 15-year net present value (NPV) of savings (\$/1000 ft²) 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 commercial building roof (Table 5, p. 41).

The TDV method assigns 15-year unit values of NPV to electricity (\$/kWh) and natural gas (\$/therm) 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 hours 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/kWh and \$7.30/therm) 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).

Measured Building Energy Savings

Many studies have measured daily A/C energy savings and peak power demand reduction from the use of cool roofs on commercial buildings in several warm-weather climates, including California, Florida, and Texas. Daily energy savings measured after increasing roof reflectance were annualized by multiplying daily savings (kWh/day) by the number of cooling days per year. Energy and peak-demand savings were also lowered to account for reflectance reduction resulting from roof weathering. Degraded annual energy savings (kWh) and peak demand reduction (kW) were normalized per 1000 ft² of roof area for comparison with simulated results (kWh/1000 ft² and kW/1000 ft²). This study uses the measured data as practical evidence that cool roofs provide energy and peak power savings, but relies solely on DOE-2.1E simulation results for the cost-effectiveness analysis.

Projected Statewide Energy Savings

A database of NRNC (RLW, 1999) describes 990 sample California commercial 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. We denote the total case-weighted roof area of daytime-conditioned⁹ 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} .

⁹ The 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/motels, community center, and libraries—are denoted "daytime-conditioned." Seven other types—C&I storage (warehouse), general C&I work (factory), other, religious worship/ auditorium/ convention, unknown, fire/police/ jails, and gymnasium—may be conditioned during the day, but are excluded from the estimated statewide cool-roof area because their cooling loads are incurred primarily in the evenings.

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

Over the period 2001-2010, the Commission predicts annual additions to NR floor area ranging from 154 to 164 Mft², averaging 158 Mft² (Commission, 2000). We assume that 80% of the NRNC would be low-sloped, and that 80% of the low-sloped NRNC would be built with a noncool roof. Hence, the total floor area of cool-roofable, low-sloped, daytime-conditioned NRNC is 80%×80%=64% of 158 Mft², or 101 Mft². This is the state NRNC floor area to which cool-roof savings are applicable, denoted $F_{CA,\text{applicable}}$.

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

Results

Simulated Building Energy Savings

Simulated cool-roof savings by climate zone are detailed in Table 6 (p. 42).

Annual electricity savings ranged from 117 to 438 kWh/1000 ft² (average 316 kWh/1000 ft²) (Figure 2, p. 46).

Annual natural gas deficits ranged from 1.8 to 10.7 therms/1000 ft² (average 5.0 therms/1000 ft²) (Figure 3, p. 46).

Annual source energy savings ranged from 0.13 to 4.3 MBTU/1000 ft² (average 2.7 MBTU/1000 ft²) (Figure 4, p. 47).

Peak power demand savings ranged from 0.15 to 0.27 kW/1000ft² (average 0.21 kW/1000 ft²) (Figure 5, p. 47).

15-year net present value savings ranged from 115 to 694 \$/1000 ft² (average \$484/1000 ft²) with TDV, and from 97 to 572 \$/1000 ft² (average \$396/1000 ft²) without TDV (Figure 6, p. 48).

As shown in Table 6 (p. 42), the greatest annual electricity savings (kWh) were found in the southern inland areas (zones 13, 14, and 15), which are hot; and on the southern coast (zones 6, 8, and 9),

where the prescribed roof insulation level is only R-11. 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).

Using prices of \$0.60/therm and \$0.10/kWh, the value of the annual natural gas penalty was typically small compared to that of the annual electricity savings (3-15% in all zones except 1 and 16, where the ratios were 45% and 26%, respectively). Therefore, geographic trends similar to those observed in the electricity savings were found in the NPV estimates.

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 total energy savings was also greatest in the southern inland and southern coastal climate zones.

Savings in peak power suggest that the air conditioner (and by extension, the air handling unit) can be downsized when the cool-roof strategy is considered. Based on a Seasonal Energy Efficiency Ratio (SEER) of 10, the peak demand savings of 0.15 to 0.27 kW/1000 ft² corresponds to an equipment capacity reduction of 0.6 to 1.1 tons. The cost savings associated with this cooling capacity reduction, about \$300 - 500, is not incorporated in this study's LCC analysis.

Measured Building Energy Savings

Cool roofs typically yielded measured summertime daily A/C savings and peak demand reductions of 10 to 30%, though values have been as low as 2% and as high as 40%. For example:

- Konopacki *et al.* (1998b) measured daily summer A/C savings of 6.3, 3.6, and 0.4 kWh/1000 ft² (18, 13, and 2%) for three California commercial buildings—two medical offices in Davis and Gilroy and a retail store in San Jose. Corresponding demand reductions were 0.31, 0.22, and 0.15 kW/1000 ft² (12, 8, and 9%). Estimated annualized A/C savings were 590, 340, and 60 kWh/1000 ft², assuming an aged solar reflectance of 0.55 (Akbari and Konopacki, 2002).
- Hildebrandt *et al.* (1998) measured daily A/C savings (annual savings / number of cooling days per year) of 2.1, 4.1, and 2.3 kWh/1000 ft² (17, 26, and 39%) in an office, a museum and a hospice in Sacramento. Estimated annualized A/C savings were 120, 240, and 200 kWh/1000 ft², assuming an aged solar reflectance of 0.55 (Akbari and Konopacki, 2002).
- Konopacki and Akbari (2001) estimated daily cooling energy savings of 3.6 kWh/1000 ft² (11%) and peak power reduction of 0.35 kW/1000 ft² (14%) in a large retail store in Austin, TX. Estimated annualized A/C savings were 630 kWh/1000 ft², assuming an aged solar reflectance of 0.55 (Akbari and Konopacki, 2002).

- Parker *et al.* (1998b) measured daily energy savings of 4.1 kWh/1000 ft² (25%) and a peak power reduction of 0.56 kW/1000 ft² (30%) for a school building in Florida. Estimated annualized A/C savings were 440 kWh/1000 ft² assuming an aged solar reflectance of 0.55 (Akbari and Konopacki, 2002).

The California building studies (Konopacki *et al.*, 1998b; Hildebrandt *et al.*, 1998) are detailed in Table 7 (p. 43).

The annualized measured energy savings are within or exceed the range of simulated annual kWh 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 standard operating assumptions;
- actual roof insulation vs. Title 24 prescriptive requirement;
- actual A/C equipment efficiencies vs. current Title 24 prescriptive requirements; and
- actual change in solar reflectance vs. 0.35 increase used in simulations.

Statewide Projected Savings

The database of 990 sample buildings indicates that there are 0.46 Mft² of daytime-conditioned roof area per Mft² of California NRNC floor area (Table 8, p. 44). Using the average Commission estimate of 158 Mft² of CA NRNC, 72 Mft² of statewide daytime-conditioned roof area is added each year to California's NR building stock, of which 46 Mft² is low-sloped and not yet cool. This yields for NRNC statewide

- annual electricity savings of 15.8 GWh;
- annual natural gas deficits of 202 ktherms;
- annual source energy savings of 141 GBTU;
- annual peak power demand savings¹⁰ of 10.0 MW;

¹⁰ "Annual" power savings refer to reductions in the annual need for power plant construction.

- TDV NPV savings of \$24.6M; and
- non-TDV NPV savings of \$20.1M (Table 9, p. 44).

Recommendations

Proposed Standards Language

The proposed standards language modifies solar reflectance and thermal emittance requirements for low-sloped roofs on NR buildings. Requirements for NR buildings with high-sloped roofs, high-rise residential buildings, and guest rooms of hotel/motel buildings are unchanged. Requirements for cool roofing products are revised to qualify low-emittance products that have exceptionally high solar reflectance, and to restrict the qualification of moderate-reflectance clay and concrete tiles to low-rise residential applications.

The proposed standards language prescribes for low-sloped roofs on NR buildings a minimum initial reflectance of 0.70 for roofs that have an initial emittance not less than 0.75. Roofs that have an initial emittance $\epsilon_{\text{initial}}$ less than 0.75 (e.g., those with metallic surfaces) must have a minimum initial solar reflectance of $0.70 + 0.34(0.75 - \epsilon_{\text{initial}})$. The reflectance requirement for low-emittance cool roofs is designed to ensure that the surface temperature of an aged low-emittance cool roof does not exceed that of an aged high-emittance cool roof (see Appendix, p.32).

The proposed language changes the standard and proposed heat gain equations in the overall envelope approach. Standard buildings are to use an initial reflectance of 0.70 for all low-sloped roofs, which is then degraded to 0.55 for aging. The proposed buildings shall use the CRRC-certified values for initial reflectance (or a default value of 0.10 if a CRRC value is unavailable), which is then degraded for aging according to Eq. (1) on p. 10.

The prescriptions for cool roofing products are revised to require the thermal-emittance-dependent minimum initial solar reflectance, and to delete product-specific reflectance and emittance requirements.

California Title 24 AB 970 Energy Efficiency Standards for Residential and Nonresidential Buildings (January 3, 2001)

Proposed additions are underlined and deletions are ~~struck~~.

Section 101 – Definitions And Rules Of Construction

COOL ROOF is a roofing material with ~~high solar reflectance and high emittance~~ high thermal emittance and high solar reflectance, or low thermal emittance and exceptionally high solar reflectance [cf. Section 143 (a)1], that reduces heat gain through the roof.

LOW-SLOPED ROOF is a roof that has a ratio of rise to run not exceeding 2:12.

Section 118 – Mandatory Requirements For Insulation and Cool Roofs

(f) Mandatory Requirements for Cool Roofs. ~~Effective January 1, 2003,~~ a A roof shall be considered a cool roof if the roofing product is certified and labeled according to requirements of Section 10-113 and if the roofing product meets conditions 1 and 2 and, for liquid applied coating products, 3 below. ~~Prior to January 1, 2003, manufacturer’s published performance data shall be acceptable to show compliance with 1 or 2 and, for liquid applied roofing products, 3.~~

~~1. Concrete tile (as defined in ASTM C55-99) and clay tile (as defined in ASTM C1167-96) roofing products shall have a minimum initial total solar reflectance of 0.40 when tested in accordance with ATSM E903 or E1918, and a minimum thermal emittance of 0.75 when tested in accordance with ASTM E408.~~

~~2. All other roofing products shall have a minimum initial total solar reflectance of 0.70 when tested in accordance with ASTM E903 or E1918, and a minimum thermal emittance of 0.75 when tested in accordance with ASTM E408.~~

1. Roofing products that have initial thermal emittance not less than 0.75 when tested in accordance with ASTM E408 shall have a minimum initial solar reflectance of 0.70 when tested in accordance with ASTM E903 or E1918.

Exception to Section 118(f)1: For low-rise residential buildings, concrete tile (as defined in ASTM C55-99) and clay tile (as defined in ASTM C1167-96) roofing products shall have a minimum initial total solar reflectance of 0.40 when tested in accordance with ATSM E903 or E1918, and a minimum thermal emittance of 0.75 when tested in accordance with ASTM E408.

2. Roofing products that have initial thermal emittance $\epsilon_{\text{initial}}$ less than 0.75 when tested in accordance with ASTM E408, including but not limited to roof products with metallic surfaces, must

have a minimum initial solar reflectance of $0.70 + 0.34(0.75 - \epsilon_{\text{initial}})$ when tested in accordance with ASTM E903 or E1918.

3. Liquid applied roofing products shall be applied at a minimum dry mil thickness of 20 mils across the entire roof surface, and meet the minimum performance requirements of ASTM D6083-97 when tested in accordance with ASTM D6083-97 for the following key properties:

- * Initial tensile strength
- * Initial elongation
- * Elongation after 1,000 hours accelerated weathering
- * Permeance
- * Accelerated weathering

Section 143 – Prescriptive Requirements For Building Envelopes

(a) Envelope Component Approach.

1. Exterior roofs and ceilings. Exterior roofs and ceilings shall have either an installed insulation R-value no less than, or an overall assembly U-factor no greater than, the applicable value in Table 1-H or 1-I.

For nonresidential buildings with low-sloped roofs (except high-rise residential buildings and guest rooms of hotel/motel buildings), roofs that have an initial thermal emittance not less than 0.75 shall have a minimum initial solar reflectance of 0.70. Low-sloped exterior roofs that have an initial thermal emittance $\epsilon_{\text{initial}}$ less than 0.75, including but not limited to those with metallic surfaces, shall have a minimum initial solar reflectance of $0.70 + 0.34(0.75 - \epsilon_{\text{initial}})$.

There are no prescriptive solar reflectance or thermal emittance requirements for nonresidential buildings with high-sloped roofs, high-rise residential buildings, or guest rooms of hotel/motel buildings.

(b) Overall Envelope Approach

This method may be used only for roof surfaces with thermal emittance not less than 0.75 (typically non-metallic surfaces). It may not be used for roofs with metallic surfaces, including but not limited to bare metal, galvanized steel, and aluminum coating.

2. Overall heat gain

EQUATION (1-E)—STANDARD BUILDING HEAT GAIN EQUATION

$$\begin{aligned}
 HG_{std} = & \sum_{i=1}^{nW} (A_{Wi} \times U_{Wi_{std}} \times TF_i) \\
 & + \sum_{i=1}^{nF} (A_{Fi} \times U_{Fi_{std}} \times TF_i) \\
 & + \sum_{i=1}^{nR} (A_{Ri} \times U_{Ri_{std}} \times TF_i) \\
 & + \sum_{i=1}^{nG} (A_{Gi} \times U_{Gi_{std}} \times TF_i) \\
 & + \sum_{i=1}^{nS} (A_{Si} \times U_{Si_{std}} \times TF_i) \\
 & + \sum_{i=1}^{nG} (WF_{Gi} \times A_{Gi} \times RSHG_{Gi_{std}}) \times SF \\
 & + \sum_{i=1}^{nS} (WF_{Si} \times A_{Si} \times SHGC_{Si_{std}}) \times SF \\
 & + \sum_{i=1}^{nR} (WF_{Ri} \times A_{Ri} \times U_{Ri_{std}} \times \alpha_{Ri_{std}} \left[1 - (0.2 + 0.7 [\rho_{Ri_{std}} - 0.2]) \right]) \times SF
 \end{aligned}$$

$\alpha_{Ri_{std}}$ = A standard roof absorptivity of 0.70 for the corresponding A_{Ri}

$\rho_{Ri_{std}}$ = For low-sloped roofs on nonresidential buildings (excluding high-rise residential buildings and guest rooms in hotel/motel buildings), a standard initial roof reflectance of 0.70 for the corresponding A_{Ri} ; for other than low-sloped roofs on nonresidential buildings, for high rise residential buildings, and for guest rooms in hotel/motel buildings, a standard roof reflectance of 0.30 for the corresponding A_{Ri} .

EQUATION (1-F)—PROPOSED BUILDING HEAT GAIN EQUATION

$$\begin{aligned}
 HG_{prop} = & \sum_{i=1}^{nW} (A_{Wi} \times U_{Wi_{prop}} \times TF_i) \\
 & + \sum_{i=1}^{nF} (A_{Fi} \times U_{Fi_{prop}} \times TF_i) \\
 & + \sum_{i=1}^{nR} (A_{Ri} \times U_{Ri_{prop}} \times TF_i) \\
 & + \sum_{i=1}^{nG} (A_{Gi} \times U_{Gi_{prop}} \times TF_i) \\
 & + \sum_{i=1}^{nS} (A_{Si} \times U_{Si_{prop}} \times TF_i) \\
 & + \sum_{i=1}^{nG} (WF_{Gi} \times A_{Gi} \times RSHG_{Gi_{prop}}) \times SF \\
 & + \sum_{i=1}^{nS} (WF_{Si} \times A_{Si} \times SHGC_{Si_{prop}}) \times SF \\
 & + \sum_{i=1}^{nR} (WF_{Ri} \times A_{Ri} \times U_{Ri_{prop}} \times \alpha_{Ri_{prop}} \left[1 - (0.2 + 0.7 [\rho_{Ri_{prop}} - 0.2]) \right]) \times SF
 \end{aligned}$$

$\alpha_{Rj_{prop}}$ = The applicable roof absorptivity for the corresponding A_{Rj} . An absorptivity of 0.45 for cool roofs (as defined in Section 118). An absorptivity of 0.7 for all other roofs.

$\rho_{Rj_{prop}}$ = the proposed initial reflectance for the corresponding A_{Rj} . If no CRRC-certified value is available, the proposed reflectance will use the default value of 0.10 for low-sloped roofs on nonresidential buildings (excluding high-rise residential buildings and guest rooms in hotel/motel buildings), or 0.30 for other than low-sloped roofs on nonresidential buildings, for high-rise residential buildings, and for guest rooms in hotel/motel buildings.

Section 149 – Additions, Alterations, And Repairs To Existing Buildings That Will Be Nonresidential, High-Rise Residential, And Motel/Hotel Occupancies

(b) Alterations

1. Prescriptive Approach

A. Alterations to the building envelope shall:

iii. Have, in the case of a roof, a solar reflectance and thermal emittance meeting the requirements of Section 143(a)(1).

Proposed ACM Language

Nonresidential Alternative Calculation Approval Method

2.2.1.4 Absorptance

Modeling Rules for Proposed Design:

~~For roofs, qualifying cool roofs shall model an absorptance of 0.45. All other roofs shall use the default value.~~

For nonresidential buildings with low-sloped roofs, the proposed design must receive user input for initial absorptance (α_{init} ; absorptance = 1 - reflectance). The ACM must calculate the corresponding aged value α_{prop} from the following equation:

$$\alpha_{prop} = 0.8 + 0.7 (\alpha_{init} - 0.8)$$

where α_{init} is the initial absorptance of the product either as rated by the CRRC or one of the defaults specified below.

Cool Roof Value: Roof = 0.45

~~To qualify as a cool roof the roof must meet the requirements of Section 118 of the Standard, which states:~~

~~(a) Effective January 1, 2003, a roof shall be considered a cool roof if the roof is certified and labeled according to requirements of Section 10-113 and if the roof meets conditions (1) or (2) below. Prior to January 1, 2003, manufacturer's published performance data shall be acceptable to show compliance with one of the following conditions.~~

~~(1) Roof of concrete tile (per ASTM C55-99) and clay tile (per ASTM C1167-96) require a minimum initial total solar reflectance of 0.40 when tested in accordance with ASTM E903 or E1918, and a minimum thermal emittance of 0.75 when tested in accordance with ASTM E408.~~

~~(2) All other roofs require a minimum initial total solar reflectance of 0.70 when tested in accordance with ASTM E903 or E1918, and a minimum thermal emittance of 0.75 when tested in accordance with ASTM E408.~~

~~(3) Liquid applied roofing products shall be applied at a minimum dry mil thickness of 20 mils across the entire roof surface, and meet the minimum performance requirements of ASTM D6083-97 when tested in accordance with ASTM D6083-97 for the following key properties:~~

~~Initial Tensile Strength~~

~~Initial Elongation~~

~~Elongation After 1000 Hours Accelerated Weathering~~

~~Permeance~~

~~Accelerated Weathering~~

~~Default~~

~~Roof = 0.70~~

~~Roof: for low-sloped roofs on nonresidential buildings (excluding high-rise residential buildings and guest rooms in hotel/motel buildings), 0.90; for other than low-sloped roofs on nonresidential buildings, for high-rise residential buildings, and for guest rooms in hotel/motel buildings, 0.70~~

~~Cool Roof Caution Warning on PERF-1 if a cool roof credit is claimed.~~

~~Modeling Rules for Reference Design (All):~~

~~For the reference method, the roof absorptance shall be modeled at 0.70.~~

~~For the reference method for nonresidential buildings with low-sloped roofs (excluding high-rise residential buildings and guest rooms in hotel/motel buildings) the roof absorptance (1 -~~

reflectance) shall be modeled at 0.30 (reflectance 0.70). For the reference method for nonresidential buildings with other than low-sloped roofs, for high-rise residential buildings, and for guest rooms in hotel/motel buildings, the roof absorptance shall be modeled at 0.70 (reflectance 0.30).

The ACM must calculate the corresponding aged value α_{ref} from the following equation.

$$\alpha_{ref} = 0.8 + 0.7 (\alpha_{std} - 0.8)$$

where α_{std} is 0.30 for nonresidential buildings with low-sloped roofs or 0.70 for other nonresidential buildings, high-rise residential buildings and guest rooms in hotel/motel buildings

2.2.1.5 Surface ~~Emissivity~~ Thermal Emittance

Description: The ratio of radiation intensity from the construction assembly's opaque exterior surface to the radiation intensity at the same wavelength from a blackbody at the same temperature (hereafter, referred to as "emittance").

Tradeoffs: ~~Neutral~~ Yes

Modeling Rules for Proposed Design:

~~The proposed design shall model a surface emissivity of 0.90.~~

For low-sloped roofs on nonresidential buildings (excluding high-rise residential buildings and guest rooms in hotel/motel buildings), the proposed design must receive user input for initial emittance. If no CRRC-certified value is available, a default value of 0.75 shall be used for non-metallic surfaces, and a default value of 0.20 shall be used for metallic surfaces, including but not limited to bare metal, galvanized steel, and aluminum coating.

For other than low-sloped roofs on nonresidential buildings, for high-rise residential buildings, and for guest rooms in hotel/motel buildings, the proposed design shall model a surface emittance of 0.90.

Modeling Rules for Reference Design (All):

~~The surface emissivity of the reference design shall be the same as the surface emissivity of the proposed design.~~

For low-sloped roofs on nonresidential buildings (excluding high-rise residential buildings and guest rooms in hotel/motel buildings), the reference design shall be modeled at 0.75.

For other than low-sloped roofs on nonresidential buildings and for roofs on high-rise residential buildings and guest rooms in hotel/motel buildings, the surface emittance of the reference design shall be the same as the surface emittance of the proposed design.

The emittance of each other opaque exterior surface shall be the same as that in the proposed design.

4.3.2.6 Absorptance and Emittance

Description: The ACM Compliance Documentation must describe how the user enters the value for the absorptance (1 - reflectance) and the emittance.

ACM Compliance Documentation must explain that the ACM user can specify opaque exterior wall or roof/ceiling construction between 0.90 and 0.20 absorptance (0.10 and 0.80 reflectance), and between 0.95 and 0.20 emittance, and that the program will print an exceptional condition on the PERF-1 whenever the absorptance (1 - reflectance) is less than 0.50 for an opaque exterior partition. The ACM Compliance Documentation must explain what happens if the user does not specify an absorptance. ~~The ACM Compliance documentation must explain to the user how to enter the values of cool roof and must describe the rating methods and installation criteria that are required for cool roofs.~~

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Appendix

Requisite Reflectance Premium For A Low-Emittance Cool Roof

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

Consider a high-emittance (HE) cool roof surface of solar reflectance ρ_{HE} and thermal emittance ϵ_{HE} . Neglecting conduction of heat into the building, the high-emittance roof’s steady-state surface temperature T_{HE} is determined by equating its solar heat gain to its radiative and convective heat losses:

$$(1 - \rho_{HE})I = \epsilon_{HE} \sigma (T_{HE}^4 - T_{sky}^4) + h_c (T_{HE} - T_{air}), \quad (2)$$

where I is insolation [$W m^{-2}$], $\sigma = 5.6685 \times 10^{-8} W m^{-2} K^{-4}$ is 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”): $I = 1000 W m^{-2}$, $h_c = 12 W m^{-2} K^{-1}$, $T_{sky} = 300 K$, and $T_{air} = 310 K$ (ASTM 1998b). This energy balance may be solved numerically to determine the high-emittance cool roof temperature T_{HE} .

We now wish to determine the minimum reflectance ρ_{LE} required of a low-emittance (LE) cool roof (emittance ϵ_{LE}) so that its surface temperature does not exceed that of the high-emittance cool roof; i.e., $T_{LE} \leq T_{HE}$.

The energy balance for the low-emittance roof has the same form as that for the high-emittance roof:

$$(1 - \rho_{LE})I = \epsilon_{LE} \sigma (T_{LE}^4 - T_{sky}^4) + h_c (T_{LE} - T_{air}). \quad (3)$$

Both Eqs. (2) and (3) can be rearranged to relate reflectance to emittance:

$$\rho_{\text{HE}} = \left[1 + h_c (T_{\text{HE}} - T_{\text{air}}) / I\right] - \left[\sigma (T_{\text{HE}}^4 - T_{\text{sky}}^4) / I\right] \varepsilon_{\text{HE}} \quad (4)$$

and

$$\rho_{\text{LE}} = \left[1 + h_c (T_{\text{LE}} - T_{\text{air}}) / I\right] - \left[\sigma (T_{\text{LE}}^4 - T_{\text{sky}}^4) / I\right] \varepsilon_{\text{LE}}. \quad (5)$$

When the LE and HE roofs are at the same temperature T_{cool} (i.e., $T_{\text{LE}} = T_{\text{HE}} = T_{\text{cool}}$), we can subtract Eq. (4) from Eq. (5) to obtain

$$\rho_{\text{LE}} - \rho_{\text{HE}} = \left[\sigma (T_{\text{cool}}^4 - T_{\text{sky}}^4) / I\right] \times (\varepsilon_{\text{HE}} - \varepsilon_{\text{LE}}). \quad (6)$$

Thus, if a low-emittance roof is to stay as cool as a high-emittance roof ($T_{\text{LE}} = T_{\text{HE}} = T_{\text{cool}}$), the reflectance premium $\Delta\rho \equiv \rho_{\text{LE}} - \rho_{\text{HE}}$ required to compensate for the emittance deficit $\Delta\varepsilon \equiv \varepsilon_{\text{HE}} - \varepsilon_{\text{LE}}$ is

$$\Delta\rho = f(T_{\text{cool}}) \times \Delta\varepsilon \quad (7)$$

where

$$f(T_{\text{cool}}) = \sigma (T_{\text{cool}}^4 - T_{\text{sky}}^4) / I. \quad (8)$$

If the reflectance premium exceeds that specified by Eq. (7), the low-emittance roof will be even cooler than the high-emittance roof.

Since roof reflectance typically changes with age (see p. 9), 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 $\Delta\rho_{\text{aged}}$ based on the surface temperature of the aged HE cool roof, $T_{\text{cool,aged}}$. Then, we determine the necessary initial reflectance premium, $\Delta\rho_{\text{initial}}$, based on the aged reflectance premium.

Equation (1) on p. 10 postulates that the relationship between initial and aged roof reflectance is $\rho_{\text{aged}} = \rho_0 + c(\rho_{\text{initial}} - \rho_0)$, where constants $\rho_0 = 0.2$ and $c = 0.7$. Thus

$$\rho_{\text{aged,HE}} = \rho_0 + c(\rho_{\text{initial,HE}} - \rho_0). \quad (9)$$

We will assume that aging does not change emittance.¹¹ We can rearrange Eq. (1) to relate initial reflectance to aged reflectance:

$$\rho_{\text{initial}} = \frac{\rho_{\text{aged}} + (c-1)\rho_0}{c}. \quad (10)$$

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

$$\Delta\rho_{\text{initial}} = \frac{\Delta\rho_{\text{aged}}}{c}. \quad (11)$$

Thus, the premium in initial solar reflectance required to ensure that an aged LE roof stays as cool as an aged HE roof is

$$\Delta\rho_{\text{initial}} = \frac{1}{c} \times f(T_{\text{cool,aged}}) \times \Delta\varepsilon_{\text{aged}}. \quad (12)$$

Example 1: Unaged Cool Roof

Consider an unaged high-emittance cool roof with solar reflectance $\rho_{\text{HE}}=0.70$ and thermal emittance $\varepsilon_{\text{HE}}=0.75$. Its surface temperature will be $T_{\text{cool}}=324.4$ K (124.3 °F), yielding $f(T_{\text{cool}})=0.169$. The surface temperature of an unaged low-emittance cool roof will not exceed that of the unaged high-emittance cool roof so long as

$$\Delta\rho \geq 0.169 \times \Delta\varepsilon. \quad (13)$$

Thus, the minimum solar reflectance required for an unaged low-emittance cool roof is

$$\rho_{\text{LE}} \geq \rho_{\text{HE}} + f(T_{\text{cool}}) \times (\varepsilon_{\text{HE}} - \varepsilon_{\text{LE}}) = 0.70 + 0.169 \times (0.75 - \varepsilon_{\text{LE}}). \quad (14)$$

An unaged roof with a 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 an unaged zero-emittance cool roof would be 0.83.

¹¹ This assumption is not strictly true, but is used for a lack of data on the on the variation of roof emittance with age.

Example 2: Aged Cool Roof

Consider a high-emittance cool roof with initial solar reflectance of $\rho_{HE,initial} = 0.70$ and initial thermal emittance of $\epsilon_{HE,initial} = 0.75$. We calculate its aged reflectance from Eq. (1) as $\rho_{HE,aged} = 0.55$. The surface temperature of the aged high-emittance roof will be $T_{cool,aged} = 346.4$ K (139.4 °F), yielding $f(T_{cool,aged}) = 0.236$. The surface temperature of an aged low-emittance cool roof will not exceed that of the aged high-emittance cool roof so long as the low-emittance cool roof has a minimum initial reflectance premium of

$$\Delta\rho_{initial} = \frac{1}{c} \times f(T_{cool,aged}) \times \Delta\epsilon_{aged} = \frac{10}{7} \times 0.236 \times \Delta\epsilon_{aged} = 0.339 \times \Delta\epsilon_{aged}. \quad (15)$$

Thus, the minimum solar reflectance required for a low-emittance cool roof is

$$\rho_{LE,initial} = \rho_{HE,initial} + \frac{1}{c} \times f(T_{cool,aged}) \times \Delta\epsilon_{aged} = 0.70 + 0.339 \times (0.75 - \epsilon_{LE,initial}). \quad (16)$$

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

A roof with a 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.

We use Eq. (16) in the prescriptive requirement for low-emittance cool roof to ensure that the surface temperature of an aged low-emittance cool roof does not exceed that of an aged high-emittance cool roof.

Table 1. Cool and noncool options for low-sloped roofs. Shown are ranges of typical values for initial solar reflectance, initial thermal emittance, and cost.

Noncool Roof Options				Cool Roof Options			
Roof Type	Reflectance	Emittance	Cost (\$/ft ²)	Roof Type	Reflectance	Emittance	Cost (\$/ft ²)
Built-up Roof			1.2 – 2.1	Built-up Roof			1.2 – 2.15
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 smooth surface	0.50 – 0.70	0.80 – 0.90	
with aluminum coating	0.25 – 0.60	0.20 – 0.50		with white roof coating	0.75 – 0.85	0.85 – 0.95	
Single-Ply Membrane			1.0 – 2.0	Single-Ply Membrane			1.0 – 2.05
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			1.5 – 1.9	Modified Bitumen			1.5 – 1.95
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			1.8 – 3.7	Metal Roof			1.8 – 3.75
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			1.1 – 1.4	Asphalt Shingle			1.2 – 1.5
black	0.04 – 0.05	0.80 – 0.90		white	0.25 – 0.27	0.80 – 0.90	
brown	0.05 – 0.09	0.80 – 0.90					
Liquid Applied Coating			0.5 – 0.7	Liquid Applied Coating			0.6 – 0.8
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			3 – 4	Concrete Tile			3 – 4
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			3 – 4	Clay Tile			3 – 4
red	0.20 – 0.22	0.85 – 0.90					
Cement Tile			3 – 4	Cement Tile			3 – 4
unpainted	0.18 – 0.22	0.85 – 0.90		white	0.70 – 0.75	0.85 – 0.90	

Table 2. Commercial-building low-sloped roofing technologies and their market shares in three Pacific Region states (NRCA 2000) and 14 Western Region states (Western Roofing, 2001).

Technology	Description	Cost ^a (\$/ft 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. (Bitumen is a tarlike hydrocarbon mixture often including nonmetallic hydrocarbon derivatives; it may be obtained naturally or from the residue of heat-refining natural substances such as petroleum.) Built-up roof membranes are typically surfaced with roof aggregate and bitumen, a liquid-applied coating, or a granule-surfaced cap sheet.	1.7	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.	1.7	10%	15%	30%	26%
Examples	Styrene-butadiene styrene (SBS) is an elastomeric modifier containing high molecular weight polymers with both thermoset and thermoplastic properties. It is formed by the block copolymerization of styrene and butadiene monomers. These polymers are used as modifying compound in SBS polymer modified asphalt-roofing membranes to impart rubber-like qualities to the asphalt. Atactic polypropylene (APP) is a thermoplastic modifier containing a group of high molecular weight polymers formed by the polymerization of propylene. Used in modified bitumen as a plastic additive to permit heat fusing (torching).		7.5%	6.2%	13%	
			2.8%	8.4%	17%	
Single-Ply Membrane	A roofing membrane that is field applied using just 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.	1.5	18%	16%	23%	22%
Examples	Ethylene-propylene-diene monomer (EPDM) is the ASTM-designated name for an elastomeric single-ply roofing membrane containing a terpolymer of ethylene, propylene, and diene. EPDM is a thermosetting synthetic elastomer—that is, a macromolecular material that returns to its approximate initial dimensions and shape after substantial deformation by a weak stress and the subsequent release of that stress. Polyvinyl chloride (PVC) is a synthetic thermoplastic polymer prepared from vinyl chloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers. Flexible forms are used in the manufacture of sheeting and roof membrane materials.		1.2%	0.4%	9.0%	
			6.0	5.4%	6.3%	

Technology	Description	Cost ^a (\$/ft ²)	PACIFIC ^b		WESTERN ^c	
			New Sales	Retrofit Sales	Sales	Area ^d
	<p>Thermoplastic olefin (TPO) is a blend of polypropylene and ethylene-propylene polymers. Colorants, flame-retardants, UV absorber, and other proprietary substances may be blended with TPO to achieve the desired physical properties. The membrane may or may not be reinforced.</p> <p>Chlorosulfonated polyethylene (CSPE) is a synthetic, rubber-like thermoset material, based on high molecular weight polyethylene with sulphonyl chloride, that is usually formulated to produce a self-vulcanizing membrane. It is best known by the DuPont trade name HypalonTM.</p>		5.6%	5.1%	6.3%	
Metal	<p>Metal roofs can be classified as <i>architectural</i> or <i>structural</i>.</p>	2.7	2.2%	1.7%	5.2%	2.8%
Examples	<p>Architectural (hydrokinetic-watershedding) standing-seam roof systems are typically used on steep slopes with relatively short panel lengths. They usually do not have sealant in the seam because they are designed to shed water rapidly. They do not provide structural capacity or load resistance, and their installation is less labor-intensive because they have a solid substrate platform that makes installation easier.</p> <p>Structural (hydrostatic-watershedding) standing-seam roof systems are versatile metal panel systems that can be used on both steep- and low-slope roofs and are designed to be water-resistant. Most structural standing-seam systems include a factory-applied sealant in the standing seams to help ensure water tightness. These panel systems provide structural capacity and load resistance.</p>		1.6%	1.2%	2.8%	
			0.6%	0.5%	2.4%	
Asphalt Shingle	<p>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. Asphalt shingles come in various colors</p>	1.3	5.8%	2.5%	3.6%	4.2%
Examples	<p>Fiberglass shingles, commonly known as "asphalt shingles," consist of fiber mats that are coated with asphalt and then covered with granules. Granules, a.k.a. mineral granules or ceramic granules, are opaque, naturally or synthetically colored aggregates commonly used to surface cap sheets and shingles.</p> <p>Organic shingles have a thick cellulose base that is saturated in soft asphalt. This saturation makes them heavier than fiberglass shingles, and less resistant to heat and humidity, but more durable in freezing conditions.</p>		5.8%	2.4%	3.6%	
			-	0.1%	n/a	
Tile	<p>Usually made of concrete or clay, tile is a combination of sand, cement, and water; the water fraction depends on the manufacturing process. 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.</p>	3.5	2.5%	3.9%	0.3%	0.1%
Polyurethane Foam (SPF)	<p>A foamed plastic material, formed by spraying two components (Polymeric Methelene Diisocyanate [PMDI] and a resin) to form a rigid, fully adhered, water-resistant, and insulating membrane.</p>	0.7	0.4%	6.3%	2.5%	5.2%
Liquid Applied Coatings	<p>These are used as a surfacing on roofs of various types, especially built-up and metal roofs. They are available in different colors, and may be divided on the basis of reflectivity into black, aluminum, white, and tinted coatings.</p>	0.4	3.2%	3.3%	2.5%	9.2%

Technology	Description	Cost ^a (\$/ft ²)	PACIFIC ^b		WESTERN ^c	
			New Sales	Retrofit Sales	Sales	Area ^d
Other	All other roofing materials that are not covered under the categories mentioned above.	1			2.1%	3.1%

a. LBNL estimates of the typical material and labor costs are approximate.

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 their 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 3. Leading roofing product manufacturers (The Freedonia Group, 1997; Builder, 1995).

Company	Market Share	Leader In	Product Mix	Sales
Owens Corning	8%	asphalt-based roofing	multi-product building materials	local dealer/distributor and factory-direct
GAF Materials Corporation	7%	asphalt-based roofing	multi-product building materials	no information
France-based Saint-Gobain (via CertainTeed)	6%	asphalt-based roofing	multi-product building materials	local dealer/distributor
Jim Walter (via Celotex)	3-4%	asphalt-based roofing, coatings	multi-product building materials	local dealer/distributor
GS Roofing Products	3-4%	asphalt-based roofing	specialty	local dealer/distributor
Johns Manville	3-4%	asphalt-based roofing	multi-product building materials	local dealer/distributor and factory-direct
Carlisle Companies (via Carlisle SynTec)	3-4%	elastomeric roofing	multi-line rubber products; metal roofing	no information
Japan-based Bridgestone (via Firestone Building Products)	3-4%	elastomeric roofing	multi-line rubber products; building materials	no information
Tamko Roofing Products	<3%	asphalt-based roofing	specialty	local dealer/distributor
United Dominion Industries (via AEP Span and Varco-Pruden Buildings)	<3%	metal roofing	specialty pre-engineered buildings	no information
Gulf States Manufacturers	<3%	metal roofing	specialty pre-engineered buildings	no information
NCI Building Systems	<3%	metal roofing	specialty pre-engineered buildings	no information
Australia-based Boral (via US Tile and Lifetile)	<3%	tile	no information	local dealer/distributor
Clarke Group of Canada	<3%	cedar shingles and shakes; fiber cement roofing	no information	no information
Elcor (via Elk)	<3%	asphalt shingles	no information	local dealer/distributor
GenCorp	<3%	thermoplastic and rubber membrane roofing	no information	no information
Hood Companies	<3%	asphalt shingles and roll roofing	no information	no information
Redland of the UK (via Monier Roof Tile)	<3%	tile	no information	local dealer/distributor
Tremco	<3%	built-up and membrane roofing	no information	no information

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

Roofing Product	Cool Variety	Cost Premium (\$/ft ²)
ballasted BUR	use white gravel	up to 0.05
BUR with smooth asphalt coating	use cementitious or other white coatings	0.10 to 0.20
BUR with aluminum coating	use cementitious or other white coatings	0.10 to 0.20
single-ply membrane (EPDM, TPO, CSPE, PVC)	choose a white color	0.00 to 0.05
modified bitumen (SBS, APP)	use a white coating over the mineral surface	up to 0.05
metal roofing (both painted and unpainted)	use a white or cool color paint	0.00 to 0.05
roof coatings (dark color, asphalt base)	use a white or cool color coating	0.00 to 0.10
concrete tile	use a white or cool color	0.00 to 0.05
cement tile (unpainted)	use a white or cool color	0.05
red clay tile	use cool red tiles	0.10

Table 5. Life expectancies of roof materials (NRCA, 1998; Lufkin and Pepitone, 1997).

Roofing material	Life expectancy (yr)
wood shingles and shakes	15 to 30
tile ^a	50
slate ^b	50 to 100
sheet metal ^c	20 to 50+
BUR/asphalt ^d	12 to 25
BUR/coat and tar ^d	12 to 30
single-ply modified bitumen	10 to 20
single-ply thermoplastic	10 to 20
single-ply thermoset	10 to 20
asphalt shingle	15 to 30
asphalt overlay	25 to 35

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

b. Depends on grade.

c. Depends on gauge of metal, quality of coating, thoroughness of design and application.

d. Depends on materials and drainage; coatings will add to life span.

Table 6. Simulated Title-24 cool roof annual energy, peak demand, and net present value (NPV) dollar savings for a Title-24 prototypical building in 16 California climate zones, with and without time dependent valuation (TDV). Savings are presented for the prescribed level of roof insulation and are normalized per 1000 ft² of air-conditioned roof area.

climate zone	roof R-value	annual energy			peak kW/ 1000 ft ²	TDV NPV			non-TDV NPV		
		kWh/ 1000 ft ²	therms/ 1000 ft ²	source MBTU/ 1000 ft ²		\$(kWh)/ 1000 ft ²	\$(therms)/ 1000 ft ²	\$(total)/ 1000 ft ²	\$ [kWh]/ 1000 ft ²	\$ [therms]/ 1000 ft ²	\$ [total]/ 1000 ft ²
1	19	117	-8.8	0.33	0.15	190	-75	115	161	-64	97
2	19	319	-6.1	2.65	0.22	536	-53	482	436	-45	392
3	19	196	-4.8	1.53	0.17	356	-43	313	269	-35	233
4	19	256	-4.5	2.18	0.19	439	-39	401	351	-33	319
5	19	198	-4.8	1.54	0.18	354	-43	312	271	-35	236
6	11	412	-4.1	3.81	0.25	677	-36	641	565	-30	535
7	11	331	-2.6	3.12	0.27	551	-25	527	453	-19	434
8	11	438	-3.9	4.09	0.27	729	-35	694	601	-29	572
9	11	426	-4.5	3.92	0.22	697	-40	656	584	-33	551
10	19	366	-3.7	3.38	0.19	599	-32	568	501	-27	474
11	19	287	-5.0	2.44	0.17	488	-44	445	393	-36	357
12	19	302	-5.3	2.56	0.21	514	-47	466	414	-39	375
13	19	375	-5.3	3.32	0.21	635	-46	590	514	-38	476
14	19	374	-4.6	3.36	0.23	613	-41	571	512	-34	478
15	19	409	-1.8	4.00	0.18	645	-16	629	560	-13	546
16	19	246	-10.7	1.45	0.20	427	-94	333	337	-78	259
min		117	-10.7	0.13	0.15	190	-94	115	161	-78	97
max		438	-1.8	4.30	0.27	729	-16	694	601	-13	572
avg		316	-5.0	2.73	0.21	528	-44	484	433	-37	396

Table 7. Measured energy savings in six California commercial buildings.

	Davis medical office	Gilroy medical office	San Jose retail	Sacramento office	Sacramento museum	Sacramento hospice
Roof						
Area (1000 ft ²)	31.7	23.8	32.9	24.6	4.9	6.0
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	R-8 rigid	R-19 fiberglass	radiant barrier	R-19	none	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	none	R-4.6	R-2	NONE	R-4.6	R-2
Location	conditioned space	plenum	plenum	conditioned space	plenum	plenum
Results						
Measured Daily A/C Energy Savings (kWh/1000 ft ² /day)	6.3	3.6	0.4	2.1	4.1	2.3
Cooling Days/Year	110	110	165	165	165	165
Degraded Annual A/C Energy Savings (kWh/1000 ft ² /yr)	590	340	60	120	240	200
Degraded Peak Demand Reduction (kW/1000 ft ²)	0.31	0.22	0.15	N/A	N/A	N/A

Table 8. Daytime-conditioned non-residential (NR) roof area; and simulated cool-roof annual energy, peak demand, and net present value (NPV) savings, with and without time dependent valuation (TDV); shown in of California’s 16 climate zones, and totaled statewide. All values are normalized per applicable Mft² (Mft²_{app}) of NR new construction in California, where applicable means low-sloped and noncool-roofed. (See page 14 for derivation of applicable area.)

Climate Zone	Mft ² daytime-conditioned roof area/ Mft ² _{app}	annual energy			peak	TDV NPV	non-TDV NPV
		MWh/ Mft ² _{app}	k therm/ Mft ² _{app}	source MBTU/ Mft ² _{app}	kW/ Mft ² _{app}	k\$/ Mft ² _{app}	k\$/ Mft ² _{app}
1	0.001	0.1	-0.01	0.3	0.1	0.1	0.1
2	0.019	6.2	-0.1	51.5	4.3	9.4	7.6
3	0.041	8.1	-0.2	63.1	6.9	13.0	9.7
4	0.051	13.1	-0.2	111.0	9.8	20.4	16.2
5	0.006	1.1	-0.03	8.8	1.0	1.8	1.3
6	0.061	25.2	-0.3	233.0	15.0	39.2	32.7
7	0.036	11.9	-0.1	112.0	9.7	18.9	15.6
8	0.041	17.8	-0.2	166.2	11.0	28.2	23.2
9	0.041	17.3	-0.2	159.3	8.9	26.7	22.4
10	0.046	16.9	-0.2	155.7	8.9	26.2	21.9
11	0.010	2.8	-0.05	23.5	1.6	4.3	3.4
12	0.057	17.2	-0.3	145.8	12.0	26.6	21.4
13	0.019	7.2	-0.1	63.5	4.0	11.3	9.1
14	0.017	6.3	-0.1	56.8	3.8	9.7	8.1
15	0.010	4.1	-0.02	40.4	1.8	6.4	5.5
16	0.001	0.2	-0.01	1.3	0.2	0.3	0.2
total	0.457	155	-2.0	1392	99	242	198

Table 9. Typical Commission-projected statewide annual non-residential new construction (NRNC) floor area; estimated statewide annual daytime-conditioned NRNC roof area; and simulated statewide cool-roof annual energy, peak demand, and net present value (NPV) savings, with and without time dependent valuation (TDV). Estimates are shown for all non-residential new-construction (NRNC), and for the subset of NRNC to which cool-roof savings are applicable (low-sloped buildings with noncool roofs).

	Mft ² floor area	Mft ² daytime conditioned roof area	annual energy			peak	TDV NPV	non-TDV NPV
			GWh	Mtherm	source GBTU	MW	M\$	M\$
All NRNC	158	72	24.6	-0.31	220	15.7	38.4	31.4
Applicable NRNC	101	46	15.8	-0.20	141	10.0	24.6	20.1

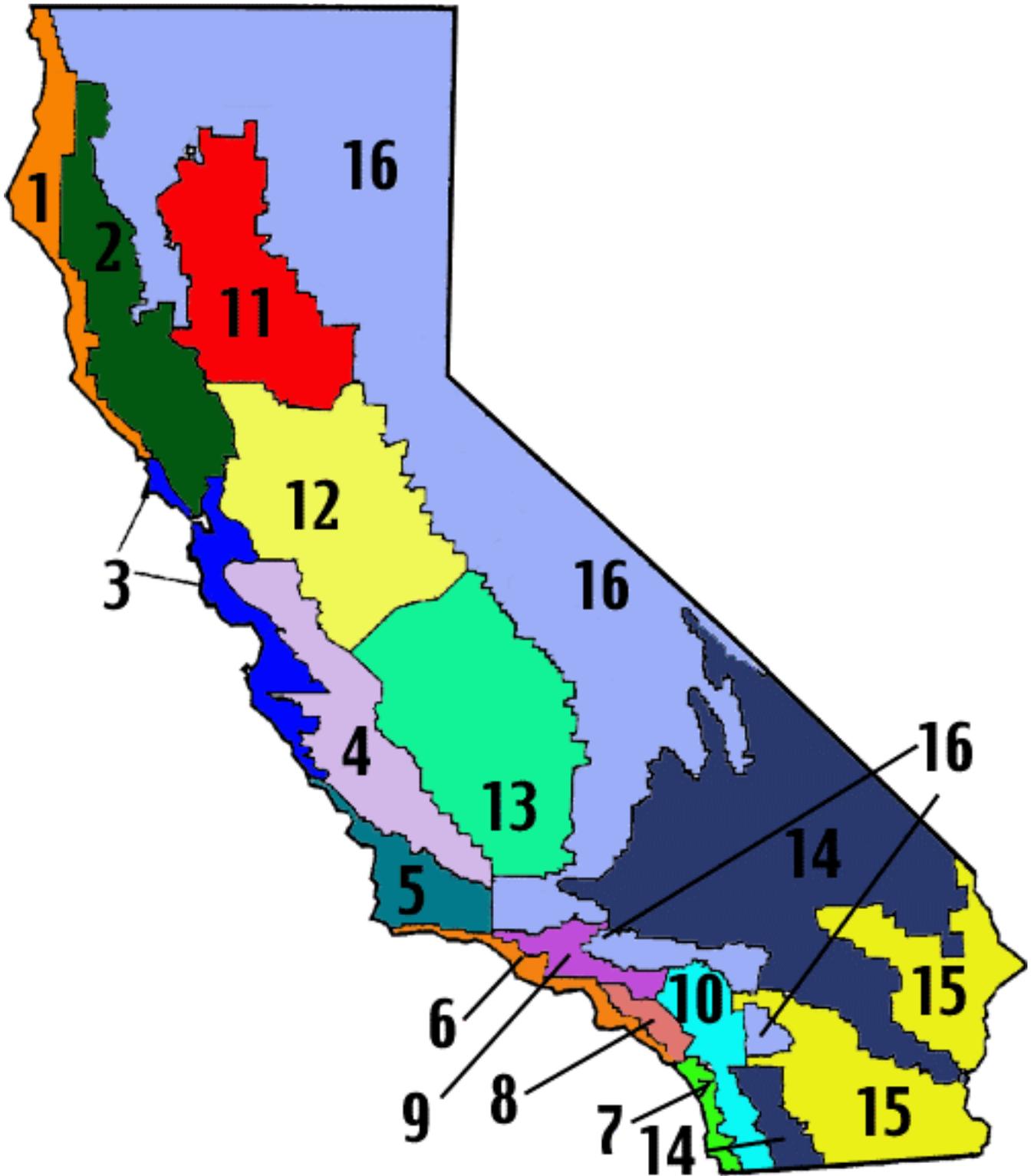


Figure 1. California's 16 climate zones.

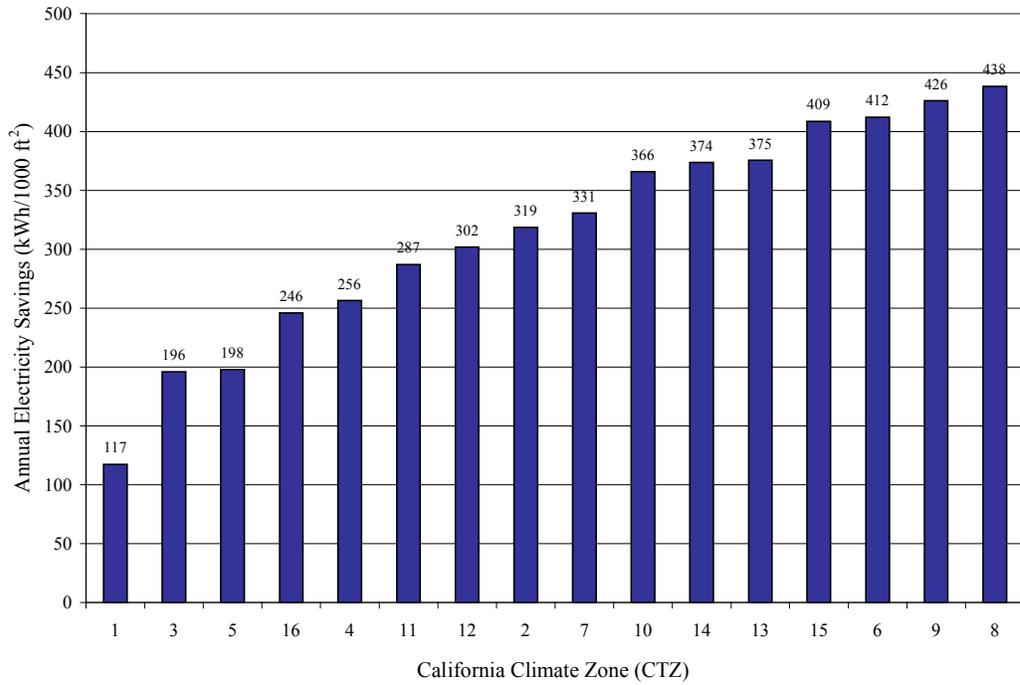


Figure 2. Annual electricity savings (kWh/1000 ft²) versus California climate zone, simulated for a prototypical Title-24 building with a cool roof.

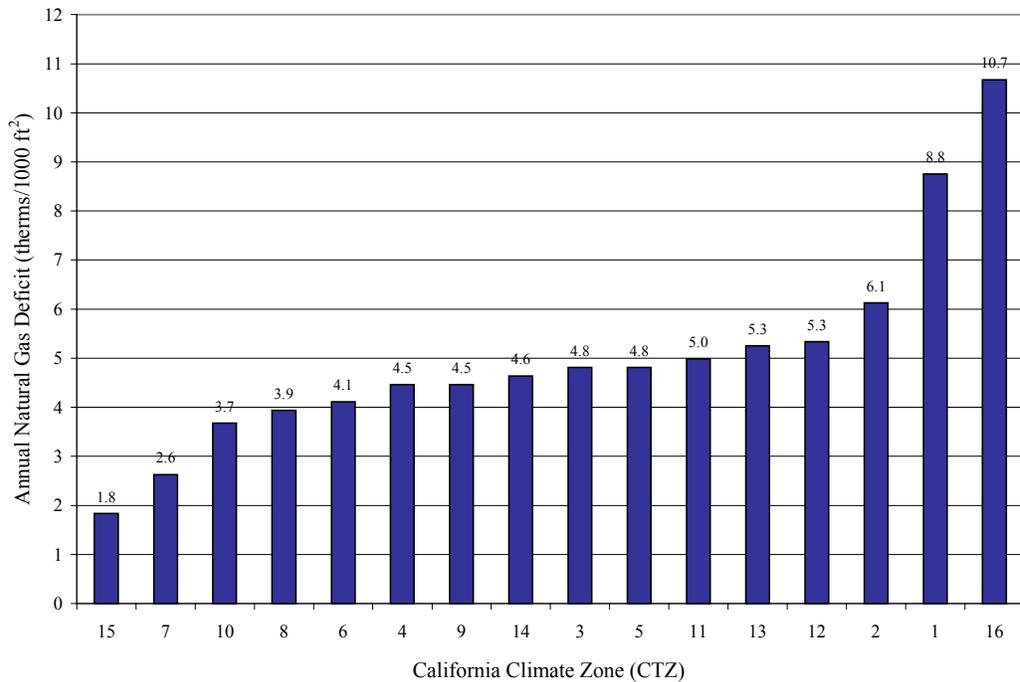


Figure 3. Annual natural gas deficit (therms/1000 ft²) versus California climate zone, simulated for a prototypical Title-24 building with a cool roof.

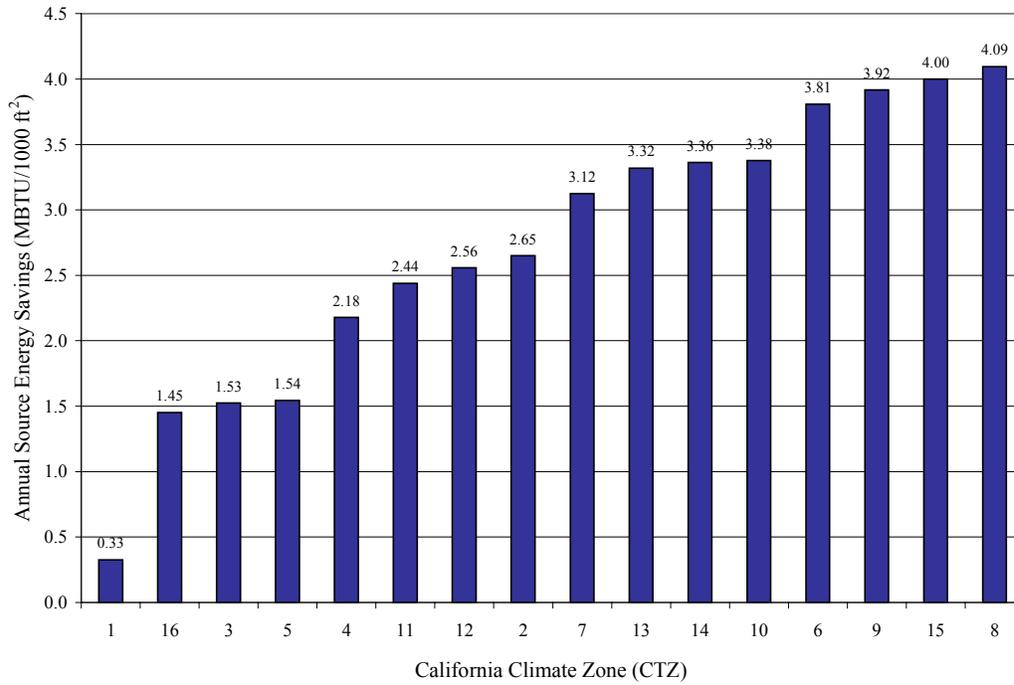


Figure 4. Annual source energy savings (MBTU/1000 ft²) versus California climate zone, simulated for a prototypical Title-24 building with a cool roof.

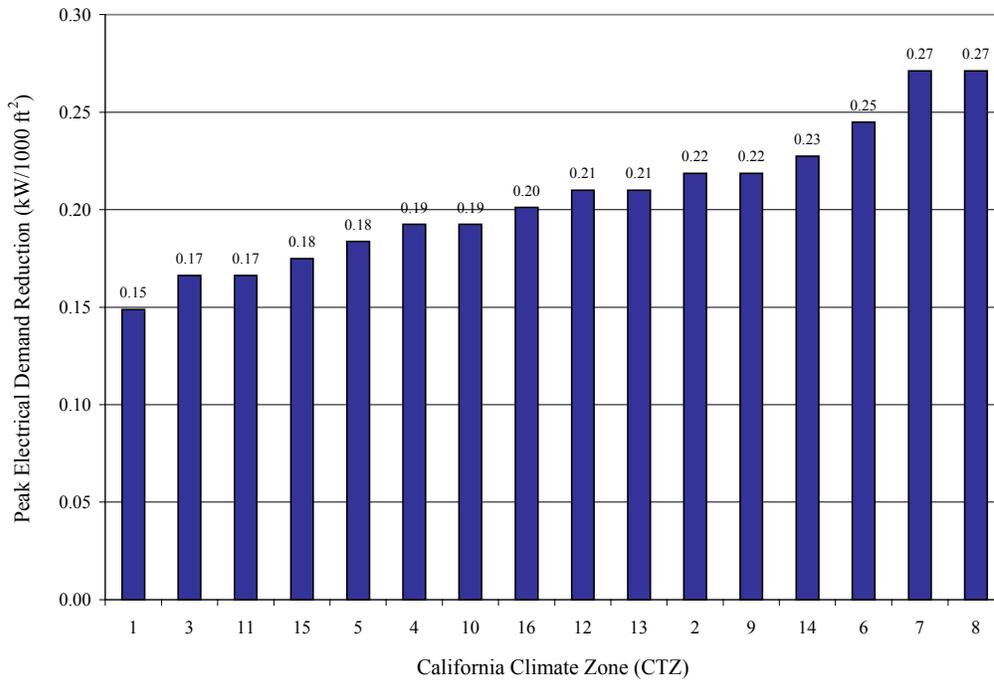


Figure 5. Annual peak electric demand reduction (kW/1000 ft²) versus California climate zone, simulated for a prototypical Title-24 building with a cool roof.

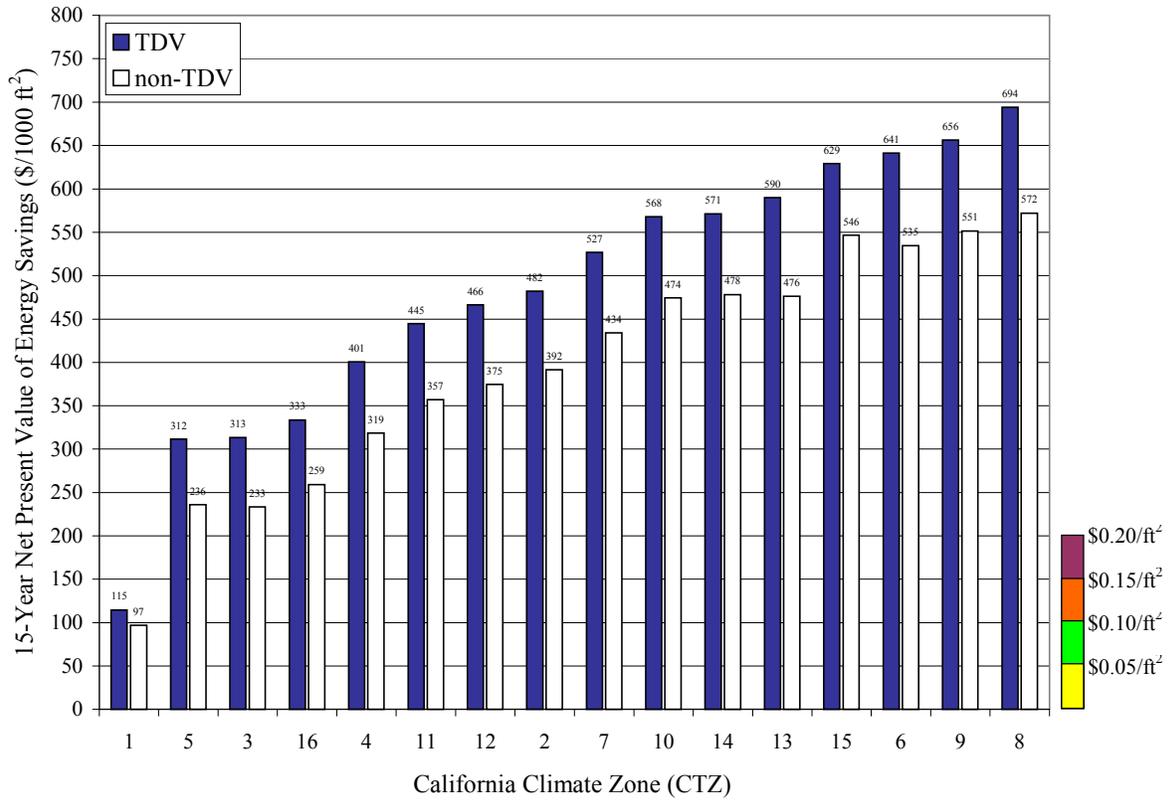


Figure 6. 15-year net present value (NPV) of energy savings (\$/1000 ft²) versus California climate zone, simulated for a prototypical Title-24 building with a cool roof. NPV is shown with and without time dependent valuation (TDV).