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4. Reduce heat loads to people and indoor environments

4.2. Cool envelope materials

Technology Group A.2

Maria Kolokotroni, Brunel University London
Ronnen Levinson, Lawrence Berkeley National Laboratory
Ardeshir Mahdavi, TU Wien
Agnese Salvati, Brunel University London
Helene Teufl, TU Wien
Michele Zinzi, Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA)

4.2.1. Physical principle(s)

4.2.1.1. Definition of a cool envelope material

The following discussion assumes that the solar (“shortwave”) spectrum is 0.3 - 2.5 μm [1], the ultraviolet (UV) spectrum is 0.3 - 0.4 μm, the visible spectrum is 0.4 - 0.7 μm[1], the near-infrared (NIR) spectrum is 0.7 - 2.5 μm, and the thermal-infrared (TIR, or “longwave”) spectrum is 4 - 80 μm.

Cool roofs and walls reduce radiative heat gain at the building’s opaque envelope to decrease heat flow into the conditioned space [5–9].

We define a cool envelope material (CEM) as a solar-opaque surface whose net radiative heat gain, equal to [absorbed solar radiation - emitted shortwave radiation (fluorescence)] + [absorbed TIR radiation - emitted TIR radiation], is lower than that of a traditional envelope material. Other strategies for reducing heat gain at or through the building envelope, such as solar-control glazing, evaporative cooling, ventilation, or insulation, lie outside the scope of cool envelope materials.

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[1] Some standards specify the visible spectrum as 0.38 – 0.78 μm [2–4], but we use the simpler range 0.4 – 0.7 μm because the human eye has limited response outside this band [1,2].

4.2.1.2. Key radiative properties

The surface's solar absorptance (fraction of incident solar radiation absorbed; scale 0-1) is typically calculated by subtracting its solar reflectance (SR, or fraction of incident solar radiation reflected, or "albedo"; scale 0-1) from unity. Its absorption and emission of TIR radiation are each proportional to its thermal emittance[2] (TE, or ratio of TIR radiative flux emitted by the surface to that emitted by a black body at the same temperature; scale 0-1). If the material fluoresces (quickly emits at a longer wavelength light absorbed at a shorter wavelength), the fraction of incident solar radiation so emitted is its fluorescence benefit (scale 0-1), and its ability to reject incident solar radiation is gauged by its effective solar reflectance (ESR, or solar reflectance + fluorescence benefit; scale 0-1) [10–12].

If an envelope product transmits sunlight its radiative properties must be evaluated over the solar-opaque substrate to which it will be applied. For example, since a thin layer of white exterior wall paint may transmit a substantial portion of incident NIR radiation, its radiative properties should be measured over a representative wall substrate.

Solar reflectance can vary with the geometry and spectral power distribution of incident sunlight. The geometric dependence is usually addressed by approximating surface reflection as Lambertian (fully diffuse, and thus independent of incidence angle), specular (fully mirrorlike), or glossy (specular at the air-surface interface and Lambertian below this interface). The spectral dependence can be addressed by measuring solar spectral reflectance (variation of reflectance with wavelength over the solar spectrum) and calculating solar reflectance as the average of solar spectral reflectance weighted with a representative solar spectral irradiance [4,13]. The solar reflectance of a horizontal or near-horizontal surface, such as a low-slope roof, can also be measured directly under certain solar and sky conditions [14]. We are usually most interested in the global (a.k.a. hemispherical) solar reflectance, or fraction of all incident sunlight that is reflected into the hemisphere facing the surface.

Thermal emittance can vary with the angle of emission or absorption, and with surface temperature (though it is usually evaluated near 300 K). TIR radiative exchange between an envelope material and its environment is typically assessed from the material's hemispherical thermal emittance [Appendix X.1 of 15].

Outer space is colder than the Earth's atmosphere. Therefore, under a clear sky high emittance in the atmospheric window (the 8 – 13 μm band in which the atmosphere is highly transmissive) coupled with low emittance in the rest of the TIR spectrum (4 – 8 μm and 13 – 80 μm) may yield more net longwave radiative heat transfer from a low-slope roof to its environment (TIR emission – TIR absorption) than achievable with uniformly high TIR emittance [16,17].

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[2] The synonym "thermal emissivity" is also used.

Solar reflectance and thermal emittance can be combined to compute solar reflectance index (SRI). SRI gauges “coolness” by comparing the temperature of a horizontal, adiabatic test surface on a reference sunny summer afternoon to that of a reference black surface (SRI 0) and to that of a reference white surface (SRI 100) [18]. SRI can be lower than 0 if the surface is exceptionally hot or exceed 100 if the surface is exceptionally cool (Table 4-1). SRI is calculated rather than measured and characterizes only quasi-adiabatic (well-insulated) roofs. It does not apply to walls because it assumes radiative and convective boundary conditions typical of horizontal, rather than vertical, surfaces.

Table 4-1 Examples of roofing products sorted by solar reflectance index (SRI). Parenthetical codes identify each product in the Rated Products Directory of the Cool Roof Rating Council (CRRC) [19]

Product (CRRC Product ID)	Initial Solar Reflectance	Initial Thermal Emittance	Initial SRI
Black Asphaltic Membrane (0616-0018)	0.03	0.93	-1
Black EPDM (1090-0002)	0.12	0.87	7
Concrete Tile (Grey) (0942-0086)	0.11	0.92	9
Clay Tile (Red) (0942-0179)	0.25	0.86	24
Shasta White Asphalt Shingle (0890-0002)	0.26	0.90	27
White Painted Metal Roof (0810-0040-008)	0.55	0.83	63
White EPDM (0738-0008)	0.76	0.90	94
White PVC (1032-0010)	0.86	0.86	108

The surface temperature of a cool envelope material depends more on its solar reflectance than on its thermal emittance. For example, on a sunny summer afternoon the temperature of a well-insulated horizontal roof surfaced with non-metallic, light-colored material (solar reflectance 0.60, thermal emittance 0.90) is about five times more sensitive to change in solar reflectance than to the same change in thermal emittance [Appendix A of 20].

The sensitivity of the envelope’s surface temperature to its thermal emittance also depends on the difference between the envelope’s surface temperature and that of its radiative exchange surface.[3] Therefore the effect on envelope temperature of changing the thermal emittance of a vertical wall that sees both ground and sky (or ground, sky, and neighbouring buildings) will typically be less than that of modifying the emittance of a horizontal roof that sees only the sky.

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[3] Strictly speaking, the longwave radiative heat exchange between two surfaces depends on the difference between the fourth powers of their absolute temperatures, but it is usually reasonable to treat the heat transfer as proportional to the simple temperature difference.

Natural exposure (weathering and soiling) tends to change the solar reflectance and thermal emittance of a building envelope surface over time. Since most changes to these properties take place within the first year or two of exposure, and the service life or a roof or wall product is about 10 – 50 years, radiative heat flows are evaluated from aged solar reflectance and aged thermal emittance.

Color and glare may be important for roofs or walls visible to pedestrians or neighbors. Where light-colored surfaces with high visible reflectance and high NIR reflectance are aesthetically undesirable, high spectral selectance (NIR reflectance minus visible reflectance) permits a “cool colored” dark surface (low visible reflectance, high NIR reflectance) to stay cooler in the sun than a conventional dark surface (low visible reflectance, low NIR reflectance) [1,21,22]. “Directionally reflective” steep roofing materials that exhibit high directional selectance (solar reflectance viewed from above minus solar reflectance viewed from the street) may also provide dark-looking surfaces with higher-than-usual solar reflectance [23].

Glare from bare-metal surfaces with high specular reflectance or bright-white surfaces with high Lambertian reflectance can be problematic. Mirrorlike envelope surfaces may pose the greatest concern, especially if a surface is vertical and concave and can focus reflected light.

Meanwhile, roughly half the sunlight reflected from a Lambertian wall will strike nearby walls and ground surfaces, diminishing the ability of a cool wall to mitigate the local urban heat island effect. Wall materials with high solar retroreflectance (ability to return sunlight toward the sun) could be used to reduce both building and urban radiative heat gains [24].

4.2.1.3. Solar heat gain at the envelope

The solar heat gain of a horizontal or near-horizontal surface can be computed from its air mass 1 global horizontal (AM1GH) solar reflectance [25,26]. The solar heat gain of a vertical surface, such as a wall, can be evaluated from its air mass 1.5 global vertical (AM1.5GV) solar reflectance [Appendix I of 27].

The ability of a cool envelope material to reduce hourly solar heat gain will scale linearly with both envelope albedo rise [9,28] and the hourly global solar irradiance at each modified surface. The effects of these gain reductions on annual cooling and heating energy uses or annual unmet cooling and heating hours will depend on concurrence with hours in which the building needs cooling or heating.

Raising the albedo of the opaque envelope tends to reduce demand for cooling in summer and increase demand for heating in winter. Therefore, the utility of a fixed-albedo cool envelope material may scale with the surface-specific ratio of mean solar irradiance in summer to that in winter [7]. A variable-albedo cool envelope material intended to minimize the winter heating penalty should be characterized by both its high albedo in the cooling season and its low albedo in the heating season.

4.2.1.4. Non-radiative properties affecting performance of cool envelope materials

An envelope product's thermal resistance, thermal capacity, and envelope ventilation (if present) can affect both heat transfer to the conditioned space and the influence of a cool surface on that heat transfer.

High thermal resistance across the cool envelope material impedes conduction, reducing the influence of the envelope's surface temperature on heat transfer to the conditioned space [29]. Envelope material ventilation—e.g., the flow of air between a roof product and the roof deck, such as that in the space below a batten-mounted tile roofing assembly—can also reduce heat transfer to the conditioned space [30]. Thus, each feature can decrease the benefit of reducing the building's surface temperature with a cool envelope material.

High thermal capacity in a cool envelope material slows heating and cooling, delaying heat transfer to and from the conditioned space. This lag can help increase the cooling benefit of a reflective roof by reducing space cooling load when electric power demand peaks in late afternoon on a summer day. It can also diminish the penalty of a reflective roof by keeping the roof and attic warmer overnight, decreasing space heating load on a winter morning [31].

The thermal resistance and thermal capacity of the building envelope (roof and wall assemblies) affect heat flow to the conditioned space, and the efficacy of cool surfaces, in manners similar to the thermal resistance and thermal capacity of the cool envelope material itself.

Cool-roof and cool-wall benefits scale with roof area and net wall area (gross wall area - window area - door area), respectively. If the roof is pitched, ceiling area (roof plan area) may be a better scaling factor for solar heat gain, though TIR exchange will still scale with roof area.[4]

4.2.2. Typologies (classifications) and design parameters

While there are no universal specifications for cool envelope materials, the general principle is that a cool envelope material is one whose enhanced solar reflectance—or enhanced effective solar reflectance if the material is fluorescent—keeps it cooler under the sun than a less-reflective conventional envelope material. Thermal emittance is a relevant but secondary consideration.

Cool envelope materials can be classified by the cooling strategy or by the technology used to achieve this goal.

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[4] This distinction is often minor because the ratio of roof area to ceiling area for a roof with typical pitch of 5:12 (23°) is 13/12 = 1.08.

4.2.2.1. Cooling strategies

Each of the following strategies uses nonselective high thermal emittance unless otherwise specified.

A. **Static[5] high solar reflectance.** This approach uses a light-colored material of high visible reflectance, high NIR reflectance, and high solar reflectance. It maximizes savings in the cooling season but may incur a penalty (increased heating load) in the heating season. The bright color of this surface may pose aesthetic or glare concerns if the surface can be seen by pedestrians or neighbors.

B. **Static high NIR reflectance.** This approach uses a cool-colored material of low to medium visible reflectance, high NIR reflectance, and medium solar reflectance. It offers a wide color palette but yields cooling savings and heating penalties smaller than those generated by maximizing both visible and NIR reflectance.

C. **Static high NIR reflectance + static NIR fluorescence.** This approach uses a fluorescent cool-colored material. It is analogous to strategy B (static high NIR reflectance) but yields greater cooling savings and heating penalties because some of the absorbed visible light is rejected by emission as invisible NIR light.

D. **Temperature-sensitive high solar reflectance.** This approach uses a thermochromic material whose reflectance increases with temperature. In warm weather, the material can act as a light-colored or cool-colored surface; in cool weather, it can behave as a conventional low-albedo material. This avoids the heating penalty associated with using a material whose reflectance is elevated in both the cooling and heating seasons.

E. **Angle-sensitive high solar reflectance.** This approach uses a surface that exhibits high solar only when the surface is illuminated by light whose diffuse reflection will not be observed by pedestrians or neighbors. This approach reduces concerns about the use of bright colors by employing a sloped material that appears dark when viewed from below—e.g., from street level—but bright when viewed from above. It will incur both cooling savings and a heating penalty, but the albedo in summer typically exceeds that in winter.

F. **Static solar retroreflection.** This approach strongly retroreflects beam sunlight to the solar disc, or at least in its general direction. This is analogous to static high solar reflectance (strategy A) but allays concerns about glare and downward reflection that can arise from use of a light-colored, diffusely reflecting surface on a tilted roof or a wall.

G. **Static near-unity solar reflectance + static selective thermal emittance.** This approach seeks to provide *negative* net radiative heat gain during the day by (a) using

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[5] "Static" indicates that variations in reflectance are not intentional. Few materials exhibit truly constant reflectance—for example, that of a glossy dark surface can increase substantially as the incidence angle approaches 90° [25].

near-unity solar reflectance to minimize solar heat gain and (b) using selective thermal emittance (high emittance in the 8 – 13 µm sky window and low emittance in the rest of the 4 – 80 µm TIR spectrum) to maximize long-wave radiative loss to the sky. This is analogous to strategy A (static high solar reflectance) but increases cooling savings, heating penalties, and potential concerns about glare and aesthetics.

4.2.2.2. Cooling technologies

Here we classify materials according to the technology used to make them cool.

Light-colored CEMs are roof and wall products that use white or other light-colored pigments to attain high visible reflectance and high NIR reflectance.[6] White products typically incorporate the highly reflective pigment titanium dioxide rutile [34]; other highly reflective pigments under investigation include nanostructured zinc aluminate [35] and bismuth titanate [36].

Light-colored options are available in most roofing product categories, including built-up, clay tile, concrete tile, liquid applied coating, metal, modified bitumen, spray foam, and single-ply membrane [20,37–39]; and in most wall product categories, including exterior wall paint (field-applied coating), painted metal cladding (factory-applied coating), vinyl siding, and architectural membrane [Appendix J, 27]. The notable exception is asphalt roofing shingles—nominally white asphalt shingles look grey and have modest solar reflectance [40].

The performance of a light-colored CEM is characterized by its solar reflectance and thermal emittance; values for roofing materials are usually reported in the Rated Products Directory of the Cool Roof Rating Council [19]. The European Cool Roofs Council also specifies a program for measuring the solar reflectance and thermal emittance of roofing products [41,42]. Building energy efficiency standards, such as ASHRAE 90.1 [43] and California Title 24 Part 6 [44]; energy efficiency product qualification programs, such as the U.S. Environmental Protection Agency's ENERGY STAR® [45]; and green building programs, such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) [46] that promote the use of light-colored materials on low-slope roofs (pitch ≤ 2:12) typically require such products to exhibit a minimum aged solar reflectance circa 0.55 – 0.65 and an aged thermal emittance of at least 0.75 [29].

There are few performance specifications for light-colored materials on walls, but Levinson et al. [Appendix P of 27] proposed that "higher-tier" cool walls should be required to demonstrate an

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[6] The radiative power in the air mass one global horizontal (AM1GH) solar spectral irradiance recommended for evaluating the solar reflectance of roofing materials is 6.6% UV, 44.7% visible, and 48.7% NIR [32]. Nearly all envelope materials other than bare metal, light-colored clay, and light-colored cement concrete exhibit low UV reflectance [1], as do non-metallic pigments; indeed, the ubiquitous white pigment, titanium dioxide rutile, strongly absorbs UV light [22,33]. High UV reflectance can also accelerate the photochemical formation of ozone in urban areas. Since (a) UV radiation comprises less than 7% of global horizontal solar radiation, (b) high UV reflectance is uncommon among high TE (non-metallic) envelope materials, and (c) high UV reflectance may degrade local air quality, light-colored CEMs typically do not incorporate high UV reflectance.

aged solar reflectance of at least 0.60 and an aged thermal emittance of at least 0.75. The Cool Roof Rating Council plans to launch a wall-product rating program by 2022 [47].

Cool-colored CEMs are analogous to light-colored materials but use spectrally selective pigments with high NIR reflectance or high NIR transmittance[7] to produce a dark-to-medium colored surface with high NIR reflectance [1,21,22,33,48–50]. One might create a cool-colored material by applying to a conventionally colored envelope product an NIR-reflective clear topcoat or film [40], analogous to a "heat mirror" solar-control window film [51].[8] Cool-colored options are available in essentially all roofing and wall product categories, with the possible exception of slate roofing [Appendix P of 27,38].[9]

The performance of a cool-colored CEM is characterized by its solar reflectance and thermal emittance; color is also important to the consumer. Building energy efficiency standards, such California Title 24, Part 6; energy efficiency product qualification programs, such as ENERGY STAR®; and green building programs, such as LEED that promote the use of cool-colored materials on steep roofs (pitch > 2:12) typically require such products to exhibit a minimum aged solar reflectance circa 0.15 – 0.30 and an aged thermal emittance of at least 0.75 [29]. There are few performance standards for cool-colored materials on walls, but Levinson et al. [Appendix P of 27] proposed that "lower-tier" cool walls should be required to demonstrate an aged solar reflectance of at least 0.40 and an aged thermal emittance of at least 0.75.

Fluorescent CEMs incorporate fluorescent cool pigments that emit some absorbed visible light as NIR radiation and reflect or transmit incident NIR radiation. A topcoat colored with the fluorescent cool pigment is applied over a substrate with high visible and NIR reflectance (e.g., a white envelope material, or a white basecoat) to (a) enhance fluorescence by increasing optical path length through the fluorescent topcoat and (b) reflect upward both incident NIR radiation that passes through the topcoat and downward-emitted NIR radiation. The fluorescence raises the CEM's effective solar reflectance, or fraction of incident sunlight rejected via reflection or fluorescence, above that of a non-fluorescent cool-colored CEM of the same color and NIR reflectance.

Fluorescent cool pigments include ruby (Al_2O_3:Cr) and Egyptian blue ($MCuSi_4O_{10}$, M = Ca, Sr, Ba). Additional colors can be created by mixing (e.g., fluorescent cool blue + non-fluorescent cool yellow = fluorescent cool green) or layering (fluorescent cool blue coating over non-fluorescent cool orange coating = fluorescent near-black) [10,11].

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[7] A spectrally selective pigment with high NIR transmittance must be applied in a color topcoat over a NIR-reflective substrate, such as a white envelope material or a white basecoat.

[8] While such coatings and films are not yet available for opaque envelope products, painted optical films are under development [52].

[9] Some naturally colored envelope materials, such as terracotta clay roofing tiles and wood shakes, happen to have high NIR reflectance and low visible reflectance, and thus qualify as cool colors [1].

The performance of a fluorescent CEM is characterized by its effective solar reflectance and its fluorescence benefit (effective solar reflectance minus solar reflectance). Color is also important to the consumer. ESR can be measured by comparing the temperature in the sun of the fluorescent material to those of two non-fluorescent reference specimens of known solar reflectance [12]. Performance standards for cool-colored CEMs should also apply to fluorescent CEMs since both technologies seek to provide cool, non-white surfaces for the building envelope.

Thermochromic CEMs incorporate a temperature-sensitive surface coating whose solar reflectance flips from low to high when the material exceeds its transition (switching) temperature [37,53–56]. Garshasbi & Santamouris [53] subdivide these technologies into dyes (e.g., Leuco dyes) and non-dyes (e.g., quantum dots, plasmonics, photo crystals, conjugated polymers, Schiff bases, and liquid crystals). They note that only the former have been tested in building envelope applications. The switchable dyes are applied over a bright substrate, such as a white concrete tile, since they can transmit or absorb light, but not scatter light [55]. Thermochromism may also be used to modulate a CEM’s thermal emittance [57].

The performance of a thermochromic CEM is characterized by its transition temperature, transition time, low solar reflectance, and high solar reflectance [58,59]. We are not aware of performance standards for this technology.

Directionally selective reflector CEMs (also known as directionally reflective materials) are steep roofing products designed to appear dark from below (“view direction”) but bright from above (“sun direction”). One approach is to apply a white coating to only one side of each granule on an asphalt roofing shingle, then install the shingle on a steep roof with the shingle’s bright side facing away from the street [60–62].

The performance of a directionally selective reflector CEM is characterized by its “summer reflectance” (maximum near normal-hemispherical solar reflectance), “winter reflectance” (mean near normal-hemispherical solar reflectance), and “annual reflectance” (average of summer and winter reflectances) [23,63]. Performance standards for cool-colored CEMs on steep roofs should also apply to directionally selective reflector CEMs since both technologies seek to provide cool, non-white surfaces for steep roofs.

Solar-retroreflective CEMs are surfaces intended to reflect beam sunlight toward the solar disc to minimize unwanted reflection from cool walls or cool steep roofs toward neighbouring people or buildings. The extensive literature on this technology is summarized by Yuan et al. [64] and Levinson, Chen, et al. [24].

The performance of a solar-reflective CEM is characterized by its solar spectral bi-directional reflectance distribution function. We are not aware of performance standards for this technology.

Daytime sky radiator CEMs are surfaces that combine near-unity solar reflectance, high emittance in the 8 – 13 µm sky window, and low emittance in the rest of the TIR spectrum (4 – 80 µm, excluding the sky window) to attain a modest net radiative heat loss during the day. Sky radiators intended to attain subambient (lower than air) temperatures should be shielded from the wind to minimize convective warming [16,17].

This technique was first demonstrated over 40 years ago [65] but is enjoying renewed attention. Santamouris & Feng [16] identified 22 different technologies, including 8 multilayered planar photonic radiative structures, 12 metamaterials or 2D/3D photonic structures, and 2 paints.

The performance of a daytime sky radiator CEM is characterized by its solar reflectance, emittance in the sky window, emittance in the rest of the TIR spectrum, daytime radiative heat loss rate, and daytime subambient temperature depression. We are not aware of performance standards for this technology.

4.2.3. Benefits and limitations

4.2.3.1. Benefits and penalties

Cool materials can decrease envelope surface temperature and diminish heat conduction into the occupied space. This lowers surface, radiant, and air temperatures inside an unconditioned building, and decreases cooling load (heat that must be removed from the occupied space to maintain setpoint), annual cooling energy use, and peak power demand in a conditioned building. With the possible exception of thermochromics, CEMs also tend to increase heating load (heat that must be added to the occupied space to maintain setpoint) and annual heating energy use in climates that have a heating season.[10]

Direct benefits and penalties. The "direct" cooling benefits and heating penalties of CEMs—meaning those attained by reducing the building's net radiative heat gain—have been assessed in over 30 countries and regions, including

- Australia [66–68]
- Brazil [69–71]
- Canada [72–78]
- China [28,79–93]
- Egypt [94–98]
- United Kingdom [86,99]
- France [97,100]

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[10] Installation of a CEM may incur little to no heating penalty if the building is sufficiently warmed by internal thermal loads.

- Ghana [70]
- Greece [50,86,97,101–103]
- Haiti [104]
- India [94,105–111]
- Iran [112,113]
- Israel [114]
- Italy [58,98,115–123]
- Jamaica [70]
- Jordan [124,125]
- Kenya [126]
- Kuwait [127,128]
- Malaysia [129]
- Mexico [130–132]
- Middle East [133]
- Morocco [134]
- Netherlands [135]
- Pakistan [136]
- Portugal [137]
- Singapore [85,138,139]
- Southeast Asia [140]
- Spain [98,141,142]
- Sri Lanka [143]
- Sweden [144]
- Thailand [145,146]
- Tunisia [147]
- Turkey [148]
- United States [6–9,20,27,30,31,76,78,85,149–163]
- many world cities [164]

Hernández-Pérez et al. [165] reviewed over 100 such works, including 16 roof heat transfer studies, 18 test-cell measurement studies, 5 computational fluid dynamics (CFD) studies, 21 building energy simulation studies, 10 whole-building measurement studies, 8 calibrated simulation studies, and 4 large-scale cool roof studies.

In hot-summer climates, the energy-cost or source-energy annual cooling savings provided by a static-albedo CEM (e.g., a light- or cool-colored roof or wall) typically exceeds the corresponding heating penalty [9,20,27,28,31,81,86,91,98,99,102,103,106,114,141,148,152,166–172]. Several studies have found that cool roofs yield annual energy cost savings in office and retail buildings across nearly the entire United States [6,152,173]. Analyses that do not account for snow in winter may substantially overestimate cool-roof winter heating penalties because both conventional roofs and cool roofs are white when covered with snow [76].

A few studies have compared the life-cycle operational energy savings and carbon emission reductions from cool roofs to those from garden roofs [91,174], or those yielded by cool roofs, garden roofs, and photovoltaic roofs [74]. Pushkar & Verbisky [114] assessed the life-cycle sum of production, operational, and maintenance-to-disposal energy uses for red and white roofs in Israel, finding that white roofs were best.

Increasing the albedo of building facades can increase the mean radiant temperature experienced by nearby pedestrians, with net changes to thermal comfort that depend on season and concurrent changes to ambient air temperature [Appendix D of 27,175–177].

Indirect benefits and penalties. Citywide application of CEMs can cool the outside air by reducing convection of heat from the building envelope. This mitigates the urban heat island effect, or elevation of urban air temperature above rural air temperature [178–193], and provides “indirect” cooling savings and heating penalties to buildings throughout the cooled city [72,155,166,168,169,184,194–201]. Cooling the urban air can slow the temperature-dependent chemical reactions that form smog [184,188,202–205], but may also increase the concentration of particulate matter by reducing planetary boundary layer height [202,205].

Global cooling benefit. CEMs induce “global cooling” (negative radiative forcing), or a reduction in the global mean atmospheric temperature, by reflecting sunlight out of the Earth system [206–209].

4.2.3.2. Limitations

Since the most important function of a CEM is to reduce solar heat gain, decreases in solar availability or solar reflectance will limit its utility.

Solar availability. Shadows cast by trees or neighbouring buildings can decrease the sunlight incident on the roof or walls of an individual building [158,210], while air pollution (e.g., aerosols) or cloud cover can reduce the sunlight incident on all buildings citywide [28,211,212].

Solar reflectance. Soiling and weathering can reduce the solar reflectance of a CEM. Roof albedo is especially sensitive to soot deposition and biological growth [133,154,171,213–227], while wall albedo is less affected by natural exposure [Appendix J of 27,228]. Cleaning can restore the initial albedo of some roofing materials [220], but this does not appear to be a common practice.

The following examples are representative but not exhaustive.

The loss of reflectance caused by aging (weathering, soiling and biological growth) depends on the initial reflectance value, the type of coating, and climate characteristics. Sleiman et al. [225] analyzed the reflectance loss of roofing products in different locations in the USA. For initial reflectance values of 0.60–0.80, the authors report a mean absolute reflectance loss after three years of 0.13, 0.05, and 0.10 in a hot-humid climate (Florida), a hot-dry climate (Arizona), and a temperate but more polluted climate (Ohio), respectively. For initial reflectance values above 0.80, the mean reflectance loss is higher, namely 0.24, 0.08, and 0.17 in the aforementioned climates. The authors also report that the solar reflectance reduction is more evident on field-applied coatings, modified bitumens, and single-ply membranes and smallest for factory-applied coating and metal products.

Levinson et al. [220] found that five to eight years of natural exposure increased the solar absorptances of initially light-colored, single-ply PVC roofing membranes by factors of 1.4 – 3.5. In accelerated bio-ageing experiments, Ferrari et al. [219] studied the effect of biological growth on the solar reflectances of different polymeric coatings and roofing membranes, finding small absolute reductions of solar reflectance for colored single ply membranes (0.01 to 0.05) and a maximum absolute reduction of 0.30 for a white field applied polymeric coating. In hot humid climates, aged field-applied white-coated roofs showed a drop in solar reflectance of about 0.16 (to 0.59 from 0.75) [229]. Similarly, in Athens, Greece, the albedos of white-coated roofs on two schools fell by 0.24 (to 0.50 from 0.74) and 0.17 (to 0.54 from 0.71), respectively, after four years of exposure [221].

4.2.4. Performance, with a focus on robustness and resilience

4.2.4.1. Overview

The performance of a CEM is typically gauged by its initial and aged radiative properties; decrease in envelope surface temperature; annual cooling site energy savings, annual heating site energy penalty, annual HVAC source energy savings, annual HVAC energy cost savings, and peak-power demand savings in a conditioned building; and by temperature reduction in the occupied space of unconditioned building.

4.2.4.2. Aged radiative properties

The Rated Products Directory of the Cool Roof Rating Council (CRRC) reports for roofing materials both initial and 3-year-aged values of solar reflectance and thermal emittance. The 3-year-aged values in this database average properties measured after three years of natural exposure at U.S. sites in Arizona, Florida, and Ohio [19]. Solar reflectance losses after three years depend strongly on material type, exposure site, and initial solar reflectance [225]. The CRRC also reports for some products "laboratory-aged" values of solar reflectance measured after exposing materials to a laboratory practice that simulates the radiative property changes that would occur after three years of natural exposure [226,227,230].

All solar reflectances in the Rated Products Directory are based on a beam-normal, rather than global, solar spectral irradiance. Use of this irradiance spectrum can overestimate the solar reflectance of a spectrally selective "cool colored" material [22,25,32].

Lawrence Berkeley National Laboratory is exposing wall products for five years (2016 – 2021) at the Arizona, Florida, and Ohio sites to assess changes to their solar reflectances and thermal emittances [Appendix J of 27,228]. The LBNL study reports a global vertical, rather than beam-normal, solar reflectance.

4.2.4.3. Envelope surface temperature reduction

The extent to which a CEM lowers envelope surface temperature depends primarily on the albedo gain (increase in solar reflectance) attained by switching to a CEM, and on solar irradiance. Envelope surface temperature and surface temperature reduction can be measured [28,31], or simply estimated under sunny summer afternoon conditions following the protocol used to compute SRI from solar reflectance and thermal emittance [18].

4.2.4.4. Energy savings in a conditioned building

The energy efficiency benefit of substituting a CEM for a conventional envelope material is usually based on its annual HVAC source energy or energy cost savings.[11] The resilient cooling benefit of a CEM depends more on its ability to deliver reliable passive cooling; small annual HVAC energy savings or even a modest annual HVAC energy penalty might be acceptable.

Annual cooling site energy savings from light-colored or cool-colored roofs and walls have been simulated by many workers. Hernández-Pérez et al. [165] summarize cooling load or cooling energy savings simulated in over 20 studies; additional simulations can be found in later studies [7,28,37,54,67,70,76,81,91,97,114,121,122,133,135,194].

These savings vary strongly with envelope albedo gain, climate (e.g., hourly solar irradiance and air temperature), envelope construction (e.g., thermal resistance and capacitance), and building operation (e.g., occupancy schedule). Choice of savings metric is also important. For example, whole-building fractional savings gauge the fraction of the building's cooling energy use that can be addressed by installing a CEM, but typically do not apply to a building with a different geometry; they may be high simply because the building requires little cooling. A more transferrable metric is savings intensity, or savings per unit envelope surface area modified.

Example 1. Rosado & Levinson [7] simulated cool-wall and cool-roof energy savings for 10 different building types of three different vintages across California and the United States. Table 4-2 summarizes annual site cooling energy savings and peak power demand[12] savings for a two-story single-family home and a three-story medium office building in ASHRAE climates zones 1 – 4; these climates map roughly to the southern half of the United States. The savings were evaluated with TMY3 weather files based on observations from 1991 to 2005 [231]. Cooling savings in current or future climates should be greater as global warming increases the number of hours each year during which buildings require cooling [232–235].

Example 2. Hernández-Pérez et al. [165] carried out a detailed review of the thermal performance of cool materials applied to the building envelope (roof and facades), including monitoring and simulation studies. The authors reported that the daily cooling energy decrease varied between 1% and 80% depending on the climate and the building construction characteristics.

Example 3. Synnefa & Santamouris [42] evaluated the cooling potential of cool roofs applied to real buildings with different uses (schools, laboratories, offices, and dwellings) and located at different latitudes (from Crete at 35.2 °N to London at 51.5 °N). They reported cooling energy saving of 10–40%.

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[11] Energy efficiency can also be gauged from annual HVAC site energy savings if the building uses only electricity for heating and cooling.

[12] Peak demand hours were defined as those between 12:00 and 18:00 local time on weekdays, June through September.

Example 4. Zinzi [97] carried out simulation studies in the Mediterranean zone reporting annual cooling energy savings up to 2.9 kWh/m² floor area per 0.1 increase of façade albedo. This reduced building annual cooling energy use by 10–20%, depending on envelope construction, cooling system, and facade albedo [121].

Table 4-2. Cool-roof and cool-wall annual cooling site energy savings in ASHRAE climates zones 1 – 4, derived from the Cool Surface Savings Database in Rosado & Levinson [7]

	Annual cooling site energy savings intensity [kWh/m²]	Annual building cooling site energy fractional savings [%]	Annual-average HVAC site peak power demand savings intensity [W/m²]	Annual-average building HVAC site peak power demand fractional savings [%]
Cool roof [a]				
Single-family home, old (pre-1980) [b]	1.5 - 5.5	3.5 - 11.8	1.1 - 2.5	3.8 - 10.2
Single-family home, new (2006-2012) [c]	0.5 - 2.4	2.2 - 9.3	0.2 - 1.0	2.2 - 7.2
Medium office building, old (pre-1980) [b]	0.8 - 7.3	2.5 - 5.2	1.1 - 3.9	2.4 - 3.6
Medium office building, new (2004-2013) [c]	0.6 - 4.4	1.8 - 3.7	0.5 - 1.9	1.8 - 3.9
Cool walls [d]				
Single-family home, old (pre-1980) [b]	3.0 - 8.2	7.9 - 24.7	1.9 - 2.8	7.2 - 18.8
Single-family home, new (2006-2012) [c]	1.0 - 4.8	7.0 - 23.5	0.5 - 1.6	5.6 - 16.0
Medium office building, old (pre-1980) [b]	1.7 - 10.9	3.0 - 8.8	1.9 - 4.3	2.4 - 4.9
Medium office building, new (2004-2013) [c]	0.6 - 4.3	1.6 - 2.8	0.5 - 1.9	1.5 - 2.9

[a] The cool-roof scenario increases roof albedo to 0.40 from 0.10 on the single-family home, and to 0.60 from 0.20 on the medium office building.

[b] "Oldest" vintage in simulations by Rosado & Levinson [7], corresponding to pre-1980 construction.

[c] "New" vintage in simulations by Rosado & Levinson [7]; year of construction corresponds to statewide building code enforced circa 2016 in the city used to represent the climate.

[d] The cool-walls scenario increases wall albedo to 0.60 from 0.25.

Shading and reflection by adjacent buildings can diminish cool-wall energy savings and penalties [158]. If a substantial fraction of light reflected from exterior walls is transmitted through the windows of neighbouring buildings, the use of cool walls may increase neighborhood cooling energy use [236].

4.2.4.5. Thermal and comfort improvements in an unconditioned building

The improvement to the thermal environment within an unconditioned building is gauged by reduction in the air, operative, and/or environmental temperature in the occupied space, or by decrease in annual discomfort hours. Hernández-Pérez et al. [165] summarize space temperature reductions measured or simulated in over 30 studies and discomfort hour reductions simulated in 4 studies. Later works also report reductions in space temperature

[58,95,108,119,126,134,137,236–239] or discomfort hours [70,87,95,108,119,134,194]. Thermal and comfort improvements depend strongly on envelope albedo gain, climate (e.g., hourly solar irradiance), and envelope construction (e.g., thermal resistance and capacitance).

Example. Synnefa, Santamouris, & Akbari [164] reported annual hours in which the indoor air temperature exceeded various thresholds for a single-story, flat-roof house simulated in 27 world cities. Increasing the albedo of the modestly insulated roof (RSI-1.2) by 0.40 reduced annual hours exceeding 27 °C by about 20% (Figure 4-1).

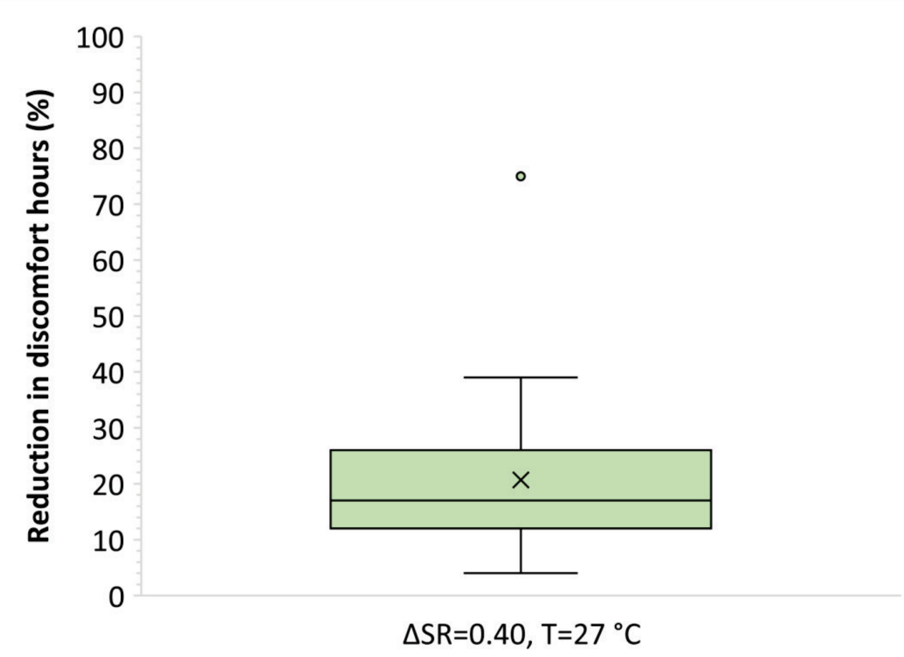

Figure 4-1. Fractional reduction in 27 world cities in the number of hours each year during which the air temperature inside a single-story home exceeds 27 °C, upon raising by 0.40 the albedo of a modestly insulated roof on a single-story unconditioned home. Data source: Synnefa, Santamouris, & Akbari [164]

4.2.4.6. Cool roof case studies

This section reports the main findings of full-scale cool roof deployments, to better understand energy and thermal performances in real operational conditions. Only the solar reflectance (SR) of the cool roof application is reported for the different applications; all products were non-metallic, with high thermal emittance (0.88 – 0.90).

Early cool-roof applications in real buildings were carried out in Florida, USA and documented by Parker & Barkaszi [160]. The first case described a one-story detached family home with a 158 m² pitched roof, which had the initial roof (SR 0.20) covered with a white elastomeric coating during summer 1993. Temperature measurements showed a maximum reduction of 18 °C on the roof surface and 11 °C in the attic air. The calculated average daily reduction of electricity use for cooling was 11.6 kWh, corresponding to 20% in typical summer days, keeping the cooling set-point unchanged at 27.5 °C. Also, the peak power demand was reduced by almost 1 kW (23%). The second demonstration was another one-story single-family home, 84 m² conditioned floor area, with an asphalt shingle roof (SR 0.08). A white elastomeric coating was placed on the existing roof. After this application, the maximum surface temperature reduction of the roof was 18 °C, while the peak air temperature drop in the attic was 16.6 °C. This yielded a 25% reduction in cooling energy use on typical days, with 47% reduction during the warmest hours. Before the white coating was applied the cooling system was not powerful enough to maintain the thermostatic setpoint; after, the setpoint was always maintained.

A cool roof case study was carried out in an experimental detached house, built in the northern outskirts of Rome, Italy [123]. The building was funded by the Italian Ministry of Industry as a state-of-the-art demonstration for building technologies. It consisted of two identical floors, the first above an unheated basement and the second below a flat roof that was finished with dark red clay pavers. The monitoring was carried out in free-floating conditions in summer 2006, during which a white cool coating (SR 0.86) was applied to the 50 m² roof. Before the coating was applied the average air temperature on the second floor was 1.8 °C higher than that on the first floor. After the coating was applied the temperature difference inverted, making the temperature on the second floor cooler than that on the first floor 90% of the time. The effect of the cool roof was estimated by regression, resulting in an average air temperature reduction of 2.1 °C on the second floor during the monitoring period.

A set of five demonstrations was implemented in the framework of the Cool Roofs (CR) project funded by the European Commission in 2009 and 2010 [42,240]. Each case study was implemented using the following methodology, based on calibrated simulations: (1) the building is monitored in free-floating conditions for limited periods before and after the cool roof application; (2) the indoor air, outdoor air, and outdoor surface measurements are used to calibrate a numerical model; and (3) simulations are carried out to estimate annual energy and thermal performances. Energy performance is calculated as annual thermal load, which refers to the heat energy that must be supplied to or removed from the occupied space to maintain its operational set-point(s) during both the heating and cooling seasons. No energy monitoring was carried out in the buildings because they were not mechanically cooled in summer.

The first CR case study was a two-floor school building in Athens, Greece, where a 410 m² section of the school's cement and gravel screed flat roof was treated with a white elastomeric coating (initial SR 0.80) [103]. The building structure was reinforced concrete. The envelope had no thermal insulation, and the building was naturally ventilated through windows. In summer, the cool coating reduced the roof surface temperature by 12 °C during the morning hours, and lowered by 1.8 °C the average hourly air temperature in a monitored room below the cool roof. Calculations were carried out to estimate energy savings in the building as it was, and in the same building with the envelope thermally insulated. The cool coating reduced annual cooling loads by 40% and 35% for the reference building and the thermally insulated configuration, respectively. It also increased their annual heating loads by 10% and 4%, respectively. Also, the peak cooling power demand decreased by 20% for the real building.

The second CR case study was carried out in Greece, namely in Iraklion, Crete Island [102]. Here a small one-floor laboratory/office building (roof area 50 m²) was equipped with the same cool material used in the Athens study. This building was well insulated and was naturally ventilated with windows. Calibrated simulations in free-floating conditions predicted an indoor temperature reduction of 1.5 °C during the summer months. They also predicted 27% cooling load savings.

The third CR case study was a single-story building containing offices and laboratories in a secondary school campus in Trapani, a city on the western part of Sicily Island in Italy [120]. The structure had no thermal insulation and was naturally ventilated with windows. The flat roof surface (706 m²) was treated with a natural coating based on milk and vinegar (initial SR 0.86). The cool coating was applied to concrete pavers (pre-coating aged SR 0.25). Measurements in summer 2009 found that the indoor air was 1.8 °C warmer than the outdoor air before the cool roof application, but 1.1 °C cooler than the outdoor air after the application. Calculations were carried out to estimate thermal load savings in the building as it is, and in the same building with the envelope thermally insulated. The cooling load savings were 54% and 24%, respectively. Calculations also showed that when the building temperature is free floating, the cool roof would reduce the fraction of summer hours with the indoor operative temperature above 27 °C to 15% from 55%.

The fourth CR case study was a 27 m² cool-roof application carried out on top of a duplex apartment in a social housing complex in La Rochelle, France [100]. The building was highly insulated and equipped with mechanical ventilation. Supply air was delivered to the living room and bedrooms, and exhausts were located in the kitchen, water closet, and bathroom. The roof, initially finished with a dark waterproof asphalt coating, was retrofitted with a white coating (SR 0.88). Simulations predicted that the operative temperature in the attic fell to 22.4 °C from 30.8 °C. Due to the presence of both the attic and the thick insulation layer, the mean operative temperature reduction on the second floor was only 0.7 °C (to 24.2 °C from 24.9 °C). More relevant improvements (up to 9 °C) were calculated for uninsulated configurations, but these are not common in the region.

The fifth CR case study carried out was implemented in London, United Kingdom [99]. A 137 m² section of the roof of a university building, over an open office area and three office rooms, was made cool. The building's roof and walls were insulated, and the building was naturally ventilated. Since the United Kingdom is a heating-dominated climate with significant cooling loads in office buildings, a pink cool coating (SR 0.70) rather than a white cool coating was selected to balance this mixed thermal requirement. Calculations showed that the cool coating significantly improved thermal comfort, reducing summer maximum and average values of operative temperature by 2.2 °C and 5.3 °C, respectively.

A case study compared innovative off-white clay tiles (SR 0.77) to conventional brown tiles (SR 0.19) for pitched-roof applications [119]. The monitoring focused on a 42 m² section of the roof on a three-story detached house and on the attic below the roof section. Daily peak surface temperature reductions of 18 °C and 15 °C were measured in June and July, respectively. The ceiling surface temperature also decreased by 6–9 °C in summer. The attic average operative temperature decreased by 2 °C in the June-August period, with a daily peak reduction of 4.7 °C in July. Corresponding temperature reductions were much smaller in winter.

Another study evaluated the impact of cool roofs in a school building in Athens, Greece, using monitoring followed by calibrated simulation [241]. The building's thermal behaviour was compared to that of a nearby school with similar thermal, use, and geometric characteristics. A cool roof coating (SR 0.89) was applied to a section of the roof covering several classrooms and a stairwell. Measurements showed that peak roof surface temperatures dropped to 40.4 °C from 54.6 °C, while a 2.5 °C peak difference of the ceiling temperature was measured before and after the cool roof application. The peak indoor temperature was 34.5 °C before the application (25.9 °C average outdoor air temperature over the pre-coating monitoring period), dropping to 32.4 °C after the cool coating, despite warmer weather (29.5 °C average outdoor air temperature during the post-coating monitoring). Calibrated calculations showed a potential 30% reduction of electricity use for ceiling fan operation in the building.

A full-scale comparison between cool and green roofs was carried out in an unoccupied office building in the city of Chongqing, China, characterized by hot summers and cold winters [81]. Three identical top-floor rooms (each 21.4 m²) had the following roof finishing layers: black coating (SR 0.20), white coating (SR 0.84), or sedum garden roof (SR 0.36). During summer, it was found that the mean ceiling temperatures below the garden and white roofs were 8.7 °C and 5 °C lower than that below the black roof. When unconditioned (on weekends), the mean cooling-season indoor air reduction with respect to the black roof was 3.2 °C for the garden roof and 1.8 °C for the white roof. Per unit roof area, the white roof also provided 4.8 kWh/m² annual cooling energy savings and 3.9 kWh/m² annual conditioning (cooling + heating) savings with respect to the black roof, outperforming the garden roof as well.

The application of a cool roof to a low-income house in a country with high solar irradiance was documented in a case study in Portmore, Jamaica [70]. A single-story semi-detached house with a flat roof (40 m²) received a white coating (SR 0.82). The ceiling and indoor air temperatures were monitored before and after the cool roof application, which took place in March–April 2016. Comparing two days with similar average ambient temperature and solar irradiation, it was found that the ceiling temperature dropped by 6.8 °C on average with 18.6 °C maximum temperature reduction; the averaged reduction in indoor air temperature was 2.3 °C. Calibrated calculations were implemented starting from the monitoring data, estimating a cooling load reduction of about 37%.

The integration of cool roofs with the night ventilation was the objective of a case study implemented in the cooling dominated city of Xiamen, China [242]. On the roof of a six-story office building the surfaces above three identical top-floor rooms (31.5 m² each) were coated: one black (SR 0.05), one yellow (SR 0.57), and one white (SR 0.79). The rooms were fully equipped to monitor indoor air temperatures during the March–April transition season when the rooms were free floating, and to monitor cooling energy use in summer when the rooms were fully air conditioned. Measurements were also used to calibrate simulations. In the transition season, the peak surface temperature of the black roof was 68.6 °C; the peak surface temperatures of the white and yellow roofs were 27 °C and 20 °C lower than that of the black roof. The air temperatures in the offices with the white and yellow roofs were 1.2 °C and 0.9 °C lower than that in the black-roofed reference room in this period, but both the white-roof room and the yellow-roof room registered the same maximum air temperature drop of 1.3 °C when the night ventilation was added. The measured cooling energy uses in summer of rooms with the white and yellow roofs were about 30% and 25% less, respectively, than that of the room with the black roof. Simulation showed that combining the white cool roof and natural ventilation can reduce annual heating and cooling site energy use by 27% compared to the black roof.

4.2.5. Application

4.2.5.1. Overview

The ability of a CEM to reduce radiative heat gain depends on the solar availability of the building envelope and thus on the latitude and climate type of the site location, the surrounding urban geometry (e.g., shading and reflection from surrounding buildings), and the building orientation. The higher the solar availability, the greater the potential benefit of a CEM.

4.2.5.2. Climate

Light- or cool-colored roofing and wall products are generally well-suited to climates with hot, sunny summers, with diminishing annual cooling and annual HVAC savings as one moves to cooler climates. They provide substantial annual HVAC source energy savings in ASHRAE climate zones 1 – 4,[13] and modest annual HVAC energy savings or penalties in ASHRAE climates zones 5 – 8 [7]. As remarked earlier, a CEM that yields an annual heating penalty comparable to its annual cooling savings may still be useful as a source of resilient cooling, even if the annual HVAC energy savings are a wash. Also, CEMs are expected to grow more useful as the global warming increases the numbers of hours each year during which buildings require cooling.

Cool roofs are particularly effective in climate regions with high solar radiation and no heating requirement [70,95,108,244,245]. This technology has also proved to be more resilient in hot-dry climates than in hot-humid ones, where the solar reflectance losses due to weathering were found

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[13] CEMs should also be useful in ASHRAE climate zone 0, which comprises the hottest portions of ASHRAE climate zone 1 [243].

to be 2–3 times greater [225]. The lower performance of CEMs in tropical regions is also due to a smaller sky radiative cooling effect due to high average cloudiness [246].

CEMs are effective on both residential and commercial buildings, though space available for cool roofs and cool walls can be limited by the presence of solar equipment on the roof and windows on the facades. Cool roofs benefit only the top floor of a multi-story conditioned building, making cool-roof savings per unit floor area greater in low-rise buildings than in high-rise buildings. Cool walls are most effective on east, west, and equator-facing facades [7]. Since total wall area is proportional to building perimeter length while total floor area is proportional to building footprint area, cool-wall savings per unit floor area are higher in buildings with a small footprint than in buildings with a large footprint.

CEMS are ideal for older, poorly insulated buildings since their benefits are inversely proportional to envelope thermal resistance [7]. Therefore, they are most helpful for retrofits.

The areal density (mass per unit area) of a roofing product is an important consideration if the roof deck can support only lightweight products. This issue often arises in warm-winter climates where roofs are not built with extra weight tolerance for snow. For example, a roof deck in Los Angeles designed to support asphalt shingles may be unable to carry concrete tiles or clay tiles, which can be 3–5 times heavier [40].

4.2.5.3. Urban environment

Shading by neighbouring buildings and trees can reduce the solar availabilities and cooling benefits of cool roofs and walls [158,210]. Soiling by soot, such as that from vehicle exhaust, is one of the factors that tends to degrade the reflectance and performance of CEMs [226].

Studies have found that increasing the albedo of building facades in cities may increase the mean radiant temperature of urban canyons, reducing outdoor thermal comfort in summer [175,176].

4.2.5.4. Installation strategy

Since the cost of a CEM is often the same as that of an otherwise comparable conventional (warm) envelope material, a low-to-no cost way to introduce CEMs is to specify their use in place of conventional envelope materials for new construction or end-of-service replacement. Installation during regularly scheduled retrofits is an especially attractive strategy in places like the United States that have an aging stock of poorly insulated buildings and little new construction. If envelope surface materials are replaced on average after 20 years of service, the envelopes of most buildings could be made cool within two decades.

4.2.6. Technology readiness level

Both white and cool-colored roof materials are mature technologies that are widely available to both building owners and building contractors [38,247], and identifiable via mature product rating systems provided by the Cool Roof Rating Council [19] and the European Cool Roofs Council [41,248]. Cool wall materials, such as light-colored paints, claddings, and sidings, and some cool-colored wall products, are similarly mature and available [Appendix P of 27]; a wall-product rating system is scheduled to begin in 2022 [47].

The dominant residential roofing product in the USA is asphalt shingles, but nominally "cool" asphalt shingles are not very reflective; substantial improvement is needed [40].

Some novel CEMS such as directionally selective reflectors are specialty products with limited availability; other CEMs, such as daytime radiators, solar retroreflectors, fluorescent cool colors, and thermochromics remain under development.

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