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Solar-reflective "cool" walls: benefits, technologies, and implementation

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ABSTRACT

Raising the albedo of a building's walls reduces unwanted solar heat gain in the cooling season. This saves electricity and lowers peak power demand by decreasing the need for air conditioning. It can also cool the outside air, which can mitigate the urban heat island effect and also improve air quality by slowing the reactions that produce smog. We quantified the energy savings, peak demand reduction, urban cooling, and air quality improvements attainable from solar-reflective "cool" walls in California; collaborated with industry to assess the performance of existing cool wall technologies, and to develop innovative cool wall solutions; and worked with government agencies, utilities, and industry to create a cool-wall infrastructure, including application guidelines, a product rating program, incentives, and building code credits.

Simulations indicate that cool walls provide annual energy savings, peak demand reduction, annual emission reduction, and summer heat island mitigation benefits comparable to those yielded by cool roofs, and are helpful across California and in United States climate zones 1 – 4. Natural exposure trials conducted at three sites in California and another three across the United States indicate that cool wall materials tend to stay clean and reflective. Significant advances were made in novel cool wall technologies, such as fluorescent cool pigments that expand the color palette for cool wall products. We prepared guidelines for the climate- and

building-appropriate use of cool walls. Ongoing efforts seek to introduce or expand cool wall provisions in building energy standards/programs and develop a cool-wall product rating system.

Introduction

The Lawrence Berkeley National Laboratory Heat Island Group has collaborated with the roofing industry and California regulators for two decades to advance the development and climate-appropriate use of solar-reflective "cool" roofs. There is now a large body of cool-roof science; a well-established cool roof rating system; cool roof requirements in building energy standards as well as voluntary incentive programs like Leadership in Energy and Environmental Design; and thousands of cool roofing products sold in the United States and abroad (Akbari and Levinson 2008; CRRC 2019).

Cool *walls* are also promising. Although the solar energy per unit area striking an east or west wall in summer is about half of what hits a horizontal roof, homes typically have about half as much wall insulation as roof insulation. For example, in a Fresno, California home with wood-framed walls, 2013 Title 24 requires R-38 (38 h·°F·ft^2/BTU) ceiling insulation, but only R-19 wall insulation. Similarly, in a Fresno nonresidential building with light mass, heavy mass, or wood-framed walls, 2013 Title 24 requires R-26 roof insulation, but only R-6 to R-17 wall insulation. This suggests that the benefit of raising wall albedo (solar reflectance)—that is, the extent to which it reduces unwanted heat conducted into the interior space—is comparable to the benefit of increasing roof albedo.

A reflective coating or cladding can increase wall albedo. Cool-wall products available today include (1) light-colored paints that reflect 60 percent to 90 percent of sunlight when new, but which may also lose reflectance as they get dirty; and (2) darker "cool-colored" paints that come in a wide palette, but typically reflect less than 50 percent of sunlight when new.

In this study, our goals were to:

- Quantify the energy savings, peak demand reduction, urban cooling, and air quality improvements attainable from cool walls in California and the U.S., through modeling.
- Collaborate with industry to assess the performance of existing cool-wall technologies, and to develop innovative cool-wall solutions.
- Work with state and federal government agencies, utilities, and industry to create a cool-wall infrastructure, including application guidelines, a product rating program, incentives, and building code credits.

Lawrence Berkeley National Laboratory, the University of Southern California, and the University of California at San Diego collaborated with 10 partners from the wall product industry to advance the science and technology of cool walls. The study had five elements:

1. **Energy and Emission Savings Analysis**. We used building-energy simulations to quantify how increasing wall albedo affects the cooling, heating, and lighting energy uses of a building and its neighbors.
2. **Environmental Analysis**. We used building-, neighborhood-, and city-scale energy simulation models to assess pedestrian comfort, evaluate outdoor air temperature reductions, and assess changes to outdoor air quality.

3. **Technology Assessment**. We evaluated the performance of available and prototype cool-wall technologies, primarily the ability to reflect sunlight. We measured how solar reflectance changed when products were exposed outdoors at sites across California and the United States, with special attention paid to the performance of self-cleaning and de-polluting photocatalytic materials.
4. **Technology Development**. We explored innovative cool-wall technologies, including fluorescent cool pigments and retroreflective materials.
5. **Infrastructure Advancement**. We promoted the infrastructure needed to advance the climate- and building-appropriate use of cool walls, including application guidelines, a product rating program, incentives, and building code credits.

Energy and Emission Savings Analysis

Savings in an Isolated Building

Cool-wall changes to annual heating, ventilation, and air conditioning (HVAC) energy use depend on climate, wall construction, wall orientation, building geometry, HVAC efficiency, and operating schedule, while changes to annual energy cost and energy-related emissions further vary with local energy prices and emission factors. We used EnergyPlus to perform more than 100,000 building energy simulations spanning 10 different building categories, three building vintages, 16 California climate zones, and 15 United States climate zones. The simulations varied parameters such as wall albedo, roof albedo, combination of walls modified, and building orientation. Cool walls yielded annual savings in source energy and energy cost, as well as reductions in emissions (carbon dioxide, carbon dioxide equivalent, nitrogen oxide, and sulfur dioxide) in all California climate zones and in warm United States (ASHRAE) climate zones. Cool walls also yielded HVAC peak power demand reduction in all California and United States climate zones.

In California, cool walls reduced whole-building annual HVAC energy use 3.0 percent to 25 percent in single-family homes, 0.5 percent to 3.7 percent in medium offices, and 0.0 percent to 9.0 percent in stand-alone retail stores. In warm United States climates – zones 1A (Miami, Florida through 4B (Albuquerque, New Mexico) – cool walls reduced whole-building annual HVAC energy use 2.0 percent to 8.5 percent in single-family homes, 0.0 percent to 4.2 percent in medium offices, and -0.5 percent to 5 percent in stand-alone retail stores. Cool walls also yielded small annual HVAC source energy savings in some cold United States climates – zones 4C (San Francisco, California) through 7 (Duluth, Minnesota) – for certain building categories and vintages. Figure 1 shows annual whole-building HVAC fractional savings across the United States for two-story single-family homes of different vintages upon raising the albedo of all walls by 0.35 or upon increasing roof albedo by 0.30.

Annual HVAC source energy savings intensities (savings per unit of surface area modified) from east, south, and west walls were similar, and always larger than those from north walls. While walls often receive less incident solar energy per unit area than roofs, they are also less insulated than roofs. Therefore, savings intensities from modifying the four walls (albedo increase 0.35) were often comparable to those from modifying the roof (albedo increase 0.30 in residential and 0.40 in commercial).

This work is detailed by Rosado and Levinson (2019) and in Appendix A of Levinson et al. (2019b).

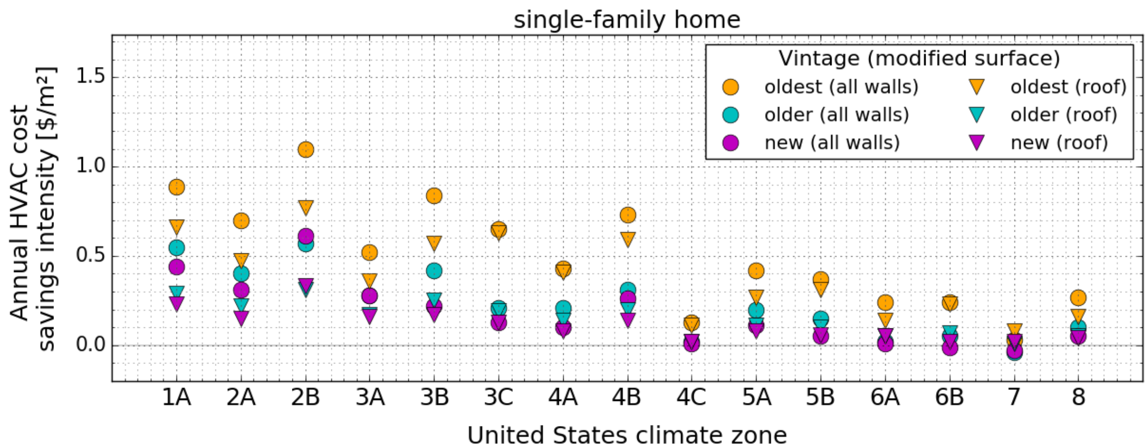

Figure 1. EnergyPlus simulations of annual whole-building source energy fractional HVAC savings in U.S. two-story single-family homes by climate zone and vintage.

Savings in a Building with Neighbors

The solar availability (incident solar radiation) of a central (modeled) building can be reduced by shadows cast by neighboring buildings and increased by sunlight reflected from neighboring buildings. We define the solar availability factor of a central building wall as the ratio of sunlight incident on the central building wall in the presence of the neighboring wall to that incident in the absence of the neighboring wall. One can scale cool-wall cooling savings, heating penalties, or HVAC savings simulated for an isolated central building (no neighbors) by the solar availability factor to account for interaction with the neighboring wall. One can also assess the effect of raising neighboring wall albedo on the solar availability of the central building wall. This analysis emphasizes simplicity, so that its results can be applied knowing only the canyon aspect ratio (ratio of building height to building separation), city, and month. It does not consider shading or reflection by surfaces other than neighboring walls, such as trees.

Monthly values of solar availability factor were evaluated in 17 climates across the United States, including three in California, for north, east, south, and west central walls, over a wide range of canyon aspect ratio (height/width). For example, solar availability factors for the walls of a single-family home in a residential neighborhood in Fresno, California range from about 0.5 to 0.9, depending on whether the wall faces a side, back, or front neighbor.

This work is detailed by Levinson (2019) and in Appendix C of Levinson et al. (2019b).

Environmental Analysis

Pedestrian Thermal Comfort

Cool walls affect the thermal environment of pedestrians by (a) increasing shortwave (solar) radiation striking the pedestrian; (b) decreasing longwave (thermal infrared) radiation incident on the pedestrian; and (c) lowering the outside air temperature. The magnitudes of these sometimes-opposing effects on pedestrians are quantified through human comfort models. Human comfort models attempt to emulate the typical human perception of environmental conditions through thermal comfort indices.

We analyzed thermal comfort for homogeneous neighborhoods. One year of typical weather data was input to a neighborhood microclimate model in three different California climate zones to understand the comfort effects of raising wall albedo on a pedestrian walking parallel to a wall 1.5 m away from the central building in a neighborhood. The latest version of the Pierce two-node model was used to compute pedestrian thermal comfort considering radiation from the sun, sky, and surrounding surfaces (for example, walls); wind speed; air temperature; humidity; metabolic activity (walking); and clothing. The principal model output is the Standard Equivalent Temperature, SET*. A higher SET* indicates that a human feels warmer, and a lower SET* indicates feeling cooler.

Near a multi-family residence in Fullerton, California (Orange County) with conventional walls of albedo 0.25, the annual average hourly SET* is about 18 °C at night and up to 30 °C during the day. During the day, cool walls raise SET* by up to 0.5 °C on average over the year. At night, cool walls lower SET* by up to 0.3 °C on average over the year. The smallest SET* rise occurs for a pedestrian near the north wall. The largest SET* rise occurs for the pedestrian near the south wall at noon in winter since winter solar irradiation on the south wall is the most of any wall orientation during any season. The absolute SET* difference induced by making walls more reflective is benign at less or equal to 0.2 °C over half of the time over the year. While SET* increases over 0.5 °C are occasionally observed, they occur exclusively during clear winter days when the pedestrian is more likely to experience a cold sensation. In that situation the SET* increase is beneficial to pedestrian thermal comfort. SET* differences by building type and climate zone were negligible. Results are sensitive to the pedestrian solar absorptance; on average over the year, a pedestrian with very light-colored clothing and light-colored skin (average solar absorptance 0.40) may even feel colder near a cool wall than near a conventional wall.

This work is detailed in Appendix D of Levinson et al. (2019b).

Urban Climate Effects of Cool Walls

The climate effects of increasing wall albedo are expected to differ from those for cool roofs and pavements for several reasons. First, the diurnal cycle and daily average values of solar irradiance (incident radiative power per unit area) on vertical walls differs from that on nearly horizontal roofs and pavements. Second, walls make up a different fraction of urban areas than do roofs and pavements. Third, air temperature affects per unit of grid cell albedo increase may differ for walls relative to roofs and pavements. We used the Weather Research and Forecasting model (WRF) version 3.7, coupled to an urban canopy model, to investigate how adopting cool walls and roofs influence albedos and near-surface canyon air temperatures in the Los Angeles basin.

To simulate the climate effects of cool walls, the researchers conducted three cases: CONTROL, in which roof, ground, and wall albedos are each set to 0.10; COOL_WALL_LOW, where wall albedo is raised to 0.50; and COOL_WALL_HIGH, where wall albedo is raised to 0.90. To compare the effect of increasing wall albedo to that of raising roof albedo, the team conducted two additional cases: COOL_ROOF_LOW, where roof albedo is raised to 0.50; and COOL_ROOF_HIGH, where roof albedo is raised to 0.90. Simulations were performed for 14 days (28 June 2012 to 12 July 2012).

Figure 2 shows the diurnal cycle of canyon air temperatures for each simulation, and changes in temperatures upon raising wall or roof albedo, spatially averaged over the urban regions of Los Angeles County. Peak temperature reductions for cool walls (that is, 0.64 K for COOL_WALL_HIGH – CONTROL and 0.28 K for COOL_WALL_LOW – CONTROL) occur at 09:00 local standard time (LST). A local minimum in temperature difference (i.e., maximum in temperature reduction) is also observed around 18:00 LST.

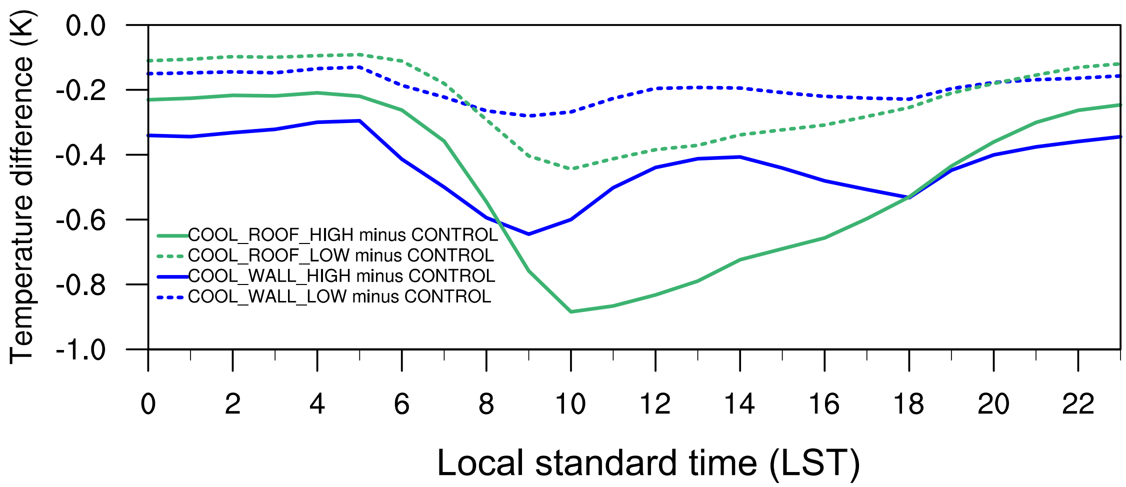

Figure 2. Canyon Air Temperature Change Upon Raising Wall or Roof Albedo. The diurnal cycle of differences in canyon air temperatures for COOL_WALL_LOW – CONTROL, COOL_WALL_HIGH – CONTROL, COOL_ROOF_LOW – CONTROL, and COOL_ROOF_HIGH – CONTROL. Values represent spatial averages in Los Angeles County for urban grid cells between July 3 and 12.

The average temperature reduction induced by cool walls (roofs) is approximately proportional to increases in wall (roof) albedo. Per 0.10 wall (roof) albedo increase, cool walls (roofs) can reduce summertime daily average canyon air temperature by 0.048–0.054 K (0.058–0.060 K). The ratio of the daily average air temperature reduction induced by cool walls to that yielded by cool roofs is about 86 percent, making their benefits comparable.

This work is detailed by Zhang et al. (2018) and in Appendix E of Levinson et al. (2019b).

Air Quality Effects of Cool Walls

We also investigated the influence of widespread deployment of cool walls on urban air pollutant concentrations, and systematically compared cool wall to cool roof effects. Simulations using a coupled meteorology-chemistry model (WRF-Chem) show that cool walls and roofs can reduce urban air temperatures, wind speeds, and planetary boundary heights in the Los Angeles Basin. Consequently, increasing wall (roof) albedo by 0.80, an upper bound scenario, leads to summertime maximum daily 8-hour average ozone concentration reductions of 0.35 (0.83) ppbv in Los Angeles County. However, cool walls (roofs) increase summertime daily average $PM_{2.5}$ concentrations by 0.62 (0.85) µg m^{-3}. We investigated the competing processes driving changes in concentrations of speciated $PM_{2.5}$. Increases in primary PM (elemental carbon and primary organic aerosols) concentrations can be attributed to reductions in ventilation of the Los Angeles Basin. Increases in concentrations of semi-volatile species (e.g., nitrate) are mainly driven by increases in gas-to-particle conversion due to reduced atmospheric temperatures.

This work is detailed by Zhang et al. (2019).

Technology Assessment

Natural Exposure of Wall Products

The solar reflectance of wall products can change over time as they soil and weather. The research team selected 69 materials from industry partners to expose in California and 55 to expose across the United States. The exposed set included factory-applied coatings, aluminum-plastic composite cladding, vinyl siding, architectural fabrics, retroreflecting materials, and different types of field-applied coatings. The latter included paint formulations with different surface finishes, some containing cool pigments and/or dirt-resistant formulations. Partners prepared paint samples on different substrates – metal, wood, concrete, and fiber cement – and provided many specimens of each product for use in natural exposure trials and additional lab testing.

The project team exposed specimens vertically, facing west, over two years at three sites in California representing different climate zones and pollution levels: the LBNL campus in Berkeley, an industrial partner facility in Fresno, and the USC campus in Los Angeles. The team similarly exposed specimens at three United States sites used by the Cool Roof Rating Council over a five-year period: New River, Arizona; Miami, Florida; and Medina, Ohio. In the California exposure program, the team deployed specimens in March/April 2016 that were retrieved quarterly for analysis at LBNL. Specimens used in the United States exposure program were deployed in August 2016 and are being collected annually.

Factory-applied coatings have shown excellent performance in all locations used for California and United States exposure, with negligible changes in solar reflectance. Composite metal cladding also exhibited great retention of initial solar reflectance values. In both cases, the use of fluorinated polymers in their formulation may explain the high performance. Factory-applied coatings with textured surfaces (for example, embossed or crinkled) behaved similarly to those with smooth surfaces (Figure 3).

In the case of field-applied coatings, the retention of initial solar reflectance values varied with coating formulation, surface finish, and substrate. Field-applied coatings colored with cool pigments were significantly more reflective than similarly colored products incorporating conventional pigments.

This work is detailed in Appendix J of Levinson et al. (2019b).

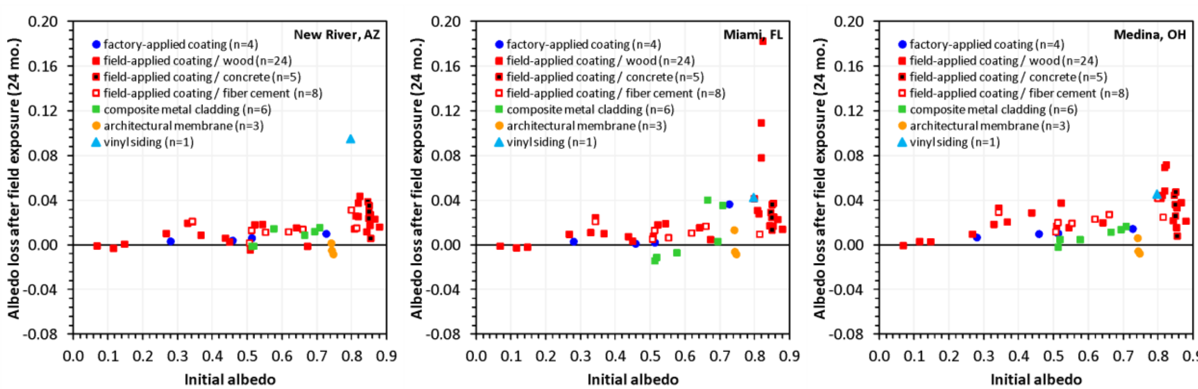

Figure 3. Most wall materials tested experienced minimal to modest albedo losses after 2 years of natural exposure at three sites across the United States in Arizona (hot/dry), Florida (hot/humid), and Ohio (temperate/polluted).

Self-cleaning and De-polluting Photocatalytic Materials

Two of the products evaluated in the natural exposure California and United States trials were architectural fabrics coated with photocatalytic titanium dioxide particles. A third material was an uncoated fabric of identical characteristics, used as a control. The project team evaluated specimens in the field and the laboratory.

The researchers exposed the photocatalytic specimens and their control vertically facing west in three sites in California representing different climate zones and pollution levels (Berkeley, Fresno, and Los Angeles) and in the three United States sites used by the Cool Roof Rating Council (CRRC): New River, Arizona (dry and hot weather); Miami, Florida (humid and hot weather); and Medina, Ohio (temperate weather with more pollution).

Photocatalytic materials exposed at the California sites showed negligible changes in solar reflectance over the course of two years. During the same period, the solar reflectance of the non-photocatalytic control decreased by 0.01—0.08. These changes reflected seasonal rainfall patterns, with soiling buildup during the dry season (April–November), and partial recovery of the initial solar reflectance value during the rainy season (December–March). These effects were more marked in Los Angeles and Fresno where ambient particulate matter levels are higher. The research team evaluated the de-polluting capacity of each photocatalytic product in the lab by measuring removal of nitrogen oxides (NO_x) from an airstream enriched in nitric oxide (NO). Tested samples included unexposed specimens and those retrieved from the field. The test conditions closely followed ISO Standard 22197-1: Test method for air-purification performance of semiconducting photocatalytic materials — Part 1: Removal of nitric oxide. Unexposed samples showed a higher NO_x-removal capacity, on the order of 0.7 micromoles of NO per hour (µmol NO h^{-1}), which was diminished by field exposure to values as low as 0.2 µmol NO h^{-1} for one of the products and 0.1 µmol NO h^{-1} for the other. During the rainy season the research team observed a recovery of the activity associated with a more effective cleaning of the catalyst surface.

This work is detailed in Appendix K of Levinson et al. (2019b).

Technology Development

Fluorescent Cool Pigments

Various pigments are used to formulate desired non-white colors that stay cooler in the sun than alternatives. These cool pigments provide a high near-infrared (NIR) reflectance in the solar infrared range of 700 nanometers (nm) to 2500 nm, and also a color specified by a reflectance spectrum in the 400 nm to 700 nm visible range. Still cooler materials can be formulated by also using fluorescence (photoluminescence) to re-emit some absorbed visible light as invisible NIR radiation.

Only a few pigments have demonstrated the potential for efficient fluorescence and also appear to have adequate (low) cost and durability. The first such pigment was ruby, which is composed of aluminum oxide doped with chromium. It can be used to produce red and pink colored materials. The second important class of materials includes the ancient pigment Egyptian blue. Egyptian blue has the chemical composition of $CaCuSi_4O_{10}$ – that is, calcium copper tetra-silicate. The most important other members of this class, the Egyptian blue family, have the same formula but with barium (Ba) or strontium (Sr) replacing calcium. The best performance to date with the Egyptian blue family has been achieved with the calcium and strontium compounds.

These blue pigments can also be blended with yellow pigment to achieve a green color, or with an orange pigment to obtain a blue-shade black.

Coatings incorporating either the ruby pigment or the Egyptian blue pigment can reject up to about 15% of incident sunlight via NIR-infrared fluorescence.

This work is detailed by Berdahl et al. (2016), Levinson et al. (2017), and Berdahl et al. (2018), and in Appendix N of Levinson et al. (2019b).

Retroreflectors

Raising a city's albedo (solar reflectance) increases the amount of incident sunlight returned to outer space, which cools cities and their buildings. Retroreflective cool walls could improve on diffusely reflecting cool walls by reflecting incoming beam radiation to the sun (if the retroreflection is three dimensional and ideal) or at least upwards (if the retroreflection is two dimensional and/or imperfect). For example, a retroreflective wall with albedo 0.60 would reflect 55 percent of incident light out of the city, while a Lambertian (perfectly diffuse) wall with the same albedo would only reflect 36 percent of incident light out of the city.

The greatest challenge in retroreflective wall design appears to be the need to operate at large incidence angles to reflect a substantial portion of incident sunlight. For example, on a summer day in Fresno, California, less than 37 percent of the beam radiation striking an east or west wall, and essentially none of that striking a south wall, will do so at an incidence angle less than or equal to 30°.

We explored wall retroreflector design using first-principle physics, ray tracing simulations, and goniometer measurements. Physics and simulations suggest that it will be difficult to achieve retroreflection at large incidence angle with surfaces that rely on total internal reflection, such as conventional safety films. This was confirmed with a simple goniometer that permits comparison of retroreflection to first-surface specular (mirrorlike) reflection, and with an advanced goniometer that measures solar spectral bi-directional reflectance intensity.

The most promising design was a two-surface retroreflector with orthogonal metal mirror faces. Attempts to fabricate this system by cutting and polishing grooves in an aluminum block indicate that residual surface roughness impedes retroreflection. Ongoing efforts focus on shaping aluminized Mylar film, a material with very high specular reflectance across the solar spectrum. This work is detailed by Levinson et al. (2019a) and in Appendix O of Levinson et al. (2019b).

Infrastructure Advancement

Cool-wall Application Guidelines

We created guidelines for the building- and climate-appropriate use of cool walls to conserve energy and reduce emissions of greenhouse gases and criteria pollutants across California and the United States. First, they explore the nature of cool walls by answering some fundamental questions such as "what is a cool wall?" and "why choose a cool wall?". Second, they provide a simple guide detailing the energy cost savings (or penalties) that arise from increasing wall reflectance in three common building categories—single-family home, medium office, and retail stand-alone. Third, they describe the operation and application of the Cool Surface Savings Explorer, a database tool that can report the cool-wall and cool-roof energy, energy cost, peak power demand, and emission savings simulated for many building categories. Fourth, they discuss how to adjust cool walls savings and penalties to account for shading and reflection by neighboring buildings by applying a “solar availability factor”.

These guidelines are presented in Appendix P of Levinson et al. (2019b).

Building Standards and Incentive Programs

Cool roofs can be found on buildings across the United States and are included in many city, state, and federal building codes/standards. To advance the adoption of cool walls, one can follow and learn from the cool-roof adoption model. Cool roofs were first incorporated in many codes/standards as credits and later became prescribed. The process was aided by the establishment of the Cool Roof Rating Council (CRRC). The CRRC is an independent organization that has developed methods for evaluating and labeling roofing products for reference by codes, standards, and rebates. It has also propagated the cool roof concept and its rating program.

ASHRAE 90.1 (2016), ASHRAE 189.1 (2014), California Green Building Standards Code; and Hawaii’s State Energy Conservation Code already reference cool walls.

We are exploring the feasibility of expanding the scope of the CRRC to include wall products. We also seek to collaborate with California utilities to develop cool-wall incentives, and to sponsor an assessment of how cool walls could be included in California’s Title 24 Building Energy Efficiency Standards.

This work is detailed in Appendix R of Levinson et al. (2019b).

Summary

Simulations indicate that cool walls save energy and reduce emissions in buildings across California and about half of the United States (climate zones 1 – 4). Thermal comfort changes for pedestrians walking next to a cool wall are small and will go unnoticed by most people. In Los Angeles, cool walls provided similar urban air temperature reductions as cool roofs per unit albedo in wall or roof albedo; cool walls and cool roofs each also reduce ozone concentration while increasing the concentration of $PM_{2.5}$.

After 24 months of natural exposure at three sites across California and another three sites across the U.S., cool-wall materials exhibited little to no loss in solar reflectance. Factory-applied coatings showed excellent performance in all locations, while the reflectance retention of field-applied coatings varied with coating formulation, surface finish, and substrate. Fluorescence (re-emission at longer wavelengths of light absorbed at shorter wavelengths) can expand the palette of colors for cool-wall products, while retroreflection (reflection of incident radiation toward its source) can increase the fraction of wall-reflected light that escapes the city.

We developed cool-wall guidelines to identify their building- and climate-appropriate use to conserve energy and reduce emissions of greenhouse gases and criteria pollutants across California and the United States. We identified existing cool-wall measures in building codes/standards and initiated contact with key stakeholders to develop new cool-wall measures, pilot credits, certification, and rebates. We also collaborated with the Cool Roof Rating Council to explore expansion of its program to include wall products.

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