

Energy Research and Development Division  
**FINAL PROJECT REPORT**

# **Solar-Reflective “Cool” Walls: Benefits, Technologies, and Implementation**

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Gavin Newsom, Governor

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## PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities - Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company - were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

*Solar-Reflective "Cool" Walls: Benefits, Technologies, and Implementation* is the final report for the Solar-Reflective "Cool" Walls: Benefits, Technologies, and Implementation project (Contract Number EPC-14-010) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916-327-1551.

## ABSTRACT

Raising the albedo (solar reflectance) 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. This project 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 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.

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 most of the southern half of the United States (that is, in U.S. climate zones 1–4). Natural exposure trials conducted at three sites in California and another three sites 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, convened a stakeholder workshop, and created a working group. Ongoing efforts seek to introduce or expand cool-wall provisions in building energy standards, green building programs, and energy efficiency incentive programs, and to develop a cool-wall product rating system.

Keywords: cool walls, cool roofs, solar reflectance, albedo, energy savings, peak power demand reduction, urban cooling, heat island mitigation, natural exposure, paint, cladding, fluorescent pigments, retroreflectors, guidelines, building energy standards, green building programs, utility incentives, product rating, EnergyPlus, TUF-IOBES, WRF

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# EXECUTIVE SUMMARY

## Introduction

California's total consumption of energy is the second highest in the nation, according to the United States Energy Information Administration. However, in terms of energy use per person, California ranked 48th (as of 2016), due in part to the state's aggressive energy efficiency efforts. Over the last 40 years, California's appliance and building efficiency standards have saved consumers billions of dollars in energy costs while helping to reduce greenhouse gas emissions and other pollutants that can harm the environment and human health.

In 2015, California passed the Clean Energy and Pollution Reduction Act (Senate Bill 350, de Leon, Chapter 547, Statutes of 2015) which established new clean energy, clean air, and greenhouse gas reduction goals for 2030 and beyond. Among other things, the act required the state to double statewide energy efficiency savings in electricity and natural gas by 2030.

One way to increase savings in buildings is to improve the efficiency of the building envelope - the roof, subfloor, exterior doors, windows, and exterior walls. For example, since 2005 California's Title 24, Part 6 Building Energy Efficiency Standards have prescribed the use of solar-reflective "cool" roofs. Cool roofs absorb less sunlight than conventional roofs, thereby reducing the need for air conditioning.

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 cool roofs. These efforts have been supported by the Energy Commission, the California Air Resources Board, Pacific Gas and Electric Company, the United States Environmental Protection Agency, and the United States Department of Energy. 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 in voluntary incentive programs like Leadership in Energy and Environmental Design; and thousands of cool roofing products sold in the United States and abroad.

Cool *walls* are also promising. Increasing the solar reflectance, or "albedo," of the building envelope reduces its solar heating, which saves electricity and reduces power demand during peak hours by decreasing the need for air conditioning in warm weather. Raising envelope albedo can also cool the outside air, boosting energy savings and power demand reduction by decreasing the difference between the inside and outside air temperatures. It can also slow global warming by reflecting unwanted solar radiation out of the atmosphere, providing "global cooling."

Lowering urban surface and air temperatures also improves air quality by slowing the reactions that produce smog. High-albedo "cool" surfaces may also increase the need for heating energy (typically natural gas) in the heating season.

Although the solar energy per unit area striking an east or west wall in summer is about half of what hits a horizontal roof, California homes typically have about half as much wall insulation as roof insulation. For example, in a Fresno home with wood-framed walls, 2013 Title 24

requires R-38 (38 h·F·ft<sup>2</sup>/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 – 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 (such as paint or stucco) or cladding (covering with another material) 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.

## **Project Purpose**

Prior to this project, cool-wall benefits had not been rigorously quantified and existing studies of the energy-saving potentials of cool walls, and the effects of cool walls on the energy uses of neighboring buildings, or on the urban environment, were limited. The state of cool-wall technology had not been assessed through systematic rating of the initial and long-term performances of cool-wall products, and little infrastructure existed to promote the building- and climate-appropriate use of cool-wall surfaces, such as building energy-efficiency standards and incentive programs prescribing or crediting the use of cool walls.

Therefore, the research team’s goals were to:

- Quantify the energy savings, peak demand reduction, urban cooling, and air quality improvements attainable from cool walls in California, 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.

## **Project Process**

A team of researchers from 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 research team undertook five parallel technical tasks, numbered 2 through 6.

- Task 2 used building-energy simulations to quantify how increasing wall albedo affects the cooling, heating, and lighting energy uses of a building and its neighbors. The simulations examined cool-wall savings for an isolated building and for a central building with neighbors. The researchers analyzed the extent to which the walls of a neighboring building shade and reflect sunlight to those of a central building to develop correction factors that can be applied to cool-wall savings simulated for an isolated building.

- Task 3 quantified the co-benefits (or penalties) of cool walls. The research team used building-, neighborhood-, and city-scale energy simulation models to assess pedestrian comfort, evaluate outdoor air temperature reductions, and explore how cool walls affect the energy-saving benefits of cool pavements. The team also examined air temperature reductions in an unconditioned home. In addition, researchers assessed the ability of a subset of cool-wall coating materials to remove nitrogen oxide pollution from the air in the lab, and estimated air quality impacts in urban areas using wall areas derived from a real-world building dataset.
- Task 4 assessed the performance of available and prototype cool-wall technologies, primarily the ability to reflect sunlight, through field and laboratory measurements. The project team developed metrics and methods to evaluate solar reflectance, de-pollution efficacy, and other material properties, then measured how solar reflectance changed when products were exposed outdoors at sites across California and the United States. Researchers paid special attention to the performance of self-cleaning and de-polluting photocatalytic materials.
- Task 5 explored innovative cool-wall technologies, including self-cleaning materials, fluorescent cool pigments, and retroreflective materials.
- Task 6 promoted the infrastructure needed to advance the climate- and building-appropriate use of cool walls. This included developing cool-wall application guidelines, hosting a cool-wall stakeholder workshop, and exploring and enhancing the treatment of cool walls in building standards and incentive programs.

## **Project Results**

### **Benefit Analysis**

The researchers found that cool walls provide annual energy savings, energy cost savings, peak power demand reduction, annual emission reduction, and summer heat island mitigation benefits comparable to those yielded by cool roofs. Highlights of the researchers' findings include:

- Isolated-building simulations of two residential and eight commercial building prototypes configured according to current, 1980s, and pre-1980 construction practices predicted that raising wall albedo to 0.60 (dull- or off-white wall) from 0.25 (conventional wall) will save energy, reduce energy cost, lower peak power demand, and decrease emissions of greenhouse gases (like carbon dioxide) and criteria pollutants (such as nitrogen oxides and sulfur dioxide) across California. These results are based on total annual heating, ventilation, and air conditioning energy use, and incorporate both cooling savings and heating penalties.
- Cool walls lowered annual heating, ventilation, and air conditioning energy cost per unit modified surface area by \$0.07-\$1.70 per square meter in single-family homes, \$0.10-\$2.10 per square meter in medium offices, and \$0.00-\$4.30 per square meter in stand-alone retail stores. Cool walls also reduced whole-building annual heating, ventilation, and air conditioning energy use by 3 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. Finally, cool walls decreased annual heating, ventilation, and air conditioning carbon dioxide equivalent emissions per unit modified surface area by 0.0 kilograms to 3.4 kilograms per square meter in single-family homes, 0.17 kilograms to 4.5 kilograms per square meter in medium offices, and 0.16 kilograms to 9.2 kilograms per square meter in stand-alone retail stores.

- The simulations found that energy use, energy cost, and emission savings from the oldest vintage buildings were generally three to six times greater than those from the new vintage. The cool-wall savings from the oldest vintage are important because they represent more than 60 percent of California's existing building stock.
- Isolated-building simulations found that cool walls also save energy, reduce energy cost, lower peak power demand, and decrease emissions in United States climate zones 1 - 4, which is roughly the southern half of the country.
- One can multiply isolated-building cool-wall savings by a "solar availability factor" to account for shading and reflection by neighboring walls. A solar availability factor is the ratio of sunlight striking the central (modeled) building wall in the presence of the neighboring wall to that received in the absence of the neighboring wall. 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.
- Simulations of building arrays found that thermal comfort changes for pedestrians walking next to a cool wall are small and will go unnoticed by most people.
- Simulations of building arrays found that cool walls decrease air temperature inside unconditioned buildings. Since buildings without air conditioning generally feel cold at night and warm during the day, the interior air temperature reduction corresponds to a slight worsening of thermal comfort at night and an improvement of thermal comfort during the day. However, the temperature changes are so small that they will go unnoticed by most people.
- Urban climate simulations found that in summer in Los Angeles County, the ratio of the daily average air temperature reduction from cool walls to that from cool roofs is about 86 percent, making their heat island mitigation benefits comparable. Cool walls (roofs) can reduce summertime daily average canyon air temperature - i.e., the temperature of the air in the U-shaped space formed by buildings on opposite sides of a street - by 0.048—0.054 Kelvin (0.058—0.060 Kelvin) per 0.10 increase in wall (roof) albedo.

### **Technology Assessment**

The research team found that there are many cool-wall products available commercially, and that they tend to stay clean and reflective.

- After 24 months of exposure at the three California sites, observed albedo losses for all 69 wall materials did not exceed 0.10, and for 67 of 69 materials did not exceed 0.05. (Albedo is measured on a scale of 0 to 1, where 0 means that no sunlight is reflected

and 1 means that all sunlight is reflected.) After 2 years of exposure at the three United States sites, albedo losses for 51 of 55 wall materials did not exceed 0.05.

- Researchers consider the albedo losses observed to date at the California and United States sites modest when compared to results from similar studies of roofing materials. A 3-year study conducted in 2010 by the same research group (data unpublished) exposed 27 roofing materials at the same three United States sites at 5° tilt (low-slope roofing) and 45° tilt (high-slope roofing). After 24 months of exposure, roof albedo losses ranged as high as 0.28.
- In the 77 materials tested, the researchers observed high albedo retention in fluoropolymer-based coatings and products with “self-cleaning” or “dirt-resistant” formulations.
- Two photocatalytic and self-cleaning architectural fabrics showed excellent year-round retention of initial albedo, in contrast with a non-photocatalytic control that showed significant soiling accumulation during the dry season and modest cleaning during the rainy season. The two photocatalytic fabrics were tested for their ability to remove nitrogen oxides from the urban atmosphere. In most cases, a measurable nitric oxide removal efficiency was partially offset by the formation of nitrogen dioxide as oxidation byproduct. However, a net nitrogen oxide deposition was present in most cases.

### **Technology Development**

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 light toward its source) can increase the fraction of wall-reflected light that escapes the city.

- The research team built a calorimetric instrument that measures effective solar reflectance, or the fraction of incident solar energy rejected by the combination of reflectance and fluorescence.
- Results showed that pink-red coatings colored with a fluorescent ruby pigment (aluminum oxide doped with chromium) can reject up to 15 percent of incident solar energy by invisibly re-emitting absorbed visible light. Blue, green, and blue-black coatings colored with fluorescent Egyptian blue or Han blue pigments provide a similar benefit.
- The fluorescent blue pigments may also be useful in fabrication of high-performance luminescent solar concentrators for photovoltaic panels.
- 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.
- The most promising retroreflector design was a two-surface retroreflector with perpendicular metal mirror faces.

## **Infrastructure Development**

The research team is working to expand and improve building energy standards, green building programs, and energy efficiency incentive programs that already consider cool walls or cool roofs.

- Research showed that there are existing cool-wall measures in building codes/standards, green building programs, and incentive programs. However, these measures should be enhanced to maximize cool-wall benefits by revising specifications and/or expanding to more climate zones.
- There is interest and momentum to develop (a) a cool-wall rating program; (b) new cool-wall measures in building codes/standards, such as California's Building Energy Efficiency Standards; (c) product incentives to manufacturers or consumers; (d) United States Environmental Protection Agency ENERGY STAR® certification; and (e) a United States Green Building Council Leadership in Energy and Environmental Design pilot credit.
- As planned, the researchers hosted a cool walls workshop for stakeholders, and developed cool-wall guidelines to specify the use of and benefits of cool walls.

## **Benefits to California**

Based on this project, the researchers expect cool walls to yield ratepayer benefits such as greater electricity reliability, lower costs, and increased safety by saving energy, reducing peak power demand, cooling the urban environment, and reducing harmful urban air pollution. Results highlighted above show that raising wall albedo lowers annual heating, ventilation, and air conditioning energy cost and emissions for both residential and nonresidential buildings across California, and as a bonus across roughly the southern half of the United States. A case study in Los Angeles County found that the urban heat island mitigation (outside air temperature reduction) benefits of cool walls are comparable to those of cool roofs.

One can ballpark statewide energy cost savings and greenhouse gas emission reductions by focusing on the benefits accrued to single-family homes, which make up the largest share of California's building stock. County assessor records indicate that the combined floor space of single-family homes statewide is about 1.2 billion square meters, while the single-family home prototype used in this project's simulations has a ratio of net wall area (gross wall area minus openings) to floor area of 86 percent. Therefore, the combined net wall area of single-family homes in California is about 1.1 billion square meters. After considering building age and adjusting for shading and reflection by neighboring buildings, the average annual heating, ventilation, and air conditioning energy cost savings and carbon dioxide equivalent emission reduction per unit area of cool wall for single-family homes in California are roughly \$0.50 per square meter and 0.5 kilograms per square meter, respectively. Multiplying each rate by the statewide net wall area yields for the stock of single-family homes annual energy cost savings of about \$500 million, and annual carbon dioxide equivalent emission reductions of about 0.5 million metric tons. Further savings would accrue from cool walls on other buildings, including but not limited to offices and stores.

The results of this project strongly suggest the need for follow-up studies, including:

- A Code and Standards Enhancement initiative for inclusion of cool walls in the 2022 edition of the California Title 24 building energy efficiency standards.
- Cool-wall measurement and demonstration projects for residential and nonresidential buildings in California.
- Continuation of the United States natural exposure trials through their conclusion in 2021.
- Adaptation to wall materials of the lab-aging practice currently available for roofing products (ASTM Standard D7897).





# CHAPTER 1:

## Introduction

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### Cool-wall Technology

Increasing the solar reflectance, or albedo, of the building envelope reduces its solar heating, which saves electricity and reduces power demand during peak hours by decreasing the need for air conditioning in warm weather. Raising envelope albedo can also cool the outside air, boosting energy savings and demand reduction by decreasing the difference between the inside and outside air temperatures. It can also slow global warming by reflecting unwanted solar radiation out of the atmosphere, providing “global cooling.”

Lowering urban surface and air temperatures also improves air quality by slowing the reactions that produce smog. High-albedo “cool” surfaces may also increase the need for heating energy (typically natural gas) in the heating season.

High wall albedo can be attained with a reflective coating (such as paint or stucco) or cladding. Cool-wall products available today include light-colored paints that reflect 60 percent to 90 percent of sunlight when new, but may lose reflectance as they soil; and darker “cool colored” paints that come in a wide palette, but typically reflect less than 50 percent of sunlight when new.

While the solar energy per unit area striking an east or west wall in summer is about half that incident on a horizontal roof, California homes typically have about half as much wall insulation as roof insulation. For example, in a Fresno home with wood-framed walls, 2013 Title 24 requires R-38 (38 h·F·ft<sup>2</sup>/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 – that is, the extent to which it reduces unwanted heat conduction into the conditioned space – is comparable to that of increasing roof albedo.

### Project Objective and Scope

Solar reflective “cool” roofs have been established in California as an effective building energy efficiency measure. Cool walls are also promising. However, prior to this project, cool-wall benefits had not been rigorously quantified, the state of cool-wall technology had not been assessed, and little infrastructure for advancing the building- and climate-appropriate use of cool wall surfaces existed. Therefore, the research team set out to (a) through modeling, quantify the energy savings, peak demand reduction, urban cooling, and air quality improvements attainable from cool walls in California; (b) collaborate with industry to assess the performance of existing cool-wall technologies, and to develop innovative cool-wall solutions; and (c) 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.

The results of this research will provide ratepayer benefits such as greater electricity reliability, lower costs, and increased safety by saving energy, reducing peak power demand, cooling the urban environment, and reducing harmful urban air pollution.

## **Overview of Project Technical Tasks**

This project had five technical tasks, numbered 2 through 6:

- Task 2: Quantify through building-energy simulations how increasing wall albedo affects the cooling, heating, and lighting energy uses of a building and its neighbors.
- Task 3: Quantify through heat transfer analysis and climate modeling how cool walls affect the urban environment (e.g., air temperature, mean radiant temperature, and air quality) and enhance the benefits of solar-reflective pavements.
- Task 4: Assess through field and laboratory measurements the performance (initial albedo, aged albedo, and - where applicable - de-pollution efficacy) of available and prototype cool-wall technologies.
- Task 5: Collaborate with industry to develop innovative cool-wall solutions with higher and/or more directional reflectance.
- Task 6: Promote the infrastructure needed to promote the appropriate use of cool walls, including guidelines, product rating, utility rebates, ENERGY STAR qualification, and credits in building energy standards and energy-efficiency programs.

Task activities and outcomes are summarized in Chapters 2 through 6, with details provided in Appendices A through R.

# CHAPTER 2:

## Quantifying Cooling, Heating, and Lighting Energy Use Savings (Task 2)

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Task 2 quantified how increasing wall albedo affects the cooling, heating, and lighting energy uses of a building and its neighbors through building-energy simulations. The research team simulated cool walls savings for an isolated building with EnergyPlus in Task 2.1, while savings for a building with neighbors were modeled with the Temperature of Urban Facets - Indoor Outdoor Building Energy Simulator (TUF-IOBES) in Task 2.2. Researchers analyzed the extent to which the walls of a neighboring building shaded and reflected sunlight to those of a central building in Task 2.3 to develop correction factors that can be applied to cool-wall savings simulated for an isolated building.

### Simulated Heating, Ventilation, and Air Conditioning Energy Savings in an Isolated Building (Task 2.1)

Solar-reflective “cool” walls reduce absorption of sunlight by the building envelope, which may decrease cooling load in warm weather and increase heating load in cool weather. 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. Changes to annual energy cost and energy-related emissions vary with local energy prices and emission factors. The project researchers 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 (solar reflectance), 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 [CO<sub>2</sub>], carbon dioxide equivalent [CO<sub>2</sub>e], nitrogen oxide [NO<sub>x</sub>], and sulfur dioxide [SO<sub>2</sub>]) 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. 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.

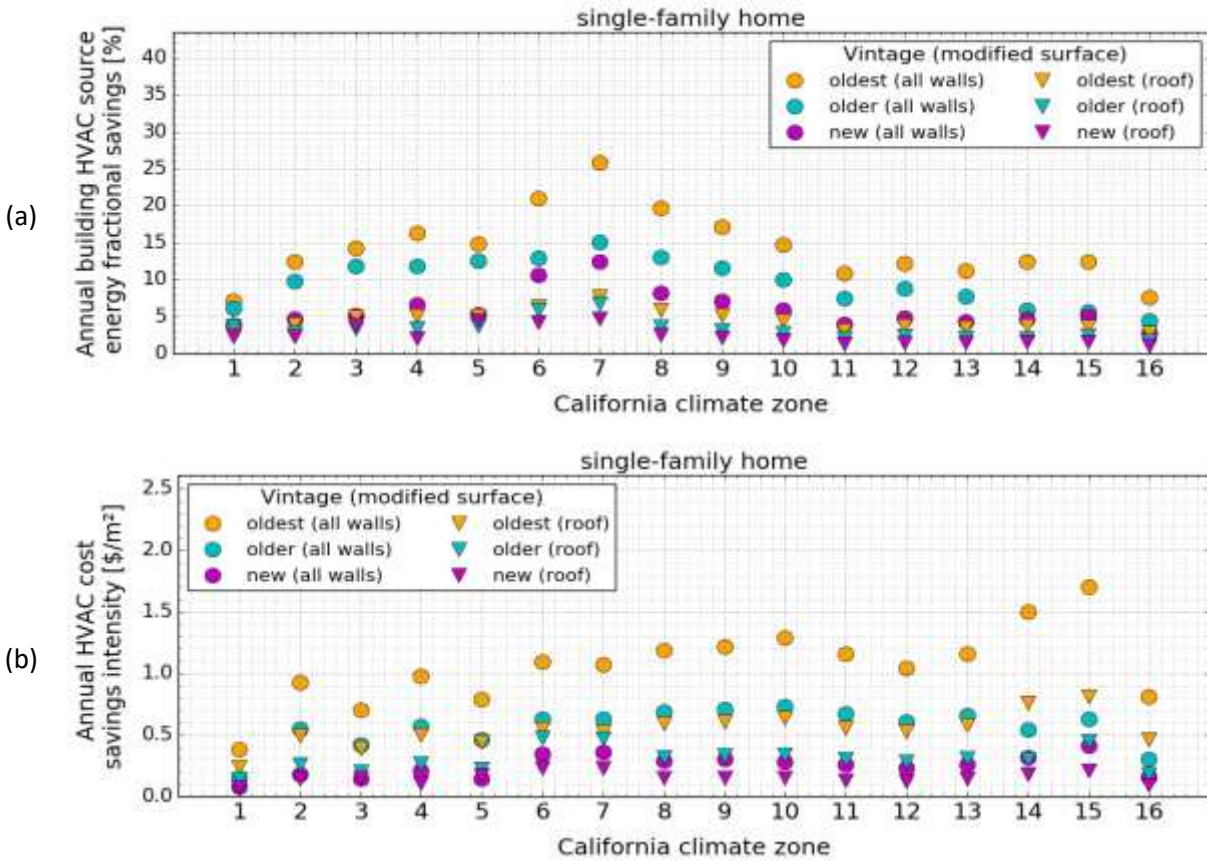
In California, cool walls lowered annual energy cost intensity (per modified surface area) \$0.07/square meter ( $\text{m}^2$ ) to \$1.7/ $\text{m}^2$  in single-family homes, \$0.10/ $\text{m}^2$  to \$2.1/ $\text{m}^2$  in medium offices, and \$0.0/ $\text{m}^2$  to \$4.3/ $\text{m}^2$  in stand-alone retail stores. In warm United States climates (zones 1A through 4B) cool walls lowered annual energy cost intensity \$0.1/ $\text{m}^2$  to \$1.1/ $\text{m}^2$  in single-family homes, \$0.0/ $\text{m}^2$  to \$1.8/ $\text{m}^2$  in medium offices, and \$0.0/ $\text{m}^2$  to \$3.7/ $\text{m}^2$  in stand-alone retail stores.

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). The ratio of whole-building savings from cool walls (raising the albedo of all four walls) to that from a cool roof also depends on the ratio of net wall area (wall area excluding openings) to roof area. In California, the ratio of whole-building cool-wall savings to cool roof savings was 1.5 to 3.5 in single-family homes, 0.40 to 1.0 in medium offices, and 0.20 to 0.85 in stand-alone retail stores. In warm United States climates (zones 1A through 4B), the ratio of whole-building cool-wall savings to cool roof savings was 1.1 to 3.0 in single-family homes, 0.20 to 1.9 in medium offices, and 0.30 to 2.1 in stand-alone retail stores.

Single-family homes are the most common buildings in California and the United States. Figure 1 shows annual whole-building HVAC fractional savings and annual energy cost savings intensity (per unit of modified area) for homes of different vintages in California upon raising the albedo of all walls by 0.35 or upon increasing roof albedo by 0.30. Figure 2 shows the same information for the United States.

The complete study is presented in the Task 2.1 report, Simulated Heating, Ventilation, and Air Conditioning Energy Savings in an Isolated Building (Appendix A). An article based on this work has been published in *Energy and Buildings* (Rosado and Levinson 2019).

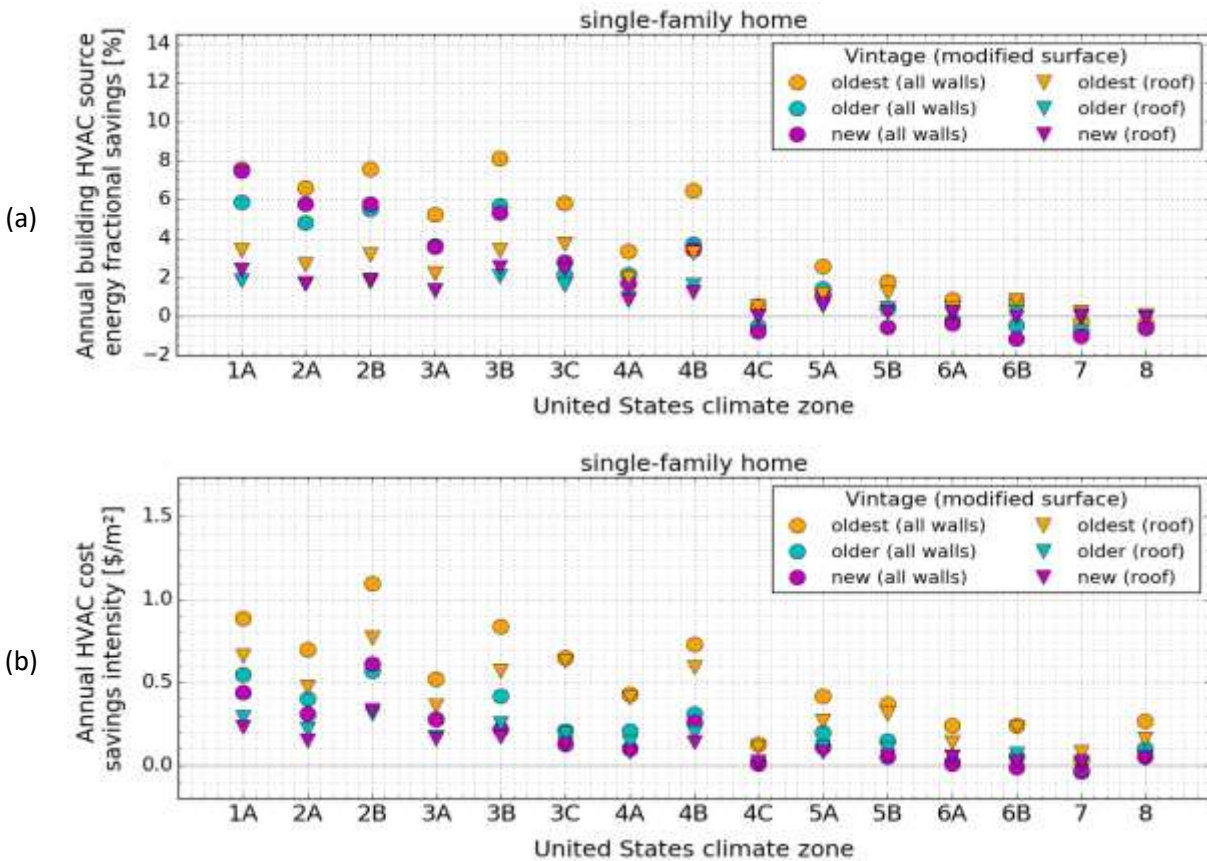
**Figure 1: Annual Heating, Ventilation, and Air Conditioning Savings for Single-family Homes in California**



EnergyPlus simulations of annual HVAC savings in California homes by climate zone and vintage, showing (a) whole-building source energy fractional savings and (b) energy cost savings intensity.

Source: Lawrence Berkeley National Laboratory

**Figure 2: Annual Heating, Ventilation, and Air Conditioning Savings for Single-family Homes in United States**



EnergyPlus simulations of annual HVAC savings in United States homes by climate zone and vintage, showing (a) whole-building source energy fractional savings and (b) energy cost savings intensity.

Source: Lawrence Berkeley National Laboratory

## Effect of Neighboring Cool Walls on Heating, Ventilation, and Air Conditioning Loads (Task 2.2)

High-albedo (“cool”) walls are exterior building walls with surface (usually paint) properties that increase reflection of solar radiation. Cool walls also increase heat transfer between urban surfaces. Consider a central building with neighbors. Raising the albedo of neighboring walls can increase reflection of downwelling sunlight – that is, light traveling downward from the sun or sky – from neighboring walls to the walls and windows of the central building. This can increase cooling load, decrease heating load, and reduce the need for artificial lighting in the central building. Theory shows that the solar heat gain of a central building wall in a regularly spaced array of rectangular buildings is proportional to the area of the modified neighboring building walls, the increase in neighboring wall albedo, the view factor from the neighboring

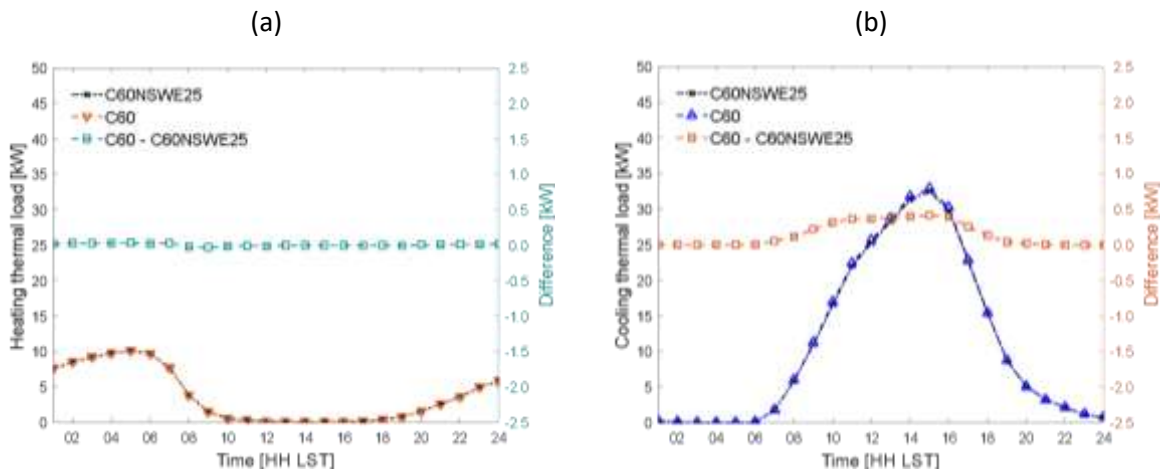
wall to the central wall, and the solar absorptance<sup>1</sup> (one minus albedo) of the central building wall. This analysis supplements the Task 2.1 report presented in Appendix A by using the Temperature of Urban Facets - Indoor Outdoor Building Energy Simulator (TUF-IOBES) model to account for building-to-building interactions on building heating and cooling loads.

The indoor and outdoor building thermal environments in a three-dimensional urban area with a 5 × 5 array of identical buildings about 23 meters apart are simulated. The indoor and outdoor energy balances are dynamically coupled and forced by outdoor weather conditions, building envelope properties, urban material properties, indoor heat sources, and HVAC systems. Building energy use effects of cool walls are quantified for a pre-1978 apartment building in Fullerton, California (Orange County, California climate zone 8).

Both diffusely reflecting and retroreflective neighboring cool walls are examined. Retro-reflective cool walls improve upon diffusely reflecting cool walls by reflecting incoming beam radiation upwards. Retroreflective walls boost the fraction of sunlight reflected out of the urban canyon.<sup>2</sup>

Figure 3a shows that daytime heating loads are near zero so changing wall albedo does not modify the daytime heating load. Figure 3b shows that nighttime cooling loads are small so changing wall albedo mostly influences the daytime cooling load.

**Figure 3: Heating and Cooling Load Cycles for Central Building with Neighbors**



TUF-IOBES simulations of average diurnal cycles of (a) heating load and (b) cooling load for the central building – a pre-1978 apartment building in Fullerton, California. The results show the effect of raising the albedo of the neighboring walls when all central walls are cool. C60NSWE25: All central building walls are cool (diffuse reflectors with albedo 0.60), while neighboring walls are conventional (diffuse reflectors with albedo 0.25). C60: All central and neighboring building walls are cool.

Source: University of California, San Diego

<sup>1</sup> The absorptance of a surface is its effectiveness in absorbing radiant energy. A surface with solar absorptance 0 absorbs no sunlight, while a surface with absorptance 1 absorbs all sunlight.

<sup>2</sup> Lambertian (perfectly diffuse) reflection distributes reflected radiation equally in all directions. Retroreflection reflects radiation back to the source. See Figure 18 for an illustration.

Raising the neighboring wall albedo increases annual cooling load of the central building by 1.2 megawatt hours (MWh) (1.2 percent) due to increased solar radiation reflected from the neighboring buildings towards the central building. The negligible effect of cool walls on annual heating loads is likely an artifact of the way that our model predicts essentially zero daytime heating load.

The cooling-load increase for the central building upon raising the albedo of all neighboring walls (1.2 MWh or 1.2 percent) is smaller than the cooling-load decrease for the central building upon raising the albedo of its own walls (5.0 MWh, or 5.0 percent). Considering the interactions between buildings, the combined cool-wall effect on all buildings is net positive.

Using retroreflective cool walls (albedo 0.60) on all neighboring buildings lowers the annual cooling load of the central building by 3.3 MWh (4.0 percent) with respect to using Lambertian cool walls (also albedo 0.60) on all neighboring buildings. However, the cooling benefit comes at the expense of a 0.9 MWh (2.6 percent) increase in annual heating load. The net effect of changing to a retroreflective wall from a Lambertian wall on the central building is a reduction in average solar radiation incident on walls, which decreases cooling loads and increases heating loads.

The complete study is presented in the Task 2.2 report *Effect of Neighboring Cool Walls on Heating, Ventilation, and Air Conditioning Loads* (Appendix B).

## **Using Solar Availability to Scale Heating, Ventilation, and Air Conditioning Energy Savings (Task 2.3)**

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. This study evaluates the solar availability factor of a central building wall, defined 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; Figure 4), 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). Figure 5 presents results for four representative aspect ratios – 0.2, 1, 2, and 10.



**Figure 4: Canyon Aspect Ratio (Building Height / Separation)**



**Scale drawings of canyon aspect ratios 0.2, 1, 2, and 10.**

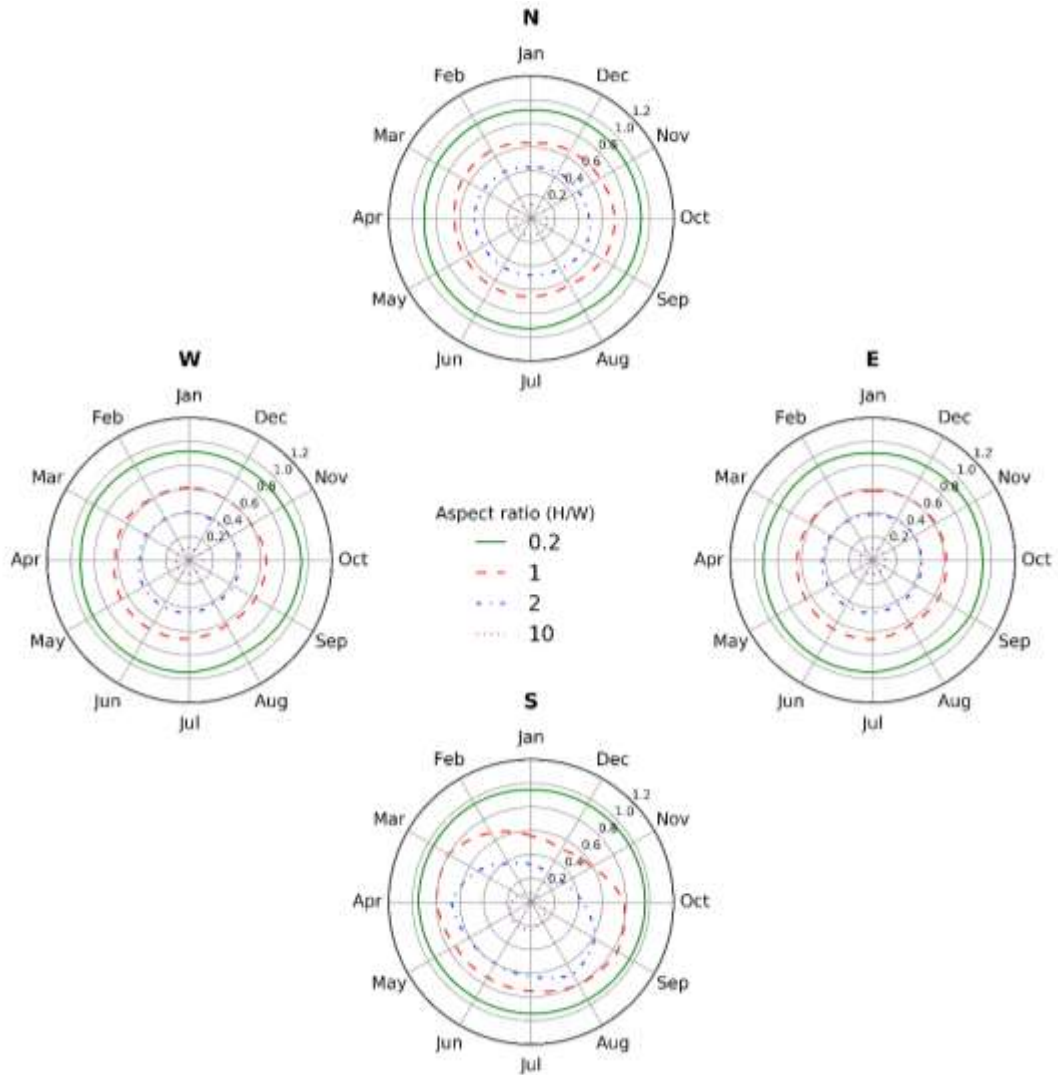
Source: Lawrence Berkeley National Laboratory

In Fresno, California, monthly solar availability factor ranges from 0.90 to 0.96 for central walls facing north, east, south, or west when the aspect ratio is 0.2 (two-story single-family homes across a street) and both the central and neighboring walls are conventional (albedo 0.25). These solar availability factors are close to unity because the sun-facing wall is rarely shaded in a canyon with low aspect ratio. Monthly solar availability factors decrease as aspect ratio rises, falling to 0.06 - 0.24 at an aspect ratio of 10 (adjacent 10-story buildings on the same side of the street). Seasonal variation in monthly solar availability factor also increases with aspect ratio, and is greatest for south central walls (Figure 5).

Percentage increases in solar availability factor (equivalent to percentage increases in irradiance) for a central wall upon raising the albedo of a neighboring wall to 0.60 (cool) from 0.25 (conventional) are modest for east, south, and west central walls, ranging 0.9 - 4.1 at aspect ratio 0.2 to 11.0 - 32.9 at aspect ratio 10. Percentage increases for a north central wall are greater because a north wall receives little beam sunlight and faces a well-illuminated south wall.

The complete study is presented in the Task 2.3 report, *Using Solar Availability to Scale Heating, Ventilation, and Air Conditioning Energy Savings* (Appendix C). An article based on this work has been published in *Solar Energy* (Levinson 2019).

**Figure 5: Monthly Solar Availability Factors in Fresno, California**



Monthly solar availability factors for a north (N), east (E), south (S), or west (W) conventional central wall (albedo 0.25) with a conventional neighboring wall (albedo 0.25), shown for canyon aspect ratios 0.2, 1, 2, and 10 in Fresno, California. Ground albedo was set to 0.20.

Source: Lawrence Berkeley National Laboratory

# CHAPTER 3:

## Quantifying the Environmental and Energy Co-benefits of Cool Walls (Task 3)

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Task 3 quantified the co-benefits (or penalties) of cool walls. Task 3.1 used the TUF-IOBES model to assess pedestrian comfort, while Task 3.2 applied the Weather Research and Forecasting Model (WRF) to evaluate outdoor air temperature reductions. EnergyPlus simulations in Task 3.3 explored how cool walls affect the energy-saving benefits of cool pavements. Task 3.4 used TUF-IOBES to assess air temperature reductions in an unconditioned home. Task 3.5 assessed the city-level NO<sub>x</sub> deposition from adopting self-cleaning walls using laboratory-measured dry deposition velocities and wall area derived from a real-world building dataset.

### **Pedestrian Mean Radiant Temperature and Thermal Comfort (Task 3.1)**

Walls are made more reflective to reduce building solar heat gain, but cool walls also 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.

The research team analyzed thermal comfort for homogeneous neighborhoods of either multi-family residences, single-family residences, or medium office buildings. 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 5 feet 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.

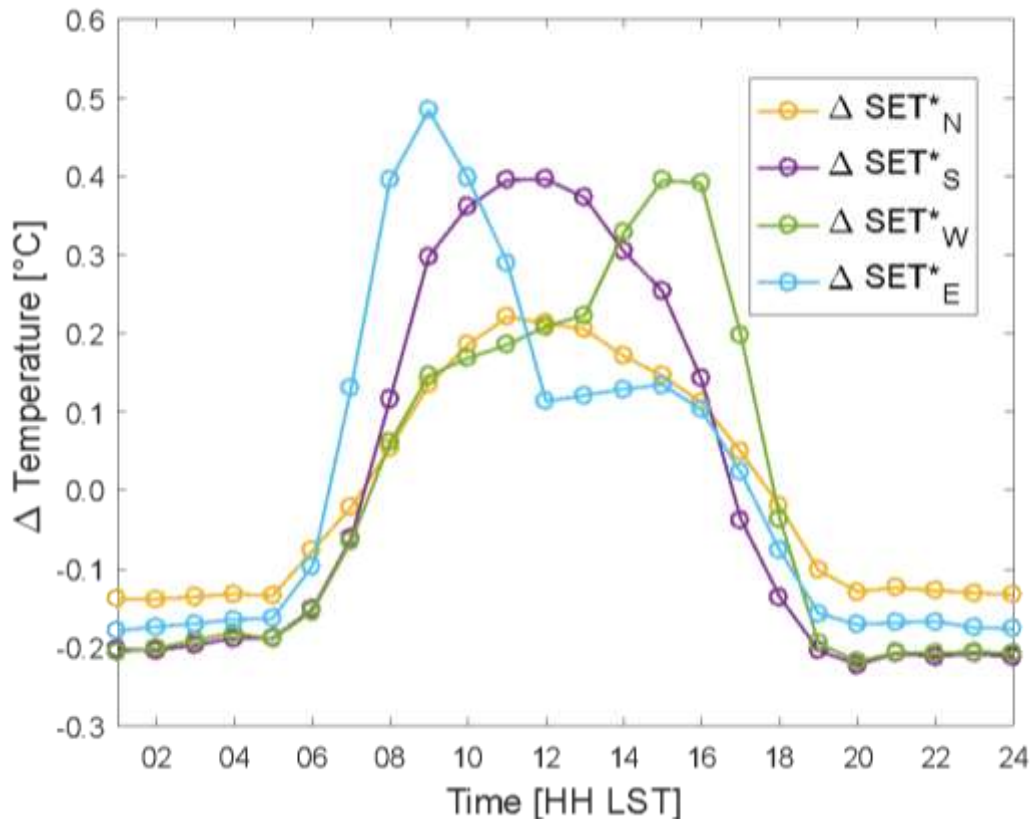
The insulation provided by clothing is assumed to vary between winter and summer: from November to April, the pedestrian is assumed to wear trousers, a T-shirt, and a long-sleeve sweater; from May to October, the pedestrian is assumed to wear trousers and a T-shirt.

The researchers calculated longwave radiation incident on the pedestrian using wall, window, and ground thermal emittances of 0.90, 0.84, and 0.95, respectively. Conventional (base case)

and cool (reflective) walls were assigned albedos (shortwave reflectances) of 0.25 and 0.60, respectively. The albedo of the ground was set to 0.10 (aged asphalt concrete).

Near a multi-family residence in Fullerton, California (Orange County; California climate zone 8) 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. Figure 6 shows that the pedestrian thermal comfort change induced by raising wall albedo is small. 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.

**Figure 6: Increase in Standard Equivalent Temperature upon Raising Wall Albedo**



Average (over the year) SET\* increase  $\Delta SET^*$  when raising wall albedo to 0.60 (cool) from 0.25 (conventional) for the multi-family residence in Fullerton, California.

Source: University of California, San Diego

SET\* rises during daytime result from increased reflection of solar radiation towards the pedestrian. But cool walls also lower local air temperatures which counteracts radiative effects. The 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.

Since thermal sensation in California is generally too warm, the SET\* rise corresponds to a slight worsening of thermal comfort. However, the SET\* rise is so small that it will go unnoticed by most people. Also, the largest daytime SET\* increases occur in winter when cool walls improve thermal comfort.

The complete study is presented in the Task 3.1 report, Pedestrian Mean Radiant Temperature and Thermal Comfort (Appendix D).

## **Urban Climate Impacts of Cool Walls (Task 3.2)**

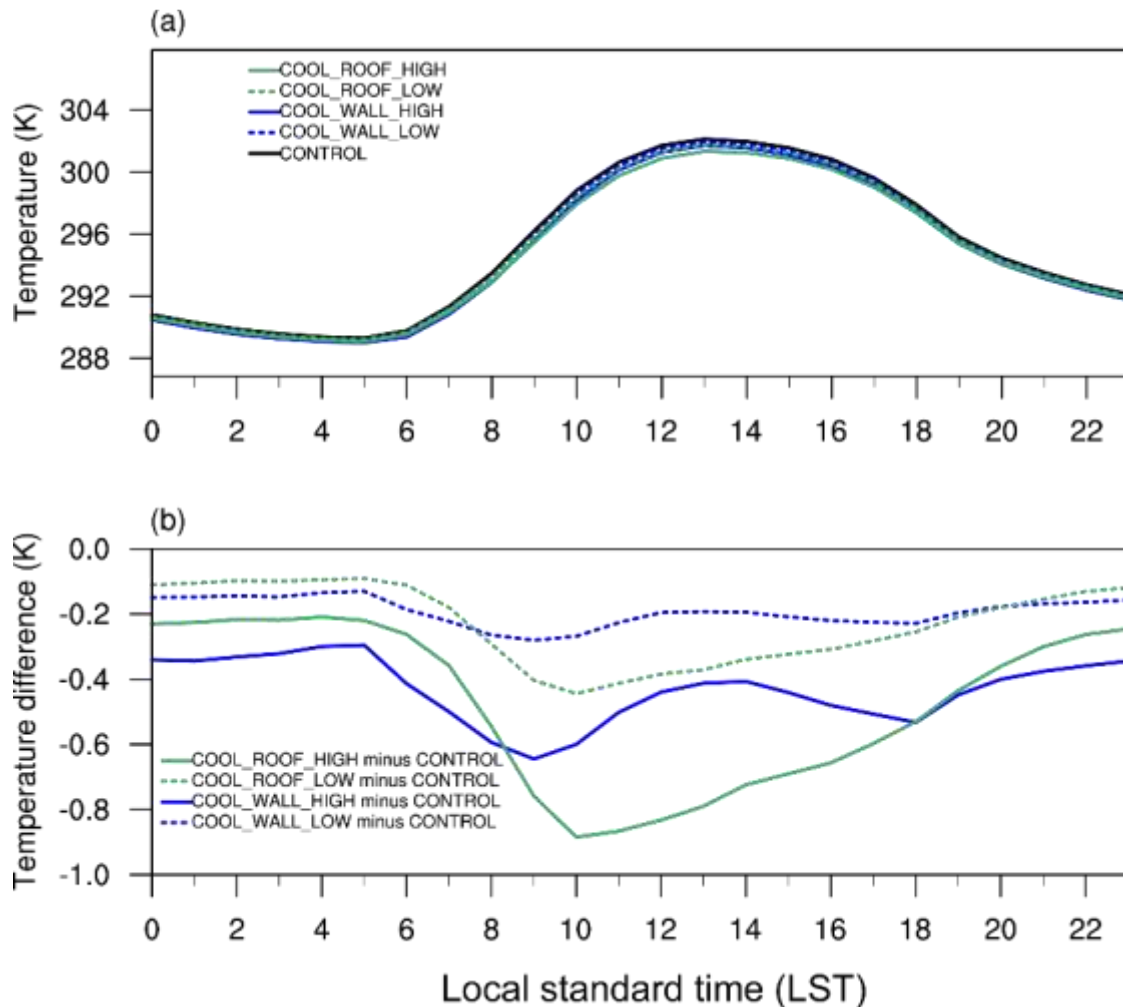
Despite previous studies that examined the urban climate effects of raising albedo of horizontal surfaces (roofs and pavements) in different cities, researchers have not yet systematically investigated the influence of increasing the albedo of vertical surfaces (walls) on urban temperatures. The climate 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 differ from those of solar irradiance on nearly horizontal roofs and pavements. Second, walls make up a different fraction of urban areas than do roofs and pavements. Third, air temperature effects per unit of grid cell albedo increase may differ for walls relative to roofs and pavements. Thus, in this study, the researchers used a regional climate model, coupled to an urban canopy model, to investigate how adopting cool walls influence albedos and near-surface canyon air temperatures in the Los Angeles basin. The team also conducted a suite of cool roof simulations assuming the same facet albedo increases. These simulations allow for systematically comparing the climate effects of cool walls versus cool roofs using a consistent modeling framework.

The research team used the Weather Research and Forecasting model (WRF) version 3.7 to investigate the effects of raising wall albedo on near-surface air temperatures in the Los Angeles basin. The team implemented a new method for selecting parameters to diagnose canyon air temperature, which better represents air temperatures near the ground in cities relative to the model-default near-surface air temperature.

To analyze the influence of cool walls on the climate of the Los Angeles basin, 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 11 July 2012).

Figure 7 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 7: Canyon Air Temperature Change upon Raising Wall or Roof Albedo**



The diurnal cycle of (a) spatially averaged canyon air temperature (K) for CONTROL, COOL\_WALL\_LOW, COOL\_WALL\_HIGH, COOL\_ROOF\_LOW, and COOL\_ROOF\_HIGH; and (b) 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.

Source: University of Southern California

Three factors contribute to the shape of the simulated diurnal cycle for canyon air temperature changes. First, the diurnal cycle of solar irradiance onto walls is concave up, meaning that walls receive the most sunlight in the early morning and late afternoon. Higher solar irradiance leads to larger cool wall induced reductions in solar absorption and heat gain. Second, buildings can retain solar heat gain throughout the day, leading to an accumulation effect of albedo increases

on wall surface temperatures. Third, the height of the planetary boundary layer (PBL) has a diurnal cycle that is concave down, meaning that the boundary layer heights are shallow in the morning and evening, with a maximum generally occurring ~13:00 LST. Shallower PBL heights reduce the volume of air heated by sensible heat fluxes. This means that given reductions in sensible heat flux caused by surface temperature decrease can lead to larger reductions in atmospheric heating rate (temperature/time) in the boundary layer when PBL heights are shallow versus deep. Thus, sensible heat flux decreases from cool-wall adoption are expected to have larger air temperature effects when the PBL is shallow. All three factors contribute to the peak in near-surface air temperature at 09:00 LST, which is two hours after the maximum solar irradiance onto walls occurs and when the PBL height is relatively low.

Figure 7 also shows that the reduction in canyon air temperature from increasing wall albedo is less than that from increasing roof albedo between 09:00 to 17:00, and greater than that from increasing roof albedo at nighttime. This is likely because walls are in the urban canyon, so they can more directly cool canyon air than can roofs. In addition, cool walls lead to a greater cooling at night relative to cool roofs. The atmosphere is stable at night, meaning that there is little vertical mixing. This means that above-canopy air temperature reductions from cool roofs would undergo less mixing into the canyon, and thus have less effect on canyon air temperatures relative to cool walls at night.

The ratio of the daily average temperature reduction for COOL\_WALL\_HIGH - CONTROL to that for COOL\_WALL\_LOW - CONTROL ( $0.43 \text{ K} / 0.19 \text{ K} = 2.3$ ) is close to the ratio of the wall albedo rises for the two scenarios ( $0.80 / 0.40 = 2$ ), indicating that the average temperature reduction induced by cool walls is approximately proportional to increase in wall albedo. A similar linear relationship between facet albedo increase and temperature reduction is also observed for cool roofs ( $0.48 \text{ K} / 0.23 \text{ K} = 2.1$ ). 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). Thus, results reported here can be interpolated to estimate the effects of increasing wall or roof albedo by other amounts.

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.

Canyon air temperature reductions from adopting cool walls or roofs in the Los Angeles basin reported in this study can be used to inform policymaking for urban heat island mitigation or climate change adaptation.

The complete study is presented in the Task 3.2 report, Urban Climate Impacts of Cool Walls (Appendix E). An article based on this work has been published in *Environmental Science & Technology* (Zhang et al. 2018).

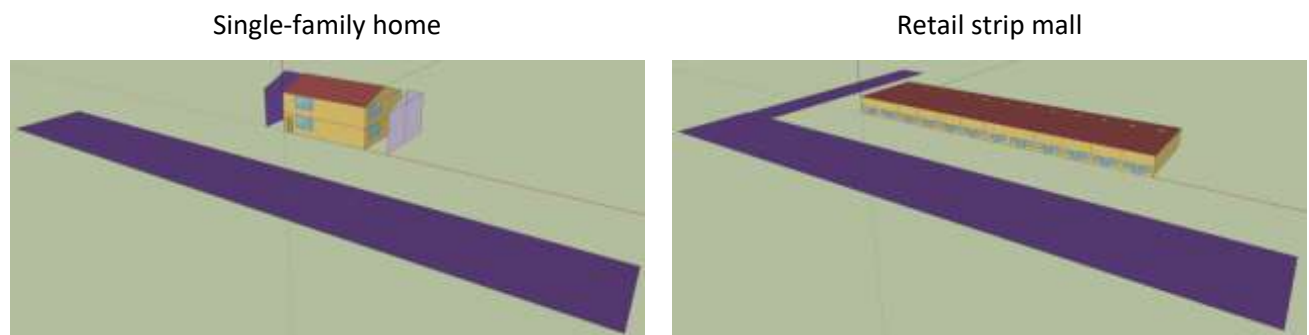
## Effects of Cool Walls on Energy-saving Benefits from Cool Pavements (Task 3.3)

“Heat island” refers to the phenomenon of having higher urban temperatures compared to the temperatures of surrounding suburban and rural areas. In the United States, pavements cover typically up to 30 percent of the urban fabric, and are hot, dry surfaces that can contribute substantially to the heat island effect.

The use of cool pavements is an urban heat island reduction strategy that increases pavement albedo (solar reflectance) to reduce convective heating of the outdoor air. This lowers the air temperature difference across the building envelope, reducing heat gain via conduction and infiltration. This “indirect” effect of reflective pavement can decrease cooling loads in summer and increase heating loads in winter. Raising pavement albedo also increases the solar flux incident on walls and windows, a “direct” effect of reflective pavement that can increase cooling loads in summer and reduce heating loads in winter. The total annual changes in cooling and heating energy loads will depend on the relative magnitudes of the indirect and direct effects. This study explored only the direct effect of cool pavements for buildings in California cities.

The magnitude of the direct effect depends on the design and properties of the building’s walls and windows. The research team prepared nine code-compliant building prototypes with external horizontal shading surfaces that represent local roads; examples are shown in Figure 8. To quantify the direct effects of cool pavements, we simulated with EnergyPlus the annual cooling and heating energy uses of each prototype, varying the road albedo, wall absorptance (1 - wall albedo), and window solar heat gain coefficient (SHGC).

**Figure 8: Building Prototypes with Adjacent Streets**



**EnergyPlus building prototypes with roads represented by horizontal shading surfaces.**

Source: Lawrence Berkeley National Laboratory

The research team used a physical model that relates each heating and cooling energy use to building properties, and to local road albedo. The team used the results from the building simulations to validate the physical model, and to generate relationships that predict the direct effect of pavement albedo change on building energy use.

The study analyzed how the location and dimension of the road with respect to the building affects its direct effect on the building energy use. For this, the researchers compared the



building-to-road view factors to their direct effect and observed a relationship in which the direct effect on cooling increases linearly with the view factor; the direct effect on heating is a linear decrease.

The direct effect from cool pavements is slightly larger through windows than walls. Their individual contributions depend heavily on the window-to-wall ratio, as well as other construction properties. In this case, the latter was similar across prototypes. Hence, after normalizing to a window-to-wall ratio of 0.40, the research team found that windows contribute 1.5 times more to the direct effect than do walls (for the base case values of wall absorptance and window SHGC).

Although increasing the pavement albedo by 0.25 caused net conditioning energy penalties that were as much as 0.80 percent (large office averaged over all climate zones), when reducing the wall absorptance by 0.25 most prototypes experienced net conditioning energy savings (as much as 4.2 percent). Similarly, when researchers reduced window SHGC by 0.05, all prototypes experienced net conditioning energy savings ranging between 0.32 percent and 3.11 percent (Table 1). Hence, the study suggests small modifications to a building’s envelope can outweigh the small cooling penalties associated with the direct effect of cool pavements.

The complete study is presented in the Task 3.3 report: Effect of Cool Walls on Energy-saving Benefits from Cool Pavements (Appendix F).

**Table 1: Savings from Cool Roads, Walls, and/or Windows**

Prototype	Source mean conditioning (cooling + heating) energy intensity savings				
	Base [MJ/m <sup>2</sup> y]	Savings from road [%]	Savings from road + wall [%]	Savings from road + window [%]	Savings from road, wall, window [%]
Single-family home	146.5	-0.59	4.17	1.64	5.82
Apartment complex	121.6	-0.50	2.20	3.11	5.31
Large hotel	705.0	-0.40	1.14	0.68	1.82
Large office	241.5	-0.80	-0.19	2.94	2.75
Medium office	398.2	-0.29	0.35	2.58	2.93
Primary school	261.3	-0.35	0.59	2.48	3.07
Retail stand-alone	309.6	-0.07	2.00	1.59	3.60
Strip mall retail	350.2	-0.09	1.75	1.39	3.13
Sit-down restaurant	903.6	0.01	0.36	0.32	0.68

Conditioning source energy savings averaged over all California climate zones.

Source: Lawrence Berkeley National Laboratory

## Effect of Wall Albedo on the Environment inside an Unconditioned Building (Task 3.4)

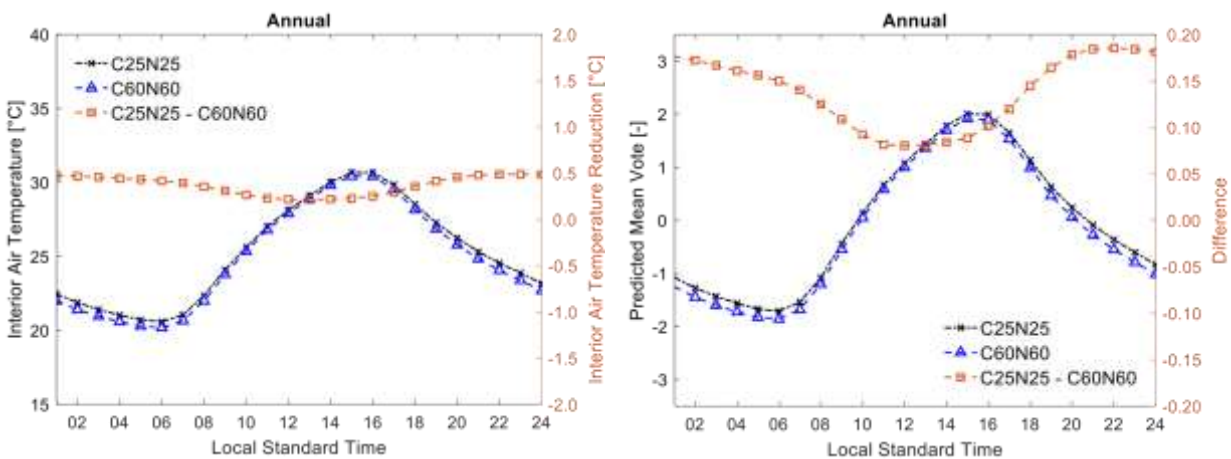
Raising a wall’s albedo decreases its solar heat gain, which can reduce heat conducted inward through the wall on a hot day, or increase heat conducted outward on a cold day. In buildings without air conditioning, cool walls are expected to affect the interior thermal environment more than in air-conditioned buildings.

The researchers simulated the building outdoor and indoor thermal environment using a building-to-canopy model that simulates heat transfer in a small neighborhood of identical buildings to obtain indoor and outdoor air temperatures; interior and exterior temperatures of walls and ceiling; and radiative, convective, and conductive heat fluxes. The team performed calculations hourly for a year of typical weather conditions for a multi-family residence in a coastal California climate zone in the Greater Los Angeles area (Fullerton).

The human temperature sensation is approximated through thermal comfort models. Such models attempt to emulate the typical human perception of environmental conditions through thermal comfort indices. Thermal comfort depends on clothing and metabolic activity as well as environmental factors including air temperature; radiation from surrounding walls, floor, and ceiling; and humidity. To understand thermal impacts of cool walls on building occupants, calculations are performed for a sitting person. The ASHRAE comfort model based on Fanger’s theory expresses thermal comfort as “Predicted Mean Vote” (PMV), which can take on values of -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), and 3 (hot).

Figure 9 shows that indoor air temperature peaks around 15:00–16:00 LST. The reduction in indoor air temperature with cool walls is between 0.2 °C midday and 0.5 °C at night.

**Figure 9: Change in Indoor Air Temperature and Comfort upon Raising Wall Albedo**



Average (over the year) daily cycle of interior air temperature (left) and predicted mean vote (PMV, right) for the multi-family residence in Fullerton with wall albedos equal to 0.25 (conventional wall, denoted as C25N25) and 0.60 (cool wall, denoted as C60N60). The right axis shows the reduction due to raising wall albedo.

Source: University of California, San Diego

Compared to a conventional wall, during daytime cool walls absorb a smaller fraction of incident solar radiation. This lowers the temperature of the wall’s outer surface, reducing heat flux through the wall and the air temperature in the occupied space. The daytime decrease in heat storage in cool walls causes lower wall temperatures and indoor air temperature to persist through the night. The thermal comfort trends during the day follow the indoor air temperature trends. On average, the building occupant tends to be slightly cool to cool during the night and slightly warm to warm during the day.

Since thermal sensation in buildings without air conditioning is generally slightly cold to cold at night and slightly warm to warm during the day, this corresponds to a slight worsening of thermal comfort at night and an improvement of thermal comfort during the day. But since homes without cooling are more common than homes without heating, in practice the worsening of thermal comfort from cool walls during nighttime would not occur and cool walls would then only improve thermal comfort during the day.

The complete study is presented in the Task 3.4 report, Effect of Wall Albedo on the Environment inside an Unconditioned Building (Appendix G).

## Effects of Self-cleaning Walls on Urban Air Quality (Task 3.5)

The researchers analyzed total NO<sub>x</sub> deposition in Los Angeles County assuming a hypothetical scenario in which all walls are painted with photocatalytic cool paints.<sup>3</sup> We use laboratory-measured dry deposition velocities for NO<sub>x</sub> (0.2 – 0.5 centimeters per second [cm s<sup>-1</sup>]) (Task 4.3), NO<sub>x</sub> concentrations measured by ambient air quality stations, and wall-to-urban land area ratios derived from a real-world building dataset. The research team compared total expected deposition to recent (2012) emissions of NO<sub>x</sub> in urban Los Angeles County to assess the magnitude of predicted deposition increases.

For a first-order approximation, the team assumed that the deposition velocity onto cool walls was constant throughout the daytime, suggesting that the flux of ultraviolet photons is not the rate-limiting factor. While this is likely not true, the goal was to quantify upper bound estimates of NO<sub>x</sub> deposition to compare with total NO<sub>x</sub> emissions in Los Angeles County. Figure 10a shows the diurnal cycle of NO<sub>x</sub> deposition in July. Based on the lower bound of measured NO<sub>x</sub> dry deposition velocity (0.02 cm s<sup>-1</sup>), NO<sub>x</sub> deposition ranges 267–709 moles per hour (mol hr<sup>-1</sup>), depending on time of day. Based on the upper bound of NO<sub>x</sub> dry deposition velocity (0.05 cm s<sup>-1</sup>), NO<sub>x</sub> deposition ranges 668 – 1,770 mol hr<sup>-1</sup>.

Figure 10b shows the hourly NO<sub>x</sub> emissions during daytime averaged in July. NO<sub>x</sub> emissions reach a maximum at 11:00 LST. NO<sub>x</sub> emissions are in the range of (1.3–2.8) × 10<sup>5</sup> mol hr<sup>-1</sup>. The emissions start to increase with the morning traffic and peak around noon. The diurnal cycle of NO<sub>x</sub> emissions is driven by the diurnal variations of on-road and off-road mobile sources and stationary sources (South Coast Air Quality Management District, 2013). Figure 10c shows the diurnal cycle of the ratio of NO<sub>x</sub> deposition to emissions. Even when assuming the maximum deposition velocity measured in experiments, the upper-bound daily maximum NO<sub>x</sub> deposition is less than 1.1 percent of NO<sub>x</sub> emissions.

Daytime (05:00 – 19:00 LST) total NO<sub>x</sub> deposition and emissions are 6.6 × 10<sup>3</sup>–1.6 × 10<sup>4</sup> mol day<sup>-1</sup> and 3.3 × 10<sup>6</sup> mol day<sup>-1</sup>, respectively. Therefore, daytime NO<sub>x</sub> deposition is 0.2–0.5% of NO<sub>x</sub> emissions in July in Los Angeles County. Thus, adopting photocatalytic cool walls is expected to have small impacts on regional air quality in Los Angeles. Note that this analysis estimates city-level NO<sub>x</sub> deposition, and does not consider whether photocatalytic self-cleaning walls may have larger air quality benefits for near-source concentrations in urban canyons. The researchers

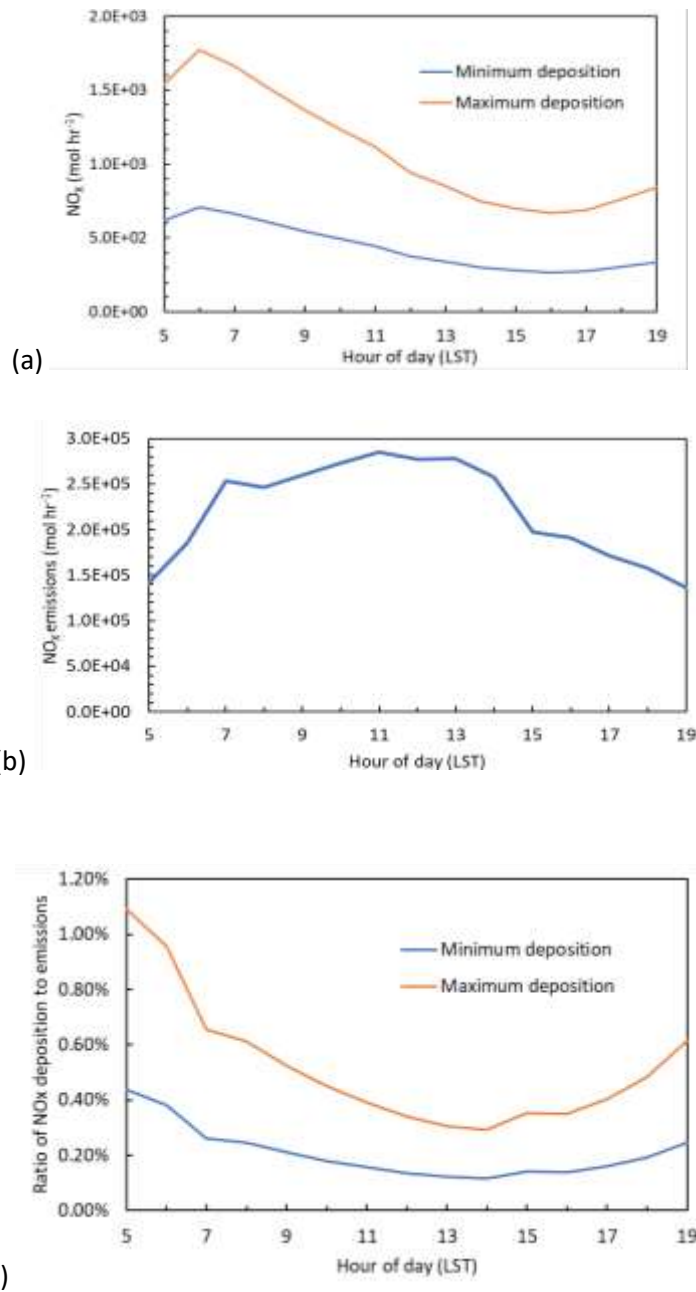
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<sup>3</sup> Photocatalytic paints contain a catalyst that absorbs UV light to accelerate breakdown of surface pollutants.

suggest future work to estimate the impact of self-cleaning walls on near-source  $\text{NO}_x$  concentrations.

The complete study is presented in the Task 3.5 report, Effects of Self-cleaning Walls on Urban Air Quality (Appendix H).

**Figure 10: Deposition of Nitrogen Oxides in Los Angeles County**



Diurnal cycles for urban Los Angeles County of (a)  $\text{NO}_x$  deposition ( $\text{mol hr}^{-1}$ ); (b)  $\text{NO}_x$  emissions ( $\text{mol hr}^{-1}$ ); and (c) the ratio of  $\text{NO}_x$  deposition to  $\text{NO}_x$  emissions. Values are averaged for July 2012. Panels (a) and (c) show upper and lower bound estimates based on variations in measured dry deposition velocities.

Source: University of Southern California

# CHAPTER 4:

## Assessing Performance of Cool-wall Technologies (Task 4)

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Task 4 assessed through field and laboratory measurements the performance of available and prototype cool-wall technologies, primarily the ability to reflect sunlight. Task 4.1 developed metrics and methods for evaluation of solar reflectance, de-pollution efficacy, and other material properties, while Task 4.2 measured how solar reflectance changed over time as products were exposed outdoors at sites across California and the United States. Task 4.3 focused on the performance of self-cleaning and de-polluting photocatalytic materials.

### Metrics and Methods to Assess Cool-wall Performance (Task 4.1)

The ability of a wall product to stay cool in the sun depends on its solar reflectance and thermal emittance. High solar reflectance reduces solar heat gain (absorption of sunlight), while high thermal emittance can help cool the surface through long-wave radiative exchange with its environment. This report addresses the metrics and methods needed to assess the evolution of the surface properties of a wall product over its service life.

Radiative properties of interest include initial and aged values of solar spectral reflectance (reflectance vs. wavelength); solar reflectance (fraction of incident sunlight that is reflected), thermal emittance (ratio of radiant power emitted to that emitted by a black body radiator, at a temperature near 300 Kelvin); color; effective solar reflectance (fraction of incident sunlight rejected by the combination of reflection and fluorescence), and solar retroreflectance (fraction of incident sunlight reflected to its origin). Nonradiative properties that influence radiative properties include soiling resistance (ability to stay clean), hydrophilicity (attraction of water), and hydrophobicity (repulsion of water).

The research team selected the following metrics and methods:

- Near normal-hemispherical solar spectral reflectance is to be measured over the spectrum 250–2,500 nm using an ultraviolet-visible-near infrared spectrophotometer equipped with an integrating sphere, following ASTM Standard E903. There is also a specified protocol for measuring soiled samples through a protective window, and for correcting those measurements for the influence of the window.
- Air mass 1.5 global-hemispherical solar reflectance is to be measured either (a) by averaging solar spectral reflectance weighted with the air mass 1.5 global solar spectral irradiance incident on a sun-facing vertical surface (AM1.5GV), following ASTM Standard E903; or (b) using the output of a solar spectrum reflectometer that corresponds to this irradiance, following ASTM Standard C1549.

- Hemispherical thermal emittance is to be measured with a portable emissometer following either ASTM Standard C1371 or the Devices & Services “Slide Method,” as appropriate to product type.
- Color coordinates are to be calculated from solar spectral reflectance following ASTM Standard E308.
- The effective solar reflectance of a fluorescent surface is to be determined with a custom apparatus developed by LBNL (Figure 11). This calorimetric technique compares the temperature in the sun of a fluorescent specimen to those of non-fluorescent reference specimens of known solar reflectance. It then interpolates effective solar reflectance from the temperature measurements and known solar reflectances.

**Figure 11: Apparatus for Measurement of Effective Solar Reflectance**



**Test and reference specimens on rotating platter pass beneath an IR thermometer (upper right). Apparatus also includes an anemometer (lower left), pyranometer (on same board as anemometer), and control electronics (underneath tripod). An air temperature sensor is hidden below the platter.**

Source: Lawrence Berkeley National Laboratory

- Solar retroreflection is assessed with a simple goniometer<sup>4</sup> that compares the intensity of retroreflection to that of first-surface specular reflection, and with an advanced goniometer that measures solar spectral bidirectional reflectance intensity.
- Initial and aged values of solar reflectance and thermal emittance are to be assessed before, during, and after a program of natural exposure at various sites across California and the United States. Aged radiative properties will be measured quarterly, for two years, in the California program, and annually, for five years, in the United States program.
- Relative and absolute values of soiling resistance are to be gauged by comparing aged solar reflectance to initial solar reflectance.
- Hydrophilicity/hydrophobicity is to be determined by measuring water contact angle.

The complete study is presented in the Task 4.1 report, Metrics and Methods to Assess Cool Wall Performance (Appendix I).

## Natural Exposure of Wall Products (Task 4.2)

The solar reflectance of wall products can change over time as they soil and weather. The research team collected product samples from its industrial partners, and selected 69 materials 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:

- Lawrence Berkeley National Laboratory (LBNL) campus in Berkeley (Figure 12).
- An industrial partner facility in Fresno.
- University of Southern California campus in Los Angeles.

The team similarly exposed specimens over a five-year period at three United States sites used by the Cool Roof Rating Council:

- New River, Arizona (near Phoenix; hot and dry weather).
- Miami, Florida (hot and humid weather).
- Medina, Ohio (near Cleveland; temperate weather, more polluted).

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<sup>4</sup> A goniometer measures the variation of reflectance with angle.



For 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. Retrieved specimens were photographed, and their solar reflectances were measured with a Devices & Services Solar Spectrum Reflectometer.

**Figure 12: Wall Product Racks Used in California Exposure Trials**



**Wall-product exposure rack on building roof at Lawrence Berkeley National Laboratory.**

Source: Lawrence Berkeley National Laboratory

Specimens exposed for 24 months in California have been retrieved quarterly and measured. Specimens exposed for 2 years across the United States have been retrieved annually and measured.

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.

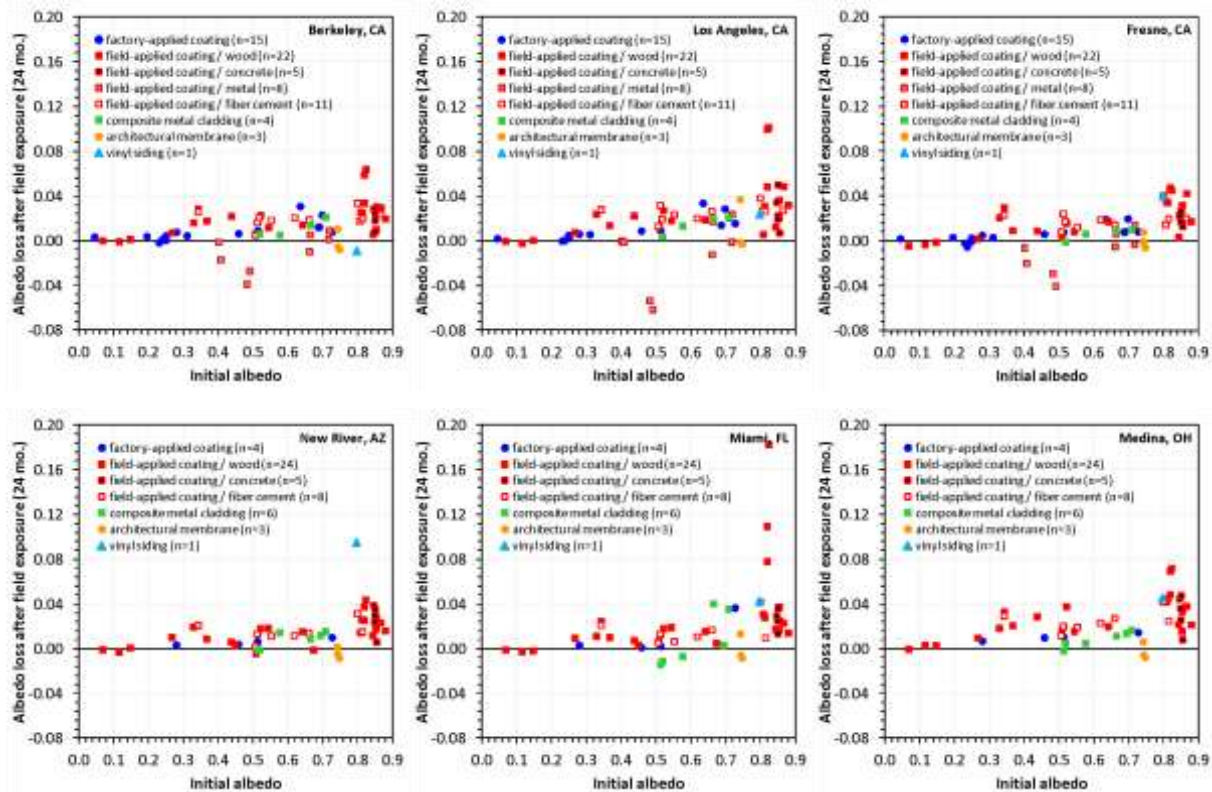
In the case of field-applied coatings, the retention of initial solar reflectance values varied with coating formulation, surface finish, and substrate (Figure 13). Field-applied coatings colored with cool pigments were significantly more reflective than similarly colored products incorporating conventional pigments. Several dirt-resistant field-applied coatings showed a higher retention of solar reflectance than control coatings representing typical formulations.



Specimens with photocatalytic self-cleaning functionalities are detailed in Task 4.3.

The complete study is presented in the Task 4.2 report, Natural Exposure of Wall Products (Appendix J).

**Figure 13: Albedo Losses for Naturally Exposed Wall Products**



Most wall materials tested experienced minimal to modest albedo losses after 2 years of exposure at three sites in California (top row) and three sites across the United States (bottom row).

Source: Lawrence Berkeley National Laboratory

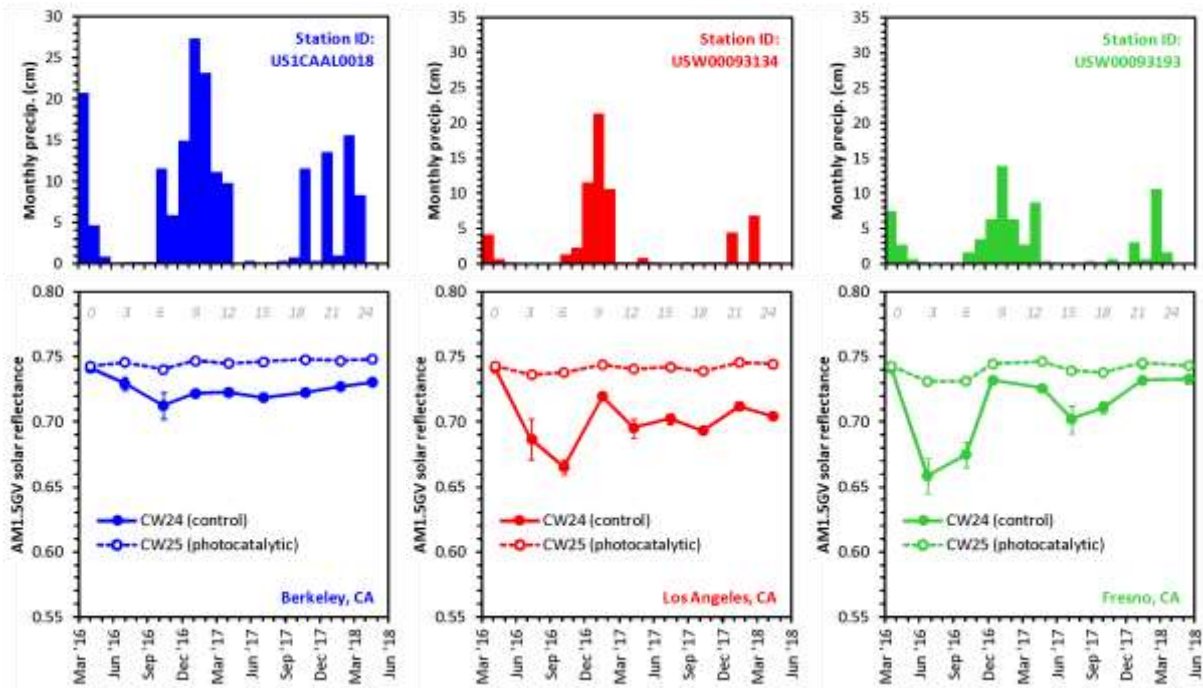
## Self-cleaning and De-polluting Photocatalytic Materials (Task 4.3)

Two of the products evaluated in the California and United States natural exposure 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): Arizona (dry and hot weather), Florida (humid and hot weather), and 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 measured values are presented in Figure 14 and photos of the specimens collected at 12 months are shown in Figure 15.

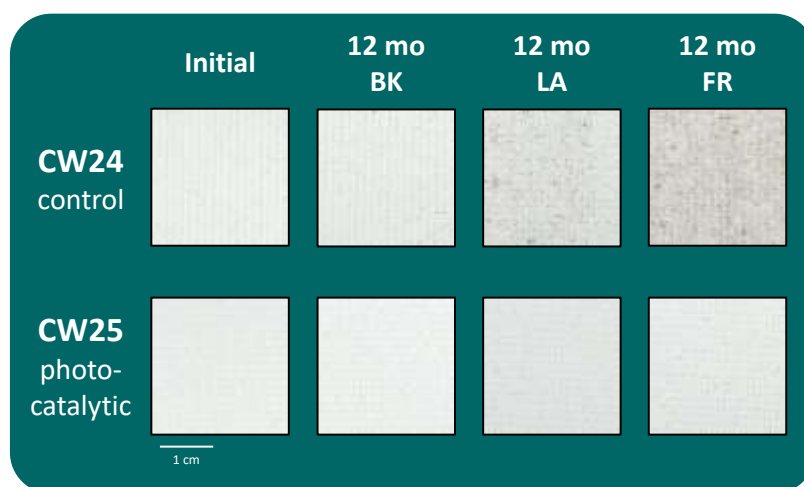
**Figure 14: Solar Reflectances of Photocatalytic and Control Fabrics**



The photocatalytic self-cleaning white fabric experienced less solar reflectance loss than its control.

Source: Lawrence Berkeley National Laboratory

**Figure 15: Images of Photocatalytic and Control Fabrics after 1 Year in California**



Photos of a photocatalytic self-cleaning fabric (CW25, bottom row) and the control sample (CW24, top row) after 12 months of exposure in Berkeley (BK), Los Angeles (LA), and Fresno (FR).

Source: Lawrence Berkeley National Laboratory

The research team evaluated the de-polluting capacity of each photocatalytic product in the lab by measuring removal of nitrogen oxides ( $\text{NO}_x$ ) 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. The team placed specimens inside a flow chamber in which they were facing a quartz window through which UV light was irradiated continuously for a period of 6 hours. A chemiluminescent  $\text{NO}_x$  detector was used downstream of the chamber to quantify the concentration of  $\text{NO}_x$  (NO and  $\text{NO}_2$ ) in real time. From the integration of this signal the researchers could determine the amounts of NO removed and  $\text{NO}_2$  formed (as an intermediate byproduct), and, by difference, the amount of nitrate formed as final byproduct. Unexposed samples showed a higher  $\text{NO}_x$ -removal capacity, on the order of 0.7 micromoles of NO per hour ( $\mu\text{mol NO h}^{-1}$ ), which was diminished by field exposure to values as low as 0.2  $\mu\text{mol NO h}^{-1}$  for one of the products and 0.1  $\mu\text{mol NO h}^{-1}$  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.

The complete study is presented in the Task 4.3 report, Self-cleaning and De-polluting Photocatalytic Materials (Appendix K).

## Assessment of Existing and New Retroreflective Materials (Task 4.4)

This activity was merged into Task 5.3 and is discussed in Chapter 5.

# CHAPTER 5: Developing Innovative Cool-wall Solutions (Task 5)

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Task 5 explored innovative cool-wall technologies, including self-cleaning materials (Task 5.1, which was merged with Task 4.3), fluorescent cool pigments (Task 5.2), and retroreflective materials (Task 5.3).

## Improvement of Self-cleaning Coatings and Claddings (Task 5.1)

This activity was merged into Task 4.3 and is discussed in Chapter 4.

## Development of Fluorescent Cool Pigments (Task 5.2)

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 utilizing the phenomenon of fluorescence (photoluminescence).

While potential fluorescent cool pigments have been screened during a prior United States Department of Energy funded project with PPG Industries, 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 (Figure 16).

**Figure 16: Pink-Red Coatings Incorporating Fluorescent Ruby Pigment**

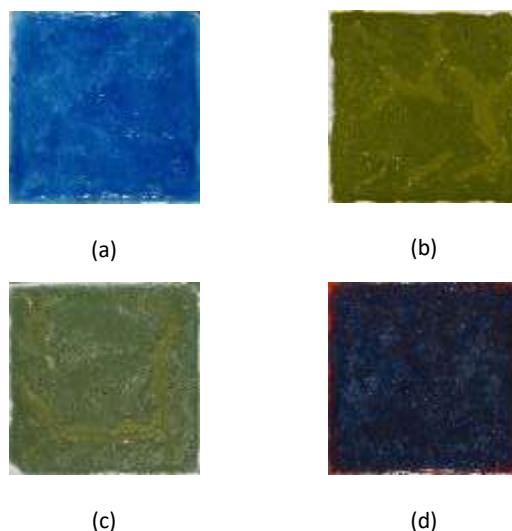


Coatings containing fluorescent ruby powders with 0, 0.2, 1, 2, 3, and 4% doping. The darker coatings contain pigments with more chromium.

Source: Lawrence Berkeley National Laboratory

The second important class of materials includes the ancient pigment Egyptian blue. Egyptian blue has the chemical composition of  $\text{CaCuSi}_4\text{O}_{10}$  – 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 barium variant is also known from ancient times as Han (or Chinese) blue. The strontium variant has no common name. 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 (Figure 17). The blending process does not diminish the near-infrared fluorescence.

**Figure 17: Blue, Green, and Blue-Black Coatings Incorporating Fluorescent Blue Pigment**



**Coatings with a fluorescent blue pigment, each over a bright white undercoat: (a) blue alone, (b) blue mixed with azo yellow, (c) blue mixed with mixed metal oxide yellow, and (d) blue over an orange coating.**

Source: Lawrence Berkeley National Laboratory

The research team built a calorimetric instrument that measures effective solar reflectance (ESR), or the fraction of incident solar energy rejected by the combination of reflectance and fluorescence (see Figure 11 in Chapter 4). Laboratory-fabricated coatings have shown that coatings with fluorescent pigments can contribute to, or boost, the ESR up to 0.17 above the ordinary solar reflectance (SR). The target for future commercial coatings is a fluorescence benefit (ESR - SR) of 0.10 to 0.15. The energy flux of full sunlight is roughly  $1,000 \text{ W m}^{-2}$ , so we can expect that future colored fluorescence materials can reduce peak heat absorption rates by 100 to  $150 \text{ W m}^{-2}$ .

Even though natural rubies are quite expensive, manufactured rubies with the same properties are not. The wholesale cost of cut and polished manufactured ruby gems for jewelry is about US\$0.30 per carat (200 mg). A layer of manufactured rubies has a pleasing dark red color with a fluorescence benefit of 0.30. Also, ruby pigment is not difficult to manufacture; manufacturers can use the same solid-state reaction techniques they currently employ for other mixed metal oxide pigments such as Fe-Cr-O cool black. Unfortunately, prototype coatings colored with ruby pigment are not as dark as desired and have a fluorescence benefit of only 0.15. Future

research may yield further improvements. In the meantime, ruby pigments can provide a dark pink color with high ESR, near 0.80. For comparison, smooth white commercial materials have SR in the range of 0.70 to 0.85 – about the same as the ruby pigment.

The Egyptian blue family of pigments comprises alkaline earth copper silicates usually synthesized by solid-state reaction techniques. Briefly, oxides or carbonates of the component metals are intimately mixed and heated in air for a few hours to a temperature near 900 °C. After the synthesis, copper oxide (CuO), a black compound, is usually present as an impurity. If too much CuO is present, the resulting pigment is gray rather than blue. Egyptian blue is available commercially from Kremer Pigmente. Thus, this company is able to control the CuO concentration to some extent. However, we have found that for fluorescent pigment applications, even more stringent limitations on CuO contamination are needed. We found that washing (leaching) the commercial pigment with hydrochloric acid (HCl) reduces but does not eliminate the CuO. The near-infrared fluorescence is enhanced by up to a factor of 2 with the HCl soak.

The fluorescence benefits of the prototype materials range from about 0.08 up to 0.17. The best material is based on washed Egyptian blue, with pigment amount of 68 g m<sup>-2</sup>. The visual reflectance (at 550 nm) is only 0.15, a medium dark blue, while the ESR is 0.57. The relatively small amount of pigment needed per unit area indicates that it is a reasonably strong pigment.

The complete study is presented in the Task 5.2 report, Development of Fluorescent Cool Pigments (Appendix N). Articles based on this work have been published in *Solar Energy Materials and Solar Cells* (Berdahl et al. 2016), *Energy and Buildings* (Levinson et al. 2017), and the *Journal of Applied Physics* (Berdahl et al. 2018).

## Development of Retroreflective Materials (Task 5.3)

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) (Figure 18). 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° (Figure 19).

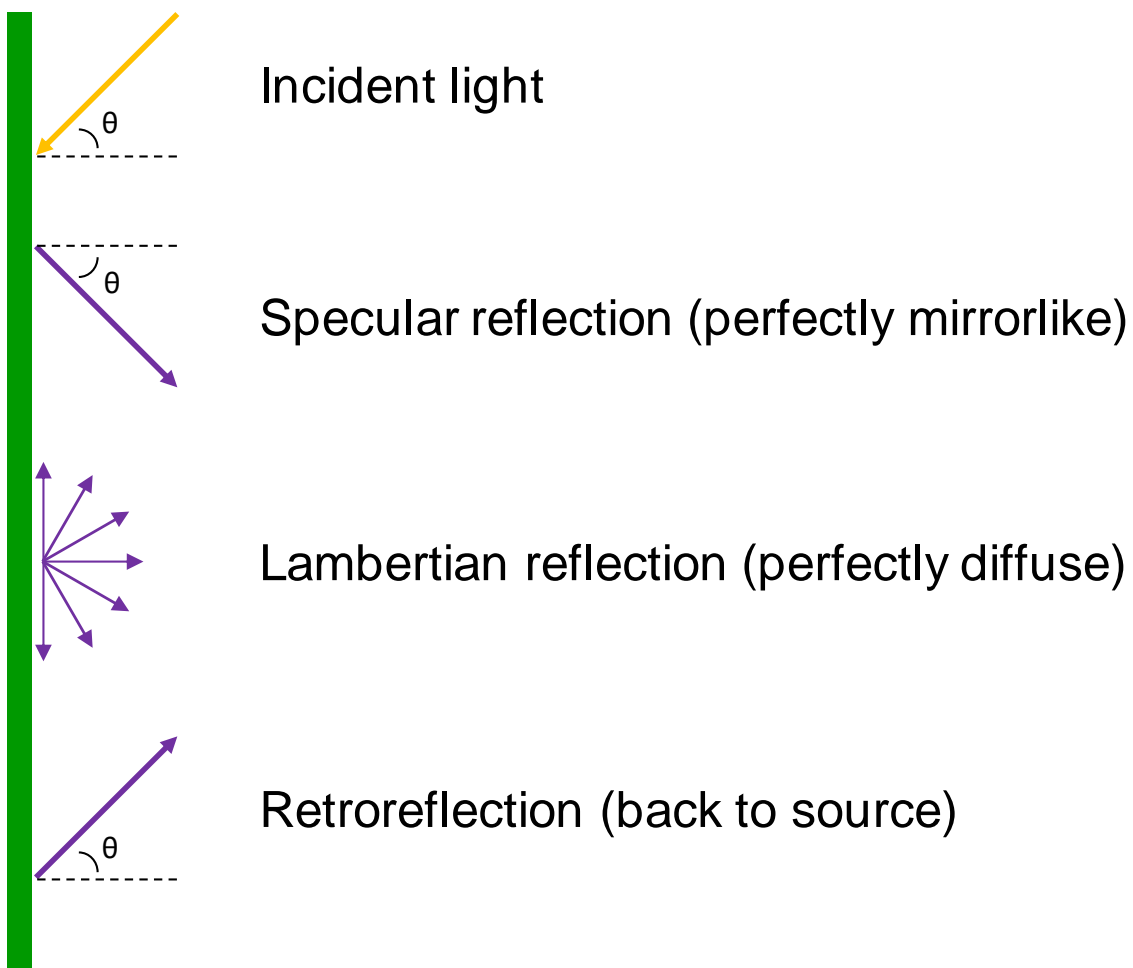
The researchers explored wall retroreflector design using first-principle physics, ray-tracing simulations, and goniometer measurements. Physics and simulations suggest that it will be difficult to achieve retroreflection at large incidence angles with surfaces that rely on total internal reflection, such as conventional safety films (Figure 20). This was confirmed with a

simple goniometer that permits comparison of retroreflection to first-surface specular (mirrorlike) reflection (Figure 21), 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 (Figure 20b). 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 (Figure 22).

The complete study is presented in the Task 5.3 report, Development of Retroreflective Materials (Appendix O).

**Figure 18: Idealized Reflections: Specular, Lambertian, and Retro**

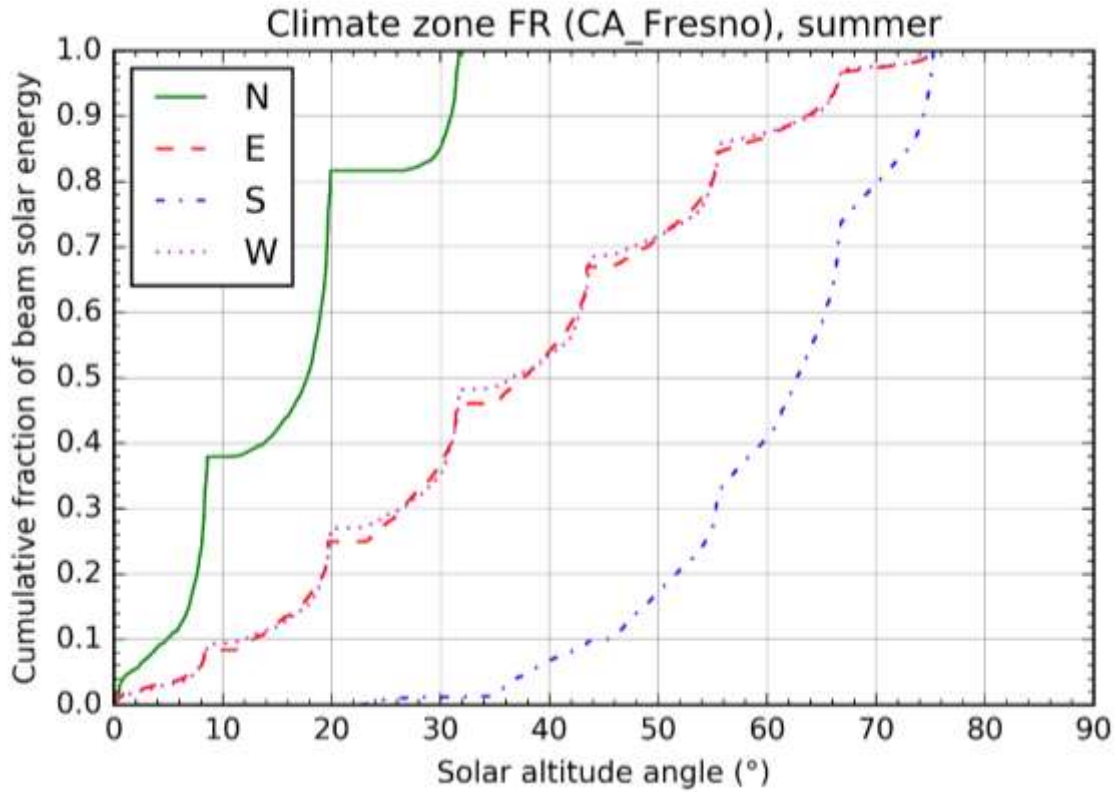


**Specular, Lambertian, and retro reflection of beam light striking a vertical surface.**

Source: Lawrence Berkeley National Laboratory



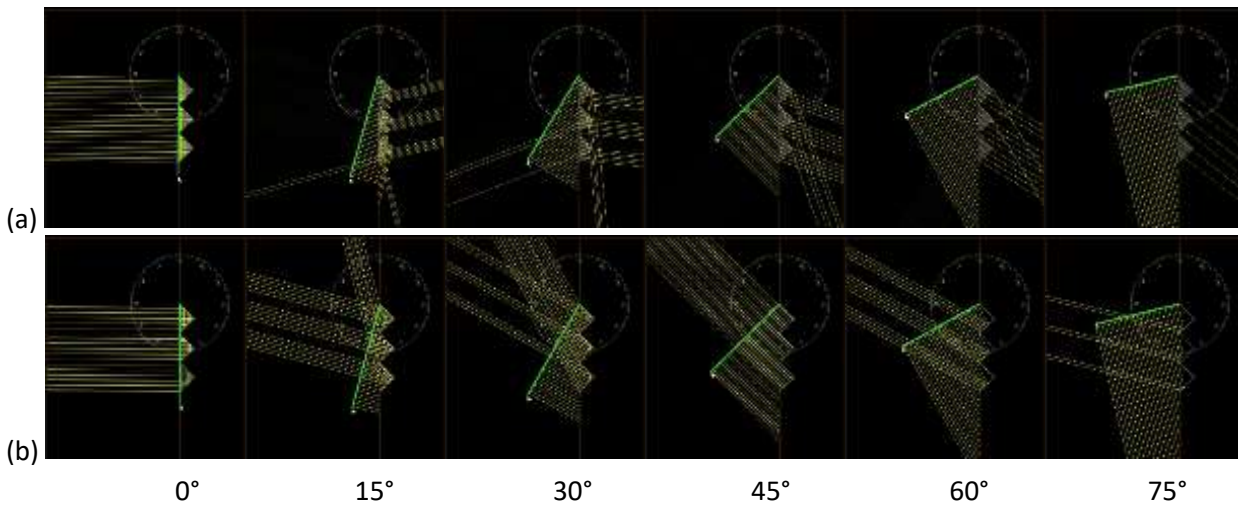
Figure 19: Distribution of Beam Solar Irradiance with Solar Altitude Angle



Variation with solar altitude angle of the cumulative fraction of beam solar energy incident on isolated north (N), east (E), south (S), and west (W) walls in Fresno, California, in June-July-August.

Source: Lawrence Berkeley National Laboratory

Figure 20: Simulated Reflections from Wall Retroreflectors

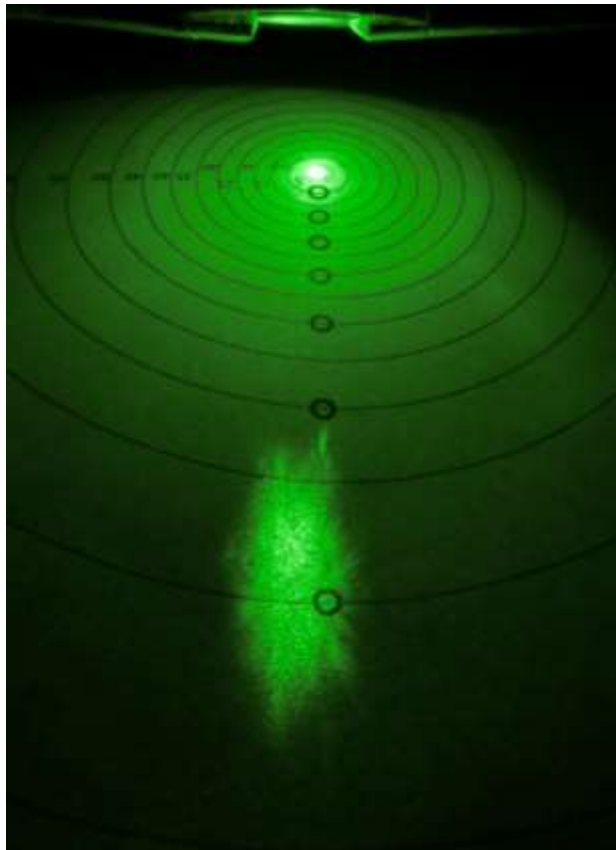


Reflection of beam light as a function of beam altitude angle, shown for (a) symmetric low-index glass (real refractive index 1.5) right triangular prisms, and (b) symmetric empty mirrors.

Source: Lawrence Berkeley National Laboratory



**Figure 21: Reflections from a Safety Film**



Retroreflection from this safety film is comparable to its specular reflection.

Source: Lawrence Berkeley National Laboratory

**Figure 22: Example of Two-Surface Empty Mirror Retroreflector**



Aluminized Mylar taped to aluminum block with 7-mm pitch orthogonal grooves.

Source: Lawrence Berkeley National Laboratory

# CHAPTER 6:

## Promoting Cool-Wall Infrastructure (Task 6)

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Task 6 promoted the infrastructure needed to advance the climate- and building-appropriate use of cool walls. This included developing cool-wall application guidelines (Task 6.1), hosting a cool-wall stakeholder workshop (Task 6.2), and exploring and enhancing the treatment of cool walls in building standards and incentive programs (Task 6.3).

### Cool-wall Application Guidelines (Task 6.1)

This task introduces the concept of solar-reflective “cool” walls, and provides guidelines for their building- and climate-appropriate use to conserve energy and reduce emissions of greenhouse gases and criteria pollutants across California and the United States. First, it explores the nature of cool walls by answering the following questions:

1. What is a cool wall?
2. Why choose a cool wall?
3. Where do cool walls save energy?
4. Is a cool wall like a cool roof?
5. Do cool walls help mitigate the urban heat island effect?
6. How do cool walls affect pedestrian comfort?
7. Are there specifications for cool walls?
8. How can I find a cool-wall product?
9. Will cool walls lose reflectance over time?
10. Do cool walls cost more than conventional products?

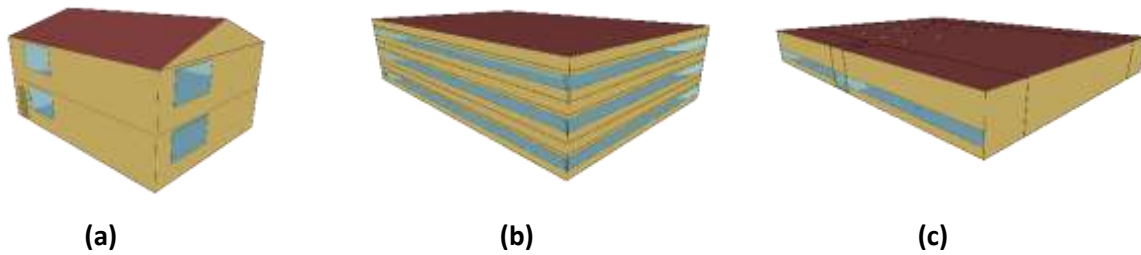
Second, the task provides a simple guide to cool-wall effects by detailing the energy cost savings (or penalties) that arise from increasing wall reflectance in three common building categories – single-family home, medium office, and retail stand-alone (Figure 23). This includes identification of building vintage, calculating energy cost savings, and gauging cost effectiveness, with worked examples. The guidelines supply lookup tables and worked examples.

Third, the task provides a detailed guide to these effects by describing 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 (Figure 24). This includes tool installation, operation, and application.

Fourth, the task discusses how to adjust cool walls savings and penalties to account for shading and reflection by neighboring buildings by applying a “solar availability factor”. Lookup tables are provided.

The complete guidelines are presented in the Task 6.1 report, Cool Wall Application Guidelines (Appendix P).

**Figure 23: Three Building Prototypes Addressed in the Guidelines**



Sketches of the (a) single-family home, (b) medium office, and (c) retail stand-alone building prototypes.

Source: Lawrence Berkeley National Laboratory

**Figure 24: Cool Surface Savings Explorer Interface**

Parameters	Value
Climate zone	USCZ_2B
City	Phoenix
State	Arizona
Vintage year	2006
Vintage group	new
Building category	single-family home w/gas furnace
Building orientation	mean
Modified surface(s)	N E S W
Base wall albedo	0.25
Albedo of modified wall(s)	0.6
Base roof albedo	0.1
Albedo of modified roof	NA

Results	Value
Annual building cooling source energy fractional savings [%]	7
Annual building combined heating source energy fractional savings [%]	-5.56
Annual building fan source energy fractional savings [%]	5.805
Annual building HVAC source energy fractional savings [%]	5.775

Cool Surface Savings Explorer used to report whole-building source energy fractional savings for a single-family home in Phoenix, Arizona.

Source: Lawrence Berkeley National Laboratory

## Cool-wall Stakeholder Workshop (Task 6.2)

The research team hosted a “Cool Wall” stakeholder workshop in October 2017 to review and discuss its research portfolio with interested parties. The one-day event at LBNL was attended by industry, state government, federal government, utility, and building code stakeholders. There were 42 in-person and 6 remote participants. Presentations from the research team addressed energy and emission savings, changes to the urban environment, product aging, novel technologies, and infrastructure. The complete proceedings presented in the Task 6.2 report, Cool Wall Workshop Proceedings (Appendix Q), document the presentations and ensuing discussions.

The morning discussion centered on the underlying assumptions of the research modeling and simulation activities to calculate the building energy, energy cost, and emission savings. There was also discussion on how to interpret the results for specific locations and building/neighborhood configurations, and discussion related to the cost, cost premium, and availability of cool-wall products.

In the afternoon, the discussion turned to the findings of the urban air temperature reductions from cool-wall deployment. Attendees asked many questions to understand how the results could potentially counter future warming and extreme heat days. They were also interested in discussing the effect of rooftop photovoltaic panels on urban climate.

Attendees posed several questions about the methods used to naturally expose and measure the cool-wall products. They were also interested to learn more about the self-cleaning and de-polluting potential of cool-wall products in the laboratory and from the climate models. Attendees shared insights on the development of retroreflective wall designs and suggested further research into applying metallic mica flakes in wall coatings.

The concluding discussion focused on advancing cool-wall adoption. Attendees inquired how long it would take to have cool-wall measures in building codes and standards, and how those measures would be specified. They expressed concern with specifying cool-wall measures for commercial buildings in which there is such variety in building design. Attendees seemed to agree that if there are cool-wall measures in California’s Building Energy Efficiency Standards, so goes the nation. They requested more field data to corroborate the simulation and modeling findings for building and city benefits.

Manufacturers cautioned that an energy savings claim on a product label has to be substantiated because they are legally liable for the claim and so would like as much concrete data as possible before marketing cool-wall products. They also expressed concern about limiting the color options for cool-wall coatings, noting that while consumers typically select one of about 10 colors, they still like to have many choices.

**Figure 25: Cool-wall Stakeholder Workshop**



**Presentation at the Cool-wall Stakeholder Workshop held at Lawrence Berkeley National Laboratory in October 2017.**

Source: Lawrence Berkeley National Laboratory

## **Advancements in Infrastructure Development: Building Standards and Incentive Programs (Task 6.3)**

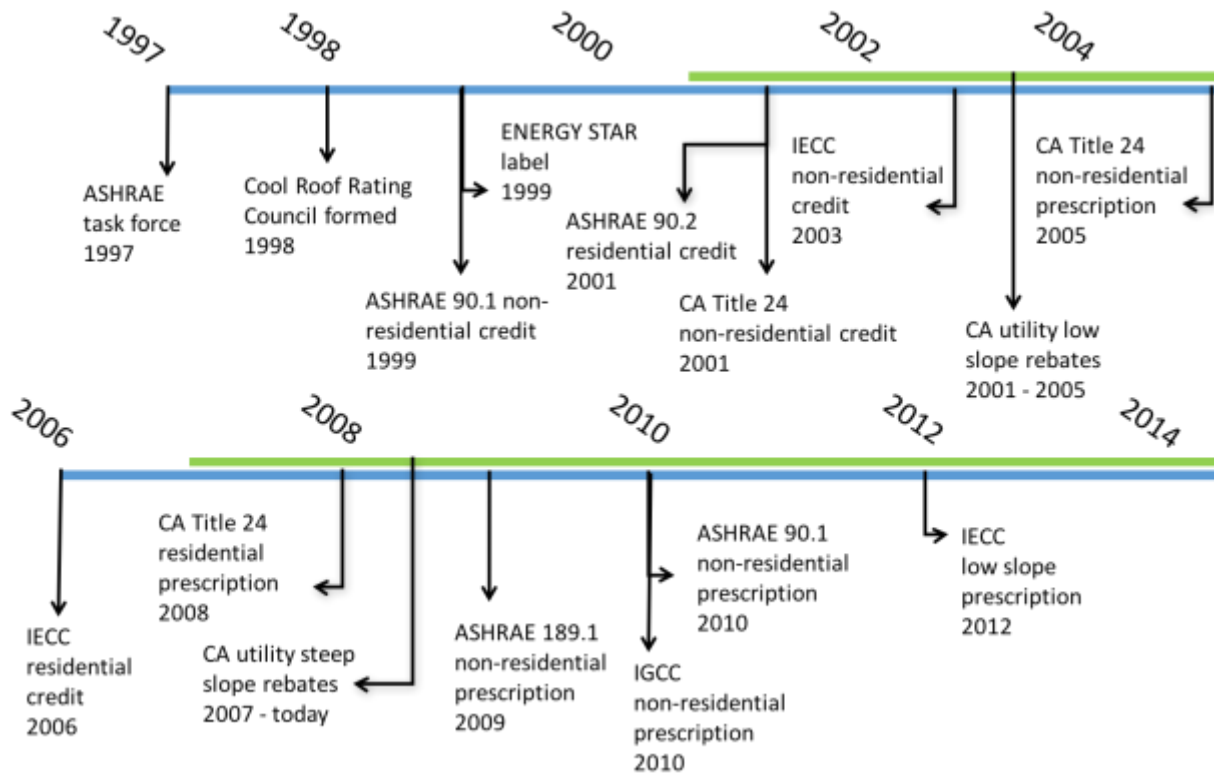
This task sought to advance the infrastructure needed to promote the appropriate use of cool-wall technologies. Following the model successfully used for cool roofs, activities included developing guidelines, evaluating feasibility of a product rating program, encouraging utility rebates, investigating ENERGY STAR label qualification, and pursuing credits/requirements in building energy standards and energy-efficiency programs (for example, California Title 24, ASHRAE 90.1, and LEED).

Cool roofs can be found on buildings across the United States. They 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 timeline in Figure 26 shows the time taken to adopt cool roofs and the accompanying incentives, such as an ENERGY STAR label and utility rebates. 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.

For cool walls, the research team began by investigating existing references to cool walls. The team found that ASHRAE 90.1 (2016), ASHRAE 189.1 (2014), the California Green Building Standards Code, the Green Building Initiative's Green Building Assessment Protocol for Commercial Buildings, and Hawaii's State Energy Conservation Code already reference cool

walls. The team also found references to cool walls in California's Property Assessed Clean Energy (PACE) program for residential buildings. This is good news because one can build upon these early cool-wall advances to increase inclusion of cool walls in other codes and programs. In addition, the researchers can share their recent findings with these organizations to improve and/or strengthen existing requirements.

**Figure 26: Cool-roof Code Development Timeline**



**A timeline of the inclusion of cool roofs in major building codes/standards and other milestones.**

Source: Lawrence Berkeley National Laboratory

The researchers are developing a pilot credit for the United States Green Building Council's LEED Sustainable Sites category, and exploring the feasibility of creating a rating organization for cool walls like the CRRC, or expanding the scope of the CRRC to include wall products.

However, much additional work beyond the project term will be needed to advance the adoption of cool walls. The researchers would like to collaborate with California utilities to develop cool-wall incentives, and to sponsor a Codes and Standards Enhancement initiative to evaluate how cool walls could be included in California's Title 24 Building Energy Efficiency Standards. In addition, the research team would like to pursue ENERGY STAR certification for cool-wall products.

Increasing the adoption of cool walls requires robust engagement from stakeholders. The adoption of cool walls will take time; thus, long term commitment from stakeholders will be critical. To facilitate stakeholder engagement, the researchers established a working group. The

objective of the working group is to advance appropriate adoption of cool walls by incorporating the technology into building codes and incentive programs, and disseminating information. The team formed the working group in fall 2017 and organized the group's first meeting in winter 2018.

The complete study is presented in the Task 6.3 report, *Advancements in Infrastructure Development: Building Standards and Incentive Programs* (Appendix R).

# CHAPTER 7:

## Conclusions

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### Highlights

#### Energy Savings and Emission Reductions

Simulations indicate that cool walls save energy and reduce emissions in buildings across California and about half of the United States. The savings outlined below assume that the albedos of all four walls are raised simultaneously to 0.60 from 0.25. Each can be scaled by a solar availability factor to account for shading and reflection of sunlight by neighboring buildings.

#### California

- Cool walls lowered annual HVAC energy cost per unit modified surface area by \$0.07/m<sup>2</sup>—\$1.7/m<sup>2</sup> in single-family homes, \$0.10/m<sup>2</sup>—\$2.1/m<sup>2</sup> in medium offices, and \$0.0/m<sup>2</sup>—\$4.3/m<sup>2</sup> in stand-alone retail stores. They also reduced whole-building annual HVAC energy use by 3.0 percent—25 percent in single-family homes, 0.5 percent—3.7 percent in medium offices, and 0.0 percent—9.0 percent in stand-alone retail stores.
- Cool walls lowered annual HVAC carbon dioxide equivalent emissions per unit modified surface area by 0.0 kg/m<sup>2</sup>—3.4 kg/m<sup>2</sup> in single-family homes, 0.17 kg/m<sup>2</sup>—4.5 kg/m<sup>2</sup> in medium offices, and 0.16 kg/m<sup>2</sup>—9.2 kg/m<sup>2</sup> in stand-alone retail stores.
- Energy use, energy cost, and emission savings from the oldest vintage were generally three to six times greater than those from the new vintage. The cool-wall savings from the oldest vintage are important since they represent over 60 percent of California's building stock.

#### United States

- In warm United States climates - zones 1A (Miami, FL) through 4B (Albuquerque, NM) - cool walls lowered annual HVAC energy cost per unit modified surface area by \$0.1/m<sup>2</sup>—\$1.1/m<sup>2</sup> in single-family homes, \$0.0/m<sup>2</sup>—\$1.8/m<sup>2</sup> in medium offices, and \$0.0/m<sup>2</sup>—\$3.7/m<sup>2</sup> in stand-alone retail stores. They also reduced whole-building annual HVAC energy use by 2.0 percent—8.5 percent in single-family homes, 0.0 percent—4.2 percent in medium offices, and -0.5 percent—5 percent in stand-alone retail stores.
- In these zones, cool walls lowered annual energy HVAC carbon dioxide equivalent emissions per unit modified surface area by -0.37 kg/m<sup>2</sup>—5.3 kg/m<sup>2</sup> in single-family homes, 0.03 kg/m<sup>2</sup>—10.3 kg/m<sup>2</sup> in medium offices, and -1.2 kg/m<sup>2</sup>—20.9 kg/m<sup>2</sup> in stand-alone retail stores.
- As in California, the oldest vintage yielded greatest cool-wall savings or penalties. This is important since the oldest vintage buildings represent in most United States locations at least 60 percent of the building stock.



## Human Comfort

Cool walls had negligible effect on indoor human comfort in an unconditioned building as well as on pedestrians passing by cool walls.

- The typical indoor air temperature reduction inside an unconditioned building with cool walls versus conventional walls was negligible. Since thermal sensation in buildings without air conditioning is generally cold at night and warm during the day this corresponds to a slight worsening of thermal comfort at night and an improvement of thermal comfort during the day.
- Thermal comfort changes for pedestrians walking next to a cool wall are small and will go unnoticed by most people.

## Urban Air Temperature Reduction and Air Quality Improvement

Cool walls in Los Angeles provided similar urban air temperature reductions as cool roofs per unit increase in wall or roof albedo.

- The researchers for the first time assessed the influence of employing solar reflective “cool” walls on the urban energy budget and summertime climate of the Los Angeles basin. The team compared the climate effects of hypothetical city-scale cool-wall adoption to cool roof adoption.
- Per 0.10 wall (roof) albedo increase, widespread adoption of cool walls (roofs) can reduce summertime daily average canyon air temperature by 0.048–0.054 K (0.058–0.060 K).

## Initial and Long-term Albedos of Wall Materials

After 24 months of natural exposure in California, cool-wall materials exhibited little to no loss in solar reflectance.

- The researchers exposed 69 cool-wall materials at three sites in California and 55 materials in three sites across the United States
- Factory-applied coatings showed excellent performance in all locations used for California and United States exposure, with negligible changes in solar reflectance.
- Field-applied coatings’ 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.

## Novel Cool-wall Technologies

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.

- The researchers built a calorimetric instrument that measures effective solar reflectance, or the fraction of incident solar energy rejected by the combination of reflectance and fluorescence.
- Pink-red coatings colored with a fluorescent ruby pigment (aluminum oxide doped with chromium) can reject up to 15 percent of incident solar energy by invisibly re-emitting absorbed visible light. Blue, green, and blue-black coatings colored with fluorescent Egyptian blue or Han blue pigments provide a similar benefit.
- The fluorescent blue pigments may also be useful in fabrication of high-performance luminescent solar concentrators for photovoltaic panels.
- 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.
- The most promising retroreflector design was a two-surface retroreflector with perpendicular metal mirror faces.

## Infrastructure

There is some existing infrastructure within which to promote cool walls. Developing all necessary infrastructure is a long-term process that must continue after the project is completed.

- The research team developed a cool-wall working group that will continue to advance cool-wall adoption in incentive programs, building codes/standards, and green building programs.
- The research results led the Cool Roof Rating Council to form its own working group to consider expansion to wall products.
- The team developed cool-wall guidelines to identify 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.
- Researchers hosted a cool-wall stakeholder workshop to share our research results and solicit feedback from stakeholders.
- The team identified existing cool-wall measures in building codes/standards and ways to expand and enhance their specifications to maximize benefits. In addition, we initiated contact with other building codes/standards, green building programs, and incentive programs to develop new cool-wall measures, pilot credits, certification, and rebates.

## California Policy Recommendations

- Incorporate cool-wall measures into California’s Title 24 Building Energy Efficiency Standards for 2022. The measures should apply not only to new construction, but also to retrofits, since existing buildings enjoy the greatest savings.
- Include cool-wall measures in CALGreen’s voluntary Tier 1 or 2 requirements for the urban heat island mitigation section for 2022. These voluntary Tier measures can then be easily adopted by local jurisdictions.
- Evaluate the contribution of photocatalytic urban surfaces to help cities, regional Air Quality Management Districts, and the California Air Resources Board meet air quality standards and goals. Analysis should also take into account that photocatalytic self-cleaning urban surfaces are able to maintain high albedo. By staying more reflective over time, the surfaces lead to greater urban temperature reductions than soiled surfaces, and can affect atmospheric chemistry.
- Change research funding structure to enable researchers to serve as technical points-of-contact for policy makers to implement and adopt beneficial EPIC research, such as cool-wall measures.
- Incorporate cool building envelope surfaces (roofs and walls) into low-income weatherization programs in warmer California climate zones to reduce energy demand in residences with air conditioning. This would support the *E-6 Increase climate resiliency in low-income and disadvantaged communities* measure in the Safeguarding California Plan: 2018 Update (CNRA, 2018), and be in coordination with California Department of Community Services and Development.

## National Policy Recommendations

- Enhance cool-wall measures in ASHRAE 90.1 and ASHRAE 189.1, revising cool-wall specifications and extending measures to additional climate zones.
- Introduce a federal tax credit to incentivize home and business owners to purchase cool-wall products.

## Next Steps

### Further Research

While the cool-wall project’s research design was comprehensive and evaluated many aspects of this technology and its application, there is need for further research.

- The climate effects of cool walls and roofs are expected to vary depending on building morphology, impervious cover, and the baseline climate of the city under investigation. Therefore, the researchers suggest future work to investigate the effects of cool-wall adoption in areas other than Los Angeles County.

- The research team initiated a 5-year national exposure program as part of this project, and have collected data from years 1 and 2. The team will need to collect data from years 3, 4, and 5 after the conclusion of the current project.
- The analysis presented here estimates city-level NO<sub>x</sub> deposition, and does not consider whether photocatalytic self-cleaning walls may have larger air quality benefits for near-source concentrations within urban canyons. The research team suggests future work to estimate the impact of photocatalytic self-cleaning walls on near-source NO<sub>x</sub> concentrations. Future work should also assess reactions removing other atmospheric contaminants, and the potential formation of gas- and particle-phase oxidation products by photocatalytic materials.
- The potential for directionally retroreflective walls to cool buildings and the urban environment is a win-win and thus merits further investigation to develop commercially viable prototypes.
- The fluorescence benefits of the prototype materials that were developed are encouraging. However, future work may be required to be apply them within building envelope materials.
- Researchers should develop a cool-wall monitoring and demonstration project that would include several building types in multiple climate zones to validate cool-wall benefits.
- Researchers should adapt to wall materials of the lab-aging practice currently available for roofing products (ASTM Standard D7897).

### **Advancing Adoption**

To further the building- and climate-appropriate adoption of cool walls, the researchers suggest the following action items that build on the research findings:

- Launch California utility incentives for cool-wall products.
- Complete a cool-wall Codes and Standards Enhancement initiative to vet requirements and language for cool-wall measures in California's Title 24 Building Energy Efficiency Standards. An expansion of this initiative could also provide non-energy benefits that would be helpful for CALGreen cool-wall measure improvement.
- Find continued funding to support the cool-wall working group to advance cool-wall measures in incentive programs, building codes/standards, and green building programs, such as ASHRAE 90.1, ASHRAE 189.1, and the United States Green Building Council's LEED.
- Develop a United States Green Building Council's LEED cool-wall pilot credit.
- Improve the existing ASHRAE 90.1 and ASHRAE 189.1 cool-wall measures to expand into United States climate zones.
- Complete United States EPA ENERGY STAR certification of cool-wall products.

- Launch a cool-wall product rating program that would develop credible methods to evaluate and label products.
- Improve the existing State of Hawai'i building energy code to clearly specify cool-wall products.
- Develop case studies of existing buildings with cool walls to note the building owner's (or design team's) decision-making process when selecting cool-wall products.
- Advance inclusion of cool-wall measures in the International Energy Conservation Code.

## GLOSSARY AND ACRONYMS

Term	Definition
Albedo	Synonym for “solar reflectance”
ASHRAE	Formerly known as the American Society of Heating, Refrigerating and Air-Conditioning Engineers; in 2012, as part of a rebranding, ASHRAE began doing business as “ASHRAE”.
ASTM	ASTM International, formerly known as American Society for Testing and Materials, is one of the world's largest international standards developing organizations.
Calorimetric	Using change in temperature to assess flow of heat
cm s <sup>-1</sup>	Centimeters per second
CO <sub>2</sub>	Carbon dioxide
CRRC	Cool Roof Rating Council
CuO	Copper oxide
EnergyPlus	A building energy use simulation tool supported by the United States Department of Energy.
EPIC	The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.
ESR	Effective solar reflectance
g m <sup>-2</sup>	Grams per square meter
Goniometer	An instrument that measures the variation of reflectance with angle
HCl	Hydrochloric acid
HVAC	Heating, ventilation, and air conditioning
ISO	International Organization for Standardization
K	Kelvin
kg	Kilogram
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design, a green building program operated by the US Green Building Council (USGBC).

<b>Term</b>	<b>Definition</b>
LST	Local Standard Time
m <sup>2</sup>	Square meter
mg	Milligram
mm	Millimeter
mol hr <sup>-1</sup>	Moles per hour
MWh	Megawatt-hour
NIR	Near infrared
NO	Nitrogen monoxide
NO <sub>2</sub>	Nitrogen dioxide
NO <sub>x</sub>	Nitrogen oxides
PACE	Property Assessed Clean Energy, a program to help property owners finance renewable energy and energy efficiency improvements.
PBL	Planetary boundary layer
PMV	Predicted mean vote
SET*	Standard Equivalent Temperature
SHGC	Solar heat gain coefficient
Solar absorptance	Fraction of incident sunlight that is absorbed
Solar reflectance	Fraction of incident sunlight that is reflected
SR	Solar reflectance
TUF-IOBES	Temperature of Urban Facets - Indoor Outdoor Building Energy Simulator, a building energy use simulation tool developed by the University of California at San Diego.
μmol h <sup>-1</sup>	Micromoles per hour
Urban canyon	The U-shaped space formed by buildings on opposite sides of a street
UV	Ultraviolet
WRF	Weather Research and Forecasting, a numerical weather prediction system.

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# LIST OF APPENDICES

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The following Appendices are available under separate cover:

Appendix A: Simulated Heating, Ventilation, and Air Conditioning Energy Savings in an Isolated Building (Task 2.1 report): See CEC-500-2019-040-APA

Appendix B: Effect of Neighboring Cool Walls on Heating, Ventilation, and Air Conditioning Loads (Task 2.2 report): See CEC-500-2019-040-APB

Appendix C: Using Solar Availability to Scale Heating, Ventilation, and Air Conditioning Energy Savings (Task 2.3 report): See CEC-500-2019-040-APC

Appendix D: Pedestrian Mean Radiant Temperature and Thermal Comfort (Task 3.1 report): See CEC-500-2019-040-APD

Appendix E: Urban Climate Impacts of Cool Walls (Task 3.2 report): See CEC-500-2019-040-APE

Appendix F: Effect of Cool Walls on Energy-saving Benefits from Cool Pavements (Task 3.3 report): See CEC-500-2019-040-APF

Appendix G: Effect of Wall Albedo on the Environment inside an Unconditioned Building (Task 3.4 report): See CEC-500-2019-040-APG

Appendix H: Effects of Self-cleaning Walls on Urban Air Quality (Task 3.5 report): See CEC-500-2019-040-APH

Appendix I: Metrics and Methods to Assess Cool Wall Performance (Task 4.1 report): See CEC-500-2019-040-API

Appendix J: Natural Exposure of Wall Products (Task 4.2 report): See CEC-500-2019-040-APJ

Appendix K: Self-cleaning and De-Polluting Photocatalytic Materials (Task 4.3 report): See CEC-500-2019-040-APK

Appendix L: Assessment of Existing and New Retroreflective Materials (Task 4.4 report): See CEC-500-2019-040-APL

Appendix M: Improvement of Self-cleaning Coatings and Claddings (Task 5.1 report): See CEC-500-2019-040-APM

Appendix N: Development of Fluorescent Cool Pigments (Task 5.2 report): See CEC-500-2019-040-APN

Appendix O: Development of Retroreflective Materials (Task 5.3 report): See CEC-500-2019-040-APO

Appendix P: Cool Wall Application Guidelines (Task 6.1 report): See CEC-500-2019-040-APP

Appendix Q: Cool Wall Workshop Proceedings (Task 6.2 report): See CEC-500-2019-040-APQ

Appendix R: Advancements in Infrastructure Development: Building Standards and Incentive Programs (Task 6.3 report): See CEC-500-2019-040-APR