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Energy and environmental consequences of a cool pavement campaign

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ABSTRACT

Raising the albedo (solar reflectance) of streets can lower outside air temperature, reduce building energy use, and improve air quality in cities. However, the production and installation of pavement maintenance and rehabilitation treatments with enhanced albedo ("cool" pavements) may entail more or less energy consumption and carbon emission that of less-reflective treatments. We developed several case studies in which a cool surface treatment is substituted for a more typical treatment (that is, a cool technology is selected instead of a more typical technology). We then assessed over a 50-year analysis period the changes in primary energy demand (PED, excluding feedstock energy) and global warming potential (GWP, meaning carbon dioxide equivalent) in Los Angeles and Fresno, California. The analysis considers two stages of the pavement life cycle: materials and construction (MAC), comprising material production, transport, and construction; and use, scoped as the influence of pavement albedo on cooling, heating, and lighting energy consumption in buildings.

In Los Angeles, substituting a styrene acrylate reflective coating or a chip seal for a slurry seal in routine maintenance, or a bonded concrete overlay on asphalt (BCOA) without supplementary cementitious materials (SCM) for mill-and-fill asphalt concrete in conventional or long-life rehabilitation, induced MAC-stage PED and GWP penalties that substantially exceeded use-stage savings, primarily due to material production. Modified rehabilitation cases in which SCM comprised 21% to 50% of the BCOA's total cementitious content by mass (portland cement + SCM) yielded smaller total (MAC + use) PED and GWP penalties, or even total PED and GWP savings. Trends in Fresno were similar, with some differences in GWP outcomes that result from Fresno's longer heating season.

The modified rehabilitation cases using BCOA with high SCM content yielded total GWP savings in each city; all other cases yielded total GWP penalties. The magnitude of the one-time GWP offset offered by global cooling from the increased albedo itself always, and sometimes greatly, exceeded the 50-year total GWP penalty or savings.

In Los Angeles, the annual building conditioning (cooling + heating) PED and energy cost savings intensities yielded by cool pavements were each about an order of magnitude smaller than the corresponding savings from cool roofs.

Key Words: life cycle assessment (LCA), cool pavement, building energy use, heating, cooling, materials and construction, supplementary cementitious materials (SCM), urban climate, global warming potential (GWP), global cooling

1 Introduction

Viewed from above the tree canopy, pavements such as streets, sidewalks, parking lots, and hardscape playgrounds typically cover 30 to 40 percent of the urban surface in United States cities [1] [2]. Historically, over 80 percent of paved surfaces are made of asphalt concrete, which has characteristically low solar reflectance, or “albedo” [3].

Albedos range from about 0.05 to about 0.35 for currently used pavement material surfaces. Over a typical service life, pavement materials that begin with high albedo tend to lose reflectance, while those with low initial albedo may gain reflectance. For example, slurry seal and asphalt concrete each have a typical initial albedo of 0.05 that increases to approximately 0.10 to 0.15, while portland cement concrete (PCC) has a typical initial albedo of 0.35 that falls to about 0.20 [4].

Solar-absorptive (“warm”) paved surfaces contribute to the urban heat island effect (UHIE). The UHIE is the elevation of the urban outdoor air temperature above that in less-developed surrounding areas. The UHIE results in part from the replacement of trees and other vegetation with buildings, paved surfaces, and other heat-absorbing infrastructure [5]. Elevated temperatures within urban heat islands threaten the health of city residents. Goggins et al. [6] found in Hong Kong that there was a 4.1% increase in mortality per 1 °C increase above 29 °C within micro heat islands, while there was a 0.7% corresponding increase in mortality in non-heat island areas.

Lowering urban air temperature can also improve health by slowing the formation of smog. In a meteorological and photochemical modeling study of Sacramento, California, Taha [7] found that raising roof, wall, and pavement albedos across the city could reduce air temperature by as much as 2 to 3 °C. This decrease in air temperature would lower the daytime ozone concentration by as much as 5 to 11 ppb (one-hour average), depending on meteorological conditions. (Sensitivity of ozone concentration to air temperature generally falls as air pollution decreases [8].) In a later study, Taha [9] estimated that this reduction in ozone could lower mortality by about 0.8%.

All else being equal, pavements with lower albedo contribute more to the UHIE than do pavements with higher albedo [5]. Raising the albedo of pavement lowers its temperature in the sun, which can in turn mitigate the UHIE. A review of nine urban albedo studies by Santamouris [10] found that increasing a city’s mean albedo by 0.1 typically lowers peak and average outside air temperatures by 0.9 and 0.3 °C, respectively.

Urban “canyons” formed by street-adjacent buildings can shade streets and absorb some of the sunlight reflected by streets. By applying an urban canyon albedo model to a detailed assessment of the building stock in Sacramento, California, Rosado et al. [11] determined that shading and absorption by the urban canyon in summer diminishes by about 10% the rate at which increasing pavement albedo raises urban albedo.

In one case study, Taha [12] modeled the effect of increasing urban albedo on city-wide peak afternoon air temperatures in the Los Angeles Basin. Rosenfeld et al. [13] used these temperature changes to calculate the energy savings and air quality improvements attainable by increasing the albedos of roofs and pavements in the Los Angeles Basin. They estimated that in the Los Angeles Basin (urban area 10,000 km^2), raising the albedo of 1,250 km^2 of pavement by 0.25 (replacing asphalt concrete with albedo 0.05 by cement concrete or other light-colored pavement with albedo

0.30) and increasing the albedo of 1,250 km^2 of roofing by 0.35 would together lower outdoor air temperatures by as much as 1.5 °C.

Raising the albedo of the urban surface, cooling the outside air, and thereby altering the air temperature difference across the building envelope can decrease the need for space cooling and increase the need for space heating. Cooling energy savings and heating energy penalties that stem from lowering the outside air temperature are labeled "indirect" and can accrue to any building in the cooled city. In their study of the Los Angeles Basin, Rosenfeld et al. [13] predicted through building energy simulations that the portion of the air temperature reduction attributed to increasing pavement albedo by 0.25 would reduce building conditioning (cooling + heating) energy cost by US$15M/y, or $0.012/y per square meter of pavement modified.

Taking another approach, Pomerantz, Rosado, and Levinson [14] analyzed aggregate electricity use measurements to bound the indirect building cooling site energy saving attainable from increasing the mean albedo of a city. They regressed city-wide hourly power demand reported by the local utility to the hourly outside air temperature to estimate the demand savings from air temperature reduction, and related air temperature reduction to increase in urban albedo. Excluding the energy effects of changing the solar heat gain of the building envelope, they estimated that in warm cities in California, such as Sacramento, increasing city-mean albedo by 0.066 (0.20 rise in albedo for one third of the city's surface, with minor effects of the urban canyon on light reflection neglected) would reduce cooling site energy use by less than 2 kWh/y per square meter of surface modified.

Reflective building envelope surfaces, such as light-colored roofs and walls, can also lower cooling energy use and raise heating energy use by decreasing the amount of solar energy absorbed by the building. These "direct" energy savings and penalties from increased albedo gain accrue only to the modified building. The direct cooling energy savings offered by cool (solar reflective) roofs have been simulated or measured by many workers [15] [16] [17] [18] [19], and provide a scale on which to gauge the indirect benefits of reflective surfaces.

Cool pavements may provide environmental benefits that help cities meet their sustainability goals. However, switching pavement management practices can also change upstream environmental burdens. The extraction, production, and transportation of pavement materials and the construction of pavement maintenance and rehabilitation (M&R) treatments generate pollution and consume energy. Life cycle assessment (LCA) provides a comprehensive evaluation of the environmental burdens from a product or service by quantifying the environmental effects of a product throughout its life cycle. In LCA, the inputs, such as energy and resource consumption, and outputs, such as pollution, are identified and inventoried over the product's entire life cycle, which usually includes material production, material transport, construction, use, and end-of-life [20].

Many LCA studies have investigated hydraulic cement concrete pavements (typically called "concrete pavement") and asphalt concrete pavements (typically called "asphalt pavement"), but these have not focused on cool materials, and often exclude the use stage [21]. Asphalt concrete is a mixture of graded sand, gravel, and mineral fines with asphalt cement (referred to as "bitumen" outside the USA); the latter is refined from the heaviest hydrocarbons found in petroleum. The asphalt cement is heated until semi-liquid, and then mixed with the sand, gravel, and mineral fines to coat and bind the aggregates.

Hydraulic cement concrete is a mixture of graded sand and gravel with hydraulic cements (cements that react with water). Hydraulic cement concrete often uses only portland cement (also known as ordinary portland cement, or OP). OP is prepared by super-heating selected types of rock in a kiln and then grinding them in a mill. Hydraulic cement mixes can also include supplementary cementitious materials (SCM), typically fly ash and/or slag. The total cementitious content in a hydraulic concrete mix includes the OP and the SCM (if present). Hydraulic cement concrete is often called portland cement concrete (PCC) even if it contains SCM.

Fly ash is a waste product from coal-fired power plants, and slag is a waste product from the manufacture of steel. Following recommended LCA practice (Chapter 4 of Ref. [20]), the global warming potential from the production of the fly ash and slag SCM is attributed to the upstream processes of power generation and steel production, rather than to production of the pavement materials, because fly ash and slag are unintended co-products that do not have economic value without additional processing and transportation. Incorporation of slag in cement concrete tends to raise albedo [22].

Studies in the last eight years have developed materials and construction inventories for a range of pavement materials [23] [24] [25], and looked at reducing the environmental impacts of portland cement concrete [26] and asphalt concrete materials [27]. Other studies have considered how allocation strategy and uncertainty in data quality contribute to variability of estimates of the environmental impacts of pavements [28] [29]; evaluated uncertainty in estimating emissions reductions for pavements with longer design lives [30]; and developed models for pavement vehicle interaction in the use stage [31] [32]. The growing consensus regarding best practice for the application of LCA to pavement has recently led to the publication of pavement LCA guidelines by the United States Federal Highway Administration [20].

The use of permeable pavements that capture and evaporate storm water and irrigation runoff to reduce local heat islands has been explored [33].

Roofing LCA studies typically assess energy or global warming potential impacts from cradle to gate (material production to constructed building) [34] [35] and may include the end-of-life stage [36], but do not include the building energy use savings and associated emission reductions that may result from increasing roof albedo. Cool roof studies tend to estimate building energy use savings and emission reductions from raising roof albedo, but not the changes in embodied energy or carbon associated with choice of roofing product [16] [18] [19].

Since the potential benefits and penalties of cool pavements can vary widely by region, and substituting cool pavement materials for typical treatment materials—that is, selecting cool, rather than typical, surface treatments—may produce undesired upstream environmental burdens, Levinson et al. [37] developed a pavement life cycle assessment (pLCA) decision tool for cities in California. The tool is intended to evaluate city-wide pavement management practices, and focuses on the life-cycle environmental impacts of substituting cool pavements for typical treatments.

The tool was designed to help cities in California understand the global warming implications of different pavement management practices. This is important because California passed the Global Warming Solutions Act of 2006 (also known as Assembly Bill 32) which directs the state to lower greenhouse gas (GHG) emissions to 1990 levels by 2020 [38], and to reduce emissions 80% below

1990 levels by 2050 [39]. Several California cities also set their own GHG reduction targets. For example, Los Angeles plans to reduce its annual GHG emissions to 20 megatonnes (Mt; also known as million metric tonnes, or MMT) CO_2e by 2025 and to 7.2 Mt CO_2e by 2050. These values are 45% and 80%, respectively, below its 1990 baseline [40]. Such ambitious targets require cities and the state to decrease GHG emissions across all sectors.

This paper presents the results of several case studies that we evaluated using the pLCA decision tool. They compare less-typical (cool) pavements to typical (warm) options for routine maintenance, rehabilitation, and long-life rehabilitation of pavements in the California cities of Los Angeles and Fresno.

2 Methodology

2.1 Development of the pavement life cycle assessment tool

The pLCA tool assesses the energy and environmental consequences of city-wide pavement management practices over a 50-year life cycle. It does not address the cost of pavement materials, construction, and maintenance, or the economic value of energy savings (or penalties). The tool focuses on city streets; sidewalks, parking areas and pedestrian areas lie outside its scope. The only use-stage life-cycle impacts considered are the direct and indirect interactions of pavement albedo with building cooling, heating, and lighting. However, it does also report changes to two environmental indicators: outside air temperature, and outdoor ozone concentration.

2.1.1 pLCA tool inputs and outputs

Given the city of interest, the fraction of that city's total pavement area to be modified[*], and two pavement scenarios (each specifying pavement type, service life, albedo, and—where applicable—thickness), the tool computes for each scenario two life-cycle impact indicators: global warming potential (GWP, meaning carbon dioxide equivalent[†]) and photochemical ozone creation potential (POCP, or smog potential). It also calculates three life-cycle flows: particulate matter less than 2.5 µm in diameter (PM2.5), primary energy demand (PED) without feedstock energy, and feedstock energy (FE).

Feedstock energy is the potential energy from combustion in a material that is used for a purpose other than fuel, such as the asphalt cement used to bind aggregate. Note that *all* PED values presented in this study exclude feedstock energy.[‡]

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[*] While the tool considers only changes to streets, it inputs the fraction of total pavement area to be modified, rather than the fraction of street pavement area to be modified, because it is easier to quantify a city's total pavement area than its total street area [37].

[†] For consistency with the LCA community, this study uses the term "global warming potential" as a synonym for carbon dioxide equivalent (CO_2e), or mass of CO_2 that would yield the same atmospheric heating as the emitted gas.

[‡] This study reports changes in feedstock energy, but emphasizes changes in primary energy demand excluding feedstock energy because the feedstock energy in asphalt binder is unlikely to be used as fuel in California. Burning asphalt binder is difficult [41] and would violate California air pollution regulations without major changes in combustion technology [42]. However, asphalt binder, also known as "bottoms" in petroleum distillation, can be refined via coking into liquid fuels, natural gas, and petroleum coke [43].

Table 1. LCA and use-stage specific metrics evaluated in the pLCA tool.

LCA metrics	**Units**
Global Warming Potential (GWP)	kg CO_2e
Photochemical Ozone Creation Potential (POCP)	kg O_3e
Particulate Matter, less than 2.5 micrometers in diameter (PM2.5)	kg
Primary Energy Demand (PED) excluding feedstock energy	MJ
Feedstock Energy (FE)	MJ
Use-stage metrics	
Annual Site Electricity Use [a]	kWh/y
Annual Site Gas Use [b]	therm/y
Outdoor Air Temperature (city mean, near top of urban canopy)	°C
Ozone Concentration (city mean at 15:00 local standard time)	ppb

[a] 1 kWh = 3.6 MJ

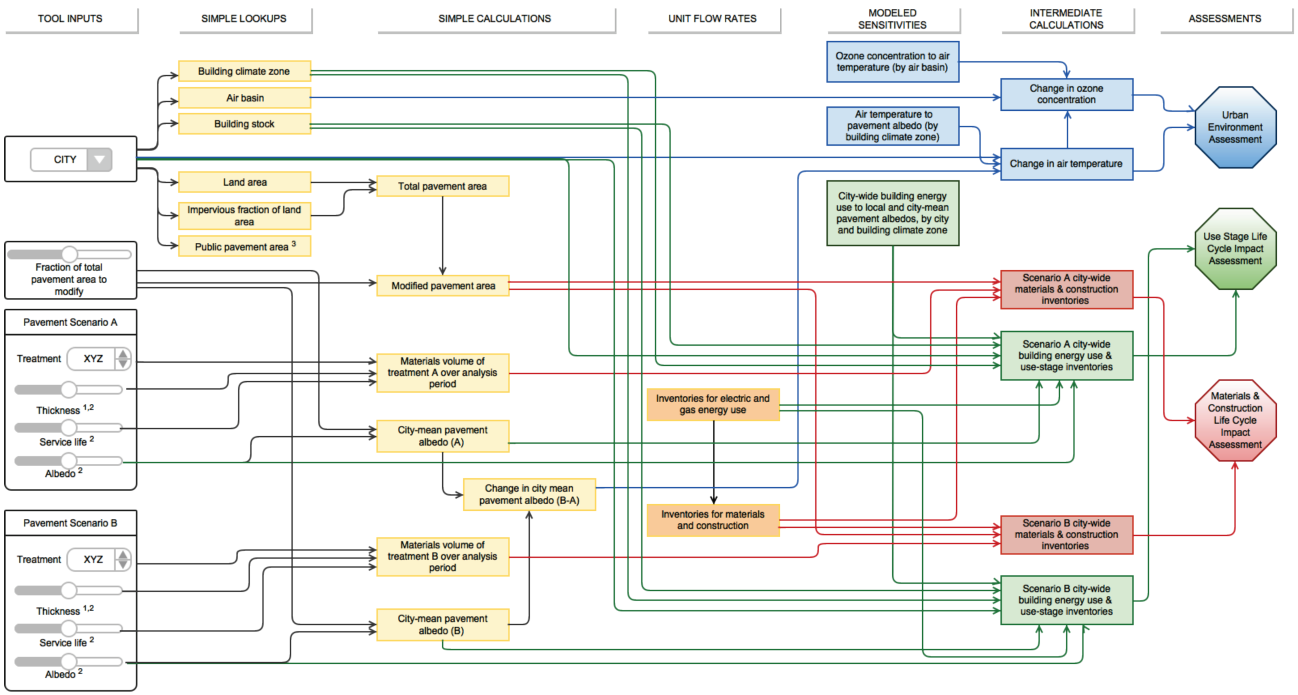
[b] 1 therm = 100 kBTU = 105.5 MJ = 2.755 m^3 gas

The tool calculates in each pavement scenario the contributions to the LCA metrics of pavement material production (the "material" component), pavement material transportation (the "transport" component), and pavement construction (the "construction" component), and those from cooling, heating, and lighting the buildings in the city. The material, transport, and construction components make up the "materials and construction", or "MAC", stage, while the building cooling, heating, and lighting components constitute the "use" stage.[§] MAC-stage metrics are representative of California, but independent of location within the state; use-stage metrics consider local climate, building construction, and building stock.

The tool also reports differences in two environmental metrics: seasonal values of city-mean hourly air temperature near the top of the urban canopy, and city-mean ozone concentration at 15:00 local standard time (LST) in summer.

Figure 1 diagrams the operation of the pLCA tool [37]. All metrics are detailed in Table 1.

[§] The tool uses the term "non-use", rather than "MAC", to describe the stage composed of the material, transport, and construction components.



CITYWIDE IMPACT CHANGE (B - A)					
Life cycle				Urban environment	
Primary energy demand [4]	Feedstock energy	Criteria air pollutants	Global warming potential	Urban air temperature	Urban ozone concentration
				✓	✓
✓		✓	✓		
✓	✓	✓	✓		

[1] Applies to some treatments
[2] Default value provided based on treatment
[3] Available for some cities; advisory only
[4] Excluding feedstock energy

Figure 1. Operation of the pavement life cycle assessment (pLCA) tool.

The annual site energy uses and the use-stage LCA metrics include the indirect effect of pavement albedo—the influence of city-wide mean pavement albedo on city-wide mean air temperature, and the variation of building energy use with that air temperature—and the direct effect of pavement albedo, meaning the influence of local street albedo on the energy uses of buildings exposed to sunlight reflected from the street.

The life cycle inventory in the pLCA tool was developed using a 2020 electricity grid mix based on projected procurement of electricity from renewable sources by the three major investor-owned utilities (IOUs) in California: Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric. While California's Renewables Portfolio Standard (RPS) requires that 33% of the state's electricity come from renewable sources by 2020, only about 28% of the total 2020 generation from these three IOUs is projected to come from renewables [44] [45] [46] [37].

California expects very little use of coal after 2020 for in-state production of electricity (6.4% of electricity mix) [47]. However, during periods of peak demand, California imports electrical energy from the Arizona/New Mexico and Northwest Pacific regions that rely on 40% and 25% hard coal-fired power plants, respectively [48].

It is important to note that the pLCA tool considers many, but not all, environmental consequences of changing the albedo of pavement materials. The tool reports the effect of increasing pavement albedo on city-wide building energy use, air temperature, and air quality. However, it does not address other potential effects of raising pavement albedo, such as reduction in demand for street lighting [49] or decrease in atmospheric temperature via global cooling [50] [51] [52]. It also does not consider other consequences of pavement choice, including changes in pavement roughness, texture, or deflection that may affect vehicle fuel economy; stormwater handling; bicycle ride comfort; tire/pavement noise; or traffic delay associated with construction.

2.1.2 pLCA tool research components

The data sets and algorithms used in the tool were developed with complementary research efforts into pavement management and maintenance practices, pavement albedo, pavement life cycle inventories, local urban climate, local air quality, and city-wide building energy use. The full methodology described in Ref. [37] included the following elements:

1. Investigation of the pavement management and maintenance practices used by local governments in California.
2. Development of California-specific pavement material life-cycle inventories to quantify the environmental burdens generated in the MAC stage (material production, transport, and construction).
3. Development of California-specific inventories for electrical energy production. These inventories use electricity generated in California and at this time do not consider purchases of electricity from outside the state. The latter may have greater global warming potential per unit of energy.

4. Modeling of urban climate to estimate city-wide air temperature reductions induced by cool pavement adoption. The climate simulations are described in more detail in our companion paper [53].

5. Estimation of urban ozone concentration decreases induced by air temperature reductions from cool pavement adoption.

6. City-wide building energy modeling to capture changes in building energy use induced by modifying pavement albedo.

2.1.3 Limitations and assumptions of the pLCA tool

We note here some of the limitations and assumptions of the pLCA tool. Ref. [37] provides the full list and further discussion.

1. The tool does not account for shading of streets by vehicles or trees.

2. The tool assumes that the entire portion of the pavement network selected for treatment is instantaneously treated at the beginning of the analysis period. This limitation was imposed by the constraints of the climate modeling. In practice, most cities do not treat more than 3 to 10% of their network in a given year based on the condition of the network and available funding [4] [37]. Many streets with low traffic will only receive maintenance treatments and will never be rehabilitated.

3. The user assigns to each pavement system a constant (presumably time average) albedo over the entire analysis period.

4. The tool assumes that each pavement is replaced with the same type of system at the end of its service life. In practice, most pavements experience treatment sequences that include both maintenance and rehabilitation.

5. The tool does not consider carbonation of concrete material when it is removed from the existing pavement. Carbonation is the reabsorption of CO_2 from the atmosphere by the hydrated cement to form calcium carbonate. Most concrete material reclaimed from existing pavement at end of service life is quickly processed and re-used in new pavement, limiting exposure to the atmosphere.

6. The pavement materials and construction impacts of the final treatment in the 50-year analysis period are linearly pro-rated if any service life remains. In other words, life-cycle MAC stage impact is calculated by scaling impact per service life by the ratio of the analysis period (50 y) to the treatment service life.

7. The tool does not track the spatial distribution of environmental effects. The results are totaled without distinguishing effect location.

8. The climate model methodology used in this study featured long simulations that represent a variety of meteorological regimes. Therefore, the air temperature reductions reported by the tool would differ from those experienced during an extreme heat event.

9. The climate modeling methodology focused on city-wide air temperature changes. The effects of higher albedo pavements in a specific neighborhood, at the micrometeorological scale, could vary from what is reported here.

10. The building prototypes used for the building energy simulations followed California's 2008 Title 24 building energy efficiency standards [54][55]. However, the median year of construction of existing residential buildings in California is 1975, and that of existing commercial buildings is between 1970 and 1979. Older buildings may have less envelope insulation, and less efficient HVAC (heating, ventilation, and air conditioning) equipment, than newer buildings.

11. The building energy simulations do not account for the reduction in long-wave (thermal infrared) radiation from pavement to building that can occur when raising pavement albedo lowers pavement surface temperature.

12. The environmental impacts of electrical energy use are based on the California 2020 renewable energy portfolio. Results will vary with the carbon intensity of the electrical grid.

13. The GWP calculations treat all GHG emissions over the analysis period as if they were released today. Kendall [56] has developed time-adjusted warming potentials that consider when emissions take place.

2.2 Case studies

2.2.1 Pavement technologies

To assess the potential effects of changing pavement management practices, we evaluated several case studies with the pLCA tool. Each case study compares a typical treatment practice to two less-typical, cool pavement practices. Case Study 1 compares pavement options for routine surface maintenance. Case Studies 2 and 3 examine options for conventional rehabilitation and long-life rehabilitation of pavements, respectively (Table 2).

2.2.1.1 Case Study 1: routine maintenance

Case Study 1 considers surface treatments that could be deployed in California cities for routine maintenance. These seal the underlying pavement structure to reduce infiltration of water and oxidation of the surface, but do not add structural capacity. Our survey of local California governments identified asphalt concrete pavement as the predominant current pavement type and slurry seal as the predominant pavement treatment practice for routine maintenance [37]. Therefore, it was selected as the typical treatment practice for the case study. Slurry seal is a thin mixture of asphalt emulsion and fine aggregate that is applied to existing pavement surfaces (Table 3). Its albedo ranges from 0.07 when new to 0.10 when aged [37]. For this analysis, we assigned it a life-cycle average albedo (hereafter, average albedo) of 0.10.

Table 2. Specifications of the three pavement case studies.

Case study	Typical treatment	Less-typical treatment	Aged albedo	Albedo increase	Service life (y)	Thickness per installation (cm)	Thickness installed over 50 y (cm) [a]
1. Routine maintenance	Slurry seal		0.10	-	7	-	-
		1A: Styrene acrylate reflective coating	0.30	0.20	5	-	-
		1B: Chip seal	0.23	0.13	7	-	-
2. Rehabilitation	Mill-and-fill AC		0.10	-	10	6	30
		2A: BCOA (no SCM)	0.25	0.15	20	10	25
		2B: BCOA (low SCM)	0.25	0.15	20	10	25
		2C: BCOA (high SCM)	0.25	0.15	20	10	25
3. Long-life rehabilitation	Mill-and-fill AC		0.10	-	20	15	37.5
		3A: BCOA (no SCM)	0.25	0.15	30	15	25
		3B: BCOA (low SCM)	0.25	0.15	30	15	25
		3C: BCOA (high SCM)	0.25	0.15	30	15	25

[a] Calculated as (thickness per installation) × (50 y LCA term) / (service life).

Table 3. Composition of each pavement treatment considered in this study [37].

Treatment	Composition
Slurry seal	6.5 kg crushed fine aggregate and 0.68 kg residual asphalt per m² pavement
Styrene acrylate reflective coating	7.7% styrene, 6% titanium dioxide, 13% butyl acroylate, 5.4% methyl acrylate, 3% methacrylic acid, 6% zinc oxide, 0.18% ammonium persulfate, 0.1% N-dodecyl mercaptan, 0.02% ammonium sulfite, 1.6% hydroxypropane-1-sulphonate, 1% azirdine, 1% ammonium hydroxide, and 55% water by mass, applied at 1 kg per m² pavement
Chip seal	1.8 L bitumen emulsion and 19 kg aggregate per m² pavement
Mill-and-fill AC (Hveem mix)	38% coarse aggregate, 57% fine aggregate, 5% dust, 4% asphalt binder, and 15% reclaimed asphalt pavement by mass
BCOA (no SCM)	1071 kg coarse aggregate, 598 kg fine aggregate, 448 kg cement, 1.8 kg polypropylene fibers, 1.9 kg water reducer (Daracern 65 at 390 mL per 100 kg of cement), 1.6 kg retarder (Daratard 17 at 325 mL per 100 kg of cement), 0.6 kg air entraining admixture (Daravair 1400 at 120 mL per 100 kg of cement), and 161 kg water per m³ wet concrete
BCOA (low SCM)	1085 kg coarse aggregate, 764 kg fine aggregate, 267 kg cement, 71 kg fly ash, 1.8 kg polypropylene fibers, and 145 kg water per m³ wet concrete
BCOA (high SCM)	1038 kg coarse aggregate, 817 kg fine aggregate, 139 kg cement, 56 kg slag, 84 kg of fly ash, and 173 kg water per m³ wet concrete

A reflective coating and a chip seal were selected as less-typical, higher-albedo surface treatments for Cases 1A and 1B, respectively. Reflective coatings are already applied to parking lots, pedestrian areas, and bicycle lanes in California, but are not typically used to maintain city streets. Albedos of reflective coatings vary depending on the product selected by the client. Ref. [37] reported aged albedos ranging from 0.20 to 0.30. For this analysis, we modeled a styrene acrylate reflective coating and assigned it an average albedo of 0.30.

A chip seal is a surface treatment in which a layer of aggregate approximately one stone thick is spread on a layer of sprayed asphalt and rolled to embed it. If the aggregate is not pre-coated in asphalt, the albedo of the aggregate dominates the albedo of this surface treatment. We assigned an average albedo of 0.23 to the chip seal, which is on the higher end of the aged albedo range for this technology (0.10 to 0.24) [37].

2.2.1.2 Case Study 2: rehabilitation

Case Study 2 considers practices for conventional pavement rehabilitation. This case study represents the pavement management practice of repairing a deteriorated city street with a structural overlay. It uses as the typical technology mill-and-fill asphalt concrete (AC), in which some of the existing AC surface layer is removed with a milling machine and then replaced with new AC. The asphalt is assumed to include 15% reclaimed asphalt pavement, which is the material produced by milling; this is typical of practice in California. The typical option (mill-and-fill AC) treatment was assigned an average albedo of 0.10, a thickness of 6 cm, and a service life of 10 years.

The three less-typical options considered are different mix designs for bonded concrete overlay on asphalt (BCOA). In BCOA, the existing AC surface layer is lightly milled to improve bonding, and then overlaid with a hydraulic (usually portland) cement concrete. The BCOA mixes incorporate varying amounts of ordinary portland cement (OP) and supplementary cementitious materials (SCM). Cases 2A, 2B, and 2C use as their less-typical treatments BCOA mixes with no SCM, low SCM, and high SCM content, respectively (Table 3). Each BCOA was assigned an average albedo of 0.25, a thickness of 10 cm, and a service life of 20 years. These values, as well as the BCOA mix designs, fall within the ranges of thickness and service life found in practice in California, and were developed based on the experience of the pavement research members of the team in consultation with an outside pavement expert (Tom Van Dam, Principal, Transportation Research Group, NCE; personal communication with Haley Gilbert, 21 April 2016).

The three BCOA mixes are intended to perform similarly in thin concrete BCOA slabs; we assume that the underlying AC will provide much of the structural capacity. The BCOA mixes with no SCM and with low SCM have been used in BCOA projects in the U.S. Each includes fibers, which are commonly used in BCOA mixes to slow crack propagation.

The BCOA with no SCM content (Case 2A) is typical of local government concrete paving applications in California.[**] There is little experience, and therefore greater perceived risk, with

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[**] There has been almost no use of BCOA in California to date, but this mix matches that used in relatively thin conventional concrete pavements built for local governments.

the use of mixes incorporating SCM or lowering total cementitious contents for any type of concrete pavement built by local governments in California.

The BCOA with low SCM content (Case 2B) has 25% less total cementitious material than the BCOA used in Case 2A, and about 21% of its total cementitious content by mass is SCM (fly ash). It attains strength at 28 days comparable to that of the no-SCM mix through use of optimized aggregate grading. This grading process uses intermediate sized aggregate, rather than cementitious material, to fill the voids between coarse and fine aggregate. The BCOA with low SCM shrinks less upon curing than the BCOA with no SCM. This reduces the risk of cracking, particularly in arid environments. However, it may take longer to develop enough strength to carry vehicles, extending traffic closures [57].

The BCOA with high SCM content (Case 2C) represents the upper limits of OP reduction and use of SCM in current concrete mix technology. The high SCM mix is commercially sold by one California manufacturer and is specifically intended to minimize global warming potential. It has 38% less total cementitious material than the BCOA mix used in Case 2A and about 50% of its total cementitious content by mass is SCM. The high SCM content might slow strength gain, but provides high durability and improves resistance to cracking induced by shrinkage [57].

2.2.1.3 Case Study 3: long-life rehabilitation

Case Study 3 is similar to Case Study 2 in that it compares BCOA to mill-and-fill asphalt concrete for pavement rehabilitation. The materials in Case Study 3 are thicker and have longer services lives than their counterparts in Case Study 2. Case 3A, 3B, and 3C specify 15 cm thick mill-and-fill AC with a 20-year service life as the typical treatment, and 15 cm thick BCOA with a 30-year service life as the less-typical treatment. They are otherwise identical to Cases 2A, 2B, and 2C, respectively.

2.2.2 Locations

The three case studies are investigated for the cities of Los Angeles and Fresno (Figure 2). Los Angeles (latitude 34 °N, longitude 118 °W) is the state's largest city. It lies along the southern coast of California, and has over 3.9 million residents [58] and nearly 400,000 residential and commercial buildings. The total conditioned floor area in the city is about 96 million m², 87% of which is residential [59]. The average daily high temperature in summer (July to September) is 26 °C, and the average daily low temperature in winter (January to March) is 11 °C [60]. Using typical meteorological year weather data developed by White Box Technologies [61], we calculated 860 cooling degree days base 18 °C (CDD18C) and 1,040 heating degree days base 18 °C (HDD18C) in Los Angeles.

Located in the Central Valley of California, Fresno (latitude 36 °N, longitude 119 °W) is the state's fifth-largest city, and ranks first in the Central Valley. It has 520,000 residents [58] and nearly 150,000 buildings, with a city-wide conditioned floor area of nearly 26 million m². Roughly 88% of Fresno's floor area is categorized as residential [62]. Summers in Fresno have an average daily high temperature of 35 °C; in winter, the average daily low temperature is 5 °C [60]. Using weather data generated by White Box Technologies [61] for Fresno, we computed 1,370 CDD18C and 1,490 HDD18C.

Thirty percent of each city's total pavement area was modified in each case study. For Los Angeles, this equals 80 km² of pavement, which is 6.6% of the city's total land area. In Fresno, 30% of the pavement area is 18 km², or 6.3% of the city's total land area.

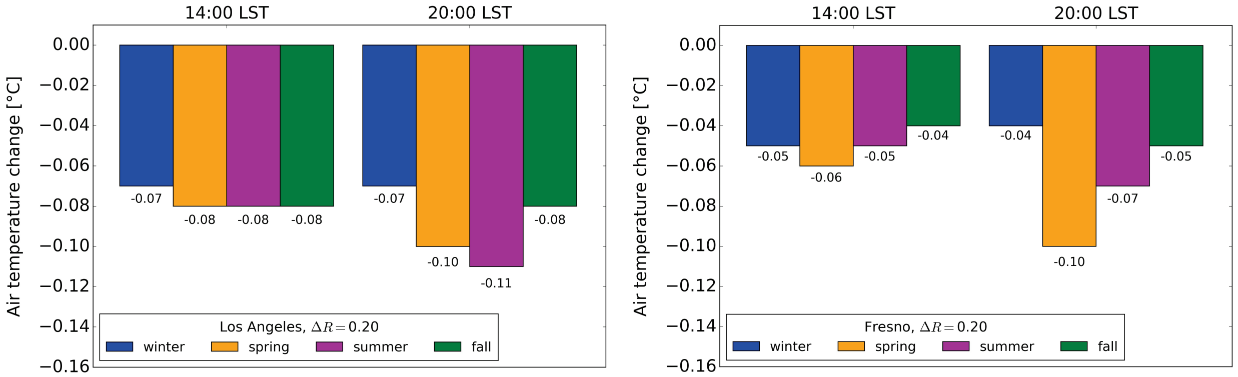
Figure 2. A topographic map of California locating the two cities studied.

3 Results

The results for the three case studies are presented below. While the tool reports additional metrics, this paper focuses on local air temperature reductions, life-cycle PED without FE, and life cycle GWP. Unless otherwise specified, all values of PED and GWP, or changes to PED and GWP, are presented for a 50-year analysis period.

3.1 Changes to city-wide ambient air temperature

Figure 3 shows seasonal mean temperature reductions at 14:00 LST (afternoon) and 20:00 LST (evening) for the cities of Los Angeles and Fresno upon increasing the albedo of the modified pavement area by 0.20 in Case 1A. These two hours were selected because peak daytime temperatures occur close to 14:00 LST, and because the UHIE is often strongest at night [37] [53]. Since climate modeling results from Refs. [37] and [53] indicate that change in air temperature is linearly proportional to change in pavement albedo, the results in this figure can be scaled to other pavement albedo gains.



(a) (b)

Figure 3. Seasonal average city-wide 2 m air temperature changes at 14:00 LST and 20:00 LST upon raising by 0.20 the albedo of 30% of pavement in (a) Los Angeles and (b) Fresno.

3.2 Life cycle metrics

MAC-stage, use-stage, and total (MAC + use) changes in PED and GWP per unit area pavement modified for each case and city are graphically compared in Figure 4 and Figure 5. Each change is less-typical treatment minus typical treatment. Figure 6 and Figure 7 disaggregate changes in Los Angeles by both stage and life-cycle component, while Table A-1 through Table A-3 in Appendix A detail both absolute and fractional changes in each city.

Life-cycle feedstock energy per unit area pavement modified decreased by 207 MJ/m² in maintenance Case 1A (reflective coating vs. slurry seal); increased by 318 MJ/m² in maintenance Case 1B (chip seal vs. slurry seal); decreased by 1,460 MJ/m² in rehabilitation Cases 2A, 2B, and 2C (no-, low-, and high-SCM BCOA vs. mill-and-fill-AC); and decreased by 1,830 MJ/m² in long-life rehabilitation Cases 3A, 3B, and 3C (no-, low-, and high-SCM BCOA vs. mill-and-fill-AC).

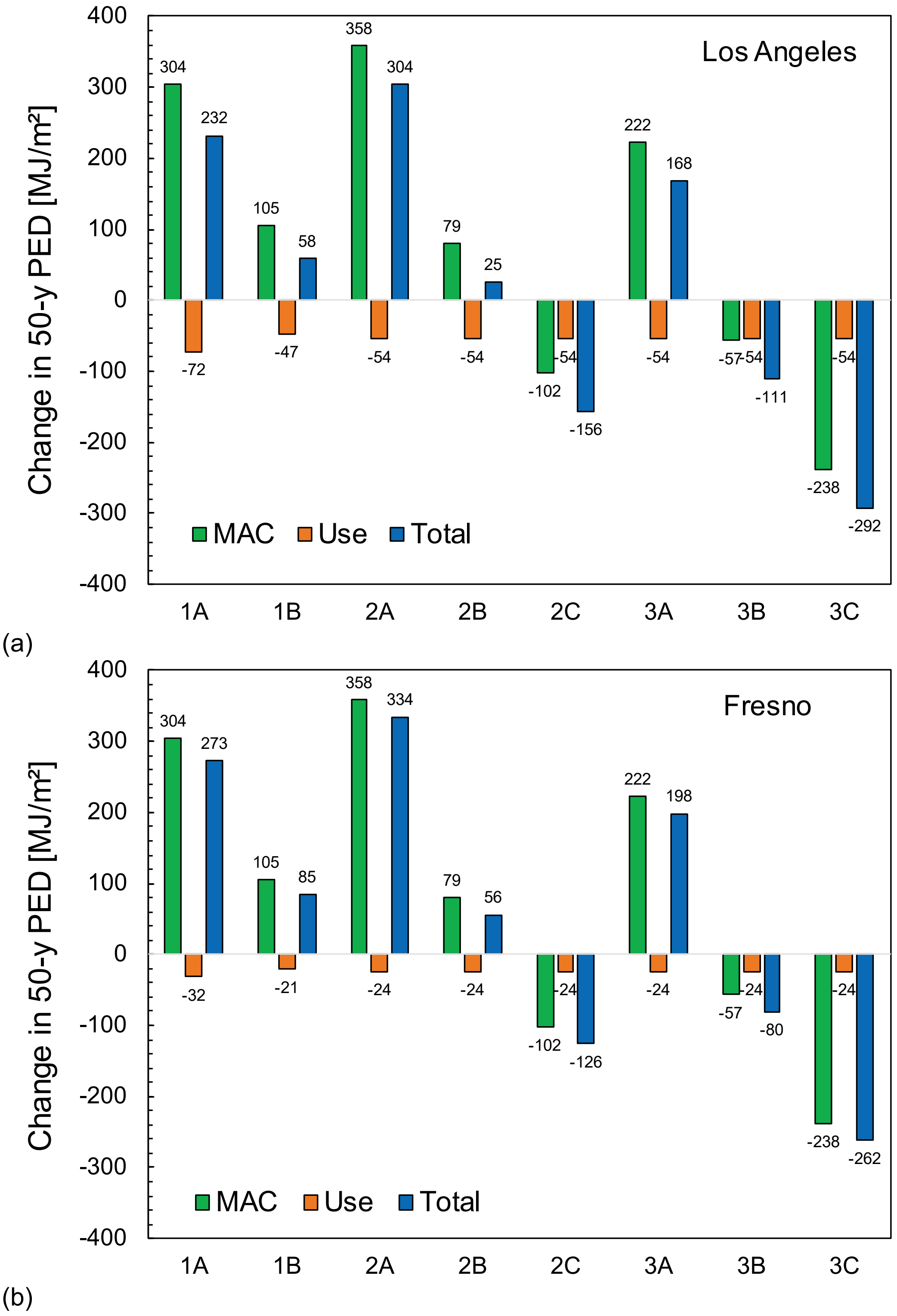
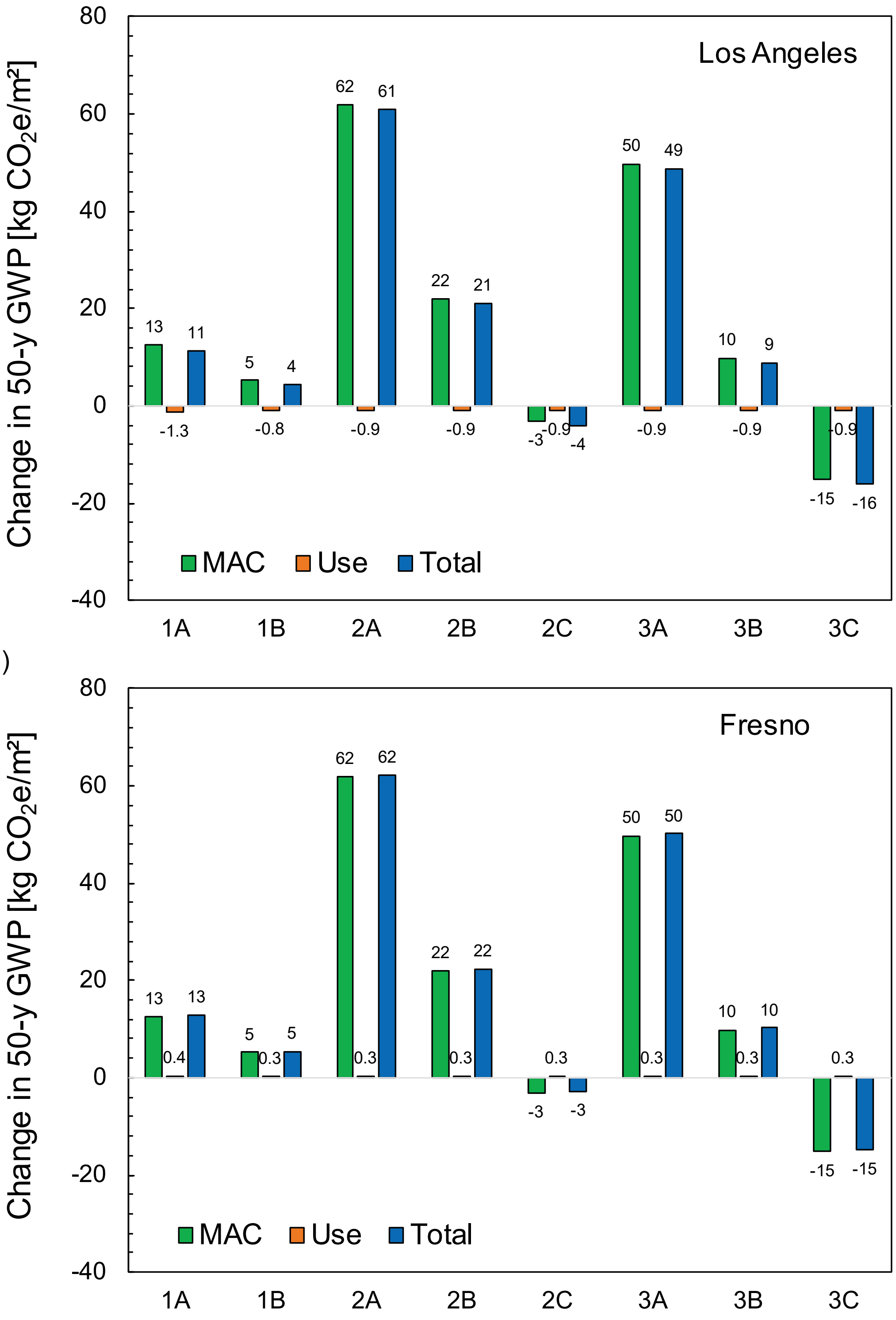


Figure 4. MAC-stage, use-stage, and total (MAC + use) changes in PED (excluding FE) per unit area pavement modified, over the 50-y life cycle, by case, in (a) Los Angeles and (b) Fresno. Cases are detailed in Table 2.



(a)

(b)

Figure 5. Same as Figure 4, but for GWP.

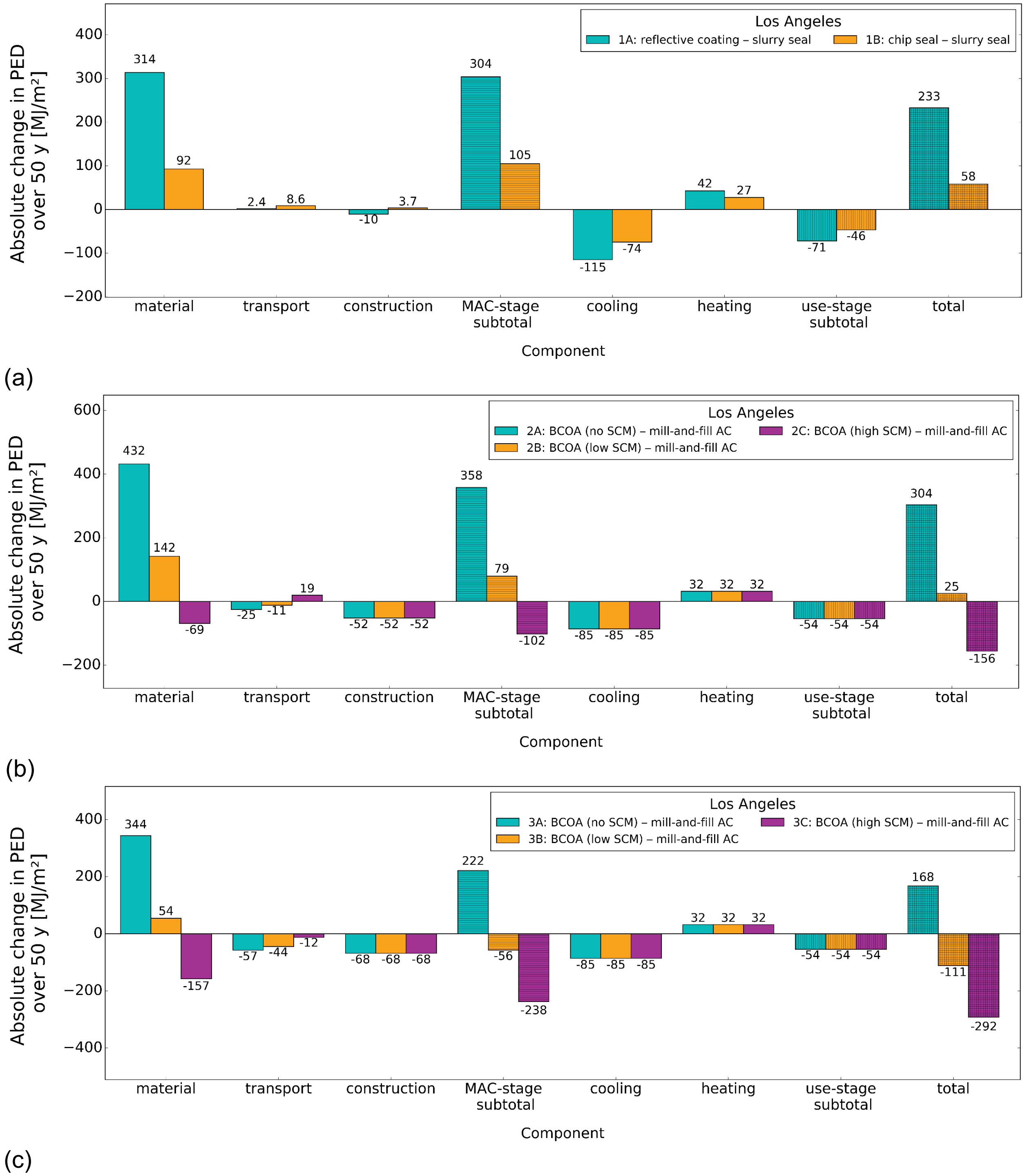


Figure 6. Absolute life-cycle changes, by stage and component, in PED (excluding FE) per unit of modified pavement area in Los Angeles for (a) routine maintenance (Cases 1A and 1B); (b) rehabilitation (Cases 2A - 2C); and (c) long-life rehabilitation (Cases 3A - 3C). Changes to lighting energy use are essentially zero, and omitted.

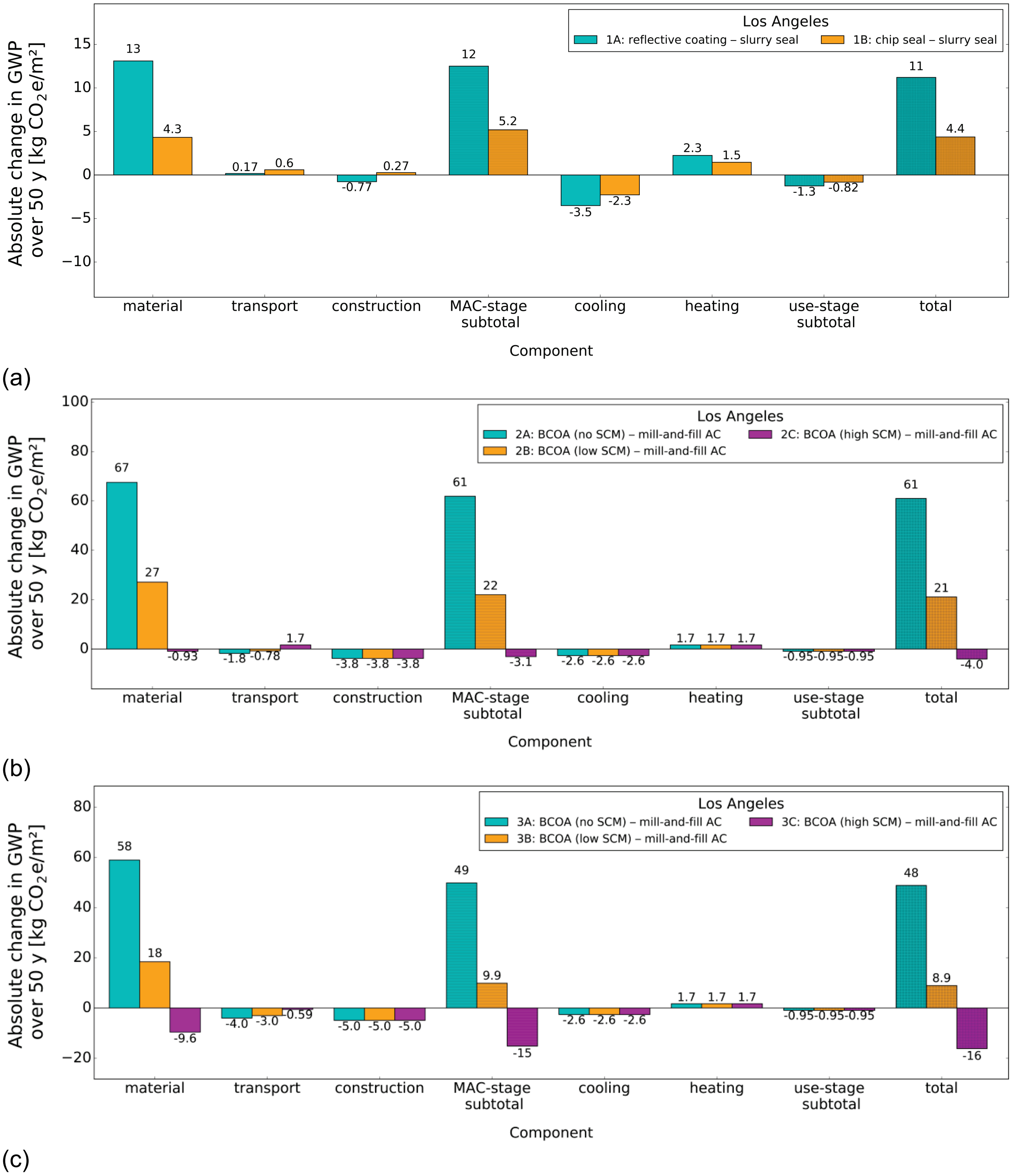


Figure 7. Same as Figure 6, but for GWP.

3.3 Direct and indirect effects of pavement albedo rise on building energy use

We calculated the direct and indirect effects of pavement albedo rise on building cooling and heating site energy uses in Los Angeles and Fresno (Table 4), and the resulting PED and GWP savings or penalties (Figure 8 and Figure 9).

The direct and indirect effects were defined in Section 2.1.1, and scale with change in pavement albedo. Therefore, we present results for Case 1A in which pavement albedo was raised by 0.20, the largest albedo increase in the three case studies (Table 2).

Figure 8 and Figure 9 presents the absolute changes in use-stage PED and GWP, respectively, per unit area of pavement modified in Los Angeles (panel a) and Fresno (panel b). The graphs are organized by effect (direct, indirect, or direct + indirect), and each effect is sub-reported as cooling, heating, and cooling + heating.

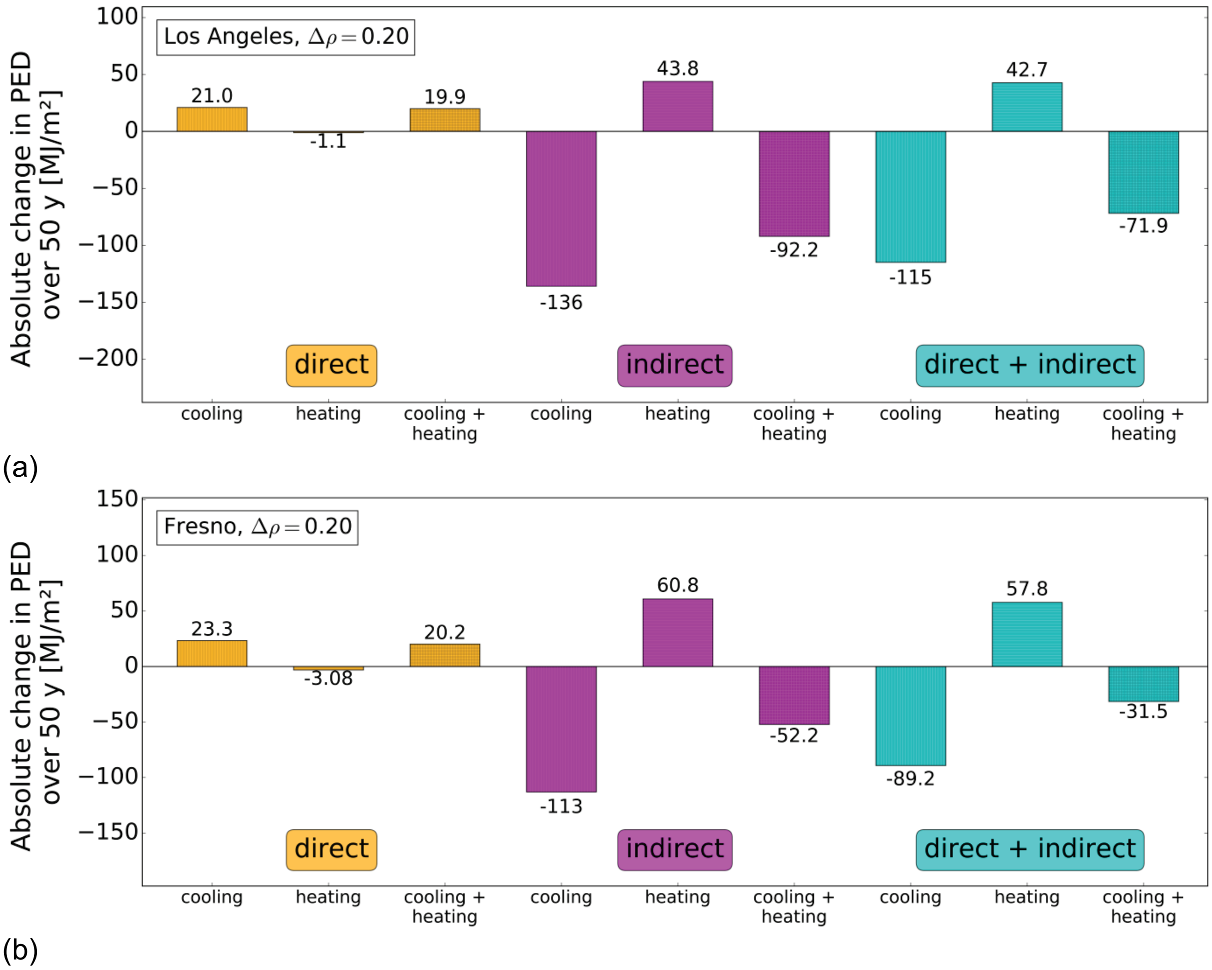


Figure 8. Direct, indirect, and direct + indirect absolute changes in PED (excluding FE) over 50 y per unit area of pavement modified from changes in cooling and heating energy uses in (a) Los Angeles and (b) Fresno. Results represent a pavement albedo increase ($\Delta\rho$) of 0.20.

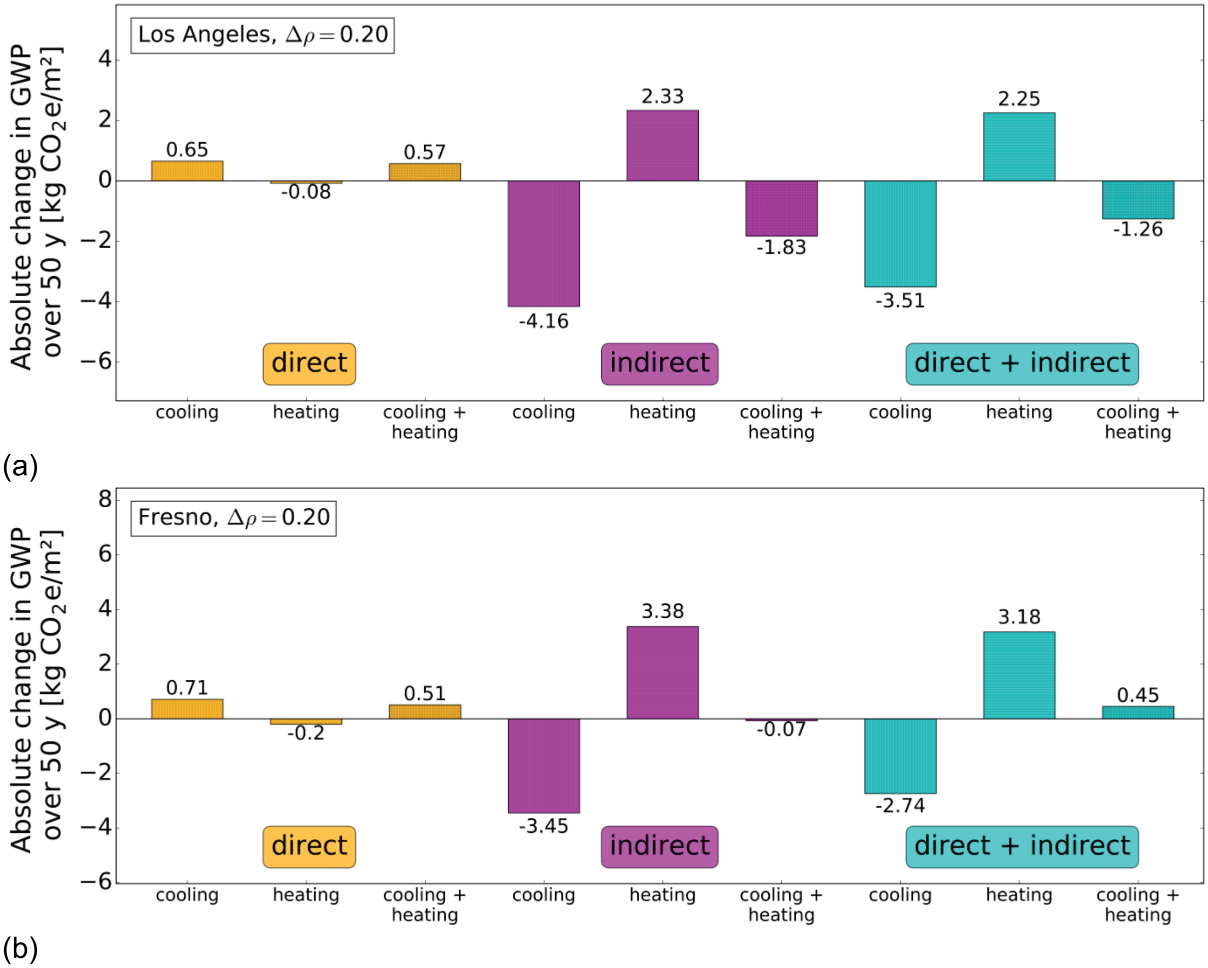


Figure 9. Same as Figure 8, but for GWP.

Table 4. Direct, indirect, and combined (direct + indirect) annual cooling and heating site energy savings per unit area of pavement modified in (a) Los Angeles and (b) Fresno, upon increasing by 0.20 the albedo of 30% of the pavement area in each city. Changes to lighting energy use are essentially zero, and omitted.

(a)

	Los Angeles	
	Cooling savings (kWh/m²·y)	Heating savings (therm/m²·y)
Direct	-0.0335	0.000259
Indirect	0.216	-0.0058
Combined (direct + indirect)	0.182	-0.00554
Magnitude of ratio of indirect effect to direct effect	6.4	22.4

(b)

	Fresno	
	Cooling savings (kWh/m²·y)	Heating savings (therm/m²·y)
Direct	-0.0371	0.000632
Indirect	0.179	-0.00892
Combined (direct + indirect)	0.142	-0.00829
Magnitude of ratio of indirect effect to direct effect	4.8	14.1

3.4 Estimating city-wide changes in PED and GWP

We calculated city-wide changes in PED and GWP by multiplying the absolute PED and GWP changes per unit area of pavement modified by the total area of pavement modified (Table 5), which was 80 km² in Los Angeles and 18 km² in Fresno. Fresno yielded smaller city-wide life-cycle PED and GWP changes than reported for Los Angeles because its modified paved area is only about 25% of that in Los Angeles.

Table 5. City-wide absolute increases in PED (excluding FE) and GWP over 50-year life cycle from each less-typical treatment option in Los Angeles and Fresno, reported by case study.

City	Case study	Increase in PED (excluding FE) over 50 y [TJ]					Increase in GWP over 50 y [Mt CO$_2$e]				
		Reflective coating [1A]	Chip seal [1B]	BCOA (no SCM) [2A, 3A]	BCOA (low SCM) [2B, 3B]	BCOA (high SCM) [2C, 3C]	Reflective coating [1A]	Chip seal [1B]	BCOA (no SCM) [2A, 3A]	BCOA (low SCM) [2B, 3B]	BCOA (high SCM) [2C, 3C]
Los Angeles	1. Routine maintenance	18,500	4,650				0.894	0.349			
	2. Rehabilitation			24,200	2,020	-12,400			4.86	1.68	-0.322
	3. Long-life rehabilitation			13,400	-8,820	-23,300			3.89	0.711	-1.29
Fresno	1. Routine maintenance	4,980	1,540				0.236	0.100			
	2. Rehabilitation			6,100	1,010	-2,300			1.14	0.407	-0.050
	3. Long-life rehabilitation			3,620	-1,470	-4,780			0.914	0.186	-0.272

4 Discussion

4.1 Air temperature reduction

At the critical times and across the year, air temperature reductions associated with increased albedo in the case studies were generally greater in Los Angeles (0.07 to 0.11 °C) than in Fresno (0.04 to 0.10 °C), but varied by time of day, city, and season (Figure 3).

Temperature reductions in spring and summer were consistently larger at 20:00 LST than at 14:00 LST. This is a consequence of the large thermal mass of pavement materials, which leads to heat uptake during the day that is released to the atmosphere after the sun goes down. This diurnal cycle in temperature change is consistent with previous research showing that in many cities, air temperature urban heat islands are larger in magnitude at night than during the day [63] [64]. Factors driving seasonal variability include differences in baseline meteorology, such as wind speed, solar irradiance at the surface, and boundary layer height. Seasonal cycles of meteorological variables, such as boundary layer height, also differ between Los Angeles and Fresno. Additional causes of variability between each city include total size of the city, urban morphology, and city-mean urban fractions [53].

As noted in Section 1, Rosado et al. [11] found that shading of incident sunlight and absorption of reflected sunlight by the walls of an urban canyon reduced by about 10% the rate at which increasing pavement albedo raises urban albedo. Therefore, we estimate that increasing by 0.20 the albedo of 30% of the pavement area (6.6% of the land area) in Los Angeles raised the city's albedo by roughly $0.20 \times 6.6\% \times 90\% = 0.012$. The peak (20:00 LST) temperature reduction in summer of 0.11 °C thus yields a rate of 0.92 °C per 0.1 increase in urban albedo. This agrees closely with the typical peak-temperature reduction rate of 0.9 °C per 0.1 increase in urban albedo reported by Santamouris [10].

4.2 PED and GWP changes by stage and component

In Cases 1A (reflective coating vs. slurry seal), 1B (chip seal vs. slurry seal), 2A (no-SCM BCOA vs. mill-and-fill AC for rehabilitation), and 3A (no-SCM BCOA vs. mill-and-fill AC for long-life rehabilitation), total changes in PED (excluding FE) and GWP are dominated by the corresponding changes in the material component (Figure 6 and Figure 7). For these four cases, the magnitudes of life-cycle PED and GWP penalties or savings in the use stage are also much smaller than those of the PED and GWP penalties in the MAC stage (Figure 4 and Figure 5). In Los Angeles, the ratio of use-stage savings to MAC-stage penalty in these four cases ranged from 0.15 to 0.44 for PED, and from 0.02 to 0.16 for GWP; in Fresno, the corresponding ranges were 0.07 to 0.20 for PED, and -0.06 to -0.01 for GWP. (GWP ratios in Fresno were negative because use-stage GWP increased, rather than decreased, in that city; see Section 4.4.3 for further discussion.) Thus, substituting the less-typical treatment for the typical treatment—that is, using the less-typical option in place of the typical option—substantially increased total PED and GWP in these four cases.

In Cases 1A, 1B, 2A, and 3A, substituting the less-typical treatment for the typical treatment in Los Angeles increased life-cycle total PED by 58.3 – 304 MJ/m² and total GWP by 4.4 – 61.0 kg

CO_2e/m^2; in Fresno, the corresponding increases were 84.5 – 334 MJ/m^2 and 5.5 – 62.2 kg CO_2e/m^2, respectively.

Replacing OP with SCM in the BCOAs used for rehabilitation and long-life rehabilitation (Cases 2B, 2C, 3B, and 3C) substantially reduced material PED and GWP. The less-typical treatments using low-SCM BCOA incurred total PED and total GWP penalties that were much smaller than those for no-SCM BCOA, while the less-typical treatments using high-SCM BCOA yielded total PED and total GWP savings (Figure 4 and Figure 5). For example, in Case Study 2 (rehabilitation), the total PED change evolved from a penalty of 304 MJ/m^2 in Case 2A (no-SCM BCOA) to a penalty of 25 MJ/m^2 in Case 2B (low-SCM BCOA) to a *savings* of 156 MJ/m^2 in Case 2C (high-SCM BCOA).

In Cases 2B and 3B, substituting low-SCM BCOA for mill-and-fill AC in Los Angeles reduced total PED by -25.3 – 111 MJ/m^2 (that is, yielded a penalty in Case 2B and a savings in Case 3B) and increased total GWP by 10.2 – 22.3 kg CO_2e/m^2; in Fresno, it reduced total PED by -55.6 – 80.4 MJ/m^2 and increased total GWP by 10.2 – 22.3 kg CO_2e/m^2.

In Cases 2C and 3C, substituting high-SCM BCOA for mill-and-fill AC in Los Angeles reduced total PED by 156 – 292 MJ/m^2 and reduced total GWP by 4.0 – 16.1 kg CO_2e/m^2; in Fresno, it reduced total PED by 156 – 262 MJ/m^2 and *reduced* total GWP by 2.8 – 14.9 kg CO_2e/m^2.

4.3 Changes in material PED, FE, and GWP

Figure 10 shows the 50-y material PED and GWP values per unit area of pavement modified for the less-typical and typical treatments. MAC-stage values are disaggregated by component in Table A-4.

In Case 1A, the 10 reflective coatings (less-typical treatment) installed over 50 y have greater cumulative material PED and GWP than the approximately 7 slurry seals (typical treatment) installed over the same period because (a) one reflective coating has higher PED and GWP than one slurry seal and (b) the reflective coating has a shorter service life. The ~7 chip seals (less-typical treatment) installed over 50 y in Case 1B also have greater material PED and GWP than the approximately 7 slurry seals (typical treatment) installed over that period, but the 50-y material PED and GWP penalties are much smaller than those yielded by the reflective coating (Figure 10) because one chip seal consumes less PED, produces less GWP, and lasts longer than one reflective coating.

In Case 2A, the 25 cm of no-SCM BCOA (less-typical treatment) installed over 50 y (2.5 installations of 10 cm each) has over twice the material PED and GWP present in the 30 cm of mill-and-fill AC (typical treatment) installed over that period. Incorporating low SCM content in the BCOA (Case 2B) reduces the material PED and GWP penalties; incorporating high SCM content in the BCOA (Case 2C) yields material PED and GWP *savings*.

The same trends are observed in Cases 3A, 3B, and 3C when comparing the 25 cm of BCOA (less-typical treatment) with no, low, or high SCM content installed over 50 y to the 37.5 cm of mill-and-fill AC (typical treatment) installed over that period. However, the material PED and GWP penalties in Cases 3A and 3B are smaller than those in Cases 2A and 2B, and the material PED and GWP savings are larger in Case 3C than in Case 2C, because the installed thickness of mill-and-fill AC in Case Study 3 (37.5 cm) is 25% greater than that in Case Study 2 (30 cm).

Per unit area of pavement, the four asphaltic treatments—slurry seal (7.1X), chip seal (7.1X), mill-and-fill AC (30 cm), and mill-and-fill AC (37.5 cm) have 50-y life cycle feedstock energies of 207, 526, 1,468, and 1,832 MJ/m², respectively. The other treatments considered in these case studies contain no feedstock energy.

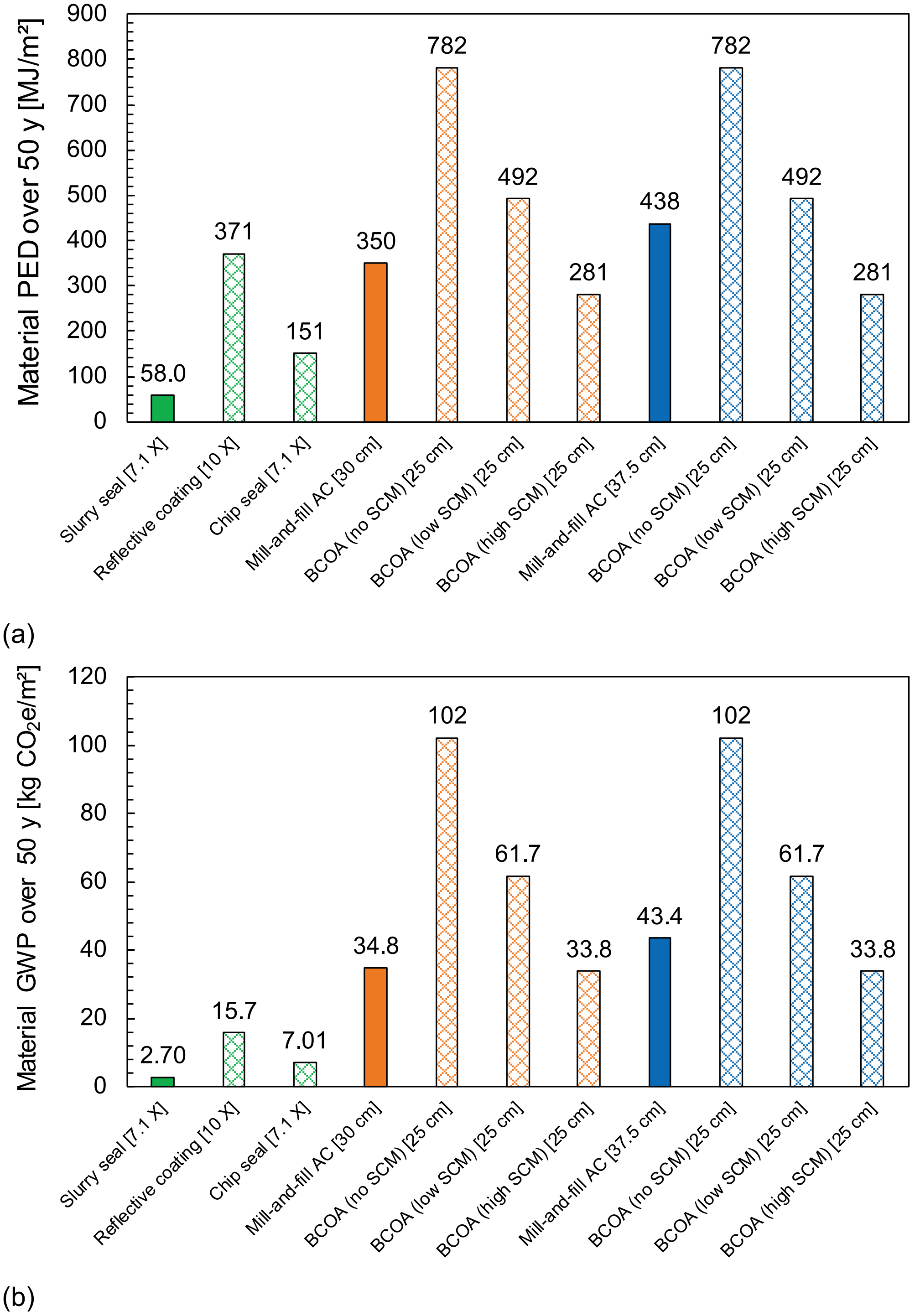


Figure 10. Material (a) PED (excluding FE) and (b) GWP per unit area of pavement for all typical treatments (solid bars) and less-typical treatments (cross-hatched bars) considered in the three case studies. Number of installations (e.g., 10 X) or cumulative thickness of installation (e.g., 30 cm) over 50 y is shown in brackets.

4.4 Building energy use changes

4.4.1 Annual site energy use and PED

The indirect effect dominated changes in cooling site energy use and heating site energy use in each city, with magnitudes of about 5 to 22 times those induced by the direct effect (Table 4). The causes are discussed in the next subsection.

The indirect cooling site energy savings from increasing pavement albedo can be compared to the direct cooling site energy savings from increasing roof albedo. Simulating the energy use of buildings in the Los Angeles Metropolitan Statistical Area, Akbari et al. [15] found that raising the albedos of residential and commercial building roofs by 0.30 and 0.45, respectively (area-weighted mean roof albedo increase 0.35) would yield for each square meter of roof modified average direct cooling site energy savings of 2.58 kWh/y and an average direct heating site energy penalty of 0.039 therm/y. These *direct* cooling site energy savings per square meter of *roof* modified (albedo increase 0.35) are about 12 times the *indirect* cooling site energy savings of 0.216 kWh/y per square meter of *pavement* modified (albedo increase 0.20) found in the current study.

We can compare cool pavement and cool roof annual PED savings by applying the site energy-to-PED multipliers in Table C-1 to the Los Angeles site energy use changes in the current study and to the Los Angeles site energy use changes from Akbari et al. [15], respectively. The annual conditioning (cooling + heating) PED savings from increasing pavement albedo by 0.20 are 2.9 MJ/y per square meter of pavement modified, while those from increasing roof albedo by 0.35 are 27.8 MJ/y per square meter of roof modified. Per unit surface area modified, the annual conditioning PED savings from the cool roof are 9.5 times those from the cool pavement.

4.4.2 Use-stage life-cycle PED

In Los Angeles and Fresno, there was a combined (direct + indirect) PED reduction for building conditioning (cooling + heating) PED in each case. The indirect effect generated larger cooling PED savings and heating PED penalties than did the direct effect (Figure 8).

The direct effect is proportional to the view factor from the street to the neighboring buildings. The view factor in this context is the fraction of radiant energy leaving the street that is intercepted by the building. The view factor from a street to a typical residential building in California is generally small (about 0.06) since homes tend to be short (one or two stories), and are set back from the street by sidewalks and front yards [37]. Since 87% of floor area in Los Angeles and 88% of floor area in Fresno is residential, only a small fraction of light reflected from streets strikes buildings. Ref. [37] details the view factor calculations for different building types and includes an assessment of California's building stock.

In each city, each less-typical treatment yielded lower combined cooling PED and higher combined heating PED than the typical treatment. The cooling PED savings exceeded the heating PED penalties, decreasing conditioning PED.

First principles suggest that annual cooling PED savings will scale with the product of air temperature reduction in the cooling season and the base-case annual cooling PED per unit floor area, and that the annual heating PED penalty will scale with the product of air temperature reduction in the heating season and the base-case annual heating PED per unit floor area (Appendix B). Average summertime temperature reductions in Los Angeles were nearly 1.4 times those in Fresno, while base-case annual cooling PED consumption per unit floor area in Los Angeles was 85% that in Fresno. Average wintertime air temperature reductions in Los Angeles were about 1.4 times those in Fresno, while the base heating PED consumption per unit floor area in Los Angeles was only 42% that of Fresno. This indicates that the cooling PED saving per unit floor area in Los Angeles should exceed that in Fresno, while the heating PED penalty per unit floor area in Los Angeles should be less than that in Fresno, yielding greater conditioning (cooling + heating) PED savings per unit floor area in Los Angeles than in Fresno. This analysis is detailed in Appendix B.

4.4.3 Use-stage life-cycle GWP

The indirect effect on GWP from building conditioning energy use was also larger than that of the direct effect (Figure 9). The combined cooling GWP savings in Los Angeles exceeded the combined heating GWP penalty. However, in Fresno, the cooling GWP savings were less than the heating GWP penalty, yielding a use-stage building conditioning GWP penalty. Hence, while Los Angeles accrued use-stage PED and GWP benefits, Fresno had a PED benefit and a GWP penalty.

Changes to use-stage GWP in each city depend on both changes to cooling and heating PEDs and on the energy sources used for building conditioning. In California, most buildings employ electricity for cooling and ventilation, and gas for heating. The 2020 California electricity grid mix used by the pLCA tool represents the projected procurement of electricity from renewable sources by three major IOUs in California in accordance with the RPS. Based on their published projections, about 28% of California's electricity in 2020 will be generated from renewable fuel sources (Table C-2), creating a cleaner electric grid mix than used today [37]. This grid is also much cleaner than the current national average or that in other hot, sunny U.S. states such as Arizona, Texas, and Florida. As noted previously, the calculations assume that all energy used is produced in California and that none is imported from other, less clean, grids. The clean grid mix assumed by the tool makes the ratio of GWP to PED per unit of site electricity smaller than that per unit of site gas. Therefore, although Fresno had small use-stage conditioning PED savings, the city experienced a use-stage conditioning GWP penalty (Appendix C).

4.5 Comparing city-wide GWP change to current and future GHG emissions in Los Angeles

To compare the city-wide GWP changes (Table 5) to current GHG emissions and to GHG reduction goals in Los Angeles, we divide the 50-y life-cycle GWP change by 50 to obtain annual change. Over the eight cases considered here, the annual GWP change ranged from a savings of 0.0258 Mt CO_2e (Case 3C) to a penalty of 0.0972 Mt CO_2e (Case 2A).

In 2013, the most recent year in which they were inventoried, GHG emissions in Los Angeles totaled 29.0 Mt CO_2e, of which 34% (9.86 Mt CO_2e) originated in the transportation sector [40]. Relative to the 2013 inventory, the city-wide GWP change from substituting a less-typical treatment for a typical treatment would range from a savings of 0.089% to a penalty of 0.34%.

The city has also established a GHG emission target of 20 Mt/y CO_2e by 2025. Relative to the 2025 target, the city-wide GWP change would range from a savings of 0.13% to a penalty of 0.49%.

4.6 Application of tool outputs within life cycle analyses

The first-order results of the pLCA tool can be input to life cycle analyses of the energy, economic, or environmental consequences of pavement choice. The applications proposed below are simply illustrations. Each worked example is from Case 1A, in Los Angeles.

4.6.1 Energy analysis

The tool reports changes to life-cycle PED associated with differences in pavement material, transport, and construction, and changes to building cooling, heating, and lighting energy use. These can be combined with other pavement-induced use-stage changes in PED outside the scope of the tool, such as those related to street lighting or vehicle rolling resistance, to prepare a more complete life-cycle analysis.

4.6.1.1 Example: Life-cycle PED

The tool predicts that substituting a reflective coating for a slurry seal will increase 50-y life cycle total PED by 233 MJ per square meter of pavement modified (Table A-1).

4.6.2 Economic analysis

The economic consequences of pavement M&R treatment choice lie outside the scope of the tool. The life-cycle cost of a treatment can be estimated as the present value of the costs of the first installation and its replacements over the service period, using current prices for the first installation and projected prices for each replacement. The historical variability in the relative costs of asphalt concrete and portland cement concrete used in pavement should be considered [65].

The tool also reports changes to annual site energy uses for cooling, heating, and lighting buildings. Changes to annual site energy use can be multiplied by site energy prices to obtain annual cost savings associated with these energy use changes, which in turn can serve as input to a pavement life-cycle cost analysis (LCCA).

4.6.2.1 Example: Annual energy cost savings

The tool predicts that per square meter of pavement modified, substituting a reflective coating for a slurry seal will reduce cooling site energy use by 0.182 kWh/y, and increase heating site energy use by 0.00554 therm/y (Table 4). At California-typical energy prices of \$0.20/kWh and \$1.2/therm, the conditioning energy cost savings per square meter of pavement modified would be \$0.030/y. This is about 2.6 times the indirect energy cost savings of \$0.012/y per square meter of pavement modified reported by Rosenfeld et al. [13]. However, scaling the Rosenfeld et al. result to match current assumptions about fraction of homes conditioned, pavement albedo change, and site energy prices yields indirect energy cost savings of \$0.037/y, which is only 23% higher than those found in the current study (Appendix D).

For comparison, we observe that at these prices, the Los Angeles cool *roof* cooling site energy savings (2.58 kWh/m²·y) and heating site energy penalty (0.039 therm/m²·y) described in Section 4.4.1 would provide a conditioning energy cost savings of $0.47/y per square meter of roof modified. The annual direct cool roof conditioning energy cost savings per unit *roof* area modified are about 15 times the annual combined (direct + indirect) cool pavement conditioning energy cost savings per unit area *pavement* modified.

4.6.3 Environmental analysis

The tool reports changes to life-cycle GWP, POCP, and PM2.5 associated with differences in pavement material, transport, and construction, and changes to building cooling, heating, and lighting energy use (Table 1). Each of these outputs can be combined with other pavement-induced changes in the environmental metrics not assessed by the tool to prepare a more complete life-cycle assessment.

4.6.3.1 Example: Life-cycle GWP

The tool predicts that substituting a reflective coating for a slurry seal will increase 50-y life-cycle total GWP by 11.2 kg CO_2e per square meter of pavement modified (Table A-1).

4.7 Other effects of changing pavement albedo

Aspects of raising pavement albedo that lie outside the scope of the pLCA tool include global cooling, thermal comfort of pedestrians and bicyclists, and thermal comfort in uncooled buildings. However, we can easily compare global cooling potential to GWP penalty for each case study evaluated here.

Akbari et al. [51] estimated that increasing by 0.01 the albedo of a square meter of the Earth's surface in the latitude range ±45° will offset (counteract) the global warming induced by the emission of 7 kg of CO_2e. This offset, which is cited by the 5th Assessment Report of the International Panel on Climate Change [52], has a range of 4.9 to 12 kg CO_2e after accounting for uncertainty in long-term global temperature change associated with GHG emissions. Using the representative offset rate of 7 kg of CO_2e per m² per 0.01 increase in albedo, raising by 0.20 the albedo of a square meter of pavement in Case 1A will provide a *one-time* (non-recurring) GWP offset of $(0.20 / 0.01) \times 7$ kg CO_2e = 140 kg CO_2e. This one-time offset is over 12 times the 50-y life cycle total GWP penalty in Case 1A in Los Angeles.

In those cases with a 50-y GWP penalty (1A, 1B, 2A, 2B, 3A, and 3B), the one-time GWP offset exceeded the 50-y GWP penalty, with an offset to penalty ratio of 1.7 to 21 in Los Angeles, and 1.7 to 17 in Fresno. In those cases with a 50-y GWP savings (2C and 3C), the one-time offset substantially augmented the 50-y savings, with an offset to savings ratio of 6.5 to 26 in Los Angeles, and 7.0 to 38 in Fresno (Figure 11).

We note that there are further uncertainties associated with computing CO_2e offsets from increasing urban albedo, such as the model-dependent relationship between urban albedo increase and global temperature decrease [66]. For example, Akbari et al. [51] used a simplified two-dimensional energy and moisture balance model, which does not resolve cloud and aerosol feedbacks [66]. Also, the extents to which raising urban albedo increases outgoing shortwave radiation at the top of the atmosphere and reduces urban air temperature each depend on clarity of the sky. That is, if the local sky is more polluted or cloudier than assumed in the climate model, the CO_2e offset and urban cooling will be smaller than predicted; conversely, if the local sky is clearer than assumed, the offset and cooling will be greater than predicted [66].

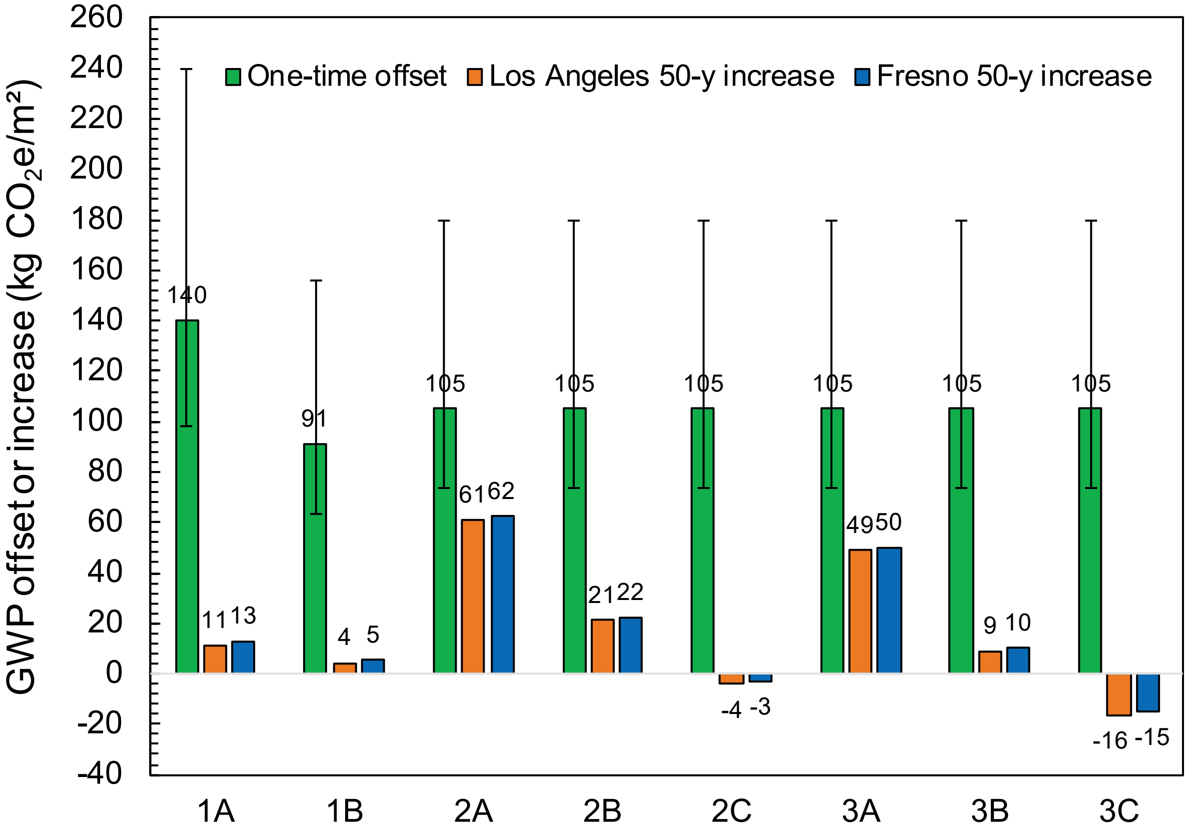


Figure 11. Location-independent one-time GWP offset induced by global cooling compared to 50-y life cycle total GWP increases in Los Angeles and Fresno, by case. Each offset is calculated for the case-specific albedo increase reported in Table 2, using the representative offset rate provided by Akbari et al. [51]. Error bars mark variability in offset stemming from uncertainty in the long-term global temperature change associated with GHG emissions [51].

5 Summary

We evaluated several case studies comparing less-typical, higher-reflectance "cool" pavement treatments to more-typical, lower-reflectance treatments for the largest city in California (Los Angeles), which is in the coastal climate zone, and for the fifth largest city (Fresno), which is also the largest in the state's Central Valley. These included pavement practices for routine maintenance (Case Study 1), rehabilitation (Case Study 2), and long-life rehabilitation (Case Study 3).

The pavement life cycle assessment (pLCA) tool used in this analysis presents first-order changes to environmental effects across the different life-cycle stages. Some assumptions about pavement management practice were imposed by computational constraints in the climate modeling, but the differences from actual practice are not expected to change the conclusions of this paper.

We assess life-cycle changes induced by using a less-typical (higher reflectance) treatment in place of a more-typical (lower reflectance) treatment. Substituting a reflective coating (Case 1A) or a chip seal (Case 1B) for a slurry seal, or no-SCM BCOA for mill-and-fill asphalt concrete (Cases 2A and 3A), increased 50-y life cycle MAC-stage PED (excluding FE) and GWP. In Los Angeles and Fresno, the use-stage PED savings were smaller than the MAC-stage PED penalties. In Los Angeles, the use-stage GWP savings were smaller than the MAC-stage GWP penalty; in Fresno, the use-stage GWP penalty was smaller than MAC-stage GWP penalty. In Los Angeles, the ratio of use-stage savings to MAC-stage penalty ranged from 0.15 to 0.44 for PED, and from 0.02 to 0.16 for GWP; in Fresno, the corresponding ranges were 0.07 to 0.20 for PED, and -0.06 to -0.01 for GWP.

In these four cases (1A, 1B, 2A, and 3A), substituting the less-typical treatment for the typical treatment in Los Angeles increased life-cycle total PED by 58.3 – 304 MJ/m² and total GWP by 4.4 – 61.0 kg CO_2e/m². The corresponding increases in Fresno were 84.5 – 334 MJ/m² and 5.5 – 62.2 kg CO_2e/m², respectively.

Replacing OP with SCM in the BCOAs used for rehabilitation and long-life rehabilitation (Cases 2B, 2C, 3B, and 3C) substantially reduced material PED and GWP. In Cases 2B and 3B, substituting low-SCM BCOA for mill-and-fill AC in Los Angeles reduced total PED by -25.3 – 111 MJ/m² and increased total GWP by 10.2 – 22.3 kg CO_2e/m²; in Fresno, it reduced total PED by -55.6 – 80.4 MJ/m² and increased total GWP by 10.2 – 22.3 kg CO_2e/m².

In Cases 2C and 3C, substituting high-SCM BCOA for mill-and-fill AC in Los Angeles reduced total PED by 156 – 292 MJ/m² and reduced total GWP by 4.0 – 16.1 kg CO_2e/m²; in Fresno, it reduced total PED by 156 – 262 MJ/m² and *reduced* total GWP by 2.8 – 14.9 kg CO_2e/m².

Increasing by 0.20 the albedo of a square meter of pavement in Los Angeles yielded indirect annual cooling site energy savings (about 0.22 kWh/m²·y), conditioning (cooling + heating) PED savings (about 2.9 MJ/y), and conditioning energy cost savings (about $0.03/y) that are each about an order of magnitude smaller than the direct annual cooling site energy savings, conditioning PED savings, and conditioning energy cost savings from increasing by 0.35 the albedo of a square meter of roof.

In the cases examined, the one-time GWP offset offered by global cooling always exceeded (sometimes greatly) the magnitude of the 50-y life cycle total GWP penalty or savings incurred by switching to a cool pavement technology. In cases with 50-y penalties (1A, 1B, 2A, 2B, 3A, and 3B), this ratio ranged from 1.7 to 21 in Los Angeles, and from 1.7 to 17 in Fresno. In cases with 50-y savings, the ratio ranged from 6.5 to 26 in Los Angeles, and 7.0 to 38 in Fresno.

6 Future work

We found that substituting some of the readily available cool pavements for more typical treatments incurred substantial PED and GWP penalties over the 50-y life cycle because the cool materials considered, such as reflective coating, chip seal, and traditional bonded concrete overlay, are more energy and carbon intensive to produce. However, replacing some of the hydraulic cement in the BCOA with supplementary cementitious materials reduced the PED and GWP of the cool pavement treatment. Use of SCM in concrete is an example of an existing technology that can be used to mitigate the life-cycle total GWP penalty of cool pavements, or even yield total GWP savings. If cool pavements are found to be cost effective relative to other strategies for reducing global warming, then further work is warranted in the development of these technologies. Outputs of the pLCA tool can inform life-cycle cost analyses used to evaluate cost effectiveness.

Future research could track the locations of environmental effects in the pavement life cycle, such as spatial distribution of emissions, changes to neighborhood-scale microclimates, and potential changes in transportation mode choice based on microclimate. Future studies should update the first-order results presented in this paper by analyzing uncertainties in materials inventories, and by using regionalized materials inventories (especially for asphalt production). GHG emission timing could be considered when assessing global warming potential. Quantitative identification of potential trade-offs between improving local micro-climates and minimizing the global environmental burden will help cities further improve their pavement management practices.

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Appendix A: Life cycle impacts by component and stage

Table A-1. Changes to PED (excluding FE) and GWP in Case Study 1 (routine maintenance) in (a) Los Angeles and (b) Fresno. Each less-typical surface treatment—reflective coating (Case 1A) or chip seal (Case 1B)—is compared to the typical treatment (slurry seal). The base value of each metric is evaluated for the typical treatment, and expressed per unit area of pavement modified. Absolute change per unit area of pavement modified is less-typical value minus typical (base) value; fractional change is absolute change divided by base value.

(a) Los Angeles

		PED (excluding FE) over 50 y [MJ/m^2]			GWP over 50 y [kg CO$_2$e/m^2]		
		Base value	Absolute change (relative change)		Base value	Absolute change (relative change)	
Stage	Component	Slurry seal	1A: Reflective coating	1B: Chip seal	Slurry seal	1A: Reflective coating	1B: Chip seal
MAC	Material	58.0	314 (540%)	92.8 (160%)	2.70	13.1 (480%)	4.32 (160%)
	Transport	4.84	2.37 (49%)	8.57 (180%)	0.338	0.168 (50%)	0.600 (180%)
	Construction	18.2	-10.6 (-58%)	3.73 (21%)	1.32	-0.767 (-58%)	0.269 (21%)
	Subtotal	81.1	304 (380%)	105 (130%)	4.33	12.5 (290%)	5.19 (120%)
Use	Cooling	11,600	-115 (-1.0%)	-74.5 (-0.60%)	355	-3.51 (-1.0%)	-2.28 (-0.60%)
	Heating	2,160	42.7 (2.0%)	27.7 (1.3%)	111	2.25 (2.0%)	1.46 (1.3%)
	Lighting	6,590	0 (0%)	0 (0%)	202	0 (0%)	0 (0%)
	Subtotal	20,300	-71.9 (-0.40%)	-46.7 (-0.20%)	668	-1.26 (-0.20%)	-0.820 (-0.10%)
MAC + use	**Total**	20,500	233 (1.1%)	58.3 (0.30%)	671	11.2 (1.7%)	4.37 (0.70%)

(b) Fresno

		PED (excluding FE) over 50 y [MJ/m^2]			GWP over 50 y [kg CO$_2$e/m^2]		
		Base value	Absolute change (relative change)		Base value	Absolute change (relative change)	
Stage	Component	Slurry seal	1A: Reflective coating	1B: Chip seal	Slurry seal	1A: Reflective coating	1B: Chip seal
MAC	Material	58.0	314 (541.1%)	92.8 (159.9%)	2.70	13.1 (480%)	4.32 (160%)
	Transport	4.84	2.37 (49%)	8.57 (177%)	0.338	0.168 (50%)	0.600 (180%)
	Construction	18.2	-10.6 (-58.3%)	3.73 (20.6%)	1.32	-0.767 (-58%)	0.269 (21%)
	Subtotal	81.1	304 (375.7%)	105 (129.6%)	4.35	12.5 (290%)	5.19 (120%)
Use	Cooling	16,000	-89.2 (-0.6%)	-58 (-0.4%)	492	-2.74 (-0.60%)	-1.78 (-0.40%)
	Heating	5,990	57.8 (1%)	37.5 (0.6%)	329	3.18 (1.0%)	2.07 (0.60%)
	Lighting	8,350	0 (0%)	0 (0%)	257	0 (0%)	0 (0%)
	Subtotal	30,400	-31.5 (-0.1%)	-20.5 (-0.1%)	1,080	0.445 (0%)	0.290 (0%)
MAC + use	**Total**	30,500	273 (0.9%)	84.6 (0.3%)	1,080	12.9 (1.2%)	5.48 (0.50%)

Table A-2. Same as Table A-1 but for Case Study 2 (rehabilitation). The less-typical treatments—no-SCM BCOA (Case 2A), low-SCM BCOA (Case 2B), or high-SCM BCOA (Case 2C)—are compared to the typical treatment (mill-and-fill AC) in (a) Los Angeles and (b) Fresno.

(a) Los Angeles

		PED (excluding FE) over 50 y [MJ/m²]				GWP over 50 y [kg CO_2e/m²]			
		Base value	Absolute change (relative change)			Base value	Absolute change (relative change)		
Stage	Component	Mill-and-fill AC	2A: BCOA (no SCM)	2B: BCOA (low SCM)	2C: BCOA (high SCM)	Mill-and-fill AC	2A: BCOA (no SCM)	2B: BCOA (low SCM)	2C: BCOA (high SCM)
MAC	Material	350	432 (120%)	142 (41%)	-69.4 (-20%)	34.8	67.5 (190%)	27.1 (78%)	-0.930 (-2.7%)
	Transport	130	-25.0 (-19%)	-11.9 (-9.1%)	19.8 (15%)	9.08	-1.76 (-19%)	-0.779 (-8.6%)	1.68 (19%)
	Construction	64.0	-52.4 (-82%)	-52.4 (-82%)	-52.4 (-82%)	4.64	-3.81 (-82%)	-3.81 (-82%)	-3.81 (-82%)
	Subtotal	545	358 (66%)	79.3 (15%)	-102 (-19%)	48.6	61.9 (130%)	22.0 (45%)	-3.09 (-6.4%)
Use	Cooling	11,600	-85.9 (-0.70%)	-85.9 (-0.70%)	-85.9 (-0.70%)	355	-2.63 (-0.70%)	-2.63 (-0.70%)	-2.63 (-0.70%)
	Heating	2,160	32.0 (1.5%)	32.0 (1.5%)	32.0 (1.5%)	110	1.69 (1.5%)	1.69 (1.5%)	1.69 (1.5%)
	Lighting	6,590	0 (0%)	0 (0%)	0 (0%)	202	0 (0%)	0 (0%)	0 (0%)
	Subtotal	20,300	-54.0 (-0.30%)	-54.0 (-0.30%)	-54.0 (-0.30%)	668	-0.949 (-0.10%)	-0.949 (-0.10%)	-0.949 (-0.10%)
MAC + use	**Total**	20,800	304 (1.5%)	25.3 (0.10%)	-156 (-0.70%)	715	61.0 (8.5%)	21.1 (2.9%)	-4.04 (-0.60%)

(b) Fresno

		PED (excluding FE) over 50 y [MJ/m²]				GWP over 50 y [kg CO_2e/m²]			
		Base value	Absolute change (relative change)			Base value	Absolute change (relative change)		
Stage	Component	Mill-and-fill AC	2A: BCOA (no SCM)	2B: BCOA (low SCM)	2C: BCOA (high SCM)	Mill-and-fill AC	2A: BCOA (no SCM)	2B: BCOA (low SCM)	2C: BCOA (high SCM)
MAC	Material	350	432 (120%)	142 (41%)	-69.4 (-20%)	34.8	67.5 (190%)	27.1 (78%)	-0.930 (-2.7%)
	Transport	130	-25.0 (-19%)	-11.9 (-9.1%)	19.8 (15%)	9.12	-1.76 (-19%)	-0.779 (-8.6%)	1.68 (19%)
	Construction	64.0	-52.4 (-82%)	-52.4 (-82%)	-52.4 (-82%)	4.66	-3.81 (-82%)	-3.81 (-82%)	-3.81 (-82%)
	Subtotal	545	358 (66%)	79.3 (15%)	-102 (-19%)	48.6	61.9 (130%)	22.0 (45%)	-3.09 (-6.4%)
Use	Cooling	16,000	-66.9 (-0.40%)	-66.9 (-0.40%)	-66.9 (-0.40%)	492	-2.05 (-0.40%)	-2.05 (-0.40%)	-2.05 (-0.40%)
	Heating	5,990	43.3 (0.70%)	43.3 (0.70%)	43.3 (0.70%)	328	2.38 (0.70%)	2.38 (0.70%)	2.38 (0.70%)
	Lighting	8,350	0 (0%)	0 (0%)	0 (0%)	257	0 (0%)	0 (0%)	0 (0%)
	Subtotal	30,400	-23.7 (-0.10%)	-23.7 (-0.10%)	-23.7 (-0.10%)	1,080	0.330 (0%)	0.330 (0%)	0.330 (0%)
MAC + use	**Total**	30,900	334 (1.1%)	55.6 (0.20%)	-126 (-0.40%)	1,130	62.3 (5.5%)	22.3 (2.0%)	-2.76 (-0.20%)

Table A-3. Same as Table A-1 but for Case Study 3 (long-life rehabilitation). The less-typical treatments—BCOA w/o SCM (Case 3A), BCOA w/low SCM (Case 3B), or BCOA w/high SCM (Case 3C)—are compared to the typical treatment (mill-and-fill AC) in (a) Los Angeles and (b) Fresno.

(a) Los Angeles

Stage	Component	PED (excluding FE) over 50 y [MJ/m²]				GWP over 50 y [kg CO_2e/m²]			
		Base value	Absolute change (relative change)			Base value	Absolute change (relative change)		
		Mill-and-fill AC	3A: BCOA (no SCM)	3B: BCOA (low SCM)	3C: BCOA (high SCM)	Mill-and-fill AC	3A: BCOA (no SCM)	3B: BCOA (low SCM)	3C: BCOA (high SCM)
MAC	Material	438	344 (79%)	54.7 (13%)	-157 (-36%)	43.4	58.9 (140%)	18.4 (42%)	-9.61 (-22%)
	Transport	162	-57.5 (-35%)	-44.4 (-27%)	-12.7 (-7.8%)	11.4	-4.04 (-36%)	-3.05 (-27%)	-0.591 (-5.2%)
	Construction	79.9	-68.4 (-86%)	-68.4 (-86%)	-68.4 (-86%)	5.81	-4.97 (-86%)	-4.97 (-86%)	-4.97 (-86%)
	Subtotal	680	222 (33%)	-56.7 (-8.3%)	-238 (-35%)	60.6	49.8 (82%)	9.88 (16%)	-15.2 (-25%)
Use	Cooling	11,600	-85.9 (-0.70%)	-85.9 (-0.70%)	-85.9 (-0.70%)	355	-2.63 (-0.70%)	-2.63 (-0.70%)	-2.63 (-0.70%)
	Heating	2,160	32.0 (1.5%)	32.0 (1.5%)	32.0 (1.5%)	110	1.69 (1.5%)	1.69 (1.5%)	1.69 (1.5%)
	Lighting	6,590	0 (0%)	0 (0%)	0 (0%)	202	0 (0%)	0 (0%)	0 (0%)
	Subtotal	20,300	-54.0 (-0.30%)	-54.0 (-0.30%)	-54.0 (-0.30%)	668	-0.949 (-0.10%)	-0.949 (-0.10%)	-0.949 (-0.10%)
MAC + use	**Total**	21,000	168 (0.80%)	-111 (-0.50%)	-292 (-1.4%)	728	48.8 (6.7%)	8.93 (1.2%)	-16.2 (-2.2%)

(b) Fresno

Stage	Component	PED (excluding FE) over 50 y [MJ/m²]				GWP over 50 y [kg CO_2e/m²]			
		Base value	Absolute change (relative change)			Base value	Absolute change (relative change)		
		Mill-and-fill AC	3A: BCOA (no SCM)	3B: BCOA (low SCM)	3C: BCOA (high SCM)	Mill-and-fill AC	3A: BCOA (no SCM)	3B: BCOA (low SCM)	3C: BCOA (high SCM)
MAC	Material	438	344 (79%)	54.7 (13%)	-157 (-36%)	43.5	58.9 (140%)	18.4 (42%)	-9.61 (-22%)
	Transport	162	-57.5 (-35%)	-44.4 (-27%)	-12.7 (-7.8%)	11.4	-4.04 (-36%)	-3.05 (-27%)	-0.591 (-5.2%)
	Construction	79.9	-68.4 (-86%)	-68.4 (-86%)	-68.4 (-86%)	5.82	-4.97 (-86%)	-4.97 (-86%)	-4.97 (-86%)
	Subtotal	680	222 (33%)	-56.7 (-8.3%)	-238 (-35%)	61.0	49.8 (82%)	9.88 (16%)	-15.2 (-25%)
Use	Cooling	16,000	-66.9 (-0.40%)	-66.9 (-0.40%)	-66.9 (-0.40%)	492	-2.05 (-0.40%)	-2.05 (-0.40%)	-2.05 (-0.40%)
	Heating	5,990	43.3 (0.70%)	43.3 (0.70%)	43.3 (0.70%)	328	2.38 (0.70%)	2.38 (0.70%)	2.38 (0.70%)
	Lighting	8,350	0 (0%)	0 (0%)	0 (0%)	257	0 (0%)	0 (0%)	0 (0%)
	Subtotal	30,400	-23.7 (-0.10%)	-23.7 (-0.10%)	-23.7 (-0.10%)	1,080	0.330 (0%)	0.330 (0%)	0.330 (0%)
MAC + use	**Total**	31,100	198 (0.60%)	-80.4 (-0.30%)	-262 (-0.80%)	1,140	50.1 (4.4%)	10.2 (0.90%)	-14.9 (-1.3%)

Table A-4. MAC-stage component and subtotal values per unit area pavement of (a) PED (excluding FE) and (b) GWP, shown over 50-y life cycle and per installation. Service life and thickness per installation (where applicable) are shown in brackets.

(a)

Treatment	PED (excluding FE) [MJ/m^2]							
	Over 50 y				Per installation			
	Material	Transport	Construction	*Subtotal*	Material	Transport	Construction	*Subtotal*
Slurry seal [7 y]	58.0	4.84	18.2	81.1	8.12	0.68	2.55	11.3
Reflective coating [5 y]	371	7.21	7.57	385	37.1	0.72	0.76	38.5
Chip seal [7 y]	151	13.4	21.8	186	21.1	1.88	3.06	26.0
Mill-and-fill AC [10 y, 6 cm]	350	130	64.0	545	70.0	26.1	12.8	109
BCOA (no SCM) [20 y, 10 cm]	782	105	11.6	902	313	42.0	4.64	361
BCOA (low SCM) [20 y, 10 cm]	492	118	11.6	624	197	47.2	4.64	249
BCOA (high SCM) [20 y, 10 cm]	281	149	11.6	442	112	59.7	4.64	177
Mill-and-fill AC [20 y, 15 cm]	438	162	79.9	680	175	64.7	32.0	272
BCOA (no SCM) [30 y, 15 cm]	782	105	11.6	902	469	63.0	6.96	541
BCOA (low SCM) [30 y, 15 cm]	492	118	11.6	624	295	70.8	6.96	374
BCOA (high SCM) [30 y, 15 cm]	281	149	11.6	442	169	89.6	6.96	265

(b)

Treatment	GWP [kg CO_2e/m^2]							
	Over 50 y				Per installation			
	Material	Transport	Construction	*Subtotal*	Material	Transport	Construction	*Subtotal*
Slurry seal [7 y]	2.70	0.338	1.32	4.33	0.38	0.05	0.18	0.61
Reflective coating [5 y]	15.7	0.506	0.550	16.8	1.57	0.05	0.05	1.68
Chip seal [7 y]	7.01	0.937	1.58	9.52	0.98	0.13	0.22	1.33
Mill-and-fill AC [10 y, 6 cm]	34.8	9.08	4.64	48.6	6.95	1.82	0.93	9.71
BCOA (no SCM) [20 y, 10 cm]	102	7.33	0.842	110	40.9	2.93	0.34	44.2
BCOA (low SCM) [20 y, 10 cm]	61.7	8.31	0.842	70.5	24.7	3.32	0.34	28.2
BCOA (high SCM) [20 y, 10 cm]	33.8	10.8	0.842	45.4	13.5	4.31	0.34	18.2
Mill-and-fill AC [20 y, 15 cm]	43.4	11.4	5.81	60.6	17.4	4.54	2.32	24.2
BCOA (no SCM) [30 y, 15 cm]	102	7.33	0.842	110	61.4	4.40	0.51	66.2
BCOA (low SCM) [30 y, 15 cm]	61.7	8.31	0.842	70.5	37.0	4.98	0.51	42.3
BCOA (high SCM) [30 y, 15 cm]	33.8	10.8	0.842	45.4	20.3	6.46	0.51	27.3

Appendix B: Estimating PED changes from temperature reductions and hours of HVAC system operation

Assume that raising pavement albedo lowers daily average outside air temperature by ΔT_{C} in the cooling season and by ΔT_{H} in the heating season. Let E_{C} and E_{H} represent annual cooling and heating energy uses per unit conditioned floor area, and let P_{C} and P_{H} represent the average power demands per unit floor area of cooling and heating equipment when in use.

Since some of the heat flow through the building envelope is proportional to the air temperature difference across the envelope, the annual cooling energy savings per unit conditioned floor area ΔE_{C} will be roughly proportional to the time integral of ΔT_{C} over those hours in which the cooling equipment operates, and the annual heating energy penalty ΔE_{H} will be roughly proportional to the time integral of ΔT_{H} over those hours in which the heating equipment operates.

We approximate the annual number of hours of cooling and heating as

$$\tau_{\mathrm{C}} \approx \frac{E_{\mathrm{C}}}{P_{\mathrm{C}}} \tag{B-1}$$

and

$$\tau_{\mathrm{H}} \approx \frac{E_{\mathrm{H}}}{P_{\mathrm{H}}}, \tag{B-2}$$

respectively. The annual cooling energy savings and heating energy penalty are approximately proportional to the product of the average air temperature change in the cooling or heating season and the annual cooling or heating hours:

$$\Delta E_{\mathrm{C}} \propto \Delta T_{\mathrm{C}} \times \tau_{\mathrm{C}} \tag{B-3}$$

and

$$\Delta E_{\mathrm{H}} \propto \Delta T_{\mathrm{H}} \times \tau_{\mathrm{H}}, \tag{B-4}$$

respectively. If city 1 and city 2 have the same values of P_{C} and P_{H}, then

$$\frac{\Delta E_{\mathrm{C1}}}{\Delta E_{\mathrm{C2}}} \approx \frac{\Delta T_{\mathrm{C1}}}{\Delta T_{\mathrm{C2}}} \times \frac{E_{\mathrm{C1}}}{E_{\mathrm{C2}}} \tag{B-5}$$

and

$$\frac{\Delta E_{\mathrm{H1}}}{\Delta E_{\mathrm{H2}}} \approx \frac{\Delta T_{\mathrm{H1}}}{\Delta T_{\mathrm{H2}}} \times \frac{E_{\mathrm{H1}}}{E_{\mathrm{H2}}}, \tag{B-6}$$

respectively. Eq. (B-5) estimates the ratio of cooling energy savings per conditioned floor area in city 1 to those in city 2, while Eq. (B-6) does the same for the heating energy penalty.

To demonstrate, we estimate for Case 1A the ratio of annual cooling PED savings and ratio of annual heating PED penalties for Los Angeles and Fresno upon substituting reflective coating for slurry seal, raising by 0.20 the albedo of 30% of the total pavement area. We then compare these estimates to those calculated from pLCA tool results.

Table B-1 lists city-wide conditioned floor areas in Los Angeles and Fresno, as well as the Case 1A base values of cooling PED and heating PED in each city, all obtained from pLCA tool output. Per unit conditioned floor area, the cooling PED in Los Angeles is 85% of that in Fresno, while the heating PED in Los Angeles is 42% of that in Fresno.

Table B-1. Conditioned floor area by city, and base values of annual cooling PED and heating PED from Case 1A.

Item	Slurry seal	
	Los Angeles	Fresno
Conditioned floor area [million m²]	96.3	25.8
Cooling PED [million MJ/y]	18,400	5,840
Heating PED [million MJ/y]	3,440	2,180
Cooling PED per unit floor area, E_C [MJ/m²·y]	191	226
Heating PED per unit floor area, E_H [MJ/m²·y]	35.7	84.5
Ratio of base cooling PED per unit floor area, $E_{\mathrm{C,\ Los\ Angeles}}/E_{\mathrm{C,\ Fresno}}$	0.85	
Ratio of base heating PED per unit floor area, $E_{\mathrm{H,\ Los\ Angeles}}/E_{\mathrm{H,\ Fresno}}$	0.42	

Table B-2 lists the cooling PED savings and heating PED penalties by city and by pavement type for the reflective coating in Case 1A. It also lists each city's 24-hour average temperature reductions in summer (representing the cooling season) and winter (representing the heating season), calculated from the seasonal hourly temperature changes reported by the tool. These seasonal temperature reductions and the base values of cooling and heating PED (Table B-1) are used to estimate the ratio (Los Angeles to Fresno) of annual cooling PED savings from Eq. (B-5) and the ratio of annual heating PED penalties from Eq. (B-6).

Average summer temperature reductions in Los Angeles are nearly 1.4 times greater than in Fresno, and cooling PED per floor area in Los Angeles is 85% that of Fresno, making the estimated ratio of cooling PED savings per floor area in Los Angeles to that in Fresno equal to $1.4 \times 0.85 = 1.13$. Similar math yields an estimated ratio of 0.65 for the heating PED penalties (Table B-3). Each estimated ratio is about 25% less than that computed from the pLCA tool output. However, the estimated and tool-output ratios each predict that per unit floor area, Los Angeles has a larger cooling PED savings and a smaller heating PED penalty than does Fresno.

Table B-2. Annual cooling energy savings, heating energy penalties, and air temperature reductions in Case Study 1.

Item	Reflective coating	
	Los Angeles	Fresno
Cooling PED savings [million MJ/y]	183	32.5
Heating PED penalty (gas + electricity) [million MJ/y]	68.1	21.0
Heating PED penalty (electricity only) [million MJ/y]	21.2	5.03
Cooling PED savings per unit floor area, ΔE_{C} [MJ/m²·y]	1.90	1.26
Heating PED penalty per unit floor area, ΔE_{H} [MJ/m²·y]	0.707	0.815
Daily average outside air temperature reduction in the cooling season, ΔT_{C} [°C]	0.090	0.068
Daily average outside air temperature reduction in the heating season, ΔT_{H} [°C]	0.065	0.042

Table B-3. Ratios (Los Angeles to Fresno) of cooling energy savings and heating energy penalties, calculated from pLCA tool output and from Eqs. (B-5) and (B-6).

Item	Computed from pLCA tool output	Estimated from Eq. (B-5) or Eq. (B-6)
Ratio of annual cooling savings, $\Delta E_{\mathrm{C,\,Los\,Angeles}} / \Delta E_{\mathrm{C,\,Fresno}}$	1.5	1.1
Ratio of annual heating penalty, $\Delta E_{\mathrm{H,\,Los\,Angeles}} / \Delta E_{\mathrm{H,\,Fresno}}$	0.87	0.65

Appendix C: Calculating heating GWP penalty from heating PED penalty

PED and GWP impacts per MJ of site electricity and per m³ of site gas, obtained from Ref. [20], are shown in Table C-1. The electricity PED impact is based on the California electricity grid mix that represents the projected procurement of electricity from renewable sources by three major IOUs [44] [45] [46] [37] in California in accordance with the RPS [47] (Table C-2). Compared to site electricity, site gas generates nearly twice as much GWP per unit of PED.

Table C-1. PED and GWP per MJ of site electricity (based on 2020 California electricity grid mix) or per MJ of site gas [20]. Also shown is the ratio of GWP to PED for a unit of site energy.

Item	PED [MJ]	GWP [kg CO_2e]	GWP / PED [kg CO_2e / MJ]
Per MJ of site electricity	3.49	0.107	0.031
Per MJ of site gas	1.11	0.062	0.056

Table C-2. Projected electricity grid mix modeled for California in year 2020 [44] [45] [46] [47].

Fuel type	Fraction of projected California electricity grid mix (%)
Total Renewables	**28.2**
Biomass	1.2
Landfill Gas	0.3
Geothermal	2.9
Small Hydro	1.6
Solar PV	10.9
Solar Thermal	2.3
Wind	9.0
Total Non-Renewables	**71.8**
Hard Coal	6.4
Hydro Large	7.0
Natural Gas	36.8
Nuclear	7.6
Unspecified	13.9
Total	**100.0**

Most California buildings are heated with gas; electricity is also used in the heating season, mainly to circulate the warmed air. The use-stage heating penalties reported in this study can be separated by energy source (electricity or gas). The fraction of heating PED penalty attributable to site electricity consumption is

$$f \equiv \frac{\Delta E_{\mathrm{H,e}}}{\Delta E_{\mathrm{H}}} \tag{C-1}$$

where $\Delta E_{\mathrm{H,e}}$ is the electric heating PED penalty and ΔE_{H} is the total (electric + gas) heating PED penalty.

Let $F_{\mathrm{PED,e}}$ and $F_{\mathrm{PED,g}}$ represent the PED per unit of site electricity and per unit of site gas, respectively. Also, let $F_{\mathrm{GWP,e}}$ and $F_{\mathrm{GWP,g}}$ be the GWP per unit of site electricity and per unit of site gas, respectively (Table B-1). The total heating GWP penalty ΔW_{H} can be calculated as

$$\Delta W_{\mathrm{H}} = \left[f \times \frac{F_{\mathrm{GWP,e}}}{F_{\mathrm{PED,e}}} + (1-f) \times \frac{F_{\mathrm{GWP,g}}}{F_{\mathrm{PED,g}}} \right] \times \Delta E_{\mathrm{H}}\,. \tag{C-2}$$

To demonstrate, we use the electric and total heating PED penalties per floor area from Case 1A to calculate the total heating GWP penalties (Table C-3). The heating PED and GWP penalties are then added to the cooling PED and GWP savings to calculate the conditioning (heating + cooling) PED and GWP changes. While both cities experienced conditioning PED savings, Los Angeles had conditioning GWP savings while Fresno had conditioning GWP penalties. This is because Fresno, with its cold winters, experienced a larger heating PED penalty than did Los Angeles. Additionally, 76% of Fresno's heating PED penalty comes from increased use of natural gas, and site gas generates nearly twice as much GWP per PED than does site electricity (Table C-1).

Therefore, the heating penalties in Fresno produce GWP penalties that exceed the cooling GWP savings.

Table C-3. Annual absolute savings and penalties in PED and GWP from heating, cooling, and conditioning energy uses in Case 1A.

Building energy	Item	Reflective coating	
		Los Angeles	Fresno
Heating	PED penalty per floor area, ΔE_{H} [MJ/m²·y]	0.707	0.815
	PED penalty per floor area (electric), $\Delta E_{\mathrm{H,e}}$ [MJ/m²·y]	0.220	0.195
	Fraction of electric heating PED penalty, f	0.312	0.239
	GWP penalty per floor area, ΔW_{H} [kg CO₂e/m²·y]	0.038	0.045
Cooling	PED savings per floor area, ΔE_{C} [MJ/m²·y]	1.90	1.26
	GWP savings per floor area, ΔW_{C} [kg CO₂e/m²·y]	0.058	0.039
Conditioning (cooling + heating)	PED savings per floor area [MJ/m²·y]	1.20	0.443
	GWP savings per floor area [kg CO₂e/m²·y]	0.021	-0.007

Appendix D: Adjusting cool pavement conditioning energy cost savings estimated by Rosenfeld et al. [13] to match assumptions of current study

Assuming that only 1.8 million out of 5 million homes in the Los Angeles Basin have air conditioning equipment—the remaining 3.2 million homes, on the coast, were considered not to need mechanical cooling—Rosenfeld et al. [13] reported Los Angeles Basin conditioning (cooling + heating) energy cost savings of \$0.012/y per square meter of pavement modified upon raising by 0.25 the albedo of 1,250 km² of pavement (about 12.5% of the total area of the Los Angeles Basin). To compare the savings rate reported by Rosenfeld et al. [13] to those obtained in the current study, we assume that indirect conditioning energy cost savings scale with pavement albedo change and with conditioned floor area. We calculate the ratio of floor area to roof area for commercial buildings in the Pacific division of the U.S. Census (Table D-1) and for residential buildings in California (Table D-2). We then calculate the conditioned floor area for residential and commercial buildings in Los Angeles for the original case in which 1.8 million homes are air conditioned and for a revised case in which all 5 million homes are air conditioned (Table D-3). Next, we multiply the Rosenfeld savings by the ratio of albedo change (0.20 / 0.25) and by the ratio of conditioned floor area reported in Table D-3 (1.94). This yields \$0.012/m²·y × (0.20 / 0.25) × 1.94 = \$0.0186/m²·y.

Rosenfeld et al. [13] assumed an electricity price of \$0.10/kWh. While they did not specify the price of natural gas used in their analysis, the U.S. residential sector price of natural gas in 1995 was \$6.16 per 1000 ft³ [67], or about \$0.60/therm at 97.3 ft³ gas per therm.

The 2015 residential sector prices for electricity and natural gas in California were \$0.1699/kWh and \$11.39 per 1000 ft³ (\$1.10/therm), respectively [68] [69]. We will assume round-number prices of \$0.20/kWh and \$1.2/therm for site energy sold in California today, which are conveniently twice the prices used in the 1998 study. Hence, if the 1998 results were scaled to today's energy prices, the savings would be \$0.0186/m²·y × 2 = \$0.037/m²·y.

Table D-1. Floor area and roof area by number of floors for commercial buildings in the Pacific division of the U.S. Census (Alaska, California, Hawaii, Oregon, and Washington), based on floor areas and number of floors reported in the 2012 Commercial Building Energy Consumption Survey (CBECS) [70].

Number of floors	Pacific division		
	Floor area (million m²) [a]	Roof area (million m²) [b]	Ratio of floor area to roof area
One	668	668	
Two	290	145	
Three	75.2	25.1	
Four to nine [c]	158	26.3	
Ten or more [d]	52.8	2.64	
Total	1240	866	1.44

[a] Table B5 in CBECS 2012 [70].

[b] Roof area computed as the ratio of floor area to number of floors.

[c] Roof area calculation based on six floors.

[d] Roof area calculation based on 20 floors.

Table D-2. Total floor area and roof area for residential buildings in California, based on floor areas and number of floors reported in the 2009 Residential Energy Consumption Survey (RECS) [71].

Number of floors	California			
	Housing units (million) [a]	Floor area (million m²) [b]	Roof area (million m²) [c]	Ratio of floor area to roof area
One	9.5	1,400	1,400	
Two	2.4	353	177	
Three or more [d]	0.20	29.4	7.40	
Total	12	1,780	1,580	1.13

[a] Table HC2.11 in RECS 2009 [71].

[b] Estimated using an average floor area per housing unit of 147 m² (Table HC10.13 in RECS 2009 [71]). This average floor area includes all basements, conditioned areas of attics, and conditioned garage space that is attached to the home. It excludes unconditioned and unfinished areas in attics and attached garages.

[c] Roof area computed as the ratio of floor area to number of floors.

[d] Roof area calculation based on four floors.

Table D-3. Floor and roof areas of commercial and residential buildings as reported by Rosenfeld et al. [13] for 1.8 million cooled homes in Los Angeles. We also report estimated floor and roof areas if all homes (5 million) in Los Angeles were cooled.

Homes cooled in Los Angeles	Residential cooled roof area (km²)	Residential cooled floor area (km²)	Commercial cooled roof area (km²)	Commercial cooled floor area (km²)	Total cooled floor area (km²)
1.8M	360	405	250	359	764
5M	1,000	1,126	250	359	1,480
Ratio (5M / 1.8M)					1.94