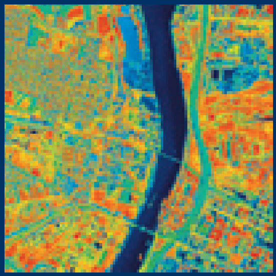
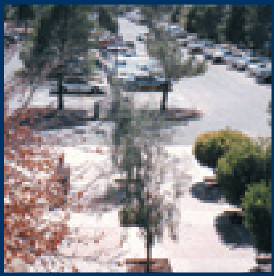
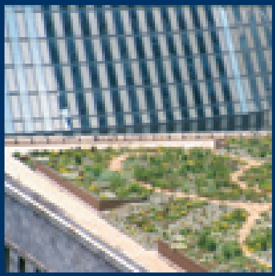
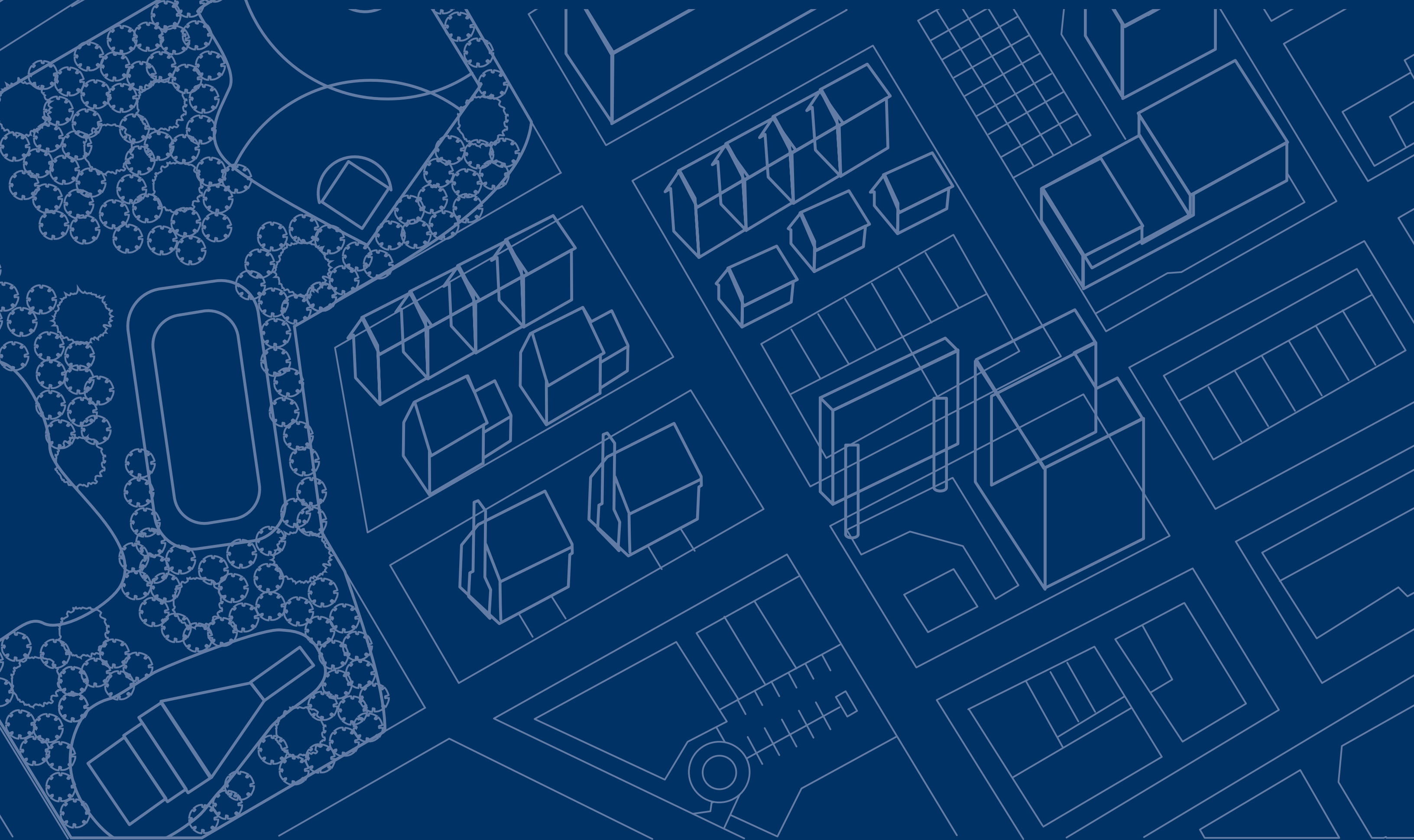


Reducing Urban Heat Islands: Compendium of Strategies

Urban Heat Island Basics



Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

PositvEnergy provided support in preparing the Trees and Vegetation, Cool Roofs, and UHI Activities chapters under contract PO #2W-0361-SATX.

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Suggested Citation: U.S. Environmental Protection Agency. 2008. "Urban Heat Island Basics." In: *Reducing Urban Heat Islands: Compendium of Strategies*. *Draft*. https://www.epa.gov/heat-islands/heat-island-compendium.

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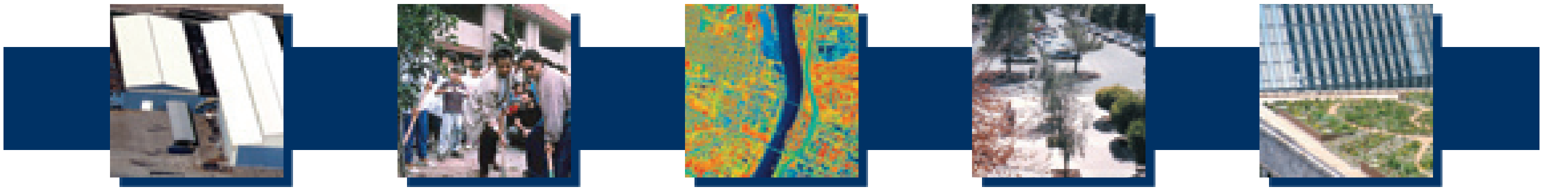


Urban Heat Island Basics

As urban areas develop, changes occur in the landscape. Buildings, roads, and other infrastructure replace open land and vegetation. Surfaces that were once permeable and moist generally become impermeable and dry.* This development leads to the formation of urban heat islands—the phenomenon whereby urban regions experience warmer temperatures than their rural surroundings.

This chapter provides an overview of different types of urban heat islands, methods for identifying them, and factors that contribute to their development. It introduces key concepts that are important to understanding and mitigating this phenomenon, as well as additional sources of information. It discusses:

- General features of urban heat islands
- Surface versus atmospheric heat islands
- Causes of urban heat island formation
- Urban heat island impacts on energy consumption, environmental quality, and human health
- Resources for further information.

1. What Are Urban Heat Islands?

Many urban and suburban areas experience elevated temperatures compared to their outlying rural surroundings; this difference in temperature is what constitutes an urban heat island. The annual mean air temperature of a city with one million or more people can be 1.8 to 5.4°F (1 to 3°C) warmer than its surroundings,[1] and on a clear, calm night, this temperature difference can be as much as 22°F (12°C).[2] Even smaller cities and towns will produce heat islands, though the effect often decreases as city size decreases.[3]

This chapter focuses on *surface* and *atmospheric* urban heat islands. These two heat island types differ in the ways they are formed, the techniques used to identify and measure them, their impacts, and to some degree, the methods available to mitigate them. Table 1 summarizes the basic characteristics of each type of heat island. These features are described in more detail in the following sections of this chapter.

* This change in landscape may differ in regions such as deserts, where moisture may increase in urban areas if development introduces grass lawns and other irrigated vegetation.

Table 1: Basic Characteristics of Surface and Atmospheric Urban Heat Islands (UHIs)[4]

Feature	Surface UHI	Atmospheric UHI
Temporal Development	• Present at all times of the day and night • Most intense during the day and in the summer	• May be small or non-existent during the day • Most intense at night or predawn and in the winter
Peak Intensity (Most intense UHI conditions)	• More spatial and temporal variation: ▪ Day: 18 to 27°F (10 to 15°C) ▪ Night: 9 to 18°F (5 to 10°C)	• Less variation: ▪ Day: -1.8 to 5.4°F (-1 to 3°C) ▪ Night: 12.6 to 21.6°F (7 to 12°C)
Typical Identification Method	• Indirect measurement: ▪ Remote sensing	• Direct measurement: ▪ Fixed weather stations ▪ Mobile traverses
Typical Depiction	• Thermal image	• Isotherm map • Temperature graph

1.1 Surface Urban Heat Islands

On a hot, sunny summer day, the sun can heat dry, exposed urban surfaces, like roofs and pavement, to temperatures 50 to 90°F (27 to 50°C) hotter than the air,[5] while shaded or moist surfaces—often in more rural surroundings—remain close to air temperatures. Surface urban heat islands are typically present day and night, but tend to be strongest during the day when the sun is shining.

On average, the difference in daytime surface temperatures between developed and rural areas is 18 to 27°F (10 to 15°C); the difference in nighttime surface temperatures is typically smaller, at 9 to 18°F (5 to 10°C).[6]

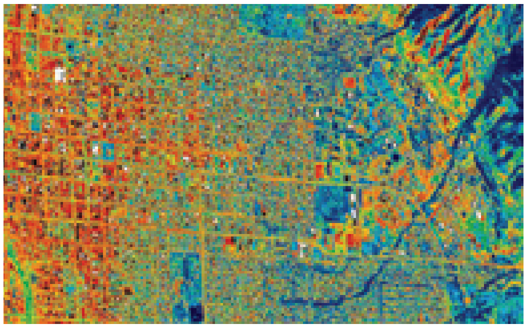
The magnitude of surface urban heat islands varies with seasons, due to changes in the sun's intensity as well as ground cover and weather. As a result of such variation, surface urban heat islands are typically largest in the summer.[7]

How Weather Influences Urban Heat Islands

Summertime urban heat islands are most intense when the sky is clear and winds are calm. Heavy cloud cover blocks solar radiation, reducing daytime warming in cities. Strong winds increase atmospheric mixing, lowering the urban-rural temperature difference. This document, *Reducing Urban Heat Islands: Compendium of Strategies,* focuses on mitigating summertime heat islands through strategies that have maximum impact under clear, calm conditions.

To identify urban heat islands, scientists use direct and indirect methods, numerical modeling, and estimates based on empirical models. Researchers often use remote sensing, an indirect measurement technique, to estimate surface temperatures. They use the data collected to produce thermal images, such as that shown in Figure 1.

Figure 1: Thermal Image Depicting a Surface Urban Heat Island



This image, taken from an aircraft, depicts a midday surface urban heat island in Salt Lake City, Utah, on July 13, 1998. White areas are around 160°F (70°C), while dark blue areas are near 85°F (30°C). Note the warmer urban surface temperatures (left side of image) and cooler surfaces in the neighboring foothills (on the right).

1.2 Atmospheric Urban Heat Islands

Warmer air in urban areas compared to cooler air in nearby rural surroundings defines atmospheric urban heat islands. Experts often divide these heat islands into two different types:

- **Canopy layer urban heat islands** exist in the layer of air where people live, from the ground to below the tops of trees and roofs.
- **Boundary layer urban heat islands** start from the rooftop and treetop level and extend up to the point where urban landscapes no longer influence the atmosphere. This region typically extends no more than one mile (1.5 km) from the surface.[8]

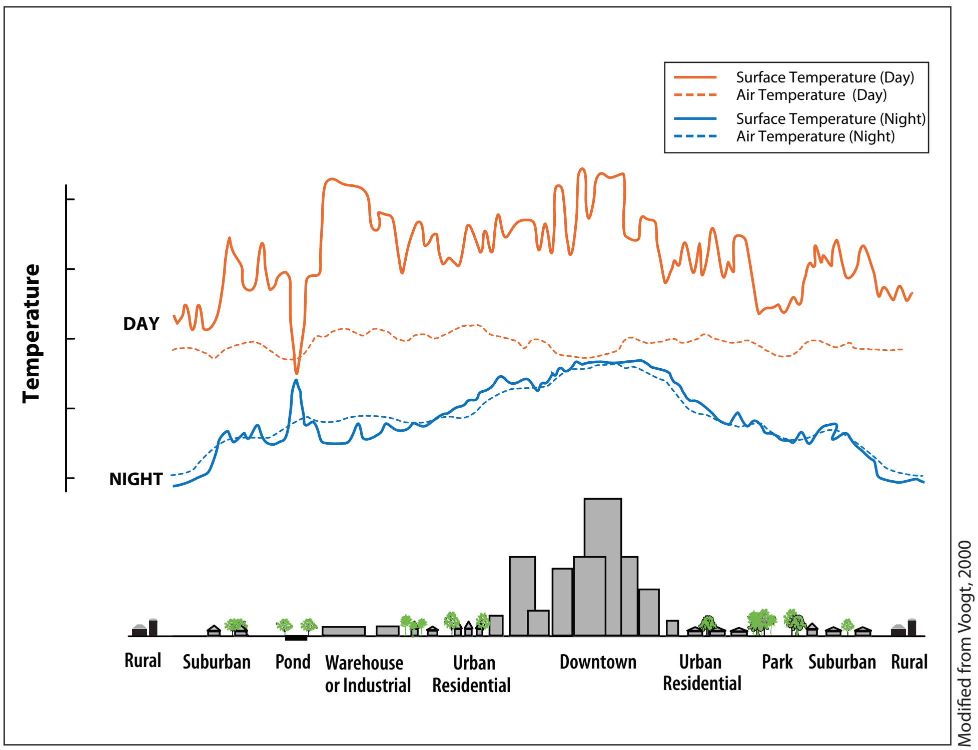
Canopy layer urban heat islands are the most commonly observed of the two types and are often the ones referred to in discussions of urban heat islands. For this reason, this chapter and compendium use the more general term *atmospheric urban heat islands* to refer to canopy layer urban heat islands.

Atmospheric urban heat islands are often weak during the late morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban infrastructure. The timing of this peak, however, depends on the properties of urban and rural surfaces, the season, and prevailing weather conditions.

Surface and Air Temperatures: How Are They Related?

Surface temperatures have an indirect, but significant, influence on air temperatures, especially in the canopy layer, which is closest to the surface. For example, parks and vegetated areas, which typically have cooler surface temperatures, contribute to cooler air temperatures. Dense, built-up areas, on the other hand, typically lead to warmer air temperatures. Because air mixes within the atmosphere, though, the relationship between surface and air temperatures is not constant, and air temperatures typically vary less than surface temperatures across an area (see Figure 2).

Figure 2: Variations of Surface and Atmospheric Temperatures



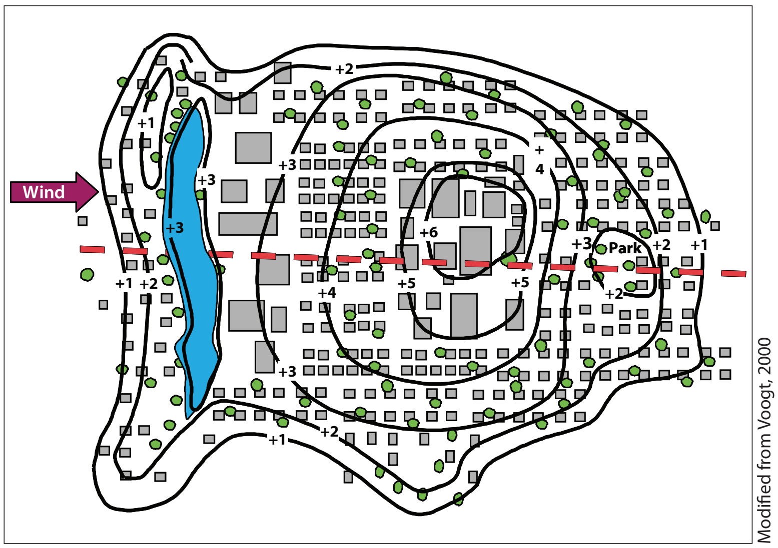
Surface and atmospheric temperatures vary over different land use areas. Surface temperatures vary more than air temperatures during the day, but they both are fairly similar at night. The dip and spike in surface temperatures over the pond show how water maintains a fairly constant temperature day and night, due to its high heat capacity.

* Note: The temperatures displayed above do not represent absolute temperature values or any one particular measured heat island. Temperatures will fluctuate based on factors such as seasons, weather conditions, sun intensity, and ground cover.

Atmospheric heat islands vary much less in intensity than surface heat islands. On an annual mean basis, air temperatures in large cities might be 1.8 to 5.4°F (1 to 3°C) warmer than those of their rural surroundings.[9]

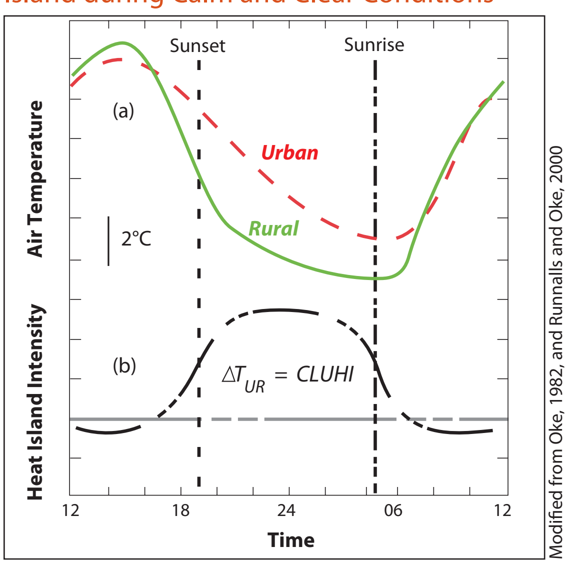
Researchers typically measure air temperatures through a dense network of sampling points from fixed stations or mobile traverses, which are both direct measurement methods. Figure 3 illustrates a conceptual isotherm map that depicts an atmospheric urban heat island. The center of the figure, which is the hottest area, is the urban core. A simple graph of temperature differences, as shown in Figure 4, is another way to show the results.

Figure 3: Isotherm Map Depicting an Atmospheric Nighttime Urban Heat Island



This conceptual map with overlaid isotherms (lines of equal air temperature) exhibits a fully developed nighttime atmospheric urban heat island. The dotted red line indicates a traverse along which measurements are taken.

Figure 4: Conceptual Drawing of the Diurnal Evolution of the Urban Heat Island during Calm and Clear Conditions



Atmospheric urban heat islands primarily result from different cooling rates between urban areas and their surrounding rural or non-urban surroundings (section (a) of Figure 5). The differential cooling rates are most pronounced on clear and calm nights and days when rural areas can cool more quickly than urban areas. The heat island intensity (section (b)) typically grows from mid- to late afternoon to a maximum a few hours after sunset. In some cases, a heat island might not reach peak intensity until after sunrise.

Urban Heat Islands, Climate Change, and Global Warming

Urban heat islands refer to the elevated temperatures in developed areas compared to more rural surroundings. Urban heat islands are caused by development and the changes in radiative and thermal properties of urban infrastructure as well as the impacts buildings can have on the local micro-climate—for example tall buildings can slow the rate at which cities cool off at night. Heat islands are influenced by a city's geographic location and by local weather patterns, and their intensity changes on a daily and seasonal basis.

The warming that results from urban heat islands over small areas such as cities is an example of local climate change. Local climate changes resulting from urban heat islands fundamentally differ from global climate changes in that their effects are limited to the local scale and decrease with distance from their source. Global climate changes, such as those caused by increases in the sun's intensity or greenhouse gas concentrations, are not locally or regionally confined.

Climate change, broadly speaking, refers to any significant change in measures of climate (such as temperature, precipitation, or wind) lasting for an extended period (decades or longer). Climate change may result from:

- Natural factors, such as changes in the sun's intensity or slow changes in the Earth's orbit around the sun
- Natural processes within the climate system (e.g. changes in ocean circulation)
- Human activities that change the atmosphere's composition (e.g. burning fossil fuels) and the land surface (e.g. deforestation, reforestation, or urbanization).

The term climate change is often used interchangeably with the term global warming, but according to the National Academy of Sciences, "the phrase 'climate change' is growing in preferred use to 'global warming' because it helps convey that there are [other] changes in addition to rising temperatures."

Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the lowest layer of the atmosphere, which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced. In common usage, "global warming" often refers to the warming that can occur as a result of increased emissions of greenhouse gases from human activities. Global warming can be considered part of global climate change along with changes in precipitation, sea level, etc.

The impacts from urban heat islands and global climate change (or global warming) are often similar. For example, some communities may experience longer growing seasons due to either or both phenomena. Urban heat islands and global climate change can both also increase energy demand, particularly summertime air conditioning demand, and associated air pollution and greenhouse gas emissions, depending on the electric system power fuel mix.

Strategies to reduce urban heat islands—the focus of this document, *Reducing Urban Heat Islands: Compendium of Strategies*—produce multiple benefits including lowering surface and air temperatures, energy demand, air pollution and greenhouse gas emissions. Thus, advancing measures to mitigate urban heat islands also helps to address global climate change.

For more information on global warming see EPA's Climate Change website, <www.epa.gov/climatechange>.

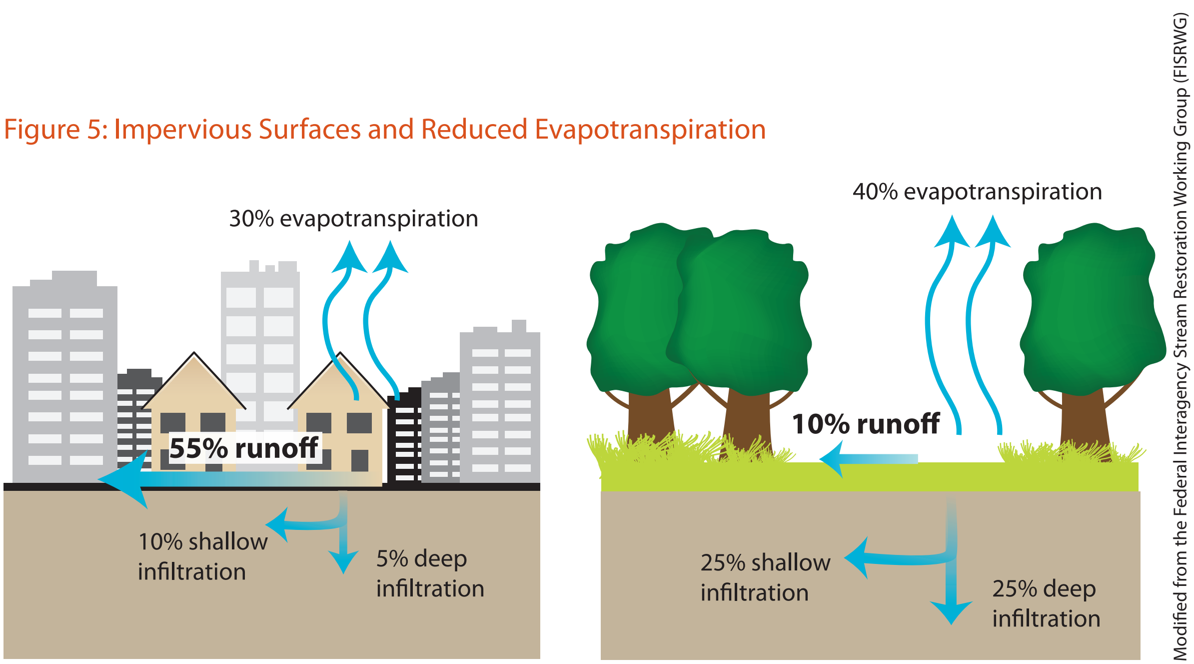
2. How Do Urban Heat Islands Form?

While many factors contribute to urban heat island formation (see Table 2), this chapter focuses on vegetative cover and surface properties because communities can directly address these factors with available technologies. See the "Trees and Vegetation," "Green Roofs," "Cool Roofs," and "Cool Pavement" chapters for detailed information on these strategies.

2.1 Reduced Vegetation in Urban Areas

In rural areas, vegetation and open land typically dominate the landscape. Trees and vegetation provide shade, which helps lower surface temperatures. They also help reduce air temperatures through a process called evapotranspiration, in which plants release water to the surrounding air, dissipating ambient heat. In contrast, urban areas are characterized by dry, impervious surfaces, such as conventional roofs, sidewalks, roads, and parking lots. As cities develop, more vegetation is lost, and more surfaces are paved or covered with buildings. The change in ground cover results in less shade and moisture to keep urban areas cool. Built up areas evaporate less water (see Figure 5), which contributes to elevated surface and air temperatures.

Figure 5: Impervious Surfaces and Reduced Evapotranspiration



Highly developed urban areas (right), which are characterized by 75%-100% impervious surfaces, have less surface moisture available for evapotranspiration than natural ground cover, which has less than 10% impervious cover (left). This characteristic contributes to higher surface and air temperatures in urban areas.

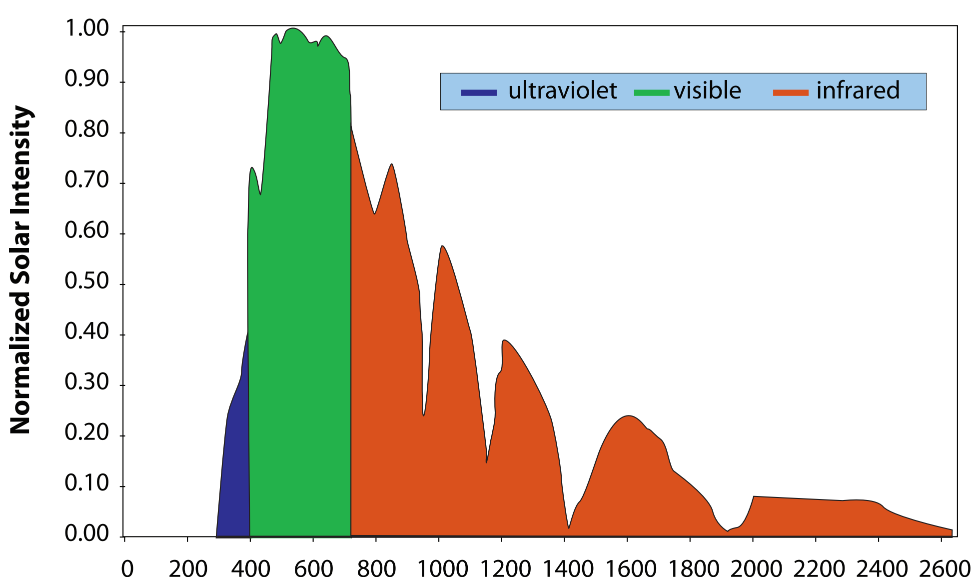
2.2 Properties of Urban Materials

Properties of urban materials, in particular solar reflectance, thermal emissivity, and heat capacity, also influence urban heat island development, as they determine how the sun's energy is reflected, emitted, and absorbed.

Figure 6 shows the typical solar energy that reaches the Earth's surface on a clear summer day. Solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: five percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn; 43 percent of solar energy is visible light, in colors ranging from violet to red; and the remaining 52 percent of solar energy is infrared, felt as heat. Energy in all of these wavelengths contributes to urban heat island formation.

Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface. Much of the sun's energy is found in the visible wavelengths (see Figure 6); thus, solar reflectance is correlated with a material's color. Darker surfaces tend to have lower solar reflectance values than lighter surfaces. Researchers are studying and developing cool colored materials, though, that use specially engineered pigments that reflect well in the infrared wavelengths. These products can be dark in color but have a solar reflectance close to that of a white or light-colored material. (See the "Cool Roofs" chapter for further discussion of cool colored roof products.)

Figure 6: Solar Energy versus Wavelength Reaching Earth's Surface



Solar energy intensity varies over wavelengths from about 250 to 2500 nanometers.

Urban areas typically have surface materials, such as roofing and paving, which have a lower albedo than those in rural settings. As a result, built up communities generally reflect less and absorb more of the sun's energy. This absorbed heat increases surface temperatures and contributes to the formation of surface and atmospheric urban heat islands.

Although solar reflectance is the main determinant of a material's surface temperature, thermal emittance, or emissivity, also plays a role. Thermal emittance is a measure of a surface's ability to shed heat, or emit long-wave (infrared) radiation. All things equal, surfaces with high emittance values will stay cooler, because they will release heat more readily. Most construction materials, with the exception of metal, have high thermal emittance values. Thus, this property is mainly of interest to those installing cool roofs, which can be metallic. See the "Cool Roofs" chapter of the compendium for more information.

Another important property that influences heat island development is a material's heat capacity, which refers to its ability to store heat. Many building materials, such as steel and stone, have higher heat capacities than rural materials, such as dry soil and sand. As a result, cities are typically more effective at storing the sun's energy as heat within their infrastructure. Downtown metropolitan areas can absorb and store twice the amount of heat compared to their rural surroundings during the daytime.[10]

Radiative and Thermal Properties—Cool Roofs and Cool Pavements

Albedo and emissivity are considered "radiative properties." Heat capacity, on the other hand, is one of several "thermal properties" a material can possess. For thin materials like roofing, which is typically placed over insulation, reflectance and emittance are the main properties to consider, as the heat capacity of a well insulated roof is low. For pavements, which are thicker than roofing products and are placed on top of the ground, which has its own set of thermal characteristics, designers and researchers need to consider a more complex set of factors that include radiative and thermal properties—such as heat capacity, thermal conductivity, and density.

2.3 Urban Geometry

An additional factor that influences urban heat island development, particularly at night, is urban geometry, which refers to the dimensions and spacing of buildings within a city. Urban geometry influences wind flow, energy absorption, and a given surface's ability to emit long-wave radiation back to space. In developed areas, surfaces and structures are often at least partially obstructed by objects, such as neighboring buildings, and become large thermal masses that cannot release their heat very readily because of these obstructions. Especially at night, the air above urban centers is typically warmer than air over rural areas. Nighttime atmospheric heat islands can have serious health implications for urban residents during heat waves (see textbox in Section 3.3, "Factors in Heat-Related Illnesses and Death.")

Researchers often focus on an aspect of urban geometry called urban canyons, which can be illustrated by a relatively narrow street lined by tall buildings. During the day, urban canyons can have competing effects. On the one hand, tall buildings can create shade, reducing surface and air temperatures. On the other, when sunlight reaches surfaces in the canyon, the sun's energy is reflected and absorbed by building walls, which further lowers the city's overall albedo—the net reflectance from surface albedo plus urban geometry—and can increase temperatures.[11] At night, urban canyons generally impede cooling, as buildings and structures can obstruct the heat that is being released from urban infrastructure.

Table 2: Factors that Create Urban Heat Islands

Factors Communities are Focusing On
• Reduced vegetation in urban regions: Reduces the natural cooling effect from shade and evapotranspiration. • Properties of urban materials: Contribute to absorption of solar energy, causing surfaces, and the air above them, to be warmer in urban areas than those in rural surroundings.
Future Factors to Consider
• Urban geometry: The height and spacing of buildings affects the amount of radiation received and emitted by urban infrastructure. • Anthropogenic heat emissions: Contribute additional warmth to the air.*
Additional Factors
• Weather: Certain conditions, such as clear skies and calm winds, can foster urban heat island formation. • Geographic location: Proximity to large water bodies and mountainous terrain can influence local wind patterns and urban heat island formation.

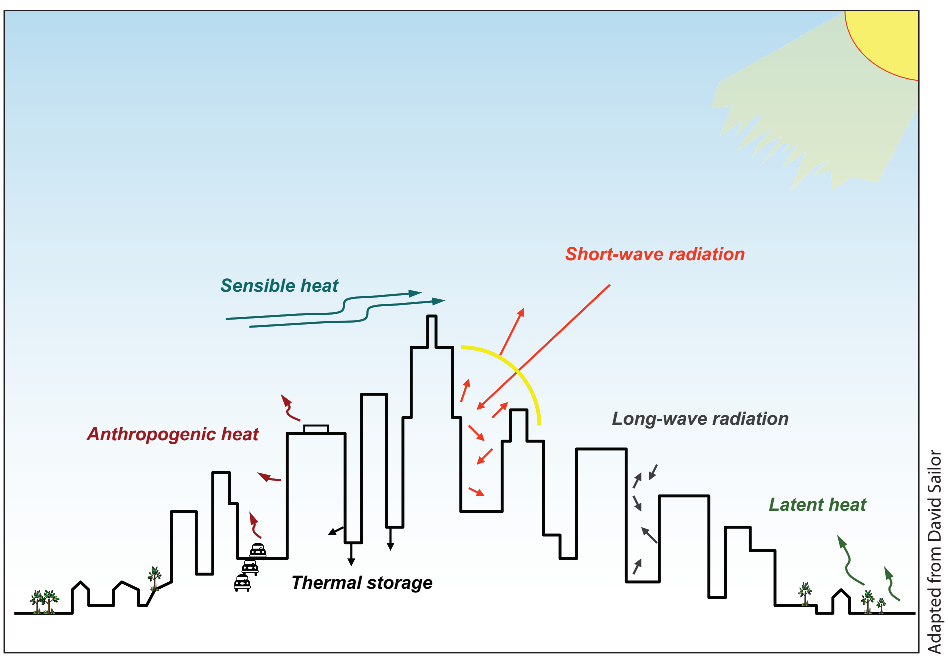
* Although communities currently can lower anthropogenic heat emissions through energy efficiency technologies in the building and vehicle sectors, this compendium focuses on modifying vegetative cover and surface properties of urban materials, as they have long been regarded as urban heat island reduction strategies. An emerging body of literature on the role waste heat plays in urban heat island formation, though, may lead communities to focus on anthropogenic heat in the near future.

The Urban Surface Energy Budget

An energy budget provides an equation that quantifies the balance of incoming and outgoing energy flows, or fluxes (see Figure 7). The surface energy budgets of urban areas and their more rural surroundings will differ because of differences in land cover, surface characteristics, and level of human activity. Such differences can affect the generation and transfer of heat, which can lead to different surface and air temperatures in urban versus rural areas. Various elements of the budget include:

- **Short-wave radiation** is ultraviolet, visible light, and near-infrared radiation from the sun that reaches the Earth (see Figure 6). This energy is a key driver of urban heat islands. Urban surfaces, compared to vegetation and other natural ground cover, reflect less radiation back to the atmosphere. They instead absorb and store more of it, which raises the area's temperature.
- **Thermal storage** increases in cities in part due to the lower solar reflectance of urban surfaces, but it is also influenced by the thermal properties of construction materials and urban geometry. Urban geometry can cause some short-wave radiation—particularly within an urban canyon—to be reflected on nearby surfaces, such as building walls, where it is absorbed rather than escaping into the atmosphere.

Figure 7: Urban Surface Energy Budget



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The Urban Surface Energy Budget (continued)

- Similarly, urban geometry can impede the release of **long-wave, or infrared, radiation** into the atmosphere. When buildings or other objects absorb incoming short-wave radiation, they can re-radiate that energy as long-wave energy, or heat. However, at night, due to the dense infrastructure in some developed areas that have low sky view factors (see section 2.3), urban areas cannot easily release long-wave radiation to the cooler, open sky, and this trapped heat contributes to the urban heat island.
- Evapotranspiration describes the transfer of **latent heat,** what we feel as humidity, from the Earth's surface to the air via evaporating water. Urban areas tend to have less evapotranspiration relative to natural landscapes, because cities retain little moisture. This reduced moisture in built up areas leads to dry, impervious urban infrastructure reaching very high surface temperatures, which contribute to higher air temperatures.*
- Convection describes the transfer of **sensible heat,** what we feel as temperature, between the surface and air when there is a difference in temperature between them. High urban surface temperatures warm the air above, which then circulates upwards via convection.
- **Anthropogenic heat** refers to the heat generated by cars, air conditioners, industrial facilities, and a variety of other manmade sources, which contributes to the urban energy budget, particularly in the winter.

* This change in landscape may differ in regions such as deserts, where moisture may increase in urban areas if development introduces grass lawns and other irrigated vegetation.

The effects of urban geometry on urban heat islands are often described through the "sky view factor" (SVF), which is the visible area of the sky from a given point on a surface. For example, an open parking lot or field that has few obstructions would have a large SVF value (closer to 1). Conversely, an urban canyon in a downtown area that is surrounded by closely spaced, tall buildings, would have a low SVF value (closer to zero), as there would only be a small visible area of the sky.

2.4 Anthropogenic Heat

Anthropogenic heat contributes to atmospheric heat islands and refers to heat produced by human activities. It can come from a variety of sources and is estimated by totaling all the energy used for heating and cooling, running appliances, transportation, and industrial processes. Anthropogenic heat varies by urban activity and infrastructure, with more energy-intensive buildings and transportation producing more heat.[12] Anthropogenic heat typically is not a concern in rural areas and during the summer. In the winter, though, and year round in dense, urban areas, anthropogenic heat can significantly contribute to heat island formation.

2.5 Additional Factors

Weather and location strongly influence urban heat island formation. While communities have little control over these factors, residents can benefit from understanding the role they play.

- **Weather.** Two primary weather characteristics affect urban heat island development: wind and cloud cover. In general, urban heat islands form during periods of calm winds and clear skies, because these conditions maximize the amount of solar energy reaching urban surfaces and minimize the amount of heat that can be convected away. Conversely, strong winds and cloud cover suppress urban heat islands.
- **Geographic location.** Climate and topography, which are in part determined by a city's geographic location, influence urban heat island formation. For example, large bodies of water moderate temperatures and can generate winds that convect heat away from cities. Nearby mountain ranges can either block wind from reaching a city, or create wind patterns that pass through a city. Local terrain has a greater significance for heat island formation when larger-scale effects, such as prevailing wind patterns, are relatively weak.

3. Why Do We Care about Urban Heat Islands?

Elevated temperatures from urban heat islands, particularly during the summer, can affect a community's environment and quality of life. While some heat island impacts seem positive, such as lengthening the plant-growing season, most impacts are negative and include:

- Increased energy consumption
- Elevated emissions of air pollutants and greenhouse gases
- Compromised human health and comfort
- Impaired water quality.

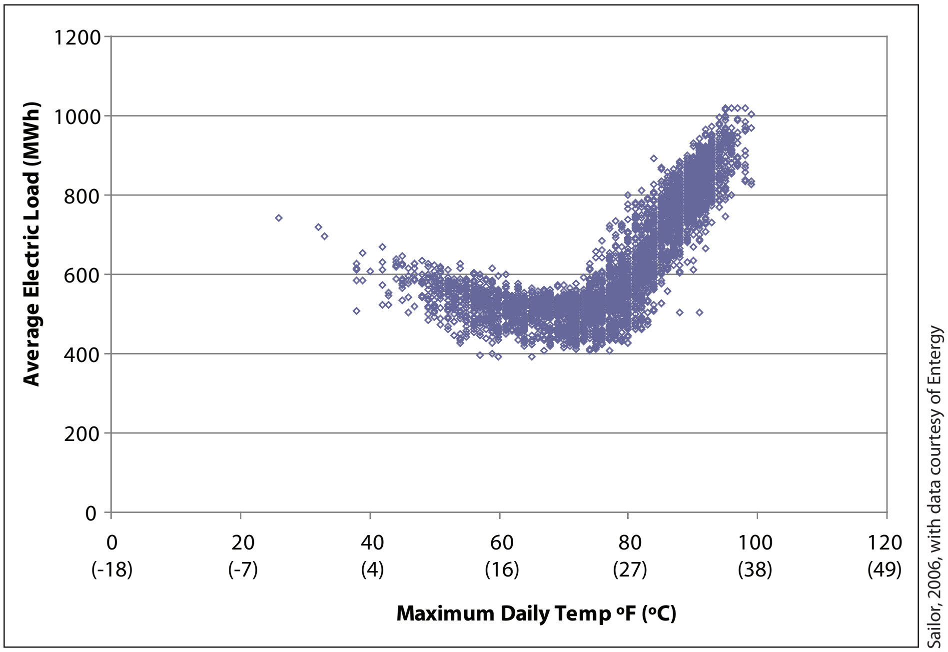
Wintertime Benefits of Urban Heat Islands

Communities may benefit from the wintertime warming effect of urban heat islands. Warmer temperatures can reduce heating energy needs and help to melt snow and ice on roads. Fortunately, urban heat island mitigation strategies—for example, trees and vegetation and green roofs—generally provide year-round benefits, or their winter penalty, such as that from cool roofs, is much smaller than their summertime benefits.

3.1 Energy Consumption

Elevated summertime temperatures in cities increase energy demand for cooling and add pressure to the electricity grid during peak periods of demand, which generally occur on hot, summer weekday afternoons, when offices and homes are running cooling systems, lights, and appliances (see Figure 8). This peak urban electric demand increases 1.5 to 2 percent for every 1°F (0.6°C) increase in summertime temperature. Steadily increasing downtown temperatures over the last several decades mean that 5 to 10 percent of community-wide demand for electricity is used to compensate for the heat island effect.[13] During extreme heat events, which are exacerbated by urban heat islands, the resulting demand for cooling can overload systems and require a utility to institute controlled, rolling brownouts or blackouts to avoid power outages.

Figure 8: Increasing Power Loads with Temperature Increases[14]



As shown in this example from New Orleans, electrical load can increase steadily once temperatures begin to exceed about 68 to 77°F (20 to 25°C). Other areas of the country show similar demand curves as temperature increases.

3.2 Air Quality and Greenhouse Gases

As discussed in Section 3.1, higher temperatures can increases energy demand, which generally causes higher levels of air pollution and greenhouse gas emissions. Currently, most electricity in the United States is produced from combusting fossil fuel. Thus, pollutants from most power plants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and mercury (Hg). These pollutants are harmful to human health and contribute to complex air quality problems such as acid rain. Further, fossil-fuel-powered plants emit greenhouse gases, particularly carbon dioxide (CO_2), which contribute to global climate change.

In addition to increases in air emissions, elevated air temperatures increase the rate of ground-level ozone formation, which is produced when NO_x and volatile organic compounds (VOCs) react in the presence of sunlight. If all other variables are equal—such as the level of precursor emissions or wind speed and direction—ground-level ozone emissions will be higher in sunnier and hotter weather.

3.3 Human Health and Comfort

Increased daytime surface temperatures, reduced nighttime cooling, and higher air pollution levels associated with urban heat islands can affect human health by contributing to general discomfort, respiratory difficulties, heat cramps and exhaustion, non-fatal heat stroke, and heat-related mortality.

Urban heat islands can also exacerbate the impact of heat waves, which are periods of abnormally hot, and often humid, weather. Sensitive populations, such as children, older adults, and those with existing health conditions, are at particular risk from these events. For example, in 1995, a mid-July heat wave in the Midwest caused more than 1,000 deaths.[15] While it is rare for a

Factors in Heat-Related Illnesses and Death

Low income elderly people who live in row homes are at a particular risk for heat-related health incidents. Living on the upper floor of a typical row home, with a dark roof, brick construction, and windows on only two sides, could contribute to the risk of heat-related illness or death during heat waves, as temperatures in these homes can be extreme.[16] These homes often lack air conditioning, especially in areas unaccustomed to high temperatures. Further, even when air conditioning is available, residents may not use it for fear of high utility bills.

Social isolation and physical health also contribute to one's vulnerability. Elderly people, especially, may not have family or friends nearby, may not report to work regularly, and may lack neighbors who can check on them, leaving them stranded during extreme heat events. The elderly may also fail to hear news or other warnings of impending heat waves and recommendations on how to cope. Finally, their bodies may be less able to handle heat stress.

The lack of nighttime relief in air temperatures is strongly correlated with increased mortality during heat waves. Some studies suggest that these oppressive nighttime temperatures may be more significant than high maximum daytime temperatures.[17]

For more information on heat-related health incidents and ways to respond, see the EPA Excessive Heat Events Guidebook <www.epa.gov/hiri/about/pdf/EHEguide_final.pdf>

heat wave to be so destructive, heat-related mortality is not uncommon. The Centers for Disease Control estimates that from 1979 to 1999, excessive heat exposure contributed to more than 8,000 premature deaths in the United States.[18] This figure exceeds the number of mortalities resulting from hurricanes, lightning, tornadoes, floods, and earthquakes combined.

3.4 Water Quality

Surface urban heat islands degrade water quality, mainly by thermal pollution. Pavement and rooftop surfaces that reach temperatures 50 to 90°F (27 to 50°C) higher than air temperatures transfer this excess heat to stormwater. Field measurements from one study showed that runoff from urban areas was about 20-30°F (11-17°C) hotter than runoff from a nearby rural area on summer days when pavement temperatures at midday were 20-35°F (11-19°C) above air temperature. When the rain came before the pavement had a chance to heat up, runoff temperatures from the rural and urban areas differed by less than 4°F (2°C).[19] This heated stormwater generally drains into storm sewers (see Figure 5) and raises water temperatures as it is released into streams, rivers, ponds, and lakes. A study in Arlington, Virginia, recorded temperature increases in surface waters as high as 8°F (4°C) in 40 minutes after heavy summer rains.[20]

Water temperature affects all aspects of aquatic life, especially the metabolism and reproduction of many aquatic species. Rapid temperature changes in aquatic ecosystems resulting from warm storm-water runoff can be particularly stressful. Brook trout, for example, experience thermal stress and shock when the water temperature changes more than 2 to 4ºF (1-2°C) in 24 hours.[21]

4. Strategies to Reduce Urban Heat Islands

Although urban climatologists have been studying urban heat islands for decades, community interest and concern regarding them has been more recent. This increased attention to heat-related environment and health issues has helped to advance the development of heat island reduction strategies, mainly trees and vegetation, green roofs, and cool roofs. Interest in cool pavements has been growing, and an emerging body of research and pilot projects are helping scientists, engineers, and practitioners to better understand the interactions between pavements and the urban climate.

This compendium *Reducing Urban Heat Islands: Compendium of Strategies* provides details about how these strategies work, their benefits and costs, factors to consider when selecting them, and additional resources for communities to further explore. It presents the multiple benefits—beyond temperature reduction—that a community can accrue from advancing heat island reduction strategies. It also gives examples of how communities have implemented these strategies through voluntary and policy efforts in the "Heat Island Reduction Activities" chapter. Communities can use this compendium as a foundation and starting point for understanding the nuts and bolts of existing urban heat island reduction strategies that communities are currently advancing.

Future policy efforts may focus on encouraging strategies to modify urban geometry and anthropogenic heat in communities to reduce urban heat islands. Research in this area is on-going, and there is a growing awareness of the importance of these factors.

5. Additional Resources

The table on the next page provides additional resources on urban heat island formation, measurement, and impacts.

Table 3: Urban Heat Island Resources

Name	Description	Web Link
General Information		
EPA's Heat Island Website	Through this website, EPA provides background information, publications, reports, access to national webcasts, a database of urban heat island activities, and links to other resources to help communities reduce urban heat islands.	<www.epa.gov/heatislands>
International Association for Urban Climate (IAUC)	This international website is the main forum in which urban climatologists communicate. Urban climate resources, including a bimonthly newsletter, and information on upcoming meetings can be found here.	<www.urban-climate.org>
Lawrence Berkeley National Laboratory (LBNL) Heat Island Group	LBNL provides background information on urban heat islands and their impacts through this website. It also presents some of the impacts heat island reduction strategies can have on temperature, energy consumption, and air quality.	<http://eetd.lbl.gov/HeatIsland>
National Center of Excellence - SMART Innovations for Urban Climate and Energy	Arizona State University's National Center of Excellence collaborates with industry and government to research and develop technologies to reduce urban heat islands, especially in desert climates. Its website provides background information on urban heat islands.	<www.asusmart.com/urbanclimate.php>
Urban Heat Islands: Hotter Cities	This article explains urban heat islands and presents solutions to mitigate them.	<www.actionbioscience.org/environment/voogt.html>
Measuring Heat Islands and Their Impacts		
National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey Landsat Program	The Landsat program is a series of Earth-observing satellites used to acquire images of the Earth's land surface and surrounding coastal regions. These images provide information from which researchers can derive surface temperatures and evaluate urban heat islands.	<http://landsat.gsfc.nasa.gov/>
National Weather Service	The National Weather Service is a source for air temperature measurements, climate and weather models, and past and future climate predictions. The site also has links to excessive heat outlooks, fatality statistics, historic data on major heat waves, drought information, and advice on how to minimize the health risks of heat waves.	<www.nws.noaa.gov/>
EPA's Excessive Heat Events Guidebook	This document is designed to help community officials, emergency managers, meteorologists, and others plan for and respond to excessive heat events by highlighting best practices that have been employed to save lives during excessive heat events in different urban areas. It provides a menu of options that officials can use to respond to these events in their communities.	<www.epa.gov/hiri/about/heatguidebook.html>

Endnotes

1 Oke, T.R. 1997. Urban Climates and Global Environmental Change. In: Thompson, R.D. and A. Perry (eds.) Applied Climatology: Principles & Practices. New York, NY: Routledge. pp. 273-287.

2 Oke. T.R. 1987. Boundary Layer Climates. New York, Routledge.

3 Oke, T.R. 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society. 108:1-24. The threshold city population for heat islands of the size 2-5°F may be closer to 100,000 inhabitants in some cases. See also Aniello, C., K. Morgan, A. Busbey, and L. Newland. 1995. Mapping Micro-Urban Heat Islands Using Landsat TM and a GIS. Computers and Geosciences 21(8):965-69.

4 From: 1) Oke, T.R. 1997. Urban Climates and Global Environmental Change. In: Thompson, R.D. and A. Perry (eds.) Applied Climatology: Principles & Practices. New York, NY: Routledge. pp. 273-287. 2) Oke. T.R. 1987. Boundary Layer Climates. New York, Routledge. 3) Voogt, J.A. and T.R. Oke. 2003. Thermal Remote Sensing of Urban Areas. Remote Sensing of Environment. 86. (Special issue on Urban Areas): 370-384. 4) Roth, M., T. R. Oke, and W. J. Emery. 1989. Satellite-derived Urban Heat Islands from Three Coastal Cities and the Utilization of Such Data in Urban Climatology. Int. J. Remote Sensing. 10:1699-1720.

5 Berdahl P. and S. Bretz. 1997. Preliminary Survey of the Solar Reflectance of Cool Roofing Materials. Energy and Buildings 25:149-158.

6 Numbers from Voogt, J.A. and T.R. Oke. 2003. Thermal Remote Sensing of Urban Areas. Remote Sensing of Environment. 86. (Special issue on Urban Areas): 370-384. Roth, M., T. R. Oke, and W. J. Emery. 1989. Satellite-derived Urban Heat Islands from Three Coastal Cities and the Utilization of Such Data in Urban Climatology. Int. J. Remote Sensing. 10:1699-1720.

7 Oke, T.R. 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society. 108:1-24.

8 Oke, T.R. 1982. The Energetic Basis of the Urban Heat Island. Quarterly Journal of the Royal Meteorological Society. 108:1-24.

9 Oke, T.R. 1997. Urban Climates and Global Environmental Change. In: Thompson, R.D. and A. Perry (eds.) Applied Climatology: Principles & Practices. New York, NY: Routledge. pp. 273-287.

10 Christen, A. and R. Vogt. 2004. Energy and Radiation Balance of a Central European City. International Journal of Climatology. 24(11):1395-1421.

11 Sailor, D.J., and H. Fan. 2002. Modeling the Diurnal Variability of Effective Albedo for Cities. Atmospheric Environment. 36(4): 713-725.

12 Voogt, J. 2002. Urban Heat Island. In Munn, T. (ed.) Encyclopedia of Global Environmental Change, Vol. 3. Chichester: John Wiley and Sons.

13 Akbari, H. 2005. Energy Saving Potentials and Air Quality Benefits of Urban Heat Island Mitigation. Retrieved 2 Jul. 2008 from <http://www.osti.gov/bridge/servlets/purl/860475-UlH-WIq/860475.PDF>.

14 Sailor, D. J. 2002. Urban Heat Islands, Opportunities and Challenges for Mitigation and Adaptation. Sample Electric Load Data for New Orleans, LA (NOPSI, 1995). North American Urban Heat Island Summit. Toronto, Canada. 1-4 May 2002. Data courtesy Entergy Corporation.

15 Taha, H. and L.S. Kalkstein, S.C. Sheridan, and E. Wong. 2004. The Potential of Urban Environmental Controls in Alleviating Heat-wave Health Effects in Five US Regions. Presented at the American Meteorological Society Fifth Conference on Urban Environment. 25 August. See also NOAA. 1995. Natural Disaster Survey Report: July 1995 Heat Wave. Retrieved 20 June 2008 from <http://www.nws.noaa.gov/om/assessments/pdfs/heat95.pdf>.

16 Kalkstein, L.S. and S.C. Sheridan. 2003. The Impact of Heat Island Reduction Strategies on Health-Debilitating Oppressive Air Masses in Urban Areas. Prepared for U.S. EPA Heat Island Reduction Initiative.

17 Kalkstein, L.S. 1991. A New Approach to Evaluate the Impact of Climate upon Human Mortality. Environmental Health Perspectives 96: 145-50.

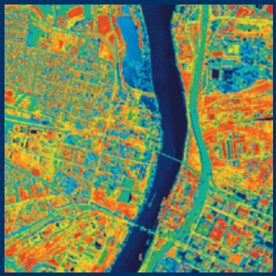
18 CDC. 2004. Extreme Heat: A Prevention Guide to Promote Your Personal Health and Safety. Retrieved 27 July 2007 from <http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp>.

19 Roa-Espinosa, A., T.B. Wilson, J.M. Norman, and Kenneth Johnson. 2003. Predicting the Impact of Urban Development on Stream Temperature Using a Thermal Urban Runoff Model (TURM). National Conference on Urban Stormwater: Enhancing Programs at the Local Level. February 17-20. Chicago, IL. Retrieved 17 Jul. 2008 from <http://www.epa.gov/nps/natlstormwater03/31Roa.pdf>.

20 EPA. 2003. Beating the Heat: Mitigating Thermal Impacts. Nonpoint Source News-Notes. 72:23-26.

21 EPA. 2003. Beating the Heat: Mitigating Thermal Impacts. Nonpoint Source News-Notes. 72:23-26.





Reducing Urban Heat Islands: Compendium of Strategies

Trees and Vegetation

Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

PositvEnergy provided support in preparing the Trees and Vegetation, Cool Roofs, and UHI Activities chapters under contract PO #2W-0361-SATX.

Experts who helped shape this chapter include:

Ryan Bell, David Cole, Ben DeAngelo, Lynn Desaultes, Ed Dickerhoff, Maury Estes, Gordon Heisler, David Hitchcock, Kim Klunich, Cheryl Kollin, Megan Lewis, Julie Magee, Greg McPherson, Dave Nowak, Philip Rodbell, Joyce Rosenthal, Misha Sarkovich, Kathy Wolf, Jim Yarbrough, and Barry Zalph.

Suggested Citation: U.S. Environmental Protection Agency. 2008. "Trees and Vegetation." In: *Reducing Urban Heat Islands: Compendium of Strategies. Draft.* https://www.epa.gov/heat-islands/heat-island-compendium.

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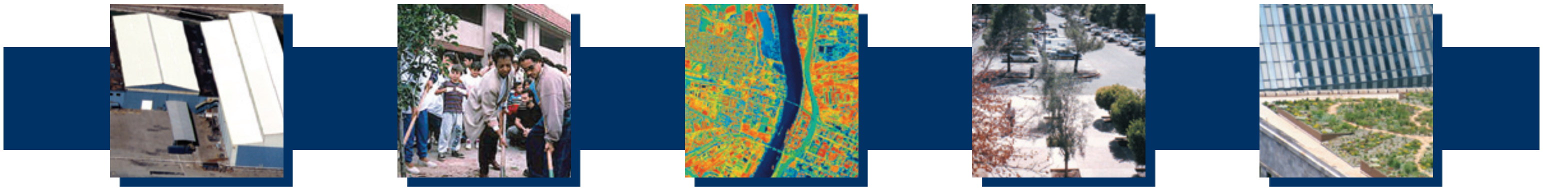


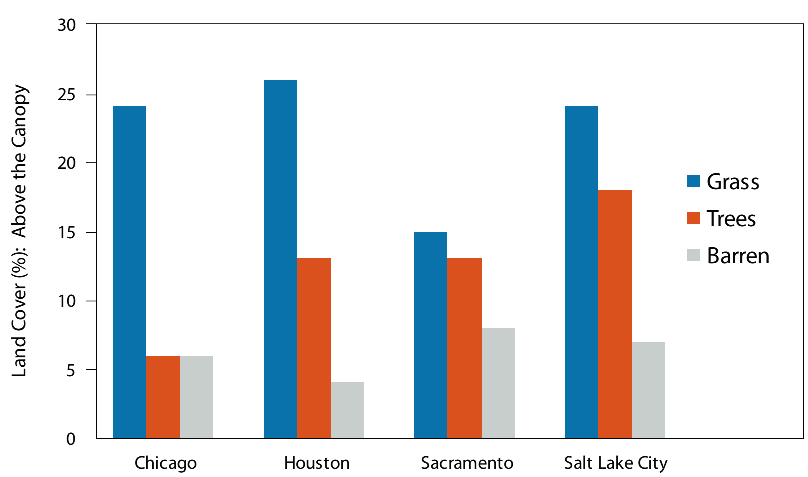
Trees and Vegetation

Shade trees and smaller plants such as shrubs, vines, grasses, and ground cover, help cool the urban environment. Yet, many U.S. communities have lost trees and green space as they have grown. This change is not inevitable. Many communities can take advantage of existing space, such as grassy or barren areas, to increase their vegetative cover and reap multiple benefits.

Opportunities to Expand the Use of Urban Trees and Vegetation

Most U.S. communities have opportunities to increase the use of trees and vegetation. As part of the U.S. Environmental Protection Agency's (EPA's) Urban Heat Island Pilot Project, the Lawrence Berkeley National Laboratory conducted analyses to estimate baseline land use and tree cover information for the pilot program cities.[1] Figure 1 shows the percentage of vegetated and barren land cover in four of these urban areas. The high percentage of grass and barren land cover show the space potentially available for additional tree canopy cover. The statistics do not show the loss of dense vegetated cover as cities expand, however. For example, a 2005 report estimates that Houston lost 10 million trees per year from 1992 to 2000.[2]

Figure 1: Land Cover Statistics for Various U.S. Cities (Above Tree Canopy)



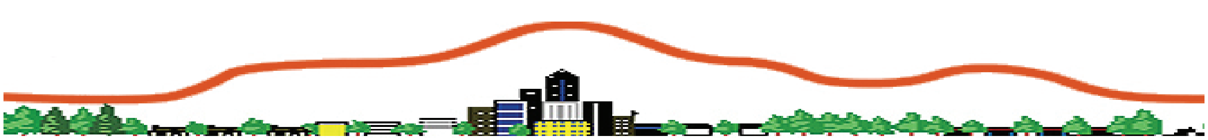
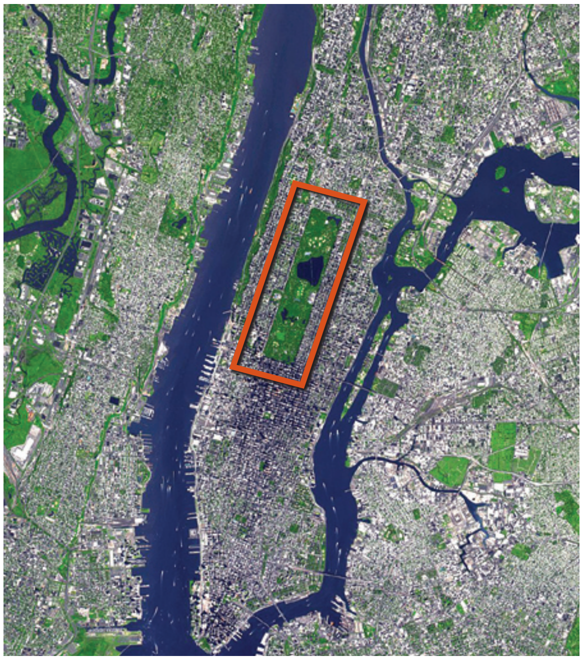


Figure 2: Vegetative Cover in New York City



NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team

New York City reveals how developed areas (gray and white in this image) can replace vegetation (green). Central Park is highlighted by the orange rectangle.

This chapter outlines some of the issues communities might consider in determining whether and how to expand the use of trees and vegetation so as to mitigate urban heat island conditions. Among the topics covered in this chapter are:

- How trees and vegetation reduce temperatures
- Some of the benefits and costs associated with trees and vegetation
- Other factors a mitigation program might consider
- Urban forestry initiatives
- Tools and resources for further information.

1. How It Works

Trees and vegetation help cool urban climates through shading and evapotranspiration.

Shading. Leaves and branches reduce the amount of solar radiation that reaches the area below the canopy of a tree or plant. The amount of sunlight transmitted through the canopy varies based on plant species. In the summertime, generally 10 to 30 percent of the sun's energy reaches the area below a tree, with the remainder being absorbed by leaves and used for photosynthesis, and some being reflected back into the atmosphere. In winter, the range of sunlight transmitted through a tree is much wider—10 to 80 percent—because evergreen and deciduous trees have different wintertime foliage, with deciduous trees losing their leaves and allowing more sunlight through.[3]

Figure 3: Trees Shade a Home

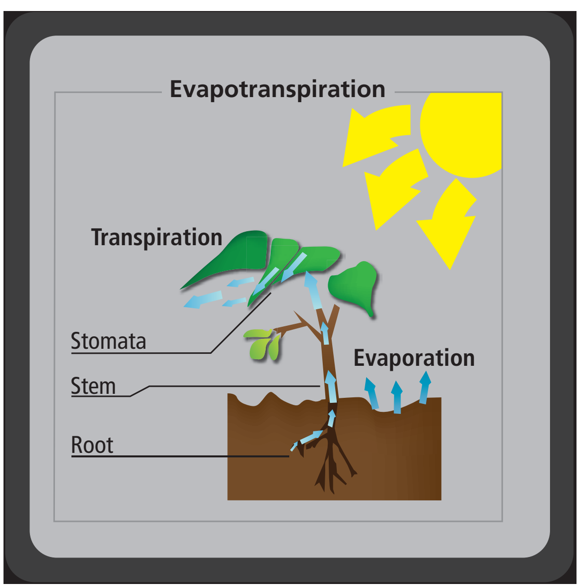
Steve Cundy

Tree canopies, such as the deciduous trees around this home in Virginia, can block much of the sunlight from reaching the ground or the building.

Shading reduces surface temperatures below the tree canopy. These cooler surfaces, in turn, reduce the heat transmitted into buildings and the atmosphere. For example, a multi-month study measured maximum surface temperature reductions ranging from 20 to 45°F (11-25°C) for walls and roofs at two buildings.[4] Another study examined the effects of vines on wall temperatures and found reductions of up to 36°F (20°C).[5] A third study found that tree shading reduces the temperatures inside parked cars by about 45°F (25°C).[6]

Evapotranspiration. Trees and vegetation absorb water through their roots and emit it through their leaves—this movement of water is called "transpiration." A large oak tree, for example, can transpire 40,000 gallons of water per year; an acre of corn can transpire 3,000 to 4,000 gallons a day.[7] Evaporation, the conversion of water from a liquid to a gas, also occurs from the soil around vegetation and from trees and vegetation as they intercept rainfall on leaves and other surfaces. Together, these processes are referred to as evapotranspiration. Evapotranspiration cools the air by using heat from the air to evaporate water.

Figure 4: Evapotranspiration



Plants take water from the ground through their roots and emit it through their leaves, a process known as transpiration. Water can also evaporate from tree surfaces, such as the stalk, or surrounding soil.

Evapotranspiration, alone or in combination with shading, can help reduce peak summer air temperatures. Various studies[8,9] have measured the following reductions:

- Peak air temperatures in tree groves that are 9°F (5°C) cooler than over open terrain.
- Air temperatures over irrigated agricultural fields that are 6°F (3°C) cooler than air over bare ground.
- Suburban areas with mature trees that are 4 to 6°F (2 to 3°C) cooler than new suburbs without trees.
- Temperatures over grass sports fields that are 2 to 4°F (1 to 2°C) cooler than over bordering areas.

Trees and other large vegetation can also serve as windbreaks or wind shields to reduce the wind speed in the vicinity of buildings. In the summertime, the impacts can be positive and negative. In the wintertime, reducing wind speeds, particularly cold north winds, can provide substantial energy benefits.

2. Using Trees and Vegetation in the Urban Landscape

Trees and vegetation are most useful as a mitigation strategy when planted in strategic locations around buildings. Researchers have found that planting deciduous species to the west is typically most effective for cooling a building, especially if these trees shade windows and part of the building's roof. Shading the east side of a structure also reduces air conditioning demand.[10,11]

Planting trees to the south generally lowers summertime energy demand, but must be done carefully. Depending on the trees, the building's height, and the distance between the trees and a building, trees may be detrimental to an energy efficiency strategy if they block useful solar energy in the winter, when the sun is low in the sky, without providing much shade during the summer, when the sun is high in the sky.

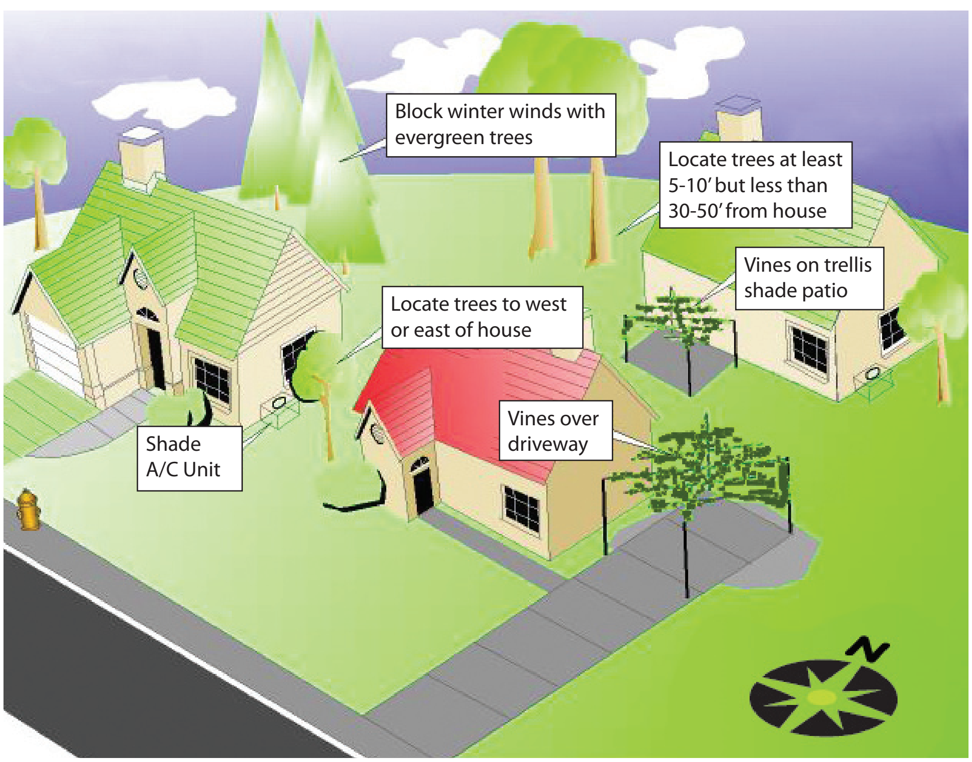
Shading pavement in parking lots and on streets can be an effective way to help cool a community. Trees can be planted around perimeters and in medians inside parking lots or along the length of streets. Strategically placed shade trees also can benefit playgrounds, schoolyards, ball fields, and similar open spaces.

Trees are not the only vegetation option. There are many areas where trees either do not fit or grow too slowly to be effective over the short term, in which case vines may work better. Vines need less soil and space and grow very quickly. Vines grown on the west side of a building, for example, will shade the exterior wall and reduce its surface temperature, thus reducing heat gain inside the building. The vines will provide some air cooling benefits through evapotranspiration as well.

Figure 6: Vines to Shade a Wall

Vines grown on trellises can provide a quick, simple source of shade.

Figure 5: Tree Placement to Maximize Energy Savings



Picking the right trees and putting them in the right location will maximize their ability to shade buildings and block winds throughout the year.

3. Benefits and Costs

The use of trees and vegetation in the urban environment brings many benefits, including lower energy use, reduced air pollution and greenhouse gas emissions, protection from harmful exposure to ultraviolet (UV) rays, decreased stormwater runoff, potential reduced pavement maintenance, and other quality-of-life benefits. At the same time, communities must also consider the costs of an urban forestry program and any potential negative impacts of increasing tree and vegetation cover. The following sections address these benefits and costs in more detail. Section 6 of this chapter summarizes software tools that calculate the range of potential benefits from urban tree and vegetation initiatives.

> **U.S. Department of Agriculture (USDA) Forest Service** research centers offer links to publications about studies of trees and their benefits to urban areas. See <www.fs.fed.us/ne/syracuse/Pubs/pubs.htm> and <www.fs.fed.us/psw/programs/cufr/>.

3.1 Benefits

Reduced Energy Use. Trees and vegetation that provide direct shading reduce energy needed to cool buildings. Benefits vary based on the orientation and size of the plantings, as well as their distance from a building. Large trees planted close to the west side of a building will generally provide greater cooling energy savings than other plants.

The examples below from a variety of studies highlight cooling and year-round energy savings from trees and vegetation.

- Joint studies by the Lawrence Berkeley National Laboratory (LBNL) and the Sacramento Municipal Utility District (SMUD) placed varying numbers of trees around houses to shade windows and then measured the buildings' energy use.[12,13] The cooling energy savings ranged between 7 and 47 percent and were greatest when trees were planted to the west and southwest of buildings.[14]
- A USDA Forest Service study investigated the energy savings resulting from SMUD's residential tree planting program. This study included over 250 program participants in the Sacramento, California, area, and estimated the effect of new shade trees planted around houses. An average of 3 new trees were planted within 10 feet (3 m) of each house.[15] Annual cooling energy savings were 1 percent per tree, and annual heating energy use decreased by almost 2 percent per tree. The trees provided net wintertime benefits because the positive wind shielding effect outweighed the negative effect of added shade.
- Another LBNL study simulated the effects of trees on homes in various communities throughout the United States. Assuming one tree was planted to the west and another to the south of a house, the model predicted that a 20-percent tree canopy over the house would result in annual cooling savings of 8 to 18 percent and annual heating savings of 2 to 8 percent.[16] Although this particular model included benefits from trees planted to the south of a building, experts generally suggest planting to the west and east of buildings, taking care when planting to the south to avoid blocking desired solar heat gain in the winter.[17]

Reduced Air Pollution and Greenhouse Gas Emissions. In addition to saving energy, the use of trees and vegetation as a mitigation strategy can provide air quality and greenhouse gas benefits:

- Leaves remove various pollutants from the air, referred to as "dry deposition"
- Shade trees reduce evaporative emissions from parked vehicles
- Trees and vegetation remove and store carbon
- Trees and vegetation reduce greenhouse gas emissions from power plants by reducing energy demand.

Researchers have investigated the potential for expanding urban tree and vegetative cover to address air quality concerns, such as ground-level ozone. One study predicted that increasing the urban canopy of New York City by 10 percent could lower ground-level ozone by about 3 percent, which is significant, particularly in places needing to decrease emissions to meet air quality standards for this pollutant.[18]

Pollutant Removal through Dry Deposition. Plants generally take up gaseous pollutants, primarily through leaf stomata, that then react with water inside the plant to form acids and other chemicals. Plants can also intercept particulate matter as wind currents blow particulates into contact with the plants' surfaces. Some particulates are absorbed into the plant while others adhere to the surface, where they can be resuspended into the atmosphere by winds or washed off by rain to the soil beneath.[19] These processes can reduce various pollutants found in the urban environment, including particulate matter (PM), nitrogen oxides (NO_X), sulfur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3).

Various studies have documented how urban trees can reduce pollutants. A 2006 study estimated total annual air pollutant removal by urban trees in the United States at 784,000 tons, with a value of $3.8 billion.[20] The study focused only on deposition of ground-level ozone, PM less than 10 microns in diameter (PM_{10}), nitrogen dioxide (NO_2), SO_2, and CO. Although the estimated changes in local ambient air quality were modest, typically less than 1 percent, the study noted that additional benefits would be gained if urban temperature and energy impacts from trees and vegetation were also included.

Reduced Evaporative Emissions. Tree shade can keep parked cars—particularly their gas tanks—cooler, which lowers evaporative emissions of volatile organic compounds (VOCs), a critical precursor pollutant in the formation of ground-level ozone. Most large urban areas have a wide range of control programs to reduce these emissions, and tree shading programs can be part of those strategies. For example, one analysis predicted that light-duty vehicle evaporative VOC emission rates throughout Sacramento County could be reduced by 2 percent per day if the community increased the tree canopy over parking lots from 8 to 50 percent.[21]

Carbon Storage and Sequestration. As trees grow, they remove carbon from the atmosphere and store, or sequester, it. As trees die or deposit litter and debris on the ground, carbon is released to the atmosphere or transferred to the soil. The net effect of this carbon cycle is a substantial level of carbon storage in trees, vegetation, and soils.

The net rate of carbon sequestered by urban trees in the continental United States in 2005 is estimated to have been around 24 million tons per year (88.5 million tons

Plants and Carbon: Storage versus Sequestration

Storage: Carbon currently held in plant tissue (tree bole, branches, and roots).

Sequestration: The estimated amount of carbon removed annually by plants, through the process of photosynthesis.

CO_2eq)[22], while current total carbon storage in urban trees in the continental United States is approximately 700 million tons of carbon. The national average urban forest carbon storage density is just over 25 tons per hectare (100,000 square feet, or 9,300 m^2), but varies widely from one community to another and corresponds generally to the percentage of land with tree cover and to tree size and health.[23] The California Air Resources Board recently approved guidelines that will allow carbon sequestered from forests to help meet the carbon emissions reductions stipulated by California's law AB32.[24]

Reduction in Greenhouse Gas Emissions through Reduced Energy Demand. As noted above, trees and vegetation can decrease energy demand. To the extent that reduced energy consumption decreases fossil fuel burning in power plants, trees and vegetation also contribute to lower carbon emissions from those power plants. One modeling study estimated that the direct energy savings from shading alone by trees and vegetation could reduce carbon emissions in various U.S. metropolitan areas by roughly 1.5 to 5 percent.[25] The study assumed that eight shade trees would be placed strategically around residential and office buildings and four around retail stores. As urban forests also contribute to air temperature reductions, the study found that there would be additional reductions in energy use and carbon emissions from those indirect effects as well.

Full Life-cycle Carbon Reductions. In order to investigate the full life-cycle impact of urban trees on annual CO_2 emissions, researchers consider:

- Annual CO_2 carbon sequestration rates
- Annual CO_2 releases from decomposition
- Annual CO_2 releases from maintenance activities
- Annual CO_2 avoided emissions because of reduced energy use.

By combining these four variables, researchers can estimate the net CO_2 reductions from urban forest resources for a specific community and calculate the associated net monetary benefits. A 2006 field study found that about 15,000 inventoried street trees in Charleston, South Carolina, were responsible for an annual net reduction of over 1,500 tons of CO_2. These benefits were worth about $1.50 per tree, based on average carbon credit prices.[26]

Improved Human Health. By reducing air pollution, trees and vegetation lower the negative health consequences of poor air quality. Also, similar to the benefits of cool roofs discussed in the "Cool Roof" chapter, shade trees can reduce heat gain in buildings, which can help lower indoor air temperatures and minimize the health impacts from summertime heat waves.

A third health benefit from trees and vegetation involves reducing direct exposure to UV rays. The sun's UV rays can have adverse health effects on the skin and eyes.

High levels of long-term exposure to UV rays are linked to skin cancer. The shade provided by dense tree canopies can help to lower UV exposure, although this should not be considered a primary preventive measure (see text box below).[27,28]

Enhanced Stormwater Management and Water Quality. Urban forests, vegetation, and soils can reduce stormwater runoff and adverse impacts to water resources. Trees and vegetation intercept rainfall, and the exposed soils associated with plants absorb water that will be returned to ground water systems or used by plants.

Rainfall interception works best during small rain events, which account for most precipitation. With large rainfalls that continue beyond a certain threshold, vegetation begins to lose its ability to intercept water. Stormwater retention further varies by the extent and nature of a community's urban forest. During the summer, with trees in full leaf, evergreens and conifers in Sacramento were found to intercept over 35 percent of the rainfall that hit them.[29]

Reduced Pavement Maintenance Costs. Tree shade can reduce the deterioration of street pavement. One field study compared pavement condition data based on different amounts of tree shade.[30] The study found that slurry resurfacing costs on a residential street could be reduced by approximately 15 to 60 percent, depending on the type of shade trees used. Although the specific costs and benefits will vary based on local conditions and paving practices, the study suggests that pavement maintenance benefits are another area to consider in evaluating the potential benefits of a street shade tree program.

Enhanced Quality of Life. Trees and vegetation can provide a range of quality-of-life benefits. Adding trees and vegetation to urban parks, streets, parking lots, or roofs can provide a habitat for birds, insects, and other living things. A well-placed row of

Reducing Exposure to UV Radiation

EPA's SunWise program <www.epa.gov/sunwise> promotes a variety of actions people can take to reduce exposure to harmful UV radiation; seeking shade is just one of them. To reduce the risk of skin cancer, cataracts, and other health effects, the program recommends:

- Wearing a hat with a wide brim
- Wearing sunglasses that block 99 to 100 percent of UV radiation
- Always using sunscreen of SPF 15 or higher
- Covering up with long-sleeve, tightly woven clothing
- Watching for the UV Index to help plan outdoor activities when UV intensity is lowest
- Avoiding sunlamps and tanning salons
- Limiting time in the midday sun (from 10:00 a.m. to 4:00 p.m.)
- Seeking shade whenever possible.

Trees and Property Value Benefits

Many studies show that trees and other vegetative landscaping can increase property values. For example, shopping centers with landscaping can be more prosperous than those without, because shoppers may linger longer and purchase more.[36,37,38,39] Other studies have found general increases of about 3 to 10 percent in residential property values associated with the presence of trees and vegetation on a property.[40] The specific impacts on residential property values vary widely based on the property, the buyer's socioeconomic status, and other factors.

STRATUM, a USDA Forest Service tool that uses tree inventory data to evaluate the benefits and costs of street and park trees, assumes an increase in residential property values from tree planting measures. For an example, see the discussion on net benefits and Figure 9 later in this chapter, which summarize data from a study that used the STRATUM tool.[41] In areas with high median residential sales prices, these are often among the largest single category of benefits for a community.

trees and shrubs can reduce urban noise by 3 to 5 decibels, while wide, dense belts of mature trees can reduce noise by twice that amount, which would be comparable to noise reduction from effective highway barriers.[31] Urban trees and vegetation have been linked to reduced crime,[32] increased property values,[33] and other psychological and social benefits that help decrease stress and aggressive behavior.[34,35]

3.2 Potential Adverse Impacts

Before undertaking an urban forestry program, it is important to know which types of trees are likely to be most beneficial and to avoid those that could cause other problems. Evapotranspiration not only cools the air but also adds moisture to it, raising humidity levels. This increase may be problematic in already humid climates. However, there is little research on the human health and comfort trade-off between temperature reductions and humidity increases in different climates.

Although beneficial in limiting ground-level ozone production by lowering air temperature and filtering ground-level ozone and precursor pollutants from the air, trees and other plants also emit VOCs. These emissions are referred to as biogenic emissions. The biogenic emissions from urban vegetation might counteract some of the air quality benefits from trees. Biogenic VOC emission rates, however, are in part dependent on temperature. Thus, to the extent that the increased use of trees and vegetation contributes to reduced temperatures, the overall biogenic VOC emissions in an urban area might still be reduced.[42]

Biogenic VOC emissions are affected by sunlight, temperature, and humidity. The emission rates of different tree species vary tremendously; even trees in the same

For more information on the **ozone-forming potential (OFP) of various trees**, see <www.fraqmd.org/Biogenics.htm>.

family and genus show wide variation in VOC emissions.[43,44] Researchers calculate an ozone-forming potential (OFP) value to rate the potential effect a tree species can have on ground-level ozone formation in a given environment. To minimize the contribution to ground-level ozone, a mitigation program can consider low-OFP species. Table 1 provides example OFP ranges for common tree species in the Los Angeles area. Communities can check with USDA Forest Service staff in their region to determine if there are additional resources to help select low-OFP tree species for a particular area and climate (see Table 5 for links to regional Forest Service web sites).

Figure 7: The Ozone-Forming Potential of Trees

Susan McDougal/USDA NRCS PLANTS database

Red maple, on the left, has a low ozone-forming potential, whereas Oregon scrub oak, above, has a high potential. Communities that want to plant trees may consider biogenic emissions as well as other properties of trees, such as their ability to survive in urban conditions.

Table 1: Examples of VOC Emissions from Trees in the Los Angeles Climate [45]

Common Name	Genus and Species	Ozone-Forming Potential		
		L	M	H
Oaks				
White Oak	*Quercus alba*		✓	
Oregon White Oak	*Quercus garryana*			✓
Scrub Oak	*Quercus laevis*		✓	
Valley Oak	*Quercus lobata*		✓	
Pines				
Sand Pine	*Pinus clausa*			✓
Red Pine	*Pinus densiflora*	✓		
Longleaf Pine	*Pinus palustris*		✓	
Maples				
Red Maple	*Acer rubrum*	✓		
Silver Maple	*Acer floridanum*	✓		
Citrus				
Lisbon Lemon	*Citrus limon*		✓	
Meyer Lemon	*Citrus limon 'Meyer'*	✓		
Valencia Orange	*Citrus sinensis 'Valencia'*	✓		

Other potential adverse effects include increased water demand, additional solid wastes from pruning and tree removal, and possible damage to sidewalks, power lines, and other infrastructure from roots or falling branches.

3.3 Costs

The primary costs associated with planting and maintaining trees or other vegetation include purchasing materials, initial planting, and ongoing maintenance such as pruning, pest and disease control, and irrigation. Other costs include program administration, lawsuits and liability, root damage, and tree stump removal. However, as the following section indicates, the benefits of urban trees almost always outweigh these costs.

3.4 Benefit-Cost Considerations

To help communities determine the value of investments in urban trees and vegetation, groups have developed tools to quantify the value of trees (see Section 6). These tools factor in the full range of urban forest benefits and costs, such as energy savings in buildings, air quality improvements, stormwater retention, property value increases, and the value of mulch or hardwood recovered during tree pruning and removal. Some tools also track greenhouse gas emissions or CO_2 reduction. The tools weigh these benefits against the costs of planting, pruning, watering, and other maintenance throughout a tree's life.

In calculating benefits, it is important to note that trees grow slowly, so it may take as long as five years for some benefits from trees, such as energy savings, to take effect. After 15 years, an average tree usually has matured enough to provide the full range of benefits.[46]

Although the benefits can vary considerably by community and tree species, they almost always outweigh the expense of planting and maintaining trees. For example, one five-city study found that, on a per tree basis, cities accrued benefits ranging from roughly \$1.50 to \$3.00 for every dollar invested. These cities spent about \$15-65 annually per tree, with net benefits ranging from approximately \$30-90 per tree. In all five cities, the benefits outweighed the costs, as shown in Figure 9.[47] Figure 9 also compares how the categories of annual costs and benefits associated with trees varied between these cities.

Studies in California also have shown net annual benefits ranging from zero to about \$85 per tree.[48,49,50] A community can develop similar analyses for its mitigation program. Places as diverse as Florence, Alabama;[51] Cedar Rapids, Iowa;[52] Portland, Oregon;[53] and Hyattsville, Maryland,[54] have all quantified the net benefits of their trees. See Section 6 for more resources on existing studies and tools that can aid this type of assessment.

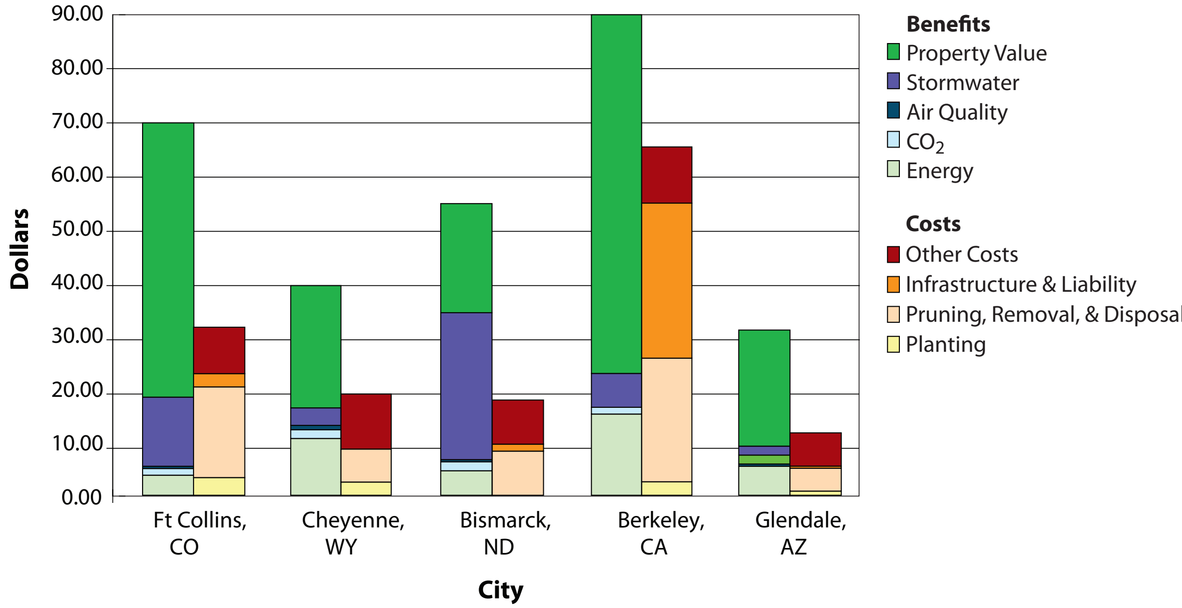
Figure 8: Tree-Stump Removal

City of New Haven

Tree programs will incur certain costs, such as tree removal.

For a simple, **online tree benefit calculator**, see <http://usage.smud.org/treebenefit/>.

Figure 9: Total Annual Benefits versus Costs (Per Tree)



Net benefits were positive for all five cities, ranging from $21 per tree in Cheyenne to $38 per tree in Ft. Collins. Blue and green categories indicate benefits; red, orange, and yellow indicate costs.

4. Other Factors to Consider

4.1 Planting Considerations

Buildings

To reduce temperatures and cooling energy needs, trees planted for summer shade should shelter western and eastern windows and walls and have branches high enough to maintain views or breezes around the windows. Trees in these locations block the sun when it is at its lowest angle: in the morning and afternoon. Planting trees at least 5 to 10 feet (1.5 to 3 m) away from the building allows room for growth, but shade trees should be no more than 30 to 50 feet (9 to 15 m) away. A building with deciduous trees for summer shade will also allow for winter heat gain to the building, especially if branches are pruned to maximize sun exposure.

It might also be beneficial to shade air conditioner condenser units and other building cooling equipment with trees, vines, or shrubbery, as these units work less efficiently when hot. It is important to follow manufacturer guidelines for ensuring adequate space to allow for proper air flow around the equipment.

In an urban setting, neighboring buildings, driveways, fences, and other features can make it difficult to follow these guidelines for planting trees. The following are the best use of trees and vegetation:

- Optimize the shade coverage from trees planted in less favorable locations by pruning tree branches to a height that blocks the summer sun, yet lets the winter sun through.
- Use bushes, shrubs, or vines to shade windows and walls in places where

For overall energy efficiency, some communities might promote the use of **evergreens** to block winter winds and **reduce heating needs.** A row of evergreens might be planted perpendicular to the main wind direction, usually to the north or northwest of a home.

Figure 10: View of a Shaded Street

E.G. McPherson

Placing trees next to the curb positions them well to shade the street, sidewalk, and any automobiles parked along the road.

trees will not fit. Shrubs and bushes can shade windows or walls without growing too large or tall. Vines grow very quickly on vertical or overhead trellises and can be used in places with little available space or soil.

- Consider a green or garden roof in addition to landscaping around a building (see the "Green Roofs" chapter).

Paved Surfaces

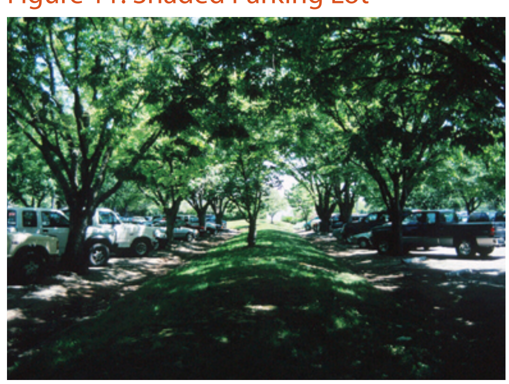
Trees and large shrubbery also can shade pavements to reduce their surface temperatures. Planting trees at regular intervals of 20 to 40 feet (6 to 12 meters) along both sides of a street (see Figure 10), as well as along medians is a common way to provide valuable shading.

Trees can also shade the perimeter and interior space of parking lots. Although end islands are often used for planting trees within parking lots,[55] planting strips that run the length of a parking bay can provide greater lot shading (see Figure 11). Some communities have ordinances that require a certain percentage of tree shade in parking lots. For example, Davis, California, and Sacramento each require 50 percent of the parking area to be shaded within 15 years after the lot is constructed.[56,57]

Permeable grass pavers can also provide some of the heat reduction benefits of larger plantings without taking up space. Grass pavers can replace traditional pavements in low-traffic parking areas, pedestrian walkways, driveways, patios, fire lanes, and other paved areas that are seldom used for vehicular traffic. Pavers are usually prefabricated lattice structures made of concrete, plastic, or metal that are specifically designed to let water drain to the soil below while they support pedestrians and light traffic loads. The openings in the lattice blocks are filled with soil and planted with grass or ground cover, or topped with gravel or sand. See the "Cool Pavements" chapter for further discussion of alternative paving options.

Playgrounds, schoolyards, and sports fields are open spaces that often offer opportunities for increasing urban tree and vegetation coverage. In addition to their cooling benefits, trees in these areas can provide increased shade to protect people, especially children, from the sun's UV rays. Shade trees are most beneficial in specific locations where people are likely to congregate, such as around team seating, spectator stands, jungle gyms, sandboxes, swings, and picnic tables. Because trees can take some time to mature, a project sponsor may wish to consider a quicker alternative, such as fast growing bushes or

Figure 11: Shaded Parking Lot



E.G. McPherson

Shading in parking lot medians can provide extensive shading coverage.

Communities can consider the use of hardy, native trees and plants in **selecting landscaping options**. See <www.epa.gov/glnpo/greenacres> for further information.

vines on trellises over seating and other areas, either in place of trees or as a first phase of adding shade vegetation.

4.2 Maintenance

Education, skill, and commitment are necessary for planting and maintaining an aesthetically, environmentally, and structurally effective urban landscape. By adhering to good landscape design and maintenance practices, many common problems may be avoided. Local cooperative extension offices can provide additional information on soil conditions and other important considerations. Also, local planting guides are often available from urban forestry agencies, utility companies, arboricultural organizations, and plant nurseries. The following are steps to consider when maintaining trees in an urban area,[58,59] helping vegetation grow faster and live a longer, healthier, and more productive life.

- *Choose the right plants*. Because trees and vegetation that are hardy enough to survive in a specific climate require little maintenance, communities might want to start by considering native species. Other characteristics to consider include:
  - The vegetation's projected height and canopy spread
  - Size and growth habits of the roots
  - The plant's sun, soil, water, and temperature requirements
  - The types of leaves, berries, and flowers it produces
  - Allergens and biogenic emissions that can contribute to ground-level ozone formation.

Local nonprofit tree organizations, cooperative extension offices, urban foresters and arborists, garden clubs, landscape architects, landscaping contractors, and other groups can provide detailed information about the best trees for a specific community's climate, along with advice about planting and maintaining them. See Section 6 for a list of plant selection resources.

- *Avoid maintenance problems*. Communities will want to avoid interference with utilities, sidewalks, and other infrastructure when planting trees to avoid future maintenance problems. Another important consideration is that trees must have adequate soil and access to water.
- *Make arrangements for regular care*. Especially in the early years after initial planting, trees require regular maintenance to survive. Maintenance requirements and costs generally decline after a tree becomes established.

Figure 12: Regular Tree Care

J. David Mattox/City of Manhattan, Kansas

Proper pruning and other regular care will help trees last longer and provide greater benefits to the community.

4.3 Safety

The use of trees and vegetation around buildings can increase fire risks. Communities, especially those in fire prone areas, can find information on tree selection and placement that minimizes those risks:

- The National Interagency Fire Center offers suggestions for tree placement and landscape maintenance to avoid losses to wildland fires. See <www.nifc.gov/preved/index.html>.
- The USDA Forest Service helps homeowners determine and minimize fire risk from landscaping via an interactive, graphical tool. See <www.ecosmart.gov/firewise>.

Project sponsors can also check with local fire departments or street tree agencies to evaluate and minimize fire risks for a specific tree and vegetation initiative.

5. Urban Forestry Initiatives

Communities can use various mechanisms to increase their vegetative cover. These efforts include forming public-private partnerships to encourage voluntary action in the private sector to enacting ordinances. As discussed in the chapter "Heat Island Reduction Activities," communities already have developed a wide range of voluntary and policy approaches for using urban trees and vegetation. For public-sector projects, local governments and organizations have undertaken efforts to expand the use of trees and vegetation in public spaces and adopted minimum landscaping policies for public buildings. Tree planting programs, used throughout many communities, often involve collaboration with nonprofit groups and electric utilities. Some states fund urban forestry program initiatives dedicated to addressing urban heat islands and other community concerns.

Figure 13: Urban Forestry Surveys and Plantings

USDA Center for Urban Forest Research

Urban forestry initiatives can take multiple forms, such as creating an inventory of existing trees or planting additional ones.

In addition, communities have enacted various ordinances to foster the urban forest, including those focused on:

- Tree protection
- Street trees
- Parking lot shade
- General landscaping.

The "Heat Island Reduction Activities" chapter provides a detailed description of these initiatives. Table 2 briefly summarizes them.

Table 2: Examples of Urban Forestry Initiatives

Type of Initiative	Description	Links to Examples
Research	USDA Forest Service programs	**<www.fs.fed.us/research/>** - USDA Forest Service operates research centers throughout the United States, including the Pacific Southwest Research Station, which specializes in urban forestry. USDA also collaborates with states and universities; for example, the Northeast Center for Urban and Community Forestry involves the Forest Service, the University of Massachusetts, and seven states.
	University programs	**<www.cfr.washington.edu/research.envmind/index.html>** - The University of Washington College of Forest Resources supports Human Dimensions of Urban Forestry and Urban Greening, a research program that focuses on the interaction of vegetation and humans in cities.
		<www.lhhl.uiuc.edu/> - A similar program at the University of Illinois, Landscape and Human Health Laboratory, studies the connections between greenery and human health and behavior.
Voluntary efforts	Demonstration projects	**<www.arborday.org/takeaction/homedepot2007/>** - Beginning in 2006, the Home Depot Foundation and the National Arbor Day Foundation partnered together to plant 1,000 trees in 10 cities across the country over a three-year period. This demonstration project is designed to increase awareness of the importance of urban trees and to create healthier communities in urban areas.
	Incentive programs	**<www.ladwp.com/ladwp/cms/ladwp000744.jsp>** - Trees for a Green LA provides Los Angeles residents with free shade trees if they participate in a tree planting and maintenance workshop and submit a program application that includes a site plan.
		<www.ci.seattle.wa.us/neighborhoods/nmf/treefund.htm> - The Tree Fund, a component of the Neighborhood Matching Fund, provides trees to neighborhood groups in Seattle to enhance the city's urban forest. The city government provides the trees, and neighbors share the work of planting and caring for them.
	Urban forestry programs	**<www.treevitalize.net/>** - TreeVitalize is a public-private partnership that uses regional collaboration to address the loss of tree cover in the five-county Southeastern Pennsylvania region. Goals include planting 20,000 shade trees; restoring 1,000 acres of forests along streams and water protection areas; and training 2,000 citizens to plant and care for trees.
		<www.groundworkelizabeth.com/> - Groundwork Elizabeth is a non-profit corporation created to "foster sustainable community regeneration" in Elizabeth, New Jersey. It is an outgrowth of a program developed by the National Park Service called Groundwork USA.
Voluntary efforts	Urban forestry	<**www.milliontreesla.org>** - Million TreesLA is a cooperative effort among the City of Los Angeles, community groups, businesses, and individuals working together to plant and provide long-term stewardship of 1 million trees.

Table 2: Examples of Urban Forestry Initiatives (continued)

Type of Initiative	Description	Links to Examples
	Outreach & education	**<www.epa.gov/heatisland/>** - EPA's Heat Island Reduction Initiative provides information on the temperature, energy, and air quality impacts from urban forestry and other heat island mitigation strategies.
		<http://cfpub.epa.gov/npdes/home.cfm?program_id=298> - EPA's Office of Water highlights design options, including trees and vegetation that reduce stormwater runoff and water pollution.
		<www.treeutah.org/> - TreeUtah is a statewide, volunteer driven, non-profit organization dedicated to tree planting and education. Since 1989, TreeUtah has worked with over 100,000 volunteers to plant over 300,000 trees throughout Utah, providing training workshops for adults and teens, education for elementary students, service learning opportunities through the University of Utah, and alternative spring break for college students to plant trees in urban neighborhoods.
		<www.ladwp.com/ladwp/cms/ladwp001087.jsp> - The Los Angeles Cool Schools Program provides students with an educational curriculum about trees and the environment, in addition to planting trees around schools.
Policy efforts	Resolutions	**<www.ci.annapolis.md.us/upload/images/government/council/Adopted/R3806.pdf>** - The Annapolis, Maryland, City Council established an Energy Efficiency Task Force in 2005 to make recommendations on how the city could reduce energy costs, energy consumption, and its reliance upon foreign petroleum. One of the Task Force's recommendations was to increase the urban tree canopy to 50 percent of the city's land area by 2036. The recommendations were approved by the City Council in 2006.
		<www.ci.austin.tx.us/trees/res_985.htm> - The Austin, Texas, City Council adopted a resolution in 2001, acknowledging the urban heat island and available mitigation efforts. The resolution called on the City Manager to evaluate the fiscal impact and cost benefits of recommendations made by the City's Heat Island Working Group.

Table 2: Examples of Urban Forestry Initiatives (continued)

Type of Initiative	Description	Links to Examples
	Tree & landscape ordinances	**<www.cityofsacramento.org/parksandrecreation/urbanforest/ordinance.htm>** - Sacramento, California, has a performance-based parking lot shading ordinance with detailed design and maintenance guidelines to help owners with compliance.
		<www.ci.austin.tx.us/trees/programs.htm> - Austin's tree preservation ordinance specifies that new development projects are evaluated on a case by case basis to ensure tree preservation and planting of high quality native and adapted trees.
Policy efforts	State Implementation Plans (SIPs)	**<www.treescleanair.org>** - This web site, sponsored by the USDA Forest Service, evaluates options for including urban forest initiatives in a SIP, a federally-enforceable air quality management plan.
		<www.houstonregionalforest.org/Events/SIPTreeWorkingSession> - This link provides materials available from a working session on issues and ideas about incorporating urban forest initiatives into a SIP.
		<www.fs.fed.us/ne/syracuse/Emerging%20Measures%20Summary.pdf> - This paper provides a brief summary of relevant EPA SIP guidance and details actions to help facilitate the inclusion of urban tree canopy increases within SIPs to meet clean air standards.
		<www.fs.fed.us/psw/programs/cufr/products/cufr_668_SacAirQualityInit6-21-06.pdf> - This link profiles the Sacramento, California, area project that is evaluating tree planting as a SIP reduction strategy for ground-level ozone.

6. Resources

6.1 Plant Selection

One of the key factors in a successful tree or vegetation mitigation project is choosing the right plants. Various web-based plant selection guides are available, including those listed in Table 3. For local information on tree selection, communities can contact tree planting organizations, community arborists, horticultural organizations, or landscape design consultants. Also, the land development codes and guidelines in many communities include lists of recommended and prohibited species, along with guidance on planting methods and site selection.

Figure 14: Green Walls

EOA/Elmslie Osler Architect

In places where it may be difficult to plant more vegetation, green roofs and green walls, such as this one on a store in Huntsville, Alabama, offer an alternative. See the "Green Roofs" chapter.

Table 3: Web-Based Plant Selection Guides*

Name	Description	Web Link
General Information		
International Society of Arboriculture Tree Selection	Overview of variables to consider, including tree function, form, size, and site conditions.	<www.treesaregood.com/treecare/tree_selection.aspx>
Databases		
Tree Guide Advanced Search	Database of trees that can be searched by variables including sun exposure, hardiness zone, tree shape, and height.	<www.arborday.org/trees/treeguide/advancedsearch.cfm>
PLANTS Database	Database of information about U.S. plants, with an advance search by name, location, and environmental variables, such as soil type, fire tolerance, and flower color.	<http://plants.usda.gov>
SelecTree for California	Database of California trees that can be searched by name or environmental variable.	<http://selectree.calpoly.edu/>
Lists of Recommended Trees		
Tree Link	List of recommended trees by USDA hardiness zone; links to regional tree information.	<www.treelink.org/docs/zonemap.phtml>; <www.treelink.org/linx/?navSubCatRef=20>
Recommended Urban Trees	Description of recommended urban trees for USDA hardiness zones 1-6, listed by tree size and planting conditions.	<www.hort.cornell.edu/uhi/outreach/recurbtree>
Cleaner Air, Tree by Tree: A Best Management Practices and Guide for Urban Trees in Southern Nevada	Handbook for cultivating recommended trees to mitigate urban heat islands in southern Nevada.	<www.forestry.nv.gov/docs/shades%20_green_bmp_guide07.pdf>
Tree Selection Guide for South Carolina	List of trees recommended for South Carolina and tips on what to consider when selecting trees.	<www.state.sc.us/forest/refsel.htm>

* For information on the ozone-forming potential of various trees, see the list in *Estimating the Ozone-forming Potential of Urban Trees and Shrubs*.[60]

6.2 Benefit-Cost and Other Tools

Mitigation programs can use existing research and tools to conduct benefit-cost analyses for urban forest projects. Some of these resources include:

Table 4: Urban Forestry Tools and Resources

Name	Description	Web Link
Tree Inventory, Benefit, and Cost Resources		
i-TREE software suite	Developed by the USDA Forest Service, the *i*-TREE software suite is available free-of-charge on CD-ROM by request. The software suite uses data gathered by the community to provide an understanding of urban forest structure, information on management concerns, cost-benefit information, and storm damage assessment. The software allows for analyses of a single street tree, a neighborhood, or an entire urban forest. *i*-Tree combines STRATUM and UFOREthe Mobile Community Tree Inventory (MCTI) (see below).	<www.itreetools.org/index.shtm>
Street Tree Resource Analysis Tool for Urban forest Managers (STRATUM)	STRATUM is a USDA Forest Service tool that uses tree inventory data to evaluate the benefits and costs of street and park trees and estimate management needs.	<www.itreetools.org/street_trees/introduction_step1.shtm>
Urban Forest Effects (UFORE)	UFORE is a USDA Forest Service tool that uses tree inventory data to model and quantify urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass, species diversity), environmental effects, and value to communities.	<www.ufore.org>
The Mobile Community Tree Inventory (MCTI)	MCTI is a USDA Forest Service tree inventory tool that can be customized to individual communities. Data can be collected either by paper tally sheet, or the Tree Inventory PDA Utility, which simplifies data input. Data collected can then be used with the STRATUM or UFORE applications.	<www.itreetools.org/applications/mcti.shtm>
ecoSmart	The Center for Urban Forest Research publishes a web-based software program designed to evaluate the economic trade-offs between different landscape practices on residential parcels. The program estimates the environmental and cost impacts of strategic tree placement, rainfall management, and fire prevention practices.	<www.ecosmart.gov/>

Table 4: Urban Forestry Tools and Resources (continued)

Name	Description	Web Link
Tree Inventory, Benefit, and Cost Resources (continued)		
Municipal Forest Resource Analysis	The Center for Urban Forest Research publishes a series of reports on benefits and costs of tree programs in various U.S. regions and communities.	<www.fs.fed.us/psw/programs/cufr/products.shtml> See "Tree Guides" and "Municipal Forest Resource Analysis."
Urban Forestry Index (UFind)	Database of current and historic urban forestry and arboriculture publications and other media compiled by the USDA Forest Service, the University of Minnesota, and TreeLink with the goal of increasing access to urban forestry material and preventing duplication of products.	<www.urbanforestryindex.com/>
A Practical Approach to Assessing Structure, Function, and Value of Street Tree Populations in Small Communities	This 14-page report gives step-by-step instructions for estimating benefits and costs of trees in a specific community, using Davis, California as a case study.	<www.fs.fed.us/psw/programs/cufr/products/cufr_128.pdf>
The Community and Urban Forest Inventory and Management Program (CUFIM)	Produced by the Urban Forest Ecosystems Institute of California Polytechnic State University, the Community and Urban Forest Inventory and Management Program (CUFIM) is a free Microsoft Excel-based program that helps to inventory urban trees and estimate an economic value of wood recovery.	User guide: <www.ufei.org/files/ufeipubs/CUFIM_Report.pdf> Program files: <www.ufei.org/files/ufeipubs/CUFIM.zip>
CITYgreen	American Forests developed CITYgreen, a graphical information system application based on the UFORE model that is available for purchase. The software calculates ecologic and economic benefits from urban trees, including energy savings, air quality, stormwater improvements, water quality, and carbon storage and sequestration. CITYgreen also models changes in land cover and can be used in planning green infrastructure.	<www.americanforests.org/productsandpubs/citygreen/>
Comfort Tool		
OUTdoor COMfort Expert System (OUTCOMES)	The USDA Forest Service developed the OUTdoor COMfort Expert System (OUTCOMES), which calculates a human comfort index by considering weather variables, tree density and shade pattern, and other neighborhood features.	<www.fs.fed.us/ne/syracuse/Tools/tools.htm>

Table 4: Urban Forestry Tools and Resources (continued)

Name	Description	Web Link
Carbon Calculators		
Individual tree carbon calculators	The USDA Forest Service has developed spreadsheet programs to estimate the carbon storage and sequestration rates for a sugar maple and a white pine. These spreadsheets provide a rough approximation of tree carbon storage and sequestration rates based on user-inputs of tree growth rates.	<www.fs.fed.us/ne/syracuse/Tools/tools.htm>
Carbon dioxide calculators for urban forestry	The USDA Forest Service provides guidelines for urban foresters and arborists, municipalities, utilities, and others to determine the effects of urban forests on atmospheric CO_2 reduction.	<www.fs.fed.us/psw/programs/cufr/products/cufr_43.pdf>
Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings	The Department of Energy has developed guidance to calculate carbon sequestration by trees in urban and suburban settings. The guidance is intended for participants in the Voluntary Reporting of Greenhouse Gases Program and provides a methodology and worksheet for calculations.	<ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/sequester.pdf>

6.3 General Information

Table 5 lists organizations and web sites that contain additional information and reference materials on urban forestry.

Table 5: Urban Forestry Organizations and Web Sites

Name	Description	Web Link
Center for Urban Forest Research, part of the USDA Forest Service's Pacific Southwest Research Station	Publishes research on the benefits and costs of urban trees, including urban heat island, energy, air quality, climate change, and water impacts. Is involved with developing the California urban forestry greenhouse gas reporting protocol and developed STRATUM and ecoSMART.	<www.fs.fed.us/psw/programs/cufr>
Urban Forest Research Unit, part of the USDA Forest Service's Northeastern Research Station	Provides research on urban forest structure and the quantification of urban forest benefits, particularly air quality. Developed the UFORE and COMFORT models and conducts national urban forest assessments.	<www.fs.fed.us/ne/syracuse>
Urban Natural Research Institute, part of the USDA Forest Service Northern Research Station	Provides monthly web casts and other online resources targeted to the science of urban forestry.	<www.unri.org>
Urban and Community Forestry Program, Northeastern Area, part of the USDA Forest Service's State and Private Forestry mission area	Resources on tree planting and care, urban forest management, and outreach and marketing. The Urban and Community Forestry Program provides technical, financial, educational, and research services to states, cities, and nonprofit groups so they can plant, protect, maintain, and utilize wood from community trees and forests to maximize environmental, social, and economic benefits.	<www.na.fs.fed.us/urban/index.shtm>
Urban Forestry South, part of the USDA Forest Service's Southern Research Station	Published the Urban Forestry manual, a 12-chapter guidebook including cost-benefit information, public policy strategies, and tree planting suggestions. Urban Forestry South also hosts the Tree Failure Database.	<www.urbanforestrysouth.org/>
TreeLink	Provides a links database, listserves, web casts, advice on grant writing, and links to local community forestry groups.	<www.treelink.org>

Table 5: Urban Forestry Organizations and Web Sites (continued)

Name	Description	Web Link
National Alliance for Community Trees (ACT)	Operates the NeighborWoods Program, offering grants to community forestry groups. The web site also has links to local community forestry groups, public policy updates, case studies of tree planting programs, a media kit, and a bi-monthly e-newsletter, and monthly web casts.	<www.actrees.org>
National Arbor Day Foundation	Provides information about local tree planting programs and events and resources for environmental educators and parents.	<www.arborday.org/>
Sustainable Urban Landscape Information Series	Covers urban landscape design, plant selection, installation, and maintenance.	<www.sustland.umn.edu/>
American Society of Landscape Architects (ASLA)	Professional association for landscape architects. Includes a search tool to locate ASLA firms. ASLA is developing a sustainability rating system for land-scaped sites, comparable to the USGBC LEED standard for buildings, as well as regional guides to best practices.	<www.asla.org>

Endnotes

1 Statistics are from urban fabric analyses conducted by Lawrence Berkeley National Laboratory. Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.
Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois. Paper LBNL-49275. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Paper LBNL-47851. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H., L.S. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California. Paper LBNL-44688. Lawrence Berkeley National Laboratory, Berkeley, CA.

2 Nowak, D.J., Principal Investigator. 2005. Houston's Regional Forest. U.S. Forest Service and Texas Forest Service. September 2005.

3 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

4 Akbari, H., D. Kurn, S. Bretz, and J. Hanford. 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings. 25:139-148.

5 Sandifer, S. and B. Givoni. 2002. Thermal Effects of Vines on Wall Temperatures—Comparing Laboratory and Field Collected Data. SOLAR 2002, Proceedings of the Annual Conference of the American Solar Energy Society. Reno, NV.

6 Scott, K., J.R. Simpson, and E.G. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions. Journal of Arboriculture. 25(3).

7 U.S. Geological Survey. 2007. The Water Cycle: Evapotranspiration. Retrieved 12 June 2007 from <http://ga.water.usgs.gov/edu/watercycleevapotranspiration.html>.

8 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

9 Kurn, D., S. Bretz, B. Huang, and H. Akbari. 1994. The Potential for Reducing Urban Air Temperatures and Energy Consumption through Vegetative Cooling. ACEEE Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy. Pacific Grove, CA.

10 Simpson, J.R., and E.G. McPherson. 2001. Tree planting to optimize energy and CO_2 benefits. In: Kollin, C. (ed.). Investing in Natural Capital: Proceedings of the 2001 National Urban Forest Conference. September 5-8., 2001, Washington D.C.

11 McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station.

12 H. Akbari, S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha, and W. Bos. 1993. Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results. Paper LBNL-34411. Lawrence Berkeley National Laboratory, Berkeley, CA.

13 H. Akbari, S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha, and W. Bos. 1993. Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results. Paper LBNL-34411. Lawrence Berkeley National Laboratory, Berkeley, CA.

14 Akbari, H., D. Kurn, S. Bretz, and J. Hanford. 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings. 25:139-148.

15 Simpson, J.R. and E.G. McPherson. 1998. Simulation of Tree Shade Impacts on Residential Energy Use for Space Conditioning in Sacramento. Atmospheric Environment. 32(1):69-74.

16 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

17 McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station.

18 Luley, C.J. and J. Bond. 2002. A Plan to Integrate Management of Urban Trees into Air Quality Planning. Report prepared for New York Department of Environmental Conservation and USDA Forest Service, Northeastern Research Station.

19 Nowak, D.J. 2000. The Effects of Urban Trees on Air Quality. USDA Forest Service: 4. Syracuse, NY.

20 Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry and Urban Greening. 4(2006):115-123.

21 Scott, K., J.R. Simpson, and E.G. McPherson. 1999. Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions. Journal of Arboriculture. 25(3).

22 U.S. EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. Retrieved 15 December from <http://www.epa.gov/climatechange/emissions/downloads06/07CR.pdf>.

23 Nowak, D.J. and D.E. Crane. 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution. 116(2002):381-389.

24 California Air Resources Board. 2007. Forestry Greenhouse Gas Accounting Principles. 25 October. Retrieved 14 January 2008 from <http://www.arb.ca.gov/cc/forestry/forestry_protocols/forestry_protocols.htm#Public>.

25 Konopacki, S. and H. Akbari. 2002. Energy Savings for Heat Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City). Paper LBNL-49638. Lawrence Berkeley National Laboratory, Berkeley, CA.

26 McPherson, E.G., J.R. Simpson, P.J. Peper, S.L. Gardner, K.E. Vargas, J. Ho, S. Maco, and Q. Xiao. 2006. City of Charleston, South Carolina Municipal Forest Resource Analysis. Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station.

27 Heisler, G.M. and R.H. Grant. 2000. Ultraviolet radiation in urban ecosystems with consideration of effects on human health. Urban Ecosystems. 4:193-229.

28 Heisler, G.M., R.H. Grant, and W. Gao. 2002. Urban tree influences on ultraviolet irradiance. In: Slusser, J.R., J.R. Herman, W. Gao, eds. Ultraviolet Ground and Space-based Measurements, Models, and Effects. Proceedings of SPIE, San Diego, CA.

29 Xiao, Q., E.G. McPherson, J.R. Simpson, and S.L. Ustin. 1998. Rainfall Interception by Sacramento's Urban Forest. Journal of Arboriculture. 24(4):235-244.

30 McPherson, E.G. and J. Muchnick. 2005. Effects of Street Tree Shade on Asphalt Concrete Pavement Performance. Journal of Arboriculture. 31(6).

31 Nowak, D.J. and J.F. Dwyer. 2007. Understanding the Benefits and Costs of Urban Forest Ecosystems. In: Kuser, J.E. Handbook of Urban and Community Forestry in the Northeast. New York: Kluwer Academic/Plenum Publishers. 25-46.

32 Kuo, Francis E. and W.C. Sullivan. 2001. Environment and Crime in the Inner City: Does Vegetation Reduce Crime? Environment and Behavior. 33(3):343-367.

33 Laverne, R.J. and K. Winson-Geideman. 2003. The Influence of Trees and Landscaping on Rental Rates at Office Buildings. Journal of Arboriculture. 29(5):281-290.

34 Wolf, K. 1998. Urban Nature Benefits: Psycho-Social Dimensions of People and Plants. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #1. Seattle, WA.

35 Hansmann, R., S.M. Hug, and K. Seeland. Restoration and stress relief through physical activities in forests and parks. Urban Forestry & Urban Greening. 6(4):213-225.

36 Wolf, K. 1998. Growing with Green: Business Districts and the Urban Forest. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #2. Seattle, WA.

37 Wolf, K. 1998. Trees in Business Districts: Comparing Values of Consumers and Business. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #4. Seattle, WA.

38 Wolf, K. 1998. Trees in Business Districts: Positive Effects on Consumer Behavior. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #5. Seattle, WA.

39 Wolf, K. 1998d. Urban Forest Values: Economic Benefits of Trees in Cities. Center for Urban Horticulture, College of Forest Resources, University of Washington, Fact Sheet #3. Seattle, WA.

40 The values cited for the increase in selling price reflect both the literature reviews and the new data in: Des Rosiers, F., M. Theriault, Y. Kestans, and P. Villeneuve. 2002. Landscaping and House Values: An Empirical Investigation. Journal of Real Estate Research. 23(1):139-162. Theriault, M., Y. Kestens, and F. Des Rosiers. 2002. The Impact of Mature Trees on House Values and on Residential Location Choices in Quebec City. In: Rizzoli, A.E. and Jakeman, A.J. (eds.). Integrated Assessment and Decision Support, Proceedings of the First Biennial Meeting of the International Environmental Modeling and Software Society. iEMSs, 2002. I:478-483.

41 McPherson, E.G., J.R. Simpson, P.J. Peper, S.E. Maco, and Q. Xiao. 2005. Municipal Forest Benefits and Costs in Five US Cities. Journal of Forestry. 103(8):411-416.

42 Nowak, D.J. 2000. The Effects of Urban Trees on Air Quality. USDA Forest Service: 4. Syracuse, NY.

43 Benjamin, M.T., M. Sudol, L. Bloch, and A.M. Winer. 1996. Low-Emitting Urban Forests: a Taxonomic Methodology for Assigning Isoprene and Monoterpene Emission Rates. Atmospheric Environment. 30(9):1437-1452.

44 Benjamin, M.T. and A.M. Winer. 1998. Estimating the Ozone-Forming Potential of Urban Trees and Shrubs. Atmospheric Environment. 32(1):53-68.

45 Benjamin, M.T. and A.M. Winer. 1998. Estimating the Ozone-Forming Potential of Urban Trees and Shrubs. Atmospheric Environment. 32(1):53-68.

46 McPherson, E.G. 2002. Green Plants or Power Plants? Center for Urban Forest Research. Davis, CA.

47 McPherson, E.G., J.R. Simpson, P.J. Peper, S.E. Maco, and Q. Xiao. 2005. Municipal Forest Benefits and Costs in Five US Cities. Journal of Forestry. 103(8):411-416.

48 McPherson, E.G., J.R. Simpson, P.J. Peper, K.I. Scott, and Q. Xiao. 2000. Tree Guidelines for Coastal Southern California Communities. Local Government Commission & Western Center for Urban Forest Research and Education. Sacramento, CA.

49 McPherson, E.G., J.R. Simpson, P.J. Peper, and Q. Xiao. 1999. Benefit-Cost Analysis of Modesto's Municipal Urban Forest. Journal of Arboriculture. 25(5):235-248.

50 McPherson, E.G., J.R. Simpson, P.J. Peper, Q. Xiao, D.R. Pettinger, and D.R. Hodel. 2001. Tree Guidelines for Inland Empire Communities. Local Government Commission & Western Center for Urban Forest Research and Education. Sacramento, CA.

51 Stokes, Trevor. 2007. Trees give more to the community than shade. Times Daily. 24 November. Retrieved 14 January 2008 from <http://www.timesdaily.com/article/20071125/NEWS/711250345/-1/COMMUNITIES>.

52 Hadish, C. 2007. Benefits of trees measured. Gazette. 15 October. Retrieved 16 October 2007 from <http://www.gazetteonline.com/apps/pbcs.dll/article?AID=/20071015/NEWS/71015023/1006/NEWS>.

53 Portland Parks and Recreation. 2007. Portland's Urban Forest Canopy: Assessment and Public Tree Evaluation. Retrieved 2 October 2007 from <http://www.portlandonline.com/shared/cfm/image.cfm?id=171829>.

54 Maryland Department of Natural Resources Forest Service. 2007. New DNR Study Shows Hyattsville's Trees Benefit The Bay, Save On Energy Bills And Mitigate Global Warming. 29 October. Retrieved 1 November 2007 from <http://www.dnr.state.md.us/dnrnews/pressrelease2007/102907b.html>.

55 McPherson, E.G. 2001. Sacramento's parking lot shading ordinance: environmental and economic costs of compliance. Landscape and Urban Planning. 57:105-123.

56 City of Davis. 1998. Parking Lot Shading Guidelines and Master Parking Lot Tree List Guidelines. Davis, CA.

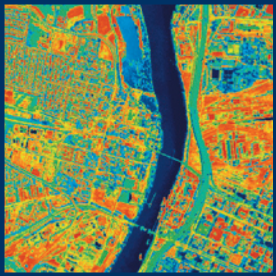
57 City of Sacramento. 2003. Tree Shading Requirements for Surface Parking Lots. Sacramento, CA.

58 McPherson, E.G. and J.R. Simpson. 2000. Carbon Dioxide Reduction through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. PSW GTQ-171. USDA Forest Service, Pacific Southwest Research Station.

59 Tree City, U.S.A. 2001. Tree Care Information. National Arbor Day Foundation, Tree City USA bulletin 19. Nebraska City, NE.

60 Benjamin, M.T., and A.M. Winer. 1998. Estimating the Ozone-Forming Potential of Urban Trees and Shrubs. Atmospheric Environment. 32(1):53-68.





Reducing Urban Heat Islands: Compendium of Strategies

Green Roofs

Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

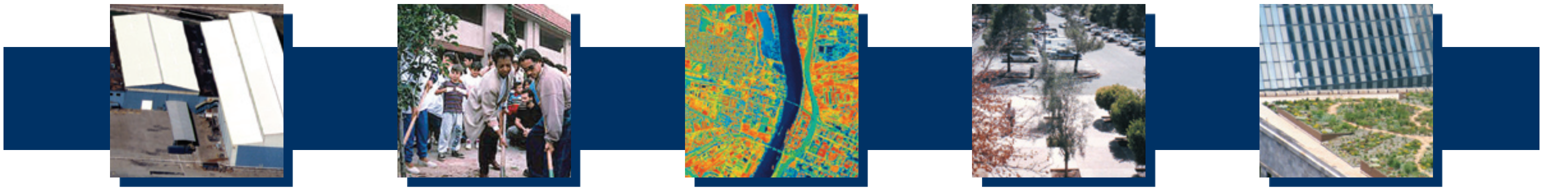
PositvEnergy provided support in preparing the Trees and Vegetation, Cool Roofs, and UHI Activities chapters under contract PO #2W-0361-SATX.

Experts who helped shape this chapter include:

Ryan Bell, Robert Berghage, Hitesh Doshi, Robert Goo, David Hitchcock, Megan Lewis, Tom Liptan, Karen Liu, Greg McPherson, Dave Nowak, Steven Peck, Katrin Scholz-Barth, Jeff Sonne, Benjamin Taube, Linda Velazquez, Kathy Wolf, Jim Yarbrough, and Barry Zalph.

Suggested Citation: U.S. Environmental Protection Agency. 2008. "Green Roofs." In: *Reducing Urban Heat Islands: Compendium of Strategies. Draft.* https://www.epa.gov/heat-islands/heat-island-compendium.

Contents



Green Roofs

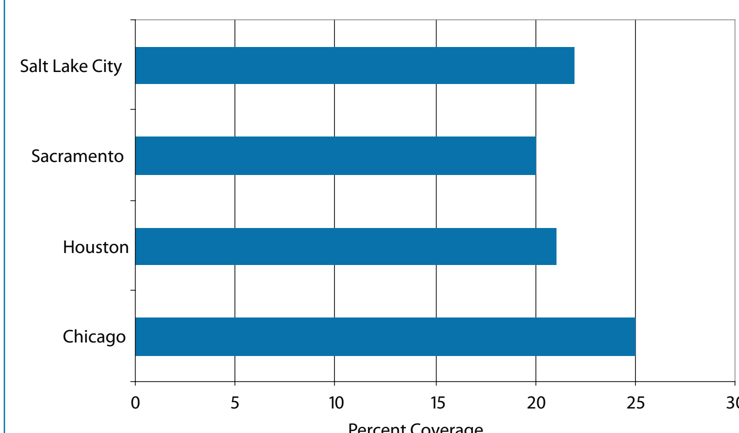
Green roofs are an emerging technology that can help communities mitigate urban heat islands. A green roof is a vegetative layer grown on a rooftop. As with trees and vegetation elsewhere, vegetation on a green roof shades surfaces and removes heat from the air through evapotranspiration. These two mechanisms reduce temperatures of the roof surface and the surrounding air. The surface of a vegetated rooftop can be cooler than the ambient air, whereas conventional rooftop surfaces can exceed ambient air temperatures by up to 90°F (50°C).[2] Green roofs can be installed on a wide range of buildings, including industrial, educational, and government facilities; offices; other commercial property; and residences. This chapter reviews:

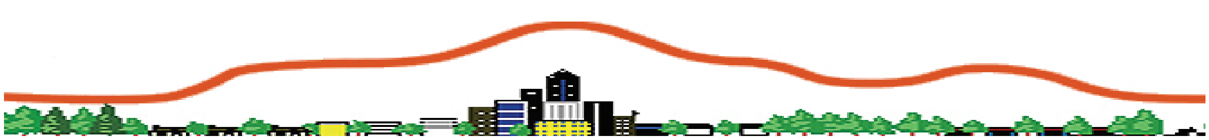
- How green roofs work to mitigate heat islands
- What types of green roofs are available
- The benefits and costs of green roofs
- Other factors to consider in using this mitigation strategy
- Initiatives used to promote green roofs
- Tools and resources to further explore this technology.

Opportunities to Expand Use of Green Roofs in Urban Areas

Most U.S. cities have significant opportunities to increase the use of green roofs. As part of EPA's Urban Heat Island Pilot Project, the Lawrence Berkeley National Laboratory conducted analyses to estimate baseline land use and tree cover information for the pilot program cities.[1] Figure 1 shows the percentage of roof cover in four of these urban areas: roofs account for 20 to 25 percent of land cover. Even though not all these areas will be likely candidates for installing a green roof, there is a large opportunity to use green roofs for heat island mitigation.

Figure 1: Roof Cover Statistics for Four U.S. Cities (Below Tree Canopy)





1. How It Works

With regard to urban heat islands, green roofs work by shading roof surfaces and through evapotranspiration. Using green roofs throughout a city can help reduce surface urban heat islands and cool the air.

Shading. The plants of a green roof and the associated growing medium, a specially engineered soil, block sunlight from reaching the underlying roof membrane. Though trees and vines may not be common on green roofs, they indicate how other vegetation on green roofs shade surfaces below them. For example, the amount of sunlight transmitted through the canopy of a tree will vary by species. In the summertime, generally only 10 to 30 percent of the sun's energy reaches the area below a tree, with the remainder being absorbed by leaves and used for photosynthesis and some being reflected back into the atmosphere. In winter, the range of sunlight transmitted through a tree is much wider—10 to 80 percent—because evergreen and deciduous trees have different wintertime foliage, with deciduous trees losing the leaves and allowing more sunlight through.[6]

Figure 2: Intensive Green Roof in Frankfurt, Germany

Wikimedia Commons

Germany has long been a leader in green roofs; an intensive green roof covers much of this building in Frankfurt.

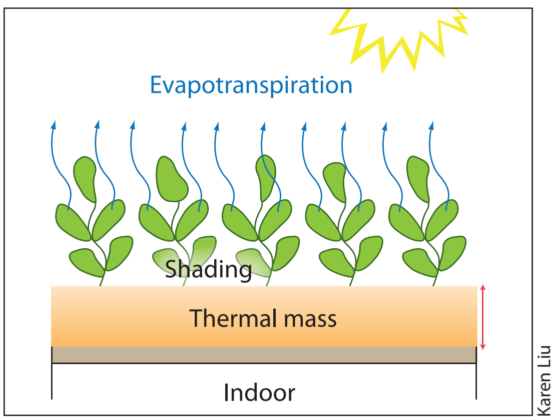
Green Roof Market

In the United States demand and interest in green roofs has grown tremendously. A survey of Green Roofs for Healthy Cities members found that 25 percent more square feet of green roofing were installed in the United States in 2005 than in 2004.[3] A Green Roofs Project Database, available at <www.greenroofs.com/projects/plist.php>, estimated a total of 6.6 million square feet (614,000 m^2) of completed or ongoing green roof projects in the United States as of June 2007. Germany, widely considered a leader in green roof research, technology, and usage, has had decades of experience with green roofs. An estimated 10 percent of all flat roofs in Germany are rooftop gardens.[4,5]

Shading reduces surface temperatures below the plants. These cooler surfaces, in turn, reduce the heat transmitted into buildings or re-emitted into the atmosphere. For example, a multi-month study measured maximum surface temperature reductions due to shade trees ranging from 20 to 45°F (11-25° C) for walls and roofs at two buildings.[7] Another study examined the effects of vines on wall temperatures, and found reductions of up to 36°F (20°C).[8] Furthermore, the growing medium of a green roof itself protects the underlying layers from exposure to wind and ultraviolet radiation.

Evapotranspiration. Plants absorb water through their roots and emit it through their leaves—this movement of water is called transpiration. Evaporation, the conversion of water from a liquid to a gas, also occurs from the surfaces of vegetation and the surrounding growing medium. Together, the processes of evaporation and transpiration are referred to as evapotranspiration. Evapotranspiration cools the air by using heat from the air to evaporate water.

Figure 3: Evapotranspiration and Shading on a Green Roof



Plant shade reduces the sunlight that reaches the roof. Evapotranspiration further cools a green roof by using heat to evaporate water from the growing medium and plant surfaces

Green roof temperatures depend on the roof's composition, moisture content of the growing medium, geographic location, solar exposure, and other site-specific factors. Through shading and evapotranspiration, most green roof surfaces stay cooler than conventional rooftops under summertime conditions. Numerous communities and research centers have compared surface temperatures between green and conventional roofs. For example:

- Chicago compared summertime surface temperatures on a green roof with a neighboring building. On an August day in the early afternoon, with temperatures in the 90s, the green roof surface temperature ranged from 91 to 119°F (33 to 48°C), while the dark, conventional roof of the adjacent building was 169°F (76°C). The near-surface air temperature above the green roof was about 7°F (4°C) cooler than that over the conventional roof.[9]
- A similar study in Florida found that the average maximum surface temperature of a green roof was 86°F (30°C) while the adjacent light-colored roof was 134°F (57°C).[10]

Reduced surface temperatures help buildings stay cooler because less heat flows through the roof and into the building. In addition, lower green roof temperatures result in less heat transfer to the air above the roof, which can help keep urban air temperatures lower as well. Some analyses have attempted to quantify the potential temperature reductions over a broad area from widespread adoption of green roof technology. A modeling study for Toronto, Canada, for example, predicted that adding green roofs to 50 percent of the available surfaces downtown would cool the entire city by 0.2 to 1.4°F (0.1 to 0.8°C). Irrigating these roofs could further reduce temperatures by about 3.5°F (2°C) and extend a 1 to 2°F (0.5-1°C) cooled area over a larger geographic region. The simulation showed that, especially with sufficient moisture for evaporative cooling, green roofs could play a role in reducing atmospheric urban heat islands.[11]

A similar study in New York City modeled air temperature reductions two meters, or 6.5 feet, above the roof surface based on a scenario assuming 100 percent conversion of all available roofs area to green roofs. The model results estimated a temperature reduction of about 0.4°F (0.2°C) for the city as a whole, averaged over all times of the day. The model projected that temperatures

Figure 4: Temperature Differences between a Green and Conventional Roof

National Center of Excellence/ASU

On a typical day, the Chicago City Hall green roof measures almost 80°F (40°C) cooler than the neighboring conventional roof.

at three o'clock in the afternoon would be reduced 0.8°F (0.4°C). The researchers also evaluated, in detail, six areas within the city. The area with the highest 24-hour average reduction in temperature had a change of 1.1°F (0.6°C), and the reductions at three o'clock in the afternoon in those six areas ranged from 0.8°F (0.4°C) to 1.8°F (1.0°C).[12]

2. Green Roof Types

A green roof can be as simple as a 2-inch (5 cm) covering of hardy, alpine-like groundcover, generally termed an "extensive" system, or as complex as a fully accessible park complete with trees, called an "intensive" system.

2.1 Extensive Green Roofs

For the simpler, lighter weight ***extensive green roof system***, plant selections typically include sedums—succulent, hardy plants—and other vegetation generally suitable for an alpine environment. The concept is to design a rugged green roof that needs little maintenance or human intervention once it is established. Plants adapted to extreme climates often make good choices and may not require permanent irrigation systems. Overall, because of their light weight, extensive systems will require the least amount of added structural support, which improves their cost-effectiveness when retrofitting an existing structure.

Extensive green roofs have been grown on roofs with slopes of 30° or more, which would equal a ratio of rise to run of 7:12 or greater. (In contrast, a low-sloped roof with a ratio of rise to run of 2:12 would have a slope of 9.5°.) The slope determines if the roof will need additional support to hold the growing medium and other parts of the vegetative layer in place. Steeper roofs may retain less stormwater than an equivalent, flatter roof.

2.2 Intensive Green Roofs

An ***intensive green roof*** is like a conventional garden, or park, with almost no limit on the type of available plants, including large trees and shrubs. Building owners or managers often install these roofs to save energy and provide a garden environment for the building occupants or the general public to enjoy. Compared to extensive green roofs, intensive green roofs are heavier and require a higher initial investment and more maintenance over the long term than extensive roofs. They generally require more structural support to accommodate the weight of the additional growing medium and public use. Intensive

Figure 5: Combination Extensive/ Intensive Green Roof—The Rooftop Garden on Chicago's City Hall

Conservation Design Forum, Elmhurst, Illinois

The photograph provides an example of a combination extensive/intensive green roof on Chicago's City Hall.

systems also need to employ irrigation systems, which can use rainwater captured from the roof or another source.

3. Benefits and Costs

Green roofs provide many of the same benefits that trees and other ground level vegetation provide. Green roofs have an advantage, though, in that they can be used in dense, built-up areas that may not have space for planting at the ground level. The benefits of vegetation were discussed in the "Trees and Vegetation" chapter and are briefly described here in the context of green roofs.

> **Green Roofs and Green Walls**
>
> In addition to green roofs, building owners can install green walls, sometimes referred to as living walls or vertical gardens. These walls can involve placing trellises or cables in front of exterior walls and allowing vines to grow up them, or can be more elaborate, with plants actually incorporated into the wall.[13]

Figure 6: Ford's Dearborn Truck Plant: An Example of an Extensive Green Roof

Green Roofs for Healthy Cities/www.greenroofs.org

Ford's Dearborn Truck Plant in Michigan covers 10.4 acres (42,100 m^2) and is anticipated to reduce the building's energy costs by 7 percent.[15]

3.1 Benefits

Reduced Energy Use. Green roofs can save energy needed to cool and heat the buildings they shelter. When green roofs are wet, they absorb and store large amounts of heat, which reduces temperature fluctuations. When dry, green roof layers act as an insulator, decreasing the flow of heat through the roof, thereby reducing the cooling energy needed to reduce building interior temperatures. In the winter, this insulating effect means that less heat from inside the building is lost through the roof, which reduces heating needs. In the summertime, green roof vegetation reduces roof surface temperatures and ambient air temperatures, thus lowering cooling energy demand. The insulating properties of green roofs vary as they are dynamic systems that change throughout the year, particularly with regard to water storage. As with cool roofs, discussed in the "Cool Roof" chapter, green roofs should not be used as a substitute for insulation.

Figure 7: Green Wall in Huntsville, Alabama


EOA/Elmslie Osler Architect

This 2,000-square foot (190 m^2) green wall on a store in Huntsville, Alabama, is one of the largest in North America. [14]

Green Roof Types—Changing Nomenclature?

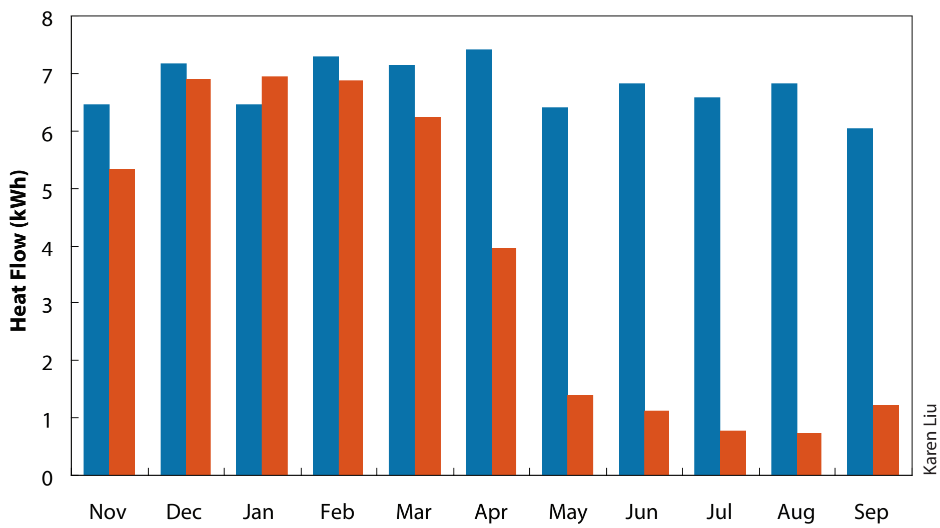
The term "low profile" has been used in place of "extensive" to describe green roofs that are lighter weight, shallower, and simpler. Similarly, "high profile" or "deep profile" has been used instead of "intensive" to describe a heavier, more complex green roof system with deeper soil.

Figure 8 compares the average daily flow of heat through a dark, conventional roof and an extensive green roof in Ottawa, Canada. During the spring and summer, from May to September 2001, the energy demand needed to remove heat that flowed through the conventional roof was six to eight kilowatt hours (kWh) a day, while the green roof's energy demand from heat flow was less than 1.5 kWh a day, a reduction of more than 75 percent. In contrast, during the fall and winter months, from November 2000 through March 2001, heat flow through the green roof was only slightly less than the reference roof in all months except January, so that the energy demand from both roofs was relatively similar. During this time, snow had accumulated, and the temperatures of both roofs stayed about the same.[16]

Although green roofs can save energy both in summer and winter, the specific savings will depend on the local climate and individual building and roof characteristics, such as size, use, and insulation. For example:

- Chicago estimates that its City Hall green roof project could provide cooling savings of approximately 9,270 kWh per year and heating savings of 740 million Btus.[18] This translates into annual, building-level energy savings of about $3,600.
- A Canadian study modeled the heating and cooling energy savings of a roughly 32,000- square foot (2,980 m^2) green roof on a one-story commercial building in Toronto.[19] The analysis estimated that the green roof could save about 6 percent of total cooling and 10 percent of heating energy usage, respectively, or about 21,000 kWh total. The study noted that the cooling energy savings would be greater in lower latitudes. For instance, when the authors ran the same simulation for Santa Barbara, California, the cooling savings increased to 10 percent.
- A study in central Florida measured year-round energy savings from a green roof. By the roof's second summer, the average rate of heat transfer, or flux, through the green roof was more than 40 percent less than for the adjacent light-colored roof. The reduced heat flux was roughly estimated to lower summertime energy consumption of the 3,300 square foot (1,000 m^2) project building by approximately 2.0 kWh per day.[20] Under winter heating conditions,

Figure 8: Comparison of Average Daily Energy Demand Due to Heat Flow Through an Extensive Green versus Conventional Roof in Ottawa, Canada[17]



This chart shows the average daily energy demand due to observed heat flow through a green and conventional roof. The period of evaluation was November 22, 2000, through September 30, 2001.

when the outdoor air temperature was less than 55°F (13°C), the heat flux was almost 50 percent less for the green roof than for the conventional roof.[21]

Reduced Air Pollution and Greenhouse Gas Emissions. As described in the "Trees and Vegetation" chapter, vegetation removes air pollutants and greenhouse gas emissions through dry deposition and carbon sequestration and storage. The reduced energy demand from green roofs also reduces air pollution and greenhouse gas emissions associated with energy production. Further, because ground-level ozone forms more readily with the rise in air temperatures, green roofs help slow the formation of ground-level ozone by lowering air temperatures. As with trees and vegetation, when selecting vegetation for a green roof, building owners in areas with poor air quality may want to consider the volatile organic compound (VOC) emissions from certain plant species, as VOCs are a ground-level ozone pre-cursor.

Plant surfaces can remove certain pollutants from the air through dry deposition. A green roof can remove particulate matter (PM) and gaseous pollutants, including nitrogen oxides (NO_X), sulfur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3) from the air. Many studies have investigated the potential air pollutant removal of green roofs:

- Researchers estimate that a 1,000-square foot (93 m^2) green roof can remove about 40 pounds of PM from the air in a year, while also producing oxygen and removing carbon dioxide (CO_2) from the atmosphere.[22] Forty pounds of PM is roughly how much 15 passenger cars will emit in a year of typical driving.[23]
- A modeling study for Washington, D.C., examined the potential air quality benefits of installing green roofs on 20 percent of total roof surface for buildings with roofs greater than 10,000 square feet (930 m^2). Under this scenario, green roofs would cover about 20 million square feet (almost 2 million m^2) and remove,

annually, about 6.0 tons of O_3 and almost 6 tons of PM of less than 10 microns (PM_{10}), or the equivalent of the pollutants that could be absorbed by about 25,000 to 33,000 street trees.[24]

- A similar study for the midtown area of Toronto modeled various green roof scenarios and compared pollutant reductions with existing baseline urban tree and shrub benefits. One scenario involved green roofs on flat roof surfaces, representing 20 percent of midtown roofs in total, such as commercial, high-rise residential, and institutional buildings. In that scenario, the green roofs removed about 10 to almost 20 percent of the pollution that existing trees and shrubs remove, depending on the pollutant examined. If green roofs were added to all available surfaces across midtown Toronto, the model predicted that green roofs' collective performance would increase to between roughly 25 and 45 percent of the reductions currently obtained by existing vegetation.[25]

Vegetation and the growing medium on green roofs also can store carbon. Because many of the plants are small and the growing medium layer is relatively thin, green roofs tend not to have as large a carbon storage capacity as trees or urban forests.

Improved Human Health and Comfort. Green roofs, by reducing heat transfer through the roof of a building, can improve indoor comfort and reduce heat stress associated with heat waves. The use of cool roofs (see "Cool Roof" chapter) provides similar indoor air temperature benefits. These improvements in building comfort can yield human health benefits, particularly in non-air conditioned buildings.

Enhanced Stormwater Management and Water Quality. Another key benefit of green roofs is that they can reduce and slow stormwater runoff in the urban environment. The plants and growing medium of a green roof, in the same manner as other natural surfaces and vegetation, absorb water that would otherwise become runoff. The amount of rainfall retained by a green roof will depend primarily on the depth of the growing medium and may also be affected by the roof slope. Studies have shown that extensive roofs will typically capture between 50 and nearly 100 percent of incoming rain, depending on the amount of growing medium used, the density of vegetation, the intensity of an individual rainstorm, and the frequency of local rain events.[26] An intensive green roof, with thicker layers of growing medium, will capture more rainfall under comparable conditions than an extensive roof. Field study results below help illustrate these findings:

- A North Carolina study of actual green roof performance found that test green roofs reduced runoff from peak rainfall events by more than 75 percent and that the roofs temporarily stored and then released, through evapotranspiration, more than 60 percent of all rainfall.[27]
- A Canadian green roof demonstration

Figure 9: Green Roof on Seattle Public Library

Green Roofs for Healthy Cities/www.greenroofs.org

Municipal buildings, such as this public library in Seattle, have often been used to demonstrate the benefits of green roofs and the feasibility of the technology.

measured significant reductions in runoff over a six-month period, with steep reductions in five of the six months, and then lower reductions in one month that had many large rain events, which did not allow the growing medium to dry out between events. Overall, this project showed the green roof reduced runoff by more than 50 percent.[28]

- A green roof demonstration project in Portland, Oregon, examined runoff reductions over a 15-month period. In that study, a green roof with about four inches (10 cm) of growing medium reduced runoff by almost 70 percent.[29] In addition, the authors noted that the retention rate appeared to increase over time, which might be related to maturing vegetation. Because of the benefits in controlling stormwater, Portland has approved green roofs (or "eco-roofs") as a technique to help meet stormwater management requirements for new development and redevelopment projects. [30]

Stormwater retention will vary with local conditions, and communities generally consider this when projecting the potential stormwater benefits of green roofs in their area.

Even when a green roof does not retain all the water from a storm, it can detain runoff for later release and reduce the runoff rate. For example, the same Portland study demonstrated that the green roof reduced peak run-off rates by 95 percent during an intense storm.[31] The North Carolina study found that average peak runoff rates from the green roofs were roughly 75-85 percent less than average peak rainfall rates, so that even when rain was falling on average at about 1.5 inches/hr (42 mm/hr), it ran off the green roof at less than 0.25 inches/hr (6 mm/hr).[32] Reduced rates of runoff can help communities minimize flooding and combined sewer overflow (CSO) events.*

> Various research projects are underway to continue **monitoring pollutants in stormwater runoff from green roofs,** such as those at Pennsylvania State University's Green Roof Research Center, North Carolina State University's Greenroof Research program, the Green Roof Test Plots research at the Chicago Center for Green Technology, and Portland, Oregon's Eco-Roof program.

The plants and growing medium of a green roof not only retain and delay the release of stormwater but also act as a filter. Findings from various studies demonstrate the ability of green roofs to remove pollutants and highlight the need to select growing media carefully to avoid elevated levels of certain pollutants, which may initially leach from organic materials. A 2005 Canadian report synthesized past studies on this issue.[33] It noted that several studies from Europe had found that green roofs can bind and retain significant levels of pollutants, with one study stating that green roofs could remove up to 95 percent of the cadmium, copper, and lead from stormwater runoff. The study also summarized findings from a monitoring program on a green roof in York, Ontario, which found decreased pollutant concentrations compared to a control roof. The reductions ranged from 80 to almost

* Combined sewer systems are single-pipe systems that carry sewage and stormwater runoff together; when they overflow during heavy rain, they discharge directly into surface waters.

95 percent for several pollutants, such as suspended solids, copper, and polycyclic aromatic hydrocarbons. The same study, however, found increased concentrations of nitrogen and phosphorous.

Recent research in Pennsylvania found improved pH in green roof runoff compared to a conventional roof, as well as reductions in total nitrate loadings based on the reduced amount of stormwater from the green roof. The concentration of other pollutants in the green roof runoff, in contrast, was generally higher than concentrations from a conventional roof.[34]

As with the field study in York, Ontario, research in North Carolina found increases in total nitrogen and total phosphorous, which the authors attributed to certain compost materials in the roof substrate.[35] Research in Portland and Toronto found that phosphorous levels appeared to decrease over time as the green roof vegetation matured and the phosphorous in the initial substrate leached during rainfall events.[36,37] A German study also revealed that a green roof retained more phosphate as it matured, with retention percentage increasing from about 26 percent in the first year to about 80 percent in the fourth.[38]

Enhanced Quality of Life. Green roofs can provide many of the same quality of life benefits as other urban greenery. People in taller, neighboring buildings may enjoy looking down at a rooftop garden. Allowing public access to rooftop gardens provides residents another green space to enjoy. Finally, some researchers are evaluating the potential for green roofs to provide a safe habitat for rare or endangered species, removing them from ground-level predators.[39]

3.2 Costs

The costs of green roofs vary depending on the components, such as the growing medium, type of roofing membrane, drainage system, use of fencing or railings, and type and quantity of plants. A 2001 report estimated that initial costs start at $10 per square foot (0.09 m^2) for the simpler, extensive roof and $25 per square foot for intensive roofs.[40] Other estimates assume $15 to $20 per square foot. Costs in Germany, where green roofs are more prevalent, range from $8 to $15 per square foot.[41] Prices in the United States may decline as market demand and contractor experience increase.

Initial green roof costs are more than those of most conventional and cool roof technologies (see “Cool Roofs” chapter). Green roofs have a longer expected life, though, than most roofing products, so the total annualized costs of a green roof may be closer to those of conventional and cool roofs. Los Angeles estimated that to retrofit a building with an extensive green roof would cost from $1.03-$1.66 per square foot, on an annualized basis, while a conventional re-roofing would range from $0.51-$1.74 per square foot.[42]

In addition to construction costs, a building owner incurs maintenance costs to care for the plants on a green roof. Although the level of care depends on plant selection, most of the expenses arise in the first years after installation, as the plants establish themselves and mature. For either an intensive or extensive roof, maintenance costs may range from $0.75 to $1.50 per square foot. The costs of maintaining an extensive roof decrease after the plants cover the entire roof, whereas maintenance costs will remain more constant for an intensive roof.[43]

3.3 Benefit-Cost Considerations

Although a green roof might have higher initial costs than most conventional or cool roofs, a full life-cycle analysis can identify how the roof benefits the building owner. In many cases, these benefits justify the cost of green roofs in densely populated areas. In addition, a building owner can directly benefit from reduced energy use, reduced stormwater management fees, and increased roof life. Finally, the widespread adoption of green roofs may provide significant, indirect net benefits to the community.

Although few detailed, full life-cycle analyses exist, researchers and communities are beginning to invest in these evaluations. A report on the use of green roofs in New York City outlined one framework for a cost-benefit analysis of green roofs.[44] The framework incorporates both private and public benefits and costs (see Table 1). Under most hypothetical scenarios, a green roof project yields net benefits when assessed with public benefits, such as reduced temperature and stormwater. Under a "high-performance" scenario that generally assumes reduced costs from widespread adoption of green roof technology and a mature market, an owner would achieve net benefits based on private benefits alone.

A University of Michigan study compared the expected costs of conventional roofs with the cost of a 21,000-square-foot (1,950 m^2) green roof and all its benefits, such as stormwater management and improved public health from the NO_X absorption. The green roof would cost $464,000 to install versus $335,000 for a conventional roof in 2006 dollars. However, over its lifetime, the green roof would save about $200,000. Nearly two-thirds of these savings would come from reduced energy needs for the building with the green roof.[45]

Portland, Oregon, meanwhile, has begun a comprehensive cost-benefit analysis of its current eco-roof program, as the city plans to expand green roof coverage from 6 acres (24,300 m^2) in 2007 to over 40 acres (162,000 m^2) in 2012.[46]

Table 1: Benefit-Cost Elements for Green Roofs

Benefits/Costs	Energy, Hydrology, and UHI Benefits	Other Benefits
Private Benefits	• Reduced energy use • Extended service life	• Noise reduction • Aesthetic value • Food production
Public Benefits	• Reduced temperature • Reduced stormwater • Reduced installation costs (from widespread technology use)	• Reduced air pollutants • Reduced greenhouse gases • Human health benefits
Private Costs	• Installation • Architecture/Engineering • Maintenance	N/A
Public Costs	• Program administration	N/A

Cool and Green Roofs: Different Options for Different Motivations

Cool and green roofs both help to mitigate urban heat islands. The two technologies have different cost and performance implications, though, and the motivations for selecting one or the other are typically different.

Cool roofs generally have a minimal incremental cost compared to their conventional equivalent. Depending on the type of product (e.g., asphalt shingle, concrete tile), costs can range roughly between $0.50 to $6.00 per square foot. Costs can vary greatly, though, depending on the size of the job, ease of access to the roof, and local market factors. The initial cost of a green roof, on the other hand, is much higher, starting from $10 per square foot for the basic, extensive green roof.

Both cool and green roofs lower surface and air temperatures and reduce summertime peak and overall energy demand. The extent of the energy savings varies depending on factors including the local climate, attic ventilation and insulation levels, and—particularly for green roofs—the design and maintenance of the roof.

Green roofs provide additional benefits, including reducing and filtering stormwater runoff, absorbing pollutants and CO_2, providing natural habitat and a sound barrier, and potentially serving as a recreational green space and having aesthetic value.

Communities or building owners with limited budgets, who are primarily interested in energy savings or reducing peak energy demand, generally focus on cool roofs. Whereas others, who can consider life-cycle costs and public benefits, and who are interested in broader environmental impacts, particularly improving stormwater management, may choose to install green roofs.

Sustainability leaders, such as Chicago, recognize the value and opportunity for both cool and green roof technologies and are supporting efforts to encourage both options.

Energy Savings and Green Roofs

For building owners and communities primarily interested in saving energy, cool roofs and other energy efficiency measures are generally more cost-effective than green roofs. (See the “Cool Roof” chapter and the ENERGY STAR website <www.energystar.gov> for information about a wide array of cost-effective energy efficient products and practices.) Green roofs provide benefits beyond energy savings, though, which is why they are attractive to diverse interest groups and sustainability advocates.

Figure 10: Green, or Eco, Roof in Portland, Oregon

Portland Bureau of Environmental Services

This apartment building in Portland, Oregon, is among the 6 acres (24,300 m^2) of green roofs in the city, as of 2007. Many roofs remain candidates to become green roofs.

4. Other Factors to Consider

4.1 Site Characteristics

Recommendations for ideal site characteristics vary and often depend on project or program objectives. For example, Chicago and New York City are focusing on “hot spot” areas, which are often found in dense, built up urban cores. Green roofs may be the only option to provide an effective amount of vegetation in these older city centers that have vast amounts of impervious cover and few opportunities to retroactively plant shade vegetation. Further, entities interested in providing recreational space or improving aesthetics may also focus on high density areas that are visible from adjoining or near by buildings.

On the other hand, stakeholders focused on saving energy and managing stormwater often target low-to-medium rise buildings that have a large roof area. These sites, such as the Ford’s Dearborn Truck Plant in Michigan, may be found in less developed areas.

From a structural standpoint, existing roofs with concrete structural systems likely will require the least amount of intervention; roofs with steel deck can require the most. Installing a green roof on a flat or low-sloped roof generally will be easier than installing one on a steep-sloped roof. Also, green roofs tend to be easier to design into new rather than existing buildings, given that loads and other requirements can be included in the design process. However, retrofit installations are becoming increasingly common in the expanding green roof market. Many existing buildings, such as low-sloped residential and commercial buildings with large roof areas, can be modified without significant disruption when replacing an old roof. For example, projects at Carnegie Mellon University, Tobyhanna Army Depot, and the Albemarle

The Green Roof Continuum

The decision to install an extensive or intensive green roof depends on available resources and the building owner's goals for how the roof will be used. For example, someone with a limited budget who desires minimal maintenance and is mainly interested in the energy and environmental benefits of a green roof, would most likely install an extensive green roof. On the other hand, someone who wants to create an accessible garden and is able to maintain the green space, will probably install a more intensive green roof. Many green roofs incorporate a combination of extensive and intensive green roof features. These "semi-extensive" or "semi-intensive" green roofs lie within the continuum of green roof types, with "extensive" and "intensive" at each end of the spectrum.

County, Virginia, office building have highlighted the ease of replacing stone-ballast on existing roofs with vegetative layers.[47]

4.2 Installation and Maintenance

Whether extensive, intensive, or somewhere in between, green roofs generally consist of the same basic components.[48] From the top layer down (see Figure 12), these include:

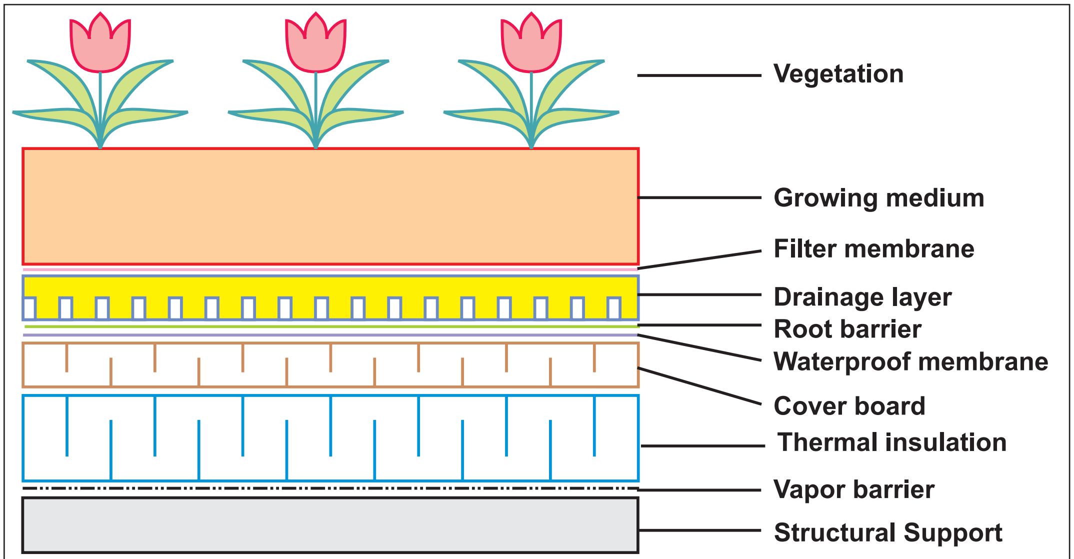
- ***Vegetation.*** The choice of vegetation depends on the type of roof (extensive or intensive), building design, local climate, available sunlight, irrigation requirements, anticipated roof use, and similar factors:
  – Extensive green roof plants are typically hardy perennials. They are preferably shallow-rooting, self-generating plants that spread rapidly and require minimal nutrients. They should tolerate sun, wind, and extreme temperature fluctuations. Succulents, such as sedums, are well adapted for green roofs because they are drought-resistant and their high water content makes them fire resistant. Sedums come

Figure 11: A Green Roof Replaces a Stone Ballast Roof

Gregor Patsch/Albemarle County

Albemarle County, Virginia, replaced the stone ballast roof on its county office building with a green roof in 2005. The project received money from the Chesapeake Bay Program through the Virginia Department of Conservation and Recreation.

Figure 12: Typical Layers of a Green Roof



in a wide variety of sizes, textures, and colors. Building owners also can ensure that the selected plants suit USDA plant hardiness zones for their area.[49]

– Intensive green roofs have deeper growing media, which allows them to incorporate larger plants, including shrubs, bushes, and trees, in their design. Most intensive green roofs also have irrigation systems that can support a wide variety of plants.

- A lightweight, engineered ***growing medium*** may or may not include soil as the primary organic matter. The planting media used in green roof systems are usually engineered to provide the best support for plants with the lightest weight and can be tailored to maximize water retention without water-logging the plants. A growing medium should ideally last as long as the roof it will cover. Typically, the growing medium will consist primarily of lightweight inorganic mineral materials (at least 80 percent) and up to 20 percent organic materials like topsoil.[50] Extensive green roofs use up to roughly 6 inches (15 cm) of growing medium[51] while intensive green roofs use 8 inches (20 cm) or more.[52]
- A ***filter membrane*** is usually a geotextile that allows excess water from the growing medium to flow out, while preventing the fine particles from washing away and clogging the roof drain.
- A ***drainage layer*** helps the excess water from the growing medium to flow to the roof drain, which prevents overloading the roof and provides a good air-moisture balance in the growing medium. Some drainage layers take the form of egg crates to allow for some water storage.
- A ***root barrier*** can protect the roof membrane from aggressive plant roots, which may penetrate the waterproofing layer and cause leaks.
- A ***waterproofing/roofing membrane*** protects the building from water penetration. Any roofing membrane can be used in green roofs, although single-ply waterproofing membranes are generally thicker and more durable on green roofs than on conventional ones. Some

membranes are naturally protected from root penetration, while others require a root barrier.

- A ***cover board*** is a thin, semi-rigid board that provides protection, separation, and support for a roofing membrane.
- ***Thermal insulation*** can be installed either above or below the membrane of a green roof. The insulation value of the growing medium in a green roof increases as its moisture content decreases. However, green roofs are not a substitute for conventional insulation; using the recommended insulation levels for one's local climate helps conserve energy.
- A ***vapor barrier*** is typically a plastic or foil sheet that resists passage of moisture through the ceiling.
- ***Building and roof structural support.*** The components of a green roof weigh more than conventional roofing materials, and thus the roof requires support panels. Not only are the roofing membranes and other materials heavier on a green roof, but the roof design also must account for the weight of water-saturated plants and growing medium. An extensive roof typically weighs from 15-30 pounds per square foot, although the range will depend on the depth of the growing medium and other site-specific factors.[53] An intensive roof can weigh much more, with significantly greater depth of growing medium, more extensive vegetation, and people using the space. Building owners must ensure that the structure can support the green roof even when fully saturated, in addition to meeting building code requirements for snow and wind loads. Reinforcing roof supports on existing buildings adds to the project cost but can usually be worked into building retrofit or renovation plans. It is often easier to put green roofs on new buildings, as the requirements for the added roof load can be included as part of the initial design parameters, and the cost for the upgrade is usually minimal.

Inverted Roof Membrane Assemblies (IRMAs) and Green Roofs

Inverted roof membrane assemblies (IRMAs) have insulation above the waterproofing membrane, as opposed to conventional roofs, which have insulation below the membrane. This design protects the membrane and prolongs the life of the roof. A green roof that has insulation between its vegetative layer and the waterproofing membrane is an IRMA, with the vegetation protecting the membrane and weighing down the insulation. More conventional IRMAs use concrete pavers or stones for ballast. These IRMAs often make good candidates for green roof retrofits, as the conventional ballast can be replaced with the necessary green roof layers.

Although both extensive and intensive green roofs share these basic components, their characteristics vary (see Figure 13). Most important, the intensive green roofs are likely to require more structural support and enhanced irrigation systems to support the wider variety of plants, increased weight loads, and desired public access. However, intensive roofs will probably also retain more rainfall and support more species.[54]

In addition, any green roof generally will require some ongoing maintenance. Extensive green roofs not designed for public access have fewer obligations. For an intensive roof, maintenance can be continuous, similar to a traditional garden, because aesthetics will be more important.

For either roof, early weed control is important to ensure that the installed plants have a chance to spread and to minimize the opportunity for invasive weeds to take root. According to a federal guide on green roofs,[55] weeding might be necessary monthly or quarterly for the first two years and might be reduced to only once a year in many cases after the plants have fully covered the roof. The guide also lists other important maintenance activities including:

- ***Fertilize.*** Given the thin layer of growing medium, building owners or managers might need to apply a slow release fertilizer once a year to avoid soil acidity, especially when the plants are first establishing themselves.
- ***Irrigate.*** An ideal green roof could rely on natural irrigation, especially for extensive roofs. However, some green roofs might require irrigation based on local climate and the stage of plant growth for a particular project. Irrigation might also be needed to reduce fire risks or to increase evaporative cooling. Almost all intensive green roofs need irrigation systems. Extensive green roofs, however, may only need them during plant establishment. For large, extensive green roofs, building owners often install a drip irrigation system, which is generally inexpensive and saves the time and effort of having someone manually water the roof.
- ***Replant.*** Over time, some level of replanting or addition to the growing medium might be necessary.

Figure 13: Comparison of Common Features of Extensive and Intensive Roofs

Extensive vs.	Intensive
(Low-Profile/Ecoroofs)	(High-Profile/Roof Gardens)
• Low growth media: 2 – 6"	• > 6"-15" and deeper
• Lightweight: 13 – 50 lbs/sf	• Heavier weights: 50+ lbs/sf
• Low growing plants: 1"– 24" H	• Trees, shrubs and more
• Less variety of plants: Alpine types, succulents, herbs, some grasses and mosses	• Huge variety of plant selection/ architectural features depending on loads, design & budget
• Usually non-accessible and non-recreational	• Designed for human recreation: gardening, socializing, etc.
• Slopes up to 30° & higher	• Relatively flat
• Less expensive: $5-$25/sf	• More expensive: $25-$40+/sf
• Low water requirements	• Irrigation usually necessary
• Low maintenance	• Higher maintenance

Linda Velasquez

There is no official definition of an extensive or intensive green roof. This chart is not meant to strictly define these green roof types and instead aims to describe the general characteristics of roofs at each end of the continuum.

Figure 14: A Modular Green Roof on a Sloped Residential Roof


Greenroofs.com and Kelly Luckett/Green Roof Blocks

This home in Arizona shows a modular green roof on a steep-sloped roof.

Modular Green Roof Systems

Some green roof systems use modular components. These components are generally plastic trays a few feet long (~0.5-1 m) on each side and several inches (~10-20 cm) deep. They are filled like flowerpots with growing media and the desired plants and placed directly on top of the existing roof. The grid of trays covers the roof's surface to provide benefits similar to built-in green roofs. Moving or replacing individual modules is potentially easier than changing or repairing parts of a non-modular green roof. Modular roofs, however, are relatively new, and have not been as widely studied as non-modular roofs.

- ***Clean Gutters.*** Similar to conventional roofs, clean gutters decrease the risk of standing water and leaks. It is also necessary to keep drains and gutters clear of plant growth to prevent blockage.

In addition to routine maintenance, green roofs may require repairs over time, although the expected life of a green roof is about twice that of a conventional roof.[56] If correctly installed, the membrane under the vegetation of a green roof is expected to last 30 to 50 years.

4.3 Fire Safety

Green roofs, when saturated with water, can retard the spread of fire,[57] but dry plants on a green roof can be a fire hazard. The most common ways to increase fire safety are to:

- Avoid grasses and plants that could dry up in summer and instead use fire resistant plants, like sedums, and a growing medium that is low in organic material content.
- Construct fire breaks on the roof—2-foot (0.6 m) widths of concrete or gravel at 130-foot (40 m) intervals.

Another precaution that some practitioners recommend is to install sprinkler irrigation systems and connect them to a fire alarm.

5. Green Roof Initiatives

Green roof research efforts are growing with an increasing number of universities offering courses or developing centers focused on improving our understanding of green roof technology. Many communities are also taking action by encouraging or sponsoring green roof projects. These initiatives are typically motivated by various environmental concerns, mainly stormwater management, but also the desire to reduce urban heat islands and enhance the urban ecosystem. Many of these efforts involve a single demonstration or showcase project as a highly visible means to promote green roof technology, such as the green roof on Atlanta's City

Many green roof projects are motivated not by government policies but by a desire to show a **commitment to sustainable design and the environment.**

Hall patio. Some cities such as Chicago, Portland, Seattle, and Toronto have been developing more coordinated programs and policies to promote green roofs. The “Heat Island Reduction Activities” chapter provides many examples demonstrating the wide range of green roof efforts. Table 2 identifies some of the research activity and options available for taking action to advance green roofs.

Green building programs in many communities provide another opportunity to encourage green roof installation. The U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Rating System (see <www.usgbc.org>) and Green Globes operated by the Green Building Initiative (GBI) in the United States (see <www.thegbi.org>), are two rating systems that communities are using. These and other systems give credit for a broad range of building and development techniques that save energy and protect the environment. Green roofs can achieve credit under multiple categories—such as stormwater management, heat island mitigation, water efficiency, energy and atmosphere, materials and resources, and innovation and design—depending on how they are constructed.

Figure 15: A Newly Installed Green Roof in New York City

©2008 J. Burling Chase for Sustainable South Bronx

Initiatives to install green roofs in urban areas reduce urban heat islands and can help to create jobs in the local economy, such as this roof installed by graduates of Sustainable South Bronx’s Bronx Environmental Stewardship Training (BEST) program.

Table 2: Examples of Green Roof Initiatives

Type of Initiative	Description	Links to Examples
Research	University programs	**<www.hrt.msu.edu/greenroof>** - Michigan State University began its Green Roof Research Program in 2000 to assist with the design and study of Ford's Rouge Plant. The program has since expanded and now investigates green roof plant selection among other topics.
		<http://hortweb.cas.psu.edu/research/greenroofcenter> - Penn State University's Center for Green Roof Research studies the energy savings, stormwater retention and filtration, and other benefits of green roofs.
		<www.bae.ncsu.edu/greenroofs> - North Carolina State University has extensive green roof test sites in Goldsboro and Kinston, North Carolina, as part of the Biological and Agricultural Engineering Program.
		<www.stormwater.ucf.edu/> - The University of Central Florida focuses primarily on stormwater management, which has led to its investigations of green roofs.
		<http://commons.bcit.ca/greenroof/> - The British Columbia Institute of Technology's Centre for the Advancement of Green Roof Technology collaborates with industry to support and improve the deployment of green roofs.
Voluntary efforts	Demonstration projects	**<www.chicagogreenroofs.org>** - For background information on Chicago City Hall's green roof, see the "Links" section of this site.
		<www.atlantaga.gov/mayor/energyconservationgreenroof.aspx> - This site provides an overview of the Atlanta City Hall green roof demonstration project.
	Incentives	**<http://egov.cityofchicago.org>** - Chicago has sponsored a green roof grant program for several years. Grants of up to $5,000 each were available in the application cycle that ended in January 2008. See the Department of Environment page and browse under "Initiatives and Programs."
		<www.toronto.ca/greenroofs/incentiveprogram.htm> - Toronto's green roof incentive program offers grants of Canadian $50 per square meter for eligible projects, up to a total of $10,000 for single-family homes and $100,000 for all other buildings.

Table 2: Examples of Green Roof Initiatives (Continued)

Type of Initiative	Description	Links to Examples
Voluntary efforts	Incentives	**<www.portlandonline.com/bes/index.cfm?c=43077>** - Portland, Oregon, offers grants, workshops, and other technical assistance to support green roofs.
		<www.houstondowntown.com/Home/Business/DoingBusiness/DevelopmentAssistance/Development%20Assistance.PDF> - The Houston Downtown Management District (HDMD) Vertical Gardens Matching Grant initiative is intended to assist in the facilitation of wall cover plantings and exceptional landscaping on blank walls, parking garages, and sidewalks; improving overall aesthetics, pedestrian comfort, and air quality; and reducing the heat island effect.
	Outreach & education	**<www.epa.gov/heatisland/>** - EPA's Heat Island Reduction Initiative provides information on the temperature, energy, and air quality impacts from green roofs and other heat island mitigation strategies.
		<http://cfpub.epa.gov/npdes/home.cfm?program_id=298> - EPA's Office of Water highlights design options, including green roofs, that reduce stormwater runoff and water pollution.
		<www.greenroofs.org/> - Green Roofs for Healthy Cities hosts a series of green roof design and implementation workshops throughout North America.
Policy efforts	Density bonus provisions in zoning codes	**<http://commons.bcit.ca/greenroof/publications/2006_regulations.pdf>** - Document that highlights efforts of Chicago; Seattle; Portland, Oregon; Toronto; and Waterloo, Ontario, to encourage green roof installations by offering density bonus incentives in their zoning codes.

6. Resources

Table 3 lists some guidance documents and organizations that promote green roofs.

Table 3: Green Roof Resources

Name	Description	Web Link
Guidance Documents		
U.S. Department of Energy Federal Technology Alert: Green Roofs	DOE's Energy Efficiency and Renewable Energy program publishes technology alerts and developed this primer on green roof technology.	<www.nrel.gov/docs/fy04osti/36060.pdf>
Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services	The journal *Bioscience* November 2007 issue contains this comprehensive article summarizing the research on green roofs and their costs and benefits.	<www.aibs.org/bioscience-press-releases/resources/11-07.pdf>
National Roofing Contractors Association Green Roof Systems Manual	The NRCA has recently released a guidebook for sale that focuses on the waterproofing needs of green roofs.	<www.nrca.net/rp/pubstore/details.aspx?id=450>
Los Angeles Green Roof Resources Guide	The City of Los Angeles developed this guide as a resource for individuals and groups interested in developing green roofs in Los Angeles. This guide includes information on how to plan, design, and maintain a green roof.	<www.fypower.org/pdf/LA_GreenRoofsResourceGuide.pdf>
Other Resources		
Green Roofs for Healthy Cities	Green Roofs for Healthy Cities offers resources on green roof installation, benefits, projects, and training. This group also publishes the *Green Roof Infrastructure Monitor*.	<www.greenroofs.org>
Greenroofs.com	Greenroofs.com provides green roof industry resources, including how-tos, plant lists, references, and an international database of green roof projects.	<www.greenroofs.com>
Chicago Green Roof Program	Chicago's Green Roof Program has online information on building green roofs in Chicago, including an aerial map of completed and planned projects, frequently asked questions, featured projects, and links to other resources.	<www.chicagogreenroofs.org>

Endnotes

1 Rose, L.S., H. Akbari, and H. Taha. 2003. "Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas." LBNL-51448, January 2003.

2 Liu, K. and B. Baskaran. 2003. "Thermal performance of green roofs through field evaluation." National Research Council of Canada-46412.

3 "Final Report, Green Roof Industry Survey, 2006," prepared by Green Roofs for Healthy Cities, April 2007. Retrieved 7 Dec. 2007 from <http://www.greenroofs.org/storage/2006grhcsurveyresults.pdf>.

4 The Green Roof Research Program at MSU. Retrieved 7 August 2007 from <http://www.hrt.msu.edu/faculty/Rowe/Green_roof.htm>.

5 Peck, S.W., C. Callaghan et al. 1999. Greenback, from Green Roofs: Forging a New Industry in Canada. Prepared for Canada Mortgage and Housing Corporation.

6 Huang, J., H. Akbari, and H. Taha. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. ASHRAE Winter Meeting, American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

7 Akbari, H., D. Kurn, S. Bretz, and J. Hanford. 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings. 25:139-148.

8 Sandifer, S. and B. Givoni. 2002. Thermal Effects of Vines on Wall Temperatures—Comparing Laboratory and Field Collected Data. SOLAR 2002, Proceedings of the Annual Conference of the American Solar Energy Society. Reno, NV.

9 Department of Energy 2004. Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.

10 Cummings, J., C. Withers, J. Sonne, D. Parker, and R. Vieira. 2007. "UCF Recommissioning, Green Roofing Technology, and Building Science Training; Final Report." FSEC-CR-1718-07. Retrieved 18 December 2007 from <http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1718-07.pdf>.

11 Liu, K. and B. Bass. 2005. Performance of Green Roof Systems. National Research Council Canada, Report No. NRCC-47705, Toronto, Canada.

12 Rosenzweig, C., W. Solecki et al. 2006. Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces. Sixth Symposium on the Urban Environment and Forum on Managing our Physical and Natural Resources, American Meteorological Society, January 31, 2006, Atlanta, GA.

13 Bass, B. and B. Baskaran. 2003. Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas. National Research Council Canada, Report No. NRCC-46737, Toronto, Canada.

14 McKeough, T. "Room to Improve." New York Times. 21 Feb. 2008. Retrieved 10 Mar. 2008 from <http://www.nytimes.com/2008/02/21/garden/21room.html>.

15 Ford Motor Company. Ford Installs World's Largest Living Roof on New Truck Plant. Retrieved 2 August 2007 from <http://media.ford.com/newsroom/release_display.cfm?release=15555>.

16 Liu, K. 2002. A National Research Council Canada Study Evaluates Green Roof Systems' Thermal Performances. Professional Roofing.

17 Bass, B. and B. Baskaran. 2003. Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas. National Research Council Canada, Report No. NRCC-46737, Toronto, Canada.

18 Department of Environment. Chicago City Hall green roof project. Retrieved 18 October 2007 from <http://egov.city ofchicago.org>.

19 Bass, B. and B. Baskaran. 2003. Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas. National Research Council Canada, Report No. NRCC-46737, Toronto, Canada.

20 Cummings, J., C. Withers, J. Sonne, D. Parker, and R. Vieira. 2007. "UCF Recommissioning, Green Roofing Technology, and Building Science Training; Final Report." FSEC-CR-1718-07. Retrieved 18 Dec. 2007 from <http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1718-07.pdf>.

21 Sonne, J. "Energy Performance Aspects of a Florida Green Roof," Fifteenth Symposium on Improving Building Systems in Hot and Humid Climates, July 24-26, 2006 Orlando, FL.

22 Peck, S. and M. Kuhn. 2003. Design Guidelines for Green Roofs. Canada Mortgage and Housing Corporation, Ottawa, and the Ontario Association of Architects, Toronto.

23 This comparison assumes each car will produce 0.1g of PM per mile (based on new federal standards that would limit PM emissions to this level or lower in passenger vehicles), and that each car is driven 12,500 miles (20,000 km) in a year, which was the average mileage for a car in America in 2004. See U.S. Department of Transportation Federal Highway Administration. "Annual Vehicle Distance Traveled in Miles and Related Data-2004." Highway Statistics 2004. October 2005. Retrieved October 19, 2007 from <http://www.fhwa.dot.gov/policy/ohim/hs04/htm/vm1.htm>.

24 Casey Trees Endowment Fund and Limno-Tech, Inc. 2005. Re-Greening Washington, D.C.: A Green Roof Vision Based on Quantifying Storm Water and Air Quality Benefits. Washington, D.C.

25 Currie, B.A. and B. Bass. 2005. Estimates of Air Pollution Mitigation with Green Plants and Green Roofs Using the UFORE Model. Sixth Biennial Canadian Society for Ecological Economics (CANSEE) Conference, October 27-29, 2005, Toronto, Canada.

26 VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez, and L. Xiao. 2005. Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth. Journal of Environmental Quality 34:1036-1044.

27 Moran, A., B. Hunt et al. 2004. A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff Quality, and Plant Growth. Paper Presented at Green Roofs for Healthy Cities Conference, Portland, OR, June 2004.

28 Liu, K. 2003. Engineering performance of rooftop gardens though field evaluation. National Research Council Canada, Report No. NRCC-46294, Ontario, Canada.

29 Hutchinson, D., P. Abrams et al. 2003. Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA. Proceedings of Greening Rooftops for Sustainable Communities, 2003, Chicago, IL.

30 Portland. 2002. City of Portland EcoRoof Program Questions and Answers. Bureau of Environmental Services, Office of Sustainable Development, City of Portland, Oregon, PL 0203, Portland, OR.

31 Hutchinson, D., P. Abrams et al. 2003. Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA. Proceedings of Greening Rooftops for Sustainable Communities, 2003, Chicago, IL.

32 Moran, A., B. Hunt et al. 2004. A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff Quality, and Plant Growth. Paper Presented at Green Roofs for Healthy Cities Conference, Portland, OR, June 2004.

33 Banting, D., H. Doshi, J. Li, and P. Missios. 2005. Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto. Department of Architectural Science, Ryerson University.

34 Berghage, R., D. Beattie, A. Jarrett, and T. O'Conner. 2007. Greenroof Runoff Water Quality. Fifth Annual Greening Rooftops for Sustainable Communities Conference, April 29-May 1, 2007.

[35] Moran, A., B. Hunt et al. 2004. A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff Quality, and Plant Growth. Paper Presented at Green Roofs for Healthy Cities Conference, Portland, OR, June 2004.

[36] Hutchinson, D., P. Abrams et al. 2003. Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA. Proceedings of Greening Rooftops for Sustainable Communities, 2003, Chicago, IL.

[37] Van Seters, T., L. Rocha, and G. MacMillan. 2007. Evaluation of the Runoff Quantity and Quality Performance of an Existing Green Roof in Toronto, Ontario. Fifth Annual Greening Rooftops for Sustainable Communities Conference, April 29-May 1, 2007.

[38] Kohler, M. and M. Schmidt. 2003. Study on Extensive 'Green Roofs' in Berlin. Translated by S. Cacanindin. Retrieved 27 April 2006 from <www.roofmeadow.com>.

[39] Banting, D., H. Doshi, J. Li, and P. Missios. 2005. Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto. Department of Architectural Science, Ryerson University.

[40] Peck, S. and M. Kuhn. 2001. Design Guidelines for Green Roofs. National Research Council Canada, Toronto, Canada.

[41] Scholz-Barth, K. 2001. Green Roofs: Stormwater Management from the Top Down. Environmental Design & Construction.

[42] City of Los Angeles, Environmental Affairs Department. 2006. Green Roofs—Cooling Los Angeles (A Resource Guide). Los Angeles, CA.

[43] Peck, S. and M. Kuhn. 2001. Design Guidelines for Green Roofs. National Research Council Canada, Toronto, Canada.

[44] Rosenzweig, C., S. Gaffin, and L. Parshall (Eds.). 2006. Green Roofs in the New York Metropolitan Region: Research Report. Columbia University Center for Climate Systems Research and NASA Goddard Institute for Space Studies. New York. 59 pages.

[45] Clark, C., P. Adriaens, and F.B. Talbot. 2007. Green Roof Valuation: A Probabilistic Analysis of Environmental Benefits.

[46] Personal correspondence with Tom Liptan, Portland Bureau of Environmental Services, 18 December 2007.

[47] In 2005, Carnegie Mellon University replaced a stone ballast roof on Hamerschlag Hall with a green roof <http://www.greenroofs.com/projects/pview.php?id=292>. When Albemarle County replaced a stone ballast roof with a green roof in 2007, it did not have to modify the roof because the saturated vegetative layer weighed about the same as the stones and the underlying membrane and insulation remained the same <http://www.albemarle.org/department.asp?department=planning&relpage=8660>. In 2006, Tobyhanna Army Depot replaced a stone ballast roof with a modular green roof. The roof had already been designed with capacity to support an extra floor, so no modification was required to install a green roof <http://aec.army.mil/usaec/publicaffairs/update/win07/win0709.html>.

[48] Peck, S. and M. Kuhn. 2001. Design Guidelines for Green Roofs. National Research Council Canada, Toronto, Canada.

[49] Department of Energy. 2004. Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.

[50] Beattie, D., and R. Bergharge. 2004. Green Roof Media Characteristics: The Basics. In Greening Rooftops for Sustainable Communities, Portland, Oregon, June 2004.

[51] Scholz-Barth, K. 2001. Green Roofs: Stormwater Management from the Top Down. Environmental Design & Construction.

52 Department of Energy. 2004. Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.

53 Department of Energy. 2004. Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.

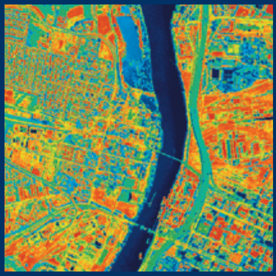
54 Coffman, R. *Vegetated Roof Systems: Design, Productivity, Retention, Habitat, and Sustainability in Green Roof and Ecoroof Technology*. (Doctoral Dissertation, The Ohio State University, 2007.)

55 Department of Energy. 2004. Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.

56 See, e.g., Department of Energy (2004). Federal Technology Alert: Green Roofs. DOE/EE-0298, Washington, D.C.; and City of Los Angeles, Environmental Affairs Department (2006). "Green Roofs—Cooling Los Angeles (A Resource Guide)." Los Angeles, CA.

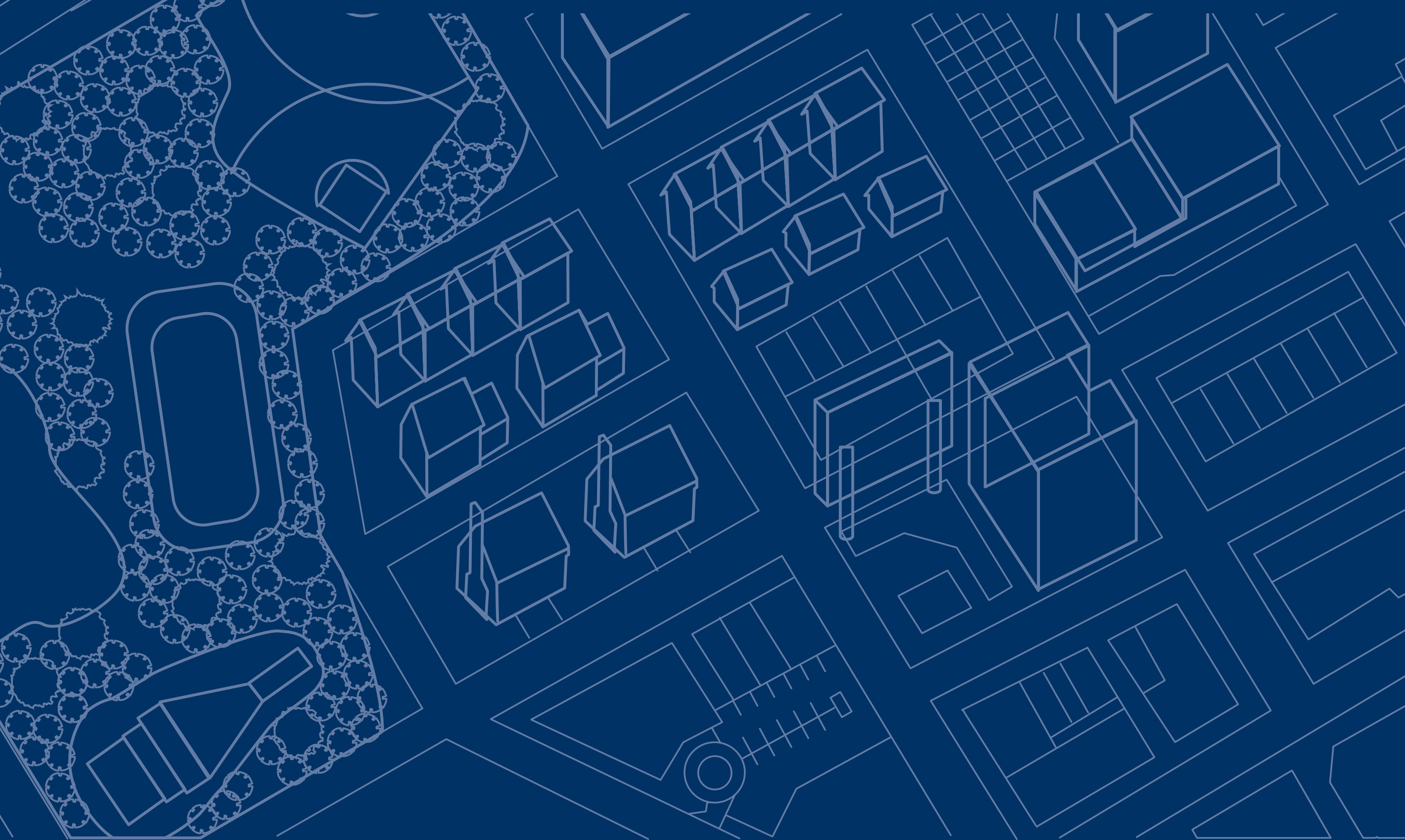
57 Peck, S. and M. Kuhn. 2001. Design Guidelines for Green Roofs. National Research Council Canada, Toronto, Canada.





Reducing Urban Heat Islands: Compendium of Strategies

Cool Roofs



Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

PositvEnergy provided support in preparing the Trees and Vegetation, Cool Roofs, and UHI Activities chapters under contract PO #2W-0361-SATX.

Experts who helped shape this chapter include:

Gregory Chin, Andre Desjarlais, Maury Estes, David Hitchcock, Megan Lewis, Danny Parker, Joyce Rosenthal, Lorraine Ross, Steve Ryan, Rachel Schmeltz, Peter Turnbull, and Barry Zalph.

Suggested Citation: U.S. Environmental Protection Agency. 2008. "Cool Roofs." In: *Reducing Urban Heat Islands: Compendium of Strategies. Draft*. https://www.epa.gov/heat-islands/heat-island-compendium.

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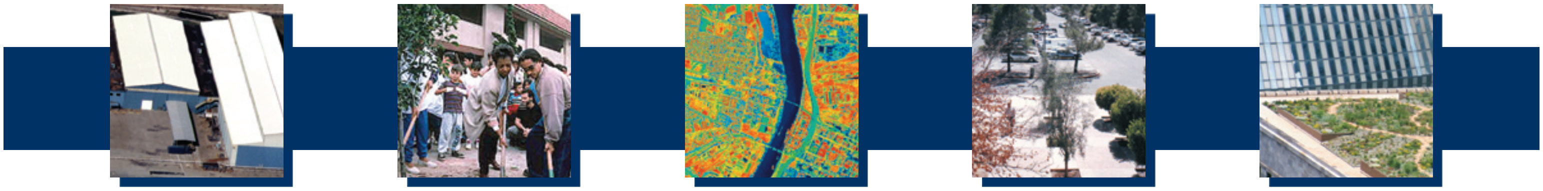


Cool Roofs

Cool roofing can help address the problem of heat islands, which results in part from the combined heat of numerous individual hot roofs in a city or suburb. Cool roofing products are made of highly reflective and emissive materials that can remain approximately 50 to 60°F (28-33°C) cooler than traditional materials during peak summer weather. Building owners and roofing contractors have used these types of cool roofing products for more than 20 years. Traditional roofs in the United States, in contrast, can reach summer peak temperatures of 150 to 185°F (66-85°C),[2] thus creating a series of hot surfaces as well as warmer air temperatures nearby.

This chapter provides detailed information that mitigation program organizers can use to understand, plan, and implement cool roofing projects and programs. The chapter discusses:

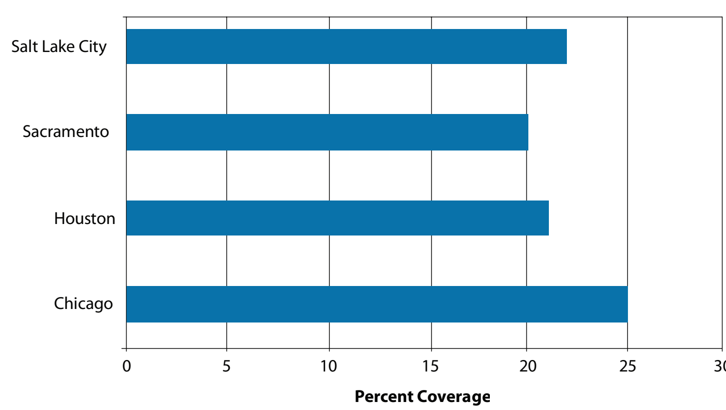
- Key cool roof properties and how they help to mitigate urban heat
- Types of cool roofing
- Specific benefits and costs of cool roofing
- Measurement and certification of cool roof products
- Installation and maintenance of cool roofs
- Tools and resources to further explore this technology.

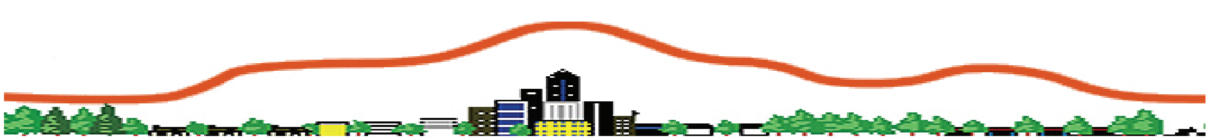
Opportunities to Expand Use of Cool Roofs in Urban Areas

Most U.S. cities have significant opportunities to increase the use of cool roofs. As part of the U.S. Environmental Protection Agency's (EPA's) Urban Heat Island Pilot Project, the Lawrence Berkeley National Laboratory conducted a series of analyses to estimate baseline land use and tree cover information for the pilot program cities.[1]

Figure 1 shows the percent of roof cover in four of these urban areas. The data are from 1998 through 2002. With roofs accounting for 20 to 25 percent of land cover, there is a large opportunity to use cool roofs for heat island mitigation.

Figure 1: Roof Cover Statistics for Four U.S. Cities (Below Tree Canopy)





1. How It Works

Understanding how cool roofing works requires knowing how solar energy heats roofing materials and how the properties of roofing materials can contribute to warming. This section explains solar energy, the properties of solar reflectance and thermal emittance, and the combined temperature effect of these two properties working together.

1.1 Solar Energy

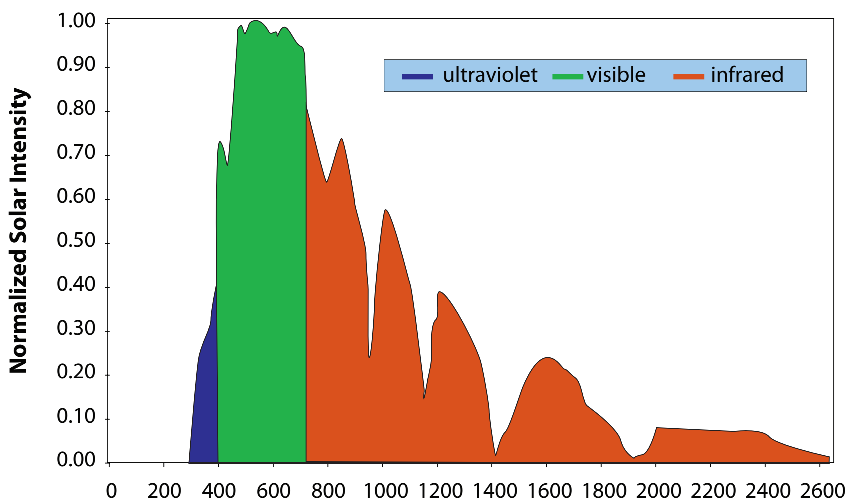
Figure 2 shows the typical solar energy that reaches the Earth's surface on a clear summer day. Solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: 5 percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn; 43 percent of solar energy is visible light, in colors ranging from violet to red; and the remaining 52 percent of solar energy is infrared, felt as heat.

Cool Roof Market

The number of ENERGY STAR® Cool Roof Partners has grown from 60 at the program's inception to nearly 200 by the end of 2007; the number of products has grown even faster, from about 100 to almost 1,600. Based on 2006 data from more than 150 ENERGY STAR Partners, shipments of ENERGY STAR products constitute about 25 percent of the commercial roofing market and about 10 percent of the residential market. The overall market share for these products is rising over time, especially with initiatives such as cool roof requirements in California.

"Cool roofing" refers to the use of highly **reflective and emissive materials.** "Green roofs" refer to rooftop gardens.

Figure 2: Solar Energy versus Wavelength Reaching Earth's Surface



Solar energy intensity varies over wavelengths from about 250 to 2500 nanometers. White or light colored cool roof products reflect visible wavelengths. Colored cool roof products reflect in the infrared energy range.

Many **cool roof products** are bright white. These products get their high solar reflectance primarily from **reflecting in the visible portion of the spectrum** depicted in Figure 2. Given the desire for colored roof products for many buildings, such as the typical single family home, manufacturers are continuing to develop cool colored **products that reflect in the "near-infrared" range,** or the infrared wavelengths from about 700 to 2500 nanometers shown in Figure 2.

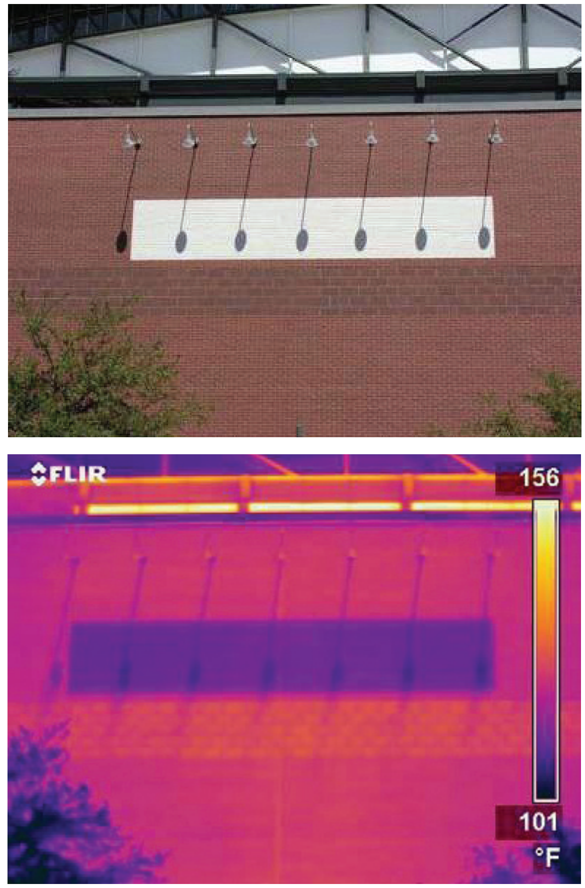
1.2 Solar Reflectance

Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface. Researchers have developed methods to determine solar reflectance by measuring how well a material reflects energy at each solar energy wavelength, then calculating the weighted average of these values (see Section 4.1). Traditional roofing materials have low solar reflectance of 5 to 15 percent, which means they absorb 85 to 95 percent of the energy reaching them instead of reflecting the energy back out to the atmosphere. The coolest roof materials have a high solar reflectance of more than 65 percent, absorbing and transferring to the building 35 percent or less of the energy that reaches them. These materials reflect radiation across the entire solar spectrum, especially in the visible and infrared (heat) wavelengths.

1.3 Thermal Emittance

Although solar reflectance is the most important property in determining a material's contribution to urban heat islands, thermal emittance is also a part of the equation. Any surface exposed to radiant energy will get hotter until it reaches thermal equilibrium (i.e., it gives off as much heat as it receives). A material's thermal emittance determines how much heat it will radiate per unit area at a given temperature, that is, how readily a surface gives up heat. When exposed to sunlight, a surface with high emittance will reach thermal equilibrium at a lower temperature than a surface with low emittance, because the high-emittance surface gives off its heat more readily.

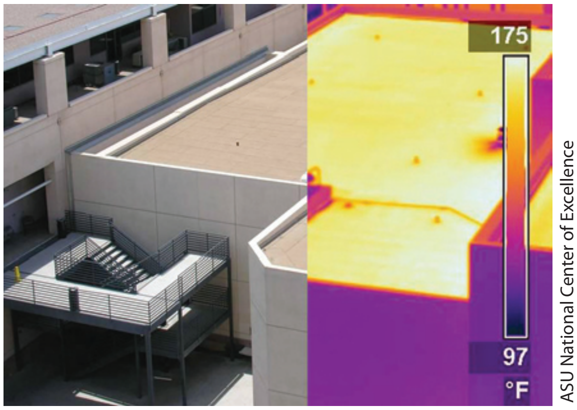
Figure 3: Effect of Albedo on Surface Temperature



ASU National Center of Excellence

Albedo alone can significantly influence surface temperature, with the white stripe on the brick wall about 5 to 10°F (3-5°C) cooler than the surrounding, darker areas.

Figure 4: Temperature of Conventional Roofing

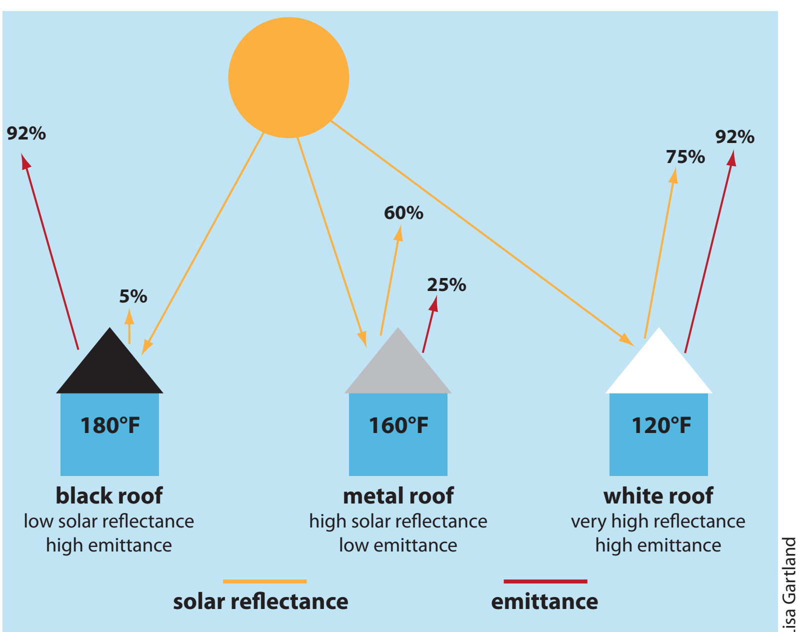


The left half of this traditional bitumen roof in Arizona is shown in visible wavelengths and the right in infrared. The roof's temperature reaches almost 175°F (80°C).

1.4 Temperature Effects

Solar reflectance and thermal emittance have noticeable effects on surface temperature. Figure 5 illustrates these differences using three different roof types. Conventional roof surfaces have low reflectance but high thermal emittance; standard black asphalt roofs can reach 165 to 185°F (74 - 85°C) at midday during the summer. Bare metal or metallic surfaced roofs have high reflectance and low thermal emittance and can warm to 150 to 165°F (66 - 77°C). Research has shown that cool roofs with both high reflectance and high emittance reach peak temperatures of only 110 to 115°F (43-46°C) in the summer sun. These peak values vary by local conditions. Nonetheless, research reveals that conventional roofs can be 55 to 85°F (31-47°C) hotter than the air on any given day, while cool roofs tend to stay within 10 to 20°F (6-11°C) of the background temperature.[3]

Figure 5: Example of Combined Effects of Solar Reflectance and Thermal Emittance on Roof Surface Temperature[4]



On a hot, sunny, summer day, a black roof that reflects 5 percent of the sun's energy and emits more than 90 percent of the heat it absorbs can reach 180°F (82°C). A metal roof will reflect the majority of the sun's energy while releasing about a fourth of the heat that it absorbs and can warm to 160°F (71°C). A cool roof will reflect and emit the majority of the sun's energy and reach a peak temperature of 120°F (49°C).

These reduced surface temperatures from cool roofs can lower air temperature. For example, a New York City simulation predicted near-surface air temperature reductions for various cool roof mitigation scenarios. The study assumed 50-percent adoption of cool roofs on available roof space and ran models to evaluate the resulting temperature changes. Averaged over all times of day, the model predicted a city-wide temperature reduction of 0.3°F (0.2°C). The city-wide, 3:00 p.m. average reduction was 0.6°F (0.3°C) and ranged from 0.7 to 1.4°F (0.4 - 0.8°C) in six specific study areas within the city.[5]

2. Cool Roof Types

There are generally two categories of roofs: low-sloped and steep-sloped. A low-sloped roof is essentially flat, with only enough incline to provide drainage. It is usually defined as having no more than 2 inches (5 cm) of vertical rise over 12 inches (30 cm) of horizontal run, or a 2:12 pitch. These roofs are found on the majority of commercial, industrial, warehouse, office, retail, and multi-family buildings, as well as some single-family homes.

Figure 6: Low-Sloped Cool Roof

Ron Whipple/SWD Urethane

Buildings with a large roof area relative to building height, such as this warehouse, make ideal candidates for cool roofing, as the roof surface area is the main source of heat gain to the building.

Steep-sloped roofs have inclines greater than a 2-inch rise over a 12-inch run. These roofs are found most often on residences and retail commercial buildings and are generally visible from the street.

2.1 Low-Sloped Cool Roofs

Low-sloped and steep-sloped roofs use different roofing materials. Traditionally, low-sloped roofs use built-up roofing or a membrane, and the primary cool roof options are coatings and single-ply membranes.

Figure 7: Cool Coating Being Sprayed onto a Rooftop

Lisa Gartland/PositivEnergy

Cool coating being sprayed onto a rooftop.

Cool Roof Coatings. Coatings are surface treatments that are best applied to low-sloped roofs in good condition. They have the consistency of thick paint and contain additives that improve their adhesion, durability, suppression of algae and fungal growth, and ability to self-wash, or shed dirt under normal rainfall. Building owners can apply cool roof coatings to a wide range of existing surfaces, including asphalt capsheet, gravel, metal, and various single-ply materials.

When purchasing cool roof elastomeric coatings, building owners can require that products meet the **ASTM international standard, ASTM D 6083-05e1,** "Standard Specification for Liquid Applied Acrylic Coating Used in Roofing," to ensure the product achieves certain specifications. There is currently no similar standard for cementitious coatings.

There are two main types of cool roof coatings: cementitious and elastomeric. Cementitious coatings contain cement particles. Elastomeric coatings include polymers to reduce brittleness and improve adhesion. Some coatings contain both cement particles and polymers. Both types have a solar reflectance of 65 percent or higher when new and have a thermal emittance of 80 to 90 percent or more. The important distinction is that elastomeric coatings provide a waterproofing membrane, while cementitious coatings are pervious and rely on the underlying roofing material for waterproofing.

Common Cool Single-Ply Materials

- **EPDM (ethylene propylene diene monomer),** a synthetic rubber material, with seams that must be glued or taped together.
- **CSPE (chlorosulfonated polyethylene),** a polymer material, with seams that can be heat-welded together.
- **PVC (polyvinyl chloride) and TPO (thermoplastic olefins),** thermoplastic materials, with seams that can be heat-welded together.

Single-Ply Membranes. Single-ply membranes come in a pre-fabricated sheet that is applied in a single layer to a low-sloped roof. The materials are generally glued or mechanically fastened in place over the entire roof surface, with the seams sealed by taping, gluing, or heat-welding. A number of manufacturers formulate these products with cool surfaces.

Building owners generally consider cool roof options when their roof begins to fail. They typically use a ***cool roof coating*** if an existing roof needs only moderate repair, and a ***single-ply membrane*** for more extensive repairs. The cut-off point between moderate and extensive repairs is not easily determined. In making a choice between these options, however, building owners can gather input from many sources, including roofing consultants and contractors, product manufacturers, and contacts at other facilities that have had cool roofing installed.

2.2 Steep-Sloped Cool Roofs

Most cool roof programs focus on the low-sloped roofing sector, but cool roof options are becoming available for the steep-sloped sector as well. Asphalt shingles are the

Figure 8: Conventional and Cool Colored Tiles

Cool roof products can be indistinguishable from their conventional counterparts. The rightmost row of curved tiles uses conventional colored pigments, whereas the other two rows use cool pigments.

most common roofing materials used on steep-sloped roofs. Other products include metal roofing, tiles, and shakes.

The market for steep-sloped cool roofing materials is growing, although the solar reflectance for these products is generally lower than for low-sloped cool roofs. A number of products are available for tiles and painted metal roofing.

The solar reflectance of traditional tiles, typically made of clay or concrete, ranges from 10 to 30 percent. Manufacturers have begun producing "cool colored" tiles that contain pigments that reflect solar energy in the infrared spectrum. The ENERGY STAR Roof Products List as of April 2008 has approved tiles for steep-sloped roofs with initial solar reflectances ranging from 25 to almost 70 percent, depending on color. These tiles come in traditional colors, such as brown, green, and terra cotta. They are durable and long-lasting, but not widely used. Where tiles are used, the cool tile alternatives can be available at little or no incremental cost over traditional tiles.[6]

Cool Colors

The California Energy Commission has sponsored the "Cool Colors Project," under which LBNL and Oak Ridge National Laboratory (ORNL) are collaborating with roofing industry partners to research and develop cool colored roof products that could expand significantly the use of cool roofing in the residential sector. See <http://coolcolors.lbl.gov/> for more information.

Figure 9: Cool Metal Roofing

Cool colored metal roofs lend themselves readily to the steep-sloped market, as this house demonstrates.

Cool colored metal roofing products also use infrared-reflecting pigments and have high durability and long life. About one-half of the products on the ENERGY STAR Roof Products List as of April 2008 were metal roofing products for steep-sloped roofs, with initial solar reflectances ranging from about 20 to 90 percent.

Asphalt shingles are the most commonly used material for steep-sloped roofs, with a market share of about 50 percent, depending on the region,[7] and a low initial cost of just over $1.00 per square foot (0.930 m^2). As of April 2008, several manufacturers offered a line of asphalt shingles on the ENERGY STAR Roof Products List, with initial solar reflectances ranging from about 25 to 65 percent. Other shingle products on the list are metal. Manufacturers, researchers, and other stakeholders are working together to develop additional, cool-colored shingle products that use infrared-reflecting pigments.[8]

3. Benefits and Costs

The use of cool roofs as a mitigation strategy brings many benefits, including lower energy use, reduced air pollution and greenhouse gas emissions, and improved human health and comfort. At the same time, there can be a cost premium for some cool roof applications versus traditional roofing materials. This section highlights some of the key benefits and costs of cool roof programs and individual projects. Section 6 also introduces cool roof energy savings calculators that community planners or individual building owners can use to help determine whether to pursue cool roofs as a mitigation option.

3.1 Benefits

Reduced Energy Use. A cool roof transfers less heat to the building below, so the building stays cooler and more comfortable and uses less energy for cooling. Every building responds differently to the effects of a cool roof. For example, Table 1 lists examples of the general characteristics and cooling energy savings of different one-story buildings in California, Florida, and Texas. The measured savings varied from 10 to almost 70 percent of each building's total cooling energy use. In addition, a 2004 report summarized more than 25 articles about the cooling energy used by buildings with cool roofs and identified energy savings ranging from 2 to over 40 percent, with average savings of about 20 percent.[9]

Local climate and site-specific factors, such as insulation levels, duct placement, and attic configuration, play an important role in the amount of savings achieved (see the range in Table 1). Other site-specific variables also can strongly influence the amount of energy a particular building will save. For example, a study of a San Jose, California, drug store documented cooling energy savings of only 2 percent. The cooling demands in this store were driven by the design of the building, including a radiant barrier under the roof and a well ventilated plenum space, so that heat transfer through the roof contributed little to the store's cooling demand.[10] Thus, in gauging potential energy savings for a particular building, the building owners will need to consider a range of factors to make cool roofing work for them.

Another benefit of cool roofing is that it saves energy when most needed—during peak electrical demand periods that generally occur on hot, summer weekday afternoons, when offices and homes are running cooling systems, lights, and appliances. By reducing cooling system needs, a cool roof can help building owners reduce peak electricity demand. The last column in Table 1 lists reductions in the peak demand for cooling energy that range from 14 to 38 percent after installation of a cool roof.

Lower peak demand not only saves on total electrical use but also can reduce demand fees that some utilities charge commercial and industrial building owners. Unlike residential customers, who pay for only the amount of electricity they use, commercial and industrial customers often pay an additional fee based on the amount of peak power they demand. Because cool roofing helps reduce their peak demand, it lowers these costs.

Insulation and R-Values

The "R-value" of building insulation indicates its ability to impede heat flow. Higher R-values are correlated with greater insulating properties.

Researchers have conducted in-depth modeling to assess how building-level energy savings can affect city-wide energy usage. The Lawrence Berkeley National Laboratory (LBNL) ran simulations to evaluate the net energy impacts of applying cool roofing in 11 U.S. cities.[11] The original study was based on 1993 energy prices and buildings that use electrical cooling systems and gas furnaces. Figure 10 uses 2003 state-level prices for electricity and natural gas, based on Energy Information Administration data for the commercial sector.

Cool roofs reflect solar energy year round, which can be a disadvantage in the winter as they reflect away desirable wintertime heat gain. The net effect is generally positive, though, because most U.S. cities have high cooling and peak cooling demand, and electricity is expensive. Figure 10 presents the total anticipated cooling energy savings and the net savings after considering increased heating costs. Although northern and mid-Atlantic cities with relatively long heating seasons, such as Chicago, Philadelphia, and Washington D.C., still reap net savings, the net benefits for New York City remain particularly high because of the high price of electricity in that area. (See Section 3.2 for further discussion of the heating penalty.)

This same LBNL study extrapolated the results to the entire United States and estimated that widespread use of cool roofs

Table 1: Reported Cooling Energy Savings from Buildings with Cool Roofs[12]

Building	Location	Citation	Size (ft^2)	Roof Insulation*	Roof Space	Annual Cooling Saved	Peak Demand Savings
Residence	Merritt Island, FL	(Parker, D., S. Barkaszi, et al. 1994)	1,800	R-25	Attic	10%	23%
Convenience Retail	Austin, TX	(Konopacki, S. and H. Akbari 2001)	100,000	R-12	Plenum	11%	14%
Residence	Cocoa Beach, FL	(Parker, D., J. Cummings, et al. 1994)	1,795	R-11	Attic	25%	28%
Residence	Nobleton, FL	(Parker, D., S. Barkaszi, et al. 1994)	900	R-3	Attic	25%	30%
School Trailer	Volusia County, FL	(Callahan, M., D. Parker, et al. 2000)	1,440	R-11	None	33%	37%
School Trailer	Sacramento, CA	(Akbari, H., S. Bretz, et al. 1993)	960	R-19	None	34%	17%
Our Savior's School	Cocoa Beach, FL	(Parker, D., J. Sherwin, et al. 1996)	10,000	R-19	Attic	10%	35%
Residence	Cocoa Beach, FL	(Parker, D., J. Cummings, et al. 1994)	1,809	None	Attic	43%	38%
Residence	Sacramento, CA	(Akbari, H., S. Bretz, et al. 1993)	1,825	R-11	None	69%	32%

* Note: These insulation levels are lower than the energy efficiency levels recommended by ENERGY STAR. If insulation levels were higher, the cooling savings likely would be less.

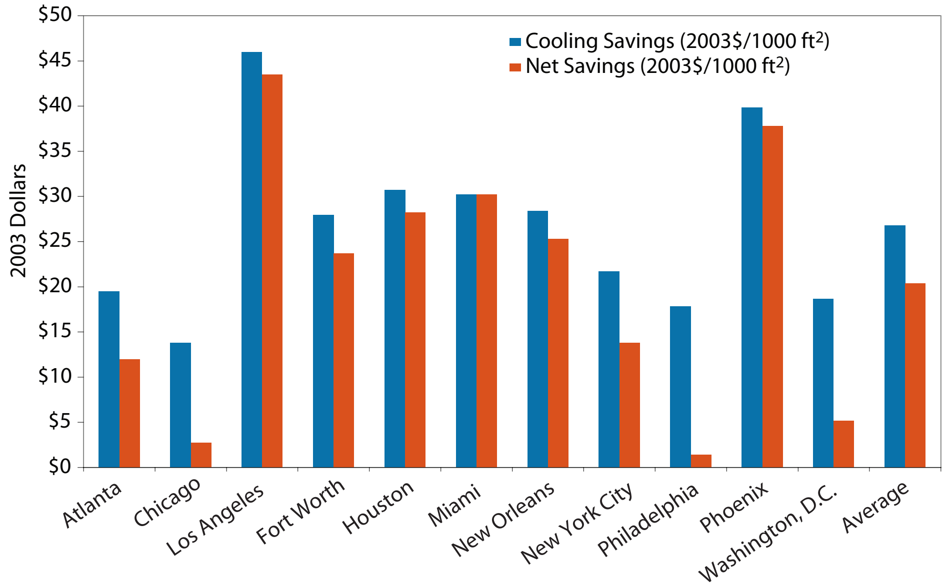
could reduce the national peak demand for electricity by 6.2 to 7.2 gigawatts (GW),[13] or the equivalent of eliminating the need to build 12 to 14 large power plants that have an energy capacity of 500 megawatts each.

Reduced Air Pollution and Greenhouse Gas Emissions. The widespread adoption of heat island mitigation efforts such as cool roofs can reduce energy use during the summer months. To the extent that reduced energy demand leads to reduced burning of fossil fuels, cool roofs contribute to fewer emissions of air pollutants, such as nitrogen oxides (NO_X), as well as greenhouse gases, primarily carbon dioxide (CO_2). The CO_2 reductions can be substantial. For example, one study estimated potential CO_2 reductions of 6 to 7 percent in Baton Rouge and Houston from reduced building energy use.[14] Reductions in air pollutant emissions such as NO_X generally provide benefits in terms of improved air quality, particularly ground-level ozone

Case Examples of Building Comfort Improvements

- **"Big-box" retailer Home Base, Vacaville, California.**[15] Installing a cool roof at this store helped solve the problem created by an incorrectly sized cooling system. This store used an undersized evaporative cooling system that was unable to meet the building's cooling loads. Indoor temperatures above 90°F (32°C) were recorded, even with the building coolers working around the clock. After adding a cool roof, peak indoor temperatures were reduced to 85°F (29°C) or lower, and 10 more shopping hours a week were deemed comfortable (below 79°F (26°C) and 60 percent humidity) inside the store. Although the evaporative coolers were still not powerful enough to meet the hottest conditions, the cool roof helped reduce temperatures inside the store.
- **Apartment complex, Sacramento, California.**[16] Adding cool roofs at these residences lowered indoor air temperatures, improving resident comfort. These non-air conditioned buildings were composed of two stories and an attic, with an R-38 level of insulation above the second story and below the attic space. Adding a cool roof lowered peak air temperatures in the attic by 30 to 40°F (17-22°C). Generally, the higher the insulation level, the less effect a cool roof will have on the space beneath it; however, in this case, even with high insulation levels, the cool roof reduced second-story air temperatures by 4°F (2°C) and first floor temperatures by 2°F (1°C).
- **Private elementary school, Cocoa Beach, Florida.**[17] Cool roof coatings at this school improved comfort and saved energy. This 10,000-square foot (930 m^2) facility had an asphalt-based roof, gray modified bitumen, over plywood decking with a measured solar reflectance of 23 percent. The dropped ceiling was insulated to R-19 levels, and insulated chiller lines were used in the hot roof plenum space. Once the roof was covered by an acrylic white elastomeric coating, the solar reflectance rose to 68 percent. The classrooms became cooler and the chiller electric use was reduced by 10 percent. School staff noticed improved comfort levels due to the new roof.

Figure 10: Modeled Net Energy Cost Savings* ($/1,000 ft^2) in Various U.S. Cities from Widespread Use of Cool Roofing[18]



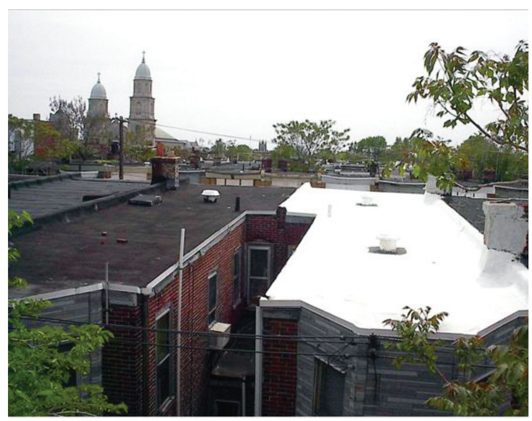
Costs are based on state-specific data applied to each city, using 2003 Energy Information Administration reported prices for the commercial sector.[19]

(smog). The relationships between pollutant reductions and improved air quality are complex, however, and require air quality modeling to demonstrate the benefits in specific urban areas.

Improved Human Health and Comfort. Ceilings directly under hot roofs can be very warm. A cool roof can reduce air temperatures inside buildings with and without air conditioning.

For residential buildings without air conditioning, cool roofs can provide an important public health benefit during heat waves. For example, Philadelphia operates a program to add cool roofs and insulation to residential buildings that lack air conditioning to prevent heat-related illnesses and deaths. A study measured significant cooling benefits from this program.[20] The study controlled for differences in outside temperature before and after the installing the cool roofs and insulation; these treatments lowered the daily maximum ceiling surface temperature by about 4.7°F (2.6°C), while daily maximum room air temperatures dropped by about 2.4°F (1.3°C). The study noted that on a 95°F (35°C) day, these types of reductions represent large reductions in heat gain to the room and significantly improve perceived human comfort.

Figure 11: Cool Roofing on Urban Row Homes



Energy Coordinating Agency, Philadelphia

Philadelphia reduced temperatures in row houses by installing cool roofs, which improves the comfort for occupants and may help reduce deaths from excessive heat events. Baltimore, with similar building stock, took similar steps following the success in Philadelphia.

3.2 Potential Adverse Impacts

Cool roofs can have a wintertime heating penalty because they reflect solar heat that would help warm the building. Although building owners must account for this penalty in assessing the overall benefits of cool roofing strategies, in most U.S. climates this penalty is not large enough to negate the summertime cooling savings because:

- The amount of useful energy reflected by a cool roof in the winter tends to be less than the unwanted energy reflected in the summer. This difference occurs primarily because winter days are shorter, and the sun is lower in the sky. The sunlight strikes the Earth at a lower angle, spreading the energy out over a larger area and making it less intense. In mid-Atlantic and northern states with higher heating requirements, there also are more cloudy days during winter, which reduces the amount of sun reflected by a cool roof. Snow cover on roofs in these climates also can reduce the difference in solar reflectivity between cool and non-cool roofs.
- Many buildings use electricity for cooling and natural gas for heating. Electricity has traditionally been more expensive than natural gas per unit of energy, so the net annual energy savings translate into overall annual utility bill savings. Note, however, that natural gas and electricity prices have been volatile in some parts of the country, particularly since 2000. As shown in Figure 10, with elevated natural gas prices in recent years, the net benefit in terms of cost savings might be small in certain northern cities with high heating demands.

California-based research indicates a **cost premium ranging from zero to 20 cents per square foot** for cool roof products.

3.3 Costs

A 2006 report (see Table 2) investigated the likely initial cost ranges for various cool roof products.[21] The comparisons in Table 2 are indicative of the trade-offs in cost and reflectance and emittance factors between traditional and cool roof options. For low-sloped roofs, the report noted that:

- Cool roof coatings might cost between $0.75 and $1.50 per square foot for materials and labor, which includes routine surface preparation like pressure-washing, but which does not include repair of leaks, cracks, or bubbling of the existing roof surface.
- Single-ply membrane costs vary from $1.50 to $3.00 per square foot, including materials, installation, and reasonable preparation work. This cost does not include extensive repair work or removal and disposal of existing roof layers.
- For either type of cool roof, there can be a cost premium compared to other roofing products. In terms of dollars per square foot, the premium ranges from zero to 5 or 10 cents for most products, or from 10 to 20 cents for a built-up roof with a cool coating used in place of smooth asphalt or aluminum coating.
- As with any roofing job, costs depend on the local market and factors such as the size of the job, the number of roof penetrations or obstacles, and the ease of access to the roof. These variables often outweigh significantly the difference in costs between various roofing material options.[22]

Table 2: Comparison of Traditional and Cool Roof Options[23]

Warmer Roof Options				Cooler Roof Options			
Roof Type	Reflectance	Emittance	Cost ($/ft²)	Roof Type	Reflectance	Emittance	Cost ($/ft²)
Built-up Roof			**1.2-2.1**	**Built-up Roof**			**1.2-2.15**
With dark gravel	0.08-0.15	0.80-0.90		With white gravel	0.30-0.50	0.80-0.90	
With smooth asphalt surface	0.04-0.05	0.85-0.95		With gravel and cementitious coating	0.50-0.70	0.80-0.90	
With aluminum coating	0.25-0.60	0.20-0.50		Smooth surface with white roof coating	0.75-0.85	0.80-0.90	
Single-Ply Membrane			**1.0-2.0**	**Single-Ply Membrane**			**1.0-2.05**
Black (PVC)	0.04-0.05	0.80-0.90		White (PVC)	0.70-0.78	0.80-0.90	
				Color with cool pigments	0.40-0.60	0.80-0.90	
Modified Bitumen			**1.5-1.9**	**Modified Bitumen**			**1.5-1.95**
With mineral surface capsheet (SBS, APP)	0.10-0.20	0.80-0.90		White coating over a mineral surface (SBS, APP)	0.60-0.75	0.80-0.90	
Metal Roof			**1.8-3.7**	**Metal Roof**			**1.8-3.75**
Unpainted, corrugated	0.30-0.50	0.05-0.30		White painted	0.60-0.70	0.80-0.90	
Dark-painted, corrugated	0.05-0.08	0.80-0.90		Color with cool pigments	0.40-0.70	0.80-0.90	
Asphalt Shingle			**0.5-2.0**	**Asphalt Shingle**			**0.6-2.1**
Black or dark brown with conventional pigments	0.04-0.15	0.80-0.90		"White" (light gray)	0.25-0.27	0.80-0.90	
				Medium gray or brown with cool pigments	0.25-0.27	0.80-0.90	
Liquid Applied Coating			**0.5-0.7**	**Liquid Applied Coating**			**0.6-0.8**
Smooth black	0.04-0.05	0.80-0.90		Smooth white	0.70-0.85	0.80-0.90	
				Smooth, off-white	0.40-0.60	0.80-0.90	
				Rough white	0.50-0.60	0.80-0.90	
Concrete Tile			**1.0-6.0**	**Concrete Tile**			**1.0-6.0**
Dark color with conventional pigments	0.05-0.35	0.80-0.90		White	0.70	0.80-0.90	
				Color with cool pigments	0.40-0.50	0.80-0.90	
Clay Tile			**3.0-5.0**	**Clay Tile**			**3.0-5.0**
Dark color with conventional pigments	0.20	0.80-0.90		White	0.70	0.80-0.90	
				Terra cotta (unglazed red tile)	0.40	0.80-0.90	
				Color with cool pigments	0.40-0.60	0.80-0.90	
Wood Shake			**0.5-2.0**	**Wood Shake**			**0.5-2.0**
Painted dark color with conventional pigment	0.05-0.35	0.80-0.90		Bare	0.40-0.55	0.80-0.90	

3.4 Benefit-Cost Considerations

Based on the benefits of cool roofs and the cost premiums noted in Table 2, a community can develop a benefit-cost analysis to determine whether a cool roof project or program will provide overall net benefits in a given area. For example, the cost study referenced in Table 2 also evaluated the cost effectiveness of low-sloped cool roofs for commercial buildings in California by quantifying five parameters (see summary results in Table 3):[24]

- Annual decrease in cooling electricity consumption
- Annual increase in heating electricity and/or gas
- Net present value (NPV) of net energy savings
- Cost savings from downsizing cooling equipment
- Cost premium for a cool roof

The study recognized that other parameters can provide benefits or reduce costs that were not part of the analysis. These include:

- Reduced peak electric demand for cooling
- Financial value of rebates or energy saving incentives that can offset the cost premiums for cool roofing materials
- Reduced material and labor costs over time resulting from the extended life of the cool roof compared to a traditional roof

Given the information at hand, the study found that expected total net benefits, after considering heating penalty costs, should range from \$0.16 to \$0.66/square foot (average \$0.47/ft^2) based on the California climate zones studied (see Table 3). California relied in part on this benefit-cost analysis to establish mandatory statewide low-sloped cool roof requirements.

In 2006, California began evaluating whether to extend the state's mandatory cool roof requirements to the steep-sloped market. One analysis in support of this approach anticipated positive cost effectiveness in many but not all California climate zones.[25] The state will consider that analysis, as well as public comments on benefits and costs in deciding what final action to take on steep-sloped roof requirements. A final rule is expected in 2008.

Although the results of Table 3 are specific to California in terms of electricity rates and typical cooling and heating energy use, the cost effectiveness approach can be replicated by other communities considering cool roof projects or programs.

Figure 12: Cool Roof on a Condominium

Homeowners can also reap the benefits of cool roofs.

Table 3: Example Cool Roof Cost/Benefit Summary for California[26]

California Climate Zone	Roof R-Value	Annual Energy/1000 ft^2			Peak Power/1000 ft^2		Net Present Value (NPV)/1000 ft^2			
		kWh	therm	Source MBTU	kW	$equip	$kWh	$therm	$energy	$total
1	19	115	-8.3	0.3	0.13	67	157	-62	95	162
2	19	295	-5.9	2.4	0.20	100	405	-43	362	462
3	19	184	-4.9	1.4	0.15	76	253	-35	218	294
4	19	246	-4.2	2.1	0.18	90	337	-31	306	396
5	19	193	-4.7	1.5	0.17	83	265	-35	230	313
6	11	388	-4.1	3.6	0.22	111	532	-29	503	614
7	11	313	-2.6	2.9	0.25	125	428	-20	408	533
8	11	413	-3.7	3.9	0.25	125	565	-28	537	662
9	11	402	-4.5	3.7	0.20	101	552	-33	519	620
10	19	340	-3.6	3.1	0.18	89	467	-26	441	530
11	19	268	-4.9	2.3	0.15	75	368	-37	331	406
12	19	286	-5.3	2.4	0.19	95	392	-39	353	448
13	19	351	-5.1	3.1	0.19	96	480	-37	443	539
14	19	352	-4.7	3.1	0.21	105	483	-33	450	555
15	19	380	-1.7	3.7	0.16	82	520	-13	507	589
16	19	233	-10.6	1.3	0.18	90	319	-78	242	332
min		115	-10.6	0.3	0.13	67	157	-78	95	162
max		413	-1.7	3.9	0.25	125	565	-13	537	662
avg		297	-4.9	2.6	0.19	94	408	-36	372	466

* This table presents dollar savings from reduced air conditioning use (in kWh) and reduced air conditioning equipment sizing ($equip), offset by natural gas heating penalty costs (measured in therms). The "Net Present Value (NPV)/1000 ft^2" column uses the kWh and therm information to project savings for energy only and in total (energy plus equipment).

4. Other Factors to Consider

4.1 Product Measurement

To evaluate how "cool" a specific product is, ASTM International has validated test methods to measure solar reflectance and thermal emittance (see Table 4). The Cool Roof Rating Council (CRRC) also has developed a test method for variegated roof products such as composite shingles, including laboratory and field tests. Laboratory measurements help determine the properties of new material samples, while field measurements are useful for evaluating how well a roof material has withstood the test of time, weather, and dirt.

The final method listed in Table 4 is not an actual test but a way to calculate the "solar reflectance index" or SRI. The SRI is a value that incorporates both solar reflectance and thermal emittance in a single value to represent a material's temperature in the sun. This index compares how hot a surface would get compared to a standard black and a standard white surface. In physical terms, this scenario is like laying a roof material next to a black surface and a white surface and measuring the temperatures of all three surfaces in the sun. The SRI is a value between zero (as hot as a black surface) and 100 (as cool as a white surface) and calculated as follows:

$$SRI = \frac{(Tblack - Tsurface)}{(Tblack - Twhite)} \times 100$$

Table 4: Test Methods to Evaluate Coolness of Roofing Materials

Property	Test Method	Equipment Used	Test Location
Solar reflectance	ASTM E 903 - Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres	Integrating sphere spectrophotometer	Laboratory
Solar reflectance	ASTM C 1549 - Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer	Portable solar reflectometer	Laboratory or field
Solar reflectance	ASTM E 1918 - Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field	Pyranometer	Field
Solar reflectance	CRRC Test Method #1 (for variegated roof products, [i.e. products with discrete markings of different colors]); used in conjunction with ASTM C1549	Portable solar reflectometer	Laboratory or field
Thermal emittance	ASTM E 408-71 - Standard Test Method for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques	Reflectometer or emissometer	Laboratory
Thermal emittance	ASTM C 1371 - Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers	Emissometer	Field
Solar reflectance index	ASTM E 1980 - Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces	None (calculation)	---

The U.S. Green Building Council, as part of its **Leadership in Energy and Environmental Design (LEED) Rating System,** has developed an SRI Calculator to assist project sponsors in calculating a roof's SRI under "LEED-NC, Version 2.2, Sustainable Site Credit 7.2: Heat Island Effect: Roof." See <www.usgbc.org>.

4.2 Product Labeling

ENERGY STAR for Roof Products and the Cool Roof Rating Council (CRRC) both operate voluntary labeling programs for manufacturers. Many building codes and energy efficiency rebate programs require that cool roofing materials meet recognized specifications and standards, and that a vendor's product be listed with either or both of these voluntary labeling programs.

Figure 13: Olympic Oval, Salt Lake City, Utah

Sika Sarnafil, Inc.

The Olympic Oval features a cool roof covering almost 205,000 square feet (19,000 m^2). ENERGY STAR partners, who helped build the oval's roof, have played key roles in advancing cool roofing technology.

ENERGY STAR for Roof Products. Manufacturers can participate voluntarily in the ENERGY STAR for Roof Products program. A product qualifies for ENERGY STAR if it meets the solar reflectance criteria expressed in Table 5. The program uses significantly different criteria for low-sloped versus steep-sloped roof products. Highly reflective products, which are currently bright white for the most part, are available for low-sloped roofs. For aesthetic reasons, bright white options are generally not marketable for steep-sloped roofs. Instead, steep-sloped cool roof products generally use moderately reflective, colored options.

Version 2.0 of the program guidelines became effective in January 2008. The guidelines require manufacturers to test their products' initial solar reflectance and maintenance of solar reflectance after at least three years of service. For the initial testing, manufacturers can rely on tests conducted for purposes of certifying a product under the Cool Roof Rating Council's Product Rating Program, if applicable. To ensure the long-term integrity of reflective products, ENERGY STAR also requires products to maintain warranties comparable to those offered for non-reflective roof products. Finally, the Version 2.0 guidelines also require manufacturers to report a product's initial emissivity as part of the application process. There is no emissivity level required, but this information can provide valuable information on the potential savings and benefits

The most up-to-date list of **ENERGY STAR qualified roof products,** and current, proposed, and prior specifications, can be found on the ENERGY STAR Web site at <www.energystar.gov>.

Table 5: ENERGY STAR for Roof Products (Version 2.0) Qualifying Criteria

Type of Roof Product	Initial Solar Reflectance		Maintenance of Solar Reflectance*	
	Standard	Test Methods	Standard	Test Methods
Low-sloped	65% or higher	ASTM E 903 or ASTM C 1549**	50% or higher	ASTM E 1918 or ASTM C 1549
Steep-sloped	25% or higher	ASTM E 903 or ASTM C 1549**	15% or higher	ASTM C 1549

* Maintenance of solar reflectance is measured on a roof that has been in service for three years or more.
** Manufacturers can also use CRRC Test Method #1 for variegated roof products and can use results from tests conducted as part of CRRC Product Rating Program certification.

of a specific product in the region where it will be used.

Based on data from almost 90 percent of the ENERGY STAR Partners, the market share of cool roof products from these manufacturers has grown in recent years. In 2004, cool roof products represented 8 percent of these manufacturers' shipments in the commercial roofing sector and 6 percent in the residential. In 2006, their shipments of commercial cool roof product tripled to represent more than 25 percent of their commercial roof products, and the residential share almost doubled, reaching 10 percent.

Cool Roof Rating Council. CRRC is a non-profit organization with members from the business, consulting, and research fields. The CRRC was formed in 1998 and applied to join the American National Standards Institute (ANSI) ten years later. In September 2002, CRRC launched its product rating program with a list of solar reflectance and thermal emittance values of roofing materials. As of February 2007, this list included only initial or new values of roofing material properties, but work is underway to add three-year weathered values to the list. The weathered values of solar reflectance and thermal emittance will come from test farms located in different areas of the country, where roof materials are exposed to the elements for three years.

See the **CRRC Rated Product Directory** at <www.coolroofs.org>.

Manufacturer participation in the CRRC program is entirely voluntary. Participating manufacturers must adhere to stringent requirements; however, to ensure accurate reported values, only agencies or laboratories accredited by CRRC can perform tests, and their test programs must use the ASTM and CRRC standards listed in Table 4.

A material does not need to meet a solar reflectance or thermal emittance value to appear on the CRRC Rated Product Directory roofing products list. Because any product can be listed, regardless of how cool it might be, it is up to the consumer to check the values on the CRRC list and decide which products meet their own criteria for cool materials. Building owners and heat island mitigation groups can use the CRRC ratings in conjunction with the ENERGY STAR guidelines to help to identify cool materials on the basis of solar reflectance.

4.3 Installation and Maintenance

A coating or single-ply membrane on a low-sloped roof can serve as the top surface of a roofing assembly and can be applied directly over a roof deck or on top of other existing materials. Proper installation is important to the long-term success of a cool roof project. For example, when applied properly, many cool roof coatings have been shown to last more than 20 years. When applied poorly, cool roof coatings can peel or flake off the roof within a couple of years. To ensure good product performance, building owners can seek appropriate warranties for both the product and the installation service.

On **steep-sloped roofs,** professionals do not recommend using cool coatings over existing shingles. This technique can cause moisture problems and water damage because the coating can inhibit normal shingle drying after rain or dew accumulation, allowing water to condense and collect under the shingles.

A key concern for cool roofs is maintaining their high solar reflectance over time. If a building's roof tends to collect large amounts of dirt or particulate matter, washing the roof according to the manufacturer's recommended maintenance procedures can help retain solar reflectance. Also, smoother surfaces and higher sloped surfaces tend to withstand weathering better. With proper maintenance, coatings are able to retain most of their solar reflectance, with decreases of only about 20 percent, usually in the first year after application of the coating.[27]

Figure 14: Installation of a Cool Single-Ply Membrane

Lisa Gartland/PositivEnergy

Cool roofs can be applied to existing buildings or designed into new ones.

4.4 Cool Roofing and Insulation

Cool roofing and roof insulation are not comparable options for saving building energy—they work very differently. Building owners must make separate decisions to upgrade roof insulation levels or install cool roofing.

Some studies have evaluated the insulation levels needed to produce the same summertime energy savings as a cool roof.[28,29,30] These studies have been used to support building codes that allow less roof insulation if cool roofing is installed.[31,32] The conditions for choosing levels of roof insulation or cool roofing vary based on climate, utility prices, building use, building and fire code considerations, and preference. Thus, the following factors for choosing insulation or cool roofing are general approximations. Building owners might consider adding roof or ceiling insulation if:

- There is less roof insulation than called for in the latest state or local building codes

- The building is in a climate with significant cold weather or heating needs
- The roof accounts for much of the building's envelope (i.e., the roof area equals or exceeds one-fourth of the building's exterior surface area, calculated as the walls plus the roof).

Cool roofing can be used on any building, but is especially useful if:

- The building is in a climate with hot and sunny weather during at least part of the year (80°F or hotter weather with clear skies for at least three months of the year)
- Significant cooling energy is used (three or more months of cooling use)
- The duct system is in the attic or plenum space
- There are problems maintaining indoor comfort in the summer (if air conditioning equipment cannot maintain the desired temperature, or without air conditioning, if indoor temperatures exceed 80°F)
- The roof accounts for much of the building's envelope (i.e., the roof area equals or exceeds one-fourth of the building's exterior surface area, calculated as the walls plus the roof)
- The roof materials tend to crack and age prematurely from sun damage (if damage begins before the warranty period or the roof life ends).

Generally, adding roof insulation means adding insulation under the roof or above the ceiling, which can be disruptive to building occupants. Another option on the market is to spray insulating foam or affix rigid insulation onto the top of the roof surface. Each of these products adds approximately an R-6 level of long-term thermal resistance for each inch (2.5 cm) of thickness added. These technologies by themselves are not cool roofing materials; however, they are often applied as part of a complete roofing system, where the top surface is a cool coating or single-ply membrane.

5. Cool Roof Initiatives

Communities have developed cool roof programs by taking action in their own buildings, often called leading by example; through voluntary incentives; and through mandatory requirements.

Local governments have frequently started by installing cool roofs in public buildings. Their efforts have included launching demonstration projects and adapting public building procurement practices to require cool roofs for new public buildings and roofing renovation projects. Beginning with the public sector allows a community to demonstrate the technology, make contractors aware of the products available, and promote the use of cool roof materials in other building sectors.

In many communities, voluntary cool roof incentives have been provided by local energy companies as part of their demand-side management programs. A few local government agencies also offer incentives to assist low-income or other households with installing cool roofs.

Some governments have mandated implementation of cool roofs in certain areas. These actions generally require adopting specific energy code provisions that require cool roofs or include cool roofs in the calculation of how much insulation is required to meet minimum energy efficiency requirements.

Mandatory requirements for cool roofs have played an increasingly significant role in implementation. Before 1995, the only regulations affecting cool roofing mandated that roof color not cause undue glare. The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) has since developed energy-efficient design standards that provide minimum requirements for both commercial and residential buildings. ANSI/ASHRAE/IESNA Standard 90.1-1999, *Energy Standards for Buildings Except Low-Rise Residential Buildings* and ANSI/ASHRAE Standard 90.2-2001, *Energy-Efficient Design of Low-Rise Residential Buildings* provide guidelines for new equipment, systems, and buildings. These standards were originally developed in response to the 1970s energy crisis and now serve as the generally accepted basis for many state building and energy codes. Both ASHRAE standards include credits pertaining to cool roofing. An example of a cool roofing credit is Addendum f to 90.2-2001, which allows the use of high-albedo roofs in hot and humid climates as part of the energy efficiency ceiling calculation for a residential building.[33]

A number of states and localities now have developed specific energy code requirements to encourage or require cool roofing. For example:

- In 1995, Georgia was the first state to add cool roofs to its energy code. The code allowed building owners to reduce roof insulation if they installed a cool roof that had a minimum solar reflectance of 75 percent and a minimum thermal emittance of 75 percent.[34] Note that if a building owner uses less insulation when installing a cool roof, he may not accrue net energy savings.
- Florida is using a similar approach to Georgia in its energy code.[35] Because of the energy efficiency gains from cool roofs, the Florida code allows commercial and multi-family residential buildings using a roof with at least 70 percent solar reflectance and 75 percent thermal emittance to reduce the amount of insulation required to meet building energy efficiency standards. The adjustment does not apply for roofs with ventilated attics or semi-heated spaces.
- In January 2003, Chicago amended its energy code requirements for low-sloped roofs.[36] This code applies to all buildings except separated buildings that have minimal peak rates of energy use and buildings that are neither heated nor cooled. Low-sloped roofs installed on or before December 31, 2008, must achieve a minimum solar reflectance (both initial and weathered) of 0.25 when tested in accordance with ASTM standards E 903 and E 1918 or by testing with a portable reflectometer at near ambient conditions. For low-sloped roofs installed after that date, roofing products must meet or exceed the minimum criteria to qualify for the ENERGY STAR Roof Products label.
- In 2001, in response to electrical power shortages, California updated its building energy code (Title 24), adding cool roofing as an energy efficiency option.[37] A cool roof is defined as having minimum solar reflectance of 70 percent and minimum thermal emittance of 75 percent, unless it is a concrete or clay tile, in which case it can have a minimum solar reflectance of 40 percent. This 40 percent rating incorporates new cool colored residential products. Owners must use specific methods to verify building energy use to account for cool roofing as an energy efficiency option. In this case, the heat

gain of the roof is reduced to account for use of a cool roof. In 2005, these cool roof provisions became mandatory for all new non-residential construction and re-roofing projects that involve more than 2,000 square feet (190 m^2) or 50 percent replacement. The code also provides alternatives to the standard criteria as additional compliance options. In 2006, California began considering planned 2008 updates to Title 24 and is studying the possibility of extending cool roof requirements to the steep-sloped market.[38]

For further information on **California Title 24,** see <www.energy.ca.gov/efficiency/blueprint/index.html>.

Table 6 lists many of the primary types of cool roof activities. The "Heat Island Reduction Activities" chapter provides more detailed examples.

6. Resources

6.1 Cool Roof Energy Savings Calculators

Federal agencies have developed two Web-based calculators that compare energy and cost savings from different cool roof technologies for various building types. Consumers also can find calculator tools on Web sites of cool roof product manufacturers. All of these tools use different assumptions and formulas and generate different results; therefore, they provide a range of potential impacts rather than precise statements of the savings any individual building owner will obtain.

Figure 15: Aerial View of Sacramento, California, with Capitol

California's Title 24 has accelerated the diffusion of cool roofing across the state. The reflective roof of the capitol in Sacramento and other buildings around Capitol Park stand out among the vegetation, pavement, and darker roofs.

ENERGY STAR Roofing Comparison Calculator. The Web-based ENERGY STAR Roofing Comparison Calculator helps to estimate the energy and money that can be saved by using ENERGY STAR roofing products on air-conditioned buildings of at least 3,000 square feet (280 m^2). This calculator estimates savings of typical building types with non-metallic-surfaced roofs under typical weather conditions.

This EPA calculator requires input on the age, type, and location of the building; the efficiency of the heating and cooling systems; the local cost of energy; and information about the roof area, insulation levels, and type of roofing systems used. Based on these factors, the tool provides an estimate of annual electricity savings in kWh and dollars per 1,000 square feet (93 m^2). The annual effects of any heating penalties are included, given in therms and dollars per 1,000 square feet if natural gas is used to fuel the heating system, or subtracted from the annual electricity savings if an electric heat pump is used. This calculator does not model electric resistance heating systems.

Table 6: Examples of Cool Roof Initiatives

Type of Initiative	Description	Links to Examples
Research	National laboratories	<**http://eetd.lbl.gov/HeatIsland**> - The Heat Island Group at Lawrence Berkeley National Laboratory provides research and information about cool roofing and other heat island mitigation measures. The Cool Roofing Materials Database lists the solar reflectance and thermal emittance of numerous roof products, including cool colored roofing.
		<**www.ornl.org**> - ORNL conducts research on reflective roofing and solar radiation control. Its Web site includes fact sheets, a cool roof calculator, background information about cool roofing, and research publications.
Voluntary efforts	Demonstration programs	<**www.swenergy.org/casestudies/arizona/tucson_topsc.htm**> - Tucson, Arizona, Cool Roof Demonstration Project (city office building).
	Incentive programs	<**www.pge.com/res/rebates/cool_roof/index.html**> - Pacific Gas & Electric's utility rebate program for cool roofs.
		<**www.sce.com/RebatesandSavings/Residential/_Heating+and+Cooling/CoolRoof/**> - Southern California Edison's Cool Roof Rebate Program.
		<**www.austinenergy.com/Energy%20Efficiency/Programs/Rebates/Commercial/Commercial%20Energy/buildingEnvelope.htm**> - Austin Energy's Reflective Roof Coating and Roof and Ceiling Insulation rebate information.
		<**http://egov.cityofchicago.org/**> - Chicago announced in Fall 2007 that it was expanding a green roof grant program to include cool roofs, with up to 55 $6,000 grants targeted per year; see information under Department of Environment portion of the City's website.
	Outreach & education	<**www.epa.gov/heatisland/**> - EPA's Heat Island Reduction Initiative provides information on the temperature, energy, and air quality impacts from green roofs and other heat island mitigation strategies.
	Weatherization programs	<**www.ecasavesenergy.org/ses/whiteroof.html**> - Philadelphia cool roof incentive program for low-income housing.
Policy efforts	State and municipal energy codes that require or provide recognition of cool roofs	<**www.energy.ca.gov/title24/index.html**> - California building energy code that requires cool roofs on nonresidential low-sloped roofs; applies to new and retrofit projects over certain size thresholds.
		<**http://rules.sos.state.ga.us/docs/110/11/1/03.pdf**> - Georgia Energy Code revision applicable to cool roofs.
		<**http://egov.cityofchicago.org/**> - See Energy Code listings under Chicago Department of Construction and Permits under local government portion of the website.

Access these **calculators on the Web:**

ENERGY STAR Calculator:
<www.energystar.gov>,
under "Roof Products."

ORNL Calculator:
<www.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>.

For information on an effort begun in 2007 to develop an integrated EPA/Department of Energy (DOE) calculator, see: **<www.govforums.org/e&w>**.

The roofing calculator is intended to estimate the savings that a reflective roof can offer to a typical building and to aid in the decision of whether to choose an ENERGY STAR-qualified roof product. It is only one of many tools that can be used in the decision making process. A more detailed building energy simulation would be needed to estimate savings for a particular building or calculate specific benefit-cost ratios for a project.

Note that the ENERGY STAR calculator estimates could underpredict the energy savings from a cool roof in some cases. This is because the equations used in the ENERGY STAR calculator were derived from multiple runs of a DOE building energy analysis model, which does not consider the effects of widely varying roof temperatures or duct location. These effects include changes in the thermal conductivity of the insulation, thermal radiation in the attic or plenum, and conduction gains to cooling ducts.

ORNL Cool Roof Calculator. This cool roof calculator is a Web-based tool that helps estimate the energy and financial impacts from installing cool roofs on buildings with low-sloped roofs that do not have ventilated attics or plenums.

To generate the equations used in this tool, researchers ran a computer model of a roof and ceiling assembly over a range of climates for roofs with varying levels of insulation, solar reflectance, and thermal emittance. This model was calibrated to emulate heat transfer measurements made on a special roof and ceiling test assembly at ORNL.[39]

This calculator requires input on building location (a choice of 235 different U.S. cities is provided); information about the insulation, solar reflectance, and thermal emittance of the proposed roof; and the cost of energy and efficiency of the heating and cooling systems. The tool provides the annual cost savings on a square-foot basis in comparison to a black roof, as well as annual heating energy savings or penalty, also in dollars per square foot.

6.2 Roofing Programs and Organizations

Table 7 lists a number of programs that actively promote cool roofs or that are currently involved in cool roof research.

Table 7: Cool Roof Programs and Organizations

Program/Organization	Role	Web Address
Cool Metal Roofing Coalition	This industry group educates architects, building owners, specifiers, code and standards officials, and other stakeholders about the sustainable, energy-related impacts of cool metal roofing.	<www.coolmetalroofing.org>
Cool Roof Rating Council (CRRC)	Created in 1998 as a nonprofit, educational organization, CRRC's members include manufacturers, utilities, researchers, and consultants. CRRC maintains a product rating program and associated product directory.	<www.coolroofs.org>
ENERGY STAR	ENERGY STAR is a joint EPA and DOE program that helps consumers save money and protect the environment through energy-efficient products and practices. Regarding cool roofs, the Web site provides information on qualified roofing products, industry partners, and case studies.	<www.energystar.gov>
National Roofing Contractors Association (NRCA)	This trade association includes roofing, roof deck, and waterproofing contractors and industry-related associate members. It provides technical and safety information, news, and calendars of industry events.	<www.nrca.net>
Roof Consultants Institute (RCI)	This international, nonprofit association includes professional roof consultants, architects, and engineers. It hosts trade conventions and develops standards for professional qualifications.	<www.rci-online.org>
Roof Coatings Manufacturers Association (RCMA)	RCMA is a national trade association representing the manufacturers of cold-applied coatings and cements for roofing and waterproofing. It promotes the availability and adaption of energy-efficient materials.	<www.roofcoatings.org>
Single Ply Roofing Industry (SPRI)	SPRI is a trade organization representing sheet membrane and component suppliers to the commercial roofing industry. It provides information about and forums to discuss industry practices, workforce training, and other concerns.	<www.spri.org>

Endnotes

1 Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.

2 These temperature ranges are compiled from the following individual reports:

Konopacki, S., L. Gartland, H. Akbari, and I. Rainer. 1998. Demonstration of Energy Savings of Cool Roofs. Paper LBNL-40673. Lawrence Berkeley National Laboratory, Berkeley, CA.

Gartland, L. n.d. Cool Roof Energy Savings Evaluation for City of Tucson.

Miller, W.A., A. Desjarlais, D.S. Parker, and S. Kriner. 2004. Cool Metal Roofing Tested for Energy Efficiency and Sustainability. CIB World Building Congress, May 1-7, 2004. Toronto, Ontario.

Konopacki, S. and H. Akbari. 2001. Measured Energy Savings and Demand Reduction from a Reflective Roof Membrane on a Large Retail Store in Austin. Paper LBNL-47149. Lawrence Berkeley National Laboratory, Berkeley, CA.

3 Ibid.

4 Konopacki, S., L. Gartland, H. Akbari, and I. Rainer. 1998. Demonstration of Energy Savings of Cool Roofs. Paper LBNL-40673. Lawrence Berkeley National Laboratory, Berkeley, CA.

5 Rosenzweig, C., W. Solecki, L. Parshall, S. Gaffin, B. Lynn, R. Goldberg, J. Cox, and S. Hodges. 2006. Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces. Sixth Symposium on the Urban Environment and Forum on Managing our Physical and Natural Resources, American Meteorological Society. Atlanta, GA.

6 Chen, Allan. Cool Colors, Cool Roofs, part 2. Science Beat Berkeley Lab. 27 August 2004. Retrieved 14 April 2008 from <http://www.lbl.gov/Science-Articles/Archive/sb/Aug-2004/3_cool-roofs-2.html>.

7 Pacific Gas and Electric Company. 2006. Inclusion of Solar Reflectance and Thermal Emittance Prescriptive Requirements for Residential Roofs in Title 24. Pacific Gas and Electric Company. Sacramento, CA.

8 Public Interest Energy Research Program. At Home with Cool-Colored Roofs. Technical Brief, CEC-500-2005-164-F111005. California Energy Commission. Sacramento, CA.

9 Haberl, J., and S. Cho. 2004. Literature Review of Uncertainty of Analysis Methods (Cool Roofs), Report to the Texas Commission on Environmental Quality. Energy Systems Laboratory, Texas A&M University, College Station, TX.

10 Konopacki, S., L. Gartland, H. Akbari, and L. Rainer. 1998. Demonstration of Energy Savings of Cool Roofs. Paper LBNL-40673. Lawrence Berkeley National Laboratory, Berkeley, CA.

11 Konopacki, S., H. Akbari, M. Pomerantz, S. Gabersek, and L. Gartland. 1997. Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. Paper LBNL-39433. Lawrence Berkeley National Laboratory, Berkeley, CA.

12 See the following reports for individual results:

H. Akbari, S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha, and W. Bos. 1993. Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results. Paper LBNL-34411. Lawrence Berkeley National Laboratory, Berkeley, CA.

Callahan, M., D. Parker, J. Sherwin, and M. Anello. 2000. Demonstrated Energy Savings of

Efficiency Improvements to a Portable Classroom. American Council for an Energy Efficient Economy. ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA.

Konopacki, S. and H. Akbari. 2001. Measured Energy Savings and Demand Reduction from a Reflective Roof Membrane on a Large Retail Store in Austin. Paper LBNL-47149. Lawrence Berkeley National Laboratory, Berkeley, CA.

Parker, D.S., J.B. Cummings, J.R. Sherwin, T.C. Stedman, and J.E.R. McIlvaine. 1994. Measured Residential Cooling Energy Savings from Reflective Roof Coatings in Florida. ASHRAE Transactions, Paper 3788. 100(2):36-49.

Parker, D.S., J.R. Sherwin, J.K. Sonne, S.F. Barkaszi. 1996. Demonstration of Cooling Savings from Light Colored Roof Surfacing in Florida Commercial Buildings: Our Savior's School. Florida Solar Energy Center, Cocoa, FL.

Parker, D., S.F. Barkaszi, and J.K. Sonne. 1994. Measured Cooling Energy Savings from Reflective Roof Coatings in Florida: Phase II Report. Florida Solar Energy Center, Cape Canaveral, FL.

13 Konopacki, S., H. Akbari, M. Pomerantz, S. Gabersek, and L. Gartland. 1997. Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. Paper LBNL-39433. Lawrence Berkeley National Laboratory, Berkeley, CA.

14 Konopacki, S., and H. Akbari 2002. Energy Savings for Heat Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City). Paper LBNL-49638. Lawrence Berkeley National Laboratory, Berkeley, CA.

15 Gartland, L. 1998. Roof Coating Evaluation for the Home Base Store in Vacaville, California. PositivEnergy, 27. Oakland, CA.

16 Vincent, B., and J. Huang. 1996. Analysis of the Energy Performances of Cooling Retrofits in Sacramento Public Housing Using Monitored Data and Computer Simulations. Contract No. 500-93-053. Prepared for the California Energy Commission, Sacramento, CA.

17 Parker, D. 1997. Cool Roofs. FSEC-PF-323-97. Roofer Magazine. 17(7).

18 Konopacki, S., H. Akbari, M. Pomerantz, S. Gabersek, and L. Gartland. 1997. Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. Paper LBNL-39433. Lawrence Berkeley National Laboratory, Berkeley, CA.

19 See Energy Information Administration. 2003. Retrieved February 11, 2008, from <http://www.eia.doe.gov/>. Electricity prices are reported as cents per kilowatt-hour. Natural gas prices were converted from dollars per 1,000 cubic feet (28,300 liters) of gas to cents per thousand Btu (1.1 MJ) based on a conversion factor of 1,021 Btu/cubic foot of gas.

20 Blasnik, M. 2004. Impact Evaluation of the Energy Coordinating Agency of Philadelphia's Cool Homes Pilot Project. M. Blasnik & Associates, Boston, MA.

21 Levinson, R., H. Akbari, S. Konopacki, and S. Bretz. 2002. Inclusion of Cool Roofs in Nonresidential Title 24 Prescriptive Requirements. Paper LBNL-50451. Lawrence Berkeley National Laboratory, Berkeley, CA.

22 Mattison, K. 1998. Factors Affecting Roof System Costs. Perspectives. 34 (December). Retrieved 9 October 2007 from <www.benchmark-inc.com/articles/Perspective%20Articles/issue34a.html>.

23 Levinson, R., H. Akbari, S. Konopacki, and S. Bretz. 2002. Inclusion of Cool Roofs in Nonresidential Title 24 Prescriptive Requirements. Paper LBNL-50451. Lawrence Berkeley National Laboratory, Berkeley, CA.

24 Ibid.

[25] Pacific Gas and Electric Company. 2006. Inclusion of Solar Reflectance and Thermal Emittance Prescriptive Requirements for Residential Roofs in Title 24. Draft Report, May 17, 2006. Sacramento, CA.

[26] See the following study which includes an analysis of annual energy peak demand reductions, cooling equipment savings, and net present value savings from expanding California cool roof requirements to portions of the residential sector:

> Pacific Gas and Electric Company. 2006. Inclusion of Solar Reflectance and Thermal Emittance Prescriptive Requirements for Residential Roofs in Title 24. Draft Report, May 17, 2006. Sacramento, CA.

[27] Bretz, S., and H. Akbari. 1997. Long-Term Performance of High-Albedo Roof Coatings. Energy & Buildings. 25(2):159-167.

[28] Akbari, H., S. Konopacki, C. Eley, B. Wilcox, M. Van Geem and D. Parker. 1998. Calculations in Support of SSP90.1 for Reflective Roofs. Paper LBNL-40260. Lawrence Berkeley National Laboratory, Berkeley, CA.

[29] Akbari, H., S. Konopacki, and D. Parker. 2000. Updates on Revision to ASHRAE Standard 90.2: Including Roof Reflectivity for Residential Buildings. American Council for an Energy Efficient Economy. ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA.

[30] Konopacki, S., and H. Akbari. 1998. Trade-off between cool roofs and attic insulation in new single-family residential buildings. American Council for an Energy Efficient Economy. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.

[31] California Energy Commission. 2006. 2005 Building Energy Efficiency Standards for Residential and Non-residential Buildings. Title 24, Publication No. CEC-400-2006-015.

[32] Georgia Energy Code. 1995. Georgia Amendment to the 1995 CABO Model Energy Code for Section 704.

[33] ASHRAE. 2003. ANSI/ASHRAE Addendum f to ANSI/ASHRAE Standard 90.2-2001, ASHRAE Standard: Energy-Efficient Design of Low-Rise Residential Buildings. ISSN 1041-2336. Atlanta, GA.

[34] Georgia Energy Code. 1995. Georgia Amendment to the 1995 CABO Model Energy Code for Section 704.

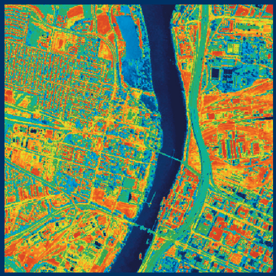
[35] Florida. 2004. Florida Building Code, Chapter 13: Efficiency. Retrieved 13 November 2007 from <http://www2.iccsafe.org/states/2004_florida_codes/>.

[36] Chicago, Illinois. 2003. Municipal Code, ch. 8-13.

[37] California Energy Commission. 2006. 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. No. CEC-400-2006-015 (replaces P400-03-001F).

[38] Pacific Gas and Electric Company. 2006. Inclusion of Solar Reflections and Thermal Emittance Prescriptive Requirements for Steep-Sloped Nonresidential Roofs in Title 24. Draft Report, May 18, 2006. Sacramento, CA.

[39] Wilkes, K. 1991. Thermal Model of Attic Systems with Radiant Barriers. Oak Ridge National Laboratory, ORNL/CON-262. Oak Ridge, TN.

Reducing Urban Heat Islands: Compendium of Strategies

Cool Pavements

Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, Neelam R. Patel, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

For the Cool Pavements chapter, Cambridge Systematics, Inc. provided support in preparing a June 2005 draft report on cool pavements under contract to EPA as part of EPA's Heat Island Reduction Initiative.

Experts who helped shape this chapter include: Bruce Ferguson, Kim Fisher, Jay Golden, Lisa Hair, Liv Haselbach, David Hitchcock, Kamil Kaloush, Mel Pomerantz, Nam Tran, and Don Waye.

Suggested Citation: U.S. Environmental Protection Agency. 2012. "Cool Pavements." In: *Reducing Urban Heat Islands: Compendium of Strategies. Draft.* https://www.epa.gov/heat-islands/heat-island-compendium.

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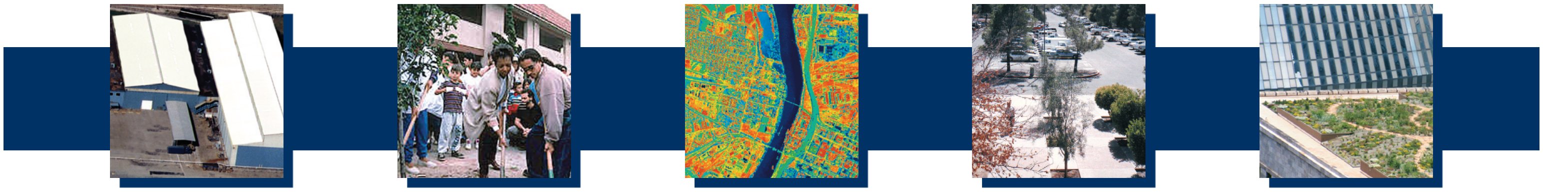


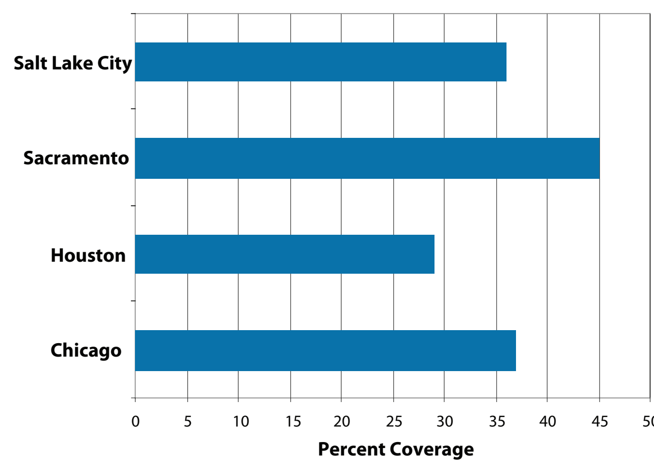
Cool Pavements

Cool pavements refer to a range of established and emerging materials. These pavement technologies tend to store less heat and may have lower surface temperatures compared with conventional products. They can help address the problem of urban heat islands, which result in part from the increased temperatures of paved surfaces in a city or suburb. Communities are exploring these pavements as part of their heat island reduction efforts.

Conventional pavements in the United States are impervious concrete* and asphalt, which can reach peak summertime surface temperatures of 120–150°F (48–67°C).[2] These surfaces can transfer heat downward to be stored in the pavement subsurface, where it is re-released as heat at night. The warmer daytime surface temperatures also can heat stormwater as it runs off the pavement into local waterways. These effects contribute to urban heat islands (especially at nighttime) and impair water quality.

In many U.S. cities, pavements represent the largest percentage of a community's land cover, compared with roof and vegetated surfaces. As part of EPA's Urban Heat Island Pilot Project, Lawrence Berkeley National Laboratory (LBNL) conducted a series of urban fabric analyses that provide baseline data on land use and land use cover, including paved surfaces for the pilot program cities.[1] Figure 1 shows the percent of paved surfaces in four of these urban areas, as viewed from below the tree canopy. The data are from 1998 through 2002, depending on the city. Paved areas, which can absorb and store much of the sun's energy contributing to the urban heat island effect, accounted for nearly 30 to 45 percent of land cover.

Figure 1: Paved Surface Statistics for Four U.S. Cities



* When new, concrete has a high solar reflectance and generally is considered a cool pavement; however, it loses reflectance over time, as discussed in Section 1.2.

Figure 2: Conventional Pavement Temperatures

National Center of Excellence on SMART Innovations at Arizona State University

This picture of Phoenix, Arizona, in the summer shows a variety of conventional pavements that reached temperatures up to 150°F (67°C).

Defining Cool Pavements

Unlike a "cool" roof, a "cool" pavement has no standard, official definition. Until recently, the term has mainly referred to reflective pavements that help lower surface temperatures and reduce the amount of heat absorbed into the pavement. With the growing interest and application of permeable pavements—which allow air, water, and water vapor into the voids of a pavement, keeping the material cool when moist—some practitioners have expanded the definition of cool pavements to include permeable pavements as well. Ongoing permeable pavement research is important because these systems, compared with conventional pavement systems, react differently and lead to different environmental impacts. Further, as we understand better how pavements affect urban climates and develop newer, more environmental technologies, additional technologies that use a variety of techniques to remain cooler are likely to emerge.

As concerns about elevated summertime temperatures rise, researchers and policymakers are directing more attention to the impact pavements have on local and global climates. This chapter discusses:

- Pavement properties and how they can be modified to reduce urban heat islands
- Conditions that affect pavement properties
- Potential cool pavement technologies
- Cool pavement benefits and costs
- Cool pavement initiatives and research efforts
- Resources for further information.

Given that cool pavements are an evolving technology and much is still unknown about them, this compendium presents basic information to give readers a general understanding of cool pavement issues to consider; it is not intended to provide decision guidance to communities. Decision-makers can work with local experts to obtain location-specific information to

Why Have Communities Promoted Cool Roofs More Than Cool Pavements?

A few decades ago when the concept of using cool roofs and pavements emerged, researchers focused on radiative properties—surface solar reflectance and thermal emittance—associated with these technologies. Scientists, engineers, and others worked together through the standards-development organization ASTM International to create test standards for these properties that could apply to both roofs and pavements. (See Section 4.1.) While researchers, industry, and supporters of energy efficiency have helped advance cool roofing into the market, cool pavement has lagged behind. Three factors, which differentiate pavements from roofs, may contribute to this difference:

1. Pavements are complex. Conditions that affect pavement temperatures, but not roofing materials, include: (a) dirtying and wearing away of a surface due to daily foot and vehicle traffic, affecting pavement surface properties; (b) convection due to traffic movement over the pavement; and (c) shading caused by people and cars, vegetation, and neighboring structures and buildings. These factors are discussed in Sections 1.2 and 2.
2. Pavement temperatures are affected by radiative and thermal characteristics, unlike cool roofs, where radiative properties are the main concern. This is discussed in Section 1.3.
3. Pavements serve a variety of functions throughout an urban area. Their uses range from walking trails to heavily trafficked highways (unlike cool roofs, which generally perform the same function and are off-the-shelf products). Different materials and specifications are needed for these different uses, and pavements are often individually specified, making it difficult to define or label a cool pavement.

further guide them in the pavement selection process. EPA expects that significant ongoing research efforts will expand the opportunities for updating existing technologies and implementing new approaches to cool pavements. At the end of Sections 4 and 5 in this document, organizations and resources with the most recent information are listed. Communities will also continue to implement new demonstration projects and cool pavement initiatives. EPA intends to provide updated information as it becomes available. Please visit <www.epa.gov/heatisland/index.htm>.

1. How It Works

Understanding how cool pavements work requires knowing how solar energy heats pavements and how pavement influences the air above it. Properties such as solar energy, solar reflectance, material heat capacities, surface roughness, heat transfer rates, thermal emittance, and permeability affect pavement temperatures.

Reducing or Shading Pavements

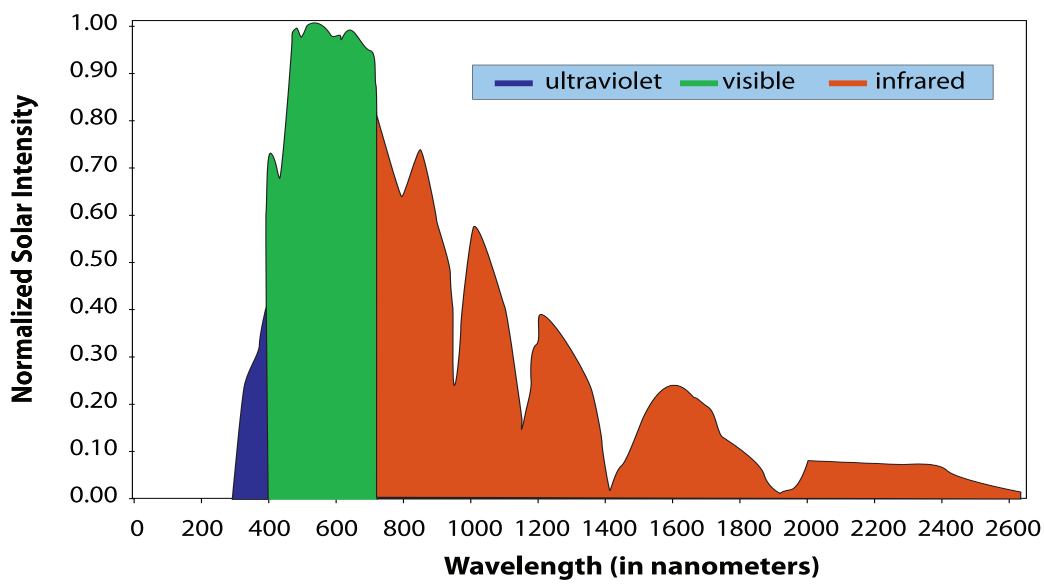
Some efforts have emerged that focus on reducing the need to pave, particularly over vegetated areas that provide many benefits, including lowering surface and air temperatures. Communities have used various options to reduce the amount of paved surface areas, such as lowering parking space requirements, connecting parking and mass transit services, allowing for narrower street widths, or providing incentives for multi-level parking versus surface lots.[3]

Concerned communities that move forward with paving often shade it with vegetation. The "Trees and Vegetation" chapter discusses the use of measures such as parking lot shading ordinances as part of a heat island mitigation strategy.

Another option some local governments and private firms are considering involves installing canopies that incorporate solar panels in parking lots. These photovoltaic canopies shade surfaces from incoming solar energy and generate electricity that can help power nearby buildings or provide energy for plug-in electric vehicles.[4]

For more information on urban planning and design approaches to minimize paved surfaces, see <www.epa.gov/smartgrowth>, and for information on vegetated surfaces, see the "Trees and Vegetation" chapter of this compendium.

Figure 3: Solar Energy versus Wavelength Reaching Earth's Surface on a Typical Clear Summer Day



Solar energy intensity varies over wavelengths from about 250 to 2,500 nanometers. Figure 3 demonstrates this variation, using a normalized measure of solar intensity on a scale of zero (minimum) to one (maximum). Currently, reflective pavements are light colored and primarily reflect visible wavelengths. However, similar to trends in the roofing market, researchers are exploring pavement products that appear dark but reflect energy in the near-infrared spectrum.[5] (See the "Cool Roofs" chapter of the compendium for more information.)

1.1 Solar Energy

Solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: 5 percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn; 43 percent of solar energy is visible light, in colors ranging from violet to red; and the remaining 52 percent of solar energy is infrared, felt as heat. Energy in all of these wavelengths contributes to urban heat island formation. Figure 3 shows the typical solar energy that reaches the Earth's surface on a clear summer day.

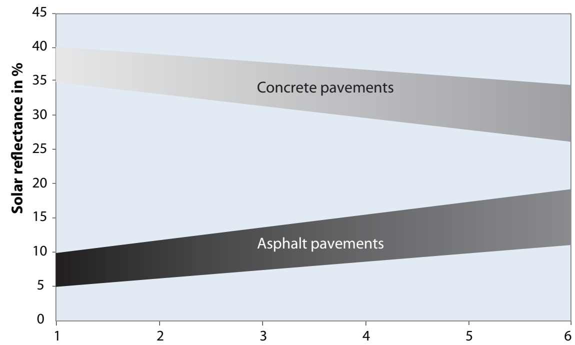
1.2 Solar Reflectance (Albedo)

Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface. Most research on cool pavements has focused on this property, and it is the main determinant of a material's maximum surface temperature.[6] Albedo also affects pavement temperatures below the surface, because less heat is available at the surface to then be transferred into the pavement. Researchers, engineers, and industry have collaborated to develop methods to determine solar reflectance by measuring how well a material reflects energy at each wavelength, then calculating the weighted average of these values.* (See Table 1 on page 7.)

Conventional paving materials such as asphalt and concrete have solar reflectances of 5 to 40 percent, which means they absorb 95 to 60 percent of the energy reaching them instead of reflecting it into the atmosphere. (See Figure 4.) However, as Figure 4 also shows, these values depend on age and material, and thus usually change over time. Figure 5 shows how changing only albedo can significantly alter surface temperatures. Although researchers, including those at LBNL, have made light-colored pavements with solar reflectances greater than 75 percent,[8] these high albedo pavements do not have widespread commercial availability.

Most existing research on cool pavements focuses on solar reflectance, which is the primary determinant of a material's maximum surface temperature. Many opportunities exist to improve this property in pavements. (See Table 2, beginning on page 15.)

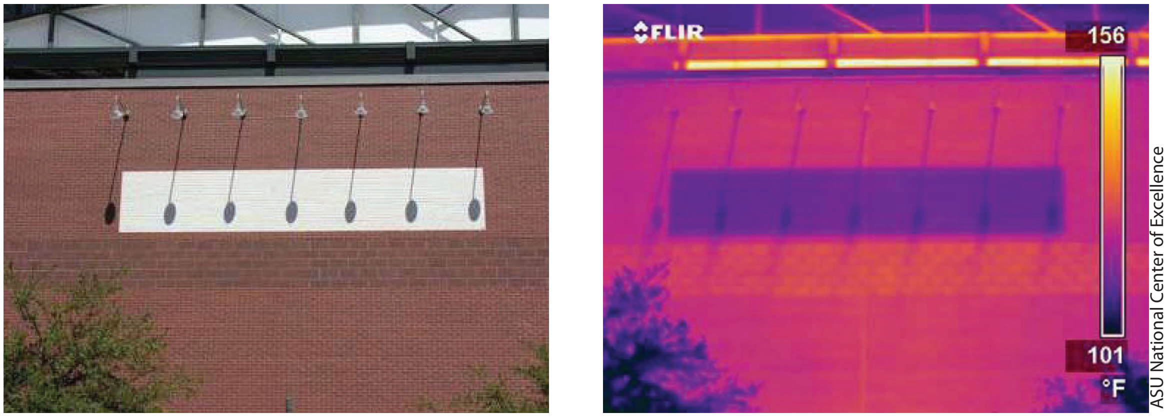
Figure 4: Typical Solar Reflectance of Conventional Asphalt and Concrete Pavements over Time



Due to weathering and the accumulation of dirt, the solar reflectances of conventional asphalt and concrete tend to change over time. Asphalt consists largely of petroleum derivatives as a binder mixed with sand or stone aggregate. Asphalt tends to lighten as the binder oxidizes and more aggregate is exposed through wear. Concrete also uses sand and stone aggregate, but in contrast to asphalt, typically uses Portland cement as a binder. [7] Foot and vehicle traffic generally dirty the cement causing it to darken over time.

* Albedo is typically measured on a scale of zero to one. For this compendium, albedo is given as a percentage, so an albedo of 0.05 corresponds to a solar reflectance of 5 percent. The "solar reflectance index" is a value on a scale of zero to 100 that incorporates both solar reflectance and thermal emittance in a single measure to represent a material's temperature in the sun. (See Table 1 on page 7 or further explanation.)

Figure 5: The Effect of Albedo on Surface Temperature



Albedo alone can significantly influence surface temperature, with the white stripe on the brick wall about 5–10°F (3–5°C) cooler than the surrounding, darker areas.

1.3 Thermal Emittance

A material's thermal emittance determines how much heat it will radiate per unit area at a given temperature, that is, how readily a surface sheds heat. Any surface exposed to radiant energy will heat up until it reaches thermal equilibrium (i.e., gives off as much heat as it receives). When exposed to sunlight, a surface with high emittance will reach thermal equilibrium at a lower temperature than a surface with low emittance, because the high-emittance surface gives off its heat more readily. As noted in Table 1 on page 7, ASTM methods can be used to measure this property.

Thermal emittance plays a role in determining a material's contribution to urban heat islands. Research from 2007 suggests albedo and emittance have the greatest influence on determining how a conventional pavement cools down or heats up, with albedo having a large impact on maximum surface temperatures, and emittance affecting minimum temperatures.[9] Although thermal emittance is an important property, there are only limited options to adopt cool pavement practices that modify it because most pavement materials inherently have high emittance values.[10]

Standards for Measuring Solar Reflectance and Thermal Emittance

To evaluate how "cool" a specific product is, ASTM International has validated laboratory and field tests and calculations to measure solar reflectance, thermal emittance, and the solar reflectance index, which was developed to try to capture the effects of both reflectance and emittance in one number. (See Table 1 below.) Laboratory measurements are typically used to examine the properties of new material samples, while field measurements evaluate how well a material has withstood the test of time, weather, and dirt.

The final method listed in Table 1 is not an actual test but a way to calculate the "solar reflectance index" or SRI. The SRI is a value that incorporates both solar reflectance and thermal emittance in a single value to represent a material's temperature in the sun. This index measures how hot a surface would get compared to a standard black and a standard white surface. In physical terms, this scenario is like laying a pavement material next to a black surface and a white surface and measuring the temperatures of all three surfaces in the sun. The SRI is a value between zero (as hot as a black surface) and 100 (as cool as a white surface).

Table 1: Solar Reflectance and Emittance Test Methods

Property	Test Method	Equipment Used	Test Location
Solar reflectance	ASTM E 903 - Standard Test Method for Solar Absorbance, Reflectance, and Transmittance of Materials Using Integrating Spheres.	Integrating sphere spectrophotometer	Laboratory
Solar reflectance	ASTM C 1549 - Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer	Portable solar reflectometer	Laboratory or field
Solar reflectance	ASTM E 1918 - Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field	Pyranometer	Field
Total emittance	ASTM E408-71 - Standard Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques	Portable, inspection-meter instruments	Laboratory or field
Solar reflectance index	ASTM E 1980 - Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces	None (calculation)	—

Pavement Surface and Subsurface Temperatures

This chapter mainly focuses on pavement surface temperatures, as most of the cited studies focus on the surface layer. For conventional pavements, most of the impacts at the surface tend to affect the subsurface similarly. For example, conventional pavements with high solar reflectance generally reduce surface and subsurface temperatures, as less heat is available at the surface to absorb into the pavement. However, permeable surfaces react differently. When dry, permeable pavement surface temperatures may be higher than their impermeable equivalent; but preliminary research shows that the subsurface generally is similar to or even cooler than the conventional equivalent, because the permeable layer reduces heat transfer below.[11] More information on subsurface heat transfer is needed to understand the potential heat island impacts because the heat stored in the subsurface may significantly affect nighttime temperature. Still, many complex interactions take place between the surface and subsurface layers. These interactions are either briefly covered in Section 1.5 or beyond the scope of this chapter.

1.4 Permeability

Although originally designed for stormwater control, permeable pavements are emerging as a potential cool pavement. These pavements allow air, water, and water vapor into the voids of the pavement. Permeable pavement technologies include porous asphalt applications, pervious concrete applications, permeable pavers, and grid pavements. To achieve both permeability objectives and structural needs for expected traffic load, these permeable pavements benefit from proper design and installation.[12]

When wet, these pavements can lower temperatures through evaporative cooling. The water passes through the voids and into the soil or supporting materials below. (See Figure 6.) Moisture within the pavement structure evaporates as the surface heats, thus drawing heat out of the pavement, similar to evaporative cooling from vegetated land cover. Some permeable pavement systems contain grass or low-lying vegetation, which can stay particularly cool because the surface temperature of well-hydrated vegetation typically is lower than the ambient air temperature.

Figure 6: Permeable versus Conventional Asphalt

U.S. Department of Agriculture

Permeable asphalt (foreground) allows water to drain from the surface and into the voids in the pavement, unlike conventional asphalt (mid- and background).

When dry, the extent to which permeable pavements can influence temperatures is more complex and uncertain. For example, the larger air voids in permeable pavements increase the available surface area. These conditions may limit heat transfer to the lower pavement structure and soils, keeping heat at the pavement's surface (and increasing daytime surface temperatures), but reducing bulk heat storage (reducing release of heat at nighttime).[13] The larger surface area also may help increase air movement—convection—over the pavement, transferring heat from the pavement to the air. Overall, the limited transfer of heat to the pavement subsurface layers would reduce the release of heat during the nighttime. Release of stored heat from urban materials is a significant contributor to the nighttime heat island experienced in many cities.

More research is needed to better understand the impacts of permeable pavement on air temperatures and urban heat island conditions. Given the complexity of these cooling mechanisms, and the wide range of conditions under which these pavements function, further field testing and validation would help to quantify and clarify the range of impacts and benefits of permeable pavements on urban climates.

1.5 Other Factors to Consider

Pavement temperatures depend on a series of factors. Reflective pavements increase the albedo of the surface to limit heat gain, whereas permeable pavements permit evaporative cooling when the pavement is moist, helping to keep it cool. As shown in Table 2 (beginning on page 15), however, actual conditions alter pavement properties, resulting in pavements that may not be "cool" under all circumstances. This chapter presents these issues for communities to consider when making pavement choices.

Water Retentive Pavements and Water Sprinkling in Japan

Some cities in Japan, such as Tokyo and Osaka, are testing the effectiveness of water retentive pavements as part of using permeable pavements to reduce the heat island effect. These porous pavements can be asphalt or concrete-based and have a sublayer that consists of water retentive materials that absorb moisture and then evaporate it through capillary action when the pavement heats up. Some of these systems involve underground water piping to ensure the pavement stays moist. Researchers have also tested water sprinkling, where pavements are sprayed with water during the day. Some cities have used treated wastewater. Results to date are promising, as both water retentive pavements and water sprinkling have been effective in keeping pavement temperatures low.[14]

Besides solar reflectance, emittance, and permeability, other properties and factors influence how readily pavements absorb or lose heat.

- **Convection.** Pavement transfers heat to the air through convection as air moves over the warm pavement. The rate of convection depends on the velocity and temperature of the air passing over the surface, pavement roughness, and the total surface area of the pavement exposed to air. Some permeable pavements have rougher surfaces than conventional pavements, which increases their effective surface area and creates air turbulence over the pavement. While this roughness can increase convection and cooling, it may also reduce a surface's net solar reflectance.

- **Thermal Conductivity.** Pavement with low thermal conductivity may heat up at the surface but will not transfer that heat throughout the other pavement layers as quickly as pavement with higher conductivity.
- **Heat Capacity.** Many artificial materials, such as pavement, can store more heat than natural materials, such as dry soil and sand. As a result, built-up areas typically capture more of the sun's energy—sometimes retaining twice as much as their rural surroundings during daytime.[15] The higher heat capacity of conventional urban materials contributes to heat islands at night, when materials in urban areas release the stored heat.
- **Thickness.** The thickness of a pavement also influences how much heat it will store, with thicker pavements storing more heat.[16]
- **Urban Geometry.** The dimensions and spacing of buildings within a city, or urban geometry, can influence how much heat pavements and other infrastructure absorb. For example, tall buildings along narrow streets create an "urban canyon." (See Figure 7.) This canyon effect can limit heat gain to the pavement during the day, when the buildings provide shade. But these same buildings may also absorb and trap the heat that is reflected and emitted by the pavement, which prevents the heat from escaping the city and exacerbates the heat island effect, especially at night. The overall impact of the urban canyon effect will depend on how a specific city is laid out, the latitude, the time of year, and other factors.

More research is needed to determine the exact impacts these properties have on pavement temperatures and the urban heat island effect.

1.6 Temperature Effects

Solar reflectance and thermal emittance have noticeable effects on surface temperatures, as discussed in Sections 1.2 and 1.3. Depending on moisture availability, permeable pavements also can lower pavement temperatures. Other properties, as noted in Section 1.5, also influence pavement surface and subsurface temperatures through a variety of complex interactions. In general, lower surface temperatures will result in lower near-surface air temperatures, with the effect decreasing as one moves farther away from the surface due to air mixing. Location-specific conditions, such as wind speed and cloud cover, can greatly influence surface and air temperatures.

Currently, few studies have measured the role pavements play in creating urban heat islands, or the impact cooler pavements can have on reducing the heat island effect. Researchers at LBNL, however, have estimated that every 10 percent increase in solar reflectance could decrease surface temperatures by 7°F (4°C). Further, they predicted that if pavement reflectance throughout a city were increased from 10 percent to 35 percent, the air temperature could potentially be reduced by 1°F (0.6°C).[17] Earlier research analyzed a combination of mitigation measures in the Los Angeles area, including pavement and roofing solar reflectance changes, and increased use of trees and vegetation. The study identified a 1.5°F (0.8°C) temperature improvement from the albedo changes.[18] A subsequent report analyzed the monetary benefits associated with these temperature improvements, and estimated the indirect benefits (energy savings and smog reductions) of the temperature reduction in Los

Figure 7: Urban Canyons

Mark Meier

The row of three- and four-story townhouses on the left creates a relatively modest urban canyon, while the skyscrapers on the right have a more pronounced effect.

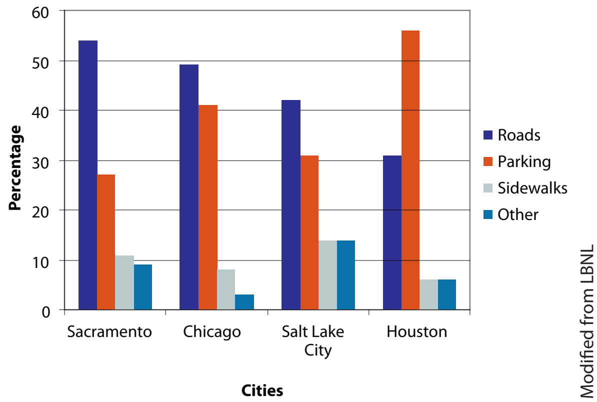
Angeles from pavement albedo improvements would be more than $90 million per year (in 1998 dollars).[19]

2. Potential Cool Pavement Types

Current cool pavements are those that have increased solar reflectance or that use a permeable material. Some of these pavements have long been established—such as conventional concrete, which initially has a high solar reflectance. Others are emerging—such as microsurfacing, which is a thin sealing layer used for maintenance.[20] Some pavement applications are for new construction, while others are used for maintenance or rehabilitation. Not all applications will be equally suited to all uses. Some are best for light traffic areas, for example. Further, depending on local conditions—such as available materials, labor costs, and experience with different applications—certain pavements may not be cost effective or feasible.

Generally, decision-makers choose paving materials based on the function they serve. Figure 8 shows the proportions of pavement used for different purposes in four cities. Parking lots typically make up a large portion of the paved surfaces in urban areas. All current cool pavement technologies can be applied to parking lots, which may explain why many research projects have been and are being conducted on them.

Figure 8: Percentage of Pavement Area by Type of Use[21]



LBNL conducted a paved surface analysis in four cities, dividing the uses into four general categories. Roads and parking lots make up the majority of paved areas.

Below are brief descriptions of potential cool pavements and their typical uses:

- **Conventional asphalt pavements,** which consist of an asphalt binder mixed with aggregate, can be modified with high albedo materials or treated after installation to raise reflectance. This material has been applied for decades in a wide range of functions from parking lots to highways.
- **Conventional concrete pavements,** made by mixing Portland cement, water, and aggregate, can be used in a wide range of applications including trails, roads, and parking lots.
- **Other reflective pavements,** made from a variety of materials, are mostly used for low-traffic areas, such as sidewalks, trails, and parking lots. Examples include:
  - **Resin based pavements,** which use clear tree resins in place of petroleum-based elements to bind an aggregate
  - **Colored asphalt and colored concrete,** with added pigments or seals to increase reflectance
- **Nonvegetated permeable pavements** contain voids and are designed to allow water to drain through the surface into the sublayers and ground below. These materials can have the same structural integrity as conventional pavements. For example, some forms of porous pavements, such as open-graded friction course (OGFC) asphalt pavements, have been in use for decades to improve roadway friction in wet weather.[22] Recently, rubberized asphalt has been used on roads and highways to reduce noise, and pervious concrete applications are being studied for roadway use. For some permeable pavement options, the typical use may be for lower traffic areas such as parking lots, alleys, or trails. Examples of nonvegetated permeable pavements include:
  - **Porous asphalt**
  - **Rubberized asphalt,** made by mixing shredded rubber into asphalt
  - **Pervious concrete**
  - **Brick or block pavers,** are generally made from clay or concrete, and filled with rocks, gravel, or soil; also available in a variety of colors and finishes designed to increase reflectance
- **Vegetated permeable pavements,** such as grass pavers and concrete grid pavers, use plastic, metal, or concrete lattices for support and allow grass or other vegetation to grow in the interstices. Although the structural integrity can support vehicle weights comparable to conventional pavements, these materials are most often used in areas where lower traffic volumes would minimize damage to the vegetation, such as alleys, parking lots, and trails, and they may be best suited to climates with adequate summer moisture.

- **Chip seals** consist of aggregate bound in liquid asphalt, and are often used to resurface low-volume asphalt roads and sometimes highways.
- **Whitetopping** is a layer of concrete greater than 4 inches (10 cm) thick, often containing fibers for added strength. Typical applications include resurfacing road segments, intersections, and parking lots.
- **Ultra-thin whitetopping** is similar to whitetopping and can be used in the same applications, but is only 2–4 inches (5–10 cm) thick.
- **Microsurfacing** is a thin sealing layer used for road maintenance. Light-colored materials can be used to increase the solar reflectance of asphalt. Researchers recently applied light-colored microsurfacing material that consisted of cement, sand, other fillers, and a liquid blend of emulsified polymer resin, and found the solar reflectance to be comparable to that of new concrete.[23]

Table 2, beginning on page 15, provides summary information for decision-makers to consider. It is meant as a preliminary guide, as more research and location-specific data are needed. Table 2 includes the following:

- A brief description of the technology
- The properties associated with it
- The potential impacts on pavement and air temperatures
- Issues to consider
- Target functions.

Regarding impacts, the "+" sign indicates a positive effect; for example, a technology generally results in lower pavement temperatures. A "-" signals a negative effect; for example, a technology may lead to higher air temperatures in certain conditions.

Slag and Fly Ash Cement

Slag and fly ash are sometimes added to concrete to improve its performance. Slag is a byproduct of processing iron ore that can be ground to produce cement, and fly ash is a byproduct of coal combustion.[24] These materials can make concrete stronger, more resistant to aggressive chemicals, and simpler to place. These cements also reduce material costs and avoid sending wastes to landfills. A key heat island benefit of slag is its lighter color, which can increase the reflectivity of the finished pavement. A 2007 study measured a solar reflectance of almost 60 percent for cement with slag, versus about 35 percent for a conventional concrete mix.[25] In contrast, fly ash tended to darken concrete unless counterbalanced, such as by added slag. However, substituting fly ash for a portion of the Portland cement reduces greenhouse gases and other emissions associated with producing Portland cement. Because of such benefits, California's Department of Transportation typically requires use of 25 percent fly ash in cement mixtures.[26]

Effects described in the table do not consider magnitude, which may be influenced by local conditions. Therefore, this information is not intended for comparison. The cool pavement technologies in Table 2 can have positive and negative impacts, depending on actual conditions such as moisture availability and urban design. The points listed under "issues and considerations" further illustrate the complexity associated with cool pavements. These bullets only discuss concerns related to urban heat islands and do not include other local factors or priorities that decision-makers generally consider when making pavement choices.

Despite its limitations, Table 2 can be used as a starting point. For example, using Table 2, a city that generally uses asphalt paving can identify alternative cool asphalt technologies for functions from bike trails to roads. They can also discern that high albedo pavements may be most effective in open areas, not surrounded by tall buildings. Most communities will further investigate the benefits and costs of the technology, as discussed in Section 3, and location-specific factors, such as political acceptance and experience with the technology.

Filling in the Gaps

As more researchers and communities install cool pavement technologies, more data will be generated and shared in forums such as the Transportation Research Board Subcommittee on Paving Materials and the Urban Climate. (See Section 4 of this chapter.)

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications

NEW CONSTRUCTION						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options						
Asphalt pavement, modified with high albedo materials or treated after installation to raise albedo.	Asphalt pavements consist of an asphalt binder mixed with sand or stone, referred to as aggregate.	• Solar reflectance, which initially may be 5%, can increase to 15–20% as conventional asphalt ages. [27] • Using light-colored aggregate, color pigments, or sealants, the reflectance of conventional asphalt can be increased. • Maintenance applications such as chip seals also can increase solar reflectance. (See below.) • Urban geometry can influence the effect of high albedo pavements.	+ Lowers pavement temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved.[28] – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the nighttime urban heat island effect, due to the additional heat that needs to be released from urban infrastructure.	• Solar reflectance increases over time, and conventional asphalt may reach a reflectance of 20% after seven years.[29] (See Section 1.2.) • Urban geometry, in particular urban canyons, influences the impact reflective pavements have on the urban climate.	• Can be used in all applications, such as trails and roads. • May be most effective when paving large, exposed areas such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Concrete: • Conventional • Modified	Portland cement mixed with water and aggregate. Cured until it is strong enough to carry traffic.	• Initial solar reflectance can be 40%. • This can be raised to more than 70% using white cement instead of gray cement mixtures.[30] • Urban geometry can influence the effect of high-albedo pavements.	+ Lowers pavement temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the nighttime urban heat island effect, due to the additional heat that needs to be released from urban infrastructure.	• Solar reflectance decreases over time, as soiling from traffic darkens the surface. • Conventional concrete may reach a reflectance of 25% after 5 years. [31] (See Section 1.2.) • Urban geometry, in particular urban canyons, influences the impact reflective pavements have on the urban climate.	• Can be used in all applications, such as trails and roads. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Other reflective pavements: • Resin based • Colored asphalt • Colored concrete	• Resin based pavements use clear colored tree resins in place of cement to bind the aggregate, thus albedo is mainly determined by aggregate color. • Colored asphalt or concrete involve pigments or seals that are colored and may be more reflective than the conventional equivalent. These can be applied when new or during maintenance.	• These alternative pavements will have varying solar reflectances based on the materials used to construct them. • Urban geometry can influence the effect high-albedo pavements have.	+ Lowers pavement temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the nighttime urban heat island effect, due to the additional heat that needs to be released from urban infrastructure.	• As with concrete, solar reflectance may decrease over time as soiling from traffic makes the pavement darker and the surface wears away. • Urban geometry, particularly urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Use depends on the pavement application. In general, these alternative pavements are used for low-traffic areas, such as sidewalks, trails, and parking lots. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Permeable Pavement Options						
Nonvegetated permeable pavements	• Porous asphalt has more voids than conventional asphalt to allow water to drain through the surface into the base. • Rubberized asphalt, or crumb rubber, involves mixing shredded rubber into asphalt. This material is generally used to reduce noise. • Other porous asphalts or open-grade course friction surfaces can also be used for reducing noise. [32]	• Provides cooling through evaporation. • Solar reflectance of these materials depends on individual materials (e.g., gravel may be white and very reflective). In general, permeable pavements may be less reflective than their nonpermeable equivalent due to the increased surface area.[33] • Increased convection may help cool the pavement due to increased surface area. [34]	+ When wet, lowers pavement temperature through evaporative cooling. – When dry, may be hot at the surface, but subsurface generally will be same temperature as nonpermeable equivalent.	+ When moist, can contribute to lower air temperatures day and night, through evaporative cooling, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – When dry, can contribute to higher daytime surface temperatures, but may not affect or may even reduce nighttime air temperatures, although air temperatures are not directly related to surface temperatures and many complicating factors are involved.	• Cooling mechanism depends on available moisture. Supplemental watering may keep them cooler.[35] • Void structure may aid in insulating the subsurface from heat absorption. • More research needed to determine permeable pavement impacts on pavement and air temperatures.	• Structurally, available for any use. Rubberized asphalt and open-graded friction course asphalt are used on roads and highways and pervious concrete actively being considered. • Technologies often applied to lower traffic areas, such as parking lots, alleys, and trails. • May be best in climates with adequate moisture during the summer.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

NEW CONSTRUCTION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Permeable Pavement Options (continued)						
Nonvegetated permeable pavements ***(continued)***	• Pervious concrete has more voids than conventional concrete to allow water to drain through the surface into the base. • Brick or block pavers are generally made from clay or concrete blocks filled with rocks, gravel, or soil.	(see prior page)	(see prior page)	(see prior page)	(see prior page)	(see prior page)
Vegetated permeable pavements: • Grass pavers • Concrete grid pavers	• Plastic, metal, or concrete lattices provide support and allow grass or other vegetation to grow in the interstices.	• Provides cooling through evapotranspiration. • Sustainability of vegetation may vary with local conditions.	+ Lowers pavement temperatures through evapotranspiration, particularly when moist. + When dry may still be cooler than other pavement options due to the natural properties of vegetation.	+ In most conditions will contribute to lower air temperatures day and night, through evapotranspiration and natural properties of vegetation. Moisture availability will greatly increase its effectiveness.	• Cooling mechanism depends on available moisture. Supplemental moisture, for example watering pavements, may keep them cooler.[36] • More research needed to determine temperature impacts from vegetated pavements under a wide range of conditions.	• Low-traffic areas, such as alleys, parking lots, and trails. • May be best in climates with adequate moisture during the summer.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

MAINTENANCE/REHABILITATION						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options						
Chip seals made with high-albedo aggregate	• Chip seals describe aggregate used to resurface low-volume asphalt roads and sometimes for highway surfaces.	• Solar reflectance of chip seals will correlate with the albedo of the aggregate used. In San Jose, CA, researchers identified albedo of 20% for new chip seals, which then decline with age. [37] • Urban geometry can influence the effect high-albedo pavements have	+ Lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the urban heat island effect.	• Solar reflectance decreases over time, as soiling from traffic makes chip seals darker. • Urban geometry, in particular urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Chip seals are most often used to resurface low-volume asphalt roads, although highway applications also exist. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

MAINTENANCE/REHABILITATION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Whitetopping	• Whitetopping is a thick layer (thickness greater than 4 inches or 10 cm) of concrete applied over existing asphalt when resurfacing or can be applied to new asphalt. It often contains fibers for added strength. • Ultra-thin whitetopping is generally 2–4 inches (5–10 cm) thick and similar to whitetopping.	• The solar reflectance of whitetopping material can be as high as concrete. • Urban geometry can influence the effect of high-albedo pavements.	+ Lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings, warming the interior of the building and contributing to the urban heat island effect.	• Solar reflectance decreases over time, as soiling from traffic makes whitetopped surfaces darker. • Urban geometry, in particular urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Whitetopping and ultra-thin whitetopping are generally used to resurface road segments, intersections, and parking lots. • May be most effective when paving large, exposed areas, such as parking lots.

Table 2: Properties that Influence Pavement Temperatures—Impacts and Applications (continued)

MAINTENANCE/REHABILITATION (continued)						
Pavement Type	Description of Technology	Properties to Consider	Pavement Temperature Impacts	Urban Climate Impacts	Issues and Considerations	Target Use
Reflective Pavement Options (continued)						
Microsurfacing with high-albedo materials	• A thin sealing layer used for road maintenance. • Light-colored materials can be used to increase the solar reflectance of asphalt.	• Solar reflectance of microsurfacing will correlate with the albedo of the materials used. • Researchers recently measured solar reflectances of microsurfacing applications over 35%.[38]	+ Lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement.	+ Can contribute to lower air temperatures day and night, although air temperatures are not directly related to surface temperatures and many complicating factors are involved. – Reflected heat can be absorbed by the sides of surrounding buildings, warming the interior of the building and contributing to the urban heat island effect.	• Solar reflectance may decrease over time, if soiling from traffic makes high-albedo microsurfacing materials darker. • Urban geometry, particularly urban canyons, influences the impact high-albedo pavements have on the urban climate.	• Used to extend pavement life and on worn pavements that need improved friction, such as low- to medium-volume roads, airport runways, and parking areas.

3. Benefits and Costs

Currently, few studies provide detailed data on the benefits and costs of cool pavements. This section aims to provide a general discussion as a starting point for decision-makers to consider and gives examples where available. Again, decision-makers will also consider location-specific factors such as functionality of pavements in the local climate, political acceptance, and experience with the technology. Resources and examples providing the latest information are listed in Sections 4 and 5.

Measuring Energy Savings from Cool Roofs versus Cool Pavements

Measuring the energy impacts from a cool roof is relatively easy compared with quantifying those from pavement installations. With a roof, one can measure energy demand before and after the installation, and in a controlled experiment, the change in demand can be associated with the roofing technology. In contrast, pavements affect building energy demand through influencing air temperature, which is a more complex relationship to isolate and measure.

3.1 Benefits

Installing cool pavements can be part of an overall strategy to reduce air temperatures, which can result in a wide range of benefits. The information below highlights existing research in this area.

Reduced Energy Use

As noted earlier, researchers predicted that if pavement reflectance throughout a city were increased from 10 to 35 percent, the air temperature could potentially be reduced by 1°F (0.6°C), which would result in significant benefits in terms of lower energy use and reduced ozone levels. For example, an earlier, separate study estimated over $90 million/year in savings from temperature reductions attributed to increased pavement albedo in the Los Angeles area.[39]

Similarly, when permeable pavements evaporate water and contribute to lower air temperatures, they also provide other energy benefits.[40] Permeable pavements can allow stormwater to infiltrate into the ground, which decreases stormwater runoff. With reduced runoff, communities may realize energy savings associated with pumping stormwater and maintaining conveyance structures. These cost savings may be significant in areas where there are old, combined sewers (where stormwater drains into the sanitary sewer system).

Air Quality and Greenhouse Gas Emissions

Depending on the electric power fuel mix, decreased energy demand associated with cool pavements will result in lower associated air pollution and greenhouse gas emissions. Cooler air temperatures also slow the rate of ground-level ozone formation and reduce evaporative emissions from vehicles. A 2007 paper estimated that increasing pavement albedo in cities worldwide, from an average of 35 to 39 percent, could achieve reductions in global carbon dioxide (CO_2) emissions worth about $400 billion.[41]

Water Quality and Stormwater Runoff

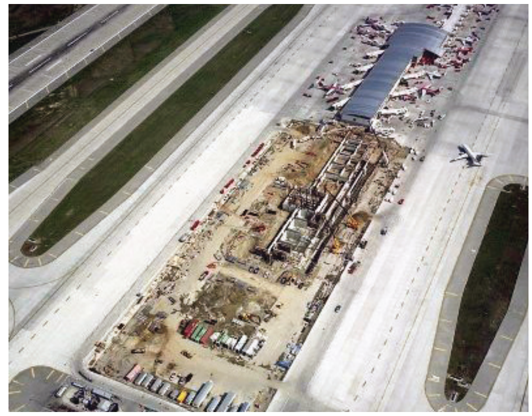
Pavements with lower surface temperatures—whether due to high solar reflectance, permeability, or other factors—can help lower the temperature of stormwater runoff, thus ameliorating thermal shock to aquatic life in the waterways into which stormwater drains.[42] Laboratory tests with permeable pavers have shown reductions in runoff temperatures of about 3–7°F (2–4°C) in comparison with conventional asphalt paving.[43]

Permeable pavements allow water to soak into the pavement and soil, thereby reducing stormwater runoff, recharging soil moisture, and improving water quality by filtering out dust, dirt, and pollutants.[44,45] Outdoor testing and laboratory measurements have found that permeable pavements can reduce runoff by up to 90 percent.[46] Reducing runoff decreases scouring of streams, and, in areas with combined sewers, this flow reduction can help minimize combined sewer overflows that discharge sewage and stormwater into receiving waters. The amount of water that these pavements collect varies based on the type of aggregate used and the porosity of the pavements, as well as on the absorptive ability of the materials supporting the pavement.

Increased Pavement Life and Waste Reduction

Reducing pavement surface temperatures can reduce the risk of premature failure of asphalt pavements by rutting (depressions in the wheelpaths) where the combination of slow heavy trucks or buses and hot temperatures make this a concern. Some full-scale testing of a typical asphalt pavement showed that it took 65 times more passes of a truck wheel to rut the pavement when the temperature just below the surface was reduced from 120°F (49°C) to 106°F (41°C).[47] In general, reducing the surface temperatures of asphalt pavements will also slow the rate of "aging" that contributes to other distresses. For concrete pavement, reducing daytime surface temperatures in locations that experience very hot temperatures in the day and cool temperatures at night will reduce the temperature-related stresses that contribute to cracking.[48]

Figure 9: Slag Cement Airport Expansion



The Detroit Metro Airport used 720,000 square feet (67,000 m^2) of slag cement in an airport terminal expansion project. In this region, the local aggregate is susceptible to alkali-silica reaction, whereas slag resists that form of corrosion better than plain cement and is easier to place in hot weather. This approach increased the life expectancy of the paved surfaces, as well as allowed for the use of a high-albedo product.[49]

Quality of Life Benefits

Cool pavements may provide additional benefits, such as:

- **Nighttime illumination.** Reflective pavements can enhance visibility at night, potentially reducing lighting requirements and saving money and energy. European road designers often take pavement color into account when planning lighting.[50]
- **Comfort improvements.** Using reflective or permeable pavements where people congregate or children play can provide localized comfort benefits through lower surface and near-surface air temperatures.[51]
- **Safety.** Permeable roadway pavements can enhance safety because better water drainage reduces water spray from moving vehicles, increases traction, and may improve visibility by draining water that increases glare.[52]

3.2 Costs

Cool pavement costs will depend on many factors including the following:

- The region
- Local climate
- Contractor
- Time of year
- Accessibility of the site
- Underlying soils
- Project size
- Expected traffic
- The desired life of the pavement.

Most cost information is project specific, and few resources exist that provide general cost information. For permeable pavement, however, the Federal Highway Administration (FHWA) has noted that porous asphalt costs approximately 10 to 15 percent more than regular asphalt, and porous concrete is about 25 percent more expensive than conventional concrete.[53] These comparisons pertain to the surface layer only.

Table 3 (below) summarizes a range of costs for conventional and cool pavements, based on available sources. The data should be read with caution, as many project-specific factors—as highlighted above—will influence costs. These costs are estimates for initial construction or performing maintenance, and do not reflect life-cycle costs. Decision-makers generally contact local paving associations and contractors to obtain more detailed, location-specific information on the costs and viability of cool pavements in their particular area.

Table 3: Comparative Costs of Various Pavements[54]

Basic Pavement Types	Example Cool Approaches	Approximate Installed Cost, \$/square foot*	Estimated Service Life, Years
New Construction			
Asphalt (conventional)	Hot mix asphalt with light aggregate, if locally available	\$0.10–\$1.50	7–20
Concrete (conventional)	Portland cement, plain-jointed	\$0.30–\$4.50	15–35
Nonvegetated permeable pavement	Porous asphalt	\$2.00–\$2.50	7–10
	Pervious concrete	\$5.00–\$6.25	15–20
	Paving blocks	\$5.00–\$10.00	> 20
Vegetated permeable pavement	Grass/gravel pavers	\$1.50–\$5.75	> 10
Maintenance			
Surface applications	Chip seals with light aggregate, if locally available	\$0.10–\$0.15	2–8
	Microsurfacing	\$0.35–\$0.65	7–10
	Ultra-thin whitetopping	\$1.50–\$6.50	10–15

* Some technologies, such as permeable options, may reduce the need for other infrastructure, such as stormwater drains, thus lowering a project's overall expenses. Those savings, however, are not reflected in this table. (1 square foot = 0.09 m^2)

3.3 Life-Cycle Cost and Environmental Impact Considerations

The term "life cycle" refers to all the phases of a pavement's life, from materials production through construction, maintenance, and use, and finishing with the end-of-life phase where the pavement is rehabilitated, recycled, or removed. Two types of calculations are typically performed for a pavement's life cycle: cost and environmental impact.

Life-cycle cost analysis (LCCA) can help in evaluating whether long-term benefits can outweigh higher up-front costs. Many agencies use LCCA to evaluate pavement structure options. The Federal Highway Administration has software for LCCA called Real Cost.[55,56,57]

Although permeable pavement costs may be higher than conventional, impermeable technologies, these costs are often offset by savings from reduced requirements for grading, treatment ponds, or other drainage features, such as inlets and stormwater pipes.[58] For a community, the cumulative reductions in stormwater flows from sites can provide significant savings in the municipal infrastructure. If the community has combined sewers, there could also be environmental, social, and cost benefits from reducing combined sewer overflows, as well as potentially avoiding part of the increased infrastructure costs associated with combined sewer operation.

Life-cycle assessment (LCA) considers the environmental impacts throughout the life of the pavement. The International Standard Organization has published a generic LCA guideline for all industrial products (the ISO 14040 series of documents).[59] The National Institute of Standards and Technology has developed Building for Environmental and Economic Sustainability (BEES), a software tool that uses the ISO 14040 series of standards to estimate life-cycle environmental impacts from the production and use of asphalt, Portland cement, fly ash cement, and other paving materials in a building environment. The BEES software also has an LCCA module.[60] Although not directly related to urban heat island mitigation, this tool can help quantify some of the environmental and cost impacts from a variety of pavement choices.

LCA for road pavements is a nascent field. A workshop was held in May 2010 regarding implementation of ISO 14040 for roads and issues that remain to be resolved.[61] LCA has not been used to date to compare the environmental impacts of permeable or reflective versus conventional pavement. In general, until more data on cool pavement environmental impacts and costs exist, communities may need to think broadly to determine if a cool pavement application is appropriate. Sustainability initiatives, in some areas, are motivating communities to try cooler alternatives, as discussed in Section 4.

4. Cool Pavement Initiatives

The growing interest in lowering urban temperatures and designing more sustainable communities has helped spur activity in the cool pavement arena. Most of the effort has focused on research, due to information gaps and the lack of specific data quantifying cool pavement benefits. More information on resources and examples are provided at the end of this section and in Section 5. Highlights of some cool pavement efforts are below:

- **Arizona State University's National Center of Excellence (NCE) SMART Innovations for Urban Climate and Energy.**[62] This group is studying established and emerging designs that optimize albedo, emissivity, thermal conductivity, heat storage capacity, and density in laboratory and field sites. NCE is developing models, particularly for the Phoenix area but also beyond, to help decision-makers predict the effects of material properties, shading, and energy use on urban temperatures.
- **The National Academies of Science's Transportation Research Board (TRB) Subcommittee on Paving Materials and the Urban Climate.** TRB established this Subcommittee in January 2008 to help advance the science of using pavements for heat island mitigation and addressing other urban climate concerns.
- **Trade association efforts.** Representatives from the asphalt and concrete trade associations are participating in cool pavement efforts, such as the TRB Subcommittee on Paving Materials and the Urban Climate, as well supporting research and training related to cool pavement. For example, the National Asphalt Pavement Association has been investigating high-albedo asphalt pavements, the National Ready Mixed Concrete Association is leading seminars on pervious concrete, and the Interlocking Concrete Pavement Institute (ICPI) is providing professional seminars on permeable pavements in cooperation with the Low Impact Development Center and North Carolina State University.[63]

These research efforts are expanding opportunities for identifying, applying, and studying cool pavement technologies.

Sustainability or green building initiatives are helping to encourage cool pavement installations.

- **Evanston, Illinois,** includes permeable pavements in its assessment of green buildings.[64]
- **Chicago's Green Alley program** aims to use green construction techniques to repave over 1,900 miles of alleys, and offers a handbook for installing permeable pavements for heat reduction, stormwater management, and other benefits.[65]
- **Environmental rating programs** such as Leadership in Energy and Environmental Design (LEED), Green Globes, and EarthCraft award points to designs that incorporate certain permeable pavements or pavements of a certain solar reflectance index. They also give points for using local and recycled materials, such as slag, and reducing the pavement used on a site.

Table 4 on page 29 summarizes other cool pavement initiatives. Refer to the "Heat Island Reduction Activities" chapter of this compendium for further examples.

Although cool pavements are still in their infancy compared with the other heat island mitigation strategies—trees and vegetation, green roofs, and cool roofs—interest and momentum are growing. Research efforts these past few years have greatly increased, particularly in the area of permeable pavements. As local and state transportation and environmental agencies work together to address energy, sustainability, heat-health, and other concerns, communities can expect to see more cool pavement installations. Activity in the private sector has also been encouraging, as architects, developers, and others are taking leadership roles in advancing sustainable technologies. This chapter, which currently provides a starting point for communities and decision-makers, will evolve as more information becomes available.

Growing Concern about Synthetic Turf

Many communities have begun to examine the health impacts from synthetic turf surfaces, which include the effects from high temperatures. One researcher in New York found that artificial sports fields could be up to 60°F (16°C) hotter than grass, potentially causing skin injuries to athletes as well as contributing to the heat island effect. These data, though not directly related to pavements, can help advance our understanding of how different materials interact with the urban climate.[66]

Figure 11: Grass Paving

David Hitchcock, HARC

This 300,000-square-foot (28,000 m^2) parking lot outside a stadium in Houston uses plastic grid pavers that allow grass to grow in the open spaces.

Alternative Paving under the Cool Houston Plan

While most communities have no, or limited, cool pavement experience, Houston's heat island initiative recommends alternative pavements as part of the city's overall approach to improving air quality and public health. The plan's three-tiered strategy includes:

- Targeting alternative paving options for specific types of paved surfaces, such as highways or parking lots, or expanding residential or commercial roadways. This requires coordination with the Texas Department of Transportation and the Texas Commission on Environmental Quality.
- Educating local and state decision-makers about public health, environmental management, and public works maintenance benefits of alternative pavements.
- Combining and embedding alternative paving incentives into larger programs and regulations, such as meeting Clean Air or Clean Water Act standards, with the support of the Greater Houston Builders Association and the Texas Aggregates and Concrete Association.

Table 4: Examples of Cool Pavement Initiatives

Type of Initiative	Description	Links to Examples
Research	Industry	<www.nrmca.org/>—Since 1928, the National Ready Mixed Concrete Association's research laboratory has helped evaluate materials and set technical standards. Recent projects include developing permeability tests and assessing concrete with high fly-ash content.
	National laboratory	<http://eetd.lbl.gov/HeatIsland/Pavements/>—The Heat Island Group at Lawrence Berkeley National Laboratory (LBNL) provides research and information about cool paving and other heat island mitigation measures. The Cool Pavements section describes the benefits of this technology, and published reports are included under Recent Publications.
	University-supported and similar consortia	<www.asusmart.com/pavements.php>—Arizona State University's National Center of Excellence collaborates with industry and government to research and develop technologies to reduce urban heat islands, especially in desert climates.
		<www.harc.edu/Projects/CoolHouston/>—The Houston Advanced Research Center (HARC) brings together universities, local governments, and other groups interested in improving air quality and reducing heat islands. It has examined how cool paving could be implemented in the Houston area to reduce urban heat island effects.
		<http://ncsu.edu/picp/index.html> and <www.bae.ncsu.edu/info/permeable_pavement/index.html>—North Carolina State University has an active permeable pavement research program, as well as a specialized collaborative effort with ICPI and the Low Impact Development Center on permeable interlocking concrete pavements.

Table 4: Examples of Cool Pavement Initiatives (cont.)

Type of Initiative	Description	Links to Examples
Voluntary efforts	Demonstration programs	<www.cityofpoulsbo.com/CityCouncil/PDFsDOCs/Works/2007/4-25minutes.pdf>—Poulsbo, Washington, used a $263,000 grant from the Washington Department of Ecology to pave 2,000 feet of sidewalk with pervious pavement, making it one of the largest pervious surface projects in the state.
		<www.heifer.org/site/c.edJRKQNiFiG/b.1484715/>—The nonprofit Heifer International used pervious pavement and other sustainable techniques for its new headquarters in Arkansas.
	Outreach & education	< www.epa.gov/heatisland/>—EPA's Heat Island Reduction Initiative provides information on the temperature, energy, and air quality impacts from cool pavements and other heat island mitigation strategies.
		<http://cfpub.epa.gov/npdes/home.cfm?program_id=298>—EPA's Office of Water highlights design options, including permeable pavements that reduce stormwater runoff and water pollution.
		<www.greenhighways.org/>—The Green Highways Partnership, supported by a number of groups including EPA and the U.S. Department of Transportation is a public-private partnership dedicated to transforming the relationship between the environment and transportation infrastructure. The partnership's Web site includes a number of cool pavement resources, especially with respect to permeable pavements.
		<http://nemo.uconn.edu/index.htm>—The University of Connecticut runs Nonpoint Education for Municipal Officials (NEMO), which helps educate local governments about land use and environmental quality.
	Tools	<www.bfrl.nist.gov/oae/software/bees/>—The National Institute of Standards and Technology (NIST) has developed a software tool, Building for Environmental and Economic Stability (BEES). The tool enables communities to conduct life cycle cost assessments for various types of building initiatives, including pavement projects.
Policy efforts	Municipal regulations that support cool pavements	<http://files.harc.edu/Projects/CoolHouston/CoolHoustonPlan.pdf>—The Cool Houston! Plan promotes cool paving as well as other techniques to reduce the region's heat island.
		<www.toronto.ca/planning/urbdesign/greening_parking_lots.htm>—Toronto's "Design Guidelines for 'Greening' Surface Parking Lots" encourage reflective and permeable pavements to reduce surface temperatures.

5. Resources

The organizations below may provide additional information on alternative, or cool, pavement technologies.

Program/Organization	Role	Web Address
The Federal Highway Administration's (FHWA) Office of Pavement Technology	The Office of Pavement Technology conducts research and training related to asphalt and concrete pavements.	<www.fhwa.dot.gov/pavement/hq/welcome.cfm>
FHWA's Office of Planning, Environment, and Realty	This office's Web site provides information regarding transportation planning and the environment.	<www.fhwa.dot.gov/hep/index.htm>
American Association of State Highway and Transportation Officials Center for Environmental Excellence (AASHTO)	AASHTO created the Center for Environmental Excellence in cooperation with the Federal Highway Administration to offer technical assistance about environmental regulations and ways to meet them.	<http://environment.transportation.org/>
Association of Metropolitan Planning Organizations (AMPO)	AMPO supports local MPOs through training, conferences, and assistance with policy development.	<www.ampo.org/>
The American Concrete Pavement Association (ACPA)	ACPA promotes concrete pavement by working with industry and government.	<www.pavement.com>
The Asphalt Pavement Alliance (APA)	A consortium of the National Asphalt Paving Association (NAPA), the Asphalt Institute (AI), and state paving associations, APA promotes hot mix asphalt through research, development, and outreach. Individual state asphalt associations are a good source for local paving considerations.	<www.asphaltalliance.com>
Interlocking Concrete Pavement Institute (ICPI)	ICPI has a document that compares permeable pavement technologies and helps readers find certified installers.	<www.icpi.org>
National Center for Asphalt Technology (NCAT)	NCAT provides up-to-date strategies for designing and constructing asphalt pavements.	<www.ncat.us>
National Ready Mixed Concrete Association	Since 1928, the National Ready Mixed Concrete Association's research laboratory has helped evaluate materials and set technical standards. Recent projects include developing permeability tests and assessing concrete with high fly-ash content.	<www.nrmca.org>
Portland Cement Association (PCA)	PCA represents cement companies in the United States and Canada and conducts research, development, and outreach.	<www.cement.org>

Endnotes

1 Statistics are from urban fabric analyses conducted by Lawrence Berkeley National Laboratory. Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.
Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois. Paper LBNL-49275. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Paper LBNL-47851. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H., L.S. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California. Paper LBNL-44688. Lawrence Berkeley National Laboratory, Berkeley, CA.

2 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA. See also Cambridge Systematics. 2005. Cool Pavement Draft Report. Prepared for U.S. EPA.

3 See, generally, U.S. EPA 2008. Green Parking Lot Resource Guide. EPA 510-B-08-001.

4 Golden, J.S., J. Carlson, K. Kaloush, and P. Phelan. 2006. A Comparative Study of the Thermal and Radiative Impacts of Photovoltaic Canopies on Pavement Surface Temperatures. Solar Energy. 81(7): 872-883. July 2007.

5 Kinouchi, T., T. Yoshinaka, N. Fukae, and M. Kanda. 2004. Development of Cool Pavement with Dark Colored High Albedo Coating. Paper for 5th Conference for the Urban Environment. Vancouver, Canada. Retrieved November 15, 2007, from <http://ams.confex.com/ams/pdfpapers/79804.pdf>.

6 National Center of Excellence on SMART Innovations at Arizona State University. 2007. What Factors Influence Elevated Pavement Temperatures Most During Day and Night? Case Study 1(1).

7 The Portland Cement Association thoroughly explains concrete cement at <www.cement.org/tech/cct_concrete_prod.asp>, and state and federal government sites, among others, define asphalt. Two useful ones are <www.virginiadot.org/business/resources/bu-mat-Chapt1AP.pdf> and <www.tfhrc.gov/hnr20/recycle/waste/app.htm>.

8 Levinson, R. and H. Akbari. 2001. Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete. Paper LBNL-48334. Lawrence Berkeley National Laboratory, Berkeley, CA.

9 National Center of Excellence on SMART Innovations at Arizona State University. 2007. What Factors Influence Elevated Pavement Temperatures Most During Day and Night? Case Study 1(1).

10 Levinson, R., H. Akbari, S. Konopacki, and S. Bretz. 2002. Inclusion of Cool Roofs in Nonresidential Title 24 Prescriptive Requirements. Paper LBNL-50451. Lawrence Berkeley National Laboratory, Berkeley, CA.

11 See:

Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

Kevern, J., V.R. Schaefer, and K. Wong. 2008. Temperature Behavior of a Pervious Concrete System. Under review for the 2009 Transportation Research Board Annual Meeting.

12 For a general overview of permeable pavements, see Ferguson, B. 2005. Porous Pavements.

13 See, generally:

Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

Kevern, J., V.R. Schaefer, and K. Wong. 2008. Temperature Behavior of a Pervious Concrete System. Under review for the 2009 Transportation Research Board Annual Meeting.

14 There are a number of resources available on Japan's efforts with water retentive pavements, although there is no centralized source that compiles these initiatives. For examples of the research and published summaries available, see the following (all Web sites accessed September 17, 2008):

Karasawa, A., K. Toriiminami, N. Ezumi, K. Kamaya. 2006. Evaluation Of Performance Of Water-Retentive Concrete Block Pavements. 8th International Conference on Concrete Block Paving, November 6-8, 2006, San Francisco, California.

Ishizuka, R., E. Fujiwara, H. Akagawa. 2006. Study On Applicability Of Water-Feed-Type Wet Block Pavement To Roadways. 8th International Conference on Concrete Block Paving, November 6-8, 2006, San Francisco, California.

Yamamoto, Y. 2006. Measures to Mitigate Urban Heat Islands. Quarterly Review No. 18. January 2006. Available online at <www.nistep.go.jp/achiev/ftx/eng/stfc/stt018e/qr18pdf/STTqr1806.pdf>.

Yoshioka, M., H. Tosaka, K. Nakagawa 2007. Experimental and Numerical Studies of the Effects of Water Sprinkling on Urban Pavement on Heat Island Mitigation. American Geophysical Union, Fall Meeting 2007, abstract #H43D-1607.

Yamagata H., M. Nasu, M. Yoshizawa, A. Miyamoto, and M. Minamiyama. 2008. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water science and technology. 57(5): 763-771. Abstract available online at <http://cat.inist.fr/?aModele=afficheN&cpsidt=20266221>.

15 Christen, A. and R. Vogt. 2004. Energy and radiation balance of a Central European city. International Journal of Climatology. 24(ii):1395-1421.

16 Golden, J.S. and K. Kaloush. 2006. Meso-Scale and Micro-Scale Evaluations of Surface Pavement Impacts to the Urban Heat Island Effects. The International Journal of Pavement Engineering. 7(1): 37-52. March 2006.

17 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA.

18 Taha, H. 1997. Modeling the impacts of large-scale albedo changes on ozone air quality in the South Coast Air Basin. Atmospheric Environment. 31(11): 1667-1676.

Taha, H. 1996. Modeling the Impacts of Increased Urban Vegetation on the Ozone Air Quality in the South Coast Air Basin. Atmospheric Environment. 30(20): 3423-3430.

19 Rosenfeld, A.H., J.J. Romm, H. Akbari, and M. Pomerantz. 1998. Cool Communities: Strategies for Heat Islands Mitigation and Smog Reduction. Energy and Buildings. 28:51-62.

20 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

21 Statistics are from urban fabric analyses conducted by Lawrence Berkeley National Laboratory. Rose, L.S., H. Akbari, and H. Taha. 2003. Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas. Paper LBNL-51448. Lawrence Berkeley National Laboratory, Berkeley, CA.
Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois. Paper LBNL-49275. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H. and L.S. Rose. 2001. Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Paper LBNL-47851. Lawrence Berkeley National Laboratory, Berkeley, CA. Akbari, H., L.S. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California. Paper LBNL-44688. Lawrence Berkeley National Laboratory, Berkeley, CA.

22 See, e.g., Mallick, R.B., P.S. Kandhal, L.A. Cooley, Jr., and P.E. Watson. 2000. Design, Construction, and Performance of New-generation Open-graded Friction Courses. Paper prepared for annual meeting of Association of Asphalt Paving Technologists, Reno, NV, March 13-15, 2000.

23 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

24 More information on fly ash is available through EPA's Coal Combustion Products Partnership, <www.epa.gov/rcc/c2p2/index.htm>.

25 Boriboonsomsin, K. and F. Reza. 2007. Mix Design and Benefit Evaluation of High Solar Reflectance Concrete for Pavements. Paper for 86th Annual Meeting of the Transportation Research Board. Washington, D.C.

26 Office of the Governor. 2006. Statement by Gov. Schwarzenegger on U.S. EPA Award for California's Leadership in the Construction Use of Waste Products. Retrieved July 15, 2008, from <http://gov.ca.gov/index.php?/press-release/4839/>

27 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements' Temperatures On Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA. See also Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

28 Aseda, T., V.T. Ca, and A. Wake. 1993. Heat Storage of Pavement and its Effect on the Lower Atmosphere. Atmospheric Environment. 30(3): 413–427. 1996.

29 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

30 Levinson, R. and H. Akbari. 2001. Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete. Paper LBNL-48334. Lawrence Berkeley National Laboratory, Berkeley, CA.

31 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

32 National Center of Excellence on SMART Innovations at Arizona State University. 2007. Alternative Paving—Recycling Crumb Rubber. Case Study, 1(3).

33 Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

34 Haselbach, L. 2008. Pervious Concrete and Mitigation of the Urban Heat Island Effect. Under review for the 2009 Transportation Research Board Annual Meeting.

35 Yamagata H., M. Nasu, M. Yoshizawa, A. Miyamoto, and M. Minamiyama. 2008. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water science and technology. 57(5): 763-771. Abstract available online at <http://cat.inist.fr/?aModele=afficheN&cpsidt=20266221>.

36 Yamagata H., M. Nasu, M. Yoshizawa, A. Miyamoto, and M. Minamiyama. 2008. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water science and technology. 57(5): 763-771. Abstract available online at <http://cat.inist.fr/?aModele=afficheN&cpsidt=20266221>.

37 Pomerantz, M., H. Akbari, S.-C. Chang, R. Levinson and B. Pon. 2003. Examples of Cooler Reflective Streets for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals. Paper LBNL-49283. Lawrence Berkeley National Laboratory, Berkeley, CA.

38 Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

39 Rosenfeld, A.H., J.J. Romm, H. Akbari, and M. Pomerantz. 1998. “Cool Communities: Strategies for Heat Islands Mitigation and Smog Reduction,” Energy and Buildings, 28, pp. 51-62.

40 Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. 2000. The Effect of Pavements’ Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA.

41 Akbari, H., and S. Menon. 2007. Global Cooling: Effect of Urban Albedo on Global Temperature. Paper for the Proceedings of the International Seminar on Planetary Emergencies. Erice, Sicily.

42 U.S. EPA. 2003. Beating the Heat: Mitigating Thermal Impacts. Nonpoint Source News-Notes. 72:23-26.

43 James, W. 2002. Green Roads: Research into Permeable Pavers. Stormwater. Retrieved May 8, 2008 from <www.stormcon.com/sw_0203_green.html>.

44 U.S. EPA. Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices. EPA 841-F-07-006, December 2007. Retrieved April 2, 2008 from <www.epa.gov/owow/nps/lid/costs07/>.

45 Booth, D. and J. Leavit. 1999. Field Evaluation of Permeable Pavement Systems for Improved Stormwater Management. Journal of the American Planning Association. 65(3): 314-325.

46 James, W. 2002. Green Roads: Research into Permeable Pavers. Stormwater. Retrieved May 8, 2008 from <www.stormcon.com/sw_0203_green.html>.

47 Pomerantz, M., H. Akbari, and J. Harvey. 2000. Durability and Visibility Benefits of Cooler Reflective Pavements. Paper LBNL-43443. Lawrence Berkeley National Laboratory, Berkeley, CA.

48 ARA Inc., ERES Consultants. 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Part 3. Design Analyis, Ch. 4 Design of New and Reconstructed Rigid Pavements. Final Report Project 1-37A. National Cooperative Highway Research Program, Transportation Research Board, National Academy of Science. Washington DC.

49 Bijen, Jan. 1996. Benefits of slag and fly ash. Construction and Building Materials 10.5: 309-314. See also the Federal Highway Administration’s summary of slag cement at <www.tfhrc.gov/hnr20/recycle/waste/bfs3.htm>.

50 U.S. Department of Transportation, Federal Highway Administration. European Road Lighting Technologies. International Technology Exchange Program: September 2001. Retrieved June 16, 2008, from <http://international.fhwa.dot.gov/euroroadlighting/index.cfm>. See also: International Commission on Illumination. 2007. Road Transport Lighting for Developing Countries. CIE 180:2007.

51 Kinouchi, T., T. Yoshinaka, N. Fukae, and M. Kanda. 2004. Development of Cool Pavement with Dark Colored High Albedo Coating. Paper for 5th Conference for the Urban Environment. Vancouver, Canada. Retrieved November 15, 2007, from <http://ams.confex.com/ams/pdfpapers/79804.pdf>.

52 U.S. Department of Transportation, Federal Highway Transportation Administration. 2005. Technical Advisory: Surface Texture for Asphalt and Concrete Pavements. Retrieved September 17, 2008, from <www.fhwa.dot.gov/legsregs/directives/techadvs/t504036.htm>. Michigan Department of Environmental Quality. 1992. Porous Asphalt Pavement. Retrieved 16 Sep 2008 from <www.deq.state.mi.us/documents/deq-swq-nps-pap.pdf>.

53 U.S. Department of Transportation, Federal Highway Administration. Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring. Fact Sheet - Porous Pavements. Retrieved April 2, 2008, from <www.fhwa.dot.gov/environment/ultraurb/3fs15.htm>.

54 Figures are taken from multiples sources and express the maximum range of the values: 1) Cambridge Systematics. 2005. Cool Pavement Draft Report. Prepared for U.S. EPA. 2) ASU's draft of the Phoenix Energy and Climate Guidebook. 3) Center for Watershed Protection. 2007. Redevelopment Projects. New York State Stormwater Management Design Manual. Prepared for New York State Department of Environmental Conservation. Retrieved June 13, 2008, from <www.dec.ny.gov/docs/water_pdf/swdmredevelop.pdf>. 4) Bean, E.Z.,W.F. Hunt, D.A. Bidelspach, and J.T. Smith. 2004. Study on the Surface Infiltration Rate of Permeable Pavements. Prepared for Interlocking Concrete Pavement Institute. 5) Interlocking Concrete Pavement Institute. 2008. Permeable Interlocking Concrete Pavements: A Comparison Guide to Porous Asphalt and Pervious Concrete. 6) Pratt, C.J. 2004. Sustainable Drainage: A Review of Published Material on the Performance of Various SUDS Components. Prepared for The Environment Agency. Retrieved June 13, 2008, from <www.ciria.org/suds/pdf/suds_lit_review_04.pdf>. 7) NDS, Inc. Technical Specifications for Grass Pavers. Retrieved June 13, 2008, from <www.ndspro.com/cms/index.php/Engineers-and-Architects.html>. 8) Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

55 Federal Highway Administration. 2002. Life Cycle Cost Analysis Primer. FHWA-IF-02-047. Office of Asset Management. Washington DC. August. 25 pp. Accessible at http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm.

56 D. Walls, J., M. Smith. 1998. Life-Cycle Cost Analysis in Pavement Design —Interim Technical Bulletin. FHWA-SA-98-079. Federal Highway Administration. September. 107pp . Accessible at http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf.

57 Federal Highway Administration. Real Cost. version 2.5. Accessible at http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm.

58 U.S. EPA. 2007. Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices. EPA 841-F-07-006. Retrieved April 2, 2008, from <www.epa.gov/owow/nps/lid/costs07/documents/reducingstormwatercosts.pdf>.

59 International Standards Organization. Documents can be purchased at http://www.iso.org/iso/catalogue_detail?csnumber=37456.

60 See the Building for Environmental and Economic Sustainability (BEES) software at <www.bfrl.nist.gov/oae/software/bees/>.

61 Information on the LCA for Pavements Workshop held in May, 2010 is available at www.ucprc.ucdavis.edu/p-lca.

62 National Center of Excellence on SMART Innovations at Arizona State University <http://asusmart.com/background.php>.

63 The National Asphalt Pavement Association conducts training and professional development (see <www.hotmix.org/>) and the National Ready Mixed Concrete Association has a research lab near College Park, Maryland, and conducts training and professional development (see <www.nrmca.org/> for details). For the Interlocking Concrete Pavement Institute seminars, see <www.ncsu.edu/picp/upcoming.html>. See also recent sponsored research efforts, such as:

Kevern, J., V.R. Schaefer, and K. Wong. 2008. Temperature Behavior of a Pervious Concrete System. Under review for the 2009 Transportation Research Board Annual Meeting.

Tran, N., B. Powell, H. Marks, R. West, and A. Kvasnak. 2008. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. Under review for the 2009 Transportation Research Board Annual Meeting.

64 For the design guidelines, see <www.cityofevanston.org/departments/communitydevelopment/planning/pdf/DGs_Final_000.pdf>.

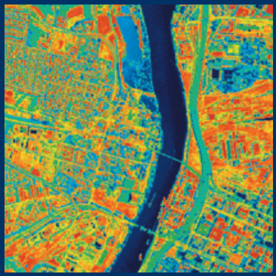
65 City of Chicago. Chicago Green Alley Handbook. Retrieved May 15, 2008, from <http://egov.cityofchicago.org/webportal/COCWebPortal/COC_EDITORIAL/GreenAlleyHandbook.pdf>.

66 See:

Claudio, L. 2008. Synthetic Turf: Health Debate Takes Root. Environmental Health Perspectives 116.3. Retrieved September 16, 2008, from <www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2265067>.

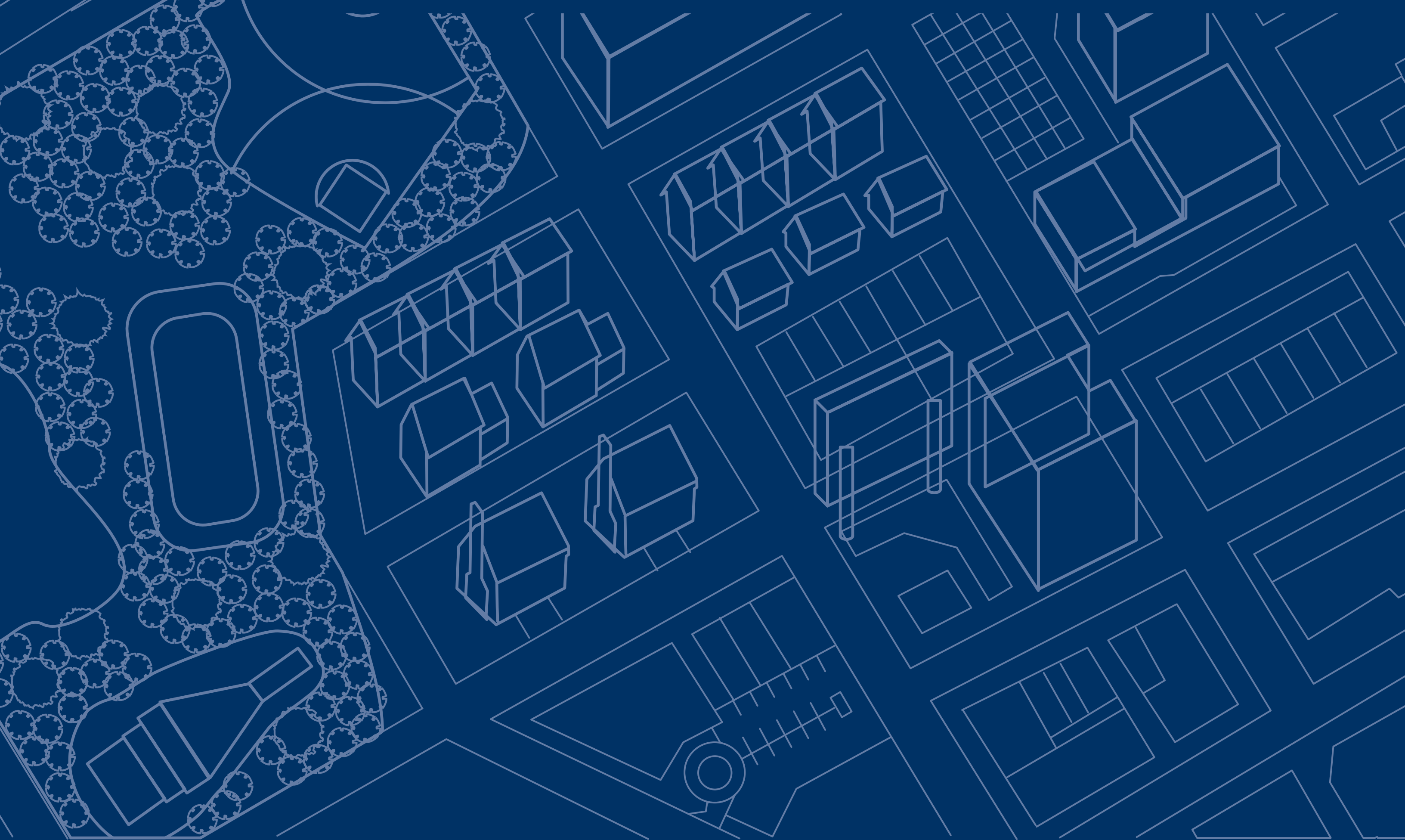
Aubrey, A. 2008. High Temps On Turf Fields Spark Safety Concerns. NPR Morning Edition, 7 Aug. Retrieved September 16, 2008, from <www.npr.org/templates/story/story.php?storyId=93364750>.





Reducing Urban Heat Islands: Compendium of Strategies

Heat Island Reduction Activities



Acknowledgements

Reducing Urban Heat Islands: Compendium of Strategies describes the causes and impacts of summertime urban heat islands and promotes strategies for lowering temperatures in U.S. communities. This compendium was developed by the Climate Protection Partnership Division in the U.S. Environmental Protection Agency's Office of Atmospheric Programs. Eva Wong managed its overall development. Kathleen Hogan, Julie Rosenberg, and Andrea Denny provided editorial support. Numerous EPA staff in offices throughout the Agency contributed content and provided reviews. Subject area experts from other organizations around the United States and Canada also committed their time to provide technical feedback.

Under contracts 68-W-02-029 and EP-C-06-003, Perrin Quarles Associates, Inc. provided technical and administrative support for the entire compendium, and Eastern Research Group, Inc. provided graphics and production services.

PositvEnergy provided support in preparing the Trees and Vegetation, Cool Roofs, and UHI Activities chapters under contract PO #2W-0361-SATX.

Experts who helped shape this chapter include:

David Cole, Nikolaas Dietsch, Gary Gero, David Hitchcock, Megan Lewis, Julie Magee, Misha Sarkovich, Jim Yarbrough, and Barry Zalph.

Suggested Citation: U.S. Environmental Protection Agency. 2008. "Heat Island Reduction Activities." In: *Reducing Urban Heat Islands: Compendium of Strategies. Draft.* https://www.epa.gov/heat-islands/heat-island-compendium.

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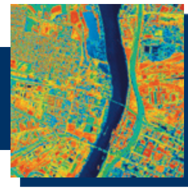


Heat Island Reduction Activities

Across the United States, a diverse group of stakeholders, from government agencies to corporations, have advanced urban heat island reduction strategies—urban forestry, green and cool roofs, and cool pavements—to lower summertime temperatures and achieve many energy and environmental benefits. Typically heat island mitigation is part of an energy, air quality, water, or sustainability effort,[1] and activities range from voluntary initiatives, such as cool pavement demonstration projects, to policy actions, such as requiring cool roofs via building codes. Some communities have elected to implement both voluntary and policy initiatives. These efforts can complement each other, and sometimes an initiative that begins as a voluntary activity becomes required over time.

This chapter draws from the experience of many different groups and covers a range of initiatives to highlight a variety of urban heat island reduction activities around the country. Examples for the following types of activities are included:

- Demonstration projects
- Incentive programs
- Urban forestry programs
- Weatherization
- Outreach and education
- Awards
- Procurement
- Resolutions
- Tree and landscape ordinances
- Comprehensive plans and design guidelines
- Zoning codes
- Green building standards
- Building codes
- Air quality standards.

Heat Island Mitigation Strategies

For more information on heat island reduction strategies, see the corresponding chapters of this compendium: "Trees and Vegetation," "Green Roofs," "Cool Roofs," and "Cool Pavements."

1. Voluntary Efforts

Most community strategies to reduce heat islands have relied on voluntary efforts, which can generally be grouped into the following categories:

- Demonstration projects
- Incentive programs
- Urban forestry programs
- Weatherization
- Outreach and education
- Awards.

Many groups choose to conduct just one kind of activity; others combine approaches. For example, some utilities have focused on cool roof rebates to encourage consumers to install reflective roofing products. Some local environment departments have sponsored demonstration projects, conducted outreach and education efforts to publicize results, and have provided grants to support use of mitigation technologies by residents and industry.

1.1 Demonstration Projects

Local governments, universities, and other organizations have used projects to demonstrate a specific heat island mitigation strategy and quantify its benefits in a controlled environment. Documenting the project and its results can provide the data and publicity needed to develop larger initiatives, promote new technologies and help get them to market, and sometimes even encourage local economic development. (See the "Stimulating Local Economies and Businesses" textbox.)

Communities have found heat island demonstration projects to be most effective when they:

- **Target high-visibility projects.** Focusing efforts on a prominent building or site helps attract attention to heat island mitigation efforts.
- **Measure benefits.** Highlighting anticipated benefits and collecting data on actual impacts provides useful information for planning future activities. These benefits also illustrate to others the reasons and means to act.
- **Convey lessons learned.** Documenting how demonstration projects are conducted makes them easier to replicate and improve.

Lead By Example

"Lead by example" programs involve implementing strategies within local and state government facilities, operations, and fleets, where appropriate. These programs offer energy, environmental, and financial benefits while creating an important opportunity for governments to demonstrate the economic feasibility of the strategies they are promoting. This leadership can raise public awareness of the benefits of urban heat island reduction strategies, which can lead to increased public and private sector support for advancing them.

A variety of organizations can be the chief agents of change and the first to test alternative technologies, often in highly visible, public facilities. Demonstration projects have taken place in parks, schools, and municipal buildings like city hall. These projects often also monitor costs and benefits, such as energy savings. Examples include:

- **Chicago installed a green roof on its city hall** that includes 20,000 plants, shrubs, grasses, vines, and trees. The city expects to save directly more than 9,270 kilowatt-hours (kWh) per year of electricity and nearly 740 million British thermal units (Btu) per year of natural gas for heating. This energy savings translates into about $3,600 annually, and savings will increase with higher energy prices. In addition to assessing energy impacts, the green roof has been designed to test different types of rooftop garden systems, success rates of native and non-native vegetation, and reductions in stormwater runoff. This city hall green roof has helped to raise the visibility of green roofs and to increase public understanding of them. Chicago's Department of Environment staff has frequently given presentations about the roof, which has won numerous awards. For further information, go to <http://egov.city ofchicago.org> and look under the Department of Environment's City Hall green roof project.
- A demonstration project for **Tucson documented how a cool roof reduced temperatures** inside and on the roof of the building and saved more than 400 million Btu annually in energy. A white elastomeric coating was installed over a 28,000-square foot (2,600 m^2), unshaded metal roof on one of the city's administration buildings. Following the installation, energy savings were calculated at 50 to 65

Figure 1: Chicago City Hall Green Roof

Katrin Barth-Scholz/Department of Energy

Chicago's commitment to green roofs includes demonstration projects, such as on its City Hall, education, incentives, and policy actions.

Stimulating Local Economies and Businesses

The non-profit group Sustainable South Bronx has developed several goals for the green roof/cool roof demonstration project on top of its office building in Hunts Point. These goals include gathering research on local benefits, establishing a resource for the community, educating New Yorkers on the value of green roofs, and advocating sustainable building practices. The demonstration project has become a springboard for developing a local green and cool roof installation company to provide employment opportunities in the South Bronx area. The group's business is called SmartRoofs and includes a job-training program for local residents. See <www.ssbx.org/greenroofs.html#> for more information.

percent of the building's cooling energy—an avoided energy cost of nearly $4,000 annually. See <www.swenergy.org/casestudies/arizona/tucson_topsc.htm> for more information.

1.2 Incentives

Incentives have proven to be an effective way to spur individual heat island reduction actions. Incentives from governments, utilities, and other organizations can include below-market loans, tax breaks, product rebates, grants, and giveaways. For example:

- Since 2006, **Baltimore County's Growing Home Campaign has provided $10 coupons** to homeowners toward the purchase of most trees at local nurseries. Each coupon represents $5 of public funds and $5 of retail funds. In order to validate their coupons, homeowners provide information including tree type and location planted, which allows the county to integrate the data with future tree canopy studies. The county began the program as an innovative way to increase tree canopy cover as part of its larger "Green Renaissance" forest conservation and sustainability plan. In the first two months of the program, 1,700 trees were planted. See <http://fpum.org/pdf/MD%20managing_forest_resources.pdf> and <www.baltimorecountymd.gov/Agencies/environment/growinghome/index.html> for further information.
- Since 1990, the **Sacramento Municipal Utility District (SMUD) has partnered with the Sacramento Tree Foundation to provide more than 350,000 free shade trees** to residents in the Sacramento area. This program encourages residents to strategically plant vegetation around their homes to reduce energy consumption. Homes with an eastern, western, or southern exposure that heats up during the summer are eligible for this program. SMUD provides trees between four and seven feet tall (1.2-2.2 m), as well as stakes, ties, fertilizer, tree delivery, and expert advice on tree selection and planting techniques free of charge. Homeowners must agree to plant and care for the trees. See <www.smud.org/residential/trees/index.html> for more information. SMUD also offers rebates to residential customers who use cool roofing technologies. The utility offers a 20-cent-per-square-foot (0.09 m^2) rebate to customers who own single-family, multi-family, or mobile homes with flat roofs and who install ENERGY STAR® cool roof products.
- After the success of its green roof demonstration project, **Chicago established green and cool roof grant programs.** The green roof program cites the ability of green roofs to "create energy savings for building," "lower surrounding urban heat temperatures," and "reduce storm water runoff, improve water quality, and create conditions for longer-lasting roof systems." Similarly, the city recognizes cool roofs "not only help reduce cooling costs, but can also have a positive environmental impact by reducing the urban heat island effect." In 2005, its first year, the program supported 20 green roof installation projects; in 2006, it helped fund 40. In the fall of 2007, the city announced that it was expanding the program to include cool roofs and expected to provide about 55 $6,000 grants. Recipients can use grants for residential, commercial, or industrial buildings. See <http://egov.cityofchicago.org/>, under the Department of Environment portion of the website, for more information.

- The **Pennsylvania Department of Environmental Protection's Energy Harvest Program has been providing grants for specific energy saving projects** since 2003. In 2007, it dispensed more than $500,000 to green roof projects across the state. The Energy Harvest Program overall aims to deploy innovative technologies and encourages "proposals that are market-driven, create jobs, and produce economic development within the Commonwealth." See Energy Harvest Program information available at: <www.depweb.state.pa.us/energy/site/default.asp>.
- In addition to green roofs, building owners can also install vertical gardens—sometimes referred to as green or living walls—on exterior walls to shade buildings and provide evapotranspiration.[2] The **Houston Downtown Management District (HDMD) Vertical Gardens Matching Grant initiative first gave grants in 2007 to encourage plantings that cover walls.** The grants also support exceptional landscaping that adds significant evapotranspiration and shade for blank walls, parking garages, and sidewalks. The program goals include improving overall aesthetics, pedestrian comfort, air quality, and reducing the heat island effect. Grants cannot exceed half of the total project cost or $20,000, and contributions can be in kind. Tenants, property owners, and registered non-profits can all apply. See <www.houston-downtown.com/Home/Business/DoingBusiness/ DevelopmentAssistance/Development%20Assistance.PDF>.
- Since 2002, **Austin Energy has given 10-cent-per-square-foot rebates for cool roof installations**. Customers must use cool roof products that have a minimum reflectivity of 75 percent, and the project must pass a cost-benefit analysis. The utility has been promoting cool roof products as a cost-effective and low-risk approach to reducing cooling loads and peak demand. As of 2005, Austin Energy had awarded more than $164,000 as rebates, representing more than 1.5 million square feet (140,000 m^2) of roof area and saving an estimated 1.25 million kWh of energy. See <www.austinenergy.com/Energy%20Efficiency/Programs/Rebates/index.htm> for more information.

Energy Incentives

The Database of State Incentives for Renewables and Efficiency (DSIRE) provides current information on state, local, utility, and select federal incentives that promote renewable energy and energy efficiency. Some of the incentives listed, particularly those that involve energy efficiency and green building practices, include heat island reduction strategies. See <www.dsireusa.org>.

1.3 Urban Forestry Programs

Urban forestry or tree planting programs exist in most large cities and counties in the United States. These programs generally have broad goals that emphasize the multiple benefits trees can provide, including helping to cool cities. Most of these programs unite diverse stakeholders, and their efforts range from short-term, one-time projects to long-term community revitalization. Moreover, many states give grants to communities and organizations that promote or maintain urban forests. For example, Wisconsin will disburse $530,000 in roughly 40 grants in 2008 as part of a program it has operated since 1993; South Dakota has run a similar program since

1991.[3,4] As of early 2008, the Washington State legislature was working on several bills that would support and expand local urban forestry efforts in recognition of how urban trees and vegetation improve air quality, reduce temperatures, enhance quality of life, and reduce and filter stormwater runoff.[5]

Frequently, urban afforestation focuses on low-income communities, where tree cover is sparse. For example:

- The **Pennsylvania Department of Conservation and Natural Resources oversees a project called TreeVitalize,** which brings together county and local governments, foundations, trade associations, and private industry to restore tree cover in the southeastern part of the state. TreeVitalize aims to plant more than 20,000 trees in approximately 40 neighborhoods in Bucks, Chester, Delaware, Montgomery, and Philadelphia counties. The $8 million program targets neighborhoods in older cities, boroughs, and townships in which tree cover is below 25 percent. See <www.treevitalize.net/> for more information.
- **Groundwork Elizabeth,** a nonprofit group in Elizabeth, New Jersey, **works to involve neighborhood residents** in community revitalization projects,

Tree Maintenance and Education

Many urban forestry programs explain that it is easy to plant trees but difficult to maintain them, particularly until they become well established. In order to ensure most trees survive, programs have enlisted and empowered volunteers to care for trees until they are established. Community participation is important because most urban trees are not under public jurisdiction.

Often tree planting programs train participants in proper tree planting techniques and care. In Pennsylvania, TreeVitalize provides nine hours of classroom and field training to community residents who want to become urban forestry leaders. The classes cover tree identification, planting, pruning, mulching, tree biology/physiology, proper species selection, community tree care, and proper pruning. Residents also can learn how to organize community-assisted tree planting projects. Graduates are eligible to participate in advanced training and other events.

Other programs require community members to pledge to maintain and protect the trees that are planted. For example, Los Angeles residents interested in free trees from the Trees for a Green LA program first participate in an online or neighborhood workshop. Then, they complete a site plan and apply for their free trees. Residents pledge on their applications to plant and care for the trees in a proper manner and allow the city to inspect their work for overall program evaluation and quality assurance. See <www.ladwp.com/ladwp/cms/ladwp000744.jsp>.

Please see the "Trees and Vegetation" chapter of this compendium for more information about urban forestry benefits and implementation considerations.

including tree planting at local schools and parks. The organization was instrumental in getting Elizabeth involved in New Jersey's Cool Cities Initiative, which aims to plant trees primarily in the large cities of New Jersey with low tree coverage. See <www.groundworkelizabeth.com> for more information.

1.4 Weatherization

Communities have used weatherization programs as an opportunity to mitigate heat islands, protect public health, and save energy. Weatherization usually involves making the homes of qualifying residents, generally low-income families, more energy efficient at no cost to the residents. States use weatherization funds provided by the U.S. Department of Energy (DOE) Weatherization Assistance Program to help recipients cover heating bills and invest in energy efficiency actions that lower costs. States can also use the funds to install cooling efficiency measures, such as screening and shading devices.

The **Energy Coordinating Agency (ECA) of Philadelphia,** which administers the city's weatherization services, **has applied cool roof coatings** as part of its package of energy efficiency treatments. Through its Cool Homes Program, more than 550 residences in the Philadelphia area have had their roofs coated. ECA commissioned a study that found the cool coatings and increased insulation eliminated 90 percent of the heat gain through the ceiling, reducing top-floor ceiling temperatures by an average of 4.7°F (2.6°C) and chest-height temperatures by 2.4°F (1.3°C). These reduced temperatures lowered air conditioning loads by about one-third in a typical rowhouse.[6] See <www.ecasavesenergy.org/ses/whiteroof/roof-coolhomes.html> for more information.

Heat Health—An Opportunity to Advance Heat Island Mitigation Strategies

Several large cities have developed programs to minimize health impacts from excessive heat events. These efforts provide an opportunity to educate communities about urban heat islands and promote heat island reduction strategies, particularly shade tree planting and cool roof applications, as a long-term mitigation or adaptation strategy. For example, Philadelphia has long been concerned with reducing heat-related mortality. The city was the first in the United States to implement a Heat Health Watch-Warning System, which has become a worldwide model for heat wave forecasting.

When the Philadelphia Public Health Department educates citizens about excessive heat events and immediate counter-measures, such as using telephone heat hotlines and taking advantage of public air-conditioned buildings, or "cooling centers," it also provides them information about longer-term heat island reduction strategies.

EPA's *Excessive Heat Events Guidebook* explains how local public health officials and others can assess their vulnerability and develop and implement notification and response programs. See <www.epa.gov/heatisland/about/heatguidebook.html>.

1.5 Outreach and Education Programs

Almost all communities have found that heat island reduction efforts involve some element of outreach and education. For example, **TreeUtah has launched a comprehensive initiative, the MetroGreening Program, that uses advertising, outreach, and educational workshops** to help promote proper planting and maintenance of trees to reduce heating and cooling costs, diminish the heat island effect, and achieve other benefits in Utah's most densely-populated regions. See <www.treeutah.org/statewide.htm> for more information.

Further, the Utah State Energy Program, Utah Department of Natural Resources, and the National Energy Foundation worked together to create the **Utah Kool Kids program to teach elementary and secondary age students about urban heat islands,** their impacts on energy and air quality, and heat island reduction strategies. The program gives teachers lesson plans, overheads, test questions, experiments, and research tools to engage students. See <http://www.nef1.org/ea/kool.html> for more information.

Some outreach and education programs focus specifically on reaching students. The **Cool Schools program in Los Angeles teaches students to become environmental stewards** through hands-on and classroom experience. Through the project, students have helped plant hundreds of trees around Los Angeles schools. Cool Schools creates an opportunity to teach lessons on biology, botany, horticulture, and related topics. See <www.ladwp.com/ladwp/cms/ladwp001087.jsp>.

1.6 Awards

Governments, community groups, and corporations have rewarded exemplary work as a way to highlight innovation and promote solutions to mitigate heat islands across the public and private sectors. Examples of award programs include:

- **Home Depot Foundation's Awards of Excellence for Community Trees.** Since 2005, this foundation has recognized public/private collaborations for their leadership and development of successful tree planting initiatives. Winning projects in large and small city categories receive $75,000 and runners-up receive $25,000. Though the city and nonprofit winners are both recognized, the award money is given to the nonprofit for continued tree planting work.
- **Green Roofs for Healthy Cities' Green Roofs Awards of Excellence.** Since 2003, this nonprofit has recognized a variety of green roof projects for integrated design and implementation. The program rewards extensive and intensive green roof projects, as well as research teams and citizens who have advanced the implementation of green roofs though public policy.
- **ENERGY STAR Awards.** Since 1993, EPA has hosted the ENERGY STAR Awards to recognize outstanding participants in the ENERGY STAR Program. National Coatings Corporation, a manufacturer of cool roof materials, was recognized in 2000. The San Diego Unified School District (SDUSD) won an award in 2007 because more than 140 of its 200 buildings met ENERGY STAR criteria. Some of those buildings included cool roofs combined with photovoltaic cells that could produce more than 3.5 MW of electricity.[7]

Figure 2: Cool Roofs with Solar Panels in San Diego

SDUSD

The San Diego Unified School District won an ENERGY STAR award in 2007 because almost 70 percent of its buildings, including this elementary school with a cool roof and solar panels, met ENERGY STAR specifications.

- **EPA's Regional Office in New England's Environmental Merit Award Program.** For more than 30 years, EPA Region 1 has honored teachers, citizen activists, business leaders, scientists, public officials, and others who have made outstanding contributions to public health and the natural environment. Awards are given across environmental disciplines and have highlighted heat island reduction strategies, such as cool roofs. In 2005, Sarnafil Roofing Systems, Inc., received a Merit Award for its highly reflective roofing products.[8]

2. Policy Efforts

Some local and state governments have included urban heat island mitigation strategies in policies or regulations, which range from purchasing guidelines to building codes. A number of these actions have helped remove barriers or provide incentives for implementing mitigation strategies. Others have prescribed minimum requirements, especially for new construction. Policy efforts can include:

- Procurement
- Resolutions
- Tree and landscape ordinances
- Comprehensive plans and design guidelines
- Zoning codes
- Green building standards
- Building codes
- Air quality standards.

2.1 Procurement

Many local governments interested in mitigating heat islands started by procuring cool technologies for municipal buildings. Since state and local governments usually put construction work and material supplies out for bid, they can revise bid specifications to include cool products.

For example, **Tucson, Arizona, requires that air-conditioned city facilities use cool roofing materials** for most new construction and roof replacements. The city revised its general bid criteria to ensure that materials used are equivalent to those on the ENERGY STAR Roofing Products list. When a local government requires contractors to use cool products in this manner, it becomes easier to encourage additional use of these products on private projects.

After successfully demonstrating the use of permeable pavements, Chicago began a Green Alley initiative that encourages use of porous paving whenever an alley needs to be re-paved. Forty-six alleys were renovated under this initiative in 2007, and ultimately, almost 2,000 miles of alleyways will be made permeable. The "Chicago Green Alley Handbook" can be found through the website < http://egov.cityofchicago.org/> under the City Department of Transportation programs.

Figure 3: Permeable Pavement in Chicago Alley

City of Chicago

Raking gravel into a Gravelpave2 system.

2.2 Resolutions

A resolution is a document stating a group's awareness of and interest in an effort, such as a heat island mitigation project. Generally, a city or county council, or organizations such as air quality boards or planning commissions, issue resolutions. A resolution does not necessarily indicate that a program will be supported financially, but it can be the first step in getting an initiative started.

In May 2001, **the Austin City Council adopted a heat island mitigation resolution** that committed the city manager to review recommendations for a variety of activities to diminish heat islands. In September of that year, the city council awarded $1 million toward implementing the recommendations, which ranged from developing a cool roof strategy to increasing enforcement of the city's tree-saving ordinance. See <www.ci.austin.tx.us/trees/res_985.htm> for more information.

In October 2006, **Annapolis, Maryland, adopted a comprehensive energy efficiency resolution** that included general goals and specific long-term targets for adopting a range of energy efficiency measures. One recommendation was to increase tree shading so that the city could sequester carbon dioxide (CO_2), reduce the urban heat island effect, and lower ozone levels. In 2007, the city adopted a new tree protection ordinance as one step towards protecting existing shade trees, discussed below. See <www.annapolis.gov/upload/images/government/council/Adopted/R3806.pdf> for more information.

Model Resolutions and Policies

The International Council for Local Environmental Initiatives (ICLEI), a nonprofit organization, runs an Urban Heat Island Initiative program that provides assistance to local governments. ICLEI hosts a website <www.hotcities.org> that provides policy information, such as sample language for developing a heat island resolution and a model policy framework.

ICLEI works with local governments to coordinate workshops throughout the United States to help understand heat island impacts and mitigation strategies. These workshops can help communities develop a heat island mitigation project or program. See <www.hotcities.org/Workshops/index.htm> for more information.

2.3 Tree and Landscape Ordinances

Many local governments have enacted tree and landscape ordinances, which can ensure public safety, protect trees or views, and provide shade. Three types of ordinances, in particular, are most useful from a heat island perspective: tree protection, street trees, and parking lot shade.

Tree Protection

Tree protection ordinances prohibit the removal or pruning of trees without a permit. Often, these ordinances apply only to native trees or trees with historical significance. The effectiveness of this type of provision depends on enforcement and how strict the requirements are for granting tree removal permits.

Some ordinances protect not only trees but also the ground under the crown area of a tree to prevent root damage. An ordinance in **Atlanta, Georgia, for example, requires that at least 16 square feet (1.5 m^2) of soil around the tree must remain unpaved** and open to the air. Toxic chemicals also must be kept away from the trees. These ordinances are less common than those that simply restrict removal.

Another approach, often linked to a local government's subdivision or development code, is protecting tree stands during new construction. In this case, developers are required to preserve tree stands during site design and protect them once construction commences. The ordinances can require protection based on the percentage of a site, or a minimum point value, with larger, mature trees earning more points.

Annapolis, Maryland, explicitly recognized the environmental value of trees and acted to protect them during construction. The "Tree Protection Ordinance" requires a survey of trees on a proposed development site and fences or other means to mark and protect designated trees during construction. The ordinance also prohibits certain activities, such as trenching or grading, within the dripline of trees, unless specific precautions are followed. More information on this ordinance is available under §17.09 City Code at <http://bpc.iserver.net/codes/annapolis/>.

Figure 4: Fences Protect a Tree During Construction

TLCforTrees

Fences can protect not just a tree's trunk and branches, but also its root system during construction.

San Antonio, Texas, requires different levels of tree protection based on tree class or location. The ordinance classifies significant trees, heritage trees, and trees within the 100-year floodplain. For example, heritage trees (defined, for most species, as trees 24 inches [60 cm] or greater in diameter at breast height [DBH]), must be preserved. The ordinance, however, generally counts total tree diameter-inches at a site, not individual trees, and gives flexibility in preservation: up to 90 percent of the tree-diameter-inches can be considered preserved if the developer plants an equal or greater number of tree-diameter-inches elsewhere. Developers can also fulfill the preservation requirement by contributing to the city's tree fund. For details, see the ordinance and its amendments at <http://epay.sanantonio.gov/dsddocumentcentral/upload/2003%20Tree%20Preservation%20Ordinance.pdf> and <http://epay.sanantonio.gov/dsddocumentcentral/upload/Revised%20Tree%20Amend%2011-06.pdf>.

Street Trees

Street tree ordinances generally govern how to plant and remove trees along public rights-of-way and land that is privately owned but accessible by the public. At a minimum, these ordinances designate the numbers or types of trees that should be planted. More effective street tree policies include guidelines on tree selection, installation, and maintenance to lengthen a street tree's life and minimize problems with pavement, electrical wires, and buildings.

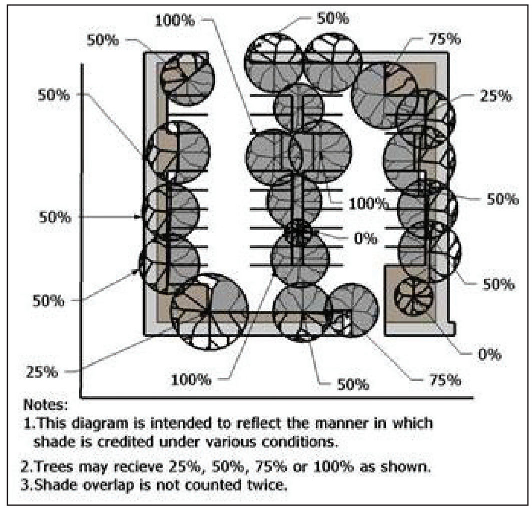
For example, **Orlando, Florida, specifies that trees must be planted along both sides of a street,** with one tree every 50 to 100 feet (15-30 m). The selected trees must eventually be capable of reaching a minimum height of 40 feet (12 m) and a crown spread of 30 feet (9 m). The ordinance is available at <www.municode.com/resources/gateway.asp?sid=9&pid=13349>.

Seattle requires a street use permit before landscaping in a planting strip in a public right-of-way. For street trees, the strip must be at least 5 feet (1.5 m) wide, unless specific approval from the city's arborist is received. Five feet is generally recommended as the minimum width for planting most trees. A guide is available to help property owners select and plant trees in accordance with the city's requirements. See <www.seattle.gov/trasportation/treeplanting.htm> for further information.

Parking Lot Shade

Some communities require parking lots be shaded to cool pavement and cars, which increases comfort, reduces the heat island effect, and lowers evaporative emissions from parked cars. For example, since 1983, **an ordinance in Sacramento's zoning code has required that enough trees be planted to shade 50 percent of new, or significantly altered, parking lots** after 15 years of tree growth. A 2001 study found that the lots were only achieving about 25 percent shading because sometimes shade was double-counted, trees did not grow to their expected size under the conditions

Figure 5: Parking Lot Shade Guidelines



City of Elk Grove, California

Shade diagrams, such as this one from Elk Grove, California, help determine if planned or actual vegetation meet the communities guidelines.

of the lot, or trees were not adequately dispersed.[9] Thus, Sacramento modified its code in 2003 to improve coverage.[10]

Chicago has a landscape ordinance that requires planting trees or shrubs on parkways and landscaping parking lots, loading docks, and other vehicular use areas, both within the sites themselves and to screen their perimeter. The ordinance applies to most new building construction, as well as to repairs, remodeling, and enlargements of a particular size and cost. The Bureau of Forestry, which maintains the standards, must inspect and approve all parkway vegetation prior to planting. The Chicago Department of Zoning reviews all building and zoning permit applications to ensure compliance with the ordinance. See <http://egov.cityofchicago.org/webportal/COCWebPortal/COC_EDITORIAL/11_Landscaping_and_Screening.pdf>.

In 2007, the city of **Baton Rouge strengthened its landscape ordinance,** which requires tree planting on all new developments, excluding single-family residences. The ordinance requires two shade trees for every 5,000 square feet (465 m^2) of site, and one shade tree per 600 square feet (55 m^2) of street frontage. Parking lot requirements include one shade tree per 15 parking spaces for a lot with one to 25 spaces; one shade tree per 12 parking spaces for a lot with 25 to 100 spaces; and one shade tree per 10 parking spaces for a lot over 100 spaces. For example, a 10,000-square-foot (465 m^2) site with 600 square feet (55 m^2) of storefront and 150 parking spaces would require 20 shade trees (i.e., four for the square footage of the site, one for the store frontage, and 15 for the parking lot). For more information on Ordinance 12692, see the city's information bulletin at <http://brgov.com/dept/planning/udc/pdf/Chapter18.pdf>.

2.4 Comprehensive Plans and Design Guidelines

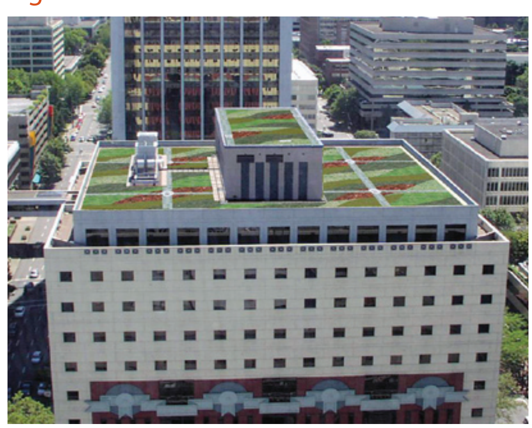
Comprehensive plans and design guidelines are another way that communities have incorporated opportunities to promote heat island reduction. Comprehensive plans, sometimes called general plans in California and other states, are adopted by a legislative body of a local government, and set forth policies, goals, and objectives to direct development and conservation that occurs within its planning jurisdiction. They generally have a broad scope and long-term vision. Design guidelines provide a connection between general planning policies and implementing regulations, such as zoning codes and subdivision regulations. Design guidelines convey a sense of the preferred quality for a place by being descriptive and suggestive.

The **"Environmental Planning Element" in the Gilbert, Arizona, general plan lists mitigating heat islands as a core goal.** Specific policies under the goal include: 1) developing criteria that will identify projects that might contribute to the heat island effect and will require an evaluation of mitigation techniques; 2) seeking sponsors such as educational institutions, utility companies, and government entities to promote heat island awareness among landowners, developers, engineers, and architects; and 3) promoting design concepts using engineered green space to maximize shading of surfaces that tend to heat up, promote education and awareness of cool roof materials and construction techniques, and promote alternative pavement technologies in parking areas. For more information see <www.ci.gilbert.az.us/generalplan/chapter07.cfm>.

Design guidelines can take a holistic approach to heat island mitigation or specific mitigation strategies. For example, **Toronto's Official Plan includes policies to reduce the urban heat island and achieve a wide range of environmental gains.** As part of that plan, the city released draft parking lot guidelines in November 2007 that call for shade trees, permeable and reflective pavements, and other design features to manage stormwater, reduce energy consumption, and lower urban temperatures.[11]

The town of **Highland, Utah, created a master plan for a 50-acre (200,000 m^2) overlay zone** to be privately developed as a town

Figure 6: Portland Eco-Roof



Portland BES

The Portland Bureau of Environmental Services (BES) has a green roof on its headquarters. The city allows denser development for projects that use green roofs, or eco-roofs as the city calls them.

center. The city design guidelines for the zone recommended several heat island mitigation elements, including reflective roofing, reflective parking lot surfaces, and landscaping. Those guidelines were then adopted into the zoning requirements for the town center.

In contrast, **Portland, Oregon, has focused on the use of eco-roofs** in the city center district, primarily for their aesthetic and stormwater management benefits. Design guidelines call for integrating vegetated roofs into central city projects. As discussed in the next section, Portland has taken specific steps in its zoning code to achieve this result.

2.5 Zoning Codes

Zoning codes implement the goals and objectives of a comprehensive plan. These regulations generally dictate function for an area, building height and bulk, population density, and parking requirements. Zoning codes can also promote heat island mitigation strategies in various ways. For example, as noted in Section 2.3, cities such as Sacramento have adopted parking lot shading requirements as part of their zoning codes.

Communities have also allowed density bonuses for construction that adopts mitigation strategies. In 2001, **Portland, Oregon, modified its zoning code to include an "eco-roof development bonus"** for developers to install rooftop gardens or "eco-roofs." In Title 33 of the Zoning Code there is a floor area ratio bonus for projects that install eco-roofs in Portland's central district. The bonus amount depends on the extent of the eco-roof coverage. If the eco-roof covers 60 percent or more of the roof surface, developers can build an additional 3 square feet (0.3 m^2) for each square foot of green roof. If the green roof covers a lower percent of the surface, the bonus is reduced. See Section 33.510 of the code at <www.portlandonline.com/shared/cfm/image.cfm?id=53363> for specific information.

Chicago also has a similar provision, with the floor area ratio density bonus based on the amount by which a green roof exceeds 50 percent of the roof surface.

2.6 Green Building Programs and Standards

Green building initiatives place a high priority on human and environmental health and resource conservation over the life cycle of a building. Many local, state, and federal governments have adopted green building programs, or standards, that capture heat island reduction strategies.

For example, local governments such as **Arlington, Virginia, and San Jose, California,**[12] are basing their municipal green building requirements on the **U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Rating System™. Green Globes,** operated by the Green Building Initiative (GBI) in the United States, is another rating system that communities are using. The **Canadian government** requires all federal buildings to meet the Canadian version of Green Globes, **Go Green** and **Go Green Plus**. States like **Arkansas and Maryland recognize both LEED and Green Globes** in their green building initiatives. Under both rating systems, buildings can earn credits towards certification by providing shade vegetation, installing cool or green roofs, and using highly reflective and emissive pavements or permeable paving products, all measures that reduce the heat island effect.

Specific to homes, programs such as **EarthCraft House,** created by the Greater Atlanta Home Builders Association and Southface Energy Institute, award points for residences that preserve and plant trees, install ENERGY STAR cool roof products, or use permeable pavement. In addition, EarthCraft Houses must meet ENERGY STAR certification. Communities from **Virginia to Florida have constructed EarthCraft homes.**

Seattle Green Factor

Seattle has adopted minimum landscape requirements, known as the Seattle Green Factor, for new developments in commercial areas in the city. This program requires that, as of late January 2007, certain new developments in neighborhood business districts must provide for vegetative cover on the equivalent of 30 percent of the applicable property. The regulations apply to developments with more than four dwelling units, more than 4,000 square feet (370 m^2) of commercial uses, or more than 20 new parking spaces. Developers can use a menu of strategies, including planting new trees, preserving trees, and installing green roofs and green walls to meet this target. The regulations are part of the city's Commercial Code and encourage planting of layers of vegetation and larger trees in areas visible to the public. The rules also include bonuses for harvesting rain water and choosing plants that need less water. The city has developed a worksheet to help applicants calculate a "score" that indicates whether various mixes of landscaping measures meet the requirements, which will allow developers to try different combinations of features. See <www.seattle.gov/dpd/permits/greenfactor/> for more information.

Figure 7: Seattle Public Library

Green Roofs for Healthy Cities

Seattle promotes green roofs, such as this one on a city library, through its Green Factor program.

Meanwhile, since 1996, the city's Neighborhood Matching Fund program has provided more than 17,200 trees to more than 600 neighborhood groups for Seattle's streets and parks, and the city has established the Emerald City Task Force, which advises the city on incentives and policies to encourage private property owners—residential and commercial—to improve their land by preserving existing trees and planting new ones. See <www.seattle.gov/trees/> for more information.

Further, the **National Association of Home Builders** is working with the **International Code Council** to develop **a national green building standard for homes** that captures heat island reduction strategies as well.

Whereas the above efforts allow building owners to choose technologies and do not guarantee that heat island reduction strategies will be included in the mix, **some communities, such as Frisco, Texas, have gone so far as to require cool roofs in their commercial green building programs.** In late 2006, the Frisco City Council approved requirements for most new commercial construction to install ENERGY STAR labeled cool roof products.

2.7 Building Codes

Building codes are regulations adopted by local and state governments that establish standards for construction, modification, and repair of buildings and other structures. An energy code is a portion of the building code that relates to energy usage and conservation requirements and standards (see <www.energycodes.gov>). Some cities and states have begun including cool roofing in their building codes because of its potential to save energy, particularly during peak loads. For example:

- In January 2003, **Chicago amended its energy code to require roof installations on or prior to December 31, 2008, to meet a minimum solar reflectance** of 25 percent. The amendments apply to most air-conditioned buildings with low-sloped roofs. After December 31, 2008, contractors must use roofing products that meet or exceed the minimum criteria to qualify for an ENERGY STAR label.
- **Georgia was the first state to add cool roofs to its energy code,** in 1995. Georgia allows a reduced roof insulation level if a cool roof with a 75 percent minimum solar reflectance and 75 percent minimum thermal emittance is installed.[13] Note that if building owners install a cool roof and simultaneously reduce insulation, there may be no net energy savings.
- **Florida also gives cool roofs credit** in its building energy code. Buildings using a roof with 70 percent minimum solar reflectance and 75 percent minimum thermal emittance are eligible to reduce the amount of insulation needed to meet building efficiency standards, as long as a radiant barrier

The Foundation for Including Cool Roofs in Energy Codes

The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) has developed energy-efficient design standards that provide minimum requirements for both commercial and residential buildings. The ASHRAE standards underlie most state building and energy codes. ANSI/ASHRAE/IESNA Standard 90.1-1999, *Energy Standards for Buildings Except Low-Rise Residential Buildings*, and ANSI/ASHRAE Standard 90.2-2001, *Energy-Efficient Design of Low-Rise Residential Buildings*, provide guidelines for new equipment, systems, and buildings. These standards originally were developed in response to the 1970s energy crisis and now include credits pertaining to cool roofing. For example, Addendum f to 90.2-2001 allows high-albedo roofs in hot and humid climates as part of the energy efficiency ceiling calculation for a residential building.

is not also installed in the roof plenum or attic space.

- In response to electrical power shortages, **California added cool roofs as an energy efficiency option to its building energy code** (Title 24) in 2001. The code defines a cool roof as having a minimum solar reflectance of 70 percent and minimum thermal emittance of 75 percent, unless it is concrete or clay tile, in which case it can have a minimum solar reflectance of 40 percent. This 40-percent rating incorporates new cool-colored residential products into the standard. In 2005, these cool roof provisions became mandatory requirements for all new non-residential construction and re-roofing projects that involve more than 2,000 square feet (180 m^2) or 50 percent replacement.[14] The code allows owners to meet these requirements in a variety of ways.
  - The simplest approach is to apply a cool roof that meets the minimum requirements.
  - Another alternative is to use roof products that do not meet the cool roof criteria and then offset the reduced performance levels by implementing other measures, such as insulation and window improvements, that exceed minimum requirements.
  - The third, and most flexible option, is to use whatever methods are deemed practicable as long as the code's specific performance goal is reached. In this scenario, the building owner creates a model of all the characteristics that affect the energy consumption of the building to determine the mix of measures that will meet the code criteria. The California Energy Commission provides computer software for this compliance option.

Cool Roofs in California

California has a long history of supporting cool roof research and implementation to alleviate peak energy demand. In 2001, the state passed legislation that activated emergency measures, including cool roofs, to reduce peak demand and mitigate the energy crisis. The cool roofs program was subsequently formalized as the Cool Savings Program, which provided rebates to building owners for installing roofing materials with high solar reflectance and thermal emittance. The highest rebate went to roofs on air conditioned buildings, while buildings with rooftop ducts and other non-residential buildings were eligible for a slightly lower rebate. The program was administered by the California Energy Commission but implemented by five organizations directly responsible for promoting the program, recruiting customers, verifying project completion, and paying incentives of 15 to 25 cents per square foot (0.09 m^2) of eligible roofing area. The program was so successful that California revised Title 24 to make cool roofs on certain new or renovated buildings mandatory starting in 2005.

California began the process of updating Title 24 in late 2005, with final revised standards due in 2008. As part of this update, California is investigating extending cool roof requirements to houses and buildings with steep-sloped roofs. See <www.energy.ca.gov/title24/2005standards/index.html> and <www.energy.ca.gov/title24/2008standards/index.html> for further information.

2.8 Air Quality Requirements

As summertime temperatures rise, the rate of ground-level ozone formation, or smog, increases. By lowering temperatures, urban heat island mitigation strategies can help reduce ground-level ozone concentrations. Many cities and counties are struggling to attain national ambient air quality standards (NAAQS), particularly for ground-level ozone. Most of these areas have adopted a wide range of emission control strategies on traditional air pollution sources and are seeking innovative ways to further reduce air pollution levels. Communities are considering urban forestry and cool roofs, in particular, as technologies that can help them reach attainment.

Under the Clean Air Act, State Implementation Plans (SIPs) are federally approved and enforceable plans that identify how each state will meet and maintain federal air quality standards. **EPA has developed three policies that help states to include heat island reduction strategies in their SIPs.** See the "Policies to Advance Heat Island Mitigation in SIPs" textbox.

A few areas have been working to include heat island reduction strategies in their SIPs, including Atlanta, Houston, Sacramento, and the Washington D.C. metropolitan area. In 2006, **Sacramento secured a large Congestion Mitigation and Air Quality (CMAQ) Improvement Program grant to work on including urban forestry in its SIP.** The project, known as the Urban Forests for Clean Air demonstration project, involves the Sacramento Tree Foundation, the USDA Forest Service, the Sacramento Area Council of Governments, and the Sacramento, El Dorado, Placer, and Feather River Air Districts. The project includes three phases: 1) initial estimates of the effects of the urban forest on air quality; 2) development of improved models to analyze these impacts; and 3) a final report on the findings. Under the first phase, the Forest Service's Center for Urban Forest Research estimated the impacts of trees on air quality using existing models and statistical analyses. That analysis predicted that one million additional trees could lower emissions of NO_x by almost a quarter ton per day and particulate matter by over one ton per day. If trees that emitted low levels of volatile organic compounds (VOCs) were chosen, ground-level ozone could also be reduced by 1.5 tons daily. The long-term goal for the project is to develop the technical support for a SIP revision that includes large-scale, urban tree planting as a ground-level ozone reduction control strategy for the Sacramento region. See <http://www.fs.fed.us/psw/programs/cufr/products/psw_cufr696_SacramentoAirQuality.pdf> and <www.sactree.org> for more information.

Heat Island Mitigation Strategies Reduce Ground-Level Ozone

Ground-level ozone forms more readily when air temperatures rise. Strategies to mitigate the urban heat island reduce air temperatures and therefore decrease concentrations of ground-level ozone. These strategies also reduce energy demand for cooling, which reduces air pollution and greenhouse gas emissions associated with energy production. When selecting vegetation for a green roof or to plant along a street or other areas, communities in areas with poor air quality may want to consider the volatile organic compound (VOC) emissions from certain plants, because VOCs are a pre-cursor chemical for ground-level ozone. With the right choice of species, the benefits of additional trees and vegetation far outweigh the costs.

Policies to Advance Heat Island Mitigation in SIPs

Currently, three EPA policies help states to include heat island reduction strategies in their SIPs:

1. The Emerging and Voluntary Measures Policy provides flexibility for states to include in their SIP nontraditional measures, which are measures that do not directly reduce emissions at their source such as a scrubber on a utility smokestack. Heat island reduction strategies can be included under this policy.
2. The Guidance on State Implementation Plan (SIP) Credits for Emissions Reductions from Electric-Sector Energy Efficiency or Renewable Energy Measures provides state and local air quality officials with information on how to incorporate energy efficiency and renewable energy measures into their SIPs. It includes a step-by-step procedure for estimating emission reductions from these measures, a list of tools and resources for more information, and examples of proposed SIP submissions. This policy encourages cool roofs particularly. See <http://www.epa.gov/ttncaaa1/t1/memoranda/ereseerem_gd.pdf >.
3. The Bundled Measures Policy allows a state to combine many projects and programs that individually would not result in large reductions of air pollution emissions. EPA considers the performance of the entire bundle (the sum of the emissions reductions from all the measures in the bundle) for SIP evaluation purposes, not the effectiveness of any single measure. In this way, the responsible agency can include innovative strategies, such as heat island mitigation measures, that may otherwise be overlooked because they do not on an individual basis provide significant air quality benefits.

The **Washington D.C. region's SIP includes a Regional Canopy Management Plan as a ground-level ozone reduction strategy.** The plan involves working with local governments to establish goals for increasing tree canopy coverage and decreasing ground-level ozone pollution. In June 2007, Fairfax County, Virginia, set a precedent by selecting an urban forestry canopy goal of 45 percent. The county developed this target after it determined that current tree management efforts would lead to a decrease in canopy size from 41 percent to 37 percent over the next 30 years. To combat this loss, the county has proposed increasing the average number of trees planted from 21,000 to 84,000, justifying the expense of additional trees by citing the multiple benefits they provide.

Figure 8: Tree Canopy in Washington D.C.

U.S./Japan ASTER Science Team

Construction in and around Washington, D.C., has reduced tree cover (green in this image), but many efforts have formed to slow or reverse this trend.

Endnotes

1 Examples of sustainable or low-impact development (LID) initiatives are The Sustainable Sites Initiative (<http://sustainablesites.org>), a collaboration between the American Society of Landscape Architects, the Lady Bird Johnson Wildflower Center, the US Botanic Garden, and other groups; and EPA's Low Impact Development Page (<www.epa.gov/owow/nps/lid/>) and Green Infrastructure Action Strategy (<http://cfpub.epa.gov/npdes/greeninfrastructure/information.cfm#greenpolicy>).

2 Bass, B. and B. Baskaran. 2003. Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas. Report No. NRCC-46737. National Research Council Canada. Toronto, Canada.

3 The Wisconsin Office of the Governor. 2008. Governor Doyle Announces $500,000 in Urban Forestry Grants. 17 January. Retrieved 18 January 2008 from <http://www.wisgov.state.wi.us/journal_media_detail.asp?locid=19&prid=3110>.

4 South Dakota Department of Agriculture. 2008. Urban & Community Forestry Comprehensive Challenge Sub-grant. Retrieved 18 January 2008 from <http://www.state.sd.us/doa/Forestry/grantsandloans/uandcf.htm>.

5 HB 2844 - 2007-08: Regarding Urban Forestry. Retrieved 26 February 2008 from <http://apps.leg.wa.gov/billinfo/Summary.aspx?bill=2844&year=2007>.

6 Blasnik, M. 2004. Impact Evaluation of the Energy Coordinating Agency of Philadelphia's Cool Homes Pilot Project. M. Blasnik & Associates. Boston, MA.

7 EPA. 2007. 2007 ENERGY STAR Awards. Retrieved 30 December 2007 from <http://www.energystar.gov/ia/partners/pt_awards/2007_award_winner_profiles.pdf>.

8 EPA. 2007. 2005 Environmental Merit Award Recipients. Retrieved 15 December 2007 from <http://www.epa.gov/region1/ra/ema/2005recipients.html>.

9 McPherson, E. G. 2001. Sacramento's parking lot shading ordinance: environmental and economic costs of compliance. Landscape and Urban Planning. 57:105-123.

10 City of Sacramento. Tree shading requirements for parking lots. §17.68.040 City Code. Retrieved 29 November 2007 from <http://www.qcode.us.codes/sacramento>.

11 City of Toronto. 2007. Design Guidelines for "Greening" Surface Parking Lots. Retrieved 29 November 2007 from <http://www.toronto.ca/planning/urbdes.gn/greening_parking_lots.htm>.

12 For further information about Arlington's and San Jose's codes, respectively, see <http://www.arlingtonva.us/departments/EnvironmentalServices/epo/EnvironmentalServicesEpoGreenBuildings.aspx> and <http://www.sanjoseca.gov/ESD/natural-energy-resources> under Green Building.

13 U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. 2008. Georgia Energy Code 1995. Retrieved 11 February 2008 from <http://www.eere.energy.gov/states/state_specific_information.cfm/state=GA>.

14 Levinson, R., H. Akbari, S. Konopacki, and S. Bretz. 2002. Inclusion of Cool Roofs in Nonresidential Title 24 Prescriptive Requirements. Paper LBNL-50451. Lawrence Berkeley National Laboratory, Berkeley, CA.