

A multi-story building under construction. The structure is made of concrete with a grid of columns and beams. Scaffolding and rebar are visible. Several workers in hard hats are working on different levels. The sky is clear and blue.

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Urban Heat and Embodied Carbon

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Urban Heat and Embodied Carbon

Urban Heat

In the US, heat is the most fatal weather event, surpassing floods, hurricanes, and tornadoes; heat is more than four times as fatal as cold.¹ Additionally, researchers have determined that even official counts of heat-related deaths are likely undercounted by at least ten-fold.² In cities, heat and its impacts are exacerbated by the Urban Heat Island (UHI) effect, which causes urban areas to be significantly warmer than their surrounding rural landscapes.

As buildings and infrastructure replace natural areas, cities lose much of the cooling that nature facilitates, as urban surfaces absorb more of the sun's energy. This raises city temperatures by about 5–9°F compared to surrounding rural areas.³ Hotter communities often pay more for electricity, are more vulnerable to heat-related health issues, experience infrastructure failures more often, and have poorer air quality. Within urban areas, low-income neighborhoods and communities of color that were historically marginalized are at a higher risk of hazardous heat due to characteristics of the built environment, such as extensive paved areas, industry sites, and a lack of tree canopy and green space.^{4,5}

Typical approaches to urban development contribute largely to the UHI effect. Abundant pavements, dense building layouts, and reduced vegetation inhibit cities' abilities to dissipate heat, causing urban materials to absorb and retain solar energy and heat. Darker, low albedo,

¹ [National Weather Service](#)

² [Effects of Heat Exposure on Human Mortality in the US](#)

³ [Urban Heat Hot Spots: Climate Central](#)

⁴ [Modification of the PM2.5- and extreme heat-mortality relationships by historical redlining](#)

⁵ [Discrimination has Trapped People of Color in Unhealthy Urban Heat Islands](#)

and impervious surfaces exacerbate this effect by raising temperatures in the air around them as well as inside buildings. As cooling demand rises in response to increasing temperatures, additional energy consumption adds emissions and further heats the surrounding environment, reinforcing the cycle.

Embodied Carbon

The materials that make up cities, buildings, and infrastructure contribute to the UHI effect by absorbing and trapping heat, while also adding to global emissions: building materials account for about 7 percent of global emissions, while infrastructure materials account for another 10 percent.

Embodied carbon refers to the greenhouse gas emissions that result from the full lifecycle of materials: their extraction, manufacturing, transport, construction, and end-of-life disposal or recycling.

This Resource

Many jurisdictions have advanced cool materials as a key strategy for mitigating the UHI effect. At the same time, jurisdictions increasingly recognize that a substantial share of material-related carbon impacts remains unaddressed. As these two tracks evolve in parallel—cool surface deployment and embodied carbon accounting—the need to understand the lifecycle performance and impact of cool materials has become increasingly important.

This resource identifies strategies and offers recommendations that policymakers, planners, designers, developers, and others can pursue to reduce the UHI effect while also minimizing the carbon and environmental impacts of the materials that are chosen to pursue those strategies.

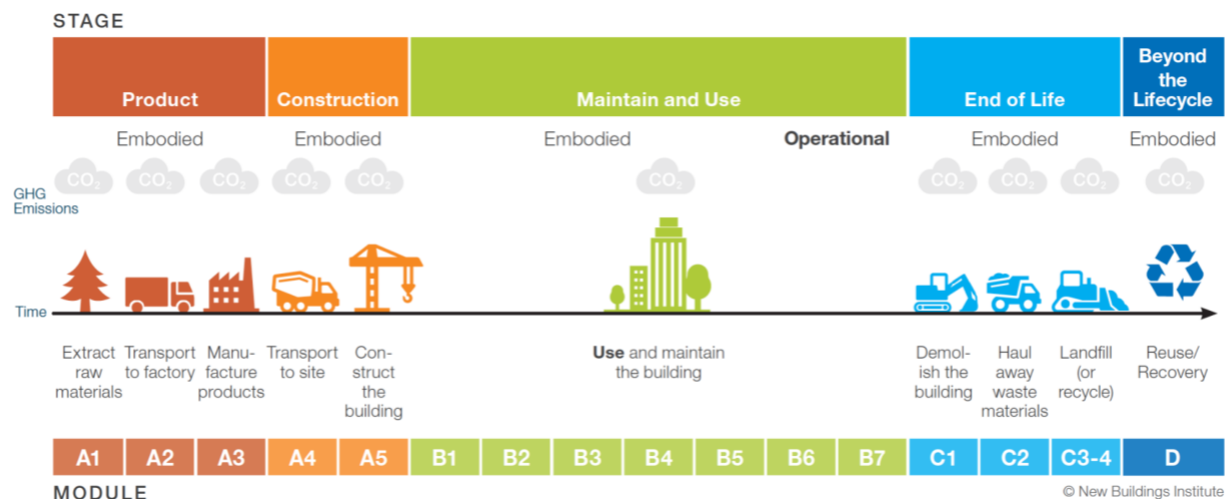
Embodied Carbon Measurement and Reporting Methods

Quantifying the embodied carbon emissions of materials is done primarily through the generation of environmental product declarations (EPDs). EPDs are based on a life cycle assessment (LCA) of the product and include manufacturer and product data, such as materials, manufacturing processes and locations, and resource use; they report a variety of environmental impacts, including global warming potential (GWP), acidification, eutrophication, ozone depletion, and smog formation.

GWP is the most common metric for measuring and evaluating materials' greenhouse gas emissions over a product's or building's lifecycle. GWP is characterized and reported as carbon dioxide equivalents (CO₂e). CO₂e includes carbon dioxide as well other greenhouse gasses such as methane and CFC. Since different GHG have different potencies, they are normalized relative to Carbon Dioxide. For example, since methane has more potency as a greenhouse gas, it counts for more CO₂ equivalents.

The typical unit for reporting on GWP is kgCO₂ equivalent units (kgCO₂e), also commonly referred to as a carbon footprint.

A life cycle assessment (LCA) is typically broken into four lifecycle stages, which are further broken up into sub-modules, illustrated below. It is common for EPDs for products to only include the cradle-to-gate (A1-A3) stages, since the environmental impacts in subsequent lifecycle stages depend on factors outside the control of the manufacturer, who is primarily responsible for the generation of the EPD. However, there is movement toward inclusion of A4 and A5, as well as the maintenance and use and end of life stages, to create cradle-to-grave (A-C) LCAs, particularly for more durable materials. Cradle-to-grave EPDs more accurately reflect the impact of maintenance and replacements over the building lifespan; something that is missing from cradle-to-gate EPDs.



Source: New Buildings Institute from EN 15978



General Principles for Embodied Carbon Reduction

This section provides an overview of embodied carbon considerations and reduction strategies. Future sections of this resource will describe how these may be applied in conjunction with UHI mitigation efforts.

Material Efficiency

Build Less and Use Less Material

Optimizing design and material use in projects is one of the most powerful and low-cost methods for reducing embodied carbon, because it decreases the demand for the material to be produced, transported, and installed in a project before it even occurs. These decisions can involve laying out programmatic design for spatial and material efficiency and optimizing structural design by rightsizing elements. Decisions about material quantity can be more influential than material type choices in determining a project's total embodied carbon: a review of 226 fully designed structural systems of buildings, for example, found that using less structural material had a stronger correlation with emissions reduction than choosing between concrete and steel systems.⁶ Embodied carbon analyses conducted early in the project allow design and engineering teams to explore alternatives and optimize structural design before materials are specified and purchased. Using fewer materials can result in lower costs for projects.⁷ Additionally, using structural materials—such as exposed concrete, masonry, and timber—as the finished surface eliminates the embodied carbon associated with the application of additional finish materials. Case studies have shown that embodied carbon can be reduced

⁶ [Material Efficiency as a Key Opportunity to Reduce Embodied Carbon in Structural Systems](#)

⁷ [ULI: Embodied Carbon in Building Materials for Real Estate](#)

by up to 46 percent for some building typologies with less than a 1 percent cost premium, in large part due to early cognizance of the impact of design choices on embodied carbon.⁸

Material Choices

Use Lower-Carbon Materials

Selecting lower-carbon materials can reduce project emissions that are used in the project; this strategy is ideally pursued after implementing design optimization and material efficiency measures. Common lower-carbon material alternatives include concrete mixes with supplementary cementitious materials (SCMs); concrete masonry (CMU), which sequesters carbon dioxide during manufacture and early in the use phase; steel produced via electric-arc furnaces with high recycled content; and bio-based materials such as mass timber or natural fiber insulation. For pavements and site materials, warm-mix asphalt, reclaimed asphalt pavement (RAP), and other recycled components can significantly reduce production impacts. Designers and material specifiers can use EPDs to compare similar products for their embodied carbon impacts. EPDs often account for the upfront emissions (A1–A3) of products, while whole-lifecycle assessment, demonstrated through an LCA, typically captures cradle-to-grave impacts (A–C, with D reported separately). In-depth descriptions of the embodied carbon associated with commonly used building and infrastructure products—both upfront and cradle-to-grave—are provided in future sections of this toolkit.

Circular Economy

Reuse Materials and Design for Future Reuse

Construction and demolition materials debris constitute a large source of waste in the US; globally, an estimated third of the world’s overall waste can be attributed to construction. More than 90 percent of the debris generated from building materials takes place as a result of demolition practices; a large portion of this debris ends up in landfills.^{9,10}

Deconstruction involves disassembling buildings and infrastructure so that materials can be reused. Recycling products that would otherwise become waste alleviates the burden of projects on landfills. Instead of adding to landfills, construction waste materials “including concrete and concrete rubble, masonry, timber, wood, glass, plastics, steel, iron, aluminum, excavated soil,” and others can be recycled for new construction projects.¹¹ Salvaged and reused materials generally represent less embodied carbon compared to new materials, because most of the emissions associated with the initial extraction and production of the materials has already happened; the early-stage emissions associated with salvaged materials, therefore, generally come from transportation, refabrication, and installation.¹²

⁸ [RMI: Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities](#)

⁹ [EPA: Advancing Sustainable Materials Management](#)

¹⁰ [BBC: The Industry Creating a Third of the World’s Waste](#)

¹¹ [A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation](#)

¹² [SE2050: Design Guidance for Reducing Embodied Carbon in Structural Systems](#)

Creating a robust local marketplace of salvaged and reused materials represents a significant opportunity to cut the high upfront emissions associated with extracting and producing new materials for construction projects. Building out a market of recycled materials can also realize substantial economic benefits: In 2016, the US EPA observed that recycling construction and demolition materials resulted in 230,000 new jobs.¹³ One example in Boulder, Colorado, included the construction of a new fire station built out of reused structural steel salvaged from the deconstruction of the Boulder Community Hospital.¹⁴ The project was a response to Boulder's deconstruction ordinance, which mandates that 75 percent the materials from deconstructed commercial and residential properties be diverted from a landfill.

Longevity

Design for Flexibility, Durability, and Longer Service Life

In many systems—such as pavements, roofing, façades, and interiors—maintenance cycles can dominate lifecycle embodied carbon impacts. These are often captured in the B-stage of an LCA, which focuses on the use stage. Designing for longevity reduces embodied carbon by lowering the frequency of repair, replacement, and major renovation over a product's life, ultimately leading to the avoided carbon emissions associated with replacing spent materials with new products. Durable materials, protective treatments, and assemblies designed for easy maintenance can all help to extend service lives. Prioritizing materials and products that can resist degradation, weathering, moisture, mechanical wear, and heat impacts can also help to ensure that initial embodied carbon investments survive for the longest period possible.

Certain UHI mitigation approaches can also help with longevity and resulting embodied carbon reduction. For example, green roofs can extend the service life of roofing membrane. Choosing long-lasting cool roof membranes that stay cleaner and are easier to clean over time can also have the longest lifespans. Cool pavements and shading from tree canopy can also extend the service lives of pavements by helping to keep the road surfaces cooling and reducing their UV damage.

¹³ [EPA: Recycling Economic Information \(REI\) Report](#)

¹⁴ [Boulder Reuse of Steel in New Fire Station](#)



Common Approaches to Embodied Carbon Regulation

Policies aimed at managing embodied carbon have targeted better quantification, reporting, and reduction of embodied emissions. These strategies have striven to guide developers, designers, contractors, and procurers towards making more informed decisions about selecting sustainable materials, adopting eco-conscious construction practices, and striving for a more carbon-efficient built environment. In general, these policies tend to fall into one of four categories: public procurement; codes and standards; demolition and deconstruction provisions; and incentives and voluntary programs.

In cities where UHI is also a prevailing issue, many of these policies may act as one side of a dual approach to addressing material impacts, both from an emissions and from a UHI standpoint, focusing on qualities such as albedo, reflectance, and permeability as well as GWP. This may help to ensure that cities encouraging the use of cool materials also understand and moderate the full lifecycle impacts of the products they are encouraging.

Public Procurement

Policies targeting the reduction of carbon emissions associated with building products require the disclosure and verification of products' GWP, typically reported by EPDs. Public procurement policies known as Buy Clean require the use of lower-carbon materials or the submission of embodied carbon documentation for materials used in publicly-funded projects. These are some of the most common approaches that utilize government purchasing power to catalyze market shifts.

To date, over a dozen states and jurisdictions require EPDs from material suppliers and for those suppliers to meet GWP thresholds that become increasingly stringent over time. Policymakers often require the submission of product- or facility-specific EPDs and reference

data from industry-wide EPDs to set GWP thresholds. These policies often cover select materials including concrete, steel, glass, insulation, wood, asphalt, and others.

Cities aiming to mitigate UHI may pair Buy Clean provisions with requirements for other material qualities that address the UHI impact of city-procured materials. Often, these requirements are found in public works standards, streetscape design manuals, green infrastructure standards, or capital project specifications.

Spotlight: Portland, Oregon

Portland has a strong low-carbon concrete procurement program as well as a set of UHI-focused pavement and green street standards.

On the embodied carbon side, the city's [Low-Carbon Concrete Initiative \(LCCI\)](#) requires EPDs for all concrete used in city projects, which must meet certain GWP mixes depending on the mix class.¹⁵ City departments must use compliant mixes for all capital projects. This program incentivizes the use of lower-carbon supplementary cementitious materials (SCMs) as well as the optimization of mixes to reduce the overall cement content in a mix. The city first established an EPD requirement for mixes used on city projects, then conducted pilot tests for different mixes to compare traditional cement mixes with lower-carbon alternatives. Based on this data collection, the city then established GWP thresholds for mixes used in public projects. In 2022, the city also established a program to sponsor pilot projects to develop sustainable sourcing requirements for wood.

On the UHI side, Portland's [Green Streets Policy](#) has required the incorporation of green streets in all city-funded development, redevelopment, and enhancement projects since 2004. Projects that are not able to meet these requirements must instead pay a fee or contribute to the Green Street Fund. This requirement evolved out of an initial batch of pilot demonstration projects, which enabled the Bureau of Environmental Services (BES) to evaluate the performance and modify design criteria before scaling implementation across the city's portfolio.¹⁶ Additionally, Portland's [Stormwater Management Manual \(SWMM\)](#) sets requirements for the use and installation of green stormwater infrastructure with the aim of maximizing onsite stormwater infiltration. These requirements are continually updated and apply to both public and private development, redevelopment, and improvement projects.

In practice, these requirements intersect. Stormwater facilities often require concrete and, as the city requires EPDs and GWP thresholds for concrete on public projects, stormwater infrastructure built under the SWMM is affected. Portland's BES, which develops and maintains the SWMM, was also represented on the Low-Embodied Carbon Concrete Threshold Committee.¹⁷

¹⁵ [Portland Current Sustainable Procurement Initiatives](#)

¹⁶ [Portland Green Streets Program](#)

¹⁷ [Portland Low-Embodied Carbon Concrete Threshold Committee](#)

Spotlight: Minnesota

The [Buy Clean Buy Fair Minnesota Act](#) (2023) mandates the collection of EPDs for state-funded building and infrastructure projects over certain sizes. Based on this data collection, the state will introduce GWP limits for concrete, asphalt, structural steel, reinforcing steel, and potentially other materials for state-constructed buildings and roads over 8 years.

In addition, the state has a full set of building design and construction requirements for projects funded by the state. The [Minnesota Sustainable Building Guidelines \(B3\)](#) addresses a wide range of topics aimed at reducing energy consumption and carbon emissions, as well as enhancing health and wellbeing for occupants and improving environmental quality. These topics include site and water; energy and atmosphere; indoor environmental quality; and material and waste.

The B3 materials and waste section includes provisions for reducing embodied carbon. Among the provisions is a requirement to submit a whole building LCA for a project of at least 20,000 square feet in size, demonstrating a reduction of the project's GWP by at least 10% compared to a functionally equivalent reference building. EPDs must also be submitted to verify commitment to using the products specified in the LCA.

The B3 Guidelines also contain requirements that can reduce UHI. For example, the guidelines promote the reduction of impervious area on site and integration of green infrastructure. Additionally, performance criteria for new construction and major renovations that include at least 1,000 square feet of land disturbance require that the site be designed so that the entire site albedo is at least 0.25. Standardized albedo values are assigned for common features on sites, including hardscape, roofs, walls, and natural features, which the project team calculates for different areas and then averages across the entire site.

Codes and Standards

A number of national, subnational, and model codes and standards have begun to incorporate requirements for embodied carbon reductions. These tend to take either a prescriptive or a performance-based approach. A prescriptive approach sets limits at the product or material level. Accounting for this level of information is done by submitting an EPD. GWP limits set by codes tend to be static values or benchmarked against a percent of industry-average values. A performance-based approach addresses embodied carbon at the project level, often setting GWP limits defined by a total limit per project or square footage, or as a percentage reduction compared to a “business as usual” baseline. The most common approach for this accounting is through the generation and submission of a whole building lifecycle assessment (WBLCA), which compares the proposed design to a modeled baseline or against a set embodied carbon cap.

Prior to establishing reduction limits in code, some jurisdictions conduct a benchmarking exercise through reporting requirements. These serve as a data collection process that helps cities understand their current state of the local market and its embodied emissions. In many cases, this informs future priorities and approaches.

Over time, the introduction of reporting requirements spurs generation of more EPDs. Embodied carbon codes have traditionally focused on buildings' structure and enclosure due to their high embodied carbon emissions. For this reason, primary structure and enclosure materials, as well as hardscape materials, covered by existing codes and complementary policies, generally have more EPDs available. Cool products that are selected for their benefit to UHI mitigation may therefore not have as much representation on the EPD market if they do not fall under these categories. In the future, code provisions may expand to require reporting on products not traditionally covered by embodied carbon policy, including roofing materials, paints, and coatings, which can spur further EPD development.

In the meantime, codes confronting these issues have tended to address UHI and embodied carbon impacts that result from material choices separately.

Spotlight: California

The [California Green Building Standards Code, or "CALGreen,"](#) is the first-in-the-nation statewide mandatory green building standards code. CALGreen has mandatory provisions affecting both residential and nonresidential construction, including new construction and qualifying alterations, as well as two voluntary tiers available for adoption by interested jurisdictions.

California's embodied carbon requirements are organized into three compliance pathway options. First, building reuse projects that retain 45% of the existing building's structure and enclosure are deemed to satisfactorily meet the code's embodied carbon provisions. Second is a prescriptive approach based on meeting referenced GWP limits for covered products: concrete, steel, flat glass, and light and heavy-density mineral wool insulation. Finally, the performance pathway is based on conducting a WBLCA and demonstrating a reduction from a comparable baseline building.

CALGreen also addresses urban heat through separate provisions. Part 6 of the code includes requirements for cool roofs, shade structures, high-albedo hardscapes, landscape efficiency, and others. Roofing products must be certified as a cool roof or meet prescriptive reflectance and emittance requirements. Building construction projects located in hotter climate zones are required to comply with both sets of requirements: embodied carbon and urban heat reduction.

In addition, California has a suite of other policies that cover the benchmarking and reduction of the embodied carbon of materials. Among them is Assembly Bill (AB) 2446, which requires the California Air Resources Board (CARB) to develop a framework for measuring and reducing the carbon intensity of building materials in new buildings. The law requires the California Air Resources Board (CARB) to create a statewide framework to measure and reduce the embodied carbon of building materials used in new construction. Senate Bill (SB) 596 builds on this by requiring CARB to develop a strategy for the cement sector in particular. AB 43 authorizes the establishment of an embodied carbon trading system, which would inform the framework for measuring the average carbon intensity of materials.

Spotlight: Marin, California

Marin, CA was the first county in the United States to adopt a [Low Carbon Concrete Code](#), under which new local building projects must choose from two pathways to comply: a total cement limit, or a GWP limit met for each concrete mix in a distinct strength category. Santa Monica, CA has recently followed suit by adopting its own [Low Embodied Carbon Concrete Requirements](#). A handful of other California jurisdictions have adopted similar requirements.

Marin's [Green Building Ordinance](#) also maintains a checklist for commercial and residential projects to incorporate CALGreen measures mandated by the state. These provisions include UHI mitigation measures including cool roof requirements for certain climate zones, SRI thresholds for roofing, shading of outdoor landscapes, and other related provisions.

Spotlight: Massachusetts

Massachusetts' [2025 Stretch Code and Specialized Opt-in Code](#) amended the 2021 International Energy Conservation Code (IECC) and International Residential Code (IRC) to introduce optional embodied carbon energy credits. Residential projects may increase their maximum allowable HERS rating by three points per unit by incorporating net zero GWP insulation or low embodied carbon concrete. Commercial projects may receive up to eight efficiency credits for each credit option, including heavy timber construction, low carbon concrete, or net zero insulation.

Spotlight: Vermont

The [2024 Vermont Commercial and Residential Building Energy Standards](#) have optional credits for GWP reporting and reduction of the GWP of insulation materials. Both the commercial and residential provisions offer three tiers for credits: the first tier (Basic) requires projects to report the GWP of insulation products, using either the default values provided in the code or product-specific values as documented by product-specific EPDs. The next two tiers award additional points for reductions that demonstrate a GWP of less than 0.5 (Advanced Tier) or zero (Stretch Tier). The Basic, reporting-only tier for commercial projects awards between one and eight points, depending on the building occupancy type; residential projects can earn one point for reporting. Commercial projects may receive 1.5 or two times the Basic tier's available points for the Advanced and Stretch tiers, respectively; residential projects receive a total of two or three points for the same reductions.

Spotlight: Denver, Colorado

The [Denver Green Code](#) requires projects using the voluntary code to meet specific GWP limits for concrete and steel products. For concrete, the total CO₂e value of mixes must not exceed a certain maximum value and must have a product-specific EPD. For steel, type III EPDs submitted for a minimum of 75% of steel products, based on cost or weight, must be provided.

Circular Economy

Several policies and initiatives focus on the end-of-life of materials to decrease the burden of construction and demolition debris on landfills. Promotion of a circular economy, in which buildings, infrastructure, and their products are recycled back into use at the end of the duration of their useful life, is promoted by policies that encourage responsible deconstruction and reuse. These efforts offer the potential to avoid the high embodied carbon impact associated with new construction and sourcing of raw materials. Policies focusing on a circular economy can include provisions requiring recycling or reuse of certain materials; diversions from landfills; and taxes on demolitions with exemptions for deconstruction.

Ordinances can mandate deconstruction for public projects or incentivize deconstruction for private projects. Jurisdictions can also develop and implement criteria, standards, and guidelines for sustainable design in public capital projects, focusing on lifecycle considerations. Cities can also establish waste diversion and material innovation centers to manage salvaged materials, including storage, quality confirmation, and resale. This can involve tracking salvaged materials for reuse, developing a searchable database to store and analyze data, and aiding in planning and setting reduction targets for material waste and associated emissions.

These same policies can optimize UHI mitigation by prioritizing salvaged materials with higher reflectance or lower heat retention for certain uses, using material reuse centers to supply reclaimed pavers, roofing, or façade elements that support cooler site conditions. Deconstruction requirements can be expanded to include documentation of surface reflectance or emissivity of recovered materials, creating a supply chain and information ecosystem for cool surface components that support UHI mitigation by testing, rating, and distributing salvaged products in both public and private projects. The use of permeable pavers in particular offers ease of reclamation as well as permeability, which offers UHI benefits regardless of albedo. If salvaged, these pavers can offer a benefit for embodied carbon and UHI as well as flood reduction. Material innovation centers can further support UHI materials with favorable thermal characteristics, while databases built for embodied carbon tracking can be extended to include surface-temperature attributes, enabling jurisdictions to plan for both carbon reduction and heat resilience across their portfolios.

Spotlight: Portland, Oregon

In Portland, for single-family or duplexes built on or before 1940 or designated as a historic resource, the city's [Deconstruction Ordinance](#) requires that construction projects seeking a demolition permit be fully deconstructed instead of mechanically demolished. When this ordinance was adopted in 2016, Portland became the first city in the country to ensure that valuable materials would be salvaged for reuse instead of crushed and landfilled.

Spotlight: Los Angeles, California

Los Angeles County's [Construction and Demolition Debris Recycling Ordinance](#) amends the county's Utilities Code to require at least 50 percent of the construction and demolition debris (by weight) generated on sites for projects exceeding \$100,000 to be recycled or reused. Project teams must submit a recycling and reuse plan (RRP) in order to be issued a permit, and additional reporting following the project's completion is required. Los Angeles City also promotes adaptive reuse at the building level through its [Adaptive Reuse Ordinance](#), which amends the city's Zoning Code to make it easier to convert vacant office and commercial spaces into housing. This ordinance demonstrates the important impacts that policy promotion of reuse can have not only on the environment, but also on the city's significant housing crisis.

Spotlight: Boulder, Colorado

Boulder, Colorado's [Sustainable Deconstruction Requirements](#) require all full structure removal and major remodeling projects to divert 75% of the materials generated from deconstruction projects (by weight) away from the landfill. This provision is enforced by requiring submission by project teams of a refundable deconstruction deposit of \$1 per square foot of the structure being taken down.

Spotlight: San Antonio, Texas

San Antonio has a [Deconstruction and Circular Economy Program](#), which requires residential structures up to fourplexes, as well as detached accessory structures, to be deconstructed rather than demolished if they were built during or before 1920 or if they are designated as historic, within a Neighborhood Conservation District, and built on or before 1945. In addition, the city supports a [Material Innovation Center](#) at its Port San Antonio campus, a former Air Force base that now serves as a center for material repair, reuse, and innovation aimed at providing the materials needed to spur a robust ecosystem of building reuse.

Spotlight: Mexico City, Mexico

Mexico City has made significant strides in [reducing the waste associated with its construction activities](#). Since 2018, the city has nearly tripled its annual waste recycling. This change is primarily driven by a 2021 policy mandating that construction and demolition waste from public and private works be disposed of at recycling plants, rather than cast into landfills or the natural environment. Projects are also required to use recycled materials for projects' non-structural elements. These policies are bolstered by the city's commitment of \$200 million, directed toward improving recycling infrastructure.

Incentives

Incentives and voluntary programs have the capacity to accelerate market transformation toward both low embodied carbon and UHI mitigation by stimulating designer and supplier investment and building the data ecosystem needed for future regulation. These programs can take many forms.

Tax credits are effective tools for encouraging sustainable and innovative building practices and material choices. These incentives can reward projects that use low-carbon materials, cool surfaces, or other strategies that reduce both embodied emissions and heat retention. In cases where requirements already exist, incentives can be structured to reward projects that go beyond basic embodied carbon thresholds or achieve minimum UHI mitigation performance levels, such as higher solar reflectance, lower surface temperatures, and increased shading.

A tax credit may provide a percentage of the project cost back to developers or owners, or may compensate expenses related to the procurement and use of certain materials and technologies. This mechanism encourages higher investment by lowering costs for developers, property owners, and project teams who might be hesitant to try more novel techniques due to their learning curve or cost premiums. Over time, projects pursuing these incentives provide proofs of concept that normalize innovative practices and enable them to scale more broadly.

Planners may also incentivize improvements through development concessions and density bonuses. Many cities grant concessions to promote priorities such as transit-proximate development and affordable housing by allowing developers to disregard a zoning standard of their choosing in return for delivering on a strategy that helps realize that priority. Zoning policy may also allow planners to grant maximum allowable height and density increases to support green building elements including low GWP material use and UHI mitigation measures in projects.

Grants can similarly support construction, renovation, research, and pilot projects that test integrated material solutions, which may cover both low-GWP as well as cool materials. Rebates may also be offered based on the actual performance of a strategy compared to established benchmarks, ensuring that incentives are tied to tangible outcomes.

Spotlight: Colorado

C-PACE is a financing program enabled by state policy designed to support energy efficiency, renewable energy, water, and resiliency measures for commercial buildings.¹⁸ Colorado recently became the first state to authorize financing for embodied carbon reduction as an eligible measure under C-PACE.¹⁹ The state released guidance, outlining the efforts that may qualify for financing.²⁰ Projects may qualify for financing of embodied carbon improvements by way of one of two pathways. The first constitutes material reduction, which is demonstrated through the submission of qualifying EPDs for any material or component to be financed. The second is a building-level reduction pathway, through which developers submit a whole building LCA documenting their building's embodied carbon intensity. The program notably also enables financing of the soft costs associated with embodied carbon reduction, including the time and labor associated with generating a whole building LCA, testing services of low embodied carbon materials, design for the use of salvaged or reused materials, embodied carbon consulting and support, and post-construction auditing.

¹⁸ [C-PACE](#)

¹⁹ [Colorado C-PACE Embodied Carbon Bill](#)

²⁰ [Colorado C-PACE Embodied Carbon Guide](#)

Spotlight: California

The state of California provides funding for the planning and implementation of projects to mitigate the impacts of extreme heat and UHI through its Extreme Heat and Community Resilience Program.²¹ Qualifying activities and projects include conducting studies; generating heat action plans and other planning documents; creating communications campaigns and programs; building out mechanical or natural shade; increasing building and surface reflectance; and developing passive or low-energy cooling strategies. Projects funded through the grant's first round of awards included the development of several cooling centers and resilience hubs; providing home cooling technologies in heat vulnerable communities; constructing heat resilient bus stop shelters; campus greening, landscaping, and installation of solar reflective coating; and regional heat action plan development.²²

²¹ [California Extreme Heat and Community Resilience Program](#)

²² [California Extreme Heat and Community Resilience Program Awardees](#)

Key Areas of Focus for Embodied Carbon and UHI Reduction

Previous sections of this toolkit provided an overview of common policies, programs, and strategies to reduce embodied carbon and outlined how these approaches may be tailored to or complemented by efforts to reduce UHI.

The table below summarizes three key areas of focus that represent opportunities to maximize impact on both embodied carbon and UHI reduction: urban forests, cool pavements, and cool and green roofs. These are detailed in the remainder of this resource.

TABLE 1: SUMMARY OF KEY AREAS OF UHI FOCUS AND ASSOCIATED STRATEGIES FOR EMBODIED CARBON REDUCTION

UHI Area of Focus	Potential Embodied Carbon Impact	Embodied Carbon Considerations	Implementation Approaches
Urban Forests, Parks, Green Corridors, and Other Greening Measures	Good	<ul style="list-style-type: none"> No embodied carbon impact of vegetation; often net carbon sink. For parks, hardscapes and structures can be minimized where possible and where necessary, be designed with low carbon and reused materials. 	<ul style="list-style-type: none"> Climate plans and urban heat island mitigation plans. Public procurement requirements. Incentives for private-sector greening.
Cool Pavements	Medium	<ul style="list-style-type: none"> Conventional concrete and asphalt are carbon-intensive. However, low-carbon and high-emittance alternatives exist. Permeable pavements can be carbon-heavy. Opportunities exist for low-carbon concrete pavers and salvaged brick and concrete pavers which have low embodied carbon. Coatings do not eliminate the carbon footprint of the underlying pavement but can extend lifespan and reduce maintenance and replacement needs. Some reflective coatings can have detrimental environmental impacts. 	<ul style="list-style-type: none"> Zoning and public works specifications. Pilot programs for cool and low-GWP pavements.
Cool Roofs	Medium	<ul style="list-style-type: none"> Polymer-based reflective coatings, membranes, and insulation can be carbon-intensive. Frequent recoating or short service lives can replicate embodied carbon impacts. Favoring low-carbon materials and coatings (durable membranes, mineral-based coatings, etc.) where feasible can reduce embodied impacts. Add something on green roofs. 	<ul style="list-style-type: none"> Building and zoning codes. Municipal ordinances. Minimum reflectance/emissivity and maximum project GWP standards.

Urban Greening

In the US, an average of 40 percent of urban areas are covered by trees, but that number is declining; impervious surfaces, meanwhile, are expanding. In many cities, the geographic divide between areas with and without tree cover mirrors demographic lines, namely race and income, contributing to hotter conditions in historically disinvested neighborhoods.^{23,24}

Trees help regulate a city's microclimate and alleviate the UHI effect by providing shade and evaporative cooling. Introducing trees and other landscaping provides shade and counterbalances the heat absorbed by manmade surfaces and buildings. Urban surfaces shaded by trees are significantly cooler than unshaded ones in the summer.²⁵ Revegetation and preservation of existing green spaces can provide seasonal shade to infrastructure, foster evapotranspiration, and minimize temperature differences on the ground.²⁶

By capturing carbon and storing it in their biomass, trees also help to control urban greenhouse gas emissions; in the US, urban forests offset climate pollution equivalent to the emissions of about 10 million cars. If left unaddressed, these emissions will continue to exacerbate the core underlying contributor to changing global temperatures and the increasing severity of the UHI effect.

Introducing new landscaping and preserving existing green spaces throughout a city can offer a range of other benefits in addition to reducing carbon emissions and average city temperatures in the summer. These include increased biodiversity; reduced pollution; decreased winter wind speeds; and positive effects on human health. Urban forests, parks, green corridors, and other greening strategies also require little new built infrastructure, meaning that they have a minimal embodied carbon impact. In addition, vegetation often acts as a carbon sink. For parks that include hardscapes or structures, choosing low-carbon, reused, or recycled materials can further reduce their impacts.

As described in a prior section on public procurement policies, low-carbon material requirements may be applied to publicly-funded projects, which can influence municipal park design and associated product selection for buildings, hardscapes, and other infrastructure. These specifications may be paired with requirements for cooler materials to enhance their UHI mitigation potential.

²³ [Tree Equity](#)

²⁴ [Residential Housing Segregation and Urban Tree Canopy in 37 US Cities](#)

²⁵ [The little-known physical and mental health benefits of urban trees](#)

²⁶ [Quebec Urban Heat Island Mitigation Strategies: 2021 Update](#)



Streets and Paving

By area, streets constitute some of the largest continuous surfaces and public spaces in a city. When designed thoughtfully, they can function as adaptable, multi-purpose environments that meet the diverse needs of the people who use them. Beyond mobility, streets also represent one of the largest sources of embodied carbon in cities, as street designs and their associated material choices have a large influence over the emissions associated with their manufacturing, transport, maintenance, and end-of-life.

The materials and design choices that make up streets also directly influence how much they absorb, store, and release heat. These same choices also shape their carbon footprint. Conventional asphalt and concrete, for example, are carbon-intensive. However, lower-carbon alternatives exist, including warm-mix asphalt, mixes with recycled asphalt pavement, and concrete with supplementary cementitious materials (SCMs).

Reflective, high-albedo and permeable pavement can significantly reduce surface and air temperatures. Reflective pavements are designed to reduce heat absorption by reflecting solar radiation.²⁷ Light-colored materials reflect more sunlight and reduce the amount of heat absorbed and reradiated by sun-exposed surfaces. Reflectivity can be achieved by choosing lighter materials, such as concrete or lighter binders and aggregates. Coating or overlaying surfaces with lighter colored materials has also become a common and lower-cost way to prevent heat buildup. Replacing dark surfaces with lighter-colored ones can reduce surface temperatures by up to 20°F during warmer months.²⁸ White surfaces can reflect between 30 and 80 percent of incoming sunlight back into the atmosphere, compared to fresh asphalt, which reflects only about 4–12 percent.

On high-volume traffic roads, the largest benefit of cool pavements is not due to their UHI mitigation potential, but rather due to their impact on road longevity and vehicle fuel

²⁷ [Urban Heat: Can White Roofs Help Cool World's Warming Cities?](#)

²⁸ [Performance of Cool Pavements for UHI Mitigation](#)

consumption. Permeable surfaces also undergo less thermal expansion compared to impermeable and darker alternatives, leading to longer service lives. Over the lifetime of a pavement, these fuel savings can add up, often offsetting the higher initial cost and impact of paving with more durable materials appropriate for high-traffic roads. Cool pavement alternatives that minimize fuel consumption can continue to cut GHG emissions in winter, assuming traffic is constant.

Placement of reflective pavements is an important consideration. Recent research has shown that walking on cool pavements can lead to higher temperatures and discomfort for pedestrians, as surface temperature is being reflected. A few studies, for example, found that people standing on reflective pavements on hot, dry days could feel over 7°F hotter compared to standing on uncoated asphalt.²⁹ This is in large part due to the glare that reflective coatings cause. This issue can be resolved by coating pavements that pedestrians do not directly stand on: treating roadways instead of sidewalks, or treating only shaded sidewalks, can lead to a reduced experience of heating for pedestrians.³⁰

In acknowledgement of this impact, many cities, including Phoenix, Los Angeles, and San Antonio, have begun programs to coat roofs with white coatings and road surfaces with more reflective coatings. As these programs and policies scale, and the projects factoring in UHI mitigation continue to increase, pairing reflectivity requirements with EPD-based material specifications can help to ensure that cooling strategies do not inadvertently increase embodied emissions. Utilizing concrete in lieu of asphalt is also effective because it offers a higher albedo and lasts longer than asphalt.

However, coatings can add their own embodied carbon and do not eliminate the footprint of the underlying pavement, but they can help reduce life cycle emissions by extending pavement life, delaying full resurfacing cycles, reducing thermal cycling and surface degradation, and contributing to global cooling through negative radiative forcing. Negative radiative forcing refers to the way that a proportion of the solar energy cool pavements reflect travels back into the atmosphere and into space. This process shifts the Earth's energy balance and effectively offsets some of the radiation trapped by greenhouse gases. The MIT Concrete Sustainability Hub found that roughly a third of the annual CO₂-equivalent emissions reductions from the radiative forcing effects of cool pavements occur in the fall and winter.³¹ There is limited research on the impacts of cold climate-specific freezing temperatures combined with de-icing salts on coating performance, but reflective coating durability is typically sensitive to environmental exposure and will likely need more frequent recoating under extreme conditions.

In addition to their potential for having lighter colors than black asphalt, some permeable paving options also provide evaporative cooling benefits that reduce surface and air temperatures. The relatively open structure of these types of paving allows them to absorb and store less heat, ultimately reducing the amount of radiation released into the air and reducing local temperatures in the summer. From an embodied carbon perspective, permeable concrete mixes with reduced

²⁹ [The Hottest Urban Heat Solution Comes with a Glaring Tradeoff](#)

³⁰ [UNEP: Beating the Heat: A Sustainable Cooling Handbook for Cities](#)

³¹ [How Cool Pavements Can Mitigate Climate Change](#)

cement content or supplementary cementitious material (SCM) substitution can cut embodied carbon significantly while delivering higher solar reflectance and evaporative cooling benefits when compared to black asphalt. Over time, cooler materials can reduce heat-related degradation, which further lowers lifecycle emissions by extending pavement life and reducing maintenance frequency.³²

Available Product Performance

A comprehensive study on the lifecycle impacts of typical “cool” paving materials, conducted by the California Air Resources Board (CARB) and the Lawrence Berkeley National Laboratory (LBNL), led to the development of a pavement LCA tool that allows cities to compare application scenarios for various paving and treatment products, including asphalt, concrete, and a wide range of coatings.³³

Across the major pavement material categories, the materials production phase tends to have the greatest impact. It is worth noting, though, that some LCA methodologies for paving materials account for vehicular emissions influenced by pavement performance in the B-stage, which makes B-stage emissions much higher; however, this particular study did not include vehicular emissions in B-stage calculations.³⁴ For pavements, the greatest impacts come from binders, which make up a small portion of the material by mass and volume but constitute a high GWP. For concrete, the use of supplementary cementitious materials (SCMs) and other changes to reduce environmental impacts can result in less than half the GHG produced by conventional portland cement concrete mix with the same thickness. For coatings, reflective options also have higher environmental impacts than do other treatments of similar thickness, such as chip and slurry seals. Finally, the study found that material quantity also has a significant impact: in general, embodied emissions increase as treatment thickness grows.³⁵

Asphalt

About half of the emissions from asphalt’s upfront stages stem from material extraction, while another third come from production. Upfront (A1–A3) emissions are driven primarily by asphalt binder production, aggregate processing, and the high temperatures required to produce hot-mix asphalt. Binder, although only a small fraction of the mix by mass, contributes a disproportionately large share of emissions because it is a petroleum-refined product. Aggregates contribute less per kilogram but make a difference due to their large volume. Asphalt plants also add significant emissions through fuel combustion to heat and dry aggregates. Transportation and construction activity (A4–A5) emissions include impacts resulting from paving, compaction, haul distance, and transportation and on-site equipment choices. Most emissions from this stage come from diesel-powered machinery.

The use (B) stage accounts for vehicular emissions. Pavement smoothness affects vehicle rolling resistance and resulting fuel consumption. For this reason, if vehicular emissions are

³² [FHWA: Climate Change Adaptation for Pavements](#)

³³ [CARB and LBNL: Life-Cycle Assessment and Co-Benefits of Cool Pavements](#)

³⁴ [MIT Sustainability Hub: Life Cycle Assessment](#)

³⁵ [CARB and LBNL: Life-Cycle Assessment and Co-Benefits of Cool Pavements](#)



accounted for in an LCA, the use stage can dominate the total lifecycle footprint of the product, which includes accounting of maintenance and rehabilitation activities.

Finally, end-of-life (C) emissions for asphalt pavements are relatively low because asphalt is highly recyclable. Most reclaimed asphalt pavement (RAP) is reused in new mixes, reducing the need for virgin binder and aggregates. This circularity means that C-stage emissions—removal, milling, and processing—are modest compared to earlier stages and are often offset by the avoided impacts of future A1–A3 stages.³⁶

Lower-carbon asphalt alternatives exist, including warm-mix asphalt, which can reduce emissions by 10–20 percent, and mixes with RAP can reduce emissions by 15–40 percent. Warm-mix asphalt consistently shows lower greenhouse gas emissions compared to traditional hot-mix because it requires lower production temperatures, reducing burner fuel use at the asphalt plant.³⁷ Similarly, asphalt mixtures incorporating RAP achieve significant reductions because RAP replaces virgin binder, the most carbon-intensive component of an asphalt mix, but the extent of the emissions reductions depends on the mix’s content and binder replacement rate.^{38,39}

Concrete

Concrete paving carries high embodied carbon. Its primary emissions source is portland cement, created through an energy- and fossil-fuel intensive production process of heating up limestone and clay to high temperatures.^{40,41} The process also releases carbon emissions from the chemical breakdown of calcium carbonate. As a result, cement alone accounts for a majority of the upfront emissions of a concrete pavement mix.⁴² Additional, lesser contributors to

³⁶ [National Asphalt Pavement Association: The Carbon Footprint of Asphalt Pavements](#)

³⁷ [Review of Sustainability in Hot Asphalt Production: Greenhouse Gas Emissions and Energy Consumption](#)

³⁸ [NAPA Recycling, WMA Survey Results](#)

³⁹ [Warm-Mix Asphalt and Reclaimed Asphalt Pavement Reduce Greenhouse Gas Emissions](#)

⁴⁰ [The Guardian: Concrete](#)

⁴¹ [Decarbonizing Cement and Concrete Value Chains](#)

⁴² [A Comparative Cradle-to-Gate LCA of Three Concrete Mix Designs](#)

concrete's embodied emissions include aggregate extraction, transportation, and the total material volume required for pavement design and construction. Thicker slabs, higher strength classes, and longer haul distances can increase the concrete's embodied carbon impact.

Industry has begun to make large strides in reducing concrete's emissions. Efforts include optimizing aggregate gradation to lower cement content, substituting a portion of cement with supplementary cementitious materials (SCMs) such as fly ash, slag, or calcined clay, and selecting leaner mixes where structural demands allow.^{43,44} Fly ash is a waste product of coal combustion. Slag is a by-product of crude iron production that, when ground up, exhibits cementitious properties of portland cement. Recycled aggregates from crushed glass or plastic may also be applied as a cement replacement. However, they must also conform to product specifications and are also subject to availability that may vary significantly on a regional basis. Importation of SMCs should also be considered, as transportation increases their carbon impact. Natural alternatives, such as materials derived from volcanic ash and clay, have also been used for thousands of years and have proven to be exceptionally durable: the Pantheon, Baths of Caracalla, and Pyramids of Giza all incorporate these materials.⁴⁵

Industry has also focused on incorporating more energy-efficient methods and alternative energy sources in the processing and heating of cement. Industry has also adopted the practice of burning dried raw materials rather than wet material to reduce the amount of energy needed to heat them. As kilns used to heat raw materials currently account for over 70 percent of energy consumption along the supply chain, these efforts make a considerable impact.

Use-stage emissions are also typically lower for concrete pavements compared to asphalt pavements. Rigid pavements like concrete require fewer replacements and less maintenance over their service life, which can often last 30–50+ years, leading to fewer emissions associated with maintenance and repair.⁴⁶ Like asphalt, vehicle fuel consumption can dominate pavement lifecycle emissions, but these depend largely on the context in which the concrete is poured and the resulting level of use. Stiffer pavements such as concrete deflect less under load, leading to lower rolling resistance, which results in lower vehicle fuel consumption, and lower lifecycle emissions, compared to driving on asphalt.⁴⁷

For concrete, the main contributors to C-phase emissions include demolition energy, steel removal, crushing, and transport of reclaimed material, which often use diesel-powered equipment and hauling. End-of-life emissions for concrete are comparatively small relative to A1–A3 and B-stage impacts. End-of-life crushing also likely leads to carbon sequestration.⁴⁸ Concrete paving can accommodate crushed and reused concrete aggregate (RCA), which avoids the need for virgin aggregate extraction.⁴⁹ Currently, use of RCA is common on most projects where existing concrete pavement is removed.

⁴³ [Reducing Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete](#)

⁴⁴ [Climate Reserve: Low Carbon Cement Production](#)

⁴⁵ [USGBC: How Ancient Egyptians Built Pyramids](#)

⁴⁶ [Impact of Use Phase in Pavement LCA](#)

⁴⁷ [Federal Highway Administration: Impact of Environmental Factors on Pavement Performance](#)

⁴⁸ [MIT Life Cycle Calculator](#)

⁴⁹ [Federal Highway Administration: Use of Recycled Concrete Aggregate in Concrete Paving Mixtures](#)

Coatings

Some high solar reflectance coatings can be applied to asphalt or concrete to increase albedo and reduce heat gain. These products include light-colored acrylic coatings that add reflectivity and resist discoloration under high temperatures. Coatings that reflect solar radiation across UV, visible, and infrared wavelengths can reduce asphalt surface temperatures.⁵³ One peer-reviewed study from Altostratus Inc. about the Cool Community Project in the Pacoima neighborhood of Los Angeles, California, found that application of solar reflective coatings on pavements reduced ambient air temperature by up to 3.5°F during extreme heat events, resulting in a 25–50 percent reduction in local UHI intensity during peak temperatures.⁵²

Photocatalytic TiO₂-based pavement coatings are heat-reducing, self-cleaning surfaces, which can degrade harmful pollutants from vehicles, including nitrogen oxides (NOx), microplastics, and total volatile organic compounds (TVOCs) while consuming thermal energy and contributing to UHI mitigation.⁵⁴ IR-reflective (NIR/IR) coatings contain pigments that reflect near-infrared and mid-infrared wavelengths, enabling up to 18–22°F surface cooling, even under intense heat exposure.⁵⁵

From an embodied carbon standpoint, high-albedo or heat-reflective pavement coatings are typically thin coatings that are applied at only a few kilograms per square meter. While coatings add to the embodied carbon of the pavements system, they can improve the overall performance and durability of the underlying material, reducing the maintenance or replacement of the pavement, which can be responsible for later-stage embodied carbon emissions.

Both reflective and conventional pavement coatings use binders to ensure that all components of the composition are evenly dispersed, which influences qualities such as gloss, durability, flexibility, and toughness. Binders typically consist of polyesters, polyurethanes, acrylics, silicates, epoxies, oils, or resins. Pigments and other additives can be added to a binder to improve performance. Reflective coatings are either solvent- or water-based. Solvent-based coatings are typically more durable than water-based coatings, but can also release Volatile Organic Compounds (VOCs), which have a negative impact on environmental and human health. Water-based coatings substitute water for solvents as the primary carrier medium and therefore reduce VOC emissions, but may achieve a relatively shorter lifespan.

The durability of reflective coatings depends on weathering and traffic conditions; reflective pavement coatings can be designed to last for 5–10 years on high-traffic roads and potentially much longer on residential roads or pedestrian and bike paths. However, coatings require periodic recoating to maintain the benefits of high reflectivity and pavement protection or preservation. One case study comparing the lifecycle impacts of different pavement coatings, however, found that reflective coatings have lower environmental impacts, even when they are applied each year, compared to conventional hot mix asphalt and portland cement concrete overlays.⁵⁰

⁵⁰ [Reflective Coatings for Cool Pavements: Information Synthesis and Preliminary Case Studies for Life Cycle Assessment](#)

TABLE 2: SUMMARY OF AVAILABLE PAVING PRODUCTS AND THEIR EMBODIED CARBON PERFORMANCE

Product Type with “Cool Alternatives”	Average Materials and Construction GWP for North America* (kgCO ₂ e/1 lane-kilometer)	Embodied Carbon Considerations
Asphalt	Hot mix asphalt: 25,200–27,500	<ul style="list-style-type: none"> Upfront (A1–A3) emissions are primarily driven by petroleum-based binder extraction, aggregate extraction and processing, and high-temperature production.
	Permeable: 54,600	<ul style="list-style-type: none"> Asphalt binder constitutes only about 5 percent of the mass of a mix but can account for over half of A1–A3 emissions due to crude oil extraction and refining.
	Permeable rubberized: 60,000	<ul style="list-style-type: none"> Aggregates make up about 95 percent of the mass but have low carbon intensity. Use-phase emissions accounting for vehicular emissions influenced by pavement performance are high; high traffic volumes increase impact of B-stage. Note: vehicular emissions are not always included in B-stage calculations.
	Rubberized: 26,800	<ul style="list-style-type: none"> End-of-life emissions are relatively low because asphalt is highly recyclable. Lower-carbon alternatives exist, including warm-mix asphalt (10–20% lower emissions) and mixes with recycled asphalt pavement (15–40% reductions).
Concrete Paving	Portland cement concrete: 85,200–241,000 depending on PCC content	<ul style="list-style-type: none"> Standard concrete paving mixes at 3,001–4,000 psi (typical for paving) often fall between 238–383 kg CO₂e/m³ due to portland cement’s calcination emissions.⁵¹ Using less cement and less concrete can significantly reduce embodied carbon
	Permeable portland cement concrete: 211,000	<ul style="list-style-type: none"> Embodied carbon reduction strategies can include optimized aggregate gradation, lower-cement mixes, and substituting cement with SCMs such as fly ash, slag cement, or calcined clay. SCMs can cut embodied carbon by 20–50%. Ultra-low and negative carbon concrete technologies also exist.
	Interlocking concrete pavers: 76,600	<ul style="list-style-type: none"> Use-stage emissions relatively low; less frequent maintenance and lower vehicle fuel consumption. Note: vehicular emissions are not always included in B-stage calculations. End-of-life emissions can be small; concrete is commonly crushed and reused as recycled concrete aggregate (RCA).
Reflective Coatings	Bisphenol A (BPA) epoxy resin: 10,400	<ul style="list-style-type: none"> Some coatings do not reduce the embodied carbon of the pavements they treat, but they can improve the overall performance and durability of the underlying material, reducing later-stage maintenance and replacement emissions.
	Polyester Styrene: 12,200	<ul style="list-style-type: none"> Solvent-based coatings are typically more durable than water-based coatings, but can also release Volatile Organic Compounds (VOCs) during installation.
	Polyurethane: 8,660	<ul style="list-style-type: none"> Need periodic recoating: lifespan is relatively short due to weathering and traffic.
	Styrene Acrylate: 5,760	<ul style="list-style-type: none"> Reflective coatings can have lower environmental impacts, even when they are applied each year, compared to conventional hot mix asphalt and portland cement concrete overlays.

* Unless otherwise noted, values come from [CARB and LBNL: Life-Cycle Assessment and Co-Benefits of Cool Pavements](#).

⁵¹ [NRMCA Industry-Average EPD](#)

Cool Roofing & Wall Products

Installing cool roofs is an inexpensive energy conservation measure to passively reduce cooling loads in warmer regions. Cool surfaces reflect sunlight and efficiently radiate heat away from the roof surface. Installing cool surfaces reduces the conduction of heat into the building, reducing the demand for air-conditioning in conditioned spaces. This saves energy and money, and the decreased load helps to moderate peak electricity grid demand during heat waves and very hot summer afternoons, thereby reducing energy costs and the risk of power outages.⁵²

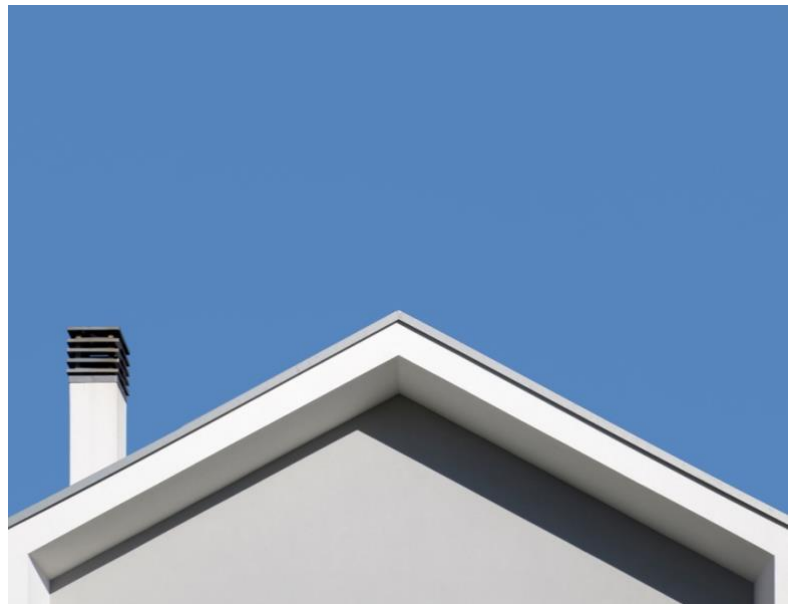
At the city scale, reflective surfaces, including cool roofs, can amplify neighborhood- and city-level cooling. If implemented at a global scale, the widespread adoption of cool roofing and wall products has the potential to help to increase the Earth's overall albedo and decreasing global energy consumption driven by the need for air conditioning.

For optimal UHI mitigation, prioritize materials with high solar reflectance and thermal emittance, or Solar Reflectance Index (SRI) values, over standard dark roof materials with a low SRI. Solar Reflectance (SR) refers to the percentage of sunlight a material reflects back into the atmosphere. An SRI is a value that combines solar reflectance and thermal emittance, or the capacity of a surface to absorb heat. SRI values typically fall between 0 and 100.

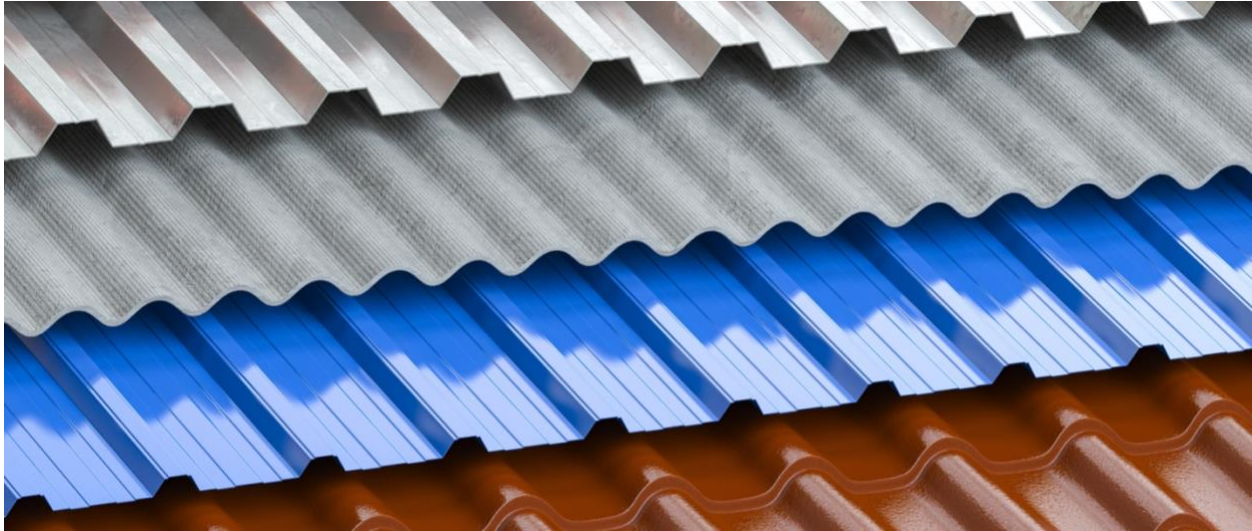
Many roofing products are in the relatively early stages of environmental data collection, compared to major structural and paving materials. Because of this, these products are often not covered by embodied carbon policy and many do not have a robust selection of EPDs. This section summarizes what is currently known about common roofing products, while acknowledging that some data gaps remain and additional research is still needed to fully characterize their embodied carbon impacts.

Available Product Performance

The table below looks at typical roofing product types that have “cool” alternatives and their relative embodied carbon impacts. Due to the relatively early status of embodied carbon data and related policy for roofing wall products, this section is intended not necessarily to inform policy, but rather to help product specifiers, designers, and others who influence project selection make informed decisions about their material choices.



⁵² [Lawrence Berkeley National Lab Heat Island Group](#)



Asphalt Shingles

Asphalt shingles absorb a lot of solar radiation due to the low-reflectivity of the foundational black asphalt layers (typically 5–32 percent solar reflectance), contributing significantly to UHI effects. They also have high embodied carbon, in large part due to their petroleum-based asphalt binders and shorter lifespans.¹² Petroleum-based binders are energy-intensive to refine and manufacture, and unlike metal or tile, they are not readily recyclable at end-of-life. Their disposal typically involves landfilling or downcycling into lower-grade fill, which adds additional end-of-life emissions to their overall impact. At the same time, shingles use relatively little material per square foot, which helps keep their per-installation embodied carbon lower than heavier systems like clay and concrete tile or slate. However, their shorter service lives (about 15–30 years) also leads to more frequent replacement over the building's life, multiplying the embodied carbon associated with manufacturing, transport, and disposal.

Metal Roofing

Metal roofing, often made out of steel or aluminum, can reflect up to 74 percent of sunlight in light colors, reducing cooling loads by 40–50 percent compared to dark asphalt shingles. Metal roofing, most commonly used on steep-slope buildings, offer high durability and long service lives. They typically have a relatively high SRI, and, when paired with appropriate surface finishes, they can also achieve high thermal emittance; adding a white or reflective coating can further increase both SR and SRI, helping the roof stay cooler.⁵³ Though often applied in sheets and with standing seams, metal shingles are also available and can mimic the style of asphalt shingles while providing the performance benefits of a metal roof. Because metal is highly conductive, a reflective metal roof cools rapidly when solar input drops, which can limit unwanted heat gain in summer, in particular at night time.

Metal shingles tend to have higher upfront embodied carbon because producing steel and aluminum is energy-intensive, especially when virgin metal is used. However, many metal shingle products incorporate a significant amount of recycled content, which can lower their upfront

⁵³ [A Practical Guide to Cool Roofs and Cool Pavements](#)

impacts. Metal shingles can also last 40–70 years, reducing the frequency of manufacturing, transport, and installation cycles. At their end-of-life, metal shingles are highly recyclable, avoiding the upfront carbon spent on future products. This combination of long service life and recyclability helps offset the higher upfront emissions associated with metal production.

Concrete or Clay Tile

Concrete and clay tile roofs provide strong benefits for heat resilience. Their mass and thickness offer thermal mass benefits, slowing heat transfer to underlying decking and spaces; however, the details of their construction are important for how they facilitate the provision of air movement on the underside of the roof to shed heat. Products are also available in light-color or reflective formulations, meaning that they have higher SR and SRI values than, for example, asphalt shingles.

Concrete roof tiles carry high upfront embodied carbon because cement production is one of the most carbon-intensive industrial processes, and concrete manufacturing requires significant energy and raw material inputs. Although the industry is making progress through clinker substitution, SCMs, and lower-carbon mix designs, concrete tiles still have a comparatively large A1–A3 footprint. Their long service life, often 50 years or more, reduces the need for multiple replacements, meaning that their upfront impact is moderated by infrequent replacement cycles.

Clay roof tiles also offer a 50-year-or-more lifespan, minimizing replacement frequency and reducing the cumulative embodied carbon impacts over a building's life. Their upfront emissions are generally lower than concrete and many metal products, because clay extraction and forming require less carbon-intensive chemical processes than cement or metal production. However, clay tiles still depend on high-temperature kiln firing.

Wood Shake or Cedar Shingle

Wood is naturally cool and has a moderate reflectance, meaning that its performance can vary.⁵⁴ They also do not have high emissivity, meaning they cannot shed absorbed heat back to the atmosphere.

Wood shakes generally have lower upfront embodied carbon, assuming the wood is responsibly sourced and not heavily processed. Their manufacturing relies on low-energy mechanical shaping rather than high-temperature industrial processes, which keeps A1–A3 emissions comparatively modest. However, wood shakes have a shorter service life than metal or tile roofing (though comparable to asphalt shingles), typically ranging between 20 and 30 years, and, in wet or fire-prone climates, this might be shorter. This means that they require more frequent replacements over a building's lifespan and this repeated manufacturing, transport, and installation can increase lifetime embodied carbon even when the per-installation footprint is relatively small.

⁵⁴ [DOE: Cool Roofs](#)

Coatings

Coatings are thick, paint-like surface treatments mostly used for low-slope roofs. They are engineered to improve adhesion, durability, biological resistance, corrosion, and dirt shedding, while also functioning as cool roofs when light-colored. They can be cementitious, elastomeric, or silicone or acrylic paints, and can provide high initial solar reflectance and thermal emittance.⁵⁵ They can be applied over an existing roofing system to provide life extension, protection against moisture, standing water, hail, ultraviolet radiation, and physical damage. Elastomeric coatings have elastic properties, allowing them to expand in hot summer conditions and then return to their original shape without cracking, which is why they are widely used in roof applications.⁵⁶ Applying white, light-colored, or transparent high reflectance coatings to surfaces can also significantly lower surface temperatures and contribute to UHI mitigation and global cooling.⁵⁷

These materials add only a modest amount of embodied carbon because the materials used are lightweight compared to heavier roofing systems. Their primary value is in the fact that they improve adhesion, durability, and corrosion resistance, which can significantly extend the service life of single-ply membranes. While a coating on its own does not offset the embodied carbon of the underlying roof, it can effectively delay replacement, reducing the frequency of carbon-intensive manufacturing and installation cycles over a building's lifespan. Because the emissions associated with producing and transporting coatings are small relative to bulk materials like concrete, clay, or metal, their contribution to total embodied carbon is minor, while their ability to extend service life makes them an impactful maintenance strategy in long-term carbon performance.

Single-Ply Membranes

Single-ply membranes are pre-fabricated sheets installed in a single layer on low-slope roofs. They are typically directly adhered or mechanically fastened across the roof surface, with seams sealed using tape, adhesives, or welding. They are also used for extensive repair on existing buildings. Many manufacturers produce them with reflective cool roof materials and colors. Common types of single-ply membranes include:

- TPO (thermoplastic olefin): Thermoplastic membranes with seams that are welded to form durable, watertight joints.⁵⁸
- PVC (polyvinyl chloride) and PVC-KEE
- KEE (ketone ethylene ester)

White EPDM (ethylene propylene diene monomer): A synthetic rubber membrane with seams that are typically glued or taped together. EPDM roofing is often black colored and a large contributor to urban heat island, but can be made to have a white surface and thus more reflective.

⁵⁵ [Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs](#)

⁵⁶ [A Practical Guide to Cool Roofs and Cool Pavements](#)

⁵⁷ [CRRC Rated Roof Products](#)

⁵⁸ [Reducing Urban Heat Islands: Compendium of Strategies Cool Roofs](#)

TABLE 3: SUMMARY OF AVAILABLE ROOFING PRODUCTS AND THEIR EMBODIED CARBON PERFORMANCE

Product Type with “Cool” Alternatives	Average Upfront GWP (A1-A3) for North America (kgCO ₂ e/m ²)	Full Lifecycle Embodied Carbon Considerations
Asphalt Shingles	4–7 ⁵⁹	<ul style="list-style-type: none"> • High embodied carbon from petroleum-based asphalt binders. • Roofing products not readily recyclable; end-of-life carbon contributions are significant. • Shorter lifespan (15–30 years) requires more frequent replacements compared to metal, tile, slate. • Lightweight compared to some other products (less mass per square foot).
Metal Roofing	Steel: 13–17 Aluminum: 15–20 ⁶⁰	<ul style="list-style-type: none"> • High upfront emissions associated with steel and aluminum production, but often contains recycled content, lowering associated upfront carbon. • Longer lifespan (40–70 years) and high recyclability lowers lifetime embodied carbon.
Concrete Tile	12–25 ⁶¹	<ul style="list-style-type: none"> • 50+ year lifespan minimizes replacements. • High upfront carbon emissions of cement/concrete production, but progress is being made in the industry to lower GWP.
Clay Tile	7–40 ⁶²	<ul style="list-style-type: none"> • 50+ year lifespan minimizes replacements. • Lower upfront carbon emissions compared to concrete and some metals. • Depends on high-temperature firing.
Green Roofs	20–120 depending on roof type ⁶³	<ul style="list-style-type: none"> • Structural layers create embodied carbon emissions: waterproofing and root barrier; drainage layer; filter fabric; growing media; structural reinforcement. • Lightweight, bio-based growing media and recycled plastic or mineral drainage layers can reduce embodied impacts. Prioritize extensive low-structure systems on existing buildings to avoid major structural upgrades. • Emissions reductions benefits are felt later in the lifecycle through longer lifespan of roofing membrane, carbon sequestration, and operational energy savings, which can realize a net reduction in GWP over the full lifecycle.⁶⁴
Coatings, Single-Ply Membrane	3–12 depending on product	<ul style="list-style-type: none"> • Boosts adhesion, durability, and corrosion resistance, extending service life of the roof. • Medium lifespan for single-ply membranes (20–30+ years). • May not offset roof embodied carbon but extends service life. • Emissions associated with manufacturing, production, and transportation of coatings relatively small compared to heavier materials.
Wood Shake	8–11 ⁶⁵	<ul style="list-style-type: none"> • Smaller upfront carbon emissions compared to asphalt, steel, and aluminum, assuming responsible sourcing. • Shorter life requires more frequent replacements (20–30 years, sometimes less, depending on location).

⁵⁹ [Asphalt Shingle Roofing System Industry-Average EPD](#)

⁶⁰ [Steel and Aluminum Cladding and Roofing Industry-Average EPD](#)

⁶¹ [Concrete Roof Tile Product-Specific EPD](#)

⁶² [Clay Roof Tile Product-Specific EPD \(no Industry-Wide available\)](#)

⁶³ [Life Cycle Assessment of Green Roofs: A Comprehensive Review](#)

⁶⁴ [Comparison of Green and Conventional Roofs from Environmental Parameters](#)

⁶⁵ [North America Softwood Lumber EPD \(no roof shake available\)](#)



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