SMART SURFACES COALITION

Cooling Cities, Slowing Climate Change and Enhancing Equity: Costs and Benefits of Smart Surfaces Adoption for Baltimore

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We thank and acknowledge the guidance from many of our 45 partners including:

The American Institute of Architects

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APHA American Public Health Association — For science. For action. For health.

Habitat for Humanity

Capital - E — Greening Our Built World

U.S. Green Building Council — USGBC

APA American Planning Association

WCA World Cement Association

ACEEE American Council for an Energy-Efficient Economy

Global Cool Cities Alliance

Carnegie Mellon University — Pittsburgh Pennsylvania 1900

The Trust for Public Land

Rocky Mountain Institute

World Resources Institute

CRRC Cool Roof Rating Council

USDN urban sustainability directors network

waternow alliance — water leaders. resilient solutions.

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NASEO National Association of State Energy Officials

IGSD

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1 Acknowledgements

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We particularly thank the Abell Foundation for funding the Smart Surfaces Coalition to undertake a detailed cost-benefit analysis of the potential for Smart Surfaces (reflective, porous, green surfaces + solar PV and trees) to enable Baltimore to manage and mitigate the heat and climate threats it faces, and to enhance its health, livability, employment, equity and economic well-being.

2 Executive Summary

Dr. Georges Benjamin, M.D., *former Secretary of Health for Maryland and current Executive Director of the American Public Health Association:*

"Extreme heat in urban communities like Baltimore imposes enormous health and financial costs, including increased heat-related deaths. This is especially true in underserved and low-income minority neighborhoods. Adoption of Smart Surfaces city-wide is an essential strategy to address the devastating impacts of climate change and achieve a cooler and healthier city. This report demonstrates how and why Baltimore's leaders, with state support, should move quickly to adopt Smart Surfaces."

Brendan Shane, *Climate Director at the Trust for Public Lands, former C-40 Regional Director for North America, former Head of Environmental Policy Washington, D.C.:*

"The new Smart Surfaces Coalition is so essential because it provides a powerful new way for cities to address both mitigation and adaptation. It will provide to cities, and groups like C-40, a powerful new way to slow climate change and improve urban resilience and livability. It is one of the largest, and perhaps the most effective, urban climate strategy to limit warming and protect our cities."

Chris Riehl, *President of the Baltimore Tourism Association:*

"Incorporating Smart Surfaces in Baltimore will overall improve the livability and appeal of the city, allowing the city to market itself as more sustainable, energy efficient, and desirable tourism destination."

2.1 The Threat to Cities

More and more cities are becoming intolerably hot in the summer, and in the coming years are increasingly at risk of becoming unlivable due to more extreme summer temperatures. This is in large part because most cities have been covered with dark, heat-absorbing, impervious surfaces, such as asphalt parking lots and dark roofs, resulting in higher peak temperatures, higher energy bills, worsened flooding, and increased air pollution. Summers are now commonly 9°F hotter in cities than the surrounding countryside, an effect commonly referred to as the urban heat island. The impact is usually even worse in lower-income neighborhoods, which generally have even fewer trees and darker surfaces, with temperatures often 10°F hotter than wealthy neighborhoods with more trees.

Climate change is making cities even hotter. Under current projections, many cities will experience a tripling of extremely hot summer days by 2050. A National Academy of Sciences report warns that the mean human-experienced temperature rise by 2070 will amount to an estimated 13° Fahrenheit.[1] And it warns that "in the absence of migration, by 2070 one third of the global population is projected to experience [summer heat of] 29 °C, currently found in only 0.8% of the Earth's land surface, mostly concentrated in the Sahara."

The National Academy of Sciences report goes on to warn that more than a billion people may have to migrate to avoid overheating. A recent Australian Institute report2 estimates that a billion people could be displaced by climate and weather disasters by 2050. Unless city policies and the pace of global warming change, many cities will become too hot in the summer for humans to survive for prolonged periods outside—or in buildings without adequate air conditioning.

The recent surges in extreme heat in traditionally cool places Seattle, Portland and much of Canada has led to hundreds of excess heat deaths in a few days and a rush to buy air conditioners where air conditioning (AC) has historically never been needed. This surge in urban AC demand raises the terrifying threat of an urban accelerating heat loop that will make urban heating and climate change even worse.

If AC does increase as projected (from 1.6 billion units now to about 5.6 billion units globally by 2050),[3] this would increase warming by 0.5°C just from increased electricity use. But the climate impact would be much larger, as AC units use and leak greenhouse gasses that are potent accelerants of global warming. Large increases in air conditioners would also mean more AC heat dumped outside onto streets, potentially increasing city temperatures by an additional 2°F, further increasing air conditioning loads. And in multi-storied building, dumped heat from operating AC units preheats air drawn in by air conditioners units above, making them less efficient and in turn requiring more AC units operating at fuller capacity more of the time, in turn increasing heat rejection outside. Unfortunately, this self-reinforcing urban overheating is the future of business as usual.

To avoid this nightmare scenario, cities must make themselves cooler, and global warming must be slowed. The only strategy available that both cools cities and slows global warming is adoption of Smart Surfaces—surfaces that are reflective, porous and green (such as cool or green roofs or reflective parking lots) along with trees and solar photovoltaic panels (PV). It is therefore important to understand the potential and cost-effectiveness of Smart Surfaces for cooling cities and slowing global warming.

Our coalition of leading health, planning, architecture, city policy, energy, affordable housing, energy and other organizations called the Smart Surfaces Coalition is dedicated to supporting expanded adoption of Smart Surfaces globally. Prior studies of potential city-wide Smart Surfaces adoption by El Paso, Philadelphia and Washington DC demonstrated Smart Surfaces to be a cost-effective, city-wide strategy to address climate change mitigation and adaptation that would also improve equity and create jobs.

In this report, we have expanded the technical depth of analysis from these prior reports. We analyze and model in detail the economic costs and benefits, as well as temperature reduction impact, of one city—Baltimore—adopting Smart Surfaces.

With a population of 610,000, Baltimore is a mid-sized city located in an average urban climactic zone. Like most cities, Baltimore is experiencing increasingly hot summers and is suffering from the effects of climate change. Also like most cities, Baltimore's wealthier neighborhoods have more trees and are cooler in the summer than low-income neighborhoods and communities of color. Baltimore serves as a representative city where policies around mitigating heat and climate change can hold vital lessons for cities globally on how to survive and even thrive in a world characterized by climate change and increasingly extreme summer heat.

2.2 Baltimore's Future

Cities everywhere, including Baltimore, have a positive vision for their futures. In a range of reports, Baltimore has described a vision for its future that includes increased livability, enhanced water and air quality, environmental justice, increased employment, greater attractiveness for tourism, and reduced carbon emissions.

Like most cities, however, Baltimore has largely covered itself in dark, impervious surfaces, resulting in increased summer heat, higher energy bills, more flooding and pollution and large structural inequities—lower-income neighborhoods are often 10 degrees F hotter than wealthy green parts of the city. See Figure 2.2, below.

And as with most cities, the gap between Baltimore's aspirations and its reality is being widened by accelerating climate change and the rising frequency of severe heat and rain events. In 2018, the rapidly rising costs of climate change led Baltimore to file *Mayor and City Council of Baltimore v. BP P.L.C.*, a lawsuit against oil companies which asserts that:

> "Baltimore is already experiencing a climatic and meteorological shift towards winters and springs with more extreme precipitation events contrasted by hotter, dryer, and longer summers. These changes have led to increased property damage, economic injuries, and impacts to public health. The city must spend substantial funds to plan for and respond to these phenomena, and to mitigate their secondary and tertiary impacts. Compounding these environmental impacts are cascading social and economic impacts… Baltimore

is expected to experience a threefold increase in the average number of days exceeding 90 degrees by 2050."[4]

2.3 Smart Surfaces for Baltimore

As noted above, cities are on average 9°F hotter in the summer due to their dark, impervious surfaces, a phenomenon known as the Urban Heat Island (UHI) effect. Smart Surfaces—including reflective, porous and green surfaces, solar photovoltaics (PV), and trees—enable cities to manage and reduce excess heat, as well as manage increasingly severe rain events.

Adverse health and economic impacts from excess heat are multiple and complex. A major review in the Annual Review of Public Health notes that "heat exhaustion and reduced human performance are often overlooked in climate change health impact analysis."[5] The ways that excess heat hurts health, productivity and economic well-being are multiple and reinforcing, as summarized in Figure 2.2 below from the Annual Review of Public Health.[6]

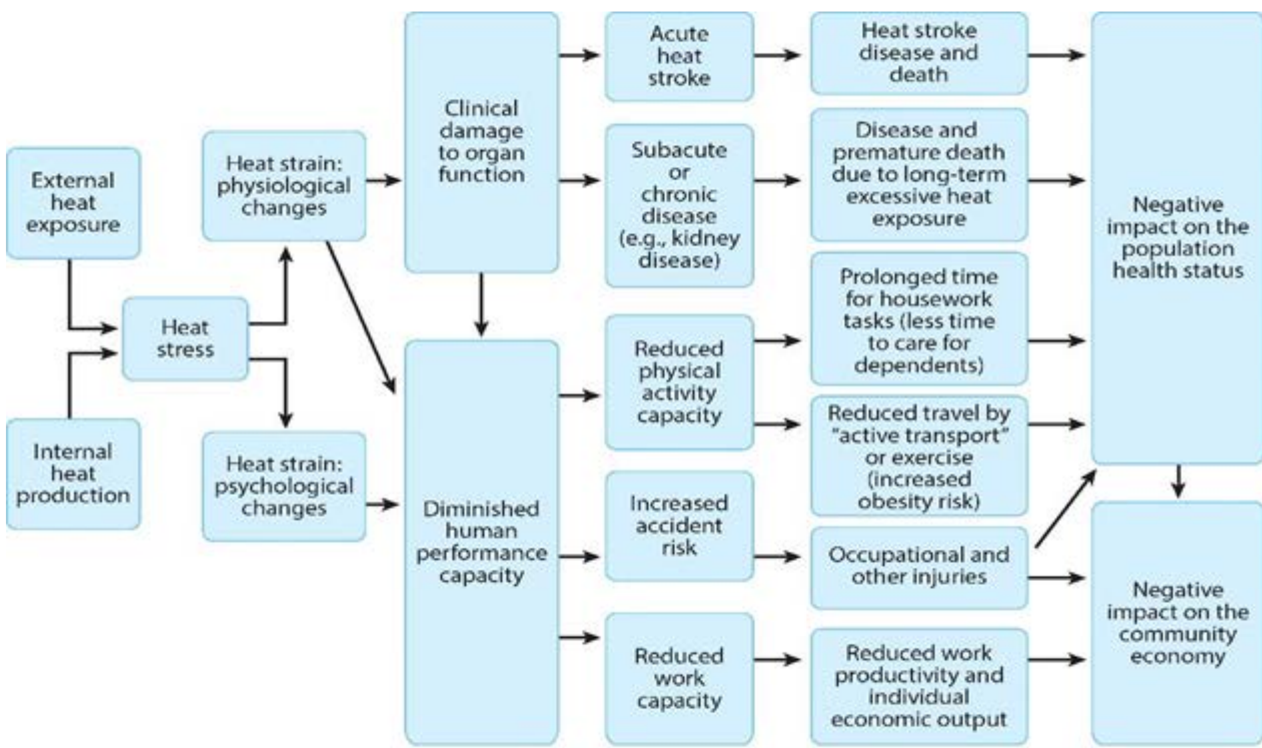

Figure 2.1. Heat and health impact pathway[7]

Shifting from dark, impervious surfaces to Smart Surfaces would measurably improve the quality of life in neighborhoods by making them cooler, greener, less polluted, and more shaded by trees—in turn enabling and encouraging more people to spend time outdoors. The increase in what the great urban activist and author Jane Jacobs calls "eyes on the street" is a fundamental measure and determinant of community strength, safety, and health. Positive impacts from more time spent outdoors include increased exercise, improved mental and physical health, stronger communities, reduced crime, and a range of other positive social and health-related outcomes. Many of these impacts are complex and difficult to quantify and therefore are typically ignored. As a result, the benefits of Smart Surfaces are grossly undercounted, so cities underinvest in Smart Surfaces in favor of lowest-first-cost, dark, impervious surfaces. The resulting costs in terms of human health and suffering are enormous.

This report by the Smart Surfaces Coalition answers the question: "How can Smart Surfaces help Baltimore—and any other city—cost-effectively secure a cooler, healthier, more productive, sustainable and equitable future despite climate change?"

The Smart Surfaces analysis detailed in the following chapters was conducted with the guidance of multiple Baltimore city agencies, officials, local non-profits, and neighborhood groups—as well as leading experts and partner organizations involved in the Smart Surfaces Coalition. These 45 Smart Surfaces Coalition partner organizations include the American Public Health Association (APHA), the American Institute of Architects (AIA), the National League of Cities (NLC), Habitat for Humanity (HFH) and the International Downtown Association (IDA). Our analysis demonstrates that Smart Surfaces can play a large role in enabling Baltimore to achieve its vision of becoming a healthier, more competitive, livable and equitable city. The benefits of Smart Surfaces adoption by Baltimore would outweigh the costs by a factor of more than 10 to 1.

2.4 Addressing Structural Inequality and Environmental Justice

In this report, we analyze the costs and benefits associated with Baltimore implementing a set of Smart Surface adoption targets. Existing Baltimore city goals used in setting Smart Surface adoption targets and analysis timeframes include the city's 2040 tree canopy goal and its 2030 emissions reduction goal.

Mapping and analysis of the costs and benefits of Smart Surfaces adoption was conducted city-wide as well as for three lower-income areas in Baltimore: Brooklyn-Curtis Bay, Cherry Hill, and Madison East End. These are predominantly communities of color and make up 5% of Baltimore by population and 8% of the city by area. Not coincidentally, these lower-income areas have tree coverage, ranging from 6% to 21%, well below the city-wide average of 29%, and far below the 40% tree coverage goal set by the city.[8]

Long-term underinvestment in trees and other Smart Surfaces in lower-income neighborhoods has resulted in higher summer temperatures, worse air quality, more health problems, and higher energy bills, both in these neighborhoods and city-wide. Like far too many cities, Baltimore exhibits a strong negative relationship between income and excess summer heat. This is environmental inequality at perhaps its most stark.

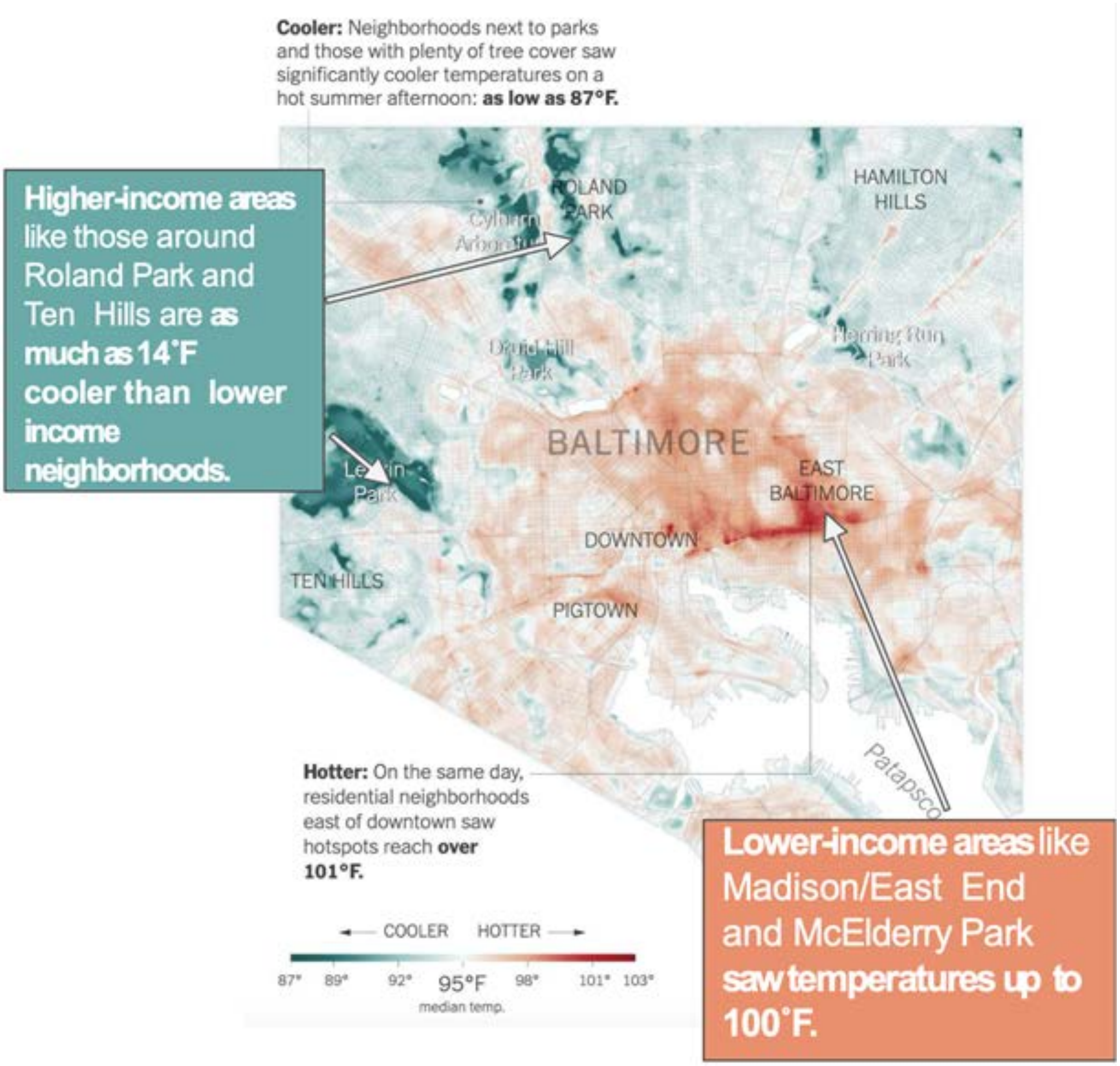

Figure 2.2. Heat map of Baltimore[9]

As illustrated above, lower-income areas such as Madison East End can be up to 14° F hotter in the summer than wealthy, predominantly white neighborhoods such as Roland Park. This huge difference reflects decades of city underinvestment in Smart Surfaces in lower-income neighborhoods compared with tree-lined wealthy neighborhoods (although all the city's residents suffer from the Urban Heat Island effect and excess summer heat).

The growing health risks to Baltimore are described and documented in an 8-part series called "Code Red."[10] An urban studies expert quoted in the documentary states:

> "Policies like redlining—a practice, beginning in the 1930s and banned by the Fair Housing Act in 1968, in which neighborhoods were marked high risk for mortgage lenders in large part based on their racial makeup—forced people of color into less desirable areas. In Baltimore, the city's hottest neighborhoods, many of which are predominantly African American, still line up fairly consistently with the neighborhoods marked "hazardous" on a 1937 map created by the Home Owners' Loan Corp."

Baltimore's 2019 Sustainability Plan affirms the above: "Baltimore's history of deliberate racial segregation has positioned people in unhealthy and inequitable circumstances, deeply affecting the well-being of many of our residents—as well as the social, economic, and environmental well-being of our city."

This on-the-ground environmental inequality stands in stark opposition to Baltimore's future vision for itself as an equitable city. It is also *entirely unnecessary.* As the following chapters document, redressing this gross structural inequality through broad adoption of Smart Surfaces—especially in lower income neighborhoods—would create financial benefits that far exceed the costs. City-wide adoption of Smart Surfaces is an overdue investment necessary for Baltimore to protect itself from accelerating climate change—and become the healthier, more resilient, and more just city it seeks to be.

2.5 Costs and Benefits of Adopting of Smart Surfaces in Baltimore

Baltimore has developed important policies to improve its quality of life. For example, it is one of the few substantial U.S. cities to increase its tree coverage over the last decade, from 28% to 29%, at a time when tree coverage in most cities in the U.S. was dropping. Adopting Smart Surfaces would help confirm Baltimore as a national urban policy leader around environmental, livability, and environmental justice issues.

2.5.1 Summary Cost-Benefit Analysis Results: 20-year Adoption Scenario

In this work for Baltimore (and funded by the Abell Foundation), the Smart Surfaces Coalition developed a customized analytic tool for the city government of Baltimore to quantify the costs and benefits of Baltimore-wide Smart Surfaces adoption. As documented in this report, the net present value of adopting Smart Surfaces is substantial. City-wide adoption of 10 Smart Surfaces strategies would yield a net present value of $13.5 billion, equal to $21,000 per resident.

Table 2.1 below summarizes the Smart Surfaces coverage and costs and benefits for deployment of 10 Smart Surface strategies over a 20-year implementation period. Smart Surfaces modeled for adoption span reflective parking lots to green roofs, increased solar PV and more trees. These are all proven, widely available strategies. Cost-effectiveness of these 10 strategies varies, but overall, city-wide adoption of these targets is compelling. These strategies would have a net present value of more than $13 billion and would reduce peak Baltimore downtown summer temperature in the hottest central areas by 4.3°F below what it would otherwise be.

BALTIMORE: 20-YEAR ADOPTION SCENARIO IMPACTS CONSOLIDATED SUMMARY							
Smart Surface	Target	Total Cost (millions, 2020$)	Benefits (millions, 2020$)	NPV (millions, 2020$, 2% Real Discount Rate)	Benefit : Cost Ratio	Employment (job years)	Peak Summer Temp Reduction Estimate [viii]
Cool Roofs [i]	Low-slope roof area: 80% Steep-slope roof area: 20%	$(112)	$862	$541	7.7	1,904	2.4 °F
Bioswale-managed Roof[ii]	Low-slope roof area: 20%	$(99)	$549	$ 301	5.5	1,391	not included
Green Roofs	Low-slope roof area: 2%	$(81)	$158	$46	2.0	1,300	not included
Solar PV[iii]	Low-slope roof area: 40% Steep-slope roof area: 20%	$(474)	$10,604	$6,704	22.4	61,042	not included
Reflective Parking [iv]	Parking area: 50%	$(44)	$103	$43	2.3	746	0.5 °F
Permeable Parking[iv]	Parking area: 5%	$48	$113	$110	14.4		not included
Bioswale-managed parking	Parking area: 20%	$(100)	$578	$F321	5.8	1,698	not included
Reflective Roads [iv]	Road area: 15%	$(10)	$27	$15	2.9	162	0.2 °F
Permeable Sidewalks	Sidewalk area: 5%	$(49)	$200	$99	4.1	539	not included
Trees[v]	City land area: 40%	$(499)	$1,330	$560	2.7	9,982	1.2 °F

[i] Reflective surfaces have a large impact on city temperature. Regional temperature reduction benefits from reflective surfaces may be large but not included in the quantified benefits due to lack of input data.

[ii] Bioswales/bioretention can manage stormwater runoff from adjacent roofs or parking lots. A small area of bioswale or tree trench can manage the water runoff of a much larger hard surface.

[iii] Solar PV assumed to be financed by a third party, paid back from first 10 years of clean power generation. Baltimore system owners will not receive an electricity value benefit until year 11 after installation.

[iv] Permeable parking only applied when a parking lot is ripped out and replaced, at which time it costs less to make the area permeable (grid-grass or grid-gravel) than to construct a new asphalt parking surface. Total Cost in this case is therefore a positive number, reflecting a first cost savings.

[v] Temperature reduction from albedo measured between 1-4pm mid-Summer in downtown/central area of city. Temperature reduction from increased tree canopy is from radiative shading only. It

TOTAL	$(1,420)	$14,524	$8,739	10 : 1	78,765	4.3 °F

Table 2.1. Consolidated Smart Surface Cost Benefit Analysis Results Summary: Baltimore 20-year Adoption Scenario (30-year Analysis) (Source: Smart Surfaces Coalition)

(Note: Above costs and benefits do not sum to net benefits indicated because they accrue over a 30-year timeframe and are discounted to a present value using a 2% discount rate. Benefits are assumed to extend for 10 years beyond their period of implementation.)

Adoption of Smart Surfaces city-wide would have a more than 10:1 benefit to cost ratio. Benefits are discussed in detail in the report and include lower energy costs, lower cost of water treatment and decreased flooding. Lower summer temperature and improved air quality would reduce health costs and risks of heat death. Smart Surfaces adoption also creates good local jobs. Avoiding summer excess heat would protect the large and jobs-intensive tourism industry, in turn contributing to increased economic activity and city revenue.

> ***Chris Riehl,*** *President of the Baltimore Tourism Association:*
>
> "The Smart Surfaces Coalition has the potential to greatly improve conditions in low-income communities by reducing urban temperatures, supplying jobs, and investing resources in underserved areas. Improving these conditions will undoubtedly have a ripple effect both for the local economy and tourism as a whole."

2.5.1.1 Employment Impact Summary Results: 20-year Adoption Scenario

The job creation impact varies by type of Smart Surface, but overall net job creation impact would be large, as summarized in Table 2.2, below.

Smart Surfaces adoption would create 78,700 job years over 30 years with 72,600 job years created during the 20-year adoption period, equal to 3,600 full-time jobs during the two decades of Smart Surfaces deployment. Job impact benefits could be even larger for the tourism sector, which is a major employer for Baltimore and Maryland and is under increasing threat from rising summer heat.

2.5.1.2 Dealing with the Threat to Baltimore Tourism and Jobs

As noted above, Baltimore is already suffering from excess summer heat, putting its large summer tourism industry at risk. Tourism is a major industry for Maryland and

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doesn't include temperature reduction from increased evapotranspiration or reduced heat ejection into the city by air conditioners due to lower ambient temperature or from shading of buildings by trees. These are substantial additional heat reduction benefits from expanding tree coverage, meaning that cooling benefits from trees are underestimated in this model.

Baltimore and a major source of jobs for both. Tourism accounts for 6.2% of total employment in Maryland (as of 2016), equal to over $1000 per household.[11] The single largest tourism draw in Maryland is Baltimore.

Employment Impact: 20-year Adoption Scenario (30-year Analysis) *Dollar values in 1,000s of dollars*										
Surface:	**Cool Roofs**	**Reflective Parking**	**Reflective Roads**	**Bioswale-managed Parking**	**Urban Trees**	**Green Roofs**	**Solar PV***	**Permeable Sidewalks**	**Bioswale-managed Roofs**	**Total Job Years**
Cost & Employment Assumptions										
Total Cost to Meet Surface Targets (30-yrs.)	$(112,022)	$(43,881)	$(9,520)	$(99,898)	$(499,089)	$(81,248)	$(5,549,233)	$(49,028)	$(99,392)	
Average Annual Salary + Benefits	$(50)	$(50)	$(50)	$(50)	$(50)	$(50)	$(50)	$(50)	$(50)	
Job Years from Direct Installation, Operations & Maintenance, and Additional Replacements										
Labor Intensity (% of total cost)	80%	80%	80%	80%	50%	50%	40%	40%	60%	
Labor Cost	$(89,618)	$(35,105)	$(7,616)	$(79,919)	$(249,545)	$(40,624)	$(2,219,693)	$(19,611)	$(59,635)	***56,027***
Job Years Created	*1,792*	*702*	*152*	*1,598*	*4,991*	*812*	*44,394*	*392*	*1,193*	
Job Years from Direct Materials										
Labor Intensity (% of total cost)	5%	5%	5%	5%	50%	30%	15%	15%	10%	
Labor Cost	$(5,601)	$(2,194)	$(476)	$(4,995)	$(249,545)	$(24,374)	$(832,385)	$(7,354)	$(9,939)	***22,737***
Job Years Created	*112*	*44*	*10*	*100*	*4,991*	*487*	*16,648*	*147*	*199*	
Total Job Years Created										
Total Job Years Created	**1,904**	**746**	**162**	**1,698**	**9,982**	**1,300**	**61,042**	**539**	**1,391**	**78,765**

Table 2.2. Employment Impact Summary: Baltimore 20-year Adoption Scenario (30-year Analysis) - Job Years Created (Source: Smart Surfaces Coalition)

Tourism is most common during the summer months due to school holidays and family travel but, as a *US News and World Report* article warned, “soaring temperatures” are a factor to consider while planning a trip to Baltimore in the summer months.[12] On our climate’s current course, Baltimore’s summer heat is projected to put the city far into an unfavorable tourism comfort range, according to the U. S. Climatic Tourism Index (see Figure 2.4 below). The combination of higher average heat, greater frequency of extreme heat, worse air pollution (including smog), and more severe rain and flooding events will make Baltimore much less attractive for tourists in the summer—unless the city adopts strategies to effectively cool the city and its neighborhoods. Smart Surfaces is the only viable strategy available to achieve city-wide or neighborhood-wide cooling.

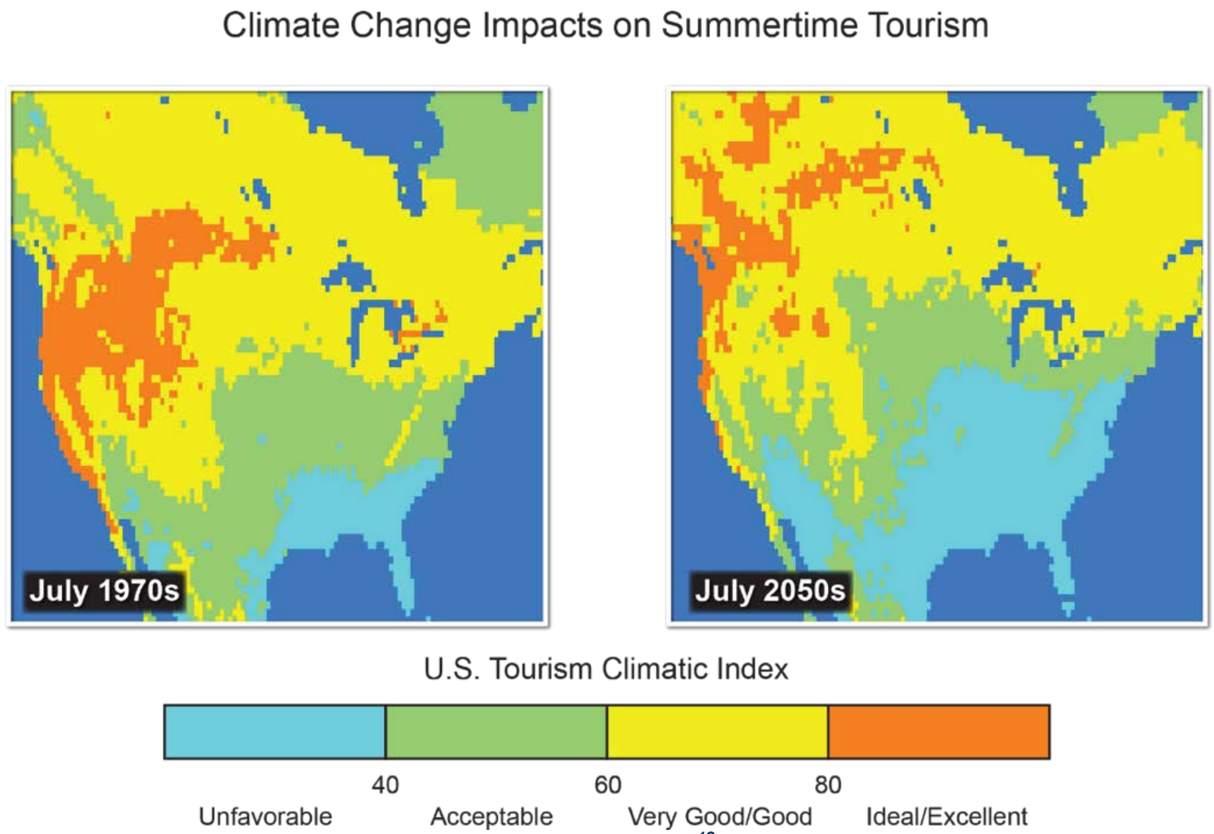

Figure 2.4 Climate Change impacts on Summer Tourism[13]

Implementation of Smart Surfaces city-wide can cut summer peak temperatures in downtown Baltimore by more than 4 degrees Fahrenheit below what it would otherwise be. *At the end of the 30-year analysis period, Baltimore can be cooler than it is today despite rising global and regional temperatures*. This would not only protect human health; it would protect Baltimore's critical tourism industry and its large economic and employment benefits.

Ren Englum, *Group Leader for the Baltimore Chapter of Citizen's Climate Lobby:*

"The Smart Surfaces Coalition illustrates the transformative potential of well-designed climate solutions. When tackled strategically, we can reduce carbon emissions and save money while also improving the livability and enjoyability of Baltimore City. We are especially hopeful that if implemented, the recommendations by Smart Surfaces Coalition will benefit our most impoverished and underserved communities by reducing energy costs, lowering summer temperatures and cutting down on air pollution. We all win with this plan and hope to help see it implemented fully."

Visitor spending in the Baltimore region sustained 86,414 total jobs directly and indirectly in 2018.[14] At least $4.3 billion in tourism-driven revenue was generated in Baltimore in June, July and August of 2018, along with $171 million in revenue for Maryland and $122 million in tourism tax revenue accruing to Baltimore. Given the threat to tourism from heat today, it can reasonably be assumed that the tripling of extremely hot days would substantially reduce tourism—although it is difficult to calculate how large a reduction would occur. Recent modeling of tourism impact in other areas from rising temperature suggests potential tourism losses in the 10% to 20% range, with potential estimated maximum tourism losses of up to 50%.[15]

Our analysis indicates that due to rising city summer temperatures, Baltimore can expect at least a 5%-20% loss of summer tourism over 30 years. These ranges are discussed in the tourism section of the report. Smart Surfaces adoption can cool Baltimore's downtown by more than 4°F over this period, more than offsetting projected warming. In other words, Smart Surfaces adoption would allow Baltimore to become cooler as the world is getting warmer. This would avoid all potential tourism losses from projected rising heat. If a potential 20% summer tourism is avoided, NPV of city-wide adoption of Smart Surfaces would rise to $24 billion with a benefit-cost ratio of over 28:1. This reflects the enormous risk to Baltimore's critical tourism industry from rising summer temperatures. In this report, we assume the lowest level of loss to summer tourism—5%. See Table 2.3 below.

20-Year Adoption Scenario	Total Cost (millions, 2020$)	Total Benefit (millions, 2020$)	NPV (2% real discount) (millions, 2020$)	Benefit-Cost Ratio	Job Years Created/Saved
Total – Before Tourism Benefit (see table 2.1)	**$(1,420)**	**$14,524**	**$8,739**	**10 : 1**	**78,765**
5% Avoided Tourism Loss		$ 6,420	$4,793		51,848
Total with 5%Tourism Benefit	**$(1,420)**	**$20,944**	**$13,532**	**15 : 1**	**130,613**

10% Avoided Tourism Loss		$12,840	$9,586		103,697
Total with 10% Tourism Benefit	**$(1,420)**	**$27,364**	**$18,325**	**19 : 1**	**182,461**
20% Avoided Tourism Loss		$25,680	$19,171		207,394
Total with 20% Tourism Benefit	**$(1,420)**	**$40,204**	**$23,964**	**28 : 1**	**286,158**

Table 2.3. Summary Analysis of Baltimore 20-Year Adoption Scenario (see table 2.1 for subtotal results by surface) with Avoided Tourism Losses of 5%, 10%, and 20% over 30 years (dollar values in millions of 2020 dollars) (Source: Smart Surfaces Coalition)

Adoption of Smart Surfaces would allow Baltimore summer temperatures to drop while the world gets hotter. A cooler Baltimore would be more attractive to tourists, especially compared with alternative tourist destinations that are getting hotter. Instead of going north to Boston to escape the summer heat, families from Virginia, Pennsylvania, or New Jersey might instead come to a cooling Baltimore for summer vacations.

Assuming the lowest level of avoided summer tourism losses of 5%, avoided tourism-related summer losses would be several thousand jobs. This would increase the positive jobs impact due to installing Smart Surfaces to about 5,300 full-time jobs in the 20-years during adoption, equal to about 3% of Baltimore's total labor force. Smart Surfaces is an important investment for Baltimore employment.

2.6 Smart Surfaces: Urgently Necessary

Baltimore's vision for its future includes better livability, enhanced water and air quality, environmental justice, increased employment, greater attractiveness for tourism, expansion of good jobs and reducing its contribution to global warming. Smart Surfaces can play a major role in enabling Baltimore to achieve these multiple objectives cost-effectively.

Smart Surfaces can mitigate rapidly mounting climate risks, thereby protecting Baltimore's economy. Smart Surfaces are well-proven and widely available solutions, and if deployed city-wide would make Baltimore cooler, more livable and financially stronger despite climate change. In contrast, business as usual (dark, impervious surfaces) is a far riskier and much more financially fraught pathway. All in all, the benefit-cost ratio documented for adoption of Smart Surfaces by Baltimore is more than 10 to 1, making this one of the few major climate mitigation strategies available to cities that more than pays for itself.

There is a compelling financial, ethical, and risk case for rapid adoption of Smart Surface solutions city-wide as the standard, baseline city policy.

2.7 Applicability to Other Cities

In this report, we analyze in detail the costs and benefits and temperature reduction impact of one city—Baltimore—adopting Smart Surfaces. With a population of 610,000, Baltimore is an average-sized city, and it is located in a populous and central urban climactic zone. These factors make Baltimore a representative city where successful policies around mitigating heat and climate change can hold important lessons for cities globally.

This report builds on and extends similar findings of impact and cost-effectiveness from the Delivering Urban Resilience — Smart Surfaces Coalition city-wide Smart Surfaces adoption analysis of/with El Paso, Philadelphia, and Washington DC. As with the other cities studies, Smart Surfaces adoption by Baltimore would strengthen the economy, expand employment, enhance urban health, reduce energy bills, and make Baltimore far more resilient in the face of climate change — protecting Baltimore's access to low-cost bond markets.[16] It would also protect and enhance city credit ratings, as documented in the *Risk & Insurance* publication, "Helping Cities Manage Climate Change: Smart Surfaces, Credit Ratings and Risk Management — Smart Surfaces Coalition." Unlike the prior reports, this report also quantifies city-wide adoption of Smart Surfaces impact on city cooling.

The detailed Smart Surfaces cost-benefit analysis undertaken in four major disparate cities consistently demonstrate that Smart Surfaces is a highly cost-effective strategy for cities across the U.S. and globally that are concerned about worsening heat, climate, health, equity, and/or resilience risks.

Under current projections, many cities will experience a tripling of extremely hot summer days by 2050. Projected warming will make many cities unlivable (outside air conditioned space) during summer months, with rapidly expanded air conditioning further accelerating global warming. To avoid this nightmare scenario, cities must be made cooler and global warming must be slowed. The only policy that does both these things cost-effectively is urban adoption Smart Surfaces—reflective, porous and green surfaces (such as reflective or green roofs or reflective parking lots) along with trees and solar PV.

2.8 Conclusion

Bill Updike, *Former Chief of Green Building & Climate branch at DC Department of Energy & Environment:*

"The Smart Surfaces cost-benefit analysis completed for Washington, DC provided a powerful and persuasive new way for the city to understand and manage its surfaces in order to address the urban heat island effect and mitigate the effects of climate change. The report and its findings have been influential within DC in enabling the city to expand Smart Surface requirements for roofs, roads, and surfaces generally."

Dr. Georges C. Benjamin, M.D., *Executive Director of the American Public Health Association, and former Secretary of Health for Maryland and former Deputy Secretary for Public Health Services for Maryland:*

"Climate change is the greatest public health crisis of our lifetime and is an especially grave and immediate threat to urban communities, particularly lower income communities, which are at a higher risk of heat related injury. The Smart Surfaces Coalition offers a transformative and cost-effective way to slow global warming and make cities cooler and healthier. Smart Surfaces are also an important strategy to mitigate the health risk from extreme heat in a cost-effective way — it must be adequately funded, rapidly implemented and brought to scale."

Baltimore can reduce its summer temperature as the world warms, and can mitigate flooding even as the number of extreme rain events rise. In so doing Baltimore can build on its already strong water management and tree planting policies to enhance livability, support economic growth, protect its vital tourism industry and become more equitable and cooler. Many of the physical inequalities that characterize and disadvantage low-income areas can be redressed with Smart Surfaces—and as demonstrated in this report—would provide large net financial returns to all its citizens.

Guided by Baltimore's vision for its future, and with the support of its agencies and NGOs, this report maps out and quantifies a pathway to a healthier, more livable, equitable and prosperous future. But this requires that Baltimore make design decisions for its surfaces differently, shifting from lowest first cost, dark, impervious surfaces to lower total cost reflective, porous, and green Smart Surfaces.

By deliberately reshaping all its surfaces to better manage its sun and rain, Baltimore can help ensure that it achieves its health, climate, equity, sustainability, and financial objectives, ensuring it is an increasingly healthy, livable and vibrant city for coming generations—and a model for other cities.

3 Introduction

In a range of surveys, studies and plans, including the 2019 Baltimore Sustainability Plan, Baltimore has laid out a vision for its future that includes increased livability, enhanced water and air quality, environmental justice, increased employment, reduced contribution to global warming, greater attractiveness for tourism and expansion of good local jobs. The Abell Foundation funded the Smart Surfaces Coalition to undertake a detailed cost-benefit analysis of the potential for Baltimore to achieve a range of quality of life and environmental objectives.

This report starts with the set of quality of life, economic, health and environmental and equity objectives that Baltimore identified as core objectives for itself, and outlines how Smart Surfaces can help Baltimore achieve these objectives cost-effectively. By deliberately changing its surfaces, Baltimore can reshape how it manages sun and rain and go a long way to achieving its objectives.

The City of Baltimore explains in the 2018 lawsuit *Mayor and City Council of Baltimore v. BP P.L.C. that,* “Baltimore is already experiencing a climatic and meteorological shift towards winters and springs with more extreme precipitation events contrasted by hotter, dryer, and longer summers. These changes have led to increased property damage, economic injuries, and impacts to public health. The City must spend substantial funds to plan for and respond to these phenomena, and to mitigate their secondary and tertiary impacts. Compounding these environmental impacts are cascading social and economic impacts, which cause injuries to the City that will arise out of localized climate change-related conditions.”[17]

In this report, we undertake a city-wide cost-benefit analysis of adopting Smart Surfaces in Baltimore. We also quantify the Smart Surfaces costs and benefits for three low-income areas in Baltimore: Brooklyn-Curtis Bay, Cherry Hill, and Madison East End. These neighborhoods are substantial, representing about 5 percent of Baltimore by population and 8 percent of the city by area. Not coincidentally, these low-income areas have less tree coverage than Baltimore as a whole. Cherry Hill’s 21 percent, Brooklyn-Curtis Bay’s 15 percent, and Madison East End’s 6 percent tree coverage are all significantly less than the city-wide figure of 28 percent.[18] Underinvestment in trees and green solutions in urban low-income areas results in higher summer temperatures, worse air quality, more health problems, and higher energy bills.

This structural inequality is inimical to Baltimore’s future vision for itself and constitutes a pervasive and ongoing environmental injustice, with large costs for the city as a whole. It is also entirely unnecessary. As this report documents and details, redressing this gross structural inequality through broad adoption of Smart Surfaces would provide financial benefits that far exceed the costs.

Baltimore has already made major investments and shifts in policies to improve its citizen's quality of life, such as expanding city tree coverage. Adopting Smart Surfaces would strengthen Baltimore's position as a national leader on environmental, quality of life and environmental justice issues.

This report demonstrates that the growing city-wide risks from extreme heat and weather events driven by climate change could be largely offset by Baltimore's adoption of Smart Surface technologies. Many of the physical inequalities that characterize and disadvantage low-income areas can also be greatly improved with Smart Surfaces and would provide substantial net financial returns to the city as a whole. In the Smart Surfaces adoption scenarios modeled, net financial benefits exceed costs both city-wide and locally in the lower-income neighborhoods. Baltimore can achieve billions of dollars in net financial benefits at a city level. These net positive financial returns constitute a strong financial, resilience and public policy case for rapid adoption of Smart Surface solutions city-wide as standard, baseline policy for Baltimore.

As detailed and documented in this report, the net present value of adopting Smart Surfaces in Baltimore is estimated to be $8.7 billion for the '20-year scenario' without tourism benefits, and $13.5 billion with tourism benefits included.

The Smart Surface Coalition has developed a cost-benefit analytic engine to quantify the costs and benefits of comprehensive Smart Surface adoption in Baltimore. While this customized cost-benefit tool was developed for and will just be provided to Baltimore officials and its Office of Sustainability, this report provides findings and analysis on the full range of Smart Surface technologies and provides insight into many of their benefits. The findings section also details the main findings from the Smart Surface Coalition's cost-benefit analysis.

Most impacts excluded from cost-benefit calculations (due to limited data and/or peer-reviewed studies, etc.) are benefits, so this report underestimates the value of Smart Surfaces.

Justin Bowers, *Baltimore Tree Trust, Assistant Director:*

"The Smart Surfaces Coalition is a powerful new organization that brings a greatly needed ability to quantify and recognize a much more complete set of benefits. This is essential if we are to shape Baltimore—and all our cities to be more livable, equitable and healthy."

3.1 About the Smart Surfaces Coalition

The Smart Surfaces Coalition is a 501(c)(3) non-profit organization that engages more than 40 partner organizations across many sectors, including the National League of Cities, the American Planning Association, the American Public Health Association, Habitat for Humanity, AIA, and the International Downtown Association, around a single mission: transforming and making more livable America's 18,000 cities and towns while combating climate change. Smart Surface solutions include cool and green roofing, porous and reflective pavements, urban trees, solar PV and integrated use of these surfaces (e.g., solar on reflective roof or on a green roof). The Smart Surfaces Coalition and Coalition partners have developed an integrated strategy to accelerate tenfold the urban adoption of Smart Surfaces to mitigate climate change, expand employment, advance equity, and reduce city temperature, air pollution and flooding, with substantial positive net present value to cities. The Coalition has also developed an analytic engine that quantifies the full range of costs and benefits of Smart Surface adoption, in order to enable more informed and cost-effective surfacing decisions.

3.2 Project Background

Supported by funding from the Abell Foundation, the Smart Surfaces Coalition developed a Baltimore-specific online cost-benefit model of the city's potential to achieve a broad range of financial and other benefits by adoption of Smart Surfaces. This analytic engine is dynamic, meaning that it can run multiple scenarios and answer "what if" questions such as: What if Baltimore increases tree coverage by 10%? Or, what are the cost and benefits of shifting to green and reflective roofs and parking lots? Essentially, it is a dynamic cost-benefit calculating engine customized for Baltimore that allows the city to model and understand the costs and benefits of a broad range of sustainable infrastructure investment options. The analytic tool and this corresponding report are intended to allow Baltimore to better understand its surfaces design options and to enable more informed and effective city policy.

Cities including Baltimore have not had the tools to-date to make informed decisions or evaluate the cost-effectiveness of deploying Smart Surfaces. Probably the best US health valuation model is EPA's BenMAP—but this deals with only a subset of Baltimore's health issues. We built on BenMAP to quantify a more comprehensive set of health costs and benefits. Doing so involved addressing and solving some benefit estimation gaps. These include: estimating the indirect energy benefit of green roofs; developing simple, yet robust temperature-based methods to estimate city ozone concentration reductions; valuing health benefits of PM2.5 emissions reductions due to installing cool roofs, green roofs, reflective pavements, and urban trees; valuing heat-related mortality reductions due to cool roofs, green roofs, reflective pavements, and urban trees; and combining new methods and existing methods to estimate costs and benefits at the neighborhood level.

The vast majority of this work has been undertaken by the Smart Surfaces Coalition, with subcontracted work around data and work with low-income neighborhoods and city agencies. Also supporting on data collection and early work exposure during the Baltimore "data day" was the Baltimore Neighborhood Indicators Alliance/the University of Baltimore.

Prior Smart Surfaces technical and cost-benefits analysis demonstrated that large cities such as Philadelphia and El Paso can save billions of dollars over several decades through investing in city-wide adoption of Smart Surfaces, and these reports inform this document.

4 Overview

4.1 What are Smart Surfaces

This report assembles and analyzes a set of technologies that are applied to the surfaces of cities, including roofs, roads, parking lots, sidewalks, etc., and describes these collectively with a relatively new term: “Smart Surfaces.” This term is used to describe a set of surfaces that can deliver a range of measurable, albeit sometimes complex, benefits and enhancements relative to conventional urban surfaces.

4.2 Why use Smart Surfaces

Cities suffer from worse air pollution and higher summer temperatures than surrounding rural areas.[19] The last decades have seen some cities begin to adopt several surface solutions that can reduce these environmental, health, and energy costs. These Smart Surface solutions include reflective (cool) roofs to cool the urban environment and decrease energy bills, green (vegetated) roofs to reduce stormwater runoff, cool the urban environment, and decrease energy bills; and rooftop solar photovoltaics (PV) to generate electricity and reduce air pollution. Urban trees, though commonly seen as a way to beautify cities, are increasingly recognized for their ability to help manage stormwater, cool the urban environment, reduce pollution, and decrease energy bills. Cool (reflective) sidewalks and pavements can also be used to cool Baltimore’s already hot summers.

Figure 4.1. Images of Smart Surfaces (from left to right and top to bottom: cool roofs, solar PV, permeable pavements, green roofs, urban trees, and reflective pavements)

These solutions have been deployed in pilots or in standalone programs by dozens of cities or towns (out of America’s 18,000 cities and towns). Often this work has been with developers, affordable housing organizations, or others to address a specific problem, such as reducing the cost of stormwater treatment. However, these initiatives tend to be standalone or pilot projects and commonly involve only one Smart Surface. Further, these programs often do not in the long-term change how cities make surface decisions. City infrastructure decisions are made by city departments that lack the expertise, authority or tools to quantify and understand critical costs and benefits or make decision based on them. *The impact categories*

that are as a rule ignored by cities in designing their surfaces include city heat, air and water pollution and quality, human health, equity, employment, livability, impact on tourism, city bond rating and climate. As a result, American cities (and cities globally) are covered with dark impervious surfaces that make then hotter, less healthy, less livable and less competitive.

The Smart Surfaces Coalition was developed to redress this systematic failure. The Coalition does so through three simultaneous integrated steps with a broad and influential set of engaged partners. These 3 steps are:

- Organize surface solutions in a single framework to enable city-wide analysis and adoption
- Build tools for cities to quantify the full costs and benefits of all surface options, model design scenarios, and make fully informed city-wide surface design decisions
- Directly support cities through integrated training, guidance, and analysis through a Coalition of leading organizations that cities already trust

Ren Englum, *Group Leader for the Baltimore Chapter of Citizen's Climate Lobby:*

"The Smart Surfaces Coalition illustrates the transformative potential of well-designed climate solutions. When tackled strategically, we can reduce carbon emissions and save money while also improving the livability and enjoyability of Baltimore City. We are especially hopeful that if implemented, the recommendations by Smart Surfaces Coalition will benefit our most impoverished and underserved communities by reducing energy costs, lowering summer temperatures and cutting down on air pollution. We all win with this plan and hope to help see it implemented fully."

4.3 Why focus on lower-income neighborhoods?

4.3.1 Urban heat island effect

Due to use of low first cost dark, impervious surfaces as the standard surfacing solutions, Baltimore and other cities experience what is called the urban heat island (UHI) effect. The UHI effect results in substantially higher summer temperatures—about 9 degrees F—and worse air pollution in cities than the surrounding suburban and rural areas. Low-income areas tend to have lower coverage of greenery and higher coverage of dark and impervious surfaces. For example, two of Baltimore's low-income neighborhoods, Brooklyn-Curtis Bay at 15 percent and Madison East End at 6 percent, have tree coverage far below the city-wide figure of 29 percent. As a result, urban low-income residents suffer disproportionately from the urban heat island effect.[20]

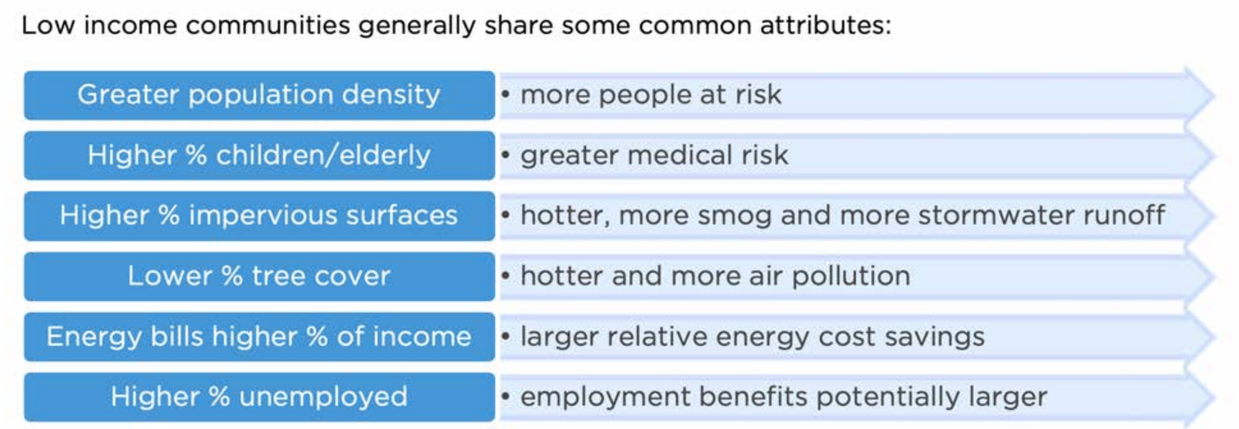

Figure 4.2. Greater risk and larger potential benefit in low-income areas. Source: SSC/Capital E

The combination of impervious surfaces, anthropogenic climate change, and the scarcity of heat-ameliorating features such as trees and reflective surfaces results in increasingly dangerous urban summer temperatures.[21] Asphalt in particular has very high surface temperature, heat storage potential, and heat emission capacity relative to other surfaces.[22] These elements contribute to high and rising urban temperatures and hurt lower-income neighborhoods disproportionately.[23] Heat-related mortality and heat-related distress calls are concentrated in low-income neighborhoods, which in Baltimore tend to be communities predominantly of color.[24]

A study conducted by the University of Maryland and Portland State University highlights the inequitable heat distribution between lower-income and high-income neighborhoods. The study found that formerly redlined areas relative to their non-redlined neighborhoods vary in land surface temperature by as much as 7°C.[25] Below is a mapping of Baltimore by an SSC partner that demonstrates the strong inverse correlation between income and temperature.

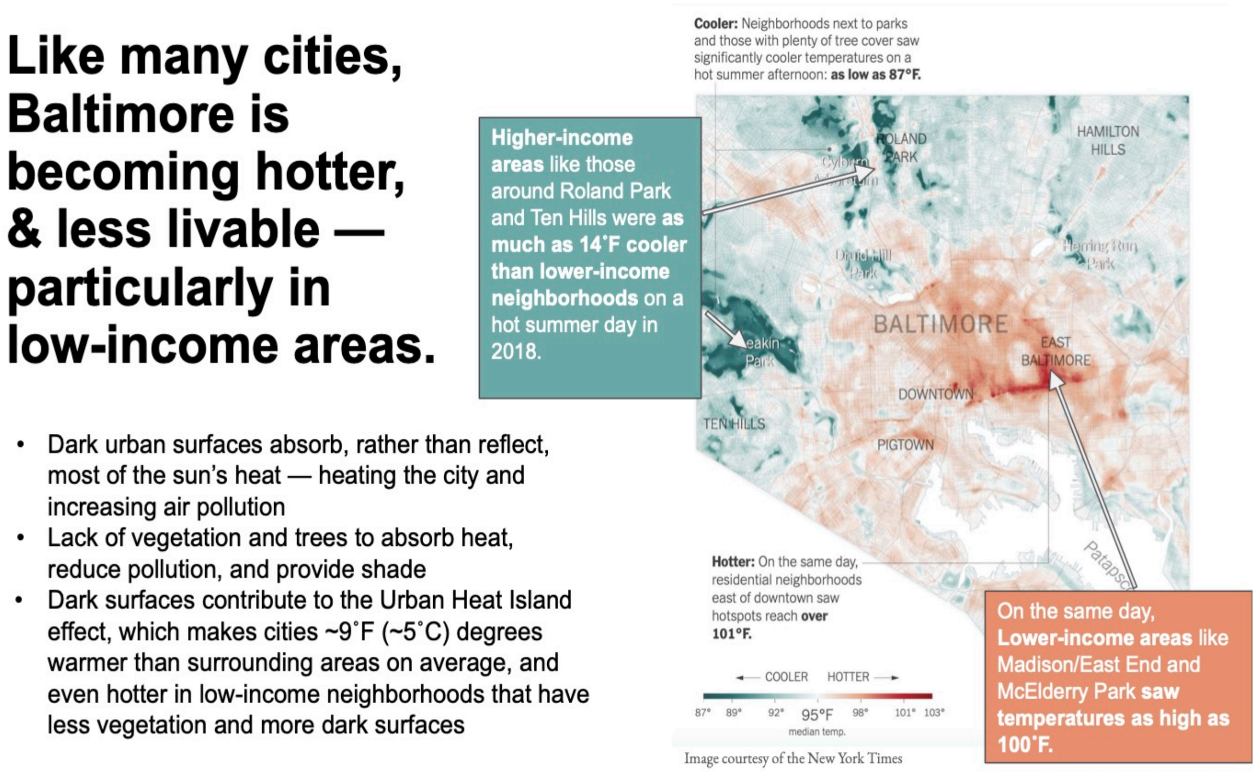

Figure 4.3. Higher heat in lower income areas in Baltimore. Source: SSC/New York Times[26]

4.3.2 Health

In *Mayor and City Council of Baltimore v. BP P.L.C.*, Baltimore states that "the City has incurred and will continue to incur expenses in planning and preparing for, and treating, the public health impacts associated with anthropogenic global warming including, but not limited to, impacts associated with extreme weather, extreme heat, decreased air quality, and vector-borne illnesses."[27] The damage and cost of increased temperature and air pollution are particularly acute for urban low-income areas. The publication Environmental Health Perspectives has noted that, "Substantial scientific evidence gained in the past decade has shown that various aspects of the built environment can have profound, directly measurable effects on both physical and mental health outcomes, particularly adding to the burden of illness among ethnic minority populations and low-income communities."[28] Increased green space and gardens has been demonstrated to have a positive correlation with reductions in asthma hospitalization.[29] Healthcare costs pose a significantly larger financial burden on low-income urban residents than higher-income residents. For example, excess heat and poor air quality in low-income areas increase emergency room visits by low-income residents, some of whom lack insurance, creating a burden of large non-reimbursed hospital costs.[30]

According to the City of Baltimore in *Mayor and City Council of Baltimore v. BP, P.L.C.*, in addition to rising heat-related mortality and morbidity and increased pollution, "the warming climate system will create disease-related public health impacts in Baltimore, including but not limited to, increased incidence of emerging and vector-borne diseases with migration of animal and insect disease vectors; physical and mental health impacts associated with severe weather events, such as flooding, when they cause population dislocation and infrastructure loss; exacerbation of existing respiratory disease, cardiovascular disease, and stroke as a result of heatwaves and increased average temperature; and respiratory distress, and exacerbation of existing disease. Public health impacts of these climatological changes are likely to be disproportionately borne by communities made vulnerable by their geographic location, and by racial and income disparities."[31]

Smart Surfaces are the only viable strategy available to reduce or even reverse climate change and UHI-driven excess urban heat. Utilizing greenspace to reduce heat can also help mitigate heat-related illnesses and heat-related emergency calls—which are most common in low-income areas.[32] Increasing urban greenspace and cooling streets can also result in increased walking and exercise, yielding health benefits associated with greater physical activity.[33]

If Baltimore reshapes its outdoors to make its neighborhoods cooler, less polluted and more shaded, this would increase outdoor activity and exercise, strengthen community and reduce crime. And, as the great Jane Jacobs noted in her seminal book, The Death and Life of Great American Cities, having "eyes on the street" is central to making communities safe and vibrant places to raise families and grow strong community. Smart Surfaces results in more "eyes on the street" and enables more active outdoor lives and more vibrant communities. In our analysis, we are able to quantify many benefits, but we do not yet have data to fully value the creation of more livable, healthy places and communities. These broad additional benefits could outweigh the benefits we do calculate below.

4.3.3 COVID-19 and Pandemic risk

The COVID-19 pandemic demonstrated that regions with higher poverty levels have higher mortality rates.[34] Living in a low-income area—which are more likely to endure higher pollution rates—can also increase the mortality rate of infected individuals. A 2020 study by Wiemers et al. provides convincing evidence that vulnerability to Covid-19 based on preexisting health conditions follows racial and socioeconomic lines.[35] By investing in infrastructure to reduce urban heat and flooding, cities can improve the health of residents and reduce pre-existing conditions that make populations more vulnerable to pandemics.

4.3.4 Address systemic inequity and energy

Energy costs make up a higher percentage of expenses for lower-income residents. Research from the Joint Center for Housing Studies of Harvard University, for example, shows that for the lowest-income renters, tenant-paid household energy costs represent approximately 15% of income, while energy costs make up about 1% of total income for the highest-income renters.[36] As a consequence, the impact of energy bill reductions is proportionally far larger for affordable housing properties. Roofs in low-income city areas also generally have low solar reflectance, meaning they absorb the majority of sunlight, which greatly increases the heat gain on the top floor of buildings, increasing the risk of heat death—and contributing to higher urban temperatures. In addition, urban low-income residents are more likely to live in areas with no tree canopy and/or greater than 50 percent impervious area.[37]

The September 2020 ACEEE Report, “How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States,” illustrates this disproportionate burden of energy bills on low-income residents and people of color. The report findings include the following:

- Nationally, low-income households experienced a median energy burden of 8.1 percent, more than 3 times higher than the median energy burden for non-low-income households (2.3 percent).
- Within the low-income category, low-income with older adults experienced the highest median energy burden (9.3 percent), followed by low-income with disability (8.7 percent) and low-income with children (under 6) (7.1 percent).
- Nationally, over 25% of all households experience a high energy burden (over 6%), and about 50% of these households experience a severe energy burden (over 10%).
- In 16 cities studied, a quarter of low-income households experienced an energy burden four times higher than that for all households, and in five of those cities, a quarter of low-income households experienced an energy burden of over 18%.
- African American households experienced a median energy burden of 4.1 percent, 43 percent greater than white households.
- Latino households experienced a median energy burden of 3.5 percent, 20 percent greater than white households.
- “High energy burdens are associated with inadequate housing conditions and have been found to affect physical and mental health, nutrition, and local economic development.”[38]

The ACEEE report found that “across the 25 municipalities studied, low-income households experience energy burdens at least two times higher than the average household in all cities. In all metro areas studied, Black and Hispanic households experience higher energy burdens than non-Hispanic white households. In addition to the negative physical and mental health outcomes associated with high energy burdens, "households with high energy burdens are more likely to stay caught in cycles of poverty," according to the report.[39]

In addition, low-income schools, neighborhoods, workplaces and homes are more likely to experience different forms of discomfort and productivity loss due to higher temperatures than wealthier and cooler neighborhoods. A New York Times editorial entitled "Temperatures Rise, and We're Cooked" summarizes findings that "students who take New York State Residents exam on a 90-degree day have a 12 percent greater chance of failing than when the temperature is 72 degrees", and that in auto factories, "a week of six days above 90 degrees reduces production by 8 percent".[40]

4.4 What is included in this report

Until the Smart Surfaces Coalition formed, there was no established methodology for estimating the full costs and benefits, including health benefits, for Smart Surface solutions. Because this report seeks to rigorously document and quantify a set of technology and policy measures, we have developed some new approaches, methodologies and even a few new terms. Detailed methodologies for each component of the analysis are included to help policymakers understand costs and benefits of each Smart Surface solution.

This report reflects the guidance of national and city partners, epidemiologists, technology, stormwater, energy experts and others, to assemble and analyze U.S. and international data and studies to build a detailed, integrated cost-benefit analytic/financial model for Baltimore. In earlier iterations of this work, we estimated the costs and benefits for individual buildings at the scale of neighborhoods and at the scale of cities—especially Philadelphia, El Paso and Washington DC.[41] These past studies inform this Baltimore analysis.

There are tens of thousands of buildings and tens of millions of square feet of pavement in Baltimore, so it is important to understand the costs and benefits of deploying Smart Surfaces solutions at a large scale. This is particularly true for low-income areas which generally suffer from higher summer temperatures, worse air quality, more severe health problems, and greater energy bills per square foot than more affluent areas (see Figure 2.2). This analysis is intended to enable more informed, cost-effective city-wide decisions to make cities healthier, more equitable and affordable, and to reduce their contribution to climate change.

4.4.1 Overview of report structure

This report starts with a brief overview of purpose. It then examines Baltimore's climate action and sustainability goals, and how Smart Surfaces might help to achieve these.

This is followed by an introduction to Smart Surface solutions and their impacts. This report then overviews methods of analysis used in cost-benefit quantification, and explains the structure of the analytic engine and our cost-benefit findings. The report concludes with the implications of key findings and a discussion of next steps. The intent is to enable Baltimore to better understand, evaluate, and estimate the full costs and benefits of smarter city surface choices, and to then adopt and implement the most cost-effective and beneficial solutions to meet its objectives.

All costs and benefits are quantified on a present value, dollars per square foot basis, with explicit and consistent assumptions on term and discount rate. This approach results in common present value and net present value per square foot ($/ft2) estimates that enable all costs and benefits to be compared to each other and/or aggregated into a single cost-benefit estimate. All dollar values are presented in 2020 dollars unless otherwise noted. This report is designed to allow evaluation of the deployment of integrated options and provides estimates of the cumulative impact of these solutions at the city-level and at the neighborhood level. By quantifying a set of costs and benefits that is far broader and more complete than other work to date, this report is intended to inform and enable more cost-effective city policy design choices.

Health impacts are large and complex. This report describes the different health impact pathways and methodologies used to estimate these costs and benefits. Because this type of analysis is new, it draws on multiple methods, studies, and models to develop an integrated methodology for estimating health impacts.

Costs (such as operations and maintenance costs), and benefits (such as ozone reduction or job creation) are mapped and calculated for each Smart Surfaces strategy. These costs and benefits are then aggregated neighborhood-wide or city-wide. While we were able to quantify many benefits, additional substantial benefits lack adequate data to allow quantification, so findings here substantially underestimate benefits and net present value of these Smart Surface solutions.

We also provide a flow chart for each impact pathway to provide a clear visual representation of causal links between each Smart Surface technology (such as a cool roof or green roof) and quantified impact (such as increased ozone or reduced CO_2). In order to simplify this representation and quantification of impacts, we include only impacts that are material. Figure 4.4 below is an example of an impact pathway diagram, in this case for the impact of increasing rooftop vegetation on ozone concentration.

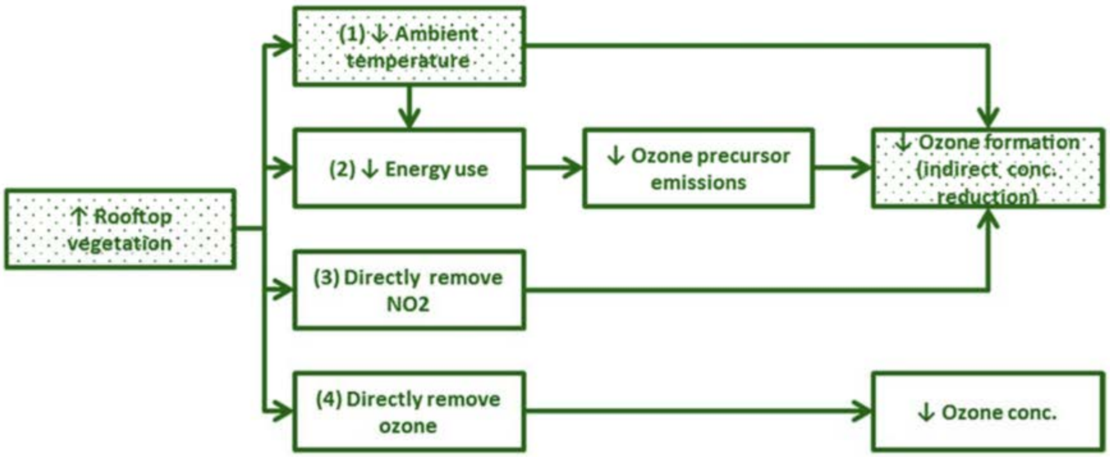

Figure 4.4. Example of Smart Surface Impact Pathway (Note: vertical arrows indicate increase or decrease while horizontal arrows indicate direction of impact.)

5 The City of Baltimore and Sustainability Efforts

5.1 Background on Baltimore sustainability goals

In 2009 the City of Baltimore adopted its first Sustainability Plan. One of the strategies to reduce pollution included the creation of a Climate Action Plan, which the Baltimore Office of Sustainability completed in 2012. This plan outlines how the city could reduce greenhouse gas emissions, and included the specific goal of reducing city-wide emissions by 15% by 2020. The City of Baltimore adopted its second Sustainability Plan in 2019 which outlines sustainability strategies across 5 themes: community, human-made systems, climate and resilience, nature in the city, and the economy. Many of the goals outlined in these influential documents can be addressed through city-wide adoption of Smart Surfaces. Since the release of these two reports, the Baltimore Office of Sustainability has updated their emissions targets and other sustainability goals - and these are described and analyzed in Section 6.

5.1.1 2019 Baltimore Sustainability Plan

The 2019 Baltimore Sustainability Plan seeks to expand the work of other city projects including the *Baltimore Green Network* (2018) which transforms vacant properties into green community assets and connects with community organizations such as schools and activity centers to utilize these spaces effectively. The Sustainability Plan also seeks to address hazards including flooding, extreme heat, and the anticipated threats of climate change by expanding the work of the *Disaster Preparedness and Planning Project* (DP3) (2018).[42]

Accountability and a commitment to reaching the city's goals serve as a large aspect of the Baltimore Office of Sustainability's work. The Sustainability Plan outlines efforts to track Baltimore's progress and ability to advance equity and sustainability goals. This includes three major responsibilities, the first is the production of an annual report, with a focus on the previous years' efforts and the effectiveness of "acting in a racially equitable way".[43] The second is an annual Open House event to check in with city residents, ask questions, and renew Baltimore's commitments. The third is periodic updates at least every three years to allow the Sustainability Plan to adapt and stay relevant by updating strategies, setting new benchmarks, and identifying new or refined metrics.

The Baltimore Sustainability Plan focuses on addressing Baltimore's sustainability challenges through an "equity lens". The report acknowledges the significance of historic inequities in Baltimore and their ties to sustainability. For example, the report highlights public health as an area where the city has glaring disparities and notes that "the majority-white neighborhood of Roland Park has an average life expectancy that is

20 years longer than the majority-African American neighborhoods of Harlem Park or Sandtown-Winchester."[44]

5.1.2 Baltimore Climate Action Plan

The Baltimore Climate Action Plan, completed in 2012, seeks to reduce GHG emissions from community-wide activities including energy, transportation, water, waste and land use. The plan also identifies key considerations to help the city prepare for the impacts of climate change.[45]

The Baltimore Climate Action Plan outlines key mitigation strategies in energy savings, land use and transportation, and growing a green city, including:

- Promoting generation of renewable energy and solar installations
- Adopting green building standards for new construction and large renovation projects
- Reduce the energy consumption of existing commercial and residential buildings and schools
- Improve water efficiency efforts
- Protect and enhance Baltimore's urban forest[46]

The Smart Surface solutions outlined in this report provide tangible ways to achieve the objectives and broader strategies outlined in Baltimore's Climate Action Plan. As residential, commercial, and industrial building energy use are responsible for approximately 70% of Baltimore's GHG emissions, Smart Surface solutions that reduce building energy consumption would contribute to reducing these emissions.[47]

5.2 Summary of cost-benefit numbers and tables

The tables below summarize the report's main findings on the cost-effectiveness of city-wide adoption of cool roofs, green roofs, solar PV, reflective pavements and urban trees. Benefits valued include energy cost savings, improved air quality and public health, reduced stormwater runoff, climate change mitigation, and increased employment. The three low-income areas we focus on, Brooklyn-Curtis Bay, Madison East End, and Cherry Hill, would realize hundreds of millions of dollars in net benefits over 40 years (see Tables 5.3, 5.4, and 5.5). All costs and benefits quantified in this report are in present value, with explicit assumptions on term and discount rate.

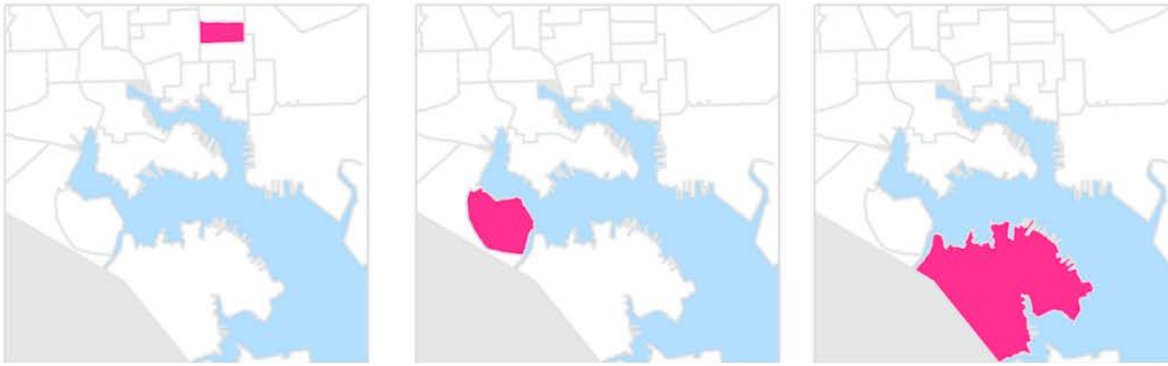

Figure 5.1. Three low-income areas of focus, from left to right, Madison East End, Cherry Hill, and Brooklyn-Curtis Bay.

Smart Surface	Target	Costs (millions 2020$)	Benefits (millions 2020$)	NPV (millions 2020$)	Benefit: Cost Ratio	Employment (job yrs)	Peak Summer Temp Reduction Estimate ****
Cool Roofs **	Low-slope roof area: 80% Steep-slope roof area: 20%	($112)	$862	$541	7.7	1,904	2.41 °F
Bioswale-managed Roof *****	Low-slope roof area: 20%	($99)	$549	$301	5.5	1,391	Not included
Green Roofs	Low-slope roof area: 2%	($81)	$158	$46	2.0	1,300	Not included
Solar PV*	Low-slope roof area: 40% Steep-slope roof area: 20%	($474)	$10,604	$6,704	22.4	61,042	Not included
Reflective Parking **	Parking area: 50%	($44)	$103	$43	2.3	746	0.52 °F
Permeable Parking ***	Parking area: 5%	$48	$113	$110	14.4		Not included
Bioswale-managed *****	Parking area: 20%	($100)	$578	$321	5.8	1,698	Not included
Reflective Roads	Road area: 15%	($10)	$27	$15	2.9	162	0.16 °F
Permeable Sidewalks	Sidewalk area: 5%	($49)	$200	$99	4.1	539	Not included
Trees	City land area: 40%	($499)	$1,330	$560	2.7	9,982	1.21 °F
TOTAL		$1,420	$14,524	$8,739	10:1	78,765	4.3 °F

Table 5.1. 20-Year adoption consolidated summary for Baltimore

NPV	**$82**
Total Cost	**$21**
Total Benefit	**$144**
Benefit-Cost Ratio	**6.8:1**
Peak Summer Temp Reduction (area-wide average estimate)	**3.08 °F**
Job Years Created	**825**

Table 5.2. Cherry Hill Results Summary (dollar values in millions of 2020 dollars)

NPV	**$144**
Total Cost	**$42**
Total Benefit	**$258**
Benefit-Cost Ratio	**6.1:1**
Peak Summer Temp Reduction (area-wide average estimate)	**3.96 °F**
Job Years Created	**1,486**

Table 5.3. Brooklyn Curtis Bay Results Summary (dollar values in millions of 2020 dollars)

NPV	**$34**
Total Cost	**$5**
Total Benefit	**$56**
Benefit-Cost Ratio	**11.3:1**
Peak Summer Temp Reduction (area-wide average estimate)	**8.29 °F**
Job Years Created	**302**

Table 5.4. Madison East-End Results Summary (dollar values in millions of 2020 dollars)

The payback times for the surface solutions vary greatly: cool roofs offer fast payback in all cases, though do not offer the largest net benefit on a per square foot basis. Overall, the net present value of deploying these solutions is $8.7 billion for Baltimore (see Table 5.1). Including the value of avoided summer tourism revenue losses increases estimated net benefits to $13.5 billion. When societal benefits are included, all technologies analyzed have a benefit-to-cost ratio greater than one. As noted above, this analysis does not capture the full set of comfort, health, and livability benefits due to complexity of areas such as health or crime, and due to limited data and limited peer reviewed studies.

5.3 Tourism benefits

Tourism revenue is affected by rising heat, and estimating this impact provides a way to quantify a portion of the comfort and livability costs of global warming. In Baltimore, the estimated 30 year avoided tourism loss due to lower urban temperatures from Smart Surface strategies is 6.4 billion (including $184 million in tax revenue for the city).

City management of water has a large impact on downstream watersheds that are important tourism destinations—especially the Baltimore Harbor and the Chesapeake Bay—that enhance the regional attractiveness as a tourist destination as well as enhancing quality of life for residents. The Chesapeake Bay Foundation notes that "pollution from urban and suburban runoff is the only major source of pollution that is continuing to grow in the Chesapeake Bay watershed…every four years an area of land the size of Washington, D.C., is paved or hardened in the Chesapeake Bay region."[48] Increasing porous surfaces and trees provides an effective way to reduce this runoff. The impact of climate change on summer tourism specifically is discussed further in Section 13 of the report.

5.4 Compounding benefits

Costs of Smart Surfaces solutions are relatively simple to calculate and typically involve two elements: the upfront capital cost to purchase and install, and ongoing operations and maintenance costs. In contrast, benefits are more numerous, complex and varied, and commonly include a large range of impacts related to health, stormwater, energy, climate change, employment etc.

The set of Smart Surfaces measures analyzed in this report commonly provide compounding benefits. For example, high albedo surfaces bounce incoming sunlight back into space, reducing global warming, but also cutting urban temperature, air pollution and air conditioning costs. Solar PV panels shade roofs, so less heat reaches buildings, reducing air conditioning costs, and improving indoor comfort. Locating PV systems on cool roofs or green roofs can reduce PV panel temperature, increasing production of electricity. Partial shading of green roofs by PV panels can improve health of green roofs, in turn making green roofs work better at cleaning the air or at stormwater management, further lowering risk and cost of extreme rain events.

From the perspective of a building owner, the cost-benefit returns of implementing smart surface solutions are commonly attractive if they are long term tenants or owners, but unlikely to be attractive for developers that build and then sell (or flip) properties. Additional, city-wide and societal benefits are large, but do not accrue to the building owner. However, most of these benefits, including improved citizen health, lower water infrastructure and treatment costs, lower energy bills, etc., accrue at a city level. The question of who benefits and how these benefits are recognized (on not recognized) is therefore an important part of city policies around selection of city surfaces.

5.5 Benefits of slowing climate change

One area of benefits that is generally not calculated or monetized is contribution to slowing climate change—and its enormous and complex costs. A 2017 report, by the Medical Society Consortium on Climate & Health, representing 11 major medical societies and more than 400,000 doctors, found that “climate change is already causing problems in communities in every region of our nation.”[49] Their report documents health impacts in three areas of health: direct harms from climate change-altered weather, increased spread of disease and contamination, and mental health effects.

1,000 U.S. cities have some form of commitment to limiting or reducing their contribution to climate change. A growing number of cities and towns take some responsibility for their climate change impact and therefore—as a baseline assumption—this report includes in the cost-benefit analysis the benefits of greenhouse gas reductions. The dollar value assigned to CO2 reductions (for example for energy efficiency from cool roofs) is based on the social cost of carbon, a cost per ton of carbon estimate developed and updated every three years by a dozen U.S. federal agencies, including the EPA and the Treasury Department.

Even excluding the climate change mitigation benefits, the Smart Surfaces strategies analyzed in this report have broad benefits for the city, especially for its low-income neighborhoods, as well as for the larger watersheds in which Baltimore sits. City leadership on Smart Surfaces can also be expected to accelerate Smart Surface adoption by cities surrounding Baltimore, in turn increasing city and region-wide cooling and health benefits, including region-wide summer peak cooling.

6 Background on Baltimore Sustainability Goals

6.1 Overview of Climate Action Plan and Sustainability Plan goals which Smart Surfaces address

6.1.1 Summary of objectives

Baltimore's Climate Action Plan and Sustainability Plan identified three primary objectives all of which can be cost-effectively achieved through the adoption of Smart Surfaces. The first objective is increasing livability. The second is to increase the economic strength of the city. The third objective is to make Baltimore neighborhoods more equitable.

6.1.2 2019 Baltimore Sustainability Plan goals and drivers

The 2019 Baltimore Sustainability Plan identified city goals, and these are the primary metrics we analyze to measure the impact of Smart Surfaces, including:

- Global warming reduction
- Air quality
- Water quality
- Heat reduction
- Tree canopy cover
- Job creation
- Credit rating
- Tourism

2019 Baltimore Sustainability Plan:

Summary of Baltimore goals that Smart Surfaces can help achieve

Goals	Driver
Community Investment + Infrastructure Improvements: Support programs and policies to increase investments in low-income neighborhoods.	Utilize cost-benefit analysis which can strengthen advocacy and provide details regarding the host of benefits for specific Smart Surface adoption scenarios.
Expedite housing renovations, demolitions, and greening efforts to increase the number of thriving, safe, neighborhoods.	Adopt city policies such as advanced permitting for Smart Surface renovations and developments.

Collectively integrate and streamline the delivery of green workforce services to increase employment and self-employment and help close the equity and opportunity gaps for Baltimore's low-income, African American, and minority residents.	Smart Surface adoption creates jobs through installation and maintenance. Low-income areas can benefit both by adopting solutions to improve livability and offering jobs to residents
Review regulatory codes and implement collaborative programs to protect vulnerable residents, such as in neighborhoods with high percentages of seniors, low-income residents, and non-English-speaking immigrants.	Solutions such as planting more trees, and reducing neighborhood temperatures by utilizing reflective pavements are the greatest for residents such as seniors more at risk of environmental related health complications, and low-income areas that tend to be hotter and more polluted
Increase green infrastructure throughout the city, targeting neighborhoods with limited access to large parks and green spaces and high disparities in health outcomes.	Run scenarios in the cost-benefit engine analyzing the low-neighborhoods modeled to make informed decisions, and implement training programs and best practices through the Smart Surfaces Coalition
Global Warming Reduction: Increase energy and water efficiency retrofits in affordable and low-income housing markets to reduce greenhouse gas emissions, expand local sector jobs, and improve the long-term viability of affordable housing.	Adopt solar PV in residential areas, or implement adjacent policies which allow for the use of renewable energy, as well as utilize porous pavements which help manage water
Modify operations and policies in city government to reduce emissions.	Reduce energy use and carbon emissions by implementing greener solutions such as use of solar PV, more urban trees, and reflective and green roofs
Protect and enhance Baltimore's urban forest, increase the acreage of maintained and protected land, as well as plant and establish more trees to ensure equitable planting distribution.	Follow Smart Surface Coalition's best practices and engage in training with SSC partner organizations, and existing organizations in Baltimore, to maintain and grow Baltimore's tree canopy
Improve Health: Create and adopt programs and codes for promoting occupant health and comfort, as well as efficiency.	Smart Surface adoption has a host of positive health benefits, many of which are explained in this report, and accrue as a result of reduce temperatures, better manage flooding, and mitigating pollution

Assess and monitor how air quality varies across the city to identify neighborhoods in greatest need of improvement and increase community awareness of how air quality impacts the health of children, the elderly, low-income communities, and communities of color.	Air quality mapping with Smart Surface Coalition partners can provide valuable input to assess Smart Surface effectiveness and priority implementation areas

6.2 Making Baltimore more livable and resilient

6.2.1 Reducing heat

As noted above, in *Mayor and City Council of Baltimore v. BP P.L.C.*, the City of Baltimore explains that "Baltimore is particularly vulnerable to rising temperatures. Because of Baltimore's urban infrastructure, increased temperatures will add to the heat load of buildings and exacerbate existing urban heat islands adding to the risk of high ambient temperatures. On some summer days, air in urban areas can be up to 10°F warmer than in other areas."[50] Baltimore adds that "extreme heat-induced public health impacts in Baltimore will result in increased risk of heat-related illnesses (mild heat stress to fatal heat stroke) and the exacerbation of preexisting conditions in the medically fragile, chronically ill, and otherwise vulnerable. Between 2000 and 2012, exposure to extreme heat events increased Baltimore residents' risk of hospitalization for heart attack by 43 percent."[51]

In the summer of 2018 in Baltimore, when the heat index reached 103 degrees, EMS calls increased dramatically city-wide for potentially fatal heat stroke and for chronic conditions: EMS calls for chronic obstructive pulmonary disorder (COPD) increased by nearly 70%, calls for respiratory distress increased by 20%, calls for cardiac arrest rose by 80%, and calls for high blood pressure more than doubled. Other conditions also spiked: psychiatric disorders, substance abuse, and dehydration, among others.[52]

Baltimore summer temperature conditions are worsened by low tree coverage, few porous surfaces, and dark roofs, roads, and parking lots. Replacing dark surfaces with highly reflective (cool) roofs, roads, and parking lots would decrease the amount of sunlight absorbed by city surfaces and re-radiated as heat, thereby decreasing air (and building) temperature. Additionally, increasing tree canopy coverage would reduce city temperature by providing shade and increasing transpiration. Baltimore is already a leader among cities in expanding tree coverage, and it seeks to expand tree coverage further to 40%.

6.2.2 Improving air quality

In 2019, the American Lung Association ranked Baltimore as one of the most ozone-polluted cities in the nation, and Baltimore County received a failing grade in the ALA annual "State of the Air" report.[53] Improvement in Baltimore's air quality can be achieved by increasing Smart Surfaces such as trees and green roofs which remove pollutants and CO2 from the air, while providing shade and reducing temperature. More reflective surfaces can also help reduce ozone by reducing ambient temperature. As the City of Baltimore in *Mayor and City Council of Baltimore v. BP P.L.C.* notes, "increased heat also intensifies the photochemical reactions that produce smog, ground-level ozone, and fine particulate matter ($PM_{2.5}$), which contribute to and exacerbate respiratory disease in children and adults. Increased heat and CO_2 enhance the growth of plants that produce pollen, which are associated with allergies. Also, between 2000 and 2012, exposure to extreme heat events in Baltimore increased risk of hospitalization for asthma by 37 percent."[54]

In addition, electricity used by Baltimore largely originates from natural gas and coal-fired power plants. These sources of energy worsen air pollution. Smart Surfaces cool cities and buildings, reducing the peak summertime load on these utilities, by reducing the demand for electricity used to run air conditioners. Adding solar PV to rooftops and as shading for parking lots and pedestrian areas also reduces the amount of energy required from non-renewable sources.

6.2.3 Reducing flood risk and improving water quality

Extreme rain events have become 70% more frequent over the past six decades,[55] exacerbating Baltimore's existing stormwater management challenges. Approximately 10% (5,200 acres) of the City's land is located within a floodplain,[56] and as recently as April 2020, parts of downtown Baltimore flooded with four feet of water.[57] In *Mayor and City Council of Baltimore v. BP P.L.C.*, the City of Baltimore noted that "because of anthropogenic global warming, Baltimore's hydrologic regime is shifting toward one characterized by more frequent and extreme precipitation events and associated flooding. These impacts will impact all sectors, and low-income communities will be particularly affected by flooding, extreme weather, and heat waves exacerbated by climate change."[58]

Additionally, Baltimore, like other large Mid-Atlantic cities, has historically had a combined sewer system where stormwater runoff and sewage flow together to wastewater treatment plants. During dry periods, the pipe infrastructure has sufficient capacity to convey the combined flow, but heavy rainfall dramatically increases the stormwater runoff (and therefore the total volume), potentially causing backups in residential areas and discharging untreated effluent into the Black River, Patapsco River, and Chesapeake Bay.

Several factors contribute to the overflow events. Baltimore is substantially impervious —the Department of Public Works estimates that 45% of total land area in Baltimore is impervious—which prevents infiltration and instead routes rainfall into the stormwater system.[59] Even bare land, when compacted, acts as an impervious surface, and residents often directly connect their roof drain pipes to street gutters.[60] Rainfall can collect and transport oil, gasoline, fertilizers and pesticides, and other urban pollutants from the impervious surfaces directly into the surrounding aquatic environments.

Consequently, the City of Baltimore has been working to improve their stormwater management infrastructure. The City is required by federal law to obtain a discharge permit from the EPA for their stormwater system, thereby establishing pollutant standards to meet water quality criteria.[61] In Baltimore, the stormwater system is called the Municipal Separate Sewer System (MS4). Baltimore received a 5-year permit in 2013 and is gathering public comments for a renewal, currently ongoing in late 2020. Baltimore has also released a Watershed Implementation Plan (WIP), and the 2015 WIP calls for "restoring 20% [4,921 acres] of the existing impervious area to the maximum extent practicable."[62] Baltimore has employed several strategies to meet this objective, including traditional and green infrastructure installation, programs like mechanical street sweeping, illicit discharge detection, and inlet screen cleaning, and promotion of stormwater management on private lands.[63]

Baltimore is already expanding Smart Surfaces included tree coverage, rain gardens and pervious surfaces. This analysis should support an acceleration of these investments.

> ***Waterkeepers Chesapeake*** *notes:*
>
> "Increasing green infrastructure and climate-Smart Surfaces provides a host of benefits for clean water. Baltimoreans are facing increasing flooding as climate change continues to spur intense rainfall, leading to sewage backups and flash floods. This flooding is devastating, costly and even life threatening. Smart Surfaces can play a key role in absorbing this runoff and interrupting the harsh, new climate norm."

6.3 Addressing Baltimore's severe asthma problems

The City of Baltimore has one of the highest rates of asthma in the United States. While the nationwide average of adult asthma is 8.6%, 12.4% of Baltimore City's adults suffer from asthma, a rate that is 44% higher than the national average.[64] As of 2019, Baltimore had the highest average prevalence of asthma in the state of Maryland. The rates of childhood asthma in Baltimore present even more significant disparities; 9.4%

of children nationally have asthma, while 20% of Baltimore City children under 18 suffer asthma at—more than twice the national rate.[65]

As a result of the high percentage of adults and children with asthma, Baltimore's rate of asthma hospitalizations was nearly three times the U.S. average in 2010 and about 2.2 times higher than Maryland's average.[66] Baltimore residents not only account for a larger percentage of hospitalizations, they also endure higher emergency room visit costs in comparison to the rest of Maryland. The average cost per asthma emergency department visit in Baltimore was $826 while the state average was $652 in 2009.[67] In addition, public insurance was the source of 72.1% of Baltimore City residents' asthma hospitalizations in comparison to 60% in the state of Maryland.[68] Reducing the asthma burden would create large financial benefits for the city, its citizens and for the state.

Children ages 5-9 were hospitalized for asthma at a higher rate than other age group in Baltimore City.[69] The rate of emergency visits in Baltimore related to pediatric asthma was more than double the rate of Maryland.[70] Asthma also contributes to missed school days which poses additional impediments to the learning trajectory of Baltimore's children. In addition to the social cost of such high pediatric asthma rates, the annual spending in Baltimore on pediatric emergency department visits is more than $3.6 million.[71]

Research by Leah Kelly and Kira Burkhart of the Environmental Integrity Project (EIP) has found "a very strong spatial correlation between asthma hospitalization and emergency room visits in Baltimore's zip codes and demographic measures of poverty, particularly median household income."[72] Their conclusion—that poor housing conditions and poverty have a major impact on asthma prevalence—has been confirmed by a Kaiser Health News and Capital News Service report published in the Washington Post.[73]

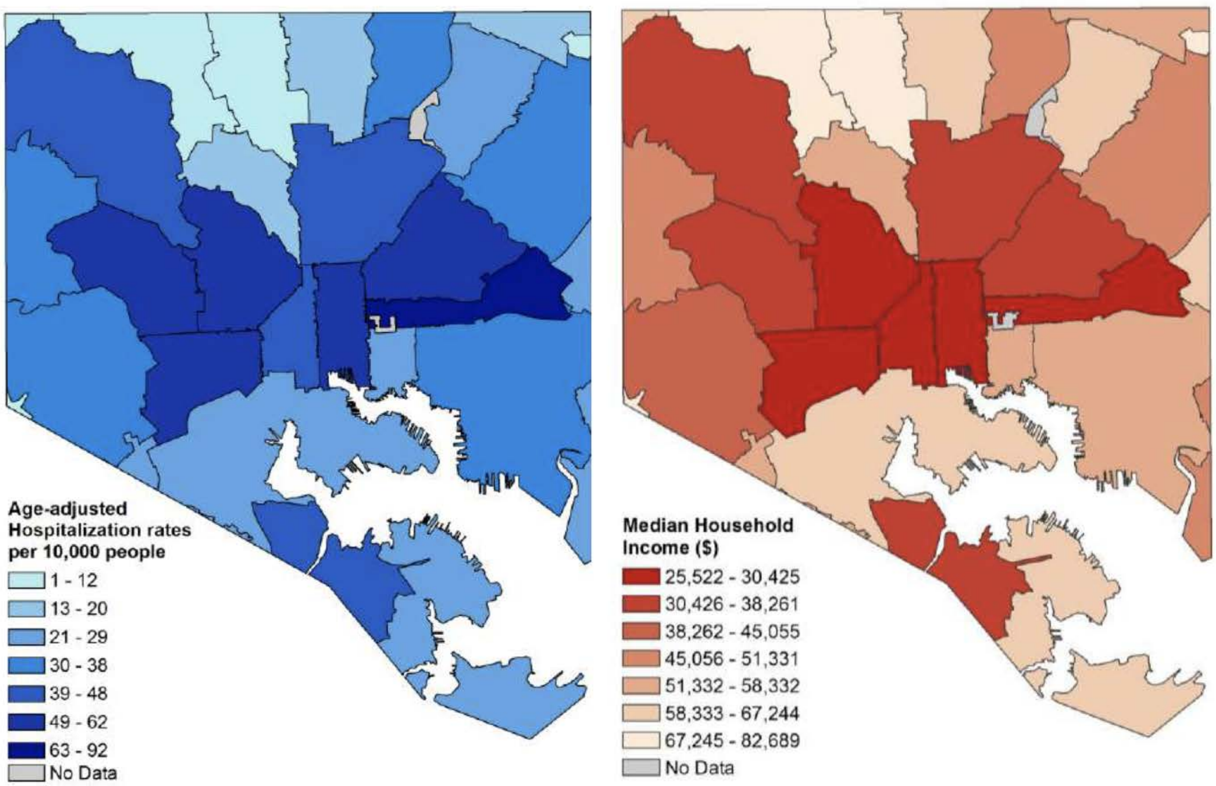

Figure 6.1. Asthma Hospitalization Rates (left) and 2013 Median Household Income (right)[74]

Kelly and Burkhart's research found that the demographic measures most closely correlated with asthma rates in Baltimore were median household income, percent of population using Medicaid, and percent of population uninsured or using Medicaid.[75] They also found that poverty had a significant correlation with asthma rates. Race also plays a large factor as asthma emergency rates and hospitalizations are higher for those African American than other racial groups in Maryland according to analyses by the state's Department of Health.[76]

Lower-income communities of color in Baltimore endure the highest rates of asthma, which poses enormous costs. Efforts to mitigate pollution and improve air quality should be focused on these neighborhoods. Such efforts include prioritizing tree planting in low-income neighborhoods—which notably and not coincidentally— tend to have substantially less tree coverage than wealthier neighborhoods in Baltimore. In addition, expanding green surfaces, increasing surface reflectivity (to reduce heat and smog) transitioning to cleaner energy city-wide including urban solar PV would reduce the impact of emissions and the higher prevalence of asthma in low-income neighborhoods. Reducing NO2, ozone, and PM exposure would mitigate the asthma disparities in Baltimore both between neighborhoods, as well as in comparison to Maryland and the rest of the country, and would result in financial benefits at the family, neighborhood, city and state levels.

The growing health risks and threats to Baltimore are described and documented in an 8-part series called "Code Red", a collaboration between the University of Maryland's Howard Center for Investigative Journalism and Capital News Service, NPR, Wide Angle Youth Media in Baltimore and WMAR television.

6.4 Increasing the economic strength of the city

6.4.1 Job creation for Baltimore

The unemployment rate for Baltimore City in January 2021 stood at 8.5%[77] while the national average was 6.3% during the same time period.[78] Smart Surfaces can contribute to reducing Baltimore unemployment; Smart Surfaces are labor intensive and provide good jobs. Investments in Smart Surfaces such as tree planting, resurfacing roads or roofs with reflective coatings, or installing green roofs or solar panels create many more jobs than dark impervious surfaces.

Smart Surfaces jobs are also more distributed and typically pay above average wages, at over $15/hour. According to U.S. News & World Report, solar photovoltaic installers made a median salary of $44,890 in 2019.[79] According to the same analysis, the median salary for painters is $40,280.[80] In the US, tree planters make an average salary of $32,803 per year, equal to $16 per hour.[81] A recent Federal study found that employees in the renewable energy sector earned an average of $48,000 annually, equal to an hourly wage of $23.89.[82] This is above the national median hourly wage of $19.14 (in 2019), equal to an annual salary of $38,000.

Shifting funding in Baltimore to Smart Surfaces would create significant jobs on a net basis. The number of jobs created from different Smart Surfaces varies, as discussed later in this report, but Smart Surfaces are on average three times as job-creative as the economy as a whole.[83]

6.4.2 Heat and air quality impact on productivity

A New York Times editorial entitled "Temperatures Rise, and We're Cooked" summarizes findings that "students who take New York State Residents exam on a 90-degree day have a 12 percent greater chance of failing than when the temperature is

72 degrees", and that in auto factories, "a week of six days above 90 degrees reduces production by 8 percent."[84]

Smart Surfaces can mitigate this effect through more reflective roofs, sidewalks and parking lots, and increased shade from trees that reduce heat within buildings as well as neighborhood-wide and city-wide.

6.4.3 Tourism

Tourism is most common during the summer months due to school holidays and family travel. Excess summer heat is a rising concern for tourists. Revenue from summer tourism in Baltimore is at risk from rising temperatures and increasing heat waves driven by climate change. As climate change continues, temperatures will become more extreme, including increases in the number of days above 90°F, 95°F, and even 100°F. Higher temperatures will also increase smog formation. The combination of higher average heat, greater frequency of extreme heat and more air pollution will make Baltimore less attractive for tourists in the summer.

Smart Surfaces would cool and make Baltimore more attractive to tourists. Smart Surfaces such as reflective roofs, roads, sidewalks, and trees would reduce temperatures in the summer therefore increasing comfort, walkability, and likely tourism numbers.

A paper by Lee et. al. indicates that cities and tourism entities that invest in sustainable and green initiatives, referred to as "smart tourism", can create urban spaces that residents and visitors both enjoy.[85] They define a smart city as a connected city that uses advanced technologies to create a sustainable metropolis, innovative commerce, and enriched quality of life for its citizens.

According to Visit Baltimore, a Baltimore non-profit dedicated to driving visitation and spurring economic growth in Baltimore, 2018 numbers indicate that tourism sustained 86,414 jobs in Baltimore directly and indirectly.[86] Tourism also generated $10.7 billion in business sales in 2018 and generated $734 million in state and city tax revenue in 2018.[87] In 2019, Visit Baltimore reported that the number of visitors and the economic impact of tourism increased by 1.1% and 2.6% respectively according to data from Longwoods International and Tourism Economics.[88]

It is also worth noting that while overall tourism numbers rose, market research conducted by Visit Baltimore found that in 2018 more than 30 percent of residents in surrounding counties reported a decrease in the frequency of their visits to the city.[89] To retain and gain visitors from surrounding counties, and boost economic activity, Baltimore should prioritize improving comfort air quality and aesthetic appeal by accelerating adoption of Smart Surfaces.

As Visit Baltimore CEO Al Hutchinson noted re COVID, "we are slowly coming back, but it has been projected that we won't fully recover until 2024."[90] By making surface changes and improvements to the city, which have a host of benefits in the summer months when tourists are most common, Baltimore can strengthen its economically essential tourism industry.

6.4.4 Enhancing economic resilience

Climate change creates new risks and exacerbates existing vulnerabilities, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth. Moody's Investors Service warns that climate change, "will be a growing negative credit factor for issuers without sufficient adaptation and mitigation strategies."[91] Various Baltimore studies have identified a range of objectives for Baltimore relating to protecting and enhancing the city's economic strength. Below are some goals identified by Baltimore that relate to economic wellbeing, and a summary of how broad adoption of Smart Surfaces can help achieve these objectives.

Increasing Baltimore's Economic Strength:

Goals	Impact of Smart Surfaces
Promote generation of renewable energy and solar installations, while working to increase Maryland's Renewable Portfolio Standard	Increasing solar PV reduces energy demand from non-renewable sources, diversifying energy production and increasing city resilience. This can protect the city's credit rating and create jobs.
Promote mixed-use development, encouraging pedestrian and transit-oriented neighborhoods while increasing access to goods and services	Smart Surfaces such as reflective or porous pavements and trees cool the city, making it more walkable, and increasing economic productivity. Homes in walkable areas on average can sell for 25% more than comparable homes in non-walkable areas.
Create agriculture land-use policies that encourage urban farms and local food production	Smart Surfaces such as green roofs can be a platform for local, urban food production.
Develop plans and systems to increase community resilience.	Smart Surfaces increase community resilience—both infrastructure and health—which can protect city credit rating.

Speed the path to decarbonization through increased deployment of renewable energy and electric vehicles.	Increased solar PV reduces GHG emissions and load on electric grid, protecting credit rating.
Increase green infrastructure throughout the city, targeting low-income neighborhoods with high disparities in health outcomes and higher temperatures and greater pollution rates	Smart Surfaces such as trees and green roofs help clean and cool the air. They can additionally help protect or even increase city tourism, while creating jobs.
Connect youth, young adults, returning citizens, and others who have limited work experience to green, work-based learning opportunities.	Smart Surface implementation will create many jobs in the green workforce both with initial implementation, and operations and maintenance.

Smart Surfaces can greatly reduce costs and risks of excess heat, smog and flooding, and can make Baltimore more livable, comfortable, and safer.

6.4.5 Reducing risk to Baltimore credit ratings

Climate change is increasing the frequency and severity of extreme and costly weather events such as storms, hurricanes, extreme rains, and heat waves. The U.S. government's 2018 National Climate Assessment Report recognizes that "Climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth."[92] These are increasing costs and risks to cities, in turn threatening their credit rating and their cost of borrowing money.

Cities that fail to adopt resilience strategies risk credit downgrades that could greatly increase cost of borrowing. A November 2017 report by Moody's Investors Service on the growing risk to city and state credit ratings emphasizes that there "will be a growing negative credit factor for issuers without sufficient adaptation and mitigation strategies." The set of resilience strategies analyzed in this report would reduce the risk of credit downgrades and could strengthen the city credit rating, in turn reducing its cost of borrowing.

A three-part analysis published in the leading industry publication Risk & Insurance titled "Here's How Cities Can Reduce Climate Change Risk" demonstrates that cities that choose not to adopt Smart Surfaces can be expected to experience significantly increased climate-related losses, increased risk of credit rating reductions, and associated increases in city borrowing costs.[93] Over time, these combined threats would increase risk of insolvency for cities that do not adopt resilience strategies such as Smart Surfaces.

As noted in the Risk & Insurance article, “If city credit rating drops, cities have to increase the amount of interest paid to bondholders in order to compensate for the excess risk the bondholder takes on. Cost of borrowing is determined by the city credit rating—and an improved credit rating reduces the cost of borrowing. For example: In 2014 when Baltimore’s credit rating improved, the Baltimore Sun noted, ‘The new credit rating is expected to allow the city to borrow money at lower interest rates for projects such as infrastructure upgrades, new schools and improved recreation centers. That in turn would save taxpayers cash on interest payments.’”[94]

Cities that choose to not adopt Smart Surfaces will experience increased climate related losses, increased risk of credit rating reductions and associated increases in city borrowing costs. Over time, these combined threats will increase risk of insolvency for cites that do not adopt resilience strategies such as Smart Surfaces.

As Smart Surfaces deployment scales up, the urban cooling benefits would also grow proportionally, further reducing regional energy bills and smog, and improving health and livability in ways that bring compounding benefits, especially for low-income populations. The phenomenon that we call “downwind summer cooling” would bring regional comfort and health benefits both within cities and across larger regions, potentially doubling cooling compared with policies only within city limits.

6.5 Addressing Baltimore-specific challenges

In Baltimore, [95] (as in many other U.S. cities) the coverage of impervious surface is generally greater in lower-income neighborhoods and communities with higher proportions of people of color.

6.5.1 Disproportionate heat effects in low-income areas

A recent study conducted by the University of Maryland along with Portland State University (a Smart Surfaces Coalition partner) highlighted the inequitable heat distribution between Baltimore neighborhoods. An NPR review noted that “Franklin Square, is hotter than about two-thirds of the other neighborhoods in Baltimore—about 6 degrees hotter than the city's coolest neighborhood. It's also in one of the city's poorest communities, with more than one-third of residents living in poverty.”[96] Across Baltimore, the hottest areas tend to be the poorest.

6.5.2 Health complications

Lower-income areas in Baltimore are generally hotter than other areas of the city, and the residents are often the most vulnerable; low-income areas tend to have a higher proportion of elderly and children who are more prone to heat-related health issues, and healthcare costs pose a significantly larger financial burden on low-income residents. Excess heat in low-income areas and worse air quality increase emergency room visits by low-income residents, some of whom lack insurance, creating large non-reimbursed hospital costs.

6.5.3 Energy burden and air conditioning

In Baltimore, low-income households experience a median energy burden (% income spent on energy bills) of 10.5 percent, according to a 2020 ACEEE report. This is 2.4 percent higher than the U.S. median low-income energy burden of 8.1 percent. In fact, out of 25 metropolitan statistical areas (MSAs) studied in the report, Baltimore's median low-income energy burden was the second highest, only behind Birmingham, Alabama's 10.9 percent.[97]

77% of Baltimore's low-income households experience a high energy burden, while 52% experience a severe energy burden, designated as greater than 10 percent. When comparing the energy burden of low-income neighborhoods and Baltimore as a whole, the ratio of low-income energy burden to median energy burden in Baltimore ranks as the third highest of metropolitan areas studies in the ACEEE report, demonstrating a large discrepancy between the energy burden of low-income households and the rest of Baltimore.[98]

These numbers underline the vulnerability of Baltimore's low-income communities to rising temperatures, increased cooling cost burdens, increased pollution, and changing climate. Smart Surfaces would reduce energy costs both in buildings and city-wide through increasing reflectivity and reducing temperature and related air conditioning load.

7 Background

This section provides an overview of the solutions analyzed in the report and provides general background information relevant to understand cost-benefit assumptions and calculations. For more detailed descriptions and discussions, please refer to the solution sections.

7.1 Urban heat islands

Urban areas commonly experience higher temperatures than their rural surroundings. This is called an urban heat island (UHI). The primary cause of UHIs is the replacement of natural, vegetated land with dark, dry urban surfaces that absorb more solar energy than the natural surfaces they replace. Other factors that contribute to UHIs include heat given off by fuel combustion (e.g., in vehicles) and by air conditioners, and from urban morphology (the dimension and spacing of buildings that tend to trap urban heat).[99]

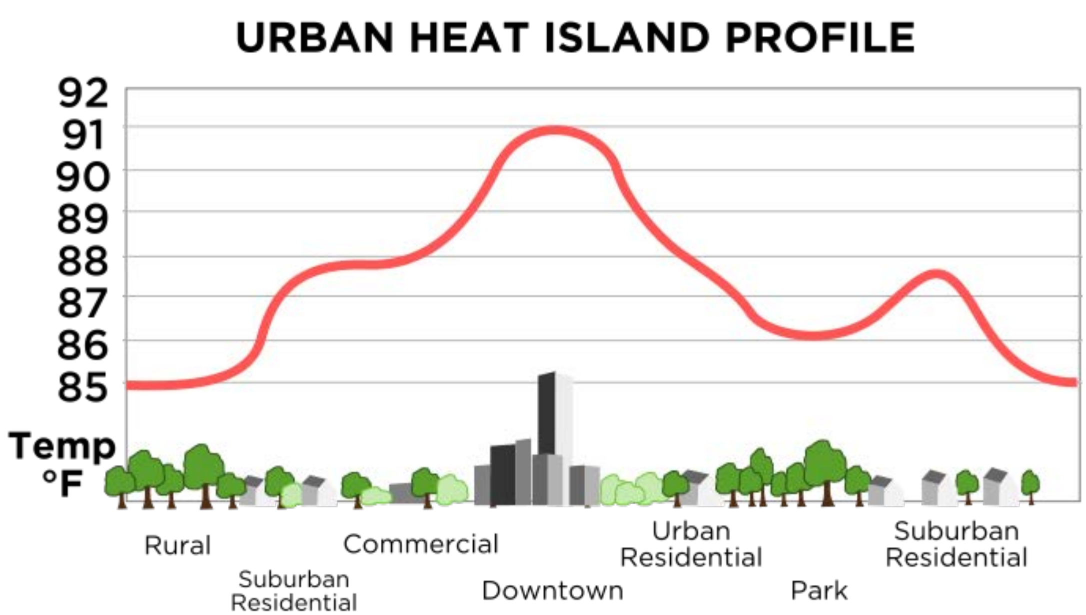

Figure 7.1. Simple illustrative example of urban heat island profile[100]

There are two types of UHIs: surface and atmospheric. Surface UHIs are characterized by higher ground surface temperatures in urban environments compared to the rural surroundings. The surface UHI effect is largest during the summer, and generally persists through the night.[101] Atmospheric UHIs are characterized by warmer urban air compared to the surrounding rural environment.

Atmospheric UHIs are most pronounced at night when surfaces warmed during the day release heat.[102] Figure 7.1 shows a simple atmospheric UHI profile. Figure 7.2

shows a more sophisticated illustration with surface and atmospheric UHIs and differences between day and night.

There are two types of atmospheric UHIs: canopy layer (or near-surface) and boundary layer.[103] Boundary layer UHIs extend from the tops of trees and buildings to where the urban environment no longer affects the atmosphere. Canopy layer UHIs occur where people live, from the ground surface to the tops of trees and buildings. Canopy layer UHIs are the most common UHI discussed. Subsequently, when this report uses the term UHI, it refers to the canopy layer/near-surface UHI, unless otherwise specified.

The surface solutions analyzed in this report can play a large role in cost-effectively mitigating UHIs and the associated negative consequences (e.g., increased energy use and poor air quality). This is discussed in more detail in Section 8, and in the solution-specific sections.

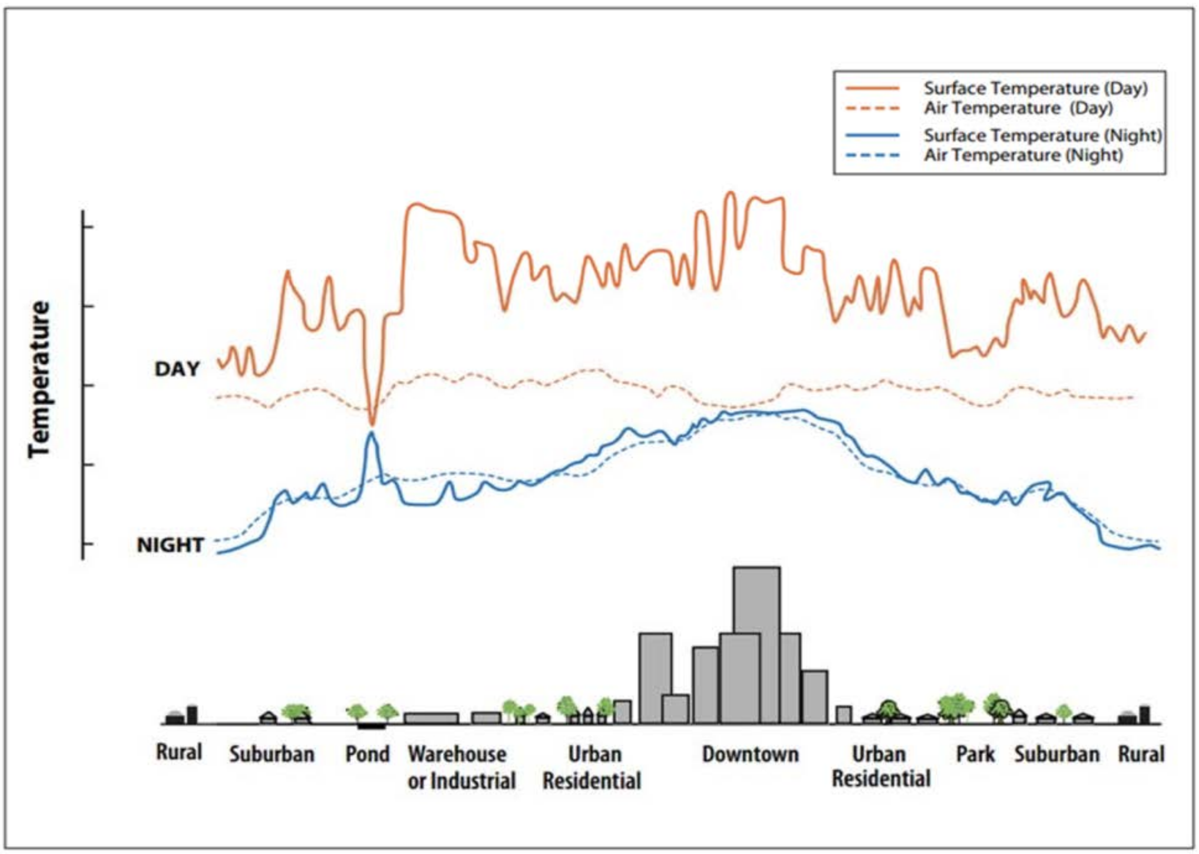

Figure 7.2 More detailed urban heat island profile[104]

7.2 Climate change projections

Climate change is accelerating. The accelerating climate warming trend led Pope Francis in November 2015 to state in an interview with Time Magazine, "Every year the problems are getting worse. We are at the limits. If I may use a strong word, I would say that we are at the limits of suicide."[105]The Spring 2020 National Oceanic and Atmospheric Administration greenhouse gas index illustrates this trend (see Figure 7.3).

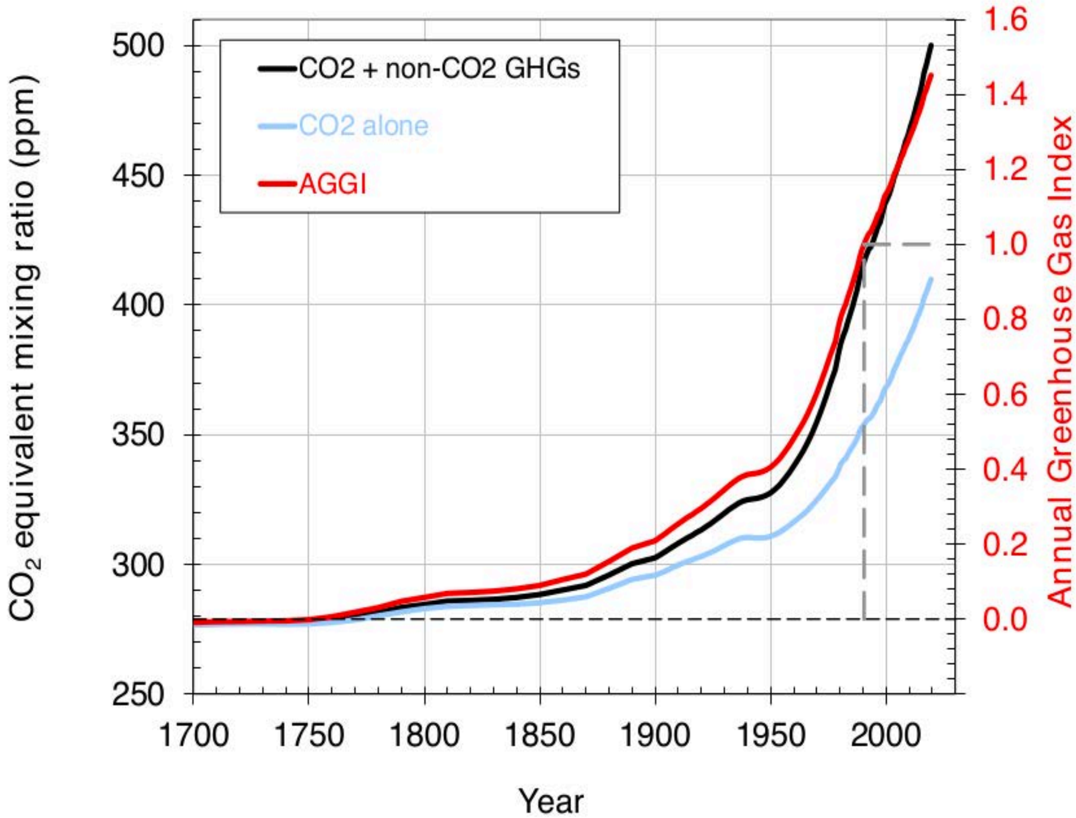

Figure 7.3. NOAA Annual Greenhouse Gas Index (updated Spring 2020).[106]

In *Mayor and City Council of Baltimore v. BP P.L.C.*, the City of Baltimore notes that "the relationship between increased average temperatures and extreme weather is non-linear—even a small increase in average daily temperatures will correlate to a substantially larger number of extremely hot days over the course of each year...Baltimore is expected to experience a threefold increase in the average number of days exceeding 90 degrees by 2050. By 2100, average annual temperatures in Baltimore are projected to increase by as much as 12°F. Baltimore has already seen an increase in the number of heat waves, and it is projected that by the end of the century, as many as 95 percent of summer days could reach extreme maximum temperatures."[107]

According to the U.S. Environmental Protection Agency, Maryland will see warmer temperatures, rising sea levels, and changing precipitation patterns due to climate change. By 2050, average annual temperatures across the U.S. Northeast are expected to increase by 4.0° F under a lower emissions scenario and by 5.1° F under a higher emissions scenario relative to 1975-2005 temperatures. Annual precipitation and frequency of heavy downpours are projected to increase, especially during winter and spring. On the other hand, average precipitation is not expected to change significantly in summer and fall, and with increasing temperatures, intensified evaporation will lead to drier soil. For these reasons, Maryland will likely see increased drought in summer and fall, and increased flooding in winter and spring. Sea level in Maryland is rising relatively rapidly, more so than in most coastal areas because the land is sinking. Rising seas lead to increased erosion and coastal flooding, among other adverse effects. [108]

7.3 Overview of Smart Surfaces

7.3.1 Cool roofs

Cool roofs have higher solar reflectance (often called albedo) than conventional dark roofs, which have a low solar reflectance. Solar reflectance, or albedo, indicates the fraction of solar energy that an object reflects. It ranges from 0 to 1, with 0 meaning an object reflects no solar energy and 1 meaning an object reflects all solar energy. (High albedo helps keep the areas such as snow or ice cool). Because of their higher solar reflectance, cool roofs reflect more sunlight and absorb less solar radiation than conventional, dark roofs. This means that cool roofs do not get as hot, reducing heat transfer to the building below and to the urban environment. Figure 7.4 below illustrates these concepts.

Cool roofs typically reflect the majority of solar radiation that reaches their surface—much of which is reflected back into space—and thus remain cooler throughout the day while reducing global warming. In contrast, dark roofs absorb the large majority of solar radiation, and their surface gets much hotter than that of a cool roof.

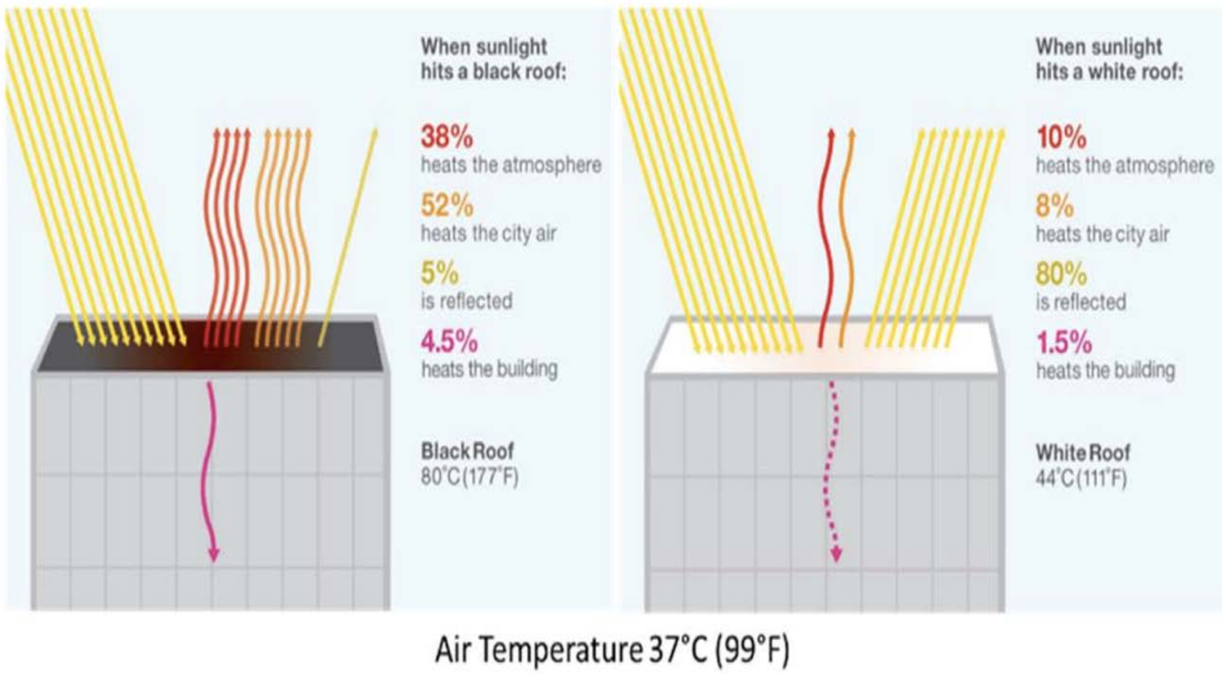

Figure 7.4 Comparison of a black roof and white roof on a summer afternoon (numbers do not sum due to rounding).[109]

Major benefits of cool roofs include ambient cooling, reduced energy use for cooling, reduced greenhouse gas emissions and global cooling, improved air quality, extended surface life (due to less thermal expansion and contraction) and reduced heat-related mortality. Other benefits include potential downwind cooling, and reduced stormwater runoff temperature. Potential drawbacks include potential for glare and increased energy use for heating due to increased roof reflectivity in the winter and winter shading by trees.

7.3.2 Green roofs

Figure 7.5. Example of a combination of cool roofs and green roofs.

Put simply, a green roof is a vegetative layer on a rooftop. More specifically, green roofs typically consist of drainage layer and soil layer on top of conventional roofing and waterproofing systems.[110] Figure 7.6 below shows conventional roofing structure and two green roof structures, one without a drainage system and one with a drainage system. Green roofs can be part of a new construction project or a retrofit project assuming structural requirements are met. Green roofs are typically installed on low slope roofs, and rarely on steep slope roofs.

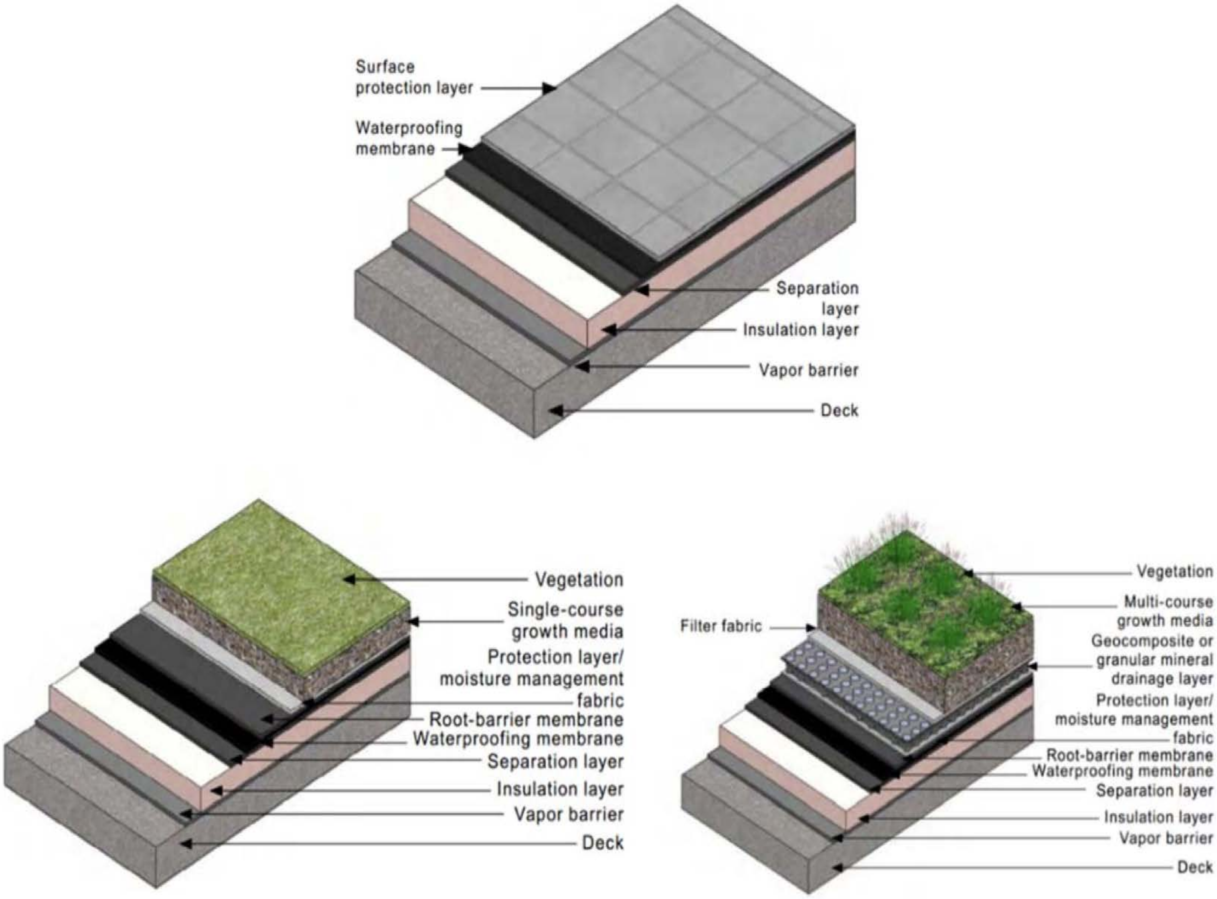

Figure 7.6. Examples of a conventional roof structure (top), green roof structure without a drainage layer (bottom left), and green roofs structure with a drainage layer (bottom right).[111]The solar reflectance of the black roof in Figure 7.6 is 0.05 and that of the white roof is 0.80.

There are two general approaches to installing green roof systems: (1) built-in place and (2) modular.[112] Built-in place green roof systems are installed as one continuous unit, whereas modular systems are installed as trays containing soil or a similar medium (referred to as growing medium in the industry) and vegetation. Modular green roofs are popular because they can be easily moved or removed if there are leaks or other issues; however, they are typically more expensive and may have lower stormwater retention rates (e.g., because of spacing between trays).[113] There is limited research into the performance differences between the two green roof system installation methods,[114] so, this report does not make a distinction between the two in cost-benefit analysis calculations below.

Major benefits of green roofs include reduced cooling and heating energy use, reduced greenhouse gas emissions, improved air quality and reduced heat-related mortality, reduced stormwater runoff, and reduced water pollution. Other benefits include downwind cooling, reduced stormwater runoff temperature, increased amenity and aesthetic value, and increased biodiversity. Potential drawbacks for some climes include increased humidity.

7.3.3 Solar PV

Solar PV converts sunlight into electricity. Combined with an inverter and other hardware (e.g., racking), solar PV panels provide electricity to the grid or to homes and buildings and offset electricity purchases from the grid.

Figure 7.7. Example of Solar PV.

There are three commonly cited PV sectors: residential, commercial, and utility scale. Utility-scale consists of large-scale PV power plants and is typically the least expensive on a unit basis due to economies of scale. Commercial and residential PV are considered distributed generation, meaning they produce electricity at the point of consumption, reducing line losses and providing shading to roofs. Distributed generation is typically located on rooftops (especially in cities where land is expensive), while utility-scale is typically ground-mounted and generally not near the point of consumption. This report focuses on PV on buildings.

Major benefits of solar PV include electricity generation, reduced greenhouse gas emissions, and improved air quality. Other impacts include shading benefits and the potential for UHI mitigation.

7.3.4 Reflective pavements

Reflective pavements work like reflective (cool) roofs. They have a higher solar reflectance than conventional pavements meaning that they reflect more solar energy, reducing the amount of heat gain and reducing urban surface temperatures. As with cool roofs, some of the reflected solar energy is reflected back to space, helping to slow global warming. Reflected solar energy may also impact nearby buildings and pedestrians (discussed in more detail in Section 9.4.3).

Figure 7.8. Example of a reflective pavement with a higher albedo than conventional pavement.

Benefits of reflective pavements include ambient cooling, reduced cooling energy use, reduced greenhouse gas emissions, global cooling, and improved air quality and reduced heat-related mortality. Other benefits include a potential increase in pavement life, reduced street lighting requirements, downwind cooling, and reduced stormwater runoff temperature. Potential drawbacks include potential for glare.

7.3.5 Urban trees

Major benefits from urban trees include ambient cooling, reduced energy use due to lower need for building cooling, reduced greenhouse gas emissions and global cooling, improved air quality, reduced heat-related mortality, and reduced stormwater runoff. Other benefits include downwind cooling, reduced stormwater runoff temperature, increased property value and aesthetic value, and increased biodiversity. Potential drawbacks are relatively small and include potential in some circumstances for increased humidity, increased emissions of biological volatile organic compounds, increased heating needs due to winter shading, and increased pollen production (increasing contribution to allergies).

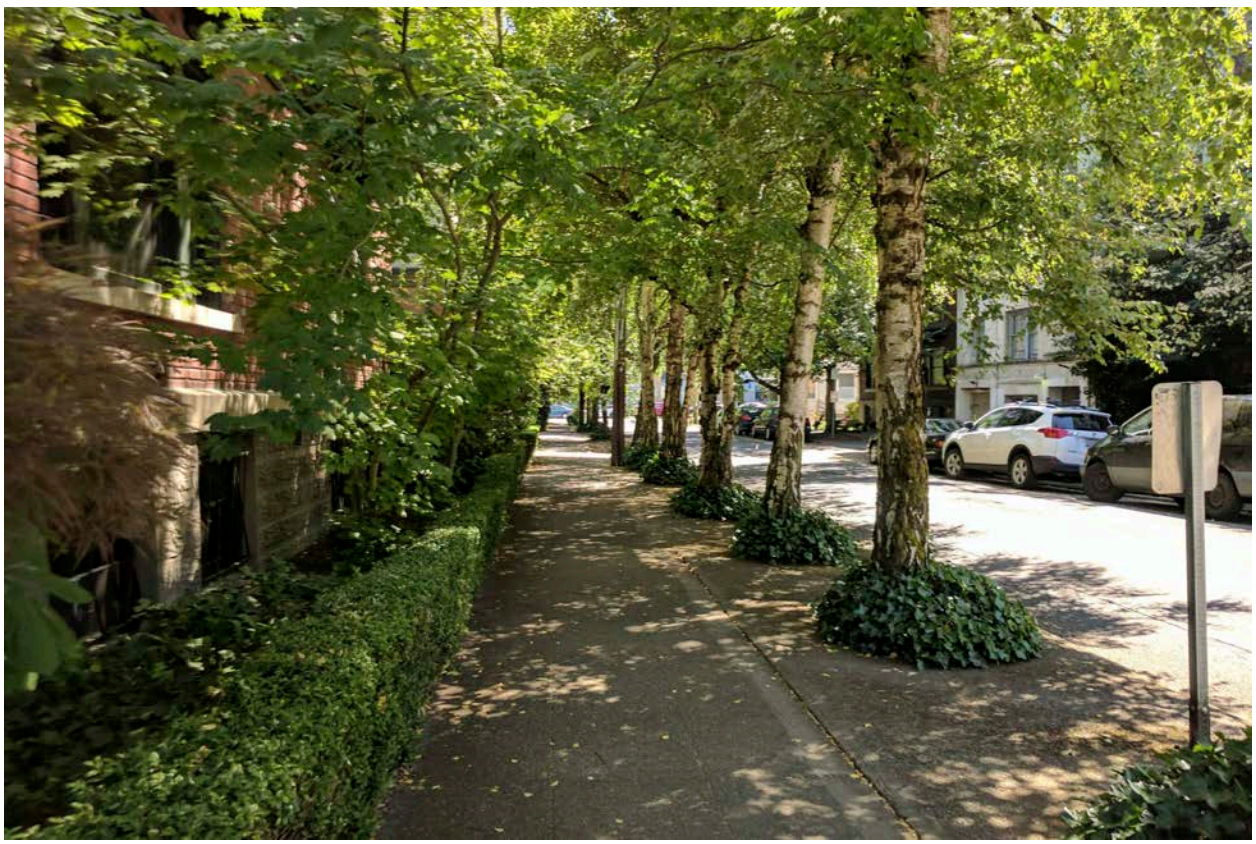

Figure 7.8. Example of Urban Trees.

7.3.6 Permeable sidewalks and parking lots

Permeable pavements are pervious surfaces that allow for stormwater infiltration and storage, as compared to conventional, impervious surfaces. This can be either permeable surfaces or impermeable surfaces such as a parking lot that drains into adjacent bioretention or tree trench that manage stormwater runoff. Major benefits of permeable sidewalks and parking lots include reduced stormwater runoff and flooding and reduced salt use due to less ice buildup. Other impacts which warrant further study include ambient cooling, which leads to reduced cooling energy use, reduced greenhouse gas emissions, improved air quality and reduced heat-related mortality, increased thermal comfort, and improved water quality.

Figure 7.9. Example of a porous pavement with a higher albedo.

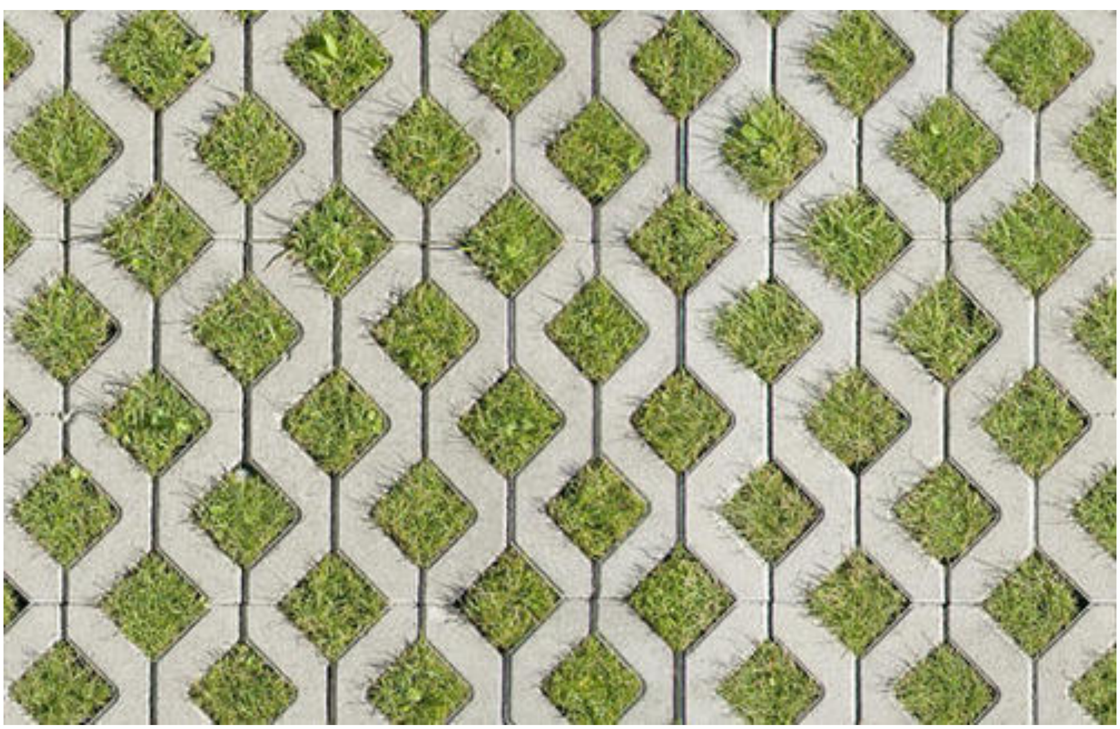

Figure 7.10. Example of a green, porous parking lot pavement.

8 Overview of Impacts

The Smart Surfaces solutions modeled in this report analyzes are well established: reflective roofs, reflective roads, green roofs, porous surfaces, rooftop PV, and urban trees. Each solution has different costs and benefits, and each has their advocates. However, city governments and affordable housing and other organizations, have not had a way to fully evaluate the cost-effectiveness of any of these solutions, either as standalone investments, as a combined investment, or in comparison with each other. The single largest gap in understanding and quantifying the benefits of these approaches—especially trees, cool roofs and green roofs—is the health-related benefits, which involves complicated impact pathways.

8.1 A note on direct and indirect impacts

The impacts of modifying the urban environment (e.g., installing cool and green roofs, and urban trees) may be best understood as falling into two main categories: (1) direct impacts and (2) indirect impacts. Direct effects occur at the individual building level. For example, the direct effect of installing a cool roof on a building is reducing building cooling load and energy costs. One example of an indirect benefit is the reduced cooling load for buildings that results from city-wide ambient cooling. Significant city-wide cooling requires widespread deployment of Smart Surfaces.

8.2 Energy and greenhouse gases

In the state of Maryland, grid electricity is substantially produced from fossil fuel-based sources. Natural gas accounted for 37 percent of the state's electricity in 2019 and coal accounted for 14 percent.[115] Baltimore electricity sources are generally becoming less polluting, and this decline in emissions/CO2 intensity of electricity is factored into the calculations.

Baltimore's objectives include reducing greenhouse gasses and shifting from fossil fuels to clean energy sources. Cool and green roofs directly reduce energy use for space conditioning by reducing heat gain and loss to the building below, making buildings more efficient and lowering energy bills. Rooftop PV reduces grid electricity purchases, and shades the roof, lowering consumption of fossil fuel fired electricity. A large portion of cooling energy reductions from cool roofs and green roofs occurs during periods of peak energy demand and can reduce the use of the least efficient and dirtiest generation capacity.[116] Rooftop PV tends to offset grid electricity use during peak demand periods, thereby reducing utility need to operate peaking power plants. Large scale deployment of cool and green roofs, reflective pavements, and urban trees reduce city-wide summer temperature. Lower ambient air temperature not only means lower cooling energy consumption, but also reduces peak electricity demand.

Buildings that require less energy and/or produce their own energy are also less dependent on the grid and more resilient.

8.3 Financial incentives

The state of Maryland has a renewable portfolio standard that was updated in May of 2019 to require that 50 percent of the state's renewable energy comes from renewable sources by 2030. This includes a minimum of 14.5 percent from solar power. The state's goals include reaching 100 percent renewable energy by 2040.[117] There are a host of financial incentives at the federal and state level. These include the federal ITC tax credit, discussed further in Section 9.3.2.4, and at the state level the Maryland Sales and Use Tax Exemption for Renewable Energy Equipment.

The Baltimore County Property Tax Credit for High Performance Buildings and Homes takes advantage of state authority that permits local governments to offer property tax credits for high performing buildings.[118]

8.4 Health

8.4.1 Ozone

Widespread deployment of cool and green roofs, reflective pavements, and urban trees would have large but diffuse health benefits. Ground-level ozone formation generally increases with higher air temperature, so lower summer air temperatures result in lower levels of ground-level ozone and decreased incidence of ozone-related health consequences (e.g., asthma, heart disease, and premature death).[119] Modeling studies demonstrate that ozone concentrations worsen with the higher temperatures caused by climate change.[120] Ozone reductions from ambient cooling due to deployment of Smart Surfaces reduce climate change-related ozone increases. Green roof vegetation and urban trees can also scrub the air of ozone pollution and ozone precursors, provided that low BVOC-emitting species are selected.[121]

8.4.1.1 Ozone basics

Ozone is a secondary pollutant formed when its two primary precursors, volatile organic compounds (VOCs) and nitrogen oxides (NOx), combine in the presence of sunlight. Ambient ozone concentration depends on a number of factors, including temperature, relative humidity, solar radiation, and wind speed.[122] As temperature increases, the rates of chemical reactions that create ozone increase, leading to greater ozone formation. Ozone levels tend to be highest during summer afternoons. The ozone season is typically defined as the beginning of May through the end of September.[123]

Ozone concentration is also dependent on the level of VOCs and NOx in the atmosphere—the rate of ozone production can be limited by VOCs or by NOx. Ozone precursors are emitted directly into the atmosphere by biogenic (natural) and anthropogenic (human) sources. The largest source of anthropogenic VOCs is motor vehicles.[124] At the regional and global scales, VOC emissions from anthropogenic sources are significantly larger than VOC emissions from vegetation. Combustion processes are the largest source of anthropogenic NOx emissions—electric power generation and motor vehicles are the two largest sources. Biogenic sources of NOx are typically much less significant than anthropogenic sources.

8.4.1.2 Health impacts of ozone

The Clean Air Act of 1963 requires EPA to regularly publish a scientific review of ozone. In EPA's most recent review, published in 2020, a panel of experts concluded that ozone pollution can cause serious health harm through multiple pathways.[125] The review found further suggestive links between ozone exposure and negative cardiovascular, nervous system, and reproductive health outcomes, as well as cancer and mortality. Figure 8.1 provides a more detailed overview of these outcomes.

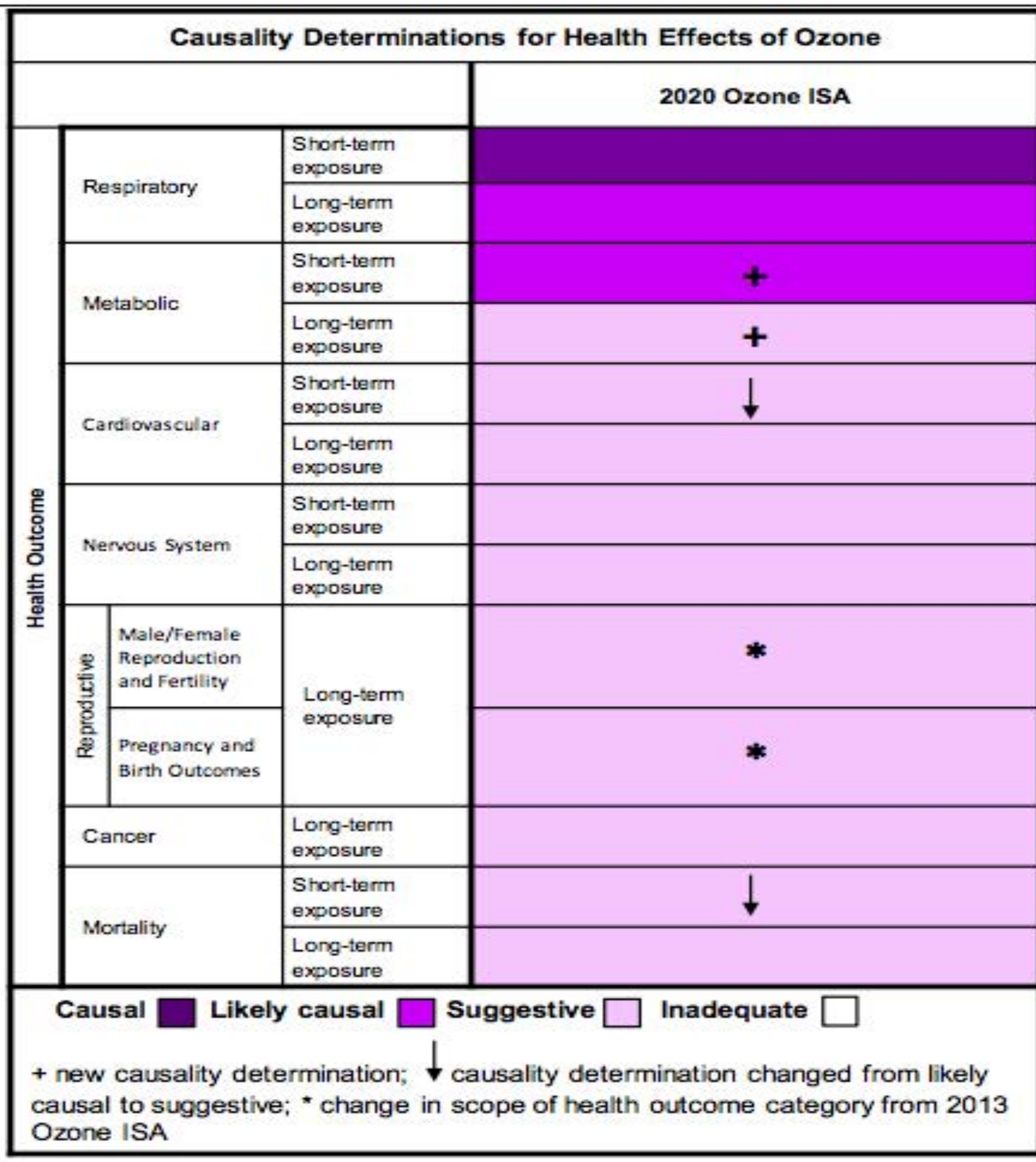

Figure 8.1. EPA's findings on the health impacts of ozone[126]

8.4.1.3 Ozone and temperature

Climate change is projected to increase ozone pollution and consequent negative human health effects. Bell et al. (2007) analyzed the effects of climate change on ozone concentrations in 50 U.S. cities and found that climate change can be expected to increase ambient ozone concentrations and thus harm human health.[127] Perera and Sanford (2011) analyzed the ozone-related health costs of climate change in 40 U.S. states and found that 1 part per billion (ppb) and 2 ppb increase in ozone concentration would increase health costs by $2.7 billion and $5.4 billion, respectively, in 2020.[128] (Few studies have examined the relationship between UHI mitigation and ozone concentration.[129] In general, these studies find reductions in ozone concentrations resulting from UHI mitigation measures such as increasing surface albedo.[vi]

8.4.2 PM2.5

Reductions in fossil fuel energy from deploying Smart Surfaces also contributes to reductions in fine particle pollution from power plants and reductions in related health impacts such as heart disease, asthma, and death.[130] Green roof vegetation and urban trees can also scrub the air of PM2.5 pollution.

8.4.2.1 PM2.5 description

There are two types of fine particles (PM2.5). Primary particles are emitted directly into the atmosphere (most commonly from burning fossil fuels), and secondary particles are formed through atmospheric chemical reactions of precursors.[131] Primary PM2.5 largely consists of carbonaceous materials (elemental carbon, organic carbon, and crustal materials like soil and ash).[132] Major sources of primary particles include fires, dust, agricultural processes, stationary fuel combustion (e.g., by electric utilities), motor vehicle operation, and industrial processes (e.g., metal smelters).[133] Secondary particles make up most of the PM2.5 pollution in the U.S.[134] Secondary PM2.5 is mainly made up of sulfates (formed from sulfur dioxide emissions), nitrates (formed from NOx emissions), ammonium (formed from ammonia emissions), and organic carbon (formed from VOCs).[135] The vast majority of sulfur dioxide emissions are from stationary fuel combustion (e.g., fossil fuel power plants). The dominant source of ammonia emissions is agricultural processes (e.g., animal feed operations).[136] In the Northeast, the main components of fine particle pollution are organic carbon and sulfates.[137]

8.4.2.2 Health impacts of PM 2.5

The Clean Air Act of 1963 requires the EPA to regularly publish a scientific review of Particulate Matter pollution. In 2009, the EPA released its second most recent Integrated Science Assessment (ISA) for Particulate Matter (PM).[138] In the review, an EPA panel of experts concluded that PM2.5 pollution can cause serious harm through multiple pathways. The American Lung Association summarized the EPA's findings (see Figure 8.2). EPA has since released one more Assessment for PM, in December 2019, which includes new evidence for increased harmful effects of PM2.5 exposure.[139]

[vi] The effect of UHI mitigation measures on air quality as a result of decreased vertical mixing remains an area for further research. Similarly for the effect of reflective surfaces with high UV reflectance on ozone formation.

EPA Concludes Fine Particle Pollution Poses Serious Health Threats

- Causes early death (both short-term and long-term exposure)
- Causes cardiovascular harm (e.g. heart attacks, strokes, heart disease, congestive heart failure)
- Likely to cause respiratory harm (e.g. worsened asthma, worsened COPD, inflammation)
- May cause cancer
- May cause reproductive and developmental harm

—U.S. Environmental Protection Agency, *Integrated Science Assessment for Particulate Matter*, December 2009. EPA 600/R-08/139F.

Figure 8.2. The American Lung Association's summary of the EPA's findings on the health impacts of PM2.5.[140] (Note: COPD stands for chronic obstructive pulmonary disease.)

According to the EPA's website, "the ISA is a critical part of the scientific basis for updating the NAAQS," or National Ambient Air Quality Standards.[141] EPA released its latest update in December 2020, in which it chose to retain the PM2.5 regulations from the previous (2013) NAAQS PM standards despite new evidence of PM2.5's harmful effects in the 2019 ISA for PM. For example, the 2009 ISA found evidence "suggestive, but not sufficient to infer" that PM2.5 causes cancer, while the 2019 ISA found that PM2.5 was "likely to be causal" of cancer. The 2019 ISA also included new evidence that long-term exposure to PM2.5 can harm the nervous system.[142]

Chris Zarba, the former director of the EPA Science Advisory Board, pointed to the new 2019 findings on the negative health impacts of PM2.5, saying that "with hundreds of thousands of Americans dying from COVID-19, a virus proven to be exacerbated by exposure to air pollution, and despite overwhelming scientific evidence linking air pollution with illness and death, it is incomprehensible that outgoing EPA Administrator Andrew Wheeler would lock in current thresholds for soot or fine particle pollution for another five years."[143] While the EPA, as of January of 2021, has not updated PM2.5 regulations, the growing science-based evidence demonstrating its harmful health effects should motivate cities such as Baltimore to act more aggressively to cut air pollution in order to protect the health of its residents and workers. (A more science-based Federal administration is more likely to accept new scientific and medical findings.)

8.4.3 Heat stress

Heat stress has many negative health outcomes, including premature death, and is expected to become more common as the planet continues to warm.[144] Furthermore, heat waves, which are expected to become more common with climate change, exacerbate urban heat islands (UHI).[145] Urban heat island mitigation through deployment of cool and green roofs, reflective pavements, and urban trees can help ameliorate the effects of heat stress.

The Centers for Disease Control and Prevention notes that extreme heat can cause discomfort and fatigue, heat cramps, increased emergency room visits and hospitalizations, and even death.[146] Heat is the leading weather-related killer in the United States.[147] The EPA also emphasizes that some populations face higher risks of death from heat-related factors. These groups include adults 65 and older, children, individuals with certain diseases such as respiratory or cardiovascular illnesses, those who are economically disadvantaged, and Black citizens.[148]

Extreme heat events are projected to be more frequent, longer lasting, and more severe as the climate warms.[149] Heat-related mortality is projected to increase by between 3,500 and 27,000 deaths per year in the U.S. by mid-century due to climate-related warming alone.[150] Considering the disproportionate impact of heat on certain populations, it should be noted that the mortality of citizens will likely be concentrated in lower-income communities and people of color. Therefore, efforts to mitigate heat stress should be focused on these, and this report provides detailed information regarding infrastructure-based solutions for doing so.

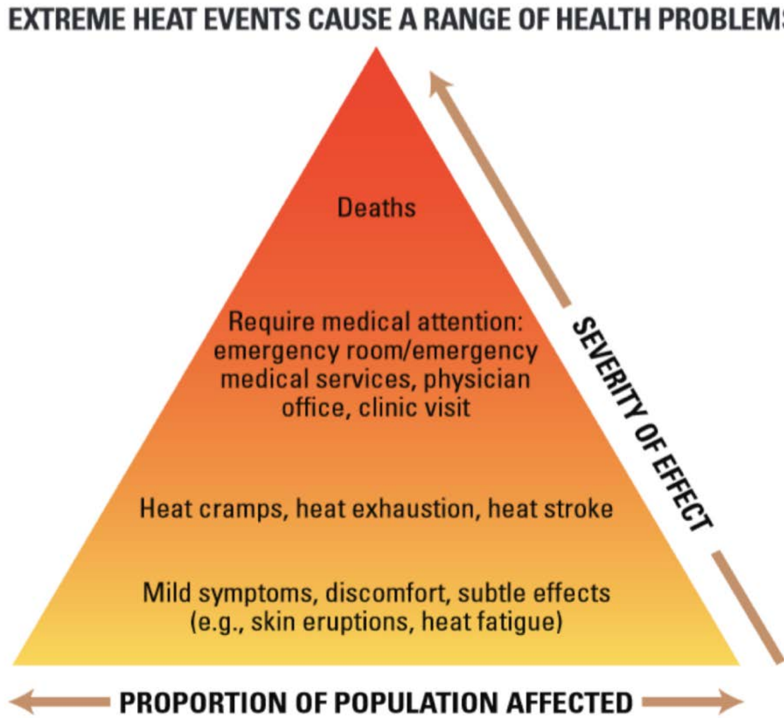

Figure 8.3. A visual representation of the number of health problems that are related to extreme heat.[151]

UHIs and climate change together are also expected to increase the number of extreme heat events in cities.[152] In addition to elevated daytime temperatures due to UHIs, cities take longer to cool off at night, so urban populations increasingly cannot recover from daytime heat and are thus more vulnerable to elevated temperatures in subsequent days.[153]

There are three ways that Smart Surfaces can reduce heat-related mortality: decrease outdoor temperatures, increase outdoor shade, and decrease indoor temperatures. Modeling studies have shown that UHI mitigation solutions can decrease urban heat-related mortalities by improving outdoor conditions.[154] However, SSC has not found adequate data/studies to quantify the heat-related mortality impact of changes in indoor conditions from the solutions analyzed in this report, despite the fact that the impact of indoor conditions may be significant.[155] This impact is particularly important for residents in homes without air conditioning or with inadequate air conditioning (not uncommon in low-income populations) and residents that live on the top floor of buildings.

8.5 Stormwater management in the Mid-Atlantic region

Stormwater management strategies provide extensive benefits. Pollutant capture and abatement in tree planters and bioswales protects downstream ecosystems and increases the safety of public recreation opportunities. Smart Surfaces—especially green roofs, porous parking lots and sidewalks, and tree planters—can also delay and minimize peak runoff, thereby reducing sewage backup flooding of residential properties and the volume of combined sewer overflows. The reduction of peak flows decreases the burden on the wastewater treatment plants in combined systems, so the facilities can continue removing nutrients effectively before discharge into water bodies.

The Smart Surfaces Coalition has already calculated stormwater management benefits in two other Mid-Atlantic cities, Philadelphia and Washington, D.C.; the latter is one of the leading cities in the nation on this issue and therefore a model for Baltimore. Water utility customers in the District of Columbia pay two distinct fees for stormwater management services on their monthly bills. DC Water, the water and sewer services provider for the D.C. metro area, collects the Clean Rivers Impervious Area Charge (CRIAC), and the Government of the District of Columbia charges a Stormwater Fee. The two fees exist because each organization is seeking to redress city-specific problems in stormwater management.

DC Water's CRIAC has three main purposes: reduce combined sewer overflow volume into the district's waterways, reduce chronic sewage flooding of residential properties, and reduce peak flows to the Blue Plains wastewater treatment plant.[156] These objectives will be accomplished through both distributed green infrastructure for site-level management and large tunnels to temporarily store runoff before treatment. Since Baltimore also has a combined sewer system, the CRIAC purposes are applicable to Baltimore, too.

Secondly, the District is required to obtain a discharge permit for their stormwater system, and as discussed in Section 6.2.3, Baltimore is also required to obtain a discharge water quality permit from the EPA. The District's Stormwater Fee covers the cost to manage and treat runoff pollution to comply with their permit,[157] and they use the funds to improve water quality before it reaches point discharge sources. For example, funded pollution control efforts in the district include street sweeping, tree planting, installation of green roofs and rain gardens, trash removal in streets, and ensuring that new construction and redevelopment projects incorporate green infrastructure.[158] Baltimore's Watershed Implementation Plan has outlined similar programs and projects. Section 10.6 will discuss the methodology used for calculating Baltimore's potential stormwater benefits, including strategies from D.C. and the City of Baltimore's own fees, discounts, and other incentives.

Lastly, the Smart Surfaces Coalition is currently quantifying stormwater management benefits associated with groundwater recharge, reduced property damages from decreased flooding, and increased property value. These benefits have yet to be finalized and therefore are not included in this report; that said, future investigations could determine that could make a significant contribution to Baltimore.

8.6 Employment estimates

Smart Surfaces are particularly jobs intensive and thus job creative. Adoption would require tree planting, the painting roads or roofs with reflective coatings, and the installation of green roofs or solar panels, all of which are very labor intensive.

This section addresses three main issues surrounding employment: the number of jobs Smart Surface adoption would create, the pay for these jobs, and ensuring that as many of these jobs as possible go the Baltimore citizens.

8.6.1 Job creation from Smart Surfaces

As of 2019 there were an estimated 9.5 million green jobs in the United States.[159] These jobs included installation of solar PV, green and reflective roofs, planting of trees, and adoption of other Smart Surfaces. The labor intensities of Smart Surface and clean energy adoption are much higher than the labor intensities of conventional energy sources. For example:

- A World Bank study estimated that wind and solar investment create 13.5 jobs per million dollars of spending, and that building retrofits which promote energy efficiency create 16.7 jobs per million dollars of spending. This is more than 3 times the 5.2 jobs per million dollars in spending for oil and natural gas.[160]
- A detailed job analysis found that 5.3 jobs were created per million dollars of fossil fuel investment, and over 3 times this, 16.7 jobs, were created per million dollars invested in clean energy (energy efficiency and renewable energy). Importantly, this analysis also documents the higher job quality and higher pay nature of clean energy jobs relative to fossil fuel employment.[161]

Each Smart Surface technology has distinct job creative potential, as discussed in the following sections, but on average Smart Surfaces are about three times as job creative as the economy as a whole.[162]

We provide estimates for job years created in the United States per million dollars invested for each Smart Surface technology as shown in Table 6.1. A job-year is the equivalent of full-time employment for one person for the duration of one year. These estimates are documented below and reflect correspondence with industry professionals.

In a typical employment analysis, three categories of job creation are estimated, direct, indirect, and induced. For this work we estimate only direct jobs. Omitting indirect and induced jobs reduces total employment impact estimates, and therefore full job creation from Smart Surfaces is substantially larger than modeled in this section.

8.6.2 Estimating direct job creation from Smart Surfaces

There are many approaches to estimating direct jobs impact. While we reference various studies, we use a transparent approach based on estimating jobs impact per million dollars spent, providing a straightforward and transparent basis for estimating and comparing jobs impacts.

Technology-specific employment estimates are detailed in Section 9. Direct jobs impacts by technology are presented in Table 8.1 below.

Table 8.1. Estimated job years created per million dollars invested in different Smart Surface solutions.

Category	Direct job years
paint roofs, roads and parking lots	17
trees	14
green roofs	14
solar panels on schools, low-income	11
porous surfaces	11

8.6.3 Estimating average salary and employee cost

A recent federal study found that employees in the renewable energy sector earned an average of $48,000 annually which is equal to an hourly wage of $23.89.[163] This is above the national median hourly wage in 2019 of $19.14, which is equal to an annual salary of $38,000. According to US News and World Report, solar photovoltaic installers made a median salary of $42,680 in 2018.[164] According to the same analysis, the median salary for painters is $38,940. For tree planters in the US, individuals make an average salary of $32,803 per year which is equal to about $16 per hour.[165]

These findings suggest an annual average salary range of $35,000-40,000 per year for employees working on Smart Surfaces, including new and very experienced workers, with an hourly salary of at least $15 and hour for workers in the Smart Surface fields. It is worth noting that new workers typically make less money than experienced workers. As cities undertake projects to paint roofs and roads, plant trees, and add green roofs and solar, they will expand the workforce substantially through new hiring—and employees will tend to be new workers with relatively lower pay. [vii]

The total or loaded cost of an employee is greater than their annual salary, as employers will have to cover additional costs associated with an employee. These additional costs commonly range in estimates from 18%–40%.[166] These costs vary and are typically lower for new workers, and higher for long term employees. Since many new hires for Smart Surface adoption will likely be newer workers—and since it is important that they have substantial training, support, and benefits (including for new Baltimore employees)—we estimate additional costs on top of salary to be above industry average, at 30%–40%.

To reiterate, we assume a higher additional cost to allow for substantial training, worker support and benefits which increases total cost per Smart Surfaces employee from the previously mentioned $35,000–$40,000 range. Our analysis suggests an all-in cost per year for an average Smart Surface employee of about $50,000 per year. This is the average loaded cost of a Smart Surface employee that we use, and as noted, it assumes above average funding for training, support, and benefits.

8.6.4 Percent of new Smart Surfaces jobs that go to Baltimore residents

For cities to realize maximum employment benefits from rapidly expanding Smart Surfaces, green jobs should be directed as much as possible to city residents. In a time of high unemployment, moving Baltimore city residents off city unemployment rolls and into tax paying jobs creates a great deal of value to the city including reduced expenditures and increased revenues.

Early investment in training, an expansion of employment, and the growth of tree planting and green roof industries in Baltimore would also position Baltimore well in a number of fast growing and labor-intensive industries. These are jobs that are attainable for people with a range of education levels and involve substantial training and pathways to management and job growth.

We assume that Smart Surface hiring programs include substantial new employee training, support, and retention programs and perhaps in-city hiring preferences—features that are common in larger city programs engaged in expanding clean energy. As noted above, we have included higher than average overhead costs to provide adequate funding for recruitment, training, and support of city residents to ensure that employment skews toward city residents.

[vii] This suggest the estimated salary average of $35,000 - $40,000 may be on the high side.

Both the adoption of trees and green roofs require substantial land to allow for the growing of tree saplings and green roof trays. As noted above, green roofs consist of trays that include hardy, low water use plants like sedum that are then transferred onto and installed on roofs.

If the trees and plants for green roof trays are grown on land in Baltimore, and the city should offer strong training programs and a preference for employing Baltimore citizens. This type of program could, ideally, include Baltimore providing land for a tree nursery and a facility for growing green roof trays required for green roofs.

Baltimore has a host of solar PV installers that provide a strong basis for the expansion of Baltimore's creation and assembly of solar systems.

Green roofs and urban trees are fast-growing, labor-intensive sectors that can take advantage of Baltimore's relatively low-cost land. By repurposing unused large adjacent lots as long term zero cost leases to grow green roofs and trees, Baltimore could help build out 3 substantial new job areas for its citizens: green roofs, trees, and solar assembly.

We assume 50% of employment growth from scaling Smart Surfaces accrues to city residents and to the city and its tax base.[167] Developing an in-city tree nursery and green roof tray facility would strengthen in city employment.

9 Quantification of Smart Surfaces Costs and Benefits

9.1 Cool roofs

This section explores the basic principles of reflective/cool roofs and their potential impacts. Major benefits include ambient cooling, reduced energy use for cooling, reduced greenhouse gas emissions and global cooling, increased roof life, and improved air quality and reduced heat-related mortality. Other benefits include downwind cooling and reduced stormwater runoff temperature. Potential drawbacks include glare and increased energy use for winter heating.

9.1.1 Cool roof basics

9.1.1.1 Low slope and steep slope roofs

There are two general classes of roof: low slope and steep slope. Low slope (or flat or almost flat) roofs[viii] are common on commercial buildings, multifamily housing, and row homes. Common types of low slope roofs are built-up roofing, modified bitumen, and single-ply membrane roofing. The most common cool roof options for low slope roofs are coatings and membranes.

Steep slope roofs[ix] are most common on single-family detached homes and some row homes. Asphalt shingles are by far the most common material for steep slope roofs. Other steep slope roofing options include metal roofs, tile roofs, and wood shingle roofs. Cool steep slope roofs are much less developed and less frequently deployed compared to cool low slope roofs.

As cool roofs age, their solar reflectance reduces due to weathering and accumulation of dirt. As a result, aged solar reflectance is the standard reflectance metric for cool roofs used in codes, laws, and research. The 3-year aged solar reflectance is the industry norm, and was developed by the Cool Roof Rating Council,[168] a nonprofit membership organization (and member of the Smart Surfaces Coalition) that maintains credible, independent roof surface characteristic ratings and data and that provides industry-wide product testing and rating. All major building codes such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and International Code Council (ICC)) reference Cool Roof Rating Council standards.

[viii] No more than 2 inches of vertical rise over 12 inches of horizontal run
[ix] Greater than 2-inch rise over 12-inch run

Conventional roofs have ranges of solar reflectance from 0.05–0.20, depending on type.[169] This report assumes a solar reflectance of 0.18 for conventional low slope roofs. Low slope cool roof solar reflectance also depends on roof type. Multipole low slope cool roof products are available that have 3-year aged albedos above 0.7. This report assumes that low slope cool roofs have an aged albedo of 0.7. Table 9.1 below presents the solar reflectance values used in this analysis.

Because asphalt shingles are the most common type of steep slope roof, this analysis uses their albedo as the baseline for steep slope roof albedo. The albedo of non-cool asphalt shingles generally ranges from 0.05-0.15.[170] This analysis, however, assumes the existing average steep slope roof albedo in Baltimore is 0.18 (i.e., on average, roofs absorb 82% of sunlight), based on guidance provided by experts in the field.[171] Steep slope cool roofs are typically cool-colored—meaning they have high solar reflectance in the near infrared band of sunlight and low reflectance in the visible band—and often have a similar color to conventional steep slope roofs (see Figure 9.1). Currently, there are many steep slope roofing products on the market that achieve 3-year aged albedos of 0.4 and higher, reflecting continuing innovation in the field.[x] It is possible to achieve albedos as high as 0.7.[172] Based on the guidance of experts in cool roof technologies,[173] this analysis assumes an aged albedo of cool steep slope roofs of 0.4. Figure 9.1 below shows cool-colored roof tiles measured by Lawrence Berkeley National Laboratory. Table 9.1 below presents the solar reflectance values used in this analysis.

Table 9.1. Conventional and cool roof albedos used in this report.

ROOF SLOPE	SOLAR REFLECTANCE	
	Conventional roof	Cool roof
Low slope	0.18	0.70
Steep slope	0.18	0.40

[x] Based on analysis of Cool Roof Rating Council Rated Product Directory in December 2020: https://coolroofs.org/directory

Figure 9.1. Cool-colored tiles (top row) look like conventional roof tiles (bottom row) but have higher solar reflectance.[174]

9.1.1.2 Installation and maintenance costs

Cool roof installation and maintenance costs presented in this report are based on recent literature and guidance from roofing professionals.[175] Roof replacement, rather than restoration, is the norm when a roof begins to show significant signs of aging.[176] Low-slope cool roofs are the same or marginally higher cost than their conventional equivalent.[177] Based on literature review and industry discussions, we assume an installation premium of $0.10 per square foot for low slope cool roofs. There is typically a higher cost premium for steep slope cool roofs. We assume an installation premium of $0.30 per square foot for steep slope cool roofs. Maintenance requirements for cool roofs are like those for conventional roofs, but cool roofs can be washed to maintain a higher albedo. There are two cleaning options for cool roofs: power washing and mop cleaning (or equivalent). We assume a maintenance cost of $0.10 per square foot every 4 years, based on guidance from experts in the field.[178] Table 9.2 below summarizes cool roof cost premiums.

Table 9.2. Cool roof cost premiums

PREMIUM	COST	
	Low slope	Steep slope
Installation	$0.10/SF	$0.30/SF
Maintenance	$0.10/SF every 4 years	$0.10/SF every 4 years

9.1.2 Impacts of cool roofs

9.1.2.1 Cool roof impact summary

Table 9.3, and Figures 9.2 and 9.3, below summarize the costs and benefits of cool roofs for Baltimore. There are more benefits than costs excluded from cost-benefit results, and excluded benefits very likely have a much higher value in aggregate than excluded costs, so our findings tend to underestimate the benefits and the net present value of cool roofs.

Table 9.3. Cool roof cost-benefit impact table (a "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact).

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Direct cooling energy reduction (+)	X	
Direct heating energy penalty (-)	X	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
Peak energy load reduction (+)		X
HVAC air intake temperature energy impact (+)		X
GHG emissions reduction (+)	X	
Global cooling (+)	X	
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Heat-related mortality reduction (+)	X	
Employment (+)	X	
Increased roof life (+)	X	
Downwind cooling (+)		X
Downwind warming (-)		X
Reduced stormwater runoff temperature (+)		X
Glare (-)		X

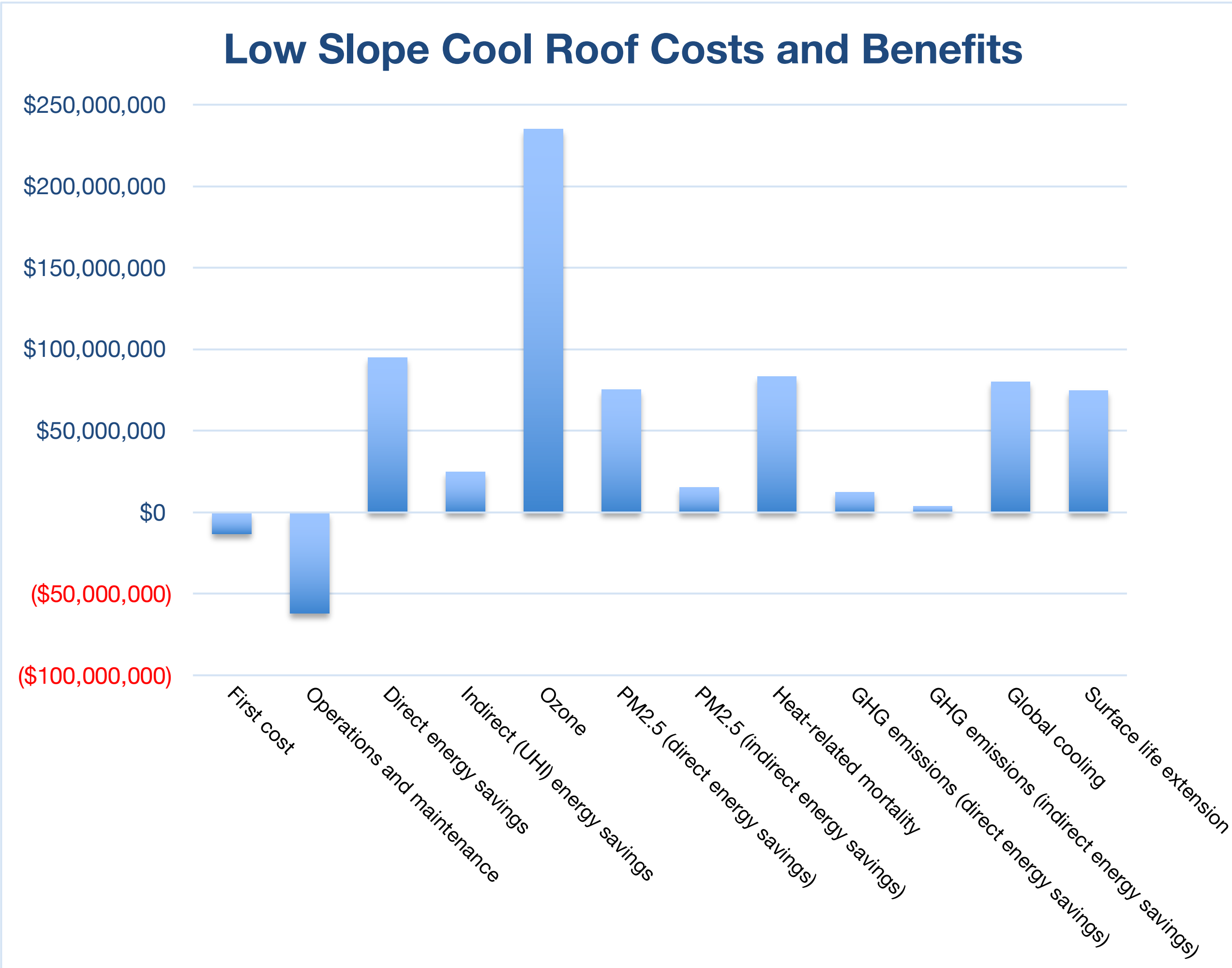

Figure 9.2. The cost and benefits of low slope cool roofs for the 20-year scenario in dollar value (costs are shown as negative and benefits are positive)

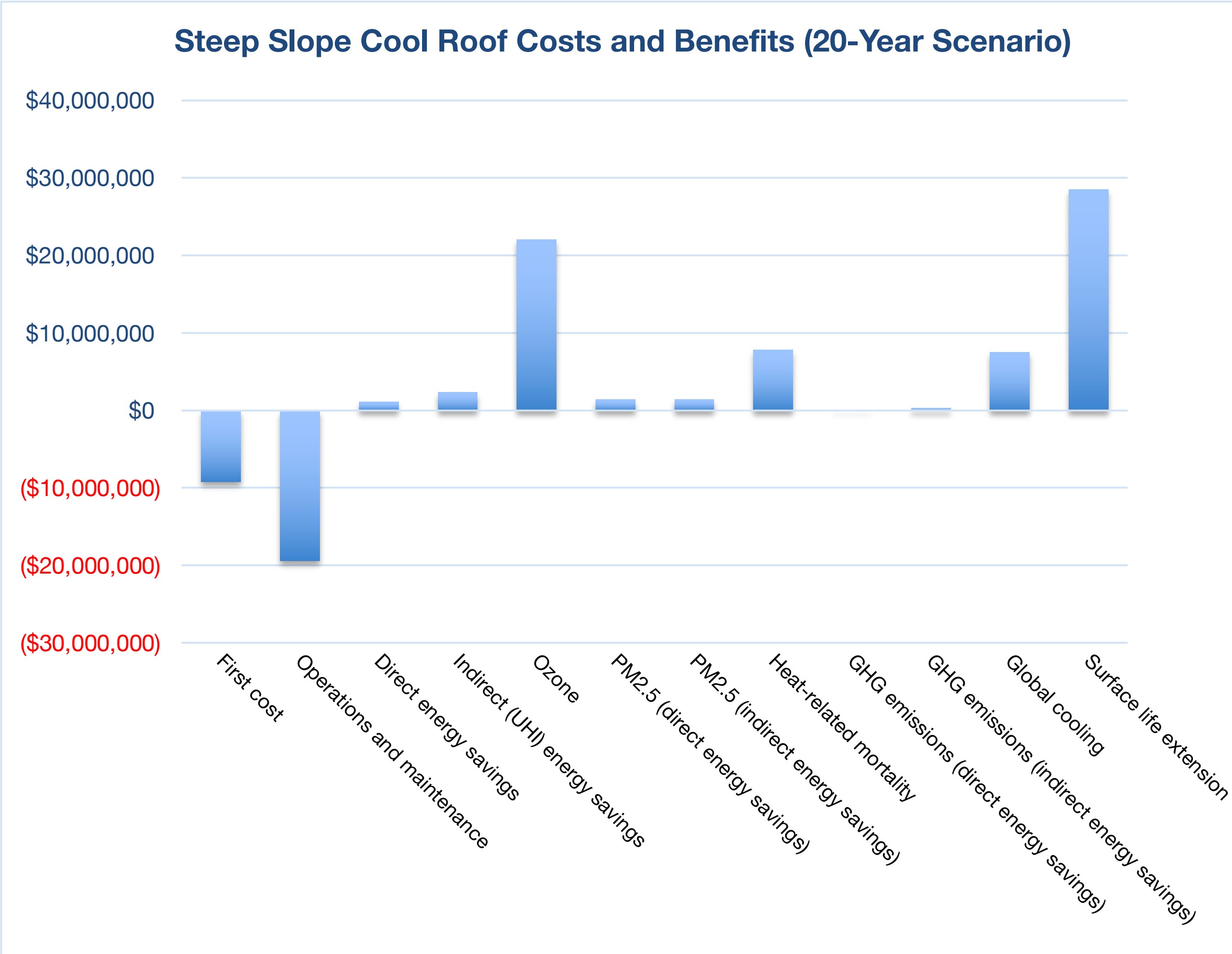

Figure 9.3. the costs and benefits of steep slope cool roofs for the 20-year scenario in dollar value (costs are shown as negative and benefits are positive)

9.1.2.2 Increased roof life

Cool roofs last longer than conventional roofs due to reduced thermal expansion and contraction and reduced UV radiation absorption.[179] For this reason, and based on guidance from roofing experts, we estimate that the first cost and maintenance premiums for cool roofs, both low-slope and steep-slope, will be offset by the financial benefit of extended roof lifespan.[180] The surface life extension benefit is $0.45 per square foot for low slope cool roofs and $0.60 per square foot for steep slope cool roofs. In essence, more reflective, longer lasting surfaces pay for their higher initial cost and higher O&M costs because they last longer, hence delaying and/ or avoiding the large expense of replacement.

9.1.2.3 Direct energy use

Because the surface temperature of a cool roof is lower than that of a conventional roof, less heat is transferred to the building below and to the air above. This means that a building with a cool roof requires less energy for cooling in the summer but can require slightly more energy for heating in the winter. The reduced solar heat gain in the winter (called the "heating penalty") is much less than cooling energy savings[181] because there is less solar radiation during the winter due to lower sun position, and due to shorter days, increased cloudiness, and the potential for winter snow coverage. Furthermore, peak demand for heating typically occurs around sunrise, which is when conventional and cool roofs are roughly the same temperature. Section 10.1 provides an overview of methods and assumptions used to estimate this benefit.

In addition to direct energy use impacts, cool roofs reduce peak electricity demand and demand charges, which benefits utilities because it reduces peak loads and some utility customers.[xi] Cool roofs can reduce air intake temperature of heating ventilation and air conditioning (HVAC) systems, reducing cooling energy consumption. For citations and further explanation of these benefits, see Section 9.1.2.8.

9.1.2.3.1 Factors that impact direct energy savings

The size of direct energy savings/penalties depends on several factors, including the thermal properties of the roof assembly, the operating schedule of a building, and HVAC equipment efficiencies.[182] Savings/penalties will be different in residential and commercial properties because of differences in design, occupancy, and HVAC schedules.[xii]

Energy loss through the roof is reduced by additional insulation, so buildings with well insulated roofs experience lower heat transfer and thus lower both summer cooling and winter heating bills. Studies from Princeton University show that insulation levels are the dominant factor controlling heating needs during the winter, and that albedo is the dominant factor controlling cooling energy needs during the summer.[183]

Heat transfer between floors in a building is minimal, so only the top floor of a building will experience material direct energy impacts from reduced roof heat transfer—for example from a reflective roof.[184] Therefore, the more floors a building has, the smaller

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[xi] Demand charges are sometimes referred to as capacity charges.

[xii] The ratio of cooling savings to heating penalty per square foot of roof area for commercial buildings is typically higher than that for residential buildings because commercial buildings are typically occupied and conditioned when cooling demand is at its peak and heating demand is at its minimum (i.e., during the day), while residential buildings are primarily occupied and conditioned while cooling demand is at its minimum and heating demand is at its peak (i.e., during the evening, night, and morning). In other words, cooling savings for commercial buildings tend to be larger than for residential buildings. And conversely, heating penalties for commercial buildings tend to be smaller than for residential buildings.

the percentage impact of a cool roof on total building energy consumption—although absolute direct building energy impacts are unchanged by the number of floors.

Direct energy savings depend on climate. For example, a broad modeling study found that cooling energy savings generally increase in warmer climates, while heating penalties generally increase in cooler climates.[185] The study estimated the load change ratio—the increase in annual heating load divided by decrease in annual cooling load—for commercial buildings around the country. A value of 1 means that the savings and penalty exactly offset each other and a load change ratio less than 1 means that the cooling load decreased more than the heating load increased, resulting in a net energy savings. In the Mid-Atlantic, the load change ratio for office buildings ranges from 0.18 to 0.34. In other words, the heating energy penalty is equal to about one quarter of the cooling energy savings when a cool roof is installed on an office building in Baltimore. In a warming world, summer cooling benefits will dominate winter heating penalty by a larger and larger multiple.

9.1.2.4 Ambient cooling and indirect energy

9.1.2.4.1 Ambient cooling

Reflective roofs stay cooler than conventional roofs, which reduces heat transfer to the urban environment. At large scale, this can materially reduce urban air temperatures, reduce the UHI, and effectively offset some or all the warming from climate change. A literature review calculated a relationship between urban albedo and air temperature based on data from UHI mitigation modeling studies. This study found that for each 0.1 increase in urban albedo, average urban air temperature decreases by 0.3°C (0.5°F) and peak temperature decreases by 0.9°C (1.6°F).[186] The relationship between urban albedo and average air temperature is much better defined than the relationship between urban albedo and peak air temperature.[xiii]

UHIs are highly location specific, so it is preferable to have a location specific ambient cooling analysis. Fortunately, a 2014 study by Li et. al. examines UHI mitigation in the Baltimore-Washington metropolitan area.[187] This study found albedo increases are effective at reducing UHI. Li et. al. (2014) is discussed in more detail in Section 10.3.

Ambient cooling has a broad range of benefits. This report does not directly estimate the value of ambient cooling from cool roofs, rather it estimates the benefits of ambient cooling through energy use reductions (this section) and related GHG emissions

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[xiii] The R2 of the regression for urban albedo and average air temperature is high, but data for urban albedo and peak air temperature is more scattered. The study does not report the R2 for the relationship between urban albedo and peak air temperature.

reductions (Section 9.1.2.5), improvements in air quality (Section 9.1.2.6), and declines in heat-related mortality (Section 9.1.2.6.3).

9.1.2.4.2 Indirect energy

As noted above, a city-wide switch from conventional, dark roofs to cool roofs can have a substantial impact on urban summer air temperature, leading to city-wide net energy savings.[xiv] The cooling effect is apparent in the cooling season (summer) and the heating season (winter), but its effect is much smaller during the heating season for reasons discussed above in the section on direct energy. Indirect energy savings/penalties are also smaller than direct energy savings/penalties. For example, a 2005 study from Lawrence Berkeley National Lab estimates that indirect electricity savings from city-wide installation of cool roofs and shade trees are less than one-fifth of combined direct and indirect electricity savings.[188][xv]

The scale of indirect energy savings/penalties from cool roof installation depends on the city building stock. For example, as average HVAC efficiency in a city increases, the indirect energy savings decreases. Similarly, as the insulation level (e.g., R-value) of building envelopes increases, the net indirect energy savings decreases. Building occupancy patterns also play a role in the scale of the indirect energy impact.[xvi] Section 10.3 provides an overview of methods and assumptions used to estimate this benefit.

9.1.2.5 Climate change mitigation

9.1.2.5.1 Greenhouse gas emissions reductions

Anthropogenic (human-caused) greenhouse gas (GHG) emissions are the dominant factor driving global climate change.[189] One of the main sources of anthropogenic GHG emissions is energy use in buildings. In 2018, commercial and residential buildings accounted for about 38% of U.S. GHG emissions.[190] Reducing energy used for space conditioning from cool roof installation reduces building related GHG emissions.

9.1.2.5.2 Global cooling

Cool roofs reflect more sunlight back into space than conventional roofs, thereby causing negative radiative forcing[xvii] and reducing global warming. Studies have found that increasing the albedo of one square foot of roof by 0.25 is equivalent to a one-time GHG offset of between 5.8 and 7.6 kg CO2e.[191] Because the global cooling impact can be large, this analysis includes this important and often overlooked impact.

[xiv] Cooling energy savings as well as smaller heating penalties.
[xv] Electric heating penalties are included in the electricity savings calculations.
[xvi] For instance, as the ratio of commercial to residential buildings increases, cooling energy savings will increase and the heating energy penalties decrease. This is because commercial buildings are typically occupied when cooling demand is at its highest and heating demand is at its lowest.
[xvii] Radiative forcing is the difference between the radiant energy received by the Earth (from the Sun) and the energy Earth radiates to space.

The impact of roof albedo changes on Earth's radiative forcing remains an active area of research. One of the key scientific questions relates to the impact of surface albedo changes on cloud formation.[192] However, clouds are one of the most complex aspects to climate modeling, with no clear conclusions, so urban-climate scientists commonly ignore or discount the impact of urban albedo changes on cloud formation.[193][xviii] Given lack of any consensus on impact, this unsettled issue is outside the scope of this report.

The methods and assumptions used to estimate cool roof climate change mitigation impact are described in Section 10.4.

Figure 9.4 shows cool roof climate change mitigation pathways.

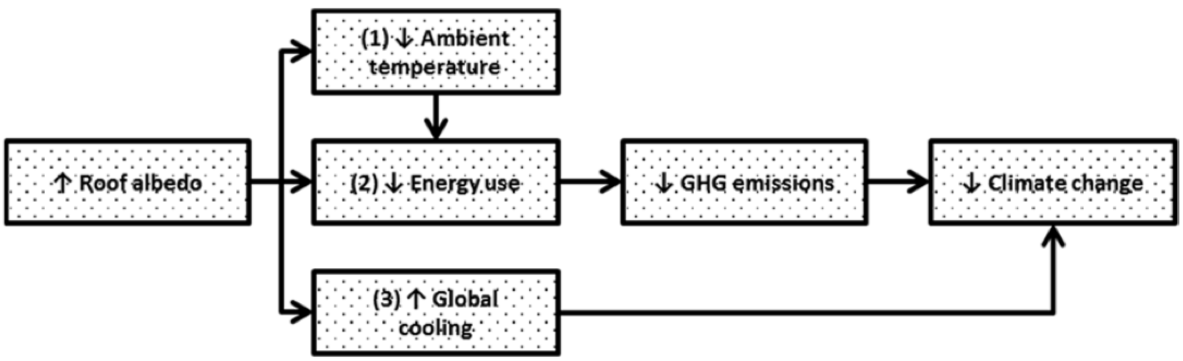

Figure 9.4. Cool roof climate change mitigation pathways (note: up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.1.2.6 Improved air quality and health

9.1.2.6.1 Cool roofs and ozone

Increasing urban albedo indirectly reduces ambient ozone concentrations by: (1) decreasing ambient temperature; and (2) decreasing summertime building energy use. As discussed above in Section 8, the chemical reactions that form ozone are temperature dependent, so decreasing ambient temperature decreases ambient ozone concentration. Decreasing ambient temperature also indirectly reduces summertime building energy use. Cool roofs directly reduce summertime building energy consumption by reducing solar heat gain and by reducing urban temperature, in turn reducing city–wide cooling loads. Decreased summertime building energy use leads to

[xviii] And note that urban areas already increase cloud formation because of particulates they produce.

decreased emissions of ozone precursors from fossil fuel power plants that are a major source of ozone precursor emissions. In general, as ozone precursor emissions decline, ozone formation declines as well.

Figure 9.5 shows the pathways through which cool roofs can reduce ozone levels. However, due to the complexities involved in photochemical air quality modeling, this report does not include the benefit of precursor emissions reductions. This report discusses the methods, assumptions, and pathways in more detail in Section 10.5.

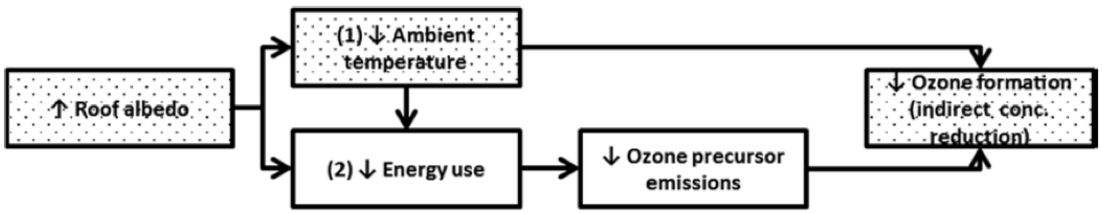

Figure 9.5. Cool roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results).

9.1.2.6.2 Cool roofs and PM2.5

Cool roofs reduce PM2.5 pollution directly by decreasing building energy use and indirectly by decreasing ambient temperature, which in turn reduces building energy use. Reducing building energy use results in decreased emissions of PM2.5 and PM2.5 precursors, decreasing primary and secondary PM2.5 pollution.

Figure 9.6 shows the PM2.5 concentration reduction pathways of cool roofs. This report describes PM2.5 impact estimation methods and assumptions in Section 10.5.

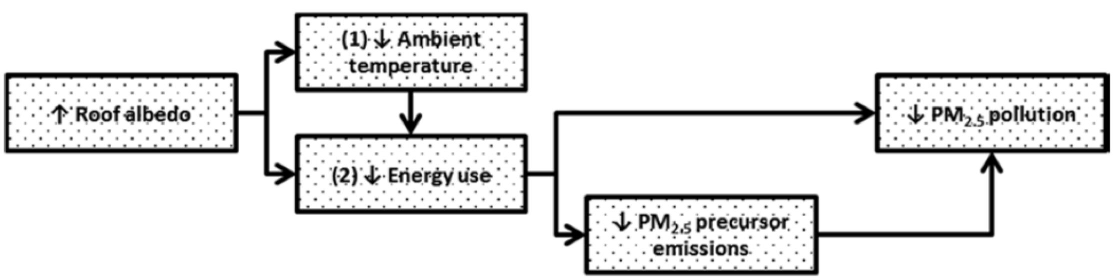

Figure 9.6. Cool roof PM2.5 concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.1.2.6.3 Cool roofs and heat-related mortality

Studies show that UHI mitigation solutions like cool roofs decrease urban heat-related mortalities by reducing air temperature.[194] As noted in Section 8.4, there are two pathways by which cool roofs can reduce heat-related mortality: (1) improving outdoor temperature conditions and (2) improving indoor temperature conditions. This report did not find sufficient rigorous work documenting the potential for cool roofs to reduce heat-related mortality by improving indoor conditions, so this benefit is not estimated in this report. However, this benefit is probably significant[195] and warrants further research.[xix] Because this analysis does not include the heat-related mortality impact of cool roofs from improving indoor conditions, heat-related mortality benefit estimates in this report should be considered conservative. This report describes heat-related mortality benefit estimation methods and assumptions in Section 10.5.

9.1.2.7 Cool roofs and employment

For resurfacing city roofs, roads, and pavements we estimate that 80% of cost is for labor in the city, with a comparatively small proportion of overall cost expended on products such as paints, brushes, and other tools.

Based on literature review and industry discussions, we estimate the number of direct jobs created per one million dollars invested. For painting roofs, roads, and pavements, the large majority (about 80%) of cost to the employer comes from labor in the city, i.e., paying painting crews, with limited costs from paints, brushes, etc. $800,000 (80% of $1 million) pays for 16 job years at $50k/job. We estimate that the other $200,000 invested in a project would go to paint and other materials and equipment. These products are made in factories that are likely remote and that have much higher capital and equipment costs, as well as lower labor input, yielding on the order of 5 job years per million dollars. This is equal to average labor intensity across the economy as a whole.[196] The $200,000 that goes to materials made in factories therefore creates 1 additional job. We estimate that a total of 17 direct job years are created per million dollars spent on reflective roofs, parking lots, and roads.

9.1.2.8 Other impacts of cool roofs

9.1.2.8.1 Reduced HVAC air intake temperature

One consequence of lower surface temperatures on cool roofs is lower near-roof surface air temperatures. If HVAC components are located on the roof, lower near-roof-surface air temperatures may cause increased air conditioning efficiency and decreased energy use because the air conditioner does not need to remove as much

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[xix] The evaluation of the Energy Coordinating Agency (ECA) of Philadelphia's Cool Homes Pilot Project provides some insight on indoor temperature reductions to be expected from cool roof installation, though it can only speculate on the impact of heat on health. In its sample of 35 homes, the ECA found white roofs reduced indoor peak air temperature in bedrooms under the roof without air conditioners by about 2°F. In bedrooms with air conditioners, the peak indoor air temperature declined by 0.4°F.

heat from cooler incoming air. This potential benefit is little studied and not well quantified.

Lower intake air temperature during the cooling season could have a significant impact on the cooling energy savings on multistory buildings. As previously described, the impact of solar heat gain or loss through the roof is only evident on the top floor of a building. The impacts of lower air intake temperature on a reflective or green roof on HVAC energy consumption would impact entire buildings' energy consumption. This benefit is probably substantial where AC systems are on roofs and should be included in future estimates of the energy consumption impact of cool roofs and deserves further research.

9.1.2.8.2 Reduced peak electricity demand

Peak roof surface temperatures generally coincide with peak electricity demand, which in warmer climes generally occur on weekday afternoons during the cooling season (summer).[197] Because cool roofs have lower peak surface temperatures, buildings with cool roofs experience reduced peak electricity demand.[198] Peak electricity demand reductions mean reduced consumption during periods with higher electricity rates during which "time of use" rates apply, and reduced capacity charges (e.g., for large commercial and industrial buildings), so reduced peak demand can provide significant cost savings. However, because of limitations in the Green Roof Energy Calculator (GREC)[199] this analysis does not quantify the benefits of peak electricity demand reductions, and energy benefit calculations are conservative as a result.

9.1.2.8.3 Downwind cooling

There is modeling evidence that reducing UHIs in upwind cities can reduce UHIs downwind. A study from the University of Maryland modeled an extreme UHI event in Baltimore in 2007.[200] The model results showed that hot air from upwind urbanization contributed to as much as 25% of Baltimore's UHI, equivalent to 1.25°C for the event modeled. Downwind cooling from city-wide adoption of Smart Surface options in Baltimore is likely to be material. Due to the limited research estimating the potential downwind cooling impacts of upwind urban cooling, this report does not include downwind cooling benefits in cost-benefit calculations. The downwind cooling benefit of region-wide deployment of the Smart Surface solutions discussed in this report is large at a regional level (especially as Smart Surfaces are adopted regionally), and this benefit merits further research, analysis and modeling.

9.1.2.8.4 Reduced stormwater runoff temperature

Because dark conventional roofs absorb most incoming solar radiation, they become very hot. During a sunny summer afternoon storm event, this heat heats rain runoff, increasing initial stormwater runoff temperatures. [201] Increased stormwater runoff temperatures can cause temperature spikes in local water bodies. Cold-water aquatic ecosystems (e.g., cold-water streams that support trout) can be particularly sensitive to heated runoff.[202]. Given the large uncertainty and the difficulty in valuing reduced stormwater runoff temperature and its likely limited impact, this analysis does not include this potential benefit of more reflective, cooler surfaces in cost-benefit calculations.

9.1.2.8.5 Increased PV efficiency

Reflective roofs may enhance performance of solar PV systems installed on them. PV panel efficiency degrades slightly with higher panel temperature, so lower near-roof air temperatures increase PV efficiency. One study compares PV power output over a black roof and green roof and found a small (0.8%–1.5%) increase in power output over a green roof (see Section 9.2.2.12 for more details). The increase in power output of a PV system over a cool roof is likely smaller in size than that of a PV system over a green roof because shading from the PV system would limit the sunlight that reaches the cool roof, thus partially negating its cooling ability. Much of the green roof ambient cooling benefit comes from evapotranspiration, which would not be as limited by shade. Lacking convincing work quantifying the impact of cool roofs on PV power output, we do not include this benefit in cost-benefit calculations.

9.1.2.8.6 Glare

Glare from roofs that reflect a large fraction of visible light (e.g., bright white roofs) might disturb occupants of nearby taller buildings.[203] In situations where this is a concern, cool-colored roofs (discussed in Section 9.1.1) that are specified to reduce glare are a good alternative. This is likely a not significant impact and is highly location specific, so it is not included in cost-benefit calculations in this analysis.

9.2 Green roofs

The sections below explore the basic principles of green roofs and their benefits, including reduced cooling energy use, reduced greenhouse gas emissions, improved air quality and reduced heat-related mortality, reduced stormwater runoff, and increased employment. Other benefits include downwind cooling, reduced stormwater runoff temperature, increased amenity and aesthetic value, and increased biodiversity.

9.2.1 Green roof basics

9.2.1.1 Extensive and intensive green roofs

There are two major types of green roof: (1) intensive and (2) extensive. Intensive green roofs are thicker, typically with soil depths greater than six inches, able to support a wider variety of larger plants (like shrubs and sometimes small trees), and are often accessible to the public. However, they are heavier and more expensive to install and maintain. Extensive green roofs, typically have soil depths between three and six inches, and support herbaceous ground cover plants (sedums are common). Extensive green roofs are lighter and less expensive to install and maintain compared to intensive green roofs.[xx] Extensive green roofs are by far the most common green roof type.[204] Figure 9.7 below shows examples of an extensive and intensive green roof.

Figure 9.7. Example of extensive green roof (left) and intensive green roof (right)[205]

9.2.1.2 Installation and maintenance costs

We assume that all green roofs modeled are of the extensive type, and these have a life of 40 years. This assumption is consistent with published cost-benefit analyses.[206] Green roof installation and maintenance costs are based on current literature and guidance from roofing professionals.[207] This report assumes that the additional cost of a green roof compared to a conventional roof is $15 per square foot.[xxi]

Maintenance of green roofs is greater than conventional or cool roofs and can include weeding, and spot planting to cover bare spots. Because plants on an extensive green roof are selected to survive without permanent irrigation, and long-term irrigation on extensive green roofs is uncommon, only long-term non-irrigated green roofs are analyzed in this report.

Based on literature review and industry discussions, this report assumes green roof maintenance premiums of $0.46 per square foot per year.[208] These maintenance premiums remain constant throughout the analysis. In addition, this report assumes a

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[xx] For more discussion on the types of green roofs [EPA](#) and [GSA](#) have good resources.
[xxi] Green roof cost per square foot generally decreases as roof area increases In addition, as the green roof industry matures, the cost per square foot of green roofs is expected to decrease due to economies of scale.

PREMIUM	COST
Installation Premium	$15/ft^2$
Maintenance Premium	$0.46/ft^2$-yr
Employee Training Premium	$0.036/ft^2$

one-time employment training cost of $0.036 per square foot. The maintenance and replacement premiums are summarized in Table 9.4.[xxii]

Table 9.4. Green roof cost premiums

9.2.2 Impacts of green roofs

9.2.2.1 Green roof impact summary

Table 9.5 and Figure 9.8 below summarize the costs and benefits of green roofs included in the cost-benefit calculations of this report. There are more benefits than costs excluded from cost-benefit calculations, and excluded benefits likely have a higher value in aggregate than excluded costs, so the findings can be considered conservative (i.e., underestimate the net value of green roofs).

Table 9.5. Green roof cost-benefit impact table (a "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact).

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Direct cooling energy reduction (+)	X	
Direct heating energy reduction (+)	X	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
Peak energy load reduction (+)		X
HVAC air intake temperature energy impact (+)		X
GHG emissions reduction (+)	X	
Global Cooling (+)	X	
Carbon sequestration (+)		X
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Heat-related mortality reduction (+)	X	

[xxii] As a reminder, the lower bound estimate assumes the highest cost estimates and the lowest benefit estimates, while the upper bound estimate assumes the lowest cost estimates and the highest benefit estimates. The middle estimate, our core estimate, assumes average or mid-point cost and benefit estimates.

Reduced stormwater runoff (+)	X	
Employment (+)	X	
Downwind cooling (+)		X
Downwind warming (-)		X
Reduced stormwater runoff temperature (+)		X
Amenity value (+)		X
Aesthetic benefit (+)		X
Biodiversity (+)		X
Increased PV efficiency (+)		X
Increased humidity (+/-)		X

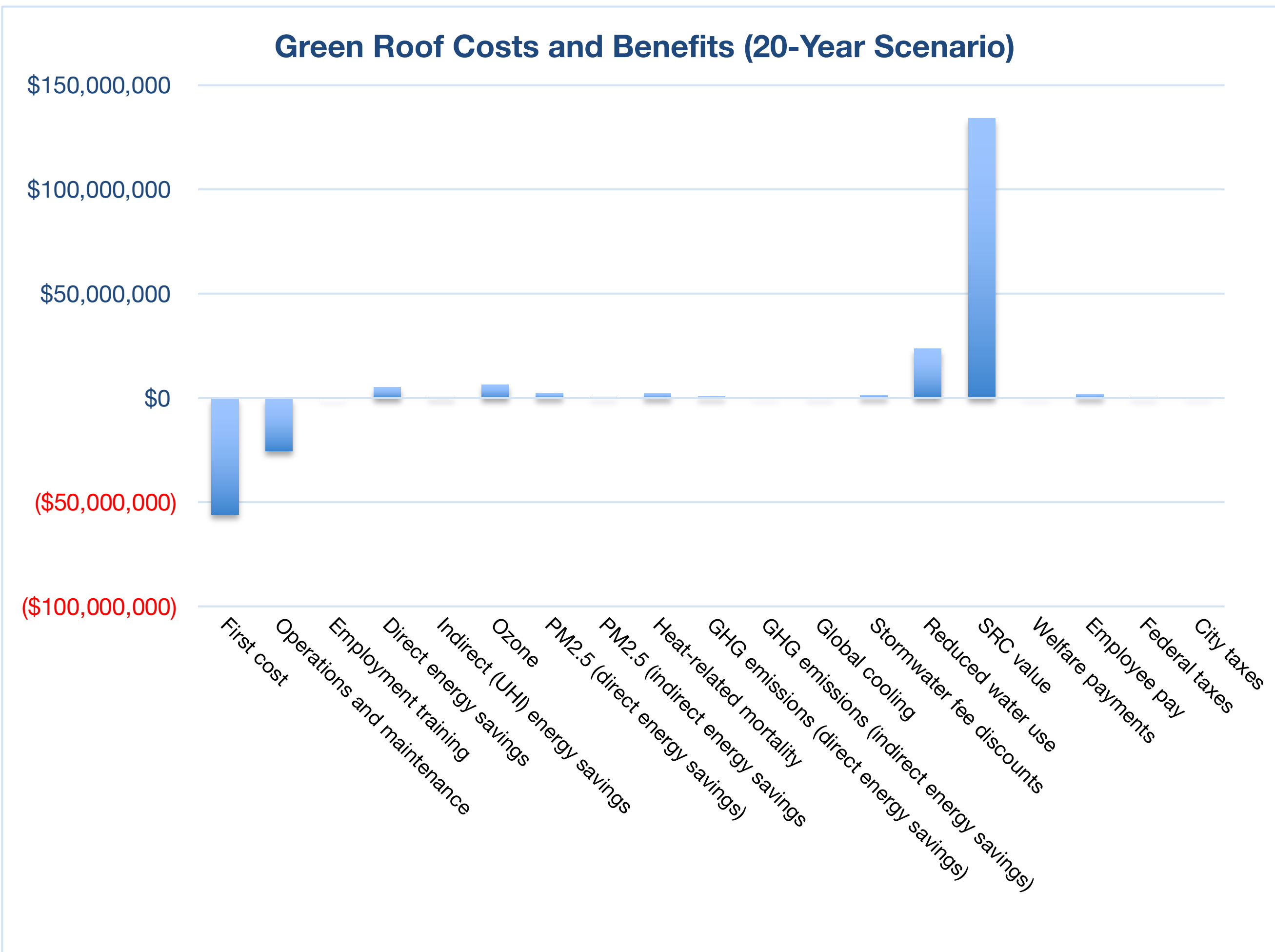

Figure 9.8. The costs and benefits of green roofs for the 20-year scenario in dollar value (costs are negative and benefits are positive)

9.2.2.2 Direct energy

There are three mechanisms by which green roofs reduce direct energy consumption: (1) increasing roof surface evapotranspiration rates, (2) shading the roof surface, and (3) increasing roof insulation and thermal mass.[209] Figure 9.9 below illustrates the three mechanisms that keep green roofs cooler than conventional roofs during the summer—the temperature difference can be as much as 50°F[xxiii,210]—leading to significant cooling energy savings. The thermal mass and thermal resistance provided by green roofs also help reduce heating energy costs in the winter. Section 10.1 provides an overview of methods and assumptions used to estimate this benefit.

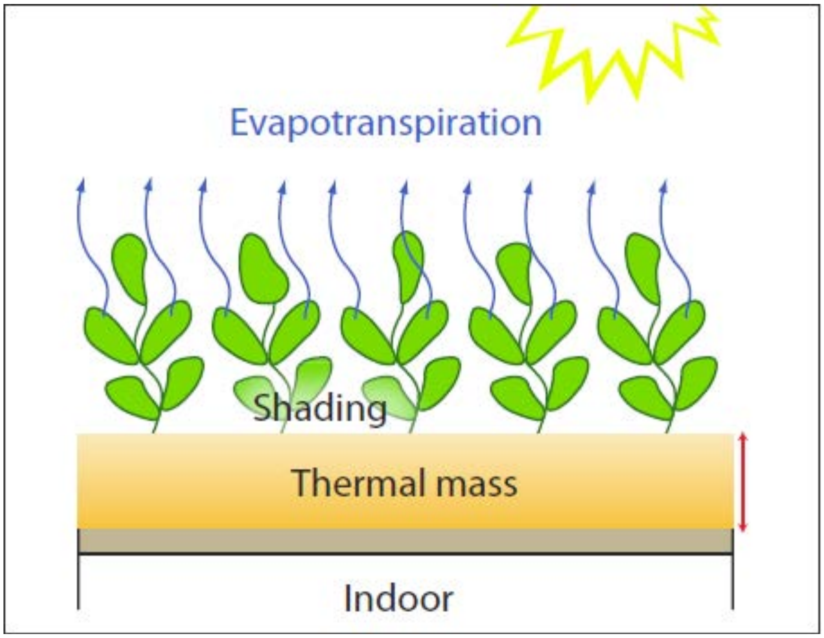

Figure 9.9. Green roof direct energy benefit features.[211]

Like cool roofs, green roofs reduce total and peak electricity demand, which provide significant benefits to utilities (because it reduces peak electricity consumption) and to some utility customers (because peak electricity and demand charges can be expensive). Green roofs may also cool air intake temperature of HVAC systems, potentially reducing cooling energy consumption. This report does not include these potentially substantial benefits in cost-benefit results due to limitations in data availability. For more explanation of these benefits see Section 9.2.2.12.[xxiv]

9.2.2.3 Evapotranspiration

[xxiii] For example, on a summer day in Chicago, the surface temperature of a green roof ranged from 91 to 119°F and that of an adjacent conventional roof was 169°F. Similarly, the near surface air temperature over a green roof was 7°F cooler than that over a conventional roof.

[xxiv] Like on a cool roof, the near-roof surface temperature on a green roof will be lower than that on a conventional roof during the summer. If HVAC components are located on the roof, lower near-roof surface air temperatures can result in increased air conditioner efficiency and decreased energy use. We do not include the direct energy impact of air conditioning efficiency increases from low near-roof surface temperatures in our direct energy savings/penalties impact because it is not well documented.

Evapotranspiration, the combination of evaporation and transpiration, occurs when heat coverts water into water vapor, keeping green roofs cooler than conventional roofs and yielding cooling energy savings for the building below. Increased evapotranspiration results in latent heat transfer (energy released or absorbed in a phase change process), meaning green roofs stay cooler in the summer than conventional roofs.[xxv,212] This results in less heat transferred to the building below, so building cooling energy needs decrease.

As one would expect, the availability of moisture in the green roof is an important factor in determining the size of the evapotranspiration impact on cooling energy. More moisture means more evapotranspiration benefits, but only up to a point.[213] The cooling energy use benefit plateaus above a certain soil moisture content.[xxvi]

Seasons and air movement also affect evapotranspiration benefit of green roofs. In the summer, when green roof plants are active and there is plenty of solar energy for evapotranspiration, green roofs provide a relatively large evapotranspiration benefit. However, in the winter, evapotranspiration is greatly reduced because there is less solar energy available for evapotranspiration, and plants are less active or are inactive.[xxvii,214] The evapotranspiration benefit also increases with air movement because humid air is moved away more rapidly, making way for drier air, thus increasing evapotranspiration cooling benefits.

9.2.2.4 Shading

Green roof vegetation shades the growing medium (soil), which reduces its solar energy absorption and results in lower surface temperatures compared to a conventional roof. This lower surface temperature due to shading decreases the amount of heat transferred to the building below and results in lower building cooling energy use.

9.2.2.5 Thermal mass and insulating properties

In addition to increased evapotranspiration rates and shading of the roof surface, green roofs have a higher thermal mass and thermal resistance than conventional roofs, [xxviii]

[xxv] The cooling process involved in evapotranspiration is the same as that the human body uses to cool itself through sweating. Evapotranspiration is the combination of transpiration and evaporation. Transpiration is the process of water movement from a plant's roots out through its leaves (and to a small extent though its stems and flowers). In evapotranspiration, heat from the sun leads to the evaporation of water from the vegetation and soil, producing a cooling effect. In other words, evapotranspiration converts sensible heat into latent heat.

[xxvi] This report does not present the quantitative findings of Sun et al. (2014) because, as the authors note, "The conclusions presented here are qualitatively generalizable."

xxvii In the northern part of the U.S., evapotranspiration typically begins in April, reaches a peak in June/July, and decreases in October.

[xxviii] Thermal mass is the ability of a material to absorb and store heat energy.

which means they take longer to absorb and release heat than conventional roofs. One consequence of this is decreased and delayed heat transfer through the roof to the building below. Furthermore, because they take longer to heat up and cool down, green roofs experience smaller swings in temperature than conventional roofs.[xxix] The net effect is reduced building energy needs and costs.[215]

As noted, green roofs provide a small insulation benefit to the building below.[216] The amount of thermal resistance (insulation) provided by green roofs depends on the thickness of the growing medium—a thicker growing medium generally means greater insulating properties—and the moisture content in the growing medium—as moisture content increases, insulation value decreases.[217] This is a small benefit, so the effect of soil moisture on the insulating properties of an extensive green roof is minimal and not included in cost-benefit calculations in this report.

9.2.2.6 Non-green roof factors

The direct energy consumption impacts of green roofs depend on many of the same factors as cool roofs, namely the thermal properties of the roof assembly, the operating schedule of the building, HVAC equipment efficiencies, and climate. Only the top floor of a building experiences direct energy consumption impacts from green roofs.

9.2.2.7 Ambient cooling and indirect energy

9.2.2.7.1 Ambient cooling

Because of evapotranspiration and shading, green roofs are typically cooler than conventional roofs, reducing heat transfer to the urban air. Green roof installation at large scale reduces urban air temperatures, helping to mitigate the UHI, in effect offsetting part of projected global warming.

A recent modeling study found that solar radiation and green roof soil moisture are the main determinants of green roof outdoor thermal performance.[218] As solar radiation increases, the green roof ambient cooling benefit decreases, but is not eliminated. Generally, as soil moisture increases, sensible heat transfer to the urban air decreases—i.e., green roof ambient cooling benefit increases.[xxx,219] The study also

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[xxix] Because they heat up slower than conventional roofs, the membrane of a green roof (where the heat transfer between the roof and building occurs) reaches peak temperature after conventional roofs, reducing peak cooling loads.

[xxx] A recent modeling study demonstrates the importance of green roof soil moisture content. Li et al. (2014) found that if green roofs are very dry, their cooling benefits are largely eliminated. It is important that green roof moisture content be monitored and not be allowed to drop below levels that could harm green roof health or enhance the UHI. This could involve installation of permanent irrigation, which would increase the upfront and maintenance costs of a green roof.

found that relative humidity does not show a strong impact on green roof ambient cooling benefit.[220]

While numerous studies examine the impacts of cool roofs, fewer studies have examined the city-wide impact of green roof installation. Two early studies, one that studied Toronto and one that studied New York City, found air temperature reductions from green roof installation.[221] A recent study examined the impact of green roofs on urban temperatures in the Baltimore-Washington metropolitan area.[222] The study modeled the cooling impacts of green and cool roofs during a 2008 heat wave and found that increasing green roof coverage generally reduces ambient temperatures. In particular, the study found that if about 90% of roofs in the Baltimore-Washington area were converted to green roofs, the daily maximum 2-m temperature (near-surface air temperature) during the heat wave was reduced by 0.5 °C. In the afternoon, when the 2-m urban heat island was less pronounced, green roofs actually had a more pronounced effect on the 2-m temperature. For instance, 50% green roof adoption was projected to result in a temperature decreases of up to 0.6 °C. Green roof installation may also increase urban humidity, which potentially has negative comfort effects that are discussed in more detail in Section 9.2.2.12.

This report does not directly estimate the value of ambient cooling from green roofs, but does estimate the benefits of ambient cooling through energy use reductions (this section) and related GHG emissions reductions (Section 9.2.2.8), improvements in air quality (Section 9.2.2.9), and declines in heat-related mortality (Section 9.2.2.9.3).

9.2.2.8 Climate change mitigation

Reducing energy use for space cooling and heating from green roofs reduces GHG emissions. Green roof installation may also lead to global cooling because green roofs have a higher albedo than conventional roofs. Green roof albedo ranges from 0.25 to 0.30.[223] Unlike for cool roofs, global cooling impact has not been studied specifically for green roofs. However, because global cooling can be a significant benefit, this analysis includes this benefit for green roofs as for cool roofs. This report uses the lower, more conservative estimate (0.25) of green roof albedo.

Plants sequester carbon through the processes of photosynthesis. Carbon is also stored in plant roots and in soil. Studies have found that extensive green roofs sequester a small amount of carbon,[224] but the amount of carbon sequestered is minimal[225] so, this report does not include carbon sequestration benefits in green roof cost-benefit analysis results.

The methods and assumptions used to estimate green roof climate change mitigation impact are described in Section 10.4. Figure 9.10 shows green roof climate change mitigation pathways.

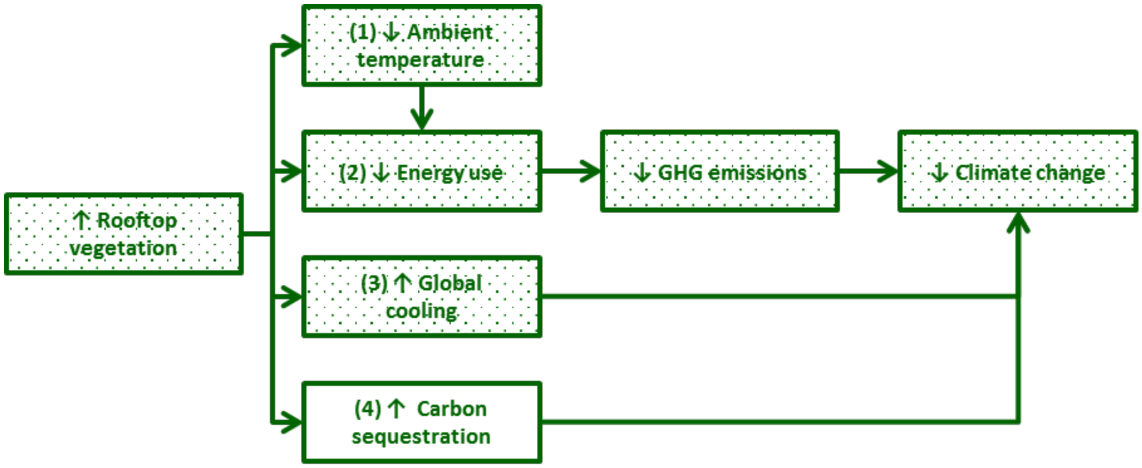

Figure 9.10. Green roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.2.2.9 Air quality and health

9.2.2.9.1 Green roofs and ozone

Compared to cool roofs, green roofs have two additional ozone reduction pathways. (The following paragraph references steps illustrated in Figure 9.11 below.) In addition to reducing ambient ozone concentrations by (1) decreasing ambient temperature and (2) decreasing building energy use, green roofs also reduce ambient ozone concentrations by (3) directly removing NO2 (an ozone precursor) from the air and (4) directly removing ozone from the air. Green roofs directly remove NO2 and ozone through dry deposition (pollution removal during non-rainy periods). Figure 9.11 illustrates the ozone concentration reduction pathways of green roofs. Due to the complexities involved in photochemical air quality modeling, this report does not include the benefit of precursor emissions reductions in cost-benefit analysis calculations. Further, direct removal of pollutants from the air by extensive green roofs is small, so this benefit is not included in the cost-benefit calculations either. As green roofs become a substantial percent of city roofs, these additional ozone reduction benefits could become substantial. This report discusses the methods, assumptions, and pathways in more detail in Section 10.5.

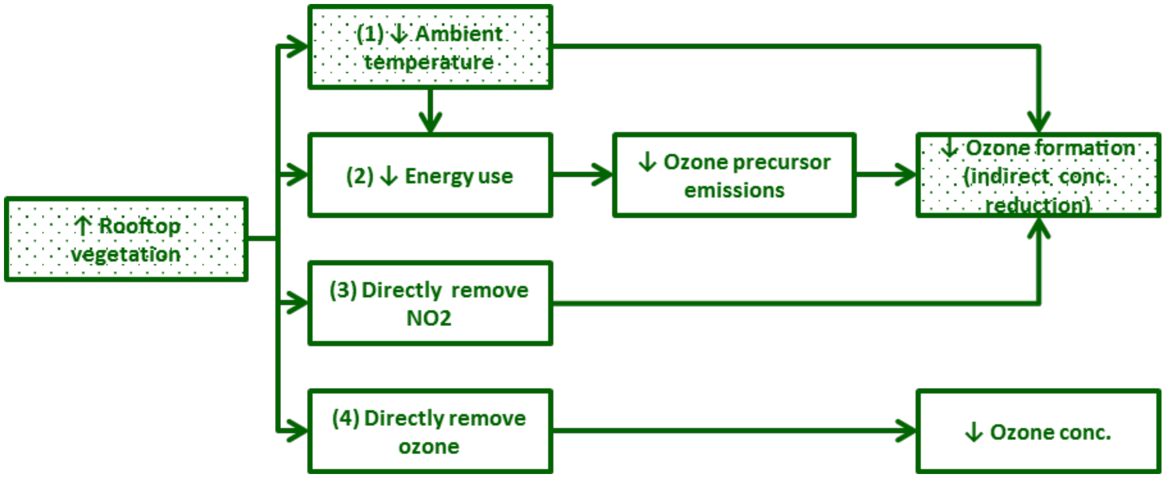

Figure 9.11. Green roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.2.2.9.2 Green roofs and PM2.5

Green roofs reduce concentration of PM2.5 in four ways. Green roof plants directly remove PM2.5 from the air by dry deposition (pathway (1) in Figure 9.12 Green roof plants also directly remove PM2.5 precursors from the air through dry deposition thereby decreasing secondary PM2.5 pollution (pathway (4) in Figure 9.12). Similar to cool roofs, green roofs reduce PM2.5 pollution by decreasing ambient temperature (pathway (2) in Figure 9.10), and by decreasing building energy use (pathway (3) in Figure 9.11). Figure 9.12 shows green roof PM2.5 concentration reduction pathways. The direct removal of pollutants from the air by extensive green roofs tends to be small, so this benefit is also not included in our cost-benefit calculations. This report describes PM2.5 impact estimation methods and assumptions in Section 10.5.

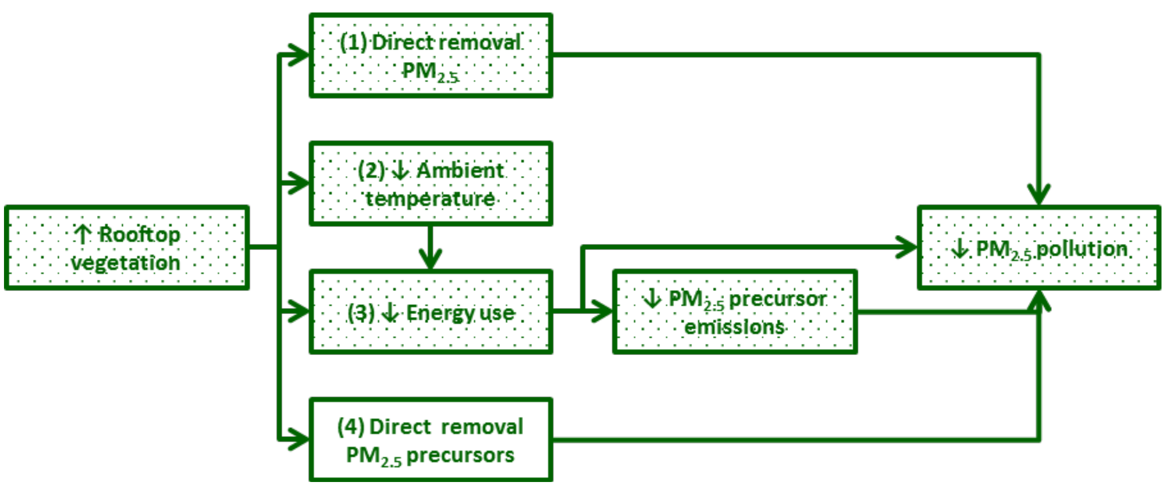

Figure 9.12. Green roof PM2.5 concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

9.2.2.9.3 Green roofs and heat-related mortality

Modeling studies have shown that UHI mitigation solutions (e.g., cool roofs and green roofs) can decrease urban heat-related mortality by reducing ambient air temperature.[226] As noted in Section 9.2.2.9, there are two pathways by which green roofs can reduce heat-related mortality: by (1) improving outdoor temperature conditions and (2) improving indoor temperature conditions. This report found only limited work documenting the potential for green roofs to reduce heat-related mortality by improving indoor conditions, but these reductions could be significant.[227] This is an area that deserves further research. Because this analysis does not include the heat-related mortality impact of green roofs from improving indoor conditions, estimated heat-related mortality benefits are underestimated. This report outlines methods and assumptions to estimate green roof heat-related mortality impact in Section 10.5.

9.2.2.10 Stormwater

As noted, Baltimore has a high percentage of impervious surface area, resulting in larger volumes of stormwater runoff during rain events. Managing this runoff is a major challenge. Stormwater runoff can result in combined sewer overflows, flash flooding, channel erosion, surface and groundwater pollution, wildlife habitat degradation, and federal fines for pollution exceedances.[228] Climate change is predicted to bring more extreme rainfall to Baltimore, increasing river pollution and stormwater management costs.[229]

There are three types of stormwater management: treatment, detention, and retention.[230] Treatment focuses on water quality control through removal of pollutants, while detention focuses on quantity control through managing the peak discharge rate of stormwater. Retention effectively provides both treatment and detention by holding stormwater onsite and cleaning it.

Green roofs are useful tools for stormwater management because they provide stormwater retention and can also help meet water quality treatment and detention requirements. The green roof growing medium captures and stores rainfall.[xxxi,231] Evapotranspiration and water storage in roof plants and growing medium provides stormwater retention capacity of green roofs. Water not captured or evaporated from the roof either runs off the roof surface or gradually discharges (see Figure 9.13). Peak runoff rate reduction, delayed peak runoff, and decreased total runoff from green roofs all relieve pressure on stormwater infrastructure and reduce water pollution. Figure

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[xxxi] German green roof guidelines suggest the growing medium generally retains 30 percent to 60 percent of rainfall when fully saturated.

9.14 illustrates these stormwater benefits of green roofs. Section 10.6 provides an overview of methods and assumptions used to estimate this benefit.

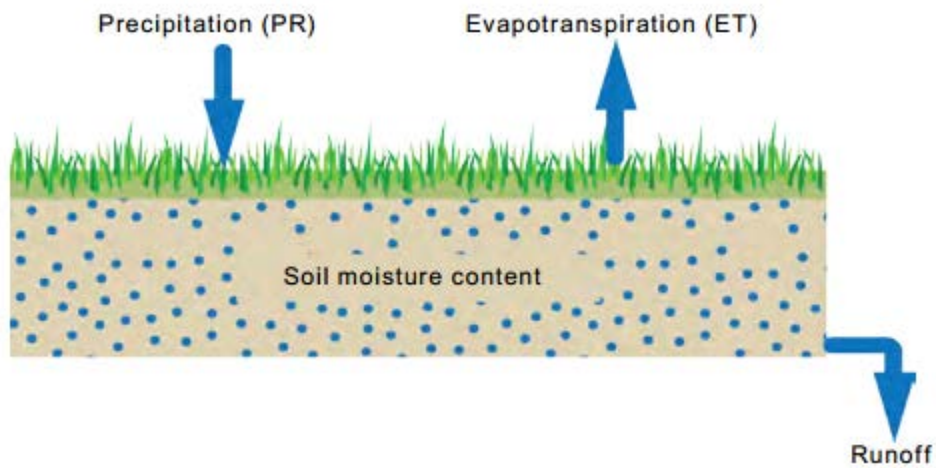

Figure 9.13. Green roof water budget.[232]

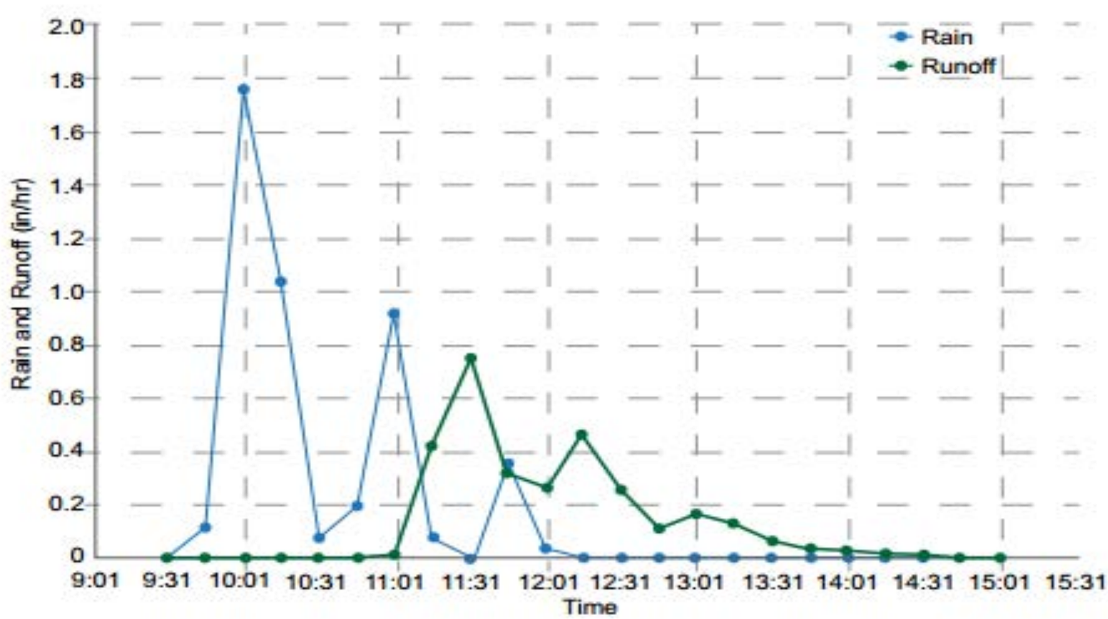

Figure 9.14. Example timeline of rainfall and green roof runoff[233]

9.2.2.10.1 Important factors that influence green roof stormwater retention

Green roof stormwater retention capacity depends on several factors. Plant selection, growing medium, drainage layer, and roof slope all affect green roof stormwater retention. Green roofs retain the most stormwater during the summer, because this is when plants are most active and evapotranspiration is at its peak.[234] The amount of water a green roof retains depends on the amount of rain that falls, the rate of rainfall, and the time elapsed since the previous rainfall.[235] As a green roof becomes more saturated, its ability to absorb rainfall decreases. Therefore, a green roof will reduce peak runoff rates less as (1) the amount of rainfall in a storm increase, (2) the rate of rainfall increases, and (3) the length of time between storms decreases.

9.2.2.11 Green roofs and employment

For this report, all green roofs are assumed to be extensive, meaning they are shallow, relatively lighter, cover a larger proportion of roof area, and grow succulents.[236] [xxxii] These plants are typically installed in shallow trays which are usually 3-5 inches deep, and do not support trees or shrubs. Green roofs adoption is similar to tree planting in that there is extensive offsite investment in planting, maintaining, and growing of plants. The timeline for growing plants used for green roof trays prior to installation is typically 12-18 months. These green trays, like tree saplings, are then transported to the city and installed. For green roofs, installation requires lifting and installing the trays onto prepared roofs. Like trees, green roofs have a large offsite labor component and as a result total job creation available to city residents depends on where these plants are grown.

Green roof installation costs vary, but the EPA estimates the cost of a green roof starts at $10 per square foot for simpler and extensive roofing.[237] Other estimates establish green roof costs between $10 and $15 per square foot.[238] Larger green roof installations cost less, and smaller roofs cost more per square foot. Deeper green roofs that can support shrubs or trees are substantially more expensive. However, as the green roof industry expands, green roofs costs are flat or declining. This is consistent with an average of $12 to $15 per square foot installation cost for urban extensive green roofs.

Based on literature review and industry guidance, we estimate that direct jobs per $1 million invested in urban green roofs includes 50% or $500,000 in direct labor costs which is equivalent to 10 job years. The remaining 50% or $500,000 would pay for green roof trays and equipment. This portion is somewhat less jobs intensive than installation and maintenance since about 40% is designated to labor cost and 60% in equipment, cost of land leasing etc. This includes an additional four job years created from the $500,000 spent on green roof trays. We estimate that a total of 14 direct job years are created per one million dollars spent on green roofs.

9.2.2.12 Other impacts of green roofs

[xxxii] Succulents include hardy plants such as sedum which are discussed further in the Growing Green Guide:
http://www.growinggreenguide.org/technical-guide/design-and-planning/plant-selection/green-roofs/

9.2.2.12.1 Reduced HVAC air intake temperature

Like cool roofs, green roofs may impact HVAC air intake temperature. Walmart compared a green roof to a white roof on a store in Chicago[239] and found that when just heat transfer energy savings were considered on a single-story Walmart store in Chicago, a green roof resulted in approximately 1.6% energy savings compared to the white roof. However, when the effect on air intake temperatures was included in energy savings calculations, the green roof saved roughly 5.3% in whole building energy use (15% cooling reduction and 11% heating reduction) compared to the white roof.[xxxiii] As noted in the cool roof impacts section (Section 9.1.2.8), this benefit may be significant and deserves future research.

9.2.2.12.2 Downwind cooling

As discussed in the cool roof impacts section (Section 9.1.2.8), hot air from urbanization heats cities and towns downwind because of heat transfer by air movement (called “advection”). The ambient cooling benefit provided by green roofs could help alleviate a portion of this downwind warming. However, as noted above, due to limited available research this analysis does not include this benefit.

9.2.2.12.3 Increased amenity value/real estate value

Amenity value is the increase in building value that accrues to its owner from installing an accessible green roof. With a green roof, a building owner may be able to charge more for rent or may achieve faster or higher occupancy or might earn revenue from hosted events on the roof.[240] The GSA estimated the “real estate effect” (the market’s value of a green roof) at $13 per square foot of roof per year.[241] For green roof installations that include building tenant access and use, this amenity value would significantly increase building value. However, because this benefit is site specific, amenity value is not included in cost-benefit calculations and the benefits of green roofs is underestimated.

9.2.2.12.4 Aesthetic value

Green space and vegetation have been shown to building occupant stress,[242] lower blood pressure,[243] and decrease neighborhood crime.[244] But extensive green roofs analyzed in this study are usually not visible by building occupants or pedestrians.

[xxxiii] Note that the results of the Walmart study are based on the analysis of a single story building with an approximately 1-to-1 floor area to roof area ratio so it is difficult to draw general conclusions for all buildings sizes. Thought experiment: HVAC equipment draws in large volumes of air. Walmart HVAC system and HVAC system of 5 story building with same floor area as Walmart store will draw in approximately same amount of outside air to maintain comfortable building environment. The Walmart HVAC system will draw in more air that has been tempered by roof than the HVAC system of the five-story building with same floor because the roof of the five-story building is 5 times smaller than the Walmart roof. As a result, air temp on cool/green roof will have less impact on cooling/heating consumption of 5 story building.

Green roofs may still provide aesthetic benefits to occupants of neighboring buildings who can see the roof.[245] However, because these studies are site-specific and because the GSA view is that for some of these studies, their "methodology is open to debate,"[246] this analysis does not value aesthetic benefits of green roofs.

9.2.2.12.5 Increased biodiversity

Biodiversity refers to the variety of life in an area. Green roofs generally increase biodiversity compared to conventional roofs.[247] The GSA notes that the most important factors in encouraging biodiversity on a green roof are plant type, growing medium depth, and variation in plant height and spacing.[248] In general, intensive green roofs will support a wider variety of species than extensive green roofs. However, there is limited ecological research examining the biodiversity benefits of different types of green roofs,[249] so, this analysis does not include biodiversity benefits in cost-benefit results.

9.2.2.12.6 Increased PV efficiency

Like cool roofs, green roofs may enhance PV performance. However, unlike cool roofs, there are studies which examine the green roof-PV relationship. As discussed, PV panel efficiency degrades slightly with higher panel temperature, so lower near-roof air temperatures on green roofs could measurably increase PV efficiency. In NREL's PVWatts model, the temperature coefficient of power for a "Premium" module is 0.35% per °C (-0.19% per °F),[250] meaning that for each additional degree PV panel temperature rises above 25°C (77°F), PV power output decreases by 0.35% (0.19%)[xxxiv] For example, at 30°C, PV power output would decrease by 1.8%.

Chemisa and Lamnatou (2014) conducted an experimental study of green roof-PV systems in a Mediterranean climate (Lleida, Spain, specifically).[251] and note that PV protects plants from high irradiance, and thus benefits the health of the green roof.

With regards to green roof-PV power output advantage over standalone PV, values ranging from 0.8% up to over 8% have been observed. Assuming an electricity cost of $0.15/kWh, a 5kW system over a green roof would earn about $13.50 more per year than the same system over a black roof.

Most studies examining the integration of green roof and PV agree that the two technologies can be successfully combined and provide beneficial results for cities such as Baltimore. Given the limited and variable data on the effect of green roofs on PV power output, this benefit is not included in cost-benefit calculations.

[xxxiv] Higher quality panels typically have lower temperature coefficients of power. For example, the "Premium" module in PVWatts has a temperature coefficient of -0.35% per °C.

9.2.2.12.7 Increased humidity

While green roofs can decrease city air temperature, they can also increase humidity and apparent temperature (how hot it feels).[xxxv] Higher moisture content in the air can increase cooling energy consumption[xxxvi] and heat-stress.[xxxvii] Thus, increases in humidity from green roofs can decrease green roof energy and comfort benefits. However, higher relative humidity is also correlated with reduced ozone concentrations,[252] which would increase the ozone reduction benefit of green roofs. Both the negative and positive impacts of higher humidity vary by location and are condition dependent. This report found no conclusive research on the negative or positive impacts of increased humidity from green roofs, and this excluded it from cost-benefit calculations.

9.3 Solar PV

This section explores the basic principles of rooftop PV systems and their potential impacts. As noted, benefits include electricity generation, reduced greenhouse gas emissions, improved air quality, shading benefits and the potential for UHI mitigation.

Solar is the fastest growing form of electricity in the US due largely to declining costs. There is a rapidly expanding the market for and sale of solar panels in Maryland and in Baltimore, as well as increasing the number local solar manufacturing/assembly firms. There are a number of solar installers working in Baltimore, all of which offer multiple financing options.[xxxviii]

[xxxv] How hot air feels is based on both temperature and moisture content.
[xxxvi] Because air conditioning systems may have to do more work to deliver air within the set humidity range.
[xxxvii] Because it is more difficult for humans to cool their bodies in more humid conditions.
[xxxviii] See Energy Sage for a list of the top ten solar providers in Baltimore: https://www.energysage.com/local-data/solar-companies/md/baltimore-county/baltimore/

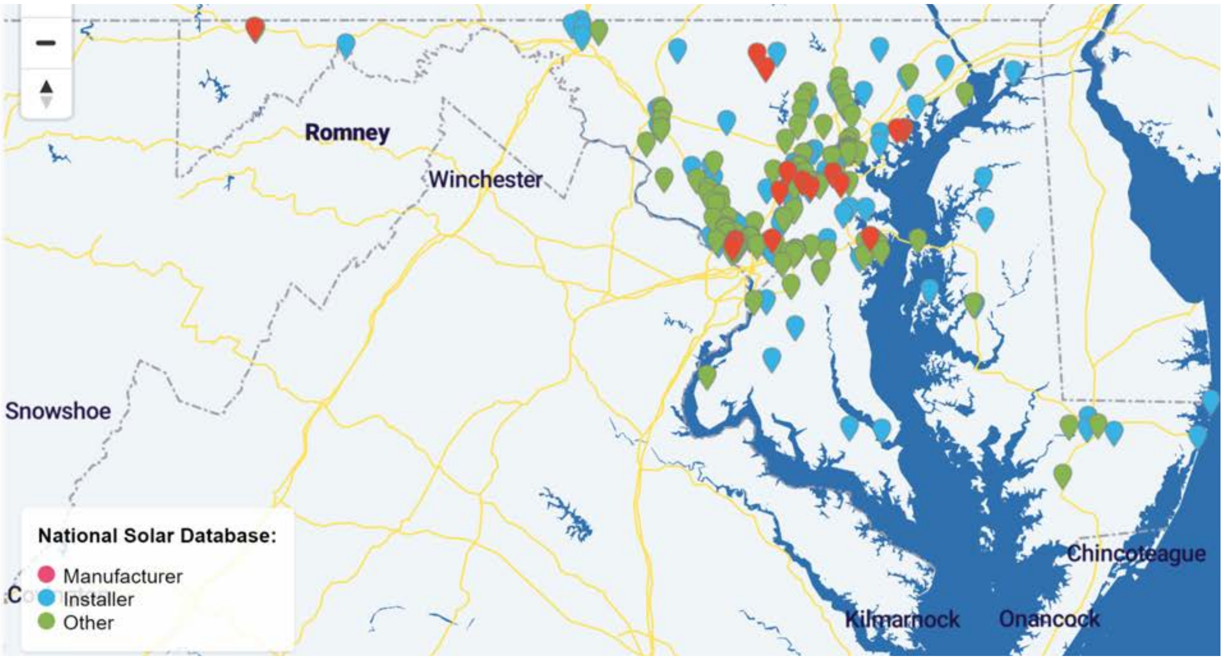

Figure 9.15. Maryland Solar SEIA.[253]

Solar installations in Baltimore include residential—on single or multi-family homes—commercial, and installations on state owned buildings. A decade ago, building owners typically had to pay upfront for a solar PV system, but today's solar installers offer multiple 3rd party financing options. Of the solar financing options, direct purchase is only one of many options.[254][xxxix] A model of fractional ownership is also growing very rapidly through the adoption of community solar where multiple buildings contract to buy power on an ongoing basis over 10 to 20 years from a single non-local power plant—all with no upfront capital costs.

Solar systems in Baltimore today have an average of a 10- or 11-year payback[255], which can be expected to continue to drop in coming years, as electricity costs rise and the installed cost of solar is projected to continue to drop.[256] [257]

As noted by EnergySage which solicits and compares solar quotes from over 500 solar vendors, including those in the Baltimore market, the platform has found that,

> "Both $0-down solar loans and $0-down solar leases/PPAs result in immediate savings, with no money out-of-pocket, because your monthly loan or lease/PPA payment will be less than your current monthly utility bill. The monthly savings

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[xxxix] A helpful resource for further information on solar in Maryland is the "Maryland Consumer's Guide to Solar" by Diana Chance and David L. Comis *https://energy.maryland.gov/residential/Documents/A%20Maryland%20Consumers%20Guide%20to%20Solar%20LR72dpi.pdf*.

> from a solar loan, however, are likely to be higher than the savings from a solar lease or PPA. This is because solar loans are typically paid down in 7 to 15 years, whereas leases require regular payments over the term of the agreement."[258]

Sustainable Capital Finance, one of many firms offering 3rd party financing for solar in Baltimore including under a PPA structure, explains that,

> "A solar PPA, or power purchase agreement, is typically an off-balance sheet financial arrangement through which an energy consumer (Commonly referred to as an off-taker) allows a third-party developer to develop, construct, operate and maintain a photovoltaic (PV) system on its property, at no upfront cost. The off taker then agrees to purchase electricity from the system's owner, over a predetermined period. The off-taker will typically a lower rate than the existing utility rate while benefitting from a more sustainable source of power and the ability to meet sustainability initiatives."[259]

Third party financing is often preferrable for public agencies as well. At the end of 2019 Baltimore County officials were evaluating third party financed solar installations on a dozen public buildings. These buildings ranged from community centers, to a police station, to a park in the Baltimore City suburb of Lansdowne. As noted in an article from the *Baltimore Sun*, "Officials are soliciting design proposals from solar development firms that would install, operate and maintain the panels, while selling the power to the county."[260]

Another option is solar leases where the installer owns the solar and the building owner "rents" the solar panel system from the solar company that owns and maintains the system. Installers offer a loan option where the host is responsible for maintenance, but the system is financed by the installer.

Property assessed clean energy (PACE) financing is another innovative mechanism for financing renewable energy. Maryland has a PACE program that is active in Baltimore. For example, C-PACE financed a solar power system and energy efficient roof system in Baltimore in 2020. It is a 56.3 kW system will save $9,000 in the first year and $260,000 over the life of the system. With C-PACE, Baltimore property owners can get solar funded on their commercial properties with no money down and terms of up to 25 years, with a positive cash flow from day one.[261] It is also worth emphasizing that third party financing is available for lower income homes in Baltimore.[xl]

[xl] More information can be found in the Baltimore Sun's article "Solar energy financing program will target low-income neighborhoods" https://www.baltimoresun.com/business/bs-bz-solar-financing-20160719-story.html.

In all these third-party financing strategies, homeowners and firms can secure a lower long-term cost of electricity and can save money without an upfront capital outlay. For this report, we assume that all solar buyers in Baltimore have a range of third-party financing options and that all solar purchases modeled in this report use one of the many third-party financing options available. With an average 10-year payback, buyers of solar systems—whether residential commercial or public—do not receive financial benefits until after year 10 of installation/operation, with the first 10 years of power output going to pay the 3rd party financing.

The state of Maryland also has several regulations worth noting, including that Maryland also provides a $1000 rebate for home solar[262] for systems over 1 kW and up to 9 kW[xli] a feature that solar installers in Baltimore promote.[263] In Maryland, the average residential solar system is 5 kW and costs about $15,350 after accounting for the federal tax credit, and almost all solar systems in Baltimore are above 1 kW.[264]

Clean Energy Technology	Eligible System Capacity Range	Rebate Amount
Solar Photovoltaic (PV)	1-8 kW-dc 8-108 kW-dc 108-250.0 kW-dc	$1,000, $1,000 + $150/kW *(capacity – 8 kW) $16,000+$100/kW*(capacity–108 kW) $20,000 maximum
Solar Photovoltaic (PV) – **rooftop only**	250.1 -375 kW-dc rooftop only	$20,000 + $80/kW*(capacity-250 kW) $30,000 maximum rooftop only

Figure 9.16. Rebates for solar PV systems in Maryland[265]

For simplicity we assume no federal or state incentives, instead we model all solar PV adoption as third party financed (see section 9.3.1 below), and we count electricity benefits only after year 10, when 3rd party solar financing is typically fully paid off so lower bills then accrue to the homeowner of business owner where the solar panels are installed.

[xli] For more information on incentives and tax credits in Maryland, Solar Reviews offers a helpful guide https://www.solarreviews.com/solar-incentives/maryland.

Because we are assuming all new solar in Baltimore is third-party financed, the first ten years of electricity generation benefits accrue to the financier, and only the last 20 years of electricity generation accrue to the residential or commercial property in Baltimore.

9.3.1 PV Basics

9.3.1.1 Installation and maintenance costs

The standard measure for estimating PV system install cost is cost per watt. System install costs have come down dramatically in the last decade and are expected to continue to fall. Average residential PV installed costs are $3.04/watt with a price per unit dropping as installations get larger. Table 9.6 shows installation cost used in this report in Baltimore for low-slope and steep slope roofs.

Accounting for trends in PV durability and longevity improvements, this report assumes a system life of 30 years for direct purchase PV systems with 20% PV efficiency.

Table 9.6. Solar PV initial installation cost and operations and maintenance costs in dollars per square foot for low-slope and steep-slope roofs.

Roof Type	First installation cost premium	Operations and maintenance premium
Low-slope	$43/SF	$0.3/SF/year
Steep-slope	$50/SF	$0.35/SF/year

9.3.1.1.1 Third-party financing

As noted above, this report assumes third party financing is used for all new solar PV installation.[266] Under a solar lease, the electricity user pays a monthly fee for the solar system and uses all the electricity the system produces, with no additional charges. Similarly, in a PPA, the electricity user typically purchases electricity from the system at a rate lower than what they would pay the utility. Loan purchase is similar to direct purchase except that the home or building owner uses a loan to finance some or all the installation cost.

9.3.2 Impacts of Solar PV

9.3.2.1 Solar PV impact summary

Table 9.7 and Figures 9.17 and 9.18 below summarize the costs and benefits of rooftop PV included in the cost-benefit results of this report. There are more benefits than costs excluded from cost-benefit analysis, and excluded benefits very likely have higher aggregate value than excluded costs, meaning our findings tend to underestimate the net value of urban solar PV.

Table 9.7. Rooftop PV cost-benefit impact table (a "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact).

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Energy generation (+)	X	
Tax Credits (+)		X
SRECs (+)		X
GHG emissions reduction (+)	X	
Ozone concentration reduction (+)		X
PM2.5 concentration reduction (+)	X	
Employment (+)	X	
Carbon sequestration (+)		X
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Direct energy reduction/penalty (+/-)		X
UHI mitigation & related benefits (+)		X
Increased home value (+)		X
Avoided peak transmission and distribution losses (+)		X

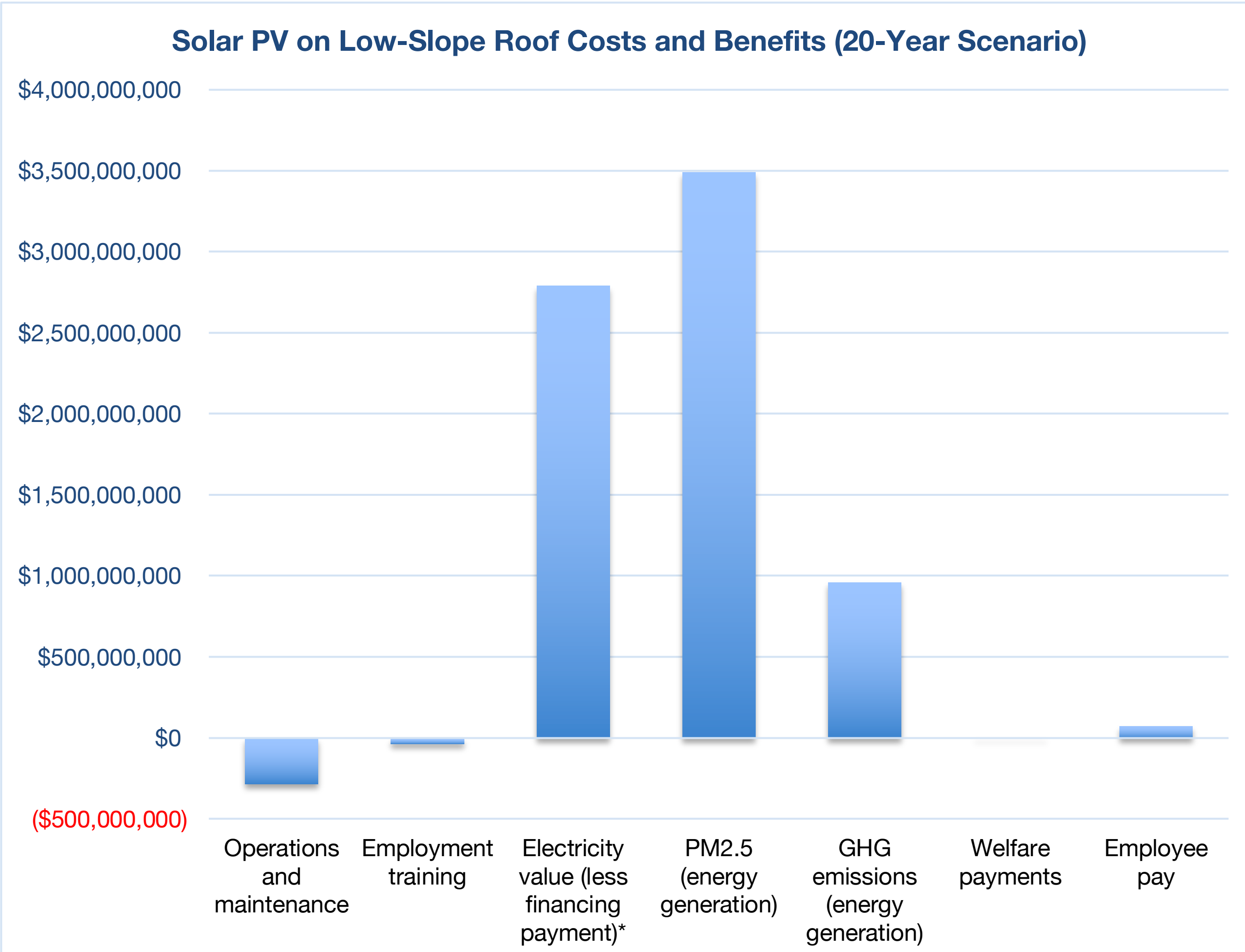

Figure 9.17. The costs and benefits of solar PV on low-slope roofs for the 20-year scenario in dollar value (costs are shown as negative and benefits are positive. Solar PV payback after year 10, this model assumes "first cost" [e.g., financing payments] are net of electricity value [electricity value is zero for first 10 years after install], and therefore first cost is zero. Third-party financiers will bear the actual first cost and Baltimore system owners will not receive an electricity value benefit until year 11 after installation; *First 10 years of electricity value benefit goes to third-party financier)

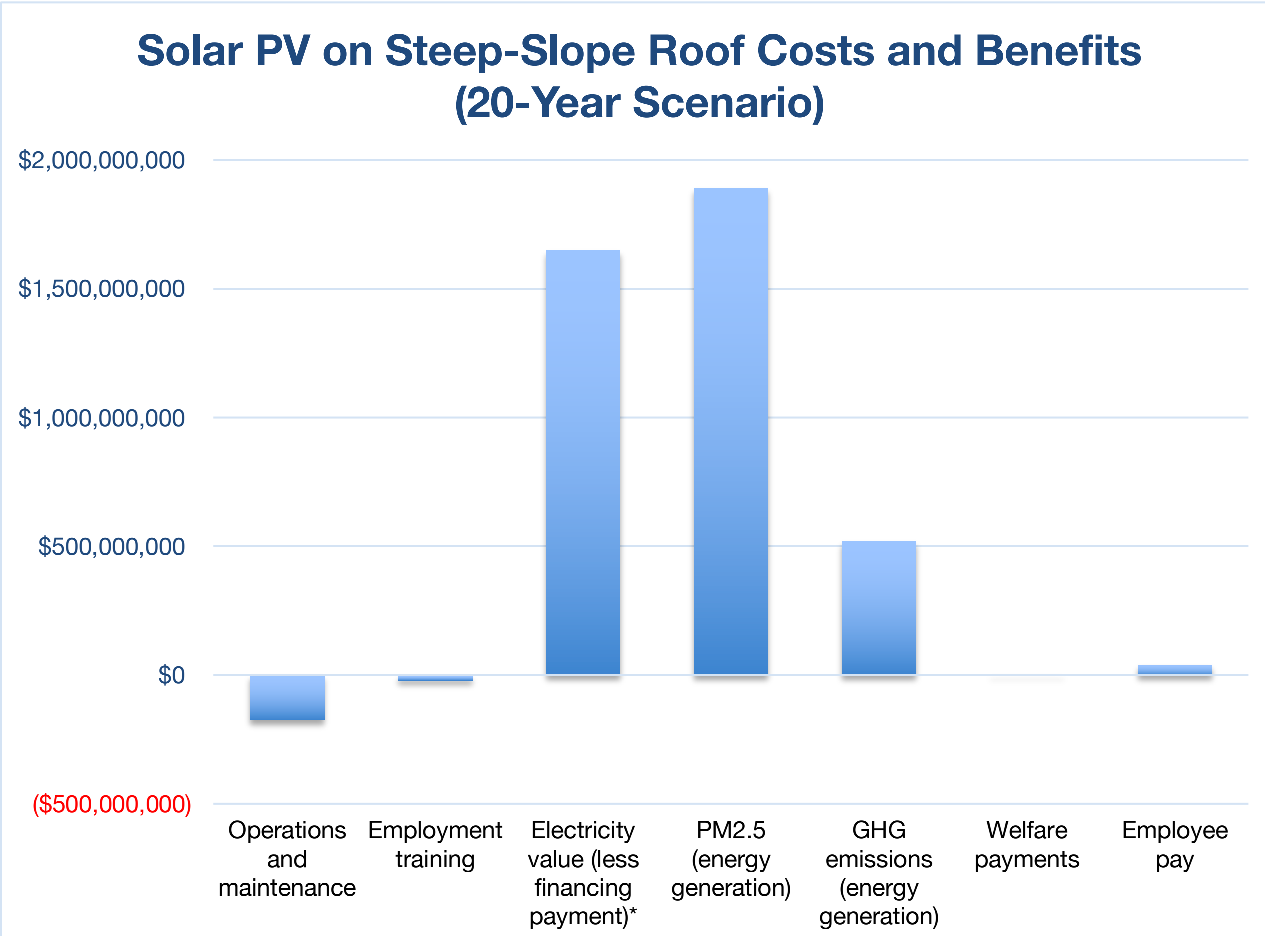

Figure 9.18. Costs and benefits of solar PV on steep-slope roofs for the 20-year scenario in dollar value (costs are shown as negative and benefits are positive Solar PV payback after year 10, this model assumes "first cost" [e.g., financing payments] are net of electricity value [electricity value is zero for first 10 years after install], and therefore first cost is zero. Third-party financiers bear the first cost and receive the value of the first 10 years of power generation *First 10 years of electricity value benefit goes to third-party financier)

9.3.2.2 Energy generation

Rooftop PV substitutes Pa clean power for grid-purchased electricity, some of which is generated by polluting fossil fuel plants. The state of Maryland has net metering laws recognizing the value of PV electricity generation at the same price as electricity purchased from the utility. Maryland also offers virtual net metering, a system that enables individuals to accrue the benefits of solar even if they do not install a solar system on their property. Individuals can share the electricity output from a shared solar array or community solar farm that is not on-site but is shared among subscribers. Individuals receive credits on their electric bills for excess energy produced based on their share of a community solar installation.[267]

9.3.2.3 Financial incentives

PV system owners can take advantage of the substantial financial incentives offered to owners, including production-based incentives (e.g., solar renewable energy credits) and tax credits. In a third-party financing arrangement, the customer typically does not receive these incentives, and as such we do not include them in our analysis.

9.3.2.4 Tax credits

The 2021 omnibus spending bill, passed in end 2020, included extension of renewable energy tax incentives and updates to the Investment Tax Credit (ITC), and ensures that commercial and utility scale solar projects that begin construction in 2021 and 2022 will be able to receive a tax credit at 26 percent. Solar projects that begin in 2023 will be eligible for a 22 percent tax credit and projects that begin construction after 2023 are only eligible for a 10% ITC credit. In 2024 and beyond commercial and utility markets will remain at 10 percent for the foreseeable future.[268] Changes to the internal revenue code under section 25D for the residential energy tax credit follows the same phase down schedule and percentages as commercial projects but will reach zero percent for residential projects beginning in 2024.[269] Because we assume in this analysis that all solar PV is financed through a third party, tax credits accrue to the third-party financers, so do not include the value of tax credits separately in cost-benefit calculations.

9.3.2.5 Solar renewable energy credits (SRECs)

Solar renewable energy credits (SRECs) are equivalent to one MWh of electricity derived from a solar system. In the state of Maryland, solar PV and solar water heat are eligible for SRECs. The price of SRECs is highly variable and fluctuates within a tradable market. To be conservative, we do not include the value of SRECs in this analysis.

9.3.2.6 Climate change mitigation

Rooftop PV has only one substantial climate change mitigation pathway by displacing polluting grid electricity. Figure 9.19 shows this climate change mitigation pathway. This benefit is included in cost-benefit calculations. For more on methods and assumptions, see Section 10.4 Solar panels on roofs have two additional smaller benefits: they typically increase a roof's effective albedo, in turn reducing urban heat gain, and they also shade the roof, reducing building air conditioning cooling needs. Both these impacts cut cost, reduce climate change and improve city air quality/lower urban temperature.

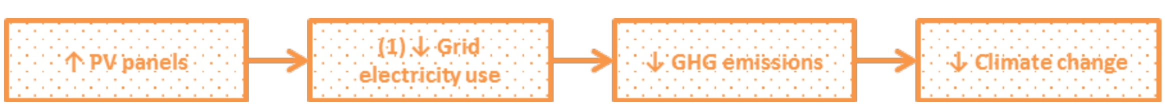

Figure 9.19. Rooftop PV climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.3.2.7 Air quality and health

Rooftop PV has one significant ozone reduction pathway and one significant PM2.5 reduction pathway. PV panels produce electricity that reduces electricity purchases from the grid. The electricity produced by the PV panels generates no emissions, whereas electricity from the grid generates a range of air pollutants, including PM2.5, PM2.5 precursors, and ozone precursors. Therefore, installing PV panels reduces ozone concentrations by decreasing electricity-related ozone precursor emissions and reduces PM2.5 concentrations by reducing emissions of PM2.5 and PM2.5 precursors.

Due to the complexities involved in photochemical air quality modeling, this report does not include the benefit of ozone precursor emissions reductions in cost-benefit analysis calculations. Figure 9.20 shows the PM2.5 reduction pathways of rooftop PV. This report describes PM2.5 impact estimation methods and assumptions in Section 10.5.

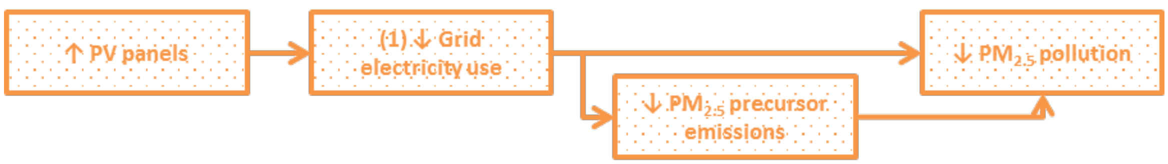

Figure 9.20. Rooftop PV PM2.5 concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.3.2.8 PV and employment

While large scale solar installations typically cover many acres, installing smaller solar arrays in cites is more labor intensive (for example lifting panels onto roofs). The large labor component of urban installation of solar PV is reflected in its high-cost relative to large-scale, or “utility scale,” solar installations.[270]

Based on research and industry discussions, we estimate that direct jobs per million dollars invested in urban solar include 40%, or $400,000, in direct labor costs, which is equivalent to eight job years at a full cost of $50,000 per job. The balance of $600,000 goes to pay for solar cells, etc., and is much less job intensive than installation and maintenance—and equal to the average job intensity of the economy as whole at five direct jobs per one million dollars.[271] The $600,000 balance translates into three job years. As a whole, therefore, the one-million-dollar investment gives us a total of 11 direct job years per million dollars invested in urban solar installations.

9.3.2.9 Other impacts of Solar PV

9.3.2.9.1 Reduced cooling energy consumption

When PV panels are installed on a roof, they shade the roof surface and reduce its temperature, providing modest cooling energy savings. Simulations of PV on a commercial low slope roof in San Diego, CA found the PV system decreased annual cooling load on the top floor of a building by 38% and had no impact on annual heating load.[272] In Baltimore, assuming an electricity price of $0.13 per kWh,[273] a cooling energy intensity of 2.5 kWh per square foot,[274] and a reduction in annual cooling load of 20% (because of lower solar insolation in Baltimore), PV shading could lead to annual cooling energy savings of about $0.065 per square foot per year on the top floor of a commercial building. However, because of uncertainty about the size of cooling load reduction in Baltimore, we do not include this benefit in cost-benefit calculations. This calculation underestimates benefits of PV and is a topic that warrants further research.

On a green roof, partial shading by PV can enhance vegetation health and allowing for greater vegetation diversity.[275] PV shading may also reduce air intake temperatures, leading to further savings. However, due to the limited amount of research on this benefit, these shading benefits are not included in the cost-benefit calculations.

9.3.2.9.2 UHI Mitigation

There is some modeling evidence that large scale deployment of solar PV can reduce urban air temperatures. A modeling study of the sensible heat flux from black roofs, white roofs, green roofs, and these three roof types with added PV panels found that putting PV panels on black roofs slightly reduces the contribution of black roofs to the UHI because total heat conduction away from the roof decreases.[276] Putting PV panels on a white or green roof increases the total sensible heat flux away from these roofs (decreasing their UHI benefit).[277] For example, a white roof without PV panels contributes less to the UHI than a white with PV panels. However, a white or green roof with PV panels is still considerably better than a bare or PV-covered black roof.[278] As the cited study notes, its results cannot be directly translated to changes in temperature,[279] but a 2015 study of Los Angeles that modeled “reasonably high” levels of solar PV deployment in the Los Angeles area found either no temperature benefit or a slight temperature benefit from installing PV.[280] The cooling benefit of PV increased with increasing PV efficiency.[xlii] For example, with a PV efficiency between 10% and 15%, there was no impact (positive or negative) on temperature. However, with PV efficiency at 30%, the study found regional cooling up to 0.15°C. The typical efficiency of PV panels currently installed is about 20%, indicating a slight cooling benefit.

[xlii] This is because as more solar energy is converted to electricity, there is less energy is available to heat urban environment. This is similar to increasing albedo.

Reductions in ambient temperature from large scale PV installation could reduce energy use, reduce GHG emissions, and improve air quality and health. Due to a limited amount of research in this area and lack of results specific to cities examined in this analysis, this benefit is not included in cost-benefit calculations.

9.3.2.9.3 Avoided transmission and distribution losses

The U.S. Energy Information Administration estimates average transmission and distribution losses of 6% in the U.S.[281] These include losses between sources of supply and locations of distribution (transmission losses) and losses in distribution to customers (distribution losses).[282] Urban rooftop solar PV coverage generally avoids transmission and distribution losses.[283] Transmission losses rise during peak periods (e.g., summer afternoons in Baltimore), and PV (especially west- and southwest-facing systems) reduces demand during this peak summer city electricity consumption period.[284] This increases value of PV systems in cities and towns over utility power generation (that overwhelmingly occurs outside cities), but this value is also not included in this analysis.

9.4 Reflective Pavements

The sections below explore the basic principles of reflective pavements and their impacts. Benefits include ambient cooling, reduced cooling energy use, reduced greenhouse gas emissions, global cooling, and improved air quality and reduced heat-related mortality. Other benefits include a potential increase in pavement life, reduced street lighting requirements, downwind cooling, and reduced stormwater runoff temperature. Potential drawbacks are much smaller and include glare and reduced thermal comfort.

9.4.1 Pavement basics

There are several common terms used in discussions about impervious pavements that are useful to know. The two basic components of pavement are aggregate and binder. Aggregate, provides strength, friction, and resistance to wear.[285] Binder, often asphalt or Portland cement, is like glue; it provides stiffness and prevents pavement from breaking apart under the stresses of traffic and weather.[286] Concrete is the composite of aggregate and binder.[287] Pavements are often built on top of a base course, which typically consists of crushed aggregate and is used to provide a stable base and proper drainage.[288] The base course is built on top of the subgrade, or soil.

The two most common types of pavements are asphalt concrete and Portland cement concrete. Asphalt concrete consists of asphalt binder (which is black in color and is made from petroleum) and aggregate.[289] Asphalt concrete (commonly called “asphalt”) is the most common roadway pavement—about 90% of roads are asphalt concrete.[290] Portland cement concrete consists of Portland cement binder (which is grey or whitish in color and is derived from calcium and silicon oxides) and aggregate. Portland cement concrete is roughly 11 percent Portland cement binder, 33 percent sand, and 56 percent coarse aggregate by weight.[291] Portland cement concrete (commonly called “concrete”) is typically used for sidewalks, bridge decks, elevated highways, parking lots, and heavily trafficked roadways (especially those with high truck traffic).[292]

9.4.1.1 Thermal performance

There are three ways heat transfers from one medium to another: conduction, convection, and radiation. Figure 9.21 presents a visual representation of heat transfer processes in pavements. Pavement is heated on the surface by the sun from solar radiation. Heat is lost through radiation from the pavement surface to the cooler atmosphere, by convection at the surface to cooler air above the pavement, and by conduction between the pavement surface, and subsurface layers (and the pavement subsurface layer and the earth).[293]

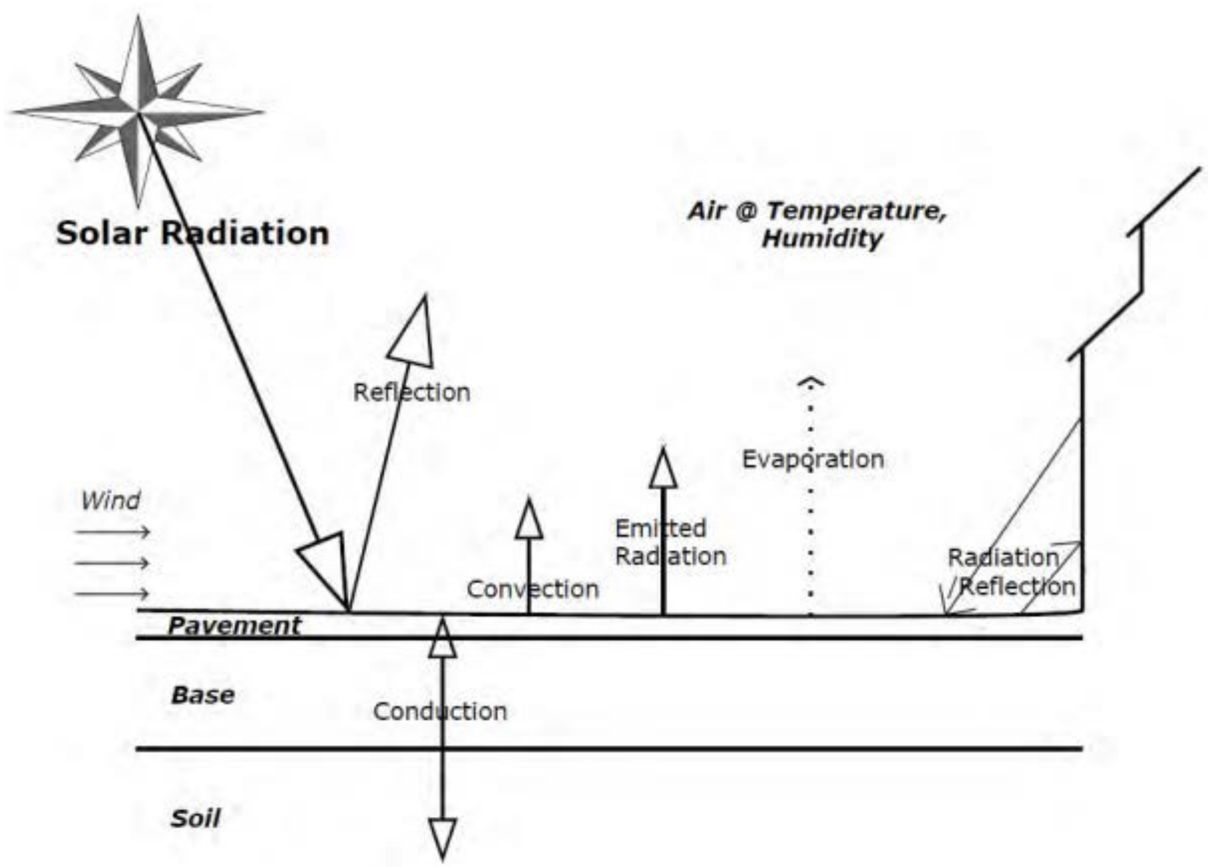

Figure 9.21. Pavement surface energy balance[294]

The size of these heat transfers is determined by several pavement properties: solar reflectance (albedo), thermal emittance,[xliii] thermal conductivity,[xliv] and specific heat.[xlv][295] The Federal Highway Administration (FWHA) notes that thermal emittance, thermal conductivity, and specific heat of asphalt and concrete pavements are very similar, so variances in albedo is the most important material property in determining differences in thermal performance between pavements.[296] As a result, this analysis focuses on pavement albedo.

There are several factors that make analysis of pavements more complicated than analysis of roofs. Roofs experience relatively consistent environments because they have little or no traffic. Pavements, in contrast, experience a range of vehicle and pedestrian traffic, leading to varied wear and increased convection due to traffic movement.[297] Pedestrians, vehicles, and nearby vegetation and structures also shade pavements[298] more than roofs. If pavement is shaded for most of the day, for example, it may not make sense to increase its solar reflectance.

9.4.1.2 Installation and maintenance

As pavements age or become damaged they need to be repaired. Ting et al. (2001) describe two classes of pavement repair: rehabilitation and maintenance.[299] Rehabilitation, which typically occurs one or two times during a pavement's lifetime, are major repairs. Examples of rehabilitation techniques for asphalt pavement include patching, surface milling (i.e., removing the top of asphalt), and overlays of a new asphalt (or potentially concrete) surface.[300]

Maintenance also includes preservation techniques. Surface treatments are a common preservation technique for asphalt pavements and include techniques like chip seals,[xlvi] asphalt emulsion sealcoats,[xlvii] slurry seals,[xlviii] and bituminous crack sealants.[xlix][301] Surface treatments extend pavement life and improve water proofing and skid

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[xliii] Thermal emittance describes how readily a surface gives off heat. The higher the thermal emittance, the more readily the surface gives off heat.

[xliv] Thermal conductivity describes a materials ability to conduct heat. Higher thermal conductivity means a material is better able to conduct heat; in other words, heat moves more quickly through materials with higher thermal conductivity.

[xlv] Specific heat is the amount of heat required to change the temperature of a material per unit mass. It is related to heat capacity. The higher the specific heat of a material, the greater the amount of heat required to change its temperature.

[xlvi] For a description of chip seals, see *https://en.wikipedia.org/wiki/Chipseal*

[xlvii] For a description of emulsion sealcoats, see *http://www.pavementinteractive.org/article/emulsified-asphalt/*

[xlviii] For a description of slurry seals, see *http://www.pavementinteractive.org/article/slurry-seals/*

[xlix] For a description of bituminous crack sealants, see *http://www.pavementinteractive.org/article/bituminous-surface-treatments/*

resistance.[302] Chip seals, asphalt emulsion seal coats, and slurry seals include very reflective options discussed below.

9.4.1.3 Solar reflectance of pavements

Unlike the three-year aged solar reflectance used for cool roofs, there is no standardized measure of aged solar reflectance for pavements, perhaps because the conditions that pavements experience are far broader than those experienced by roofs. The sections below describe the solar reflectance of conventional and reflective pavements drawn from literature and discussion with pavement professionals. There is no standard industry solar reflectance measure used.

9.4.1.4 Conventional pavements

The albedo of new asphalt pavement ranges from 0.05 to 0.10. But as asphalt ages its albedo increases due to weathering and soiling, stabilizing between 0.10 and 0.20.[303] The albedo of new concrete pavement ranges from 0.35 to 0.40, but in contrast to asphalt pavements, as concrete pavements age, their albedo decreases, stabilizing between 0.25 and 0.35.[304] Albedo will vary to some extent by geography because of different pavement mix design standards.[l,305] This analysis assumes a conservative conventional citywide average pavement albedo of 0.18 (see Table 9.8).

Brick is an important material for sidewalks, especially in older cities like Baltimore. Red brick has an albedo between 0.20 and 0.30.[306] This report does not quantify the effects of increasing sidewalk albedo.

Table 9.8. Solar reflectance of conventional pavements

PAVEMENT TYPE	ALBEDO
Asphalt	0.15
Concrete	0.30
Conventional pavement average	0.18

9.4.1.5 Reflective pavements

Reflective pavements work in a similar way to reflective (cool) roofs. They have a higher solar reflectance than conventional pavements, meaning that they reflect more solar energy, reducing the amount of pavement heat gain and reducing surface temperatures. As with cool roofs, some of the reflected solar energy is reflected back to space. Reflected solar energy may also impact nearby buildings and pedestrians (discussed in more detail in Section 9.4.3.5).

As noted in a report by ACEEE, experiments…show quantitatively that at pavement temperatures greater than 40 °C the amount of rutting increases dramatically. Similarly,

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[l] For example, choice of aggregate is highly dependent on local geology (because aggregate is heavy and thus expensive to transport).

under simple shear stress, samples suffer larger permanent shear distortion when their temperatures are elevated. Temperatures greater than 50 °C, at which the pavements degrade more rapidly, are known to occur in actual roads even in temperate climates. The peak pavement temperature can be reduced by about 4°C for each increase of 0.1 of albedo.[307]

The most cost-effective way to increase existing road and parking lot reflectivity is through surface treatments or overlays, essentially resurfacing the existing pavement surface.[308] 20 cities and towns are coordinating to cool their cities by painting roads with reflective seals/paint. Los Angeles is hoping that broad application of white paints on roads can help lower city temperature by up to 3 degrees.[309]

One Smart Surfaces Coalition initiative is the Cool Roadways Partership, now involving 2 dozen cities and is led by the Global Cool City Alliance (an SSC partner). The initiative already involves a dozen cites applying reflective resurfacing to increase reflectivity, cut local temperature and extend the life of road surfaces. This ongoing imitative provides a good example of urban reflective Smart Surfaces.

Thinner pavement layers are also less expensive because they require less material.[310] This report focuses on changing the albedo of only the pavement layer exposed to the sun. For pavements that support car traffic (i.e., roads and parking lots) this means applying surface treatments to increase albedo. As noted in Section 9.4.2, this report models reflective paints such as CoolSeal[311] and SunShield[312] on roads and parking lots to reflect more sun and reduce neighborhood and city temperature.

This report assumes a reflective parking lot and road albedo of 0.35 based on the guidance of professionals in the field.[313] Albedo assumptions for conventional and reflective pavements are listed in Table 9.9.

Table 9.9. Albedo of conventional and reflective pavements

PAVEMENT TYPE	CONVENTIONAL ALBEDO	REFLECTIVE ALBEDO
Road	0.18	0.35
Parking Lot	0.18	0.35

9.4.1.6 Solar reflectance and temperature

Several studies have examined the relationship between pavement albedo and pavement surface temperature. Rosenfeld et al. (1995) reported that pavement surface temperature decreases by about 8°F (5°C) for every 0.1 increase in surface albedo.[314] Experiments by Pomerantz et al. (2000) demonstrated that surface temperature of asphalt pavement decreases by 5-9°F (3-5°C) for every 0.1 increase in surface albedo.[315] Similarly, Pomerantz et al. (2003) found that surface temperature of concrete pavement decreases by about 9°F (5°C) for every 0.1 increase in surface albedo. Li et al. (2013), studied both asphalt and concrete pavement and found pavement temperature decreases by about 6°C for every 0.1 increase in pavement albedo, a similar relationship to the previous studies.[316] The similar relationship between albedo and surface temperature for both asphalt and concrete pavement reflects their similarity in thermal properties.[317]

9.4.2 Cost and timeline

9.4.2.1 Roads

9.4.2.1.1 Cost and timeline

There are four phases of a road's use phase when it can be made reflective: (1) during initial construction, (2) during reconstruction, (3) during resurfacing, and (4) during preservation. During construction (1) and reconstruction (2), a new wearing surface (the layer that vehicles drive on) is constructed, among other additions or modifications. During these phases, a reflective layer could be applied on top of the new wearing surface, requiring limited additional work. During resurfacing (3), a few inches of asphalt are removed and replaced with a new wearing surface. Similar to new construction and reconstruction, a thin reflective layer could be applied on top of the new wearing surface. In preservation (4), no surface material is removed. Instead, a surface treatment is applied to increase the time until the next servicing.

In Baltimore, road preservation surface treatments include slurry seals,[li] with a unit cost of around $4 per square yard ($0.45 per square foot).[318] This analysis assumes a $0.022 per square foot cost premium for a reflective slurry seal. CoolSeal and SunShield are examples of effectively used reflective sealants or slurry seals.

Reflective surfaces get less hot, which means surfaces experience less daily thermal expansion and contraction. Therefore, there is less cracking and these surfaces last longer. The value of extending the surface life generally exceeds the cost of adding a reflective layer. During each instance of preservation, this analysis assumes the added cost of a reflective slurry seal is the difference in cost between the unit costs of the reflective slurry seal and the standard slurry seal (i.e., $0.022 per square foot). This makes sense because the city would be applying a slurry seal regardless of reflectivity, so it will only pay for the extra cost, or the cost premium, of the reflective layer. The reflective seal cost premium (i.e., $0.022 per square foot) for the reflective slurry seal, as an additional process is fully offset (Figure 7.17) by road life extension.

This analysis assumes that a slurry seal is needed for pavement condition purposes 10 years after initial construction, reconstruction, or resurfacing and every 7 years after.[319] For simplicity, we assume the first reflective slurry seal is applied 10 years after initial construction, reconstruction, or resurfacing, when the first slurry seal would be applied.

[li] A slurry seal is an asphalt emulsion combined with fine aggregate.

Two subsequent reflective slurry seals are applied at 7-year intervals (this analysis assumes reflective slurry seals have a 7-year life due to road life extension benefits). During this three-cycle slurry seal application phase after new construction or reconstruction, the reflective slurry seal is applied at the cost premium (as noted above). After the three-cycle slurry seal application, this analysis assumes the pavement is resurfaced and the reflective slurry seal is applied at full cost, since conventional roads are not sealed during construction, reconstruction, or resurfacing. After the 10-year resurfacing life, this analysis assumes a two-cycle slurry seal application phase.[lii]

Parking lots are commonly privately owned and do not experience heavy traffic volume.[320] Therefore, this report assumes, after initial construction, parking lots do not undergo resurfacing for 15 years—any maintenance in the meantime is likely crack sealing and filling potholes. Any reflectivity increase for parking lots will come at the full cost of $0.43 per square foot initially, and at $0.022 per square foot when the parking lot is resurfaced or sealed after 15 years.

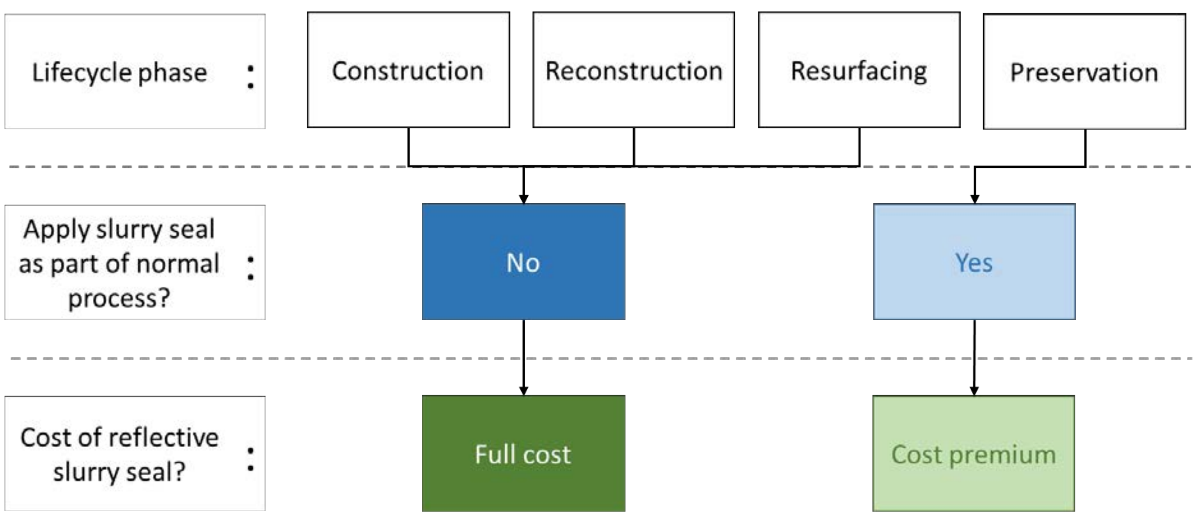

Figure 9.22. Flow chart to determine if pay full cost or cost premium for reflective slurry seal.

9.4.3 Impacts of reflective pavement

9.4.3.1 Reflective pavements impact summary

Table 9.10 and Figures 9.23 and 9.24 below summarize the costs and benefits of reflective pavements included in the cost-benefit results of this report.

[lii] This report does not estimate costs and benefits for transition of reflective roads starting during new construction or reconstruction and during resurfacing because these cycles are cost prohibitive.

Table 9.10. Reflective pavement cost-benefit impact table (a "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact).

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
GHG emissions reduction (+)	X	
Global cooling (+)	X	
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Heat-related mortality reduction (+)	X	
Employment (+)	X	
Increased surface life (+)	X	
Direct cooling energy reduction (+)		X
Direct heating energy penalty (-)		X
Enhanced nighttime visibility (+)		X
Downwind cooling (+)		X
Downwind warming (-)		X
Reduced stormwater runoff temperature (+)		X
Glare (-)		X
Reduced/improved thermal comfort (+/-)		X
Increased upward UV radiation (-)		X

Decreased visibility of roadway markings (-)	X

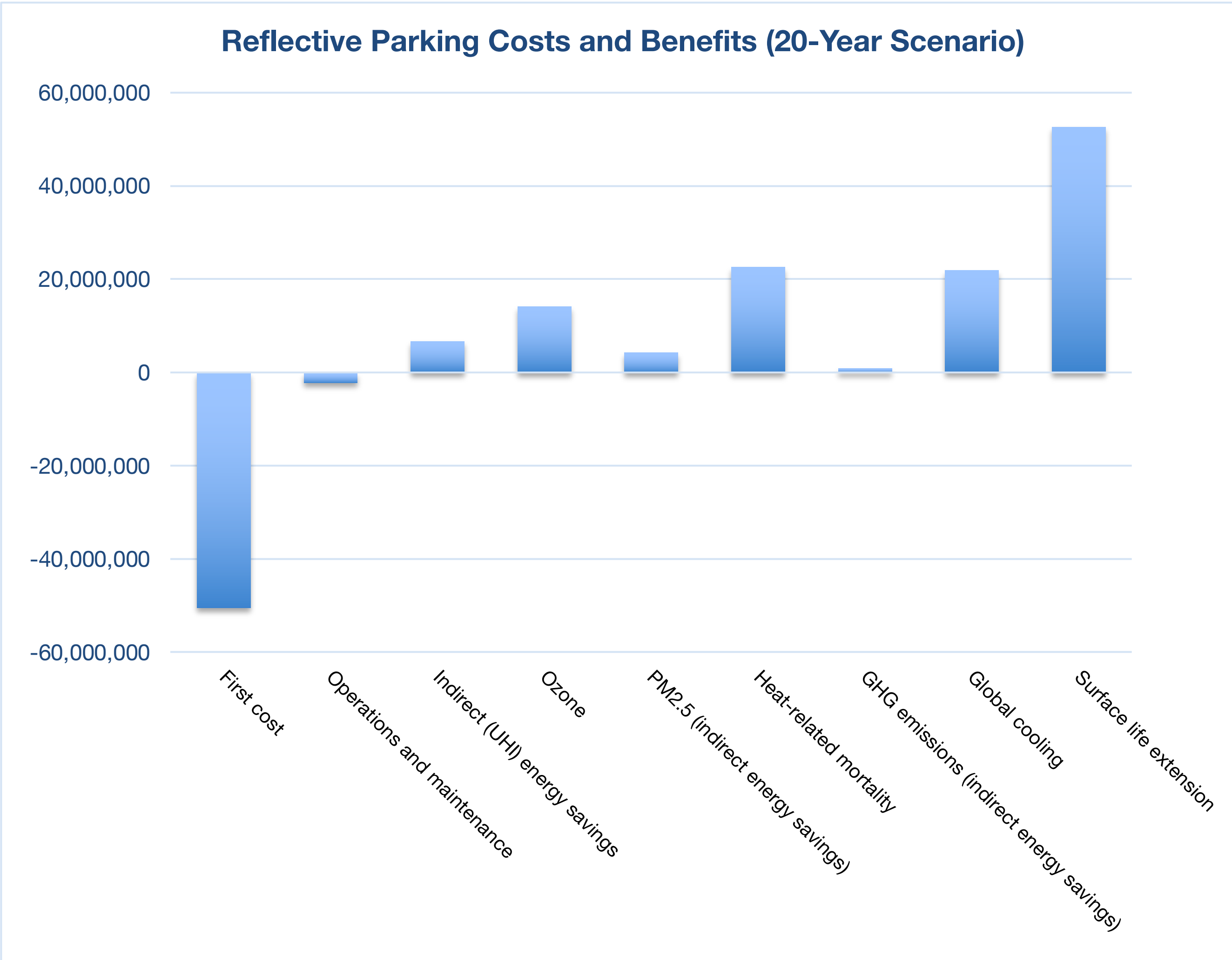

Figure 9.23. The costs and benefits of reflective parking lots for the 20-year scenario in dollar value (costs are shown in negative values and benefits are positive)

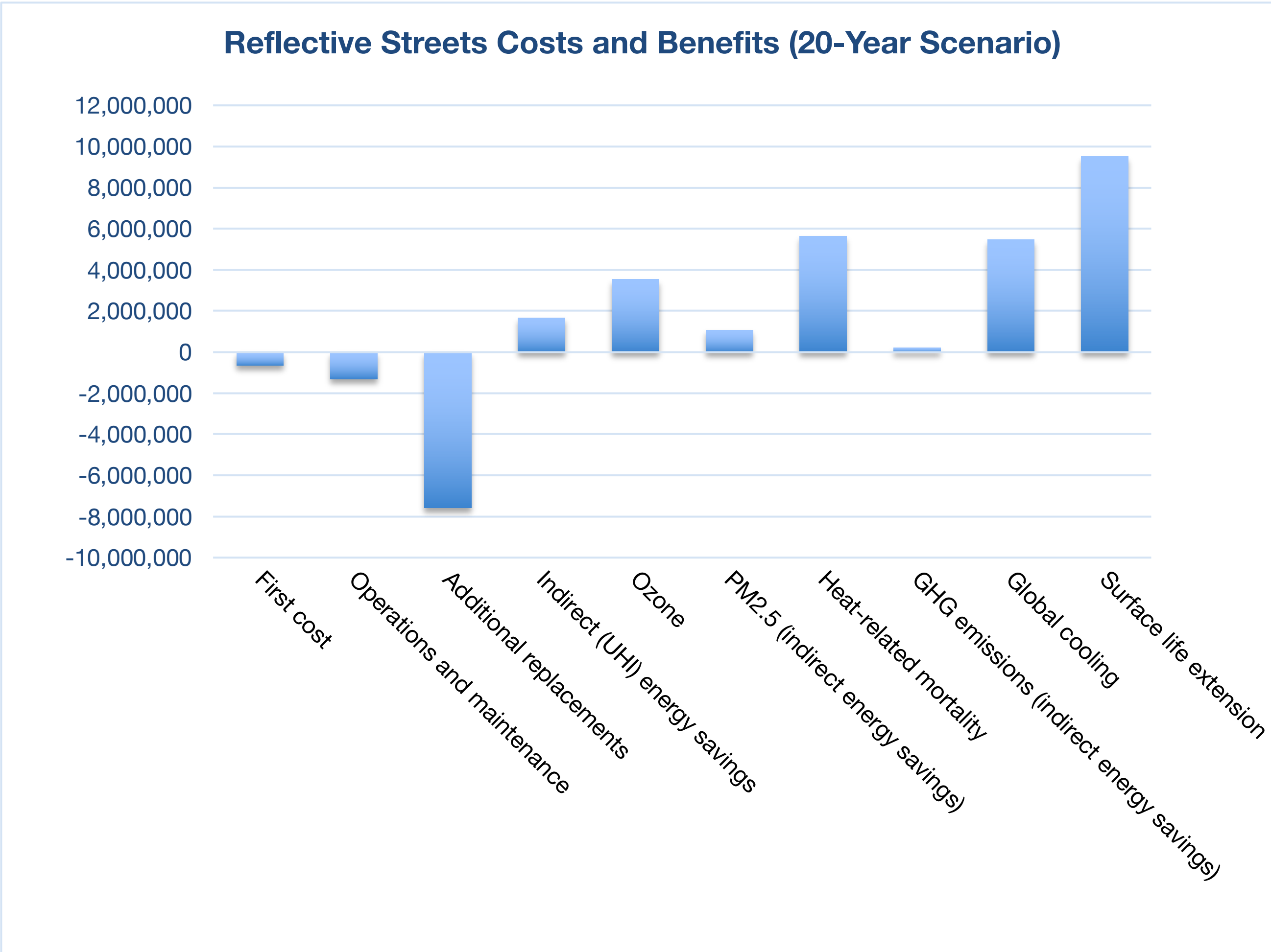

Figure 9.24. The costs and benefits of reflective streets for the 20-year scenario in dollar value (costs are negative values and benefits are positive values)

9.4.3.2 Ambient cooling and indirect energy

9.4.3.2.1 Ambient cooling

The mechanism by which reflective pavements provide indirect energy benefits is similar to that of cool roofs. Reflective pavements (i.e., those with high albedo) absorb less solar energy than standard pavements, so they heat up less and transmit less heat to urban air, reducing ambient temperatures. Higher albedo surfaces also experience less thermal expansion and contraction, reduced cracking and as a result last longer.

As noted in the cool roof section (Section 9.1), there is a generally established relationship between urban albedo increases and air temperature decreases. A 2000 study from Lawrence Berkeley National Lab derives an approximate formula for the maximum theoretical change in peak air temperature caused by changes in pavement albedo.[321] They estimate that in typical cases,[liii] increasing pavement albedo from 0.10 to 0.35[liv] across the entire city would reduce peak air temperatures by up to 1°F (0.6°C). Other studies of city-wide albedo changes examine only cool roofs or an average urban albedo increase (i.e., a combination of cool roofs and reflective pavements). LA is seeking to reduce city temperature by three degrees F by applying reflective slurry seals to its roads to make them more reflective.[322]

This report does not directly estimate the value of ambient cooling from reflective pavements, rather it indirectly estimates the benefits of ambient cooling through energy use reductions (this section) and related GHG emissions reductions (Section 9.4.3.3) and improvements in air quality and declines in heat related mortality (Section 9.4.3.3).

9.4.3.2.2 Indirect energy

A modeling study of Los Angeles estimated that increasing the albedo of all 1250 km2 of pavement in Los Angeles by 0.25 would lead to a temperature change of 0.6°C (about 1F) and indirect energy savings of $15 million (1998$) per year ($0.01 per square foot of pavement per year).[323][lv]

Section 10.3 provides an overview of methods and assumptions used to estimate this benefit.

9.4.3.2.3 Climate change mitigation

Reflective pavements reduce building space conditioning energy consumption through ambient cooling, reducing GHG emissions from power plants. Like cool roofs, much of the light reflected by reflective pavements is reflected back to space, helping to counter global warming. Because this impact can be significant, it is included in cost-benefit calculations.

This report describes the methods and assumptions used to estimate the climate change mitigation impact of reflective pavements in Section 10.4. Figure 9.25 shows the climate change mitigation pathways of reflective pavements.

[liii] This formula applies to cities in which "winds do not mix the air from outlying areas;" in other words, it does not apply to windy cities or cities located near large bodies of water. The study cites the Los Angeles Basin, Phoenix, and Dallas as examples.
[liv] This is approximately equivalent to replacing asphalt pavements with concrete pavements.
[lv] This is equivalent to about $22 million today, or about $0.002 per square foot.

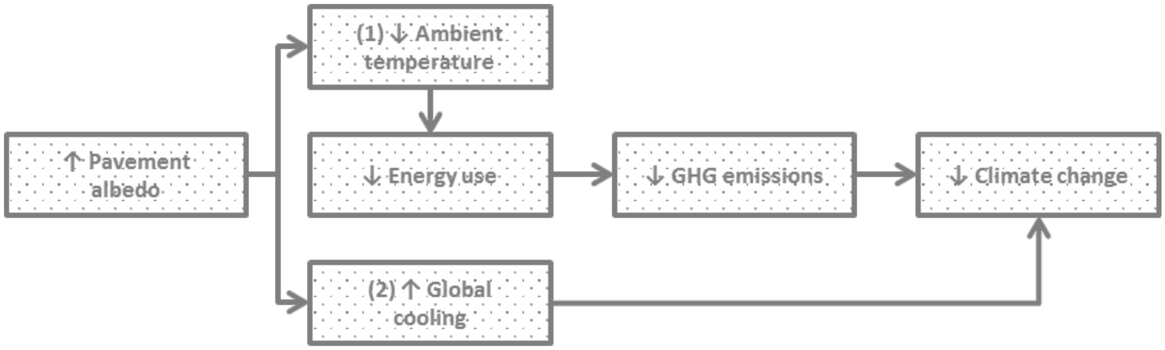

Figure 9.25. Climate change mitigation pathways of reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.4.3.3 Air quality and health

9.4.3.3.1 Reflective pavements and ozone

The chemical reactions that form ozone are dependent on temperature, and decreasing ambient temperature decreases ambient ozone concentration. Decreasing ambient temperature also indirectly reduces summertime building energy use, leading to decreased ozone precursor emissions. In general, as precursor emissions decline, ozone formation declines as well. Figure 9.26 shows the pathways through which reflective pavements can reduce ozone levels. Due to the complexities involved in photochemical air quality modeling, this report does not include the benefit of precursor emissions reductions in cost-benefit calculations. This report discusses the methods, assumptions, and pathways involved in the ozone-benefits analysis in more detail in Section 10.5.

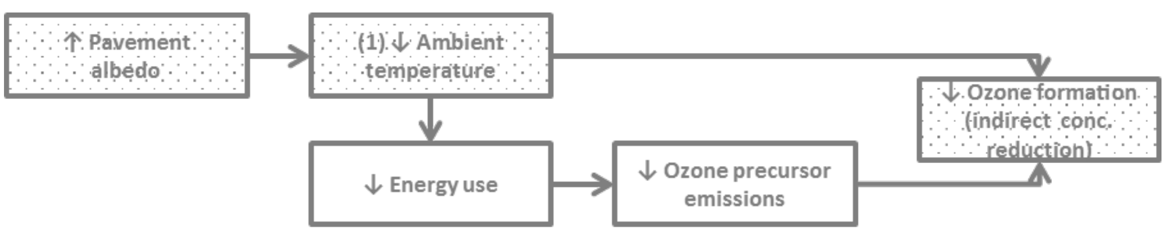

Figure 9.26. Ozone concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.4.3.3.2 Reflective pavements and PM2.5

Reflective pavements reduce PM2.5 pollution indirectly by decreasing ambient temperature, which in turn reduces building energy use. Reducing building energy use results in decreased power plant emissions of PM2.5 and PM2.5 precursors, decreasing primary and secondary PM2.5 pollution. Figure 9.27 shows the PM2.5

concentration reduction pathways of reflective pavements. This report describes PM2.5 impact estimation methods and assumptions in Section 10.5.

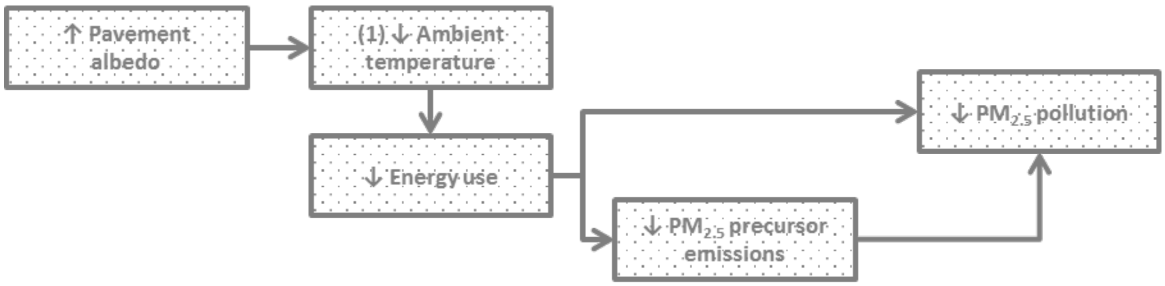

Figure 9.27. PM2.5 concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.4.3.3.3 Reflective pavements and heat-related mortality

Unlike cool roofs and green roofs that can impact heat-related mortality by two pathways, reflective pavements reduce heat-related mortality by only one significant pathway: improving outdoor temperature conditions. Several modeling studies have found that city-wide increases in albedo can reduce heat-related mortality.[324] This report describes heat-related mortality benefit estimation methods and assumptions in Section 10.5.

9.4.3.4 Reflective pavements and employment

Employment assumptions for reflective roofs and pavements are reviewed in Section 9.1.2.7.

9.4.3.5 Other impacts of reflective pavements

9.4.3.5.1 Direct energy

There are two mechanisms by which reflective pavements directly influence building energy consumption: (1) increased heat gain and (2) decreased artificial lighting requirements. Some of the sunlight reflected from reflective pavements is absorbed by surrounding buildings. The building heat gain also decreases building heating load in the winter, though this effect appears much smaller.[325] The increased amount of reflected sunlight from reflective pavements can also slightly reduce nearby buildings' artificial lighting needs, which has two direct energy benefits.[326] Reducing a buildings artificial lighting reduces energy used for lighting and reduces heat given off by internal lighting, which could reduce cooling energy requirements in the summer (and increases heating requirements in the winter).

There are no comprehensive studies that examine the combined impact of increased heat gain and decreased artificial lighting requirements caused by reflective pavements. As a result, this impact is not included in cost-benefit calculations.

9.4.3.5.2 Increased pavement life

Increasing pavement albedo leads to increased pavement life because the lower peak temperatures of reflective pavements mean less thermal expansion and contraction, slowing the aging process. Research has shown that increasing the albedo of asphalt reduces the risk of premature failure due to rutting (a particular type of asphalt pavement failure).[327] For concrete, lower daytime surface temperature reduces the temperature-related stresses that contribute to cracking.[328] As noted above this surface life extension offsets cost of reflective surfaces application and O&M costs.

9.4.3.5.3 Enhanced nighttime visibility

Increasing pavement reflectivity can enhance nighttime visibility.[329] This can increase driver and pedestrian safety and reduce street lighting needs because reflective pavements better reflect street and vehicle lights.[330] When new light fixtures are installed, fewer streetlights are required to achieve desired lighting levels with reflective pavements, meaning lights can be located further apart. When lights are replaced on existing fixtures, reflective pavements would mean lower power lights can be installed, reducing city energy bills and cutting related pollution. While light load reduction benefits including spacing streetlights further apart are now well documented, because Baltimore is not doing much in the way of adding new streetlights, the savings are excluded from cost-benefit analysis calculations. As the city upgrades its lights, use of higher albedo surfaces would reduce the cost of lighting upgrades (smaller light fixtures), though more efficient LED street lighting means lower energy savings and/or high visibility.

9.4.3.5.4 Reduced stormwater runoff temperature

As with cool and green roofs, reflective pavements would reduce initial summer stormwater runoff temperatures, helping reduce thermal shock to aquatic life in nearby water bodies. However, this analysis does not include the potential benefit of reduced stormwater runoff temperature in cost-benefit calculations.

9.4.3.5.5 Downwind cooling

As discussed in the cool roof impacts section (Section 9.1.2.8), hot air from urbanization heats downwind areas because of heat transfer by advection. The ambient cooling benefit provided by reflective pavements could help alleviate a portion of this downwind warming. However, as discussed, this analysis does not include this benefit due to limited available research. At a larger regional level (e.g., installing Smart Surfaces in the larger Baltimore metro area), downwind cooling benefits could be large.

9.4.3.5.6 Glare

Glare is caused by excessive brightness and can be uncomfortable or disabling, but glare is also subjective.[331] Brightness is caused by too much visible light entering the eye, so reflective pavements that reflect strongly in the visible spectrum can cause glare. For most people, small increases in pavement solar reflectance will not cause glare-related problems because many people encounter these kinds of pavements everyday—people drive, bike, and walk on concrete pavements around the country.[332]

This report found limited research examining the relationship between increased pavement reflectivity and glare, so the impacts of glare are not included in cost-benefit calculations. In addition, this report assumes no investment in increasing sidewalk albedo, eg it is not deployed in either scenario modeled in this report.

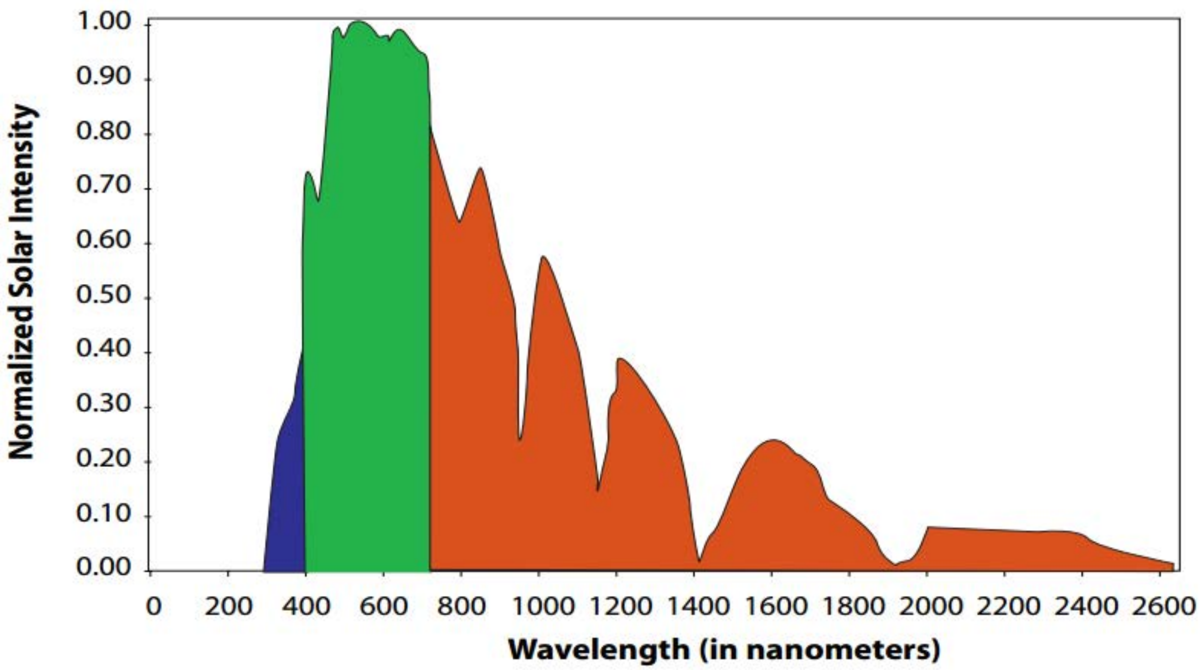

Figure 9.28. Solar energy versus wavelength reaching Earth's surfaces on a typical clear summer day (blue is ultraviolet wavelengths, green is visible wavelengths, and orange is near-infrared wavelengths)[333]

9.5 Urban Trees

The sections below explore the basic principles of urban trees and their impacts. As noted in Section 7.3.5, major benefits from urban trees include ambient cooling, reduced energy use for cooling and heating, reduced greenhouse gas emissions and global cooling, improved air quality and reduced heat-related mortality, and reduced stormwater runoff. Other benefits include downwind cooling, reduced stormwater runoff temperature, increased property value and aesthetic value, increased biodiversity, carbon sequestration, reduced crime, and improved thermal comfort. Potential drawbacks are fewer and smaller and may include potential for increased humidity, increased emissions of biological volatile organic compounds, increased winter heating needs due to ambient cooling, and increased pollen production.

9.5.1 Urban tree basics

9.5.1.1 Costs

The initial cost of planting a tree includes purchasing the tree and the cost of planting. There is a wide range of estimates for tree planting costs. For Baltimore, this report assumes $283 per tree, based on discussions with American Forests, TPL, Casey Trees, and the US Forest Service. This cost is slightly inflated to provide funding for additional training to expand trained workforce. Field measurements conducted by the US Forest Service indicate the average urban tree crown size in Baltimore is 581 square feet per tree. In addition, we assume 2% of new trees planted will not survive and need to be replaced. There are also costs for maintaining trees including pruning, pest and disease control, irrigation, program administration, liability issues, root damage repair (e.g., to sidewalks), and stump removal.[334] A regional summary of the costs and benefits of trees by the U.S. Forest Service, and discussion with American Forests and Casey Trees, leads this report to assume maintenance costs for trees in Baltimore of $0.47 per square foot of tree canopy per year.[335]

Table 9.11. Tree planting and maintenance costs used for Baltimore

PREMIUM	COST
Installation (planting)	$283/tree
Maintenance	$0.47/SF/year

There are several organizations in Baltimore that focus on planting new trees and providing resources to communities, including free or discounted tree planting. Blue Water Baltimore's Forestry Program focuses on planting and caring for trees in an effort to increase tree canopy. Each year Blue Water Baltimore gives away 1,000 trees to Baltimore County and City residents.[336] The Baltimore Tree Trust, nonprofit organization, is also a leader in increasing the tree canopy on private properties and in low-canopy neighborhoods throughout the city.[337]

9.5.2 Impacts of urban trees

Urban trees provide direct and indirect benefits. Direct benefits include energy savings due to shading of adjacent buildings and windbreak. Urban trees also sequester CO2, remove harmful pollutants from the air, and reduce stormwater runoff. Indirect benefits of urban trees include ambient cooling through evapotranspiration and shading (which reduces cooling energy use city-wide), reduced ambient ozone concentrations and related health costs, and heat-related mortality. Urban trees also indirectly achieve pollution reductions (e.g., CO2, ozone precursors, PM2.5 and PM2.5 precursors) by reducing demand for electricity. Akbari et al., EPA, and Casey Trees provide excellent descriptions of the benefits of urban trees.[338] Much of the discussion and references cited below draw from these sources.

9.5.2.1 Urban tree impact summary

Table 9.12 and Figure 9.29 below summarize the costs and benefits of urban trees included in the cost-benefit calculations of this report. There are more benefits than costs excluded from cost-benefit calculations, and excluded benefits very likely have a much higher value in aggregate than excluded costs, so this report's findings underestimate the net value of urban trees.

Table 9.12. Urban tree cost-benefit impact table (A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact).

IMPACT	INCLUDED	NOT INCLUDED
Planting (-)	X	
Maintenance and other expenses (-)	X	
Direct cooling energy reduction (+)	X	
Direct heating energy reduction (+)	X	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
GHG emissions reduction (+)	X	
Global cooling (+)	X	
Carbon sequestration (+)		X
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Air pollution uptake (+)	X	
Heat-related mortality reduction (+)	X	
Reduced stormwater runoff (+)	X	
Improved thermal comfort (+)		X
Downwind cooling (+)		X
Downwind warming (-)		X
Reduced stormwater runoff temperature (+)		X
Amenity value (+)		X
Aesthetic benefits (+)		X
Biodiversity (+)		X
Reduced crime (+)		X
Reduced UV light exposure (+)		X
Increased humidity (-)		X
Increased BVOC emissions (-)		X
Increased pollen production (-)		X

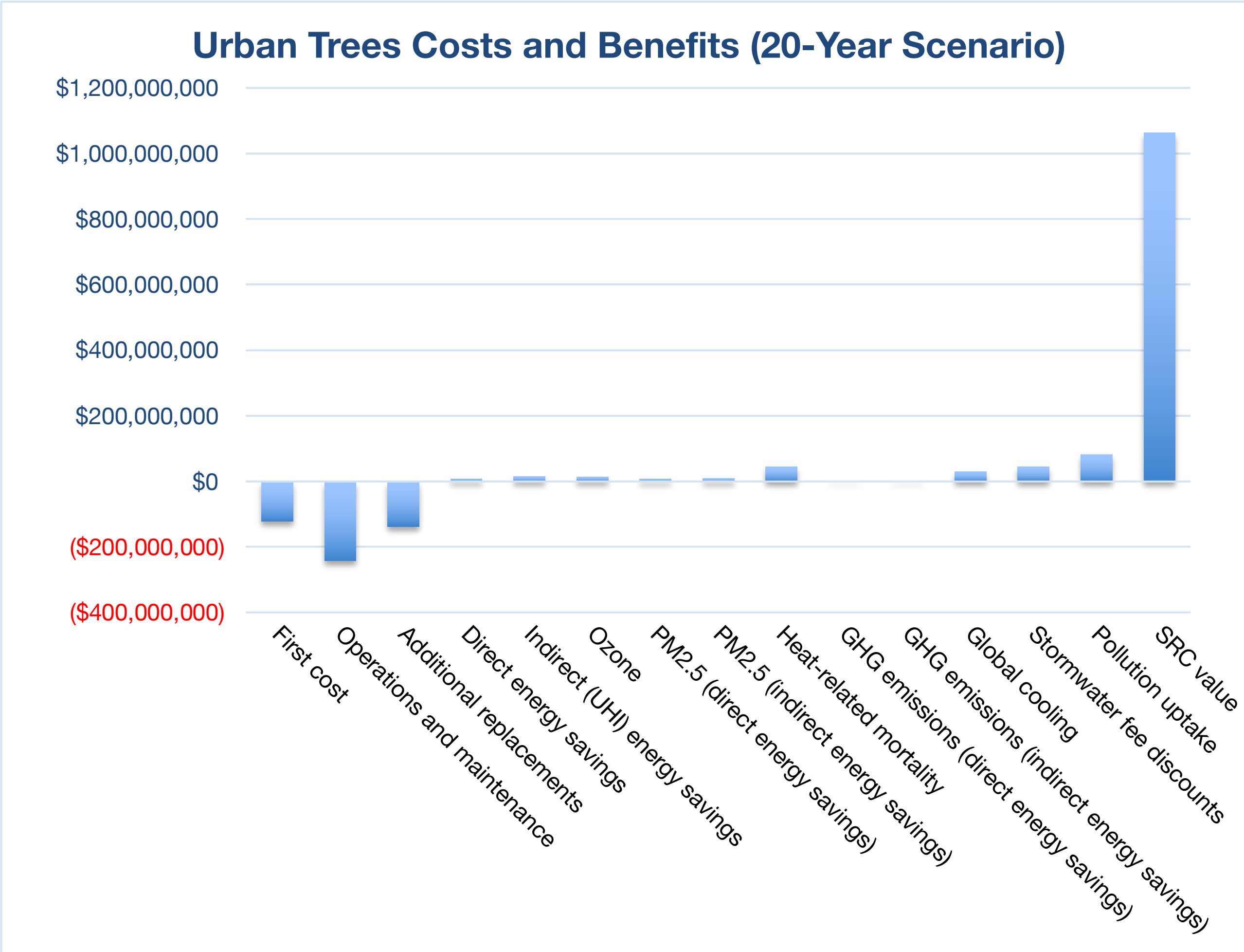

Figure 9.29. The costs and benefits of urban trees for the 20-year scenario in dollar value (cost values are negative and benefit values are positive)

9.5.2.2 Direct energy

Urban trees can directly reduce energy use of adjacent buildings by shading, decreasing the amount of solar radiation absorbed by the building surface or passed through windows. This reduces building surface and internal temperatures[339] , which in turn reduces building cooling energy needs. Huang et al. (1990) estimated that during the summer, 10% to 30% of solar energy reaches surfaces under a tree's canopy.[340] In the winter, up to 80% of incident solar energy reaches the surfaces below deciduous tree canopy, proving useful natural warmth to building in winter months. Deciduous trees are the norm in Baltimore.

Trees can also serve as windbreaks (i.e., wind shields), reducing the wind speed in the vicinity of buildings.[341] This can reduce winter infiltration of cold air into the shielded building, leading to reduced heating energy use. The effect of evergreen trees, which do not lose foliage in the winter, is larger than the wind-slowing effect of deciduous trees, which lose foliage in the winter. In summer, the effect of a windbreak can be positive or negative,[342] but potential air conditioning use increases from windbreaks are generally much less than savings due to shading.[343]

One study of a utility tree planting program found cooling energy savings of 1% per tree and heating energy savings of 2% per tree.[344] A simulation study of trees in various U.S. cities found 20% tree canopy cover over a home yielded between 8% and 18% savings on cooling energy use and between 2% and 8% savings on heating energy use.[345]

Section 10.1 provides an overview of methods and assumptions used to estimate this benefit.

9.5.2.3 Ambient cooling and indirect energy

Evapotranspiration and shading from urban trees lead to ambient cooling, reducing cooling-related energy use.[346]

The extent of ambient cooling in the U.S varies by city. A modeling study simulated the impact of increasing the urban forest in 10 U.S. cities and found that, on average, increasing tree cover could reduce temperatures at 2pm between 0.3 and 1°C.[347] A UHI mitigation potential analysis for New York City found that open space tree planting (10.8% of the city) and curbside planting (6.7% of the city) could reduce summer temperatures at 3pm by 0.2°F and 0.4°F, respectively.[348] Similarly, a study that modeled changes in a city's vegetated cover and changes in temperature found that increasing vegetation by 10% of total surface area reduced maximum temperature by 0.18°C in Washington D.C and by 0.27°C in Philadelphia.[349] A study conducted in 2018 looks at the radiative shading effect trees have on the urban built environment in multiple cities across the United States. The results indicate a 10% absolute increase in tree canopy can result in a 1.1°F peak summer temperature reduction due to the radiative shading effect of trees.[350] Our analysis uses this 1.1°F temperature reduction in determining an estimated peak summer temperature reduction from trees. The results indicate that approximately ten years after the end of the 20-year adoption period, Baltimore can expect to see a 40% tree canopy cover, up from 29% today. Applying the simple temperature reduction formula deduced from the results of the Wang, Wang, and Yang 2018 report, we estimate that Baltimore will experience approximately and conservatively 1.2°F peak summer temperature reduction due to the shading effect of the additional tree canopy.

9.5.2.3.1 Indirect energy

Indirect energy savings will also vary by city. The ten-city modeling study cited above found that ambient cooling due to greater numbers of urban trees would lead to annual indirect energy savings between $1 and $3 per 1000 ft2 of roof in Washington, DC.[lvi,351] It is reasonable to expect that Baltimore would see similar savings due to its similar climate. We do not directly apply these results, though, and instead use the findings of Akbari and Konopacki (2005) to estimate indirect energy benefit due to urban trees.[352] The resulting estimate for savings is comparable to the value found for Washington, DC, in the previously mentioned modeling study.

Section 10.3 provides an overview of methods and assumptions used to estimate this benefit.

9.5.2.4 Climate change mitigation

Urban trees contribute to climate change mitigation in four ways: by reducing direct and indirect energy use (and thus reducing greenhouse gas emissions from power plants), by directly sequestering and storing CO2,[353] and by global cooling (discussed in Section 9.1.2.5).

A modeling study of CO2 emissions reduction benefits of urban trees in Los Angeles found that each tree would reduce power plant CO2 emissions by 18 kg of CO2 per year.[lvii354] When a tree dies, most of the CO2 it stored is released to the atmosphere through decomposition, though different disposal techniques can prolong the release.[355lviii] Rosenfeld et al. (1998) found the sequestration benefit to be less than one fourth of the emissions reductions (i.e., less than 4.5 kg of CO2 per year).[356] Given the limited CO2 sequestration from Baltimore tree planting, this report does not include sequestration from urban tree planting in cost-benefit calculation, resulting in a slight underestimate of the benefits or urban tree plantings.[lix] Large scale tree planting across cities and towns would have a significant carbon sequestration benefit.

Planting urban trees may also lead to global cooling (discussed in Section 9.5.2) because trees typically have a higher albedo than conventional roofs or pavements they cover—tree albedo ranges from 0.25 to 0.30.[357] Since global cooling can be a significant benefit, this analysis includes this benefit for trees as for cool and green roofs and reflective pavements. This report uses the low estimate (0.25) of tree albedo. Figure 9.30 shows urban tree climate change mitigation pathways. Refer to Section 10.4 for an overview of methods and assumptions.

[lvi] In other words, a building with a 10,000 square foot roof would expect $10 to $30 of indirect energy savings with more trees planted in Washington, DC.

[lvii] This includes emissions reductions due to direct and indirect energy savings.

[lviii] For example, mulching will release stored CO2 more quickly than using the wood to make furniture.

[lix] This agrees with guidance we received from urban tree experts.

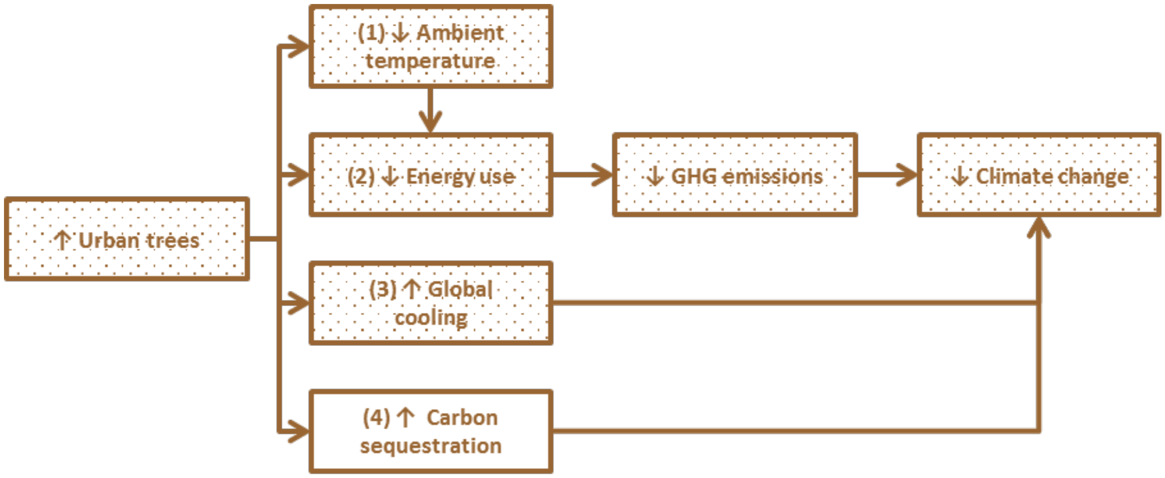

Figure 9.30. Urban tree climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.5.2.5 Air quality and health

9.5.2.5.1 Urban trees and ozone

Urban trees have the same ozone reduction pathways as green roofs. Urban trees reduce ambient ozone concentration by (1) decreasing ambient temperature, (2) decreasing building energy use, (3) directly removing NO2 (an ozone precursor) from the air, and (4) directly removing ozone from the air. Urban trees directly remove NO2 and ozone from the air through dry deposition (pollution removal dry periods). Figure 9.31 shows the ozone concentration reduction pathways of urban trees. Due to the complexities involved in photochemical air quality modeling, this report does not include the benefit of ozone precursor emissions reductions in cost-benefit analysis calculations. In contrast to green roofs, much work has been done on estimating the value of pollution removal by urban trees. This report includes this benefit for urban trees (see below). Methods and assumptions are discussed in more detail in Section 10.5.

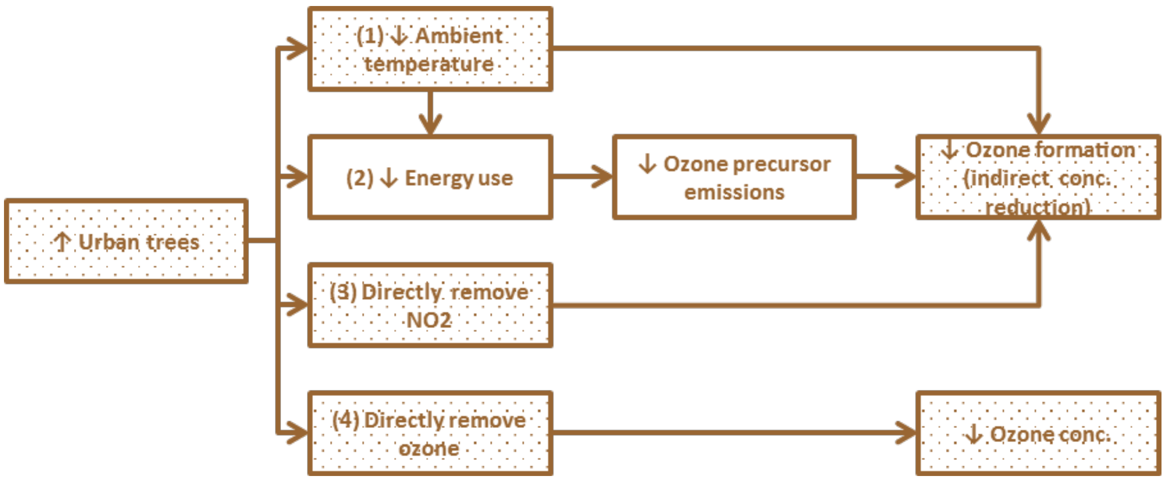

Figure 9.31. Urban tree ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

9.5.2.5.2 Urban trees and PM2.5

Urban trees reduce PM2.5 concentrations in the same four ways as green roofs do. Urban trees remove PM2.5 from the air by dry deposition (pathway (1) in Figure 9.32). Urban trees also remove PM2.5 precursors from the air through dry deposition, thereby decreasing secondary PM2.5 pollution (pathway (4) in Figure 9.32). Urban trees reduce PM2.5 pollution by decreasing ambient temperature (pathway (2) in Figure 9.32) and by decreasing building energy use (pathway (3) in Figure 9.32). In contrast to green roofs, much work has been done on estimating the value of urban tree pollution uptake. This report includes this benefit for urban trees (see below). This report describes PM2.5 impact estimation methods and assumptions in Section 10.5.

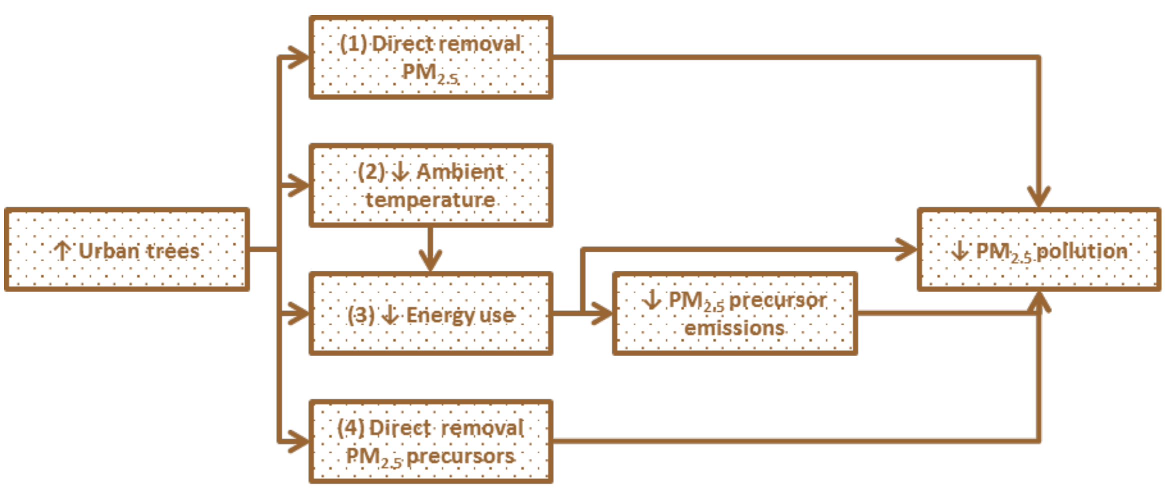

Figure 9.32. Urban tree PM2.5 concentration reduction pathways (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease shaded boxes indicate pathways included in cost-benefit results)

9.5.2.5.3 Urban trees and pollution uptake

In addition to removing CO2 from the air through sequestration, trees also directly remove other air pollutants through dry deposition, essentially filtering the air. Air pollutants removed through dry deposition include ozone, PM10 and PM2.5, carbon monoxide (CO), sulfur dioxide (SO2), and nitrogen dioxides (NOx). Gaseous pollutants are primarily removed through leaf stomata, while particulates are intercepted by leaves and other tree surfaces as air moves through the tree canopy.[358] A group of researchers from the U.S. Forest Service estimated that U.S. urban trees in 2006 removed about 711,000 metric tons of pollutants (O3, PM10, NO2, SO2, CO), valued at $3.8 billion.[359] Despite the large value of pollutant removal, actual changes in local ambient air quality are modest and are typically less than 1%,[360] although this increases with rising urban tree coverage. The impact of direct removal of pollutants, though modest, is well documented, so it is included in cost-benefit calculations. Refer to Section 10.5.4 for a description of assumptions.

9.5.2.5.4 Urban trees and heat-related mortality

Urban trees can reduce heat-related mortality through the same pathways as cool roofs and green roofs. Urban trees can reduce heat-related mortality by keeping buildings cooler through shading. In addition, urban trees can reduce heat-related mortality through ambient cooling. Modeling studies find that increasing urban vegetation reduces heat-related mortality.[361] This report did not find analyses documenting the potential for urban trees to reduce heat-related mortality by improving indoor conditions, but these reductions could be significant.[362] By not including this benefit, this report underestimates total benefits. This report describes methods and assumptions to estimate green roof heat-related mortality impact in Section 10.5.

9.5.2.6 Stormwater

Trees, like green roofs, also reduce stormwater runoff volumes and delay time of peak runoff.[363] Tree surfaces intercept rain as it falls. The soil around urban trees also absorb rainwater, where it infiltrates into the ground, is absorbed by the tree through its roots, or evaporates. Figure 9.33 illustrates these and other stormwater runoff reduction pathways. Simulation studies estimate that urban trees reduce citywide stormwater.[364]

Interception and soil capture are most effective at reducing stormwater runoff during small rain events, which account for most precipitation events and are responsible for most roadway pollution wash-off (e.g., vehicle oils).[365] During large rain events or extended periods of rain, an urban tree's capacity for interception and soil absorption trees capacity will be reached.[366]

Refer to Section 10.6 for an overview of methods and assumptions.

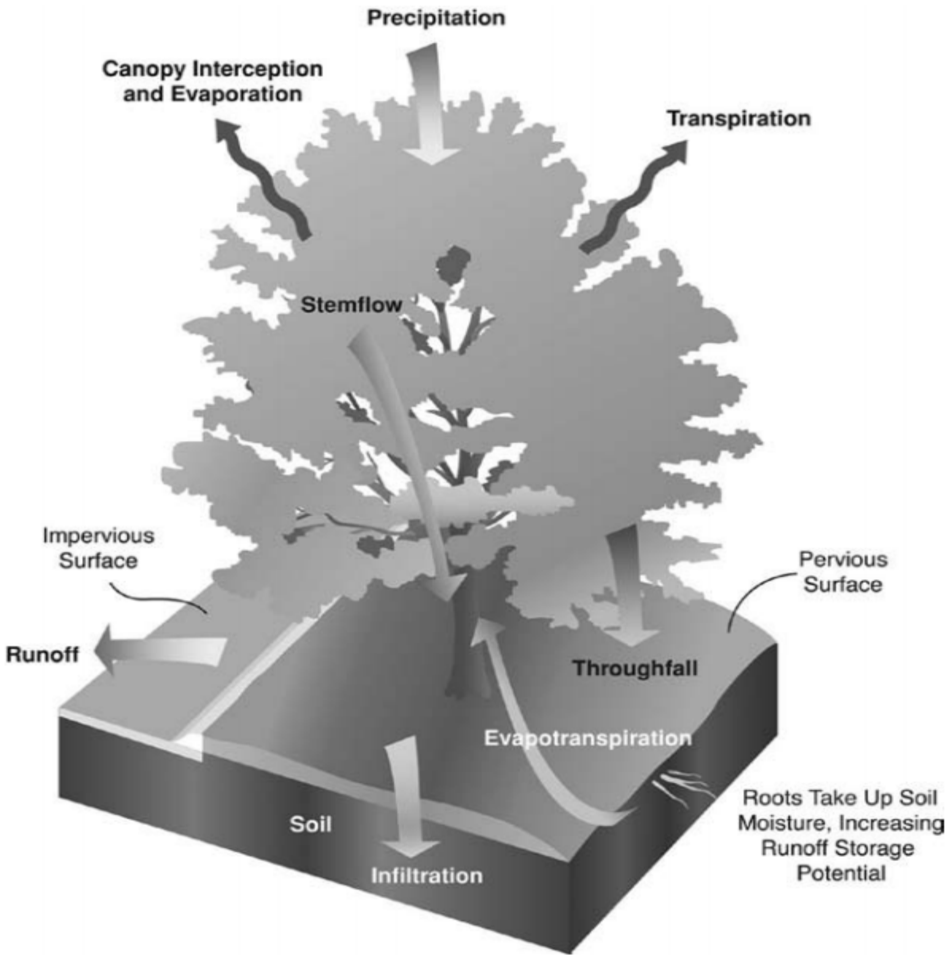

Figure 9.33. Illustration of tree stormwater runoff reduction pathways[367]

9.5.2.7 Urban trees and employment

Based on literature review and discussion with tree experts, we estimate that the number direct jobs created per million dollars invested in tree planting includes 50%, or $500,000, in direct labor costs, yielding 10 job years at $50,000 per job. We estimate that the other $500,000 would go towards buying saplings to plant and other supplementary materials. We estimate that a total of 14 direct job years are created per million dollars spent on tree planting.

Saplings ready for planting cost on average $283 per tree, according to American Forests. They can be grown within city boundaries but are more commonly grown remotely where lower land and labor costs more than offset higher transport cost, so the employment benefits of sapling growth may not accrue at the city level. Baltimore can provide incentives or preferences for saplings grown in the city and/or sapling growth projects that employ city residents. For example, Baltimore can provide land in the city for tree nurseries that also grows green roof trays that make up green roofs. Smart Surfaces Coalition partners, including American Forests and Trust for Public Lands encourage establishment or expansion of tree nurseries within city jurisdictions, to increase employment and reduce transportation costs. This is an important policy option decision for Baltimore.

9.5.2.8 Other impacts of urban trees

9.5.2.8.1 Improved thermal comfort

Numerous studies have demonstrated thermal comfort benefits from urban trees in different climates.[368] The most important local climate factor in the thermal comfort impact of urban trees is mean radiant temperature, which is a measure of the amount of direct and reflected radiation experienced by a surface. For small scale plantings of trees (e.g., along a single street), there is only a small reduction in air temperature.[369] Large-scale tree planting is required to provide cities with substantial air temperature reductions.

Tree shading reduces radiant temperature, thus enhancing thermal comfort. The size of the thermal comfort impact directly in the shadow of a tree depends on climate. A U.S. simulation study of a hot-dry climate found planting trees in a street canyon reduced physiological equivalent temperature (PET)[lx,370] by over 20°C in summer conditions.[371] Similarly, a simulation study in Freiburg, Germany, found shade under the tree canopy reduced PET by up to 15°C in summer conditions, which the authors note is two steps on a thermal sensation scale (e.g., from “hot” to “warm” to “slightly warm”).[372] The thermal comfort benefits described above serve as an upper bound because the impacts were estimated directly under tree canopy. In reality, pedestrians will only experience tree shade part of the time.

[lx] Physiological equivalent temperature (PET) is defined as the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed [Chen and Ng (2012*),* [ref 371]. In other words, PET is the hypothetical indoor air temperature at which an individual, performing a defined activity and in a standard set of clothes, would experience the same physiological response, and thus experiences the same level of thermal comfort/discomfort, as the conditions under study.

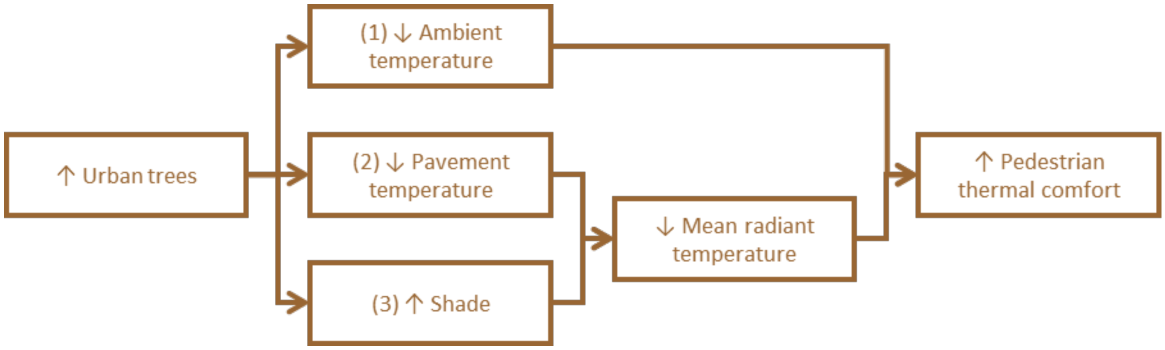

Figure 9.34. Impact of urban trees on summertime pedestrian thermal comfort

Adding trees can reduce thermal comfort in winter,[373] but deciduous trees block little winter solar radiation.[374] In Baltimore net thermal comfort benefits from shade are large.

Given the difficulty in valuing thermal comfort impacts, particularly impacts of shade, this report does not include thermal comfort benefits of trees directly in cost-benefit calculations. However, we do include a discussion of increased thermal comfort on the impact of tourism, including an estimate of benefits from Smart Surface installations city-wide, including trees—and the potential benefits of avoided tourism losses.

9.5.2.8.2 Crime reduction

Smart Surfaces cannot single-handedly create a safe community for citizens, but they are an integral component of a comprehensive public-safety strategy. Among the surface types outlined in this report, well-maintained trees and green spaces can contribute to crime reduction. Scientists from the University of Vermont and the US Forest Service investigated this relationship in Baltimore City and County. Specifically, the scientists examined robbery, burglary, theft, and shootings, both fatal and attempted.[375] Their findings are particularly convincing because they kept an extensive number of variables constant when comparing neighborhoods' crime rate vs. tree cover. The surveyors ensured each location had the same median income, population density, race, amount of agricultural land, percent of households classified as "rural," housing age, type, and tenure.[376]

The research concluded that neighborhoods with 10% greater tree-canopy cover experienced 11.8% less crime than similar neighborhoods.[377] Well-designed green space could decrease crime by attracting people to spend time outdoors,[378] resulting in an informal system of surveillance.[379] The author Jane Jacobs termed this "eyes on the street."[380] Pruning and watering vegetation signifies residents actively care about and are involved in their surroundings.[381] Put simply, people like trees, they like neighborhoods with trees, and they are much more likely to spend time outdoors where trees provide shade and a comfortable place for socializing.[382] More eyes on the street makes neighborhoods safer.

As discussed above, Smart Surfaces reduce ambient summer temperature. And lower summer temperature has in multiple studies correlated with lower crime. For example, research indicates that an increase of 3.6°F in ambient temperature in the US could increase the rate of aggravated assault by 2.3% and the murder rate by 2.2%.[383] A 2019 study concluded that 3.6°F increase (2°C) was associated with a homicide rate increase of 1.5%.[384] Researchers in Spain documented that intimate partner femicides increased by 28.8% for each degree in daily maximum temperature above 93.2°F.[385]

In addition to the larger impact of tree shading, trees canopies can lower city-wide temperatures by 1.8°F and an additional 3.6°F in the local area.[386] Safe Streets Baltimore—an outreach program to reduce gun violence among youth—has decreased homicides by 56% in the Cherry Hill neighborhood.[387] Smart Surfaces can be an important tool to augment the work of organizations like Safe Streets Baltimore and help create a safer better quality of life for community members.

9.5.2.8.3 Increased humidity

Urban trees add water to the air through evapotranspiration, which decreases temperature but raises humidity. Increasing humidity can have adverse impact on comfort and may even increase cooling energy use.[lxi] However, EPA notes both negative or positive impacts of increased humidity from urban trees, and net impact is unclear, so it is not included in cost-benefit calculations.

9.5.2.8.4 Increased biological volatile organic compounds emissions (BVOCs)

Trees can also emit ozone precursor biologic volatile organic compounds (BVOCs), that for certain trees could counteract the ozone reductions that result from reduced ambient air temperature.[lxii,388] However, this is a well-known risk of increasing urban tree canopy, so city planners select from lists of tree species with low or very low volatile organic compound emissions.[389] Trees with low ozone-forming potential typically are prioritized for urban tree programs, avoiding the potential health costs. This potential health cost of tree VOCs is therefore not estimated in this analysis, which may cause a slight undercounting of costs.

Urban trees can enhance quality of life in multiple ways. First, they increase habitat for birds and other living things.[390] Trees reduce urban noise,[391] are linked to reduced crime, [392] and provide other psychological and social benefits that help reduce stress and aggressive behavior.[393] Urban trees reduce stormwater runoff temperature

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[lxi] Because air conditioning units would have to remove more moisture.
[lxii] The rate at which trees emit VOCs is affected by sunlight, temperature, and humidity; it also varies by species. Generally, as temperature increases, biogenic VOC emissions increase. But as Nowak (2002) [ref 376] points out, even though adding trees will increase the biogenic VOC emission potential, the added trees will likely reduce ambient temperatures so the overall biogenic VOC emissions could still decrease.

because they shade urban hardscape from solar radiation, reducing urban surface temperatures and thus runoff temperatures from these surfaces.

These myriad benefits of trees discussed above are large but are not quantified in this report because of limited extant research. Not including these benefits of urban trees means that tree benefits are undercounted and are larger than estimated in this report. Among other things, this means that actual benefit cost ratio for urban trees is substantially underestimated in this report—as well as more generally in urban policy.

9.6 Permeable Sidewalks and Parking Lots

The sections below explore the basic principles of permeable pavements and their potential impacts. While permeable pavements can be used for most pedestrian and vehicular applications, this report focuses on sidewalk and parking lot applications.

As previously noted, major benefits of permeable sidewalks and parking lots include reduced stormwater runoff and reduced winter salt use due to reduced ice buildup. Permeable sidewalks are far less likely to have ice buildup, greatly reducing potential for falling and reducing related health and liability damages.

Other impacts which warrant further study include ambient cooling, which leads to reduced cooling energy use, reduced greenhouse gas emissions, improved air quality and reduced heat-related mortality, increased thermal comfort, and improved water quality.

9.6.1 Permeable pavement basics

Common permeable pavements include pervious asphalt (called “porous asphalt”), pervious concrete, permeable interlocking concrete pavers (called “permeable pavers”), and lattice structures containing gravel or grass. These permeable pavements all have similar structural components.[394]

- The *surface layer* is the top layer that pedestrians see. This is the layer that cars drive on and people walk on. Under the surface layer are the bedding layer, the reservoir layer, underdrain (optional), filter layer (optional), and subgrade.
- The *bedding layer* typically consists of small, open-graded aggregate. It provides a level surface under the surface layer.
- The *reservoir layer*, which consists of the open-graded base reservoir and sometimes the open-graded subbase reservoir, is usually crushed stone. This layer provides load support and water storage. Pavement use, desired water storage, and the characteristics of the underlying soil determine the depth of the reservoir. Depending on the pavement use, a subbase reservoir may not be required.

- An *underdrain* is a perforated pipe that conveys excess stormwater to the storm drain. Underdrains are optional but are often used when permeable pavements are installed over low-infiltration soils such as clay.
- The *filter layer* is an optional fabric or small sized aggregate layer that is used to prevent soil from entering the base/subbase layers. The subgrade is the soil layer that underlies the permeable pavement system. The infiltration rate of the underlying soil influences the thickness of the reservoir layer and whether an underdrain is needed.

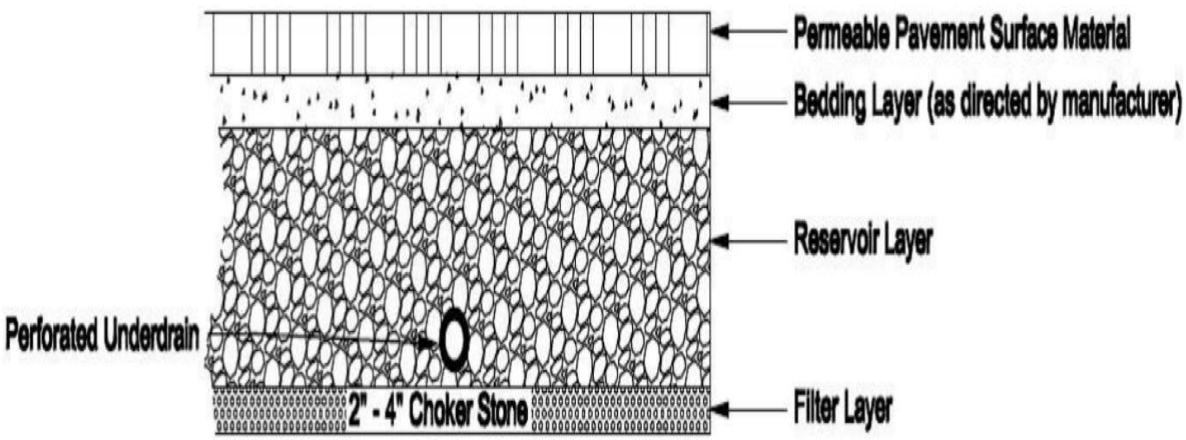

Figure 9.35. Example cross section of permeable pavement.[395]

9.6.2 Examples of permeable pavements

9.6.2.1 Porous asphalt

Porous and impervious asphalt have a very similar appearance and method of installation.[396] The main difference is that porous asphalt has reduced sand or fines, resulting in air voids for water to drain through.[397] Air voids typically make up 15 to 20 percent of the volume of porous asphalt.[398] The thickness of the porous asphalt surface layer depends on the expected traffic load and is typically 3 to 7 inches thick.[399] Porous asphalt can be used for pedestrian walkways, sidewalks, driveways, parking lots, and low-volume roadways, but is rarely used for high-volume and/or high-speed roadways because it usually cannot long term bear sustained high traffic load.[400]

Figure 9.36. Example of porous asphalt pavement.[401]

9.6.2.2 Pervious concrete

Similar to porous asphalt, the surface layer of pervious concrete pavement is simply Portland concrete cement with reduced sand or fines, resulting in air voids for water to drain through.[402] Air voids account for between 15 to 20 percent of the pervious concrete surface layer.[403] The thickness of the pervious concrete surface layer typically ranges from 4 to 8 inches.[404]

Figure 9.37. Example of pervious concrete pavement surface layer, with quarter to for scale.[405]

9.6.2.3 Permeable interlocking concrete pavements

Permeable interlocking concrete pavements (henceforth referred to as “permeable pavers”) consist of impervious concrete blocks, or pavers, installed in patterns that leave space for stormwater to infiltrate to lower pavement layers.[406] The proportion of the pavement surface area that is open space varies based on the specific type of pavement and manufacturer. Open spaces can be filled with gravel, aggregate, topsoil and grass, or coarse sand, among others.[407] Permeable interlocking concrete pavements can be used for the same applications as porous asphalt pavements—pedestrian and vehicular applications except high-volume/high-speed roadways.[408]

Figure 9.38. Examples of permeable pavers.[409]

9.6.2.4 Grid pavements

Grid permeable pavements employ plastic, metal, or concrete lattices for support, with the open space filled with soil, sand or aggregate that can allow grass or other vegetation to grow.[410] These pavements are often called concrete grid pavers or plastic reinforced grid pavers, depending on the material used for the lattices. These pavements contain significantly more open area than the permeable pavements discussed above so hold more water and are typically only used for areas that experience low traffic volume (e.g., alleys, side streets, parking lots, driveways, patios, and trails).[411] Grid pavements are generally not used for sidewalks.

Figure 9.39. Examples of grid pavements.[412]

9.6.2.5 Permeable pavement thermal performance

For a full picture of the thermal performance of permeable pavements, it is necessary to understand how they perform under both dry and wet conditions. During dry summer weather, permeable pavement tends to have a higher daytime surface temperature than an impervious pavement made of the equivalent material, suggesting permeable pavements may increase daytime air temperatures.[413]

However, at night dry permeable pavements tend to have lower surface temperature than the impervious equivalent because permeable pavements store less energy, suggesting permeable pavements may decrease nighttime air temperatures.[414] The daytime and nighttime surface temperature of a wet permeable pavement tends to be less than that of the wet impervious equivalent.[415] This difference is due to much greater evaporative cooling from permeable pavements. Unsurprisingly, as surface-moisture level decreases (e.g., as the number of days since the last rain increases), the surface temperature difference between a permeable pavement and the impervious equivalent decreases.[416] Because energy/heat in the pavement evaporates surface moisture during evaporative cooling, there is less energy available to heat the air or surroundings. At scale, evaporative cooling from permeable pavements could lead to measurable air temperature reductions in neighborhoods and city-wide.

9.6.2.6 Solar reflectance of permeable pavement

In general, permeable pavements may be slightly less reflective than their impervious equivalent, perhaps because of their increased roughness and void space.[417] Based on the limited information available, porous asphalt has a similar initial albedo to impervious asphalt.[418] Pervious concrete may have a slightly lower initial albedo than impervious concrete,[419] and permeable pavers have a similar initial albedo to impermeable pavers.[420] Grid pavers' albedo is largely determined by the filler. High albedo filler, such as light-colored gravel, would provide a higher albedo surface.

We found no studies on the aged albedo of permeable pavements. Nevertheless, we can expect albedo changes in permeable pavements to be similar to that of traditional pavements (i.e., albedo of asphalt pavements will increase with age and albedo of concrete pavements will decrease with age).

9.6.2.7 Permeable pavement maintenance

The primary maintenance concern for permeable pavements is protecting against sediment and particle build up that can clog the air voids and reduce the effectiveness of stormwater infiltration water absorption.[421] Sediment and particle sources include vehicles, the atmosphere, and runoff.[422]

Clogging increases with age and use; however, permeable pavements are effective even when partially clogged.[423] Sediment and soil deposits should be removed as needed.[424]

Because of reduced freeze/thaw stress, a permeable asphalt parking lot can last 15 years longer than a traditional asphalt parking lot in the same conditions.[425] Porous asphalt pavements tend to develop fewer cracks and potholes than impervious asphalt.[426]

9.6.2.8 Cost and timeline

Due to the differences in materials and structural requirements between permeable pavement and impervious pavement, permeable pavements are generally only an option for new construction or for impervious pavement replacement.

9.6.2.9 Costs

The cost of installing a permeable parking lot varies widely. This report focuses on plastic grid pavers for parking lots and on permeable pavers for sidewalks. The plastic lattices themselves cost on average $2.00 per square foot.[427] With a cost multiplier of 1.4 to cover additional costs like construction management and design,[428] this equates to $2.80 per square foot. The cost of the material used to fill the lattice varies. For grass we assume a cost of $1.62 per square foot installed.[429] For gravel, we assume a cost of $1.30 per square foot installed.[lxiii] In total, plastic grid with grass and plastic grid with gravel cost $4.42 per square foot and $4.10 per square foot, respectively. The cost of permeable pavers averages about $10.50 per square foot.[430]

We assume conventional concrete sidewalks cost $5.02 per square foot, and conventional brick sidewalks cost $10.78 per square foot. We assume a conventional asphalt parking lot cost of $5.50 per square foot.[431] We assume that permeable pavements are installed when sidewalks or parking lots are already in need of replacement. Because grid pavers have lower first cost than conventional pavements, permeable pavement installation first costs actually represent a net cost reduction to Baltimore. In addition, permeable pavements have longer lifespans than conventional pavements, so replacement costs are incurred less frequently, further contributing to a net benefit accrued during first costs.

Based on an analysis prepared for the Maryland Department of the Environment, the yearly maintenance cost of non-vegetated permeable pavements averages about $0.05 per square foot, and the yearly maintenance cost for vegetated permeable pavements averages about $0.07 per square foot.[432]

[lxiii] Based on a pea gravel cost of $50 per cubic yard, a 2-inch-thick layer, and a cost multiplier of 1.4 to cover additional costs like management and design (same as before).

9.6.2.10 Timeline

Timeline assumptions for traditional asphalt parking lots are the same as discussed under reflective pavements (Section 9.4.2), with a complete replacement required every 15 years. Permeable alternatives can extend surface life.

Little research has been done on the lifespan on gravel or grass filled lattice systems. However, products such as the Grasspave2, Gravelpave2, and True Grid systems claim to have lifespans of 25 years for the gravel filled products and 60 years for the grass-filled products (we use 40 years for this analysis because 60 years is beyond the bounds of our analysis).[433] This lifespan can vary depending on how heavily the parking lot is used and the material used to fill the lattice, but for simplicity we use these numbers. In this report, we assume the parking lot needs to be completely replaced at the end of its life.

Table 9.13. Permeable parking lot lifespans

Parking lot pavement type	Lifespan (years)
Conventional asphalt	15
Plastic grid with gravel	25
Plastic grid with grass	40

As noted in Section 9.4.2, this report assumes conventional sidewalks are replaced every 40 years. Pavers typically last longer than conventional pavement,[434] which is why we assume permeable sidewalks last the full 30-year analysis period as well.

9.6.3 Impacts of permeable sidewalks and parking lots

9.6.3.1 Permeable sidewalk and parking lot impact summary

Table 9.14 and Figures 9.40 and 9.41 below summarize the costs and benefits of permeable sidewalks and parking lots included in the cost-benefit results of this report. For cities that get serious about health, UHI mitigation, and climate change mitigation, permeable pavements can be a part of the solution.

Table 9.14. Permeable sidewalk and parking lot cost-benefit impact table (NOTE: A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact)

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Reduced stormwater runoff (+)	X	
Reduced pavement salt use (+)	X	
Ambient cooling/warming and co-impacts (+/-))		X
Reduced/improved thermal comfort (+/-)		X
Improved water quality (+)		X

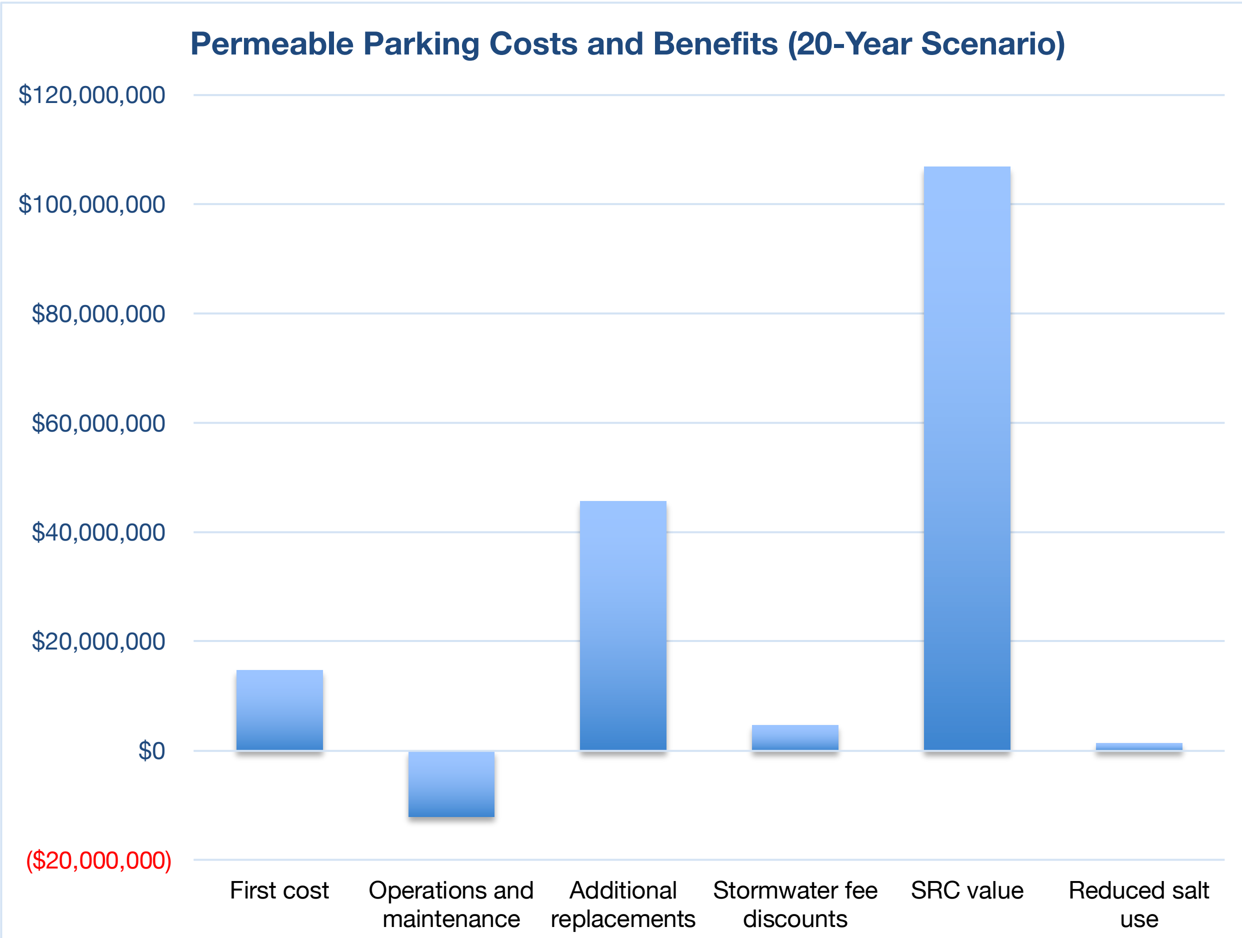

Figure 9.40. The costs and benefits of permeable parking lots for the 20-year goal scenario in dollar value (cost values are negative and benefit values are positive. Because new permeable parking lots cost less to install than their new conventional alternatives, installation is a net benefit for permeable parking)

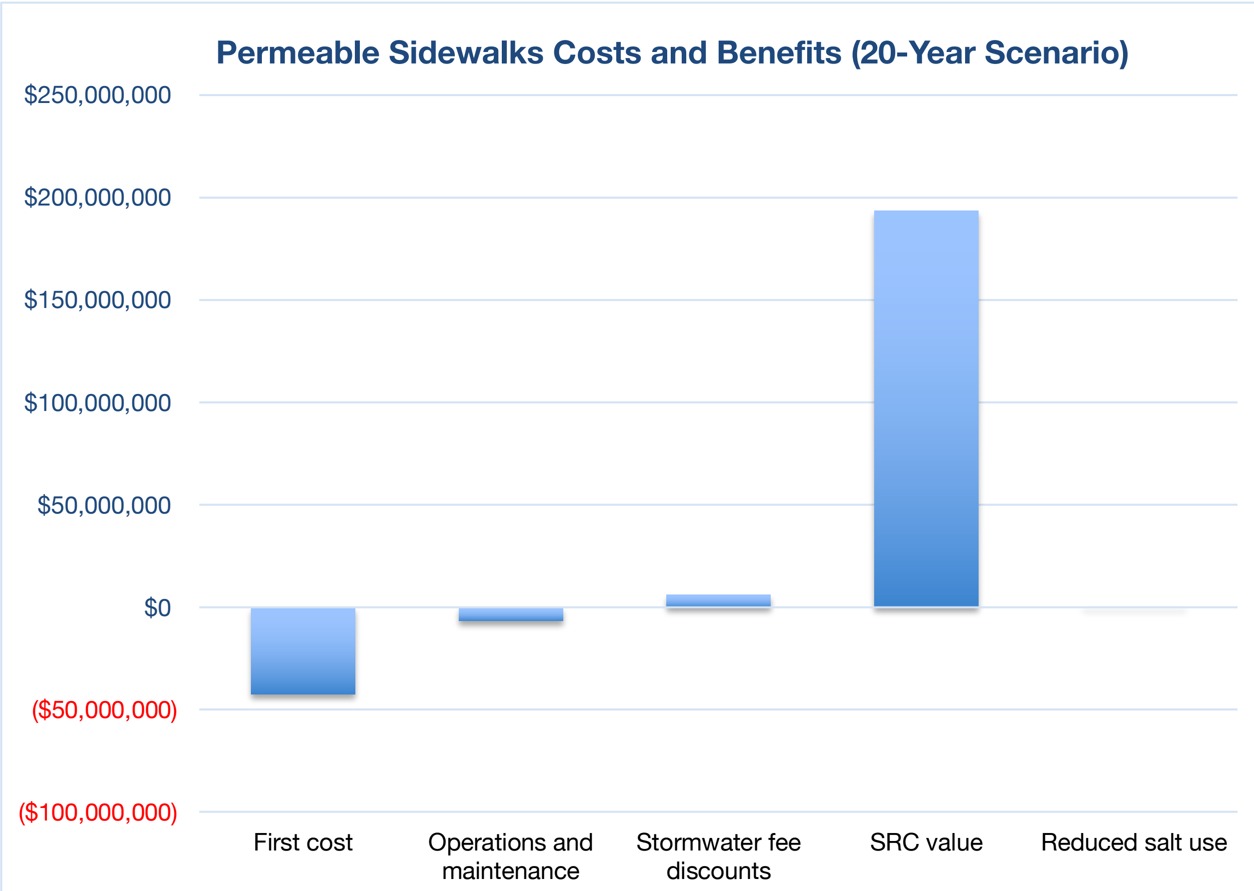

Figure 9.41. The costs and benefits of permeable sidewalks for the 20-year goal scenario in dollar value (cost values are negative and benefit values are positive)

9.6.3.2 Stormwater

Permeable pavement is widely recognized as an effective stormwater management measure. Permeable pavement contains air voids, which allows water to pass through the surface layer to subsurface layers and then to infiltrate the ground and/or be conveyed to storm sewers.[435] The air voids in the surface layer also provide water storage capacity.[436]

Permeable pavements can reduce the total and peak stormwater runoff volumes by more slowly conveying stormwater to the conventional stormwater system, by allowing stormwater to gradually infiltrate the soil below the pavement, and marginally through evaporation of water from the surface layer of the pavement. The degree to which permeable pavements reduce stormwater runoff depends on a number of factors including the aggregate used for the retention layer, the porosity of the pavement surface, the characteristics of the underlying soil, and whether an underdrain is used.[437] Refer to Section 10.6 for an overview of methods and assumptions in our stormwater benefits calculations.

Maintenance is required to avoid excess clogging and to maintain a permeable pavement's stormwater retention capabilities. However, as mentioned, only very rarely does clogging render permeable pavements completely ineffective. Vacuum sweeping and dry sweeping are effective methods to reduce pore clogging and restore permeable pavement effectiveness.[438]

9.6.3.3 Sidewalk and parking lot salt use

Snow and ice are less likely to accumulate on permeable surfaces, and melt faster on permeable pavements than impervious pavements, so far less deicing material is required to treat permeable pavements in the winter, improving water quality (and potentially reducing water treatment needs) and reducing salting costs.[439] For example, research in New Hampshire found that permeable asphalt pavement required about 75% less salt than conventional asphalt.[440] Research shows melted water immediately infiltrates pervious concrete, limiting the potential for refreezing.[441] It appears reasonable that pervious concrete requires less salting compared to traditional concrete. Similar results are expected for permeable pavers and lattice structures as well. Refer to Section 10.8 for an overview of assumptions.

9.6.3.4 Permeable sidewalks and parking and employment

Porous surfaces relative to conventional roads, sidewalks, or parking surfaces are generally 15%-30% more expensive and more labor intensive than conventional surfaces. However, the initial construction cost of porous asphalt sidewalks is lower than those of conventional concrete sidewalks.[442] The initial cost of porous asphalt roads is about 15%-20% more than conventional asphalt, and porous concrete is about 25%-30% more than conventional concrete.

Porous surfaces include modified versions of conventional surfaces such as pavers or bricks, and structured surfaces such as rigid plastic lattices filled in with pebbles or grass.[443] These surfaces can be placed near trees to support water penetration to roots.

We estimate that the number of direct jobs created for each one million dollars invested in porous surfaces includes 40%, or $400,000, in direct labor costs, which yields eight job years at $50,000 per job. The balance of $600,000 would go to pay for lattices, pebbles, and other materials, production of which is less jobs intensive than porous pavement installation. We assume a labor intensity for production of materials equal to the average job intensity of the economy of the whole, at five jobs per million dollars.[lxiv] The balance of $600,000 therefore goes to create another three direct jobs. We estimate a total of 11 direct job years are created per million dollars invested in porous surfaces.

[lxiv] See this Economic Policy Institute report on updated employment multipliers for the U.S. economy: https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/

Note this estimate may be high for pervious asphalt and pervious concrete and may be low for pavers, brick, and lattice-type surface structures. These general estimates therefore merit additional and more detailed analysis. For now, however, we will use the above estimate of 11 jobs years per million dollars invested in porous surfaces.

9.6.3.5 Other impacts of permeable sidewalks and parking lots

9.6.3.5.1 Ambient cooling

Permeable pavements can lead to ambient cooling and other benefits. However, their UHI (urban heat island) mitigation potential is less understood than the other solutions analyzed in this report. Because permeable pavements are less thermally massive, they cool off faster at night, which improves nighttime UHI.

When dry, the surface temperature of permeable pavement tends to be greater than the impervious equivalent, suggesting contribution to daytime UHIs. But permeable pavements store less energy than their impervious equivalent, suggesting they can mitigate nighttime UHIs because they have less potential to warm up urban air.[444] On the other hand, evaporative cooling can occur when water is present in the surface layer of permeable pavements,[445] meaning permeable pavements tend to be cooler than impermeable pavements after it rains. Permeable pavements may be particularly useful for UHI mitigation in these circumstances.

A modeling study of the July daytime air temperature impact of various traditional and permeable pavements around a building in Taiwan found slightly lower air temperatures around a building with permeable pavements than with traditional pavements.[446] However, a different empirical study in Davis, California found slightly higher daytime air temperatures above dry permeable pavement compared to dry impervious pavement and slightly lower daytime air temperatures above wet permeable pavement.[447] At night, the air temperature above permeable pavement was generally lower than that above impervious pavement under both dry and wet conditions.[448]

Current literature suggests permeable pavements are effective at mitigating nighttime UHIs and decreasing nighttime urban air temperatures. Under the appropriate conditions, large scale installations of permeable pavement could reduce daytime and nighttime air temperatures, with the largest impact occurring at night and/or when pavement is wet. This is an area that deserves further study.

Converting conventional asphalt parking lots to plastic grid pavers with gravel or grass will likely have a small beneficial impact on urban temperatures because of increased albedo and evapotranspiration. In the case of both parking lots and sidewalks, the area of conventional pavement converted to permeable pavement is likely to be small, resulting in only a small impact of urban temperatures. As a result, this benefit is not included in cost-benefit calculations.

9.6.3.5.1.1 Co-benefits of ambient cooling

The available literature suggests that except under dry daytime conditions, permeable pavements are effective at reducing ambient air temperature. Co-benefits include ambient cooling, including reduced energy use, reduced pollutant emissions from power plants, improved air quality, and reduced heat-related mortality. However, permeable pavements may support ambient warming during dry daytime conditions, increasing energy use and emissions from power plants, contributing to worse air quality, and increasing heat-related mortality. If this ambient warming during dry daytime conditions is large enough, it could offset the benefits of ambient cooling during more favorable conditions. This is an area that merits further study.

9.6.3.5.2 Thermal comfort

Based on permeable pavement surface temperature and near-surface temperature studies cited above, permeable pavements likely enhance thermal comfort during wet conditions and nighttime conditions. Few studies have examined the thermal comfort impacts of permeable pavements under dry daytime conditions. A study of permeable pavements in Taiwan generally found permeable pavements improve summer daytime thermal comfort, though thermal sensation did not change.[449] However, this study also found air temperature improvements over dry permeable pavement, so its results may not be consistent with the studies that found higher air temperature above dry permeable pavement during the day. This is an area that deserves further study.

9.6.3.5.3 Water quality

Permeable pavements improve urban water quality. EPA has summarized several studies that quantify pollutant removal by permeable pavements, including dirt, dust, heavy metals, and landscaping nutrients.[450] However, there is still insufficient data to quantify this benefit.

9.6.3.5.4 Pedestrian safety

The properties of permeable pavements that lead to reduced salt use likely also mean that permeable pavements form ice slower, and clear of ice faster. This means permeable pavements are safer for pedestrians in the winter, due to fewer falling accidents. However, data to estimate this potential benefit is limited, and we do not include it in cost-benefit calculations.

10 Overview of Methodology

The kind of full, integrated analysis presented in this report required that we solve a large set of benefit estimation challenges, such as estimating the indirect energy benefit of green roofs; developing simple, yet robust temperature-based methods to estimate city ozone concentration reductions; valuing health benefits of PM2.5 emissions reductions due to installing cool roofs, green roofs, reflective pavements, and urban trees; valuing heat-related mortality reductions due to cool roofs, green roofs, reflective pavements, and urban trees; and combining new methods and existing methods to estimate costs and benefits. As a rule, we proceeded cautiously and conservatively in developing estimating methods. The sections below provide an overview of the methods used to estimate the benefits included in cost-benefit calculations.

10.1 Direct energy

This report uses the Green Roof Energy Calculator (GREC) v2.0 to estimate direct energy savings/penalties from the installation of cool and green roofs on low slope roofs. To estimate the direct energy savings/penalties from the installation of cool roofs on steep slope roofs[lxv] this report uses GAF's Cool Roof Energy Savings Tool (CREST), which generates energy savings estimates using Oak Ridge National Laboratory cool roof calculators. Due to limitations in GREC this report does not quantify the peak energy demand and consumption reduction benefits of installing cool roofs or green roofs.[lxvi]

This report uses results of i-Tree Eco analyses to estimate direct energy impacts of trees. i-Tree Eco only estimates energy benefits for residential buildings.

10.2 Energy generation

This report estimates the energy output of rooftop PV systems using NREL's PVWatts Calculator. This report assumes that 100% of solar PV systems are financed by third parties, and the photovoltaics are 20% efficient. n the adoption timeframe.

10.3 Ambient cooling and indirect energy

[lxv] This report assumes green roofs are not installed on steep-slope roofs.

[lxvi] GREC only provides annual energy savings/penalties estimates so its outputs are not resolved enough to estimate peak demand benefits.

10.3.1 Estimating ambient cooling impacts

Based on a broad literature review, this report uses Li et al. (2014) as the basis for ambient cooling calculations for cool roofs and green roofs.[451] For reflective pavements, this report uses Kalkstein et al. (2013) as the basis for ambient cooling calculations.[452] For urban trees, this report uses Sailor (2003) as the basis for ambient cooling calculations for Baltimore.[453]

10.3.2 Estimating indirect energy impacts

The basis of our indirect energy calculations is from Akbari and Konopacki (2005).[454]

10.4 Climate change

10.4.1 Estimating climate change mitigation impacts of emissions reductions

For emissions intensities in Baltimore, this report uses the most recent numbers available from the Baltimore emissions survey and assumes a projected business as usual decrease in emissions intensity of 3% per year (the grid CO2 intensity is dropping as fossil fuel power plants are gradually being replaced with wind and solar).[455]

This report estimates the value of GHG emissions reductions from cool roofs, green roofs, rooftop PV, reflective pavements, and urban trees using the social cost of carbon (SCC). The SCC is an estimate of the economic damages/benefits associated with a small increase or decrease in CO2 emissions.[456] Developed by a dozen U.S. federal agencies, including the Department of the Treasury and the Environmental Protection Agency, the SCC reflects the best current science and economic understanding of the impact of climate change.

10.4.2 Estimating climate change impacts of global cooling

To estimate the CO2-equivalent impact of the global cooling effects of cool roofs and reflective pavements, this report uses Akbari et al. (2009) and Menon et al. (2010).[457] For green roofs and urban trees, this report scales the results of Akbari et al. (2009) and Menon et al. (2010) to match the albedo of green roofs and urban trees. This report uses the Federally developed Social Cost of Carbon (SSC) for determining the value of CO2 reductions/global cooling benefits.

10.5 Health

10.5.1 Estimating ozone health impacts

This report estimates the ozone impact of cool and green roofs, reflective pavements, and urban trees using the relationship between temperature and ozone formation. This report uses temperature reductions calculated using the work described in Section 10.3. This report applies temperature-ozone relationship from Bloomer et al. (2009) to the temperature reductions to determine the impact of temperature reductions on ozone concentrations.[458][lxvii] To estimate the health impact of ozone pollution reduction, this report uses EPA's Benefits Mapping and Analysis Program-Community Edition (BenMAPCE) v1.1.[lxviii] This report uses scale-specific population breakdowns to estimate the ozone health impacts at the city-wide and low-income region scales.

10.5.2 Estimating PM2.5 health impacts

The basis of the PM2.5 health benefits assessment in this report is Machol and Rizk (2013).[459] Machol and Rizk (2013) develop a method to determine the PM2.5-related health benefits per kWh of electricity. This report utilizes their methodology for PM2.5 benefit calculations. Put simply, this report multiplies the energy savings calculated using the methods in Sections 10.1, 10.2, and 10.3 by the health benefits factors from Machol and Rizk (2013) to estimate the PM2.5-related health impacts.

10.5.3 Estimating heat-related mortality impacts

Kalkstein et al. (2013) and Stone et al. (2014) form the basis for the heat-related mortality impact assessment in this report.[460] This report estimates the value of avoided heat-related mortality using the Value of Statistical Life (VSL).[461]

The studies above consider population at the city-scale or larger. Therefore, we scale the city-wide heat-related mortality impact estimates by the ratio of low-income region population to city-wide population in order to better approximate the heat-related mortality impact in the low-income regions.

10.5.4 Estimating pollution uptake by urban trees

This report estimates the health impacts of pollution uptake by urban trees using results from location-specific i-Tree Landscape analyses. i-Tree Landscape bases its health impact estimates on county- or city-level population data.[462] Therefore, for low-income regions we scale the county or city-wide health estimates by the ratio of low-income region population to county/city population to better approximate the pollution uptake impact in low-income regions.

[lxvii] OCPs relate a change in air temperature to a change in ozone concentrations.
[lxviii] BenMAP was developed to facilitate the process of applying health impact functions and economic valuation functions to quantify and value mortality and morbidity impacts due to changes in air quality.

10.6 Stormwater impacts

We have calculated the benefits from converting 1700 acres of impervious surfaces into permeable surfaces over 20 years; permeable options include detention basins, porous parking lots and sidewalks, green roofs, tree wells, sidewalk planters, and rain gardens. To calculate this target, we used Baltimore's existing objectives for impervious surfaces and the actual number of acres that have been converted since 2010 to estimate the potential 2020-2040 transformation. We assumed volunteer and development contributions maintain the same rate, the Stormwater Fee Credit program reaches the same rate as the volunteer program, and the municipal government can complete all intended projects using the suite of Smart Surface types. In fact, these assumptions achieve a switch of almost 2000 acres from impervious surfaces into permeable surfaces by 2040, and we decreased the target to 1700 acres by 2040 to provide a more conservative, more easily achievable estimate.

The 2015 version of Baltimore's Watershed Implementation Plan calls for "restoring 20% [4,921 acres] of the existing impervious area to the maximum extent practicable."[463] The Department of Public Works, the City of Baltimore, and the local organization CleanWater Baltimore collectively developed this restoration goal; it has been reaffirmed and incorporated into more recent publications, including the 2019 Baltimore Sustainability Plan, developed by the Baltimore Office of Sustainability.[464]

Baltimore has utilized both projects and programs to meet their 20% restoration objective, including traditional and green infrastructure installation, street sweeping and illicit discharge detection, and promotion of stormwater management on private lands.[465] In the 2019 MS4 annual report, Baltimore City stated that they exceeded the impervious area restoration goal.[466] However, they note, "the majority of the restoration is provided by programs, specifically street sweeping."[467] Many traditional large-scale projects—detention basins, wetlands, and ponds—have been cancelled and most small-scale projects, like bioswales and rain gardens, are currently still in the design phase.[468]

Street sweeping prevents an excessive number of pollutants, like nitrogen and phosphorus, from entering waterways and is an important component of stormwater management. However, street sweeping doesn't eliminate the root of the challenges: the impervious surfaces themselves. Furthermore, as mentioned in Section 6.2, both the average annual rainfall and extreme rain event frequency are expected to increase in the upcoming decades. Smart Surfaces, which would convert impervious surfaces into permeable options, would help the City of Baltimore address immediate challenges, secure long-term benefits, and improve urban resilience int face of projected accelerating climate change and associated sever and extreme weather events.

The community members of Baltimore are clearly interested and invested in the physical transformation of surfaces in their city. As the 2019 MS4 report notes, voluntary community initiatives—removal of impervious surfaces, afforestation, rain harvesting in cisterns, installation of rain gardens, bioswales, and sidewalk planters—have transformed 165 acres of Baltimore since 2010, exceeding the Watershed Implementation Plan's expected volunteer contribution of 95 acres.[469] Since 2010, development within Baltimore City has created an additional 206 acres of detention basins and 280 acres of small-scale bioretention strategies.[470] Non-municipal groups have collectively transformed 660 acres of land into Smart Surfaces over the 2010-2020 decade. This report assumes that the non-municipal groups will not increase their rate, so over the intended implementation period of 20 years, they will convert 1,320 additional impervious acres to permeable surfaces.

Like the Government of the District of Columbia, the City of Baltimore charges property owners a Stormwater Fee. The Stormwater Fee Credit program, which provides a fee discount for installing on-site stormwater retention, incentivizes Smart Surfaces development, but only 6 acres have been credited to the program in the 2010-2020 decade, less than the objective of 34 acres.[471] Blue Water Baltimore, a local water quality organization, highlights this challenge. They state that many residents don't understand the benefits they can derive from green stormwater management in their neighborhoods and aren't aware of the credits they could earn towards their stormwater fee.[472] Furthermore, residents who do install retention practices reportedly still don't receive fee credits, even several years after project completion.[473]

Blue Water Baltimore discusses recommendations in their 2019 Green Stormwater Infrastructure report, such as developing a task force to streamline project approvals and increase coordination between local government agencies.[474] Baltimore's Office of Sustainability also supports these initiatives, recommending removing application obstacles for properties under 5,000 ft^2 and creating a committee to evaluate and approve policies for accelerated implementation.[475] We assume that these organizations will drive the expansion of the Stormwater Fee Credit program, and that over the implementation period of 20 years, property owners utilizing the Credit program will convert an additional 330 acres from impervious to permeable.

The final key contributor is, of course, the City of Baltimore itself. Raising capital funding is often a challenge for stormwater management, particularly because Baltimore's population has been consistently decreasing, and as Baltimore notes it is difficult to install and maintain infrastructure projects when approximately 14,000 Baltimore lots are vacant and almost 20% of Baltimore households live under the poverty line.[476] That said, the 2019 MS4 annual report states stormwater management projects were cancelled not for cost reasons, but rather due to issues related to implementation. Many large-scale traditional infrastructure projects—detention basins, wetlands, and ponds (all between 3 and 100 acres)—were cancelled due to access problems and conflict with existing recreation opportunities.[477] Some small-scale bioretention projects, ranging in size from 0.2 to 3 acres, were cancelled due to similar problems.[478]

Fortunately, the suite of potential Smart Surfaces creates flexibility in implementation and achieving the desired stormwater runoff reduction—while also supporting the functional use of the site. For example, a parking lot's transformation through use of bioretention retains its functionality and is easy to access for maintenance. Narrow sidewalks may only be able to incorporate tree wells and stormwater planters in a few locations, but the entire sidewalk could become porous.

The largest stormwater infiltration (and therefore largest benefits) will occur with a shift from completely impervious surfaces to tree wells, stormwater planters, bioswales, and even urban farms. The Baltimore Office of Sustainability's 2019 Plan suggests implementing green infrastructure on "vacant lots created by the demolition of vacant buildings."[479] Other options include installation of green roofs on commercial buildings and the conversion of paved parking lots into high albedo surfaces served by adjacent bioretention/tree trenches.

10.6.1 Stormwater benefits from fee discounts and stormwater retention credits

The Smart Surfaces Coalition has calculated stormwater management benefits for other Mid-Atlantic cities, and this report builds upon this to determine the benefits for Baltimore. Section 8.5 discussed the two stormwater management fees in the District of Columbia; one fee funded pollution control efforts and maintenance of the stormwater system and the second fee aimed to reduce combined sewer overflow (CSO) volumes. To determine a given customer's two fees, the District and DC Water calculate that property's Equivalent Residential Unit (ERU). The ERU is "a statistical median of the amount of impervious surface area in a single-family residential property,"[480] and D.C. declares one ERU is equal to 1,000 ft^2 of impervious surface. Currently, the monthly Stormwater Fee for D.C. infrastructure maintenance and pollution control is $2.67/ERU.[481]

Baltimore's Stormwater Fee is analogous to D.C.'s Fee, funding the "maintenance, operations, and improvement of the stormwater management system" to improve water quality.[482] However, Baltimore charges $4.98/1,000 ft^2 of impervious surface (per month); this value is used in the calculations.[483] Residents can install and maintain practices outlined in the Stormwater Fee Credit program to reduce their monthly payment and can achieve a maximum discount of 45%.[484] Discounts can be renewed every three years.

The second D.C. stormwater fee focused on decreasing CSO volumes, but Baltimore has a somewhat different situation. In the early 20th Century, the City of Baltimore separated its stormwater and sewer systems; the systems run parallel to each other and flow downhill by gravity. However, over time the parallel pipes started leaking and exchanging water, leading to sewer discharges into streets, streams, and homes and businesses.[485] To address this return towards a CSO situation, Baltimore officials approved a $1.6 billion, 13-year plan to improve the sewer infrastructure in 2017. A local newspaper notes, "residents will pay for the work through years of expected sewer bill increases"[486] and water utility customers have seen their bills regularly increase by 10% per year.

The Chesapeake Bay Foundation notes that Baltimore property owners have already paid hundreds of millions of dollars since 2002 to fund the City's previous sewer agreement with the EPA, and yet the deadline expired in 2015 with unmet objectives.[487] In 2017, there were 5,000 sewage backups in homes; the City has offered $2,500 per backup event to residents.[488] Unfortunately, despite these significant costs and impact on community members, we could not estimate the Smart Surfaces benefits for reduced CSO events in Baltimore. Unlike in D.C., Baltimore has not established a fee to specifically reduce overflow volumes, and therefore citizens cannot take advantage of any incentives to install Smart Surfaces for a reduced fee.

The Baltimore Office of Sustainability has proposed an Offsite Stormwater Mitigation Credit strategy;[489] a program similar to one already in place in Washington, D.C. District property owners who install stormwater management practices not only receive discounts on the two fees, but also generate Stormwater Retention Credits (SRCs). Large development projects in the D.C. metro area can then meet up to 50% of their required stormwater runoff retention by purchasing SRCs from off-site sellers.[490] The average 2020 market price in D.C. for SRCs was $1.64 per SRC,[491] where one SRC corresponds to one gallon of stormwater retention for one year. For a conservative estimate, we made two assumptions. First, we assumed a lower price of $1.40 per SRC in D.C. and, second, we assumed this price will stay constant over the entire implementation timeframe. Finally, we conservatively used only 50% of our assumed D.C. market price for Baltimore, resulting in an assumed Baltimore value of $0.70 per SRC. This is number we use to estimate water management benefits from Smart Surfaces for Baltimore.

We calculated stormwater management benefits for all green infrastructure surfaces using both the Stormwater Fee discount and the Offsite Stormwater Mitigation Credit program. For example, the maximum 45% discount of the Stormwater Fee is $2.24 per 1,000 ft^2 of impervious surface managed, or a value of $0.00224 per square foot of managed impervious surface. Residents and property owners in Baltimore can then calculate the total benefit from the Fee discount if they know how much impervious surface will be converted to porous alternatives. For example, bioswales adjacent to buildings can manage stormwater runoff from the roof. Using our conservative $0.70 per SRC estimate, bioswale-managed roofs can generate an annual value of $0.70469 per square foot of roof area managed.

10.7 Employment

See Section 8.6 for general employment assumptions. See Sections 9.1.2.7 (cool roofs), 9.2.2.11 (green roofs), 9.3.2.8 (solar PV), 9.4.3.4 (reflective pavements), 9.5.2.7 (urban trees), and 9.6.3.4 (permeable pavements) for technology specific employment assumptions. This report values labor impacts in Baltimore using O'Sullivan et al. (2014).[492]

This report also values labor impacts using an average annual loaded cost, or income, per job year of $50,000.[lxix]

As noted, this report considers only direct and indirect job creation and not induced jobs, which underestimates the total jobs that Smart Surface solutions would create.

10.8 Summary of key assumptions

10.8.1 Universal

Analysis year 1: 2022
Discount rate: 2% (real)

Dollar year: 2020

10.8.2 Cool roofs

Table 10.1. Conventional and cool roof albedos used in this report

ROOF SLOPE	SOLAR REFLECTANCE	
	Conventional Roof	Cool Roof
Steep slope	0.16	0.35
Low slope	0.16	0.70

Note, the industry best steep-slope shingle has a reflectance of 0.4.

[lxix] Future, more detailed analysis of tax impact would more carefully model out revenue and tax issues. This draft is intended to provide a first order estimate.

Table 10.2. Cool roof lifespan assumptions used in this report

Low slope cool roof life	Steep slope cool roof life
30 years	30 years

Table 10.3. Cool roof cost premiums.

PREMIUM	COST	
	Low slope	Steep slope
Installation	$0.10/SF	$0.30/SF
Maintenance	$0.10/SF every 4 years	$0.10/SF every 4 years

10.8.3 Green roofs

Green roof life: 40 years

Table 10.4. Green roof cost premiums.

COSTS	$/SF	COST ACCRUED
Installation premium	$13.00/SF	one-time
Operations and Maintenance	$0.46/SF-yr	ongoing
Employment Training	$0.036/SF	one-time

10.8.4 Rooftop PV

Table 10.5. PV system size footprint calculation

System size (kW)	kW/m2	Avg. Efficiency	Array Area (m2)	Array Area (ft2)
1	1	20%	5	53.8

Direct purchase and third-party financing system life: 30 years
PV system purchase breakdown: 100% third-party financing
PV Efficiency is set to 20% as the average PV installed over the 20-year adoption period. This is a conservative number as PV efficiency is becoming more efficient, as costs continue to decline. In previous reports, 15% efficiency was used, but today many new rooftop PV systems exceed this efficiency, and 20% efficient panels are becoming the norm.

To determine emissions reduction potential from solar PV adoption this report uses the emissions from electricity generation reported in the Baltimore emissions report from 2017. Additionally, to account for the current and expected future reduction in emissions intensity, this analysis assumes an annualized 3% expected emissions intensity reduction from 2017 and assumes installation of PV goals begins in 2022, with an accelerated adoption through 2030 to meet the city's emission reduction goals.

This report calculates the energy production from one SF of solar PV per year in Baltimore using NREL's PV Watts calculator (see Tables 10.6 and 10.7). Using these we find the following generation potential:

Table 10.6. Electricity generation potential from solar PV for Baltimore, MD

Surface type	Output per SF of PV surface (kWh/yr)
Low slope roof	24.13
Steep slope roof	21.89
Parking lot	24.13

For emissions reduction calculations, we determine that a reasonable Solar PV adoption goal for 2030 and 2040 as % of available low slope and steep slope roofs is as follows:

Table 10.7. Solar PV adoption goals, assuming start in 2022

ROOF TYPE	By End-2030	Total Over 20-Years
Low-slope roofs	25%	40%
Steep-slope roofs	12%	20%

Note: Parking lots offer additional areas for solar PV during this period and can be used to fulfill low-slope roof targets as the direction the panels face, and angle (and therefore output), are not limited by roof-slope.

The area to be converted each year is multiplied the per SF cost of solar on low-slope and steep-slope, along with operations and maintenance (O&M) costs, and the one-time employment training costs.

The per year net benefit (cost) is then calculated across the analysis periods and the net present value is taken using a real discount rate of 2% equal to 4% nominal discount rate.

Total generation from new rooftop solar PV installed over the analysis period is summed using the SF/kWh in the Table 10.8 and offsets projected annual emissions, calculated using a 3% annual decrease from the 2017 Baltimore emissions inventory, from residential and commercial electricity consumption to provide an estimate of direct emissions reduction.

10.8.5 Reflective pavements

Table 10.8. Solar reflectance of pavements used in this analysis

PAVEMENT TYPE	CONVENTIONAL PAVEMENT ALBEDO	REFLECTIVE PAVEMENT ALBEDO
Parking lot	0.16	0.35
Road	0.16	0.35

10.8.6 Urban trees

Table 10.9. Baltimore tree canopy background information

Existing canopy (%)	29%
Future target canopy (%)	40%
New canopy needed (SF)	248,243,213
Average crown size of urban tree (SF)	581
Number of trees needed to meet target	427,084
Install cost per tree ($2020)	$283.00
Total install cost ($2020)	$120,864,841
Total install cost per SF ($2020)	$0.49

Note the costs in the table above (Table 10.9) indicate the total install cost in 2020 dollars if all trees needed to reach the Baltimore tree goal were to be planted in one year. This analysis spreads adoption over 20 years and uses a discount rate of 2% to determine net present value of planting all trees necessary to meet Baltimore's 40% tree canopy goal by 2040. The initial install cost per tree used in this analysis is conservative, slightly higher than the actual cost for an individual tree sapling, as it includes a buffer to account for potential costs incurred if planting trees in boxes (constructing boxes), or additional maintenance that may be required in first two years after tree planted (e.g., in addition to the included $0.0474/SF-yr of tree canopy maintenance included in the analysis).

In addition, there will be some overlap in tree crowns. As such, we use 581 SF as an average tree crown size, this comes from field observations and measurements from US Forest Service researchers, and is reflects discussions with American Trees, Casey Trees and TPL.

Table 10.10. Tree planting and maintenance costs used for Baltimore

COSTS	IMPACT TYPE	$/SF

First cost	one-time	$0.49/SF
Operations and maintenance	ongoing	$0.0474/SF
Additional replacements	ongoing: 2% of new canopy per year	$1.35/SF

Urban tree replacement: Following discussions with American Forests and Casey Trees, we estimate 2% of new urban trees planted will need to be replaced per year.

11 Cost-Benefit Analysis

A customized cost-benefit analytic tool has been developed for the Baltimore City. (Baltimore organizations that wish to access the framework may be able to submit a download request online.) The online analytic engine will allow a user to create scenarios based on adoption of various Smart Surfaces and 10 different Smart Surface options. The calculator uses the adoption mix as an input to determine the adoption scenario's net financial benefit, temperature reduction impact, job years created, and CO2-equivalent reduction.

Justin Bowers, *Assistant Director of the Baltimore Tree Trust:*

"Smaller community-based programs often struggle to scale urban tree canopy growth. With the help and backing of a rigorous cost-benefit analytic engine, organizations like ours can gain the resources necessary to demonstrate fuller benefits to city developers and expand planting programs."

Figure 11.1. The six main categories available to users in the Smart Surfaces Coalition's online cost-benefit analytic engine.

11.1 Location category

The first category titled "where" has four main options for the engine user to select from including the entire city of Baltimore, or one of three low-income neighborhoods: Madison East End, Cherry Hill, or Brooklyn-Curtis Bay. These neighborhoods would benefit from above-city-average Smart Surface adoption intensity, which is discussed further in Section 4.3.

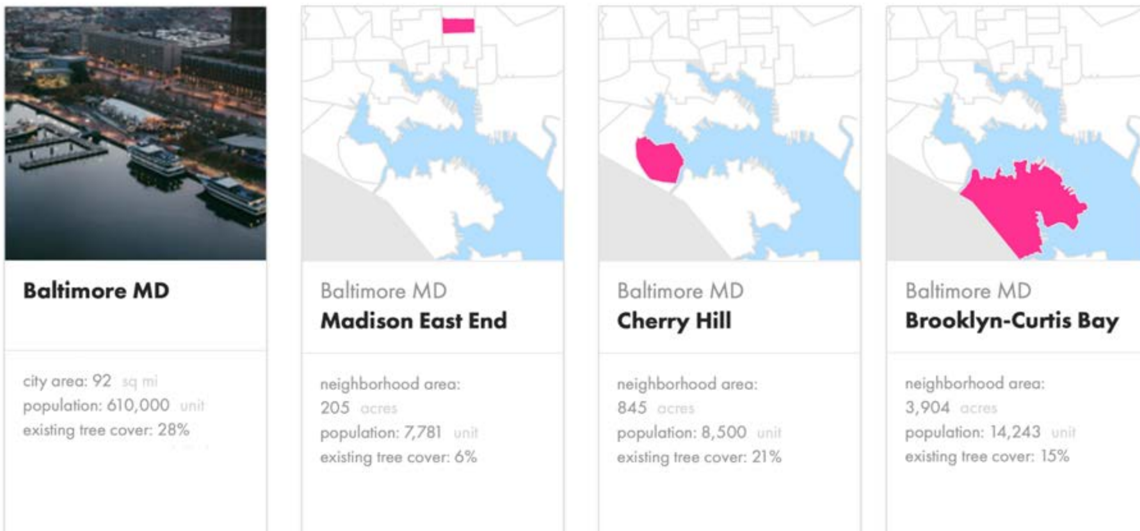

Figure 11.2. Includes four main options to select while creating Smart Surface adoption scenarios including the entire city of Baltimore, Madison East End, Cherry Hill, or Brooklyn-Curtis Bay.

After selecting a neighborhood, the user has the option to customize surface area options. The tool provides a basic ‘surface inventory’ based on city data and estimates. The tool uses these areas as the total area available for a given target. The default surface inventory. default surface inventory.

roof (commercial, low slope)	90300000	ft²
roof (commercial, steep slope)	28510000	ft²
roof (residential detached, low slope)	6220000	ft²
roof (residential detached, steep slope)	55940000	ft²
roof (residential attached, low slope)	73610000	ft²
roof (residential attached, steep slope)	73610000	ft²
roof (residential multi-family, low slope)	15790000	ft²
roof (residential multi-family, steep slope)	4990000	ft²
parking	195520000	ft²
roads	195520000	ft²
sidewalks	128630000	ft²
other city area	1704000000	ft²

Figure 11.3. Surface area measured in feet squared for roofs, parking, roads, sidewalks, and other city area that can be adjusted in the cost-benefit tool. Current numbers are based on city data and estimates.

11.2 Time frame section

The section labeled “when” allows the user to select a time frame for adoption of Smart Surface. The overall target areas will be held constant.

Over 10 years	Over 20 years	Over 30 years
Achieve your targets by incrementally replacing existing surfaces over 10 years: from 2020 through 2030. Observe their costs and ongoing benefits in 2040.	Achieve your targets by incrementally replacing existing surfaces over 20 years: from 2020 through 2040. Observe their costs and ongoing benefits in 2050.	Achieve your targets by incrementally replacing existing surfaces over 30 years: from 2020 through 2050. Observe their costs and ongoing benefits in 2060.

Figure 11.4. Three available options for time frame targets.

11.3 Roofing section

The third section titled “roofing” allows the user to determine how much of the city will be converted to include cool roofs, cool roofs with rainwater harvesting, green roofs, and photovoltaic panels.

Users can select a target commitment from three percentage-based choices including minimal, moderate, and extensive roof upgrades. These will translate into total areas of specific roofing surfaces to be upgraded over your selected time period. The impact of those selections will be evident in the first + operational costs but more critically in the 10, 20, and 30 year returns on investments.

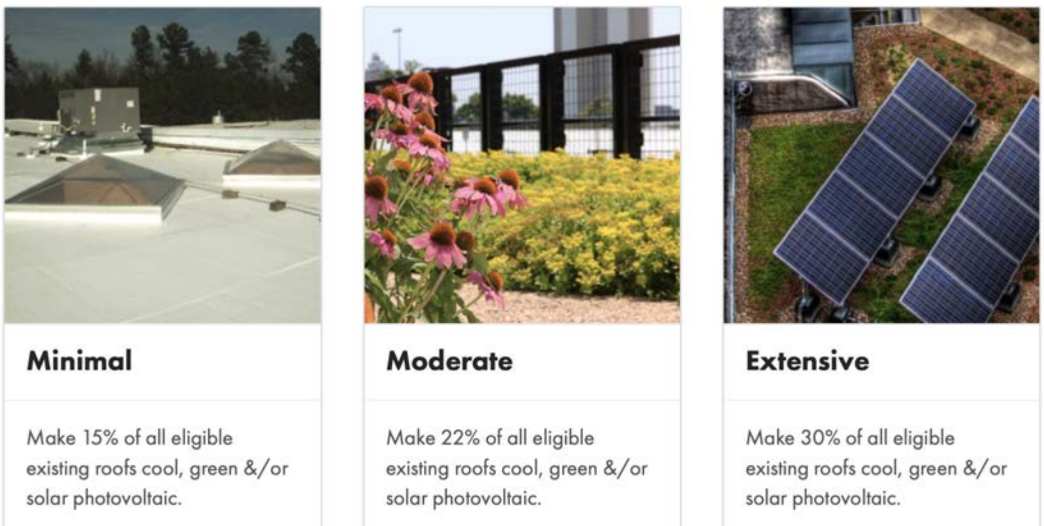

Figure 11.5. Three categories of roofing options include minimal, moderate or extensive roofing for cool roofs, green and/or solar PV solutions on eligible and existing roofs.

After selection of a roofing option, the analytic engine offers a possible breakdown of how to meet established targets. This breakdown is customizable using drop-down sliders adjustable by % of existing surface eligible to be converted to each Smart Surface. This percentage is then broken into feet squared of each Smart Surface option.

11.3.1 Engine roofing solutions details

Cool roofs reflect more sunlight back into space and absorb less solar radiation than conventional dark roofs. As a result, cool roofs do not get as hot which reduces heat transfer to the building below and to the urban environment.

Cool roofs can be combined with rainwater management though adjacent bioretention such as a swale.

As described in more detail in the previous Section 7.3.2, a green roof is a landscaped layer on a rooftop which consists of an insulation layer, a drainage layer, a soil layer, and vegetation on top of conventional roofing and waterproofing systems. Green roofs reduce cooling and heating energy use, reduce greenhouse gas emissions, reduce stormwater runoff and improve air quality. Other benefits include downwind cooling, reduced temperatures in stormwater runoff, increased employment, increased amenity and aesthetic value, reduced heat related mortality, and increased biodiversity.

A rooftop solar photovoltaic panel system is an assembly of solar cells that generates clean electricity. Major benefits include clean electricity generation, reduced greenhouse gas emissions, and improved air quality.

11.4 Parking lots

The fourth section titled "parking lots" estimates how much of the city's parking lots are converted to Smart Surfaces.

The user can select a minimal, moderate or extensive target commitment from these percentage-based choices for improving parking lots for managing heat and rain.

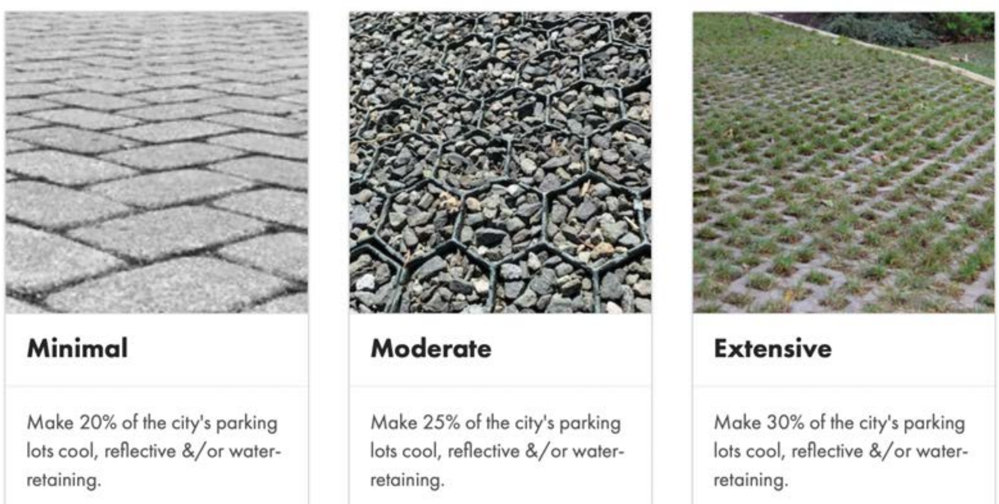

Figure 11.6. Three categories of parking lot options include minimal, moderate or extensive surfacing for cool, reflective, and/or water-retaining solutions. Each pre-set surface goal is fully adjustable using drop-down sliders.

11.4.1 Parking lot solutions details

Parking lots are a major contributor to urban heat and flooding. Reflective pavements have a higher solar reflectance than conventional dark pavements, so reduce the amount of pavement heat gain, and reduce surface and air temperatures.

To cope with rainfall, tree trenches or bioswales can be added to manage rainfall runoff from parking lots.

Structured stormwater detention tanks can also be integrated into parking lot upgrades to store even the most intensive rainfalls with either slow release or grey water reuse for landscaping and other demands. Finally, parking lots can be good sites for solar photovoltaic arrays which generate electricity, provide shade for automobiles, can provide protection form rain for pedestrians, can provide for nighttime lighting for safety and convenience, and can provide vehicle recharging.

11.5 Streets and sidewalks

This fifth section titled "streets and sidewalks" determines how much of the city's streets and sidewalks will be converted to include reflective pavements and rainwater permeable and storage solutions.

The user can select a minimal, moderate or extensive target commitment from these percentage-based choices for improving streets and sidewalks for managing heat and rain.

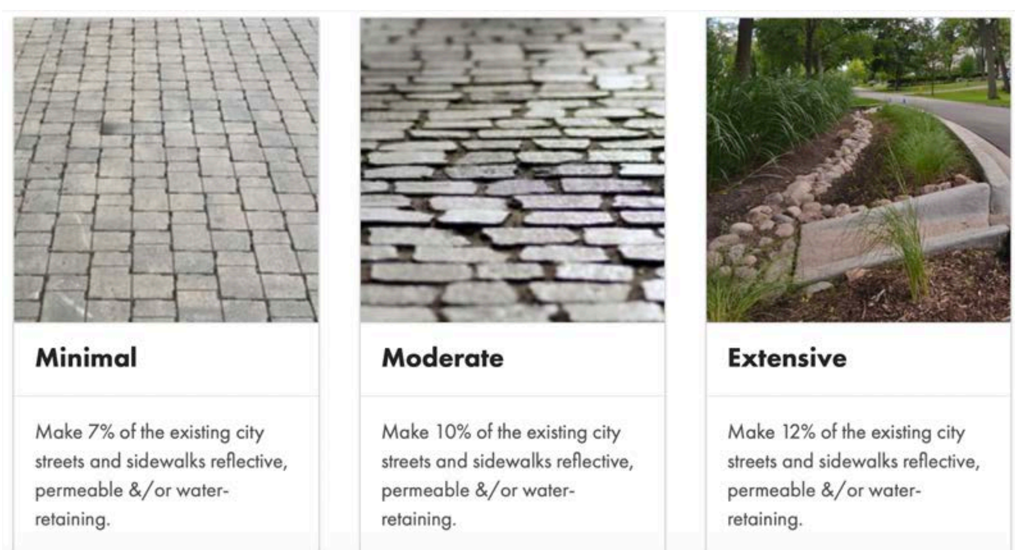

Figure 11.7. Three categories of city streets and sidewalk options include minimal, moderate or extensive surfacing for reflective, permeable, and/or water-retaining solutions.

11.5.1 Streets and sidewalk solutions details

Similarly, to the benefits and solutions discussed for parking lots in Section 11.4, Baltimore's streets and sidewalks can help address urban heat, and stormwater management.

11.6 Trees

The sixth section in the engine is titled “trees” and determines how much of Baltimore will be adding trees.

The user can select a target commitment for these choices for urban trees from the minimal, moderate or extensive percentage-based choices.

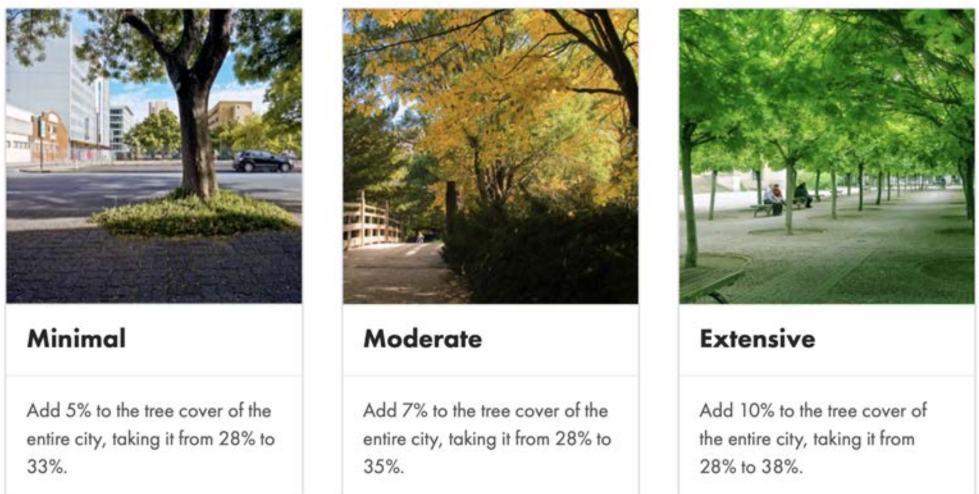

Figure 11.8. Three categories of tree coverage options include minimal, moderate and extensive.

11.7 Results

Once the user has specified the scenario they wish to test, they run the analysis to get the corresponding impact and financial results. The engine will present a net cost or benefit that is broken down by category, and it is also possible to isolate the costs and benefits breakdown for each individual Smart Surface technology.

11.8 Low-income areas

In conducting our cost-benefit analysis we selected three lower income neighborhoods of color that might benefit the most from the adoption of Smart Surface solutions. Urban low-income neighborhoods of color systematically endure higher temperatures due to a higher prevalence of dark and impervious surfaces, and a lack of tree canopy. This reflects practices such as red-lining in the 1930s, which designated city neighborhoods with larger percentages of residents of color as “risky investments” and impacted the development of neighborhoods into the 21st century. A recent New York Times article indicates that in cities, including Baltimore, neighborhoods that are poorer and have more residents of color can be 5 to 20°F hotter in the summer than wealthier, whiter parts of the same city. In Baltimore, the New York Times found that on one of the hottest days of the summer in 2018, the coolest part of the city recorded a temperature of 87 degrees, while the hottest parts of the city hovered between 98 and 99 degrees, with some lower income areas reaching as high as 102 degrees[493].

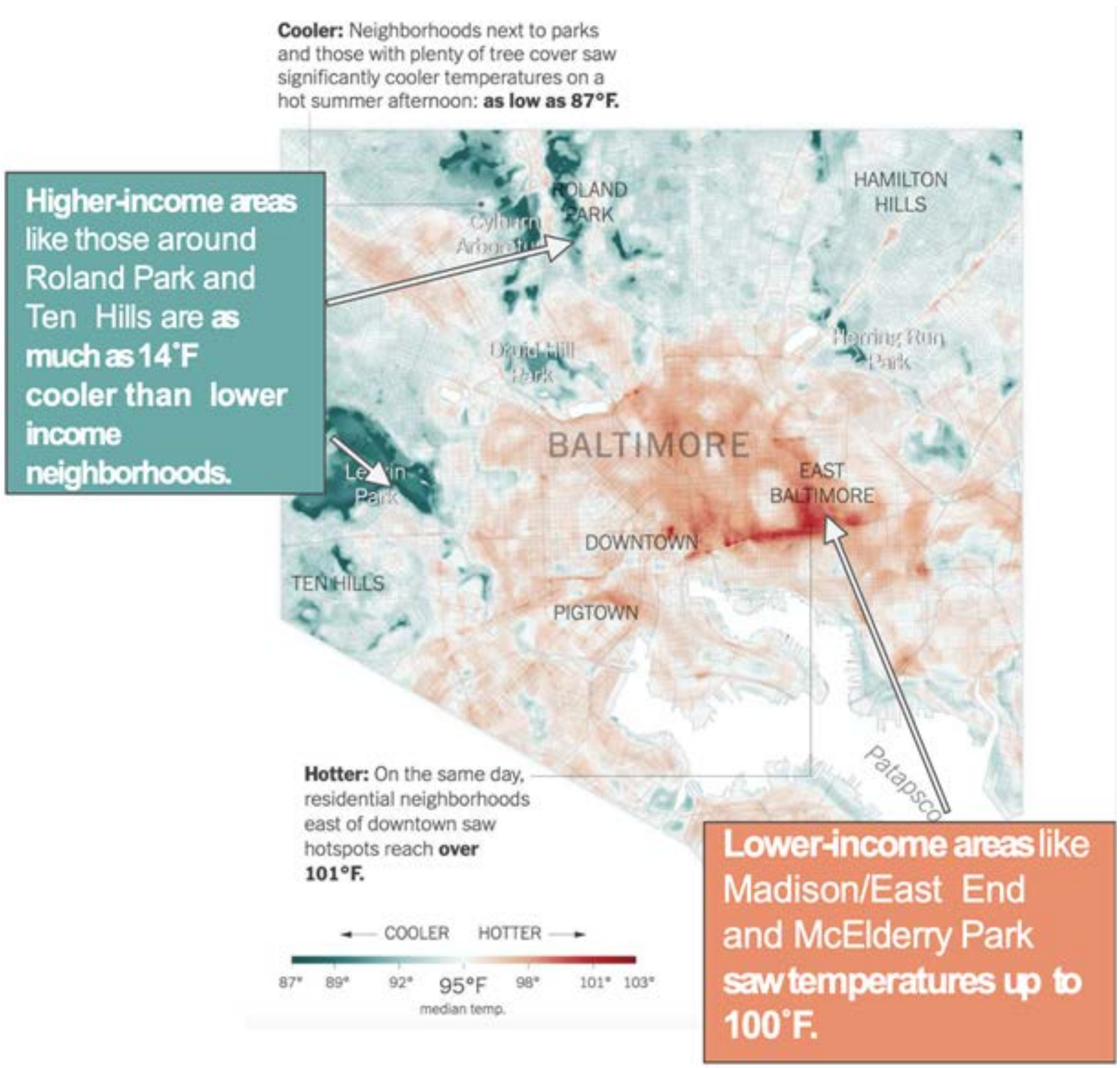

Figure 11.9. Heat map of Baltimore with low-income neighborhoods[494]

Considering the severe effect of heat on Baltimore’s neighborhoods we selected several lower-income neighborhoods and communities of color that would benefit the most from Smart Surface adoption. We were also advised on this by TreeBaltimore. The neighborhoods selected are Cherry Hill, Madison East End, and Brooklyn-Curtis Bay.

The Cherry Hill, Madison East End, and Brooklyn-Curtis Bay neighborhoods present a great opportunity for Smart Surfaces to improve the livability and walkability of areas that comprise 5% of Baltimore's population and 8% of the city's area. Making the right surface decisions can effectively boost tree coverage, reduce urban heat, and address additional climate challenges such as flooding and environmental justice all while creating jobs and reducing energy bills. In each neighborhood we assess various targets including roofing options (cool roofs, bioswale-managed roofs, green roofs, and solar PV), parking lot options (reflective, permeable, and bioswale-managed parking), as well as reflective roads, permeable sidewalks, and trees.

Our analysis of the Cherry Hill neighborhood indicates that Smart Surfaces would provide a benefit-cost ratio of 6.8:1 resulting in a peak summer temperature reduction of an estimated 3.1 °F, roughly 825 job years created, and a net present value of $81,770,936. Though tree cover is actually roughly 20% compared to Madison East-End's 6%, there is a lot of low slope roofs and the area size is nearly five times bigger than the Madison East-End. It is also located in one of the southernmost parts of the city and is fairly new. While the benefit cost ratio of Smart Surfaces in Cherry Hill is highest for solar PV, permeable parking, and cool roofs respectively, trees actually account for nearly 2.11 °F of peak summer temperature reduction. Therefore, an integrated system approach of combining all these solutions would be most effective in getting the full potential out of these surface considerations.

Results from the Madison East-End neighborhood show that Smart Surfaces would have a benefit-cost ratio of 11.3:1, reduce peak summer temperature by 8.29 °F, create roughly 302 job years, and have a net present value of $34,385,205. In this neighborhood, the surfaces with the largest reductions of peak summer temperature are actually cool roofs (4.29 °F) and trees (3.71 °F). This neighborhood is centrally located in the city, contains several brownfields, and has some of the lowest property value in the country. It is also extremely dense with an abundance of low slope, dark roofs and minimal tree cover (only 6% of total area), which explains the large potential for temperature reduction. The benefit cost ratio of Smart Surfaces in Madison East-End is highest for bioswale managed roofs, solar PV, and permeable parking respectively. Based on the large potential for reduction in peak summer temperature, installing cool roofs and trees are vital for making Madison East-End more walkable and livable, yet the compounding benefits of Smart Surfaces means an integrated approach would too be effective.

The implementation of Smart Surfaces in the Brooklyn Curtis Bay neighborhood would have a benefit-cost ratio of 6.1:1, reduce peak summer temperature by about 3.96 °F, create roughly 1,486 job years, and have a net present value of $143,960,554. In this neighborhood, the surfaces with the largest reductions of peak summer temperature are trees (2.79 °F), which also can create over 500 job years. Despite this Brooklyn Curtis Bay having the largest land area of the three neighborhoods, it still only has roughly 14% tree cover and plethora of vacant lots, parking lots, and low slope roofs. In this southern neighborhood, there is a lot of industrial activity and redevelopment projects. While trees are critical for Brooklyn Curtis Bay in terms of employment and temperature reduction because there is so little now, surfaces like solar PV, permeable parking, and cool roofs aid the benefit-cost ratio and create jobs as well (Solar PV can create 778 job years in this neighborhood). Often times these surfaces offset costs for each other and the combination of numerous designs can provide further benefits.

These numbers reflect a 20-year adoption scenario in which impacts are calculated for an additional 10 years after project completion to reflect compounding benefits. In each of these three neighborhoods solar PV installments have the highest potential for employment and in two of the three neighborhoods, it has the highest impact on the benefit-cost ratio (it ranks second behind bioswale-managed roofs in Madison East-End). Also, tree planting has been proven to create jobs and significantly reduce peak summer temperatures, but at times, they can be costly. It is therefore important to recognize the benefits from every surface so that it can offset that cost.

Table 11.1 indicates data from the Baltimore Neighborhood Indicators Alliance such as median household income, life expectancy, and demographic percentages for the three neighborhoods selected. We provide data from Baltimore City and Greater Roland Park/Poplar Hill, which is a higher income neighborhood in Baltimore for comparison and context. The data indicates that in comparison to Baltimore as a whole, and higher-income regions, the three neighborhoods we indicated have a lower median household income and life expectancy. Cherry Hill and Madison East-End also have a higher population of Black, Hispanic, Asian, and non-white residents.

Table 11.1. Selected Baltimore citywide and neighborhood-level statistics (source: BNIA 2018 and 2019 Vital Signs data)[495]

	Cherry Hill	Madison East-End	Brooklyn-Curtis Bay	Baltimore average	Greater Roland Park/Poplar Hill
Median household income	$26,654.10	$37,328.30	$39,162.10	$50,379	$120,733.30
Life expectancy	70.3	68.4	69.5	72.7	82.7
Percent of family households living below the poverty line	37.8%	34.4%	24.6%	16.0%	1.4%
Percent Black/African-American	88.0%	85.3%	34.2%	61.9%	6.1%
Percent Asian, Hispanic, or non-White	7%	11.7%	22.1%	10.5%	17%
Percent White/Caucasian	5.1%	2.9%	43.8%	27.5%	76.9%

As noted in the explanation of the location category in Section 11.1, each of these three neighborhoods can be modeled separately in the cost-benefit analytic engine.

12 Findings

12.1 Baltimore 20-year scenario summary of findings

12.1.1 Baltimore 20-year scenario summary of cost-benefit findings

Table 12.1. Roofing targets for 20-year scenario

Surface Type	Cool Roofs	acres	Bioswale-managed[lxx]	acresNPV (millions 2020$)	Green Roofs	acres	Solar PV[lxxi]	acres
Low slope roofs adoption	80%	3414	20%	853.57	2%	85	40%	1707
Steep slope roofs adoption	20%	749	N/A		N/A		25%	749
Adoption timeframe (yrs)	20		20		20		20	

Table 12.2. Pavement targets for 20-year scenario

Surface Type	Reflective	acres	Porous/Permeable[lxxii]	acres	Bioswale-managed[lxx]	acres
Parking	50%	2244	5%	224	20%	898
Streets	15%	673	N/A			
Sidewalk	0%	-	5%	148		
Adoption timeframe (yrs) & acres installed per year	20	146	20	18.6	20	45

Table 12.3 Urban tree target for 20-year scenario

Surface Type	Tree Canopy	acres (new canopy)
City Area (% of total)	40%	5699
Adoption timeframe (yrs)	20	

[lxx] Bioswales/bioretention can manage stormwater runoff from adjacent roofs or parking lots. Bioswale-managed roofs and parking lots are calculated using SF or % of the area managed by a bioswale, not SF of bioswale – the size of the bioswale is about 4.5% of the impervious area managed. I.e., a small area of bioswale or tree trench can manage the water runoff of a much larger hard surface.

[lxxi] PV can be put on any roof (e.g., PV can go on a regular roof, green roofs, or reflective/cool roofs, and standard roofs).

[lxxii] Permeable parking only applied when a parking lot is ripped out and replaced, at which time it costs less to make the area permeable (grid-grass or grid-gravel) than to construct a new asphalt parking surface. Total Cost in this case is therefore positive number because it costs less to install permeable parking when the hard surface parking lot is replaced, reflecting a first cost savings.

Table 12.4. 20-year scenario summary (dollar values in millions of 2020 dollars)

Total NPV (2% real discount rate)	$8,739
Total Cost	($1,420)
Total Benefit	$14,524
Benefit-Cost Ratio	10.2:1
Peak Summer Temperature Reduction Estimate (1-4 PM in central/downtown area)	4.3 °F
Job Years Created	78,765

Table 12.5. 20-year scenario summary with avoided tourism loss included (dollar values in millions of 2020 dollars)

Estimated Avoided Tourism Loss	$6,420
Total Benefit + Avoided Tourism Loss	$20,944
Benefit-Cost Ratio (with tourism benefit)	14.8:1
NPV (with tourism benefit, 2% real discount rate)	$13,532

12.1.1.1 Roofing costs and benefits for 20-year scenario

Table 12.6. Costs and benefits summary for Smart Surface roofing targets (20-year scenario, dollar values in thousands of 2020 dollars)

Existing Surface	Low-slope Roofing				Steep-slope Roofing	
Smart Surface	**Cool Roofs**	**Bioswale-managed Roof**	**Green Roofs**	**Solar PV**	**Cool Roofs**	**Solar PV**
Adoption target (% of existing surface)	80%	20%	2%	40%	20%	20%
Adoption timeframe (years)	20	20	20	20	20	20
Analysis timeframe (years)	30	30	30	30	30	30
COSTS	($86,261)	($99,392)	($81,248)	($319,616)	($25,761)	($154,659)
First cost	($14,873)	($68,744)	($55,772)	-[lxxiii]	($7,337)	-[lxxiii]
Operations and maintenance	($70,645)	($20,842)	($25,344)	($283,633)	($15,489)	($138,880)
Additional replacements	($744)	($9,805)			($2,935)	
Employment training			($132)	($35,982)		($15,779)
BENEFITS	$800,485	$549,322	$158,122	$7,321,898	$61,215	$3,281,719
Energy	$135,976		$6,088	$2,789,182	$2,794	$1,318,679
Direct energy savings	$107,472		$5,375		$919	
Indirect (UHI) energy savings	$28,503		$713		$1,875	
Electricity value[lxxiii]				$2,789,182		$1,318,679
Health	$467,655		$12,197	$3,491,959	$26,275	$1,511,748
Ozone	$268,517		$6,713		$17,662	
PM2.5 (direct energy savings)	$85,961		$2,677		$1,168	
PM2.5 (indirect energy savings)	$17,951		$427		$1,181	
PM2.5 (energy generation)				$3,491,959		$1,511,748
Heat-related mortality	$95,226		$2,381		$6,264	
Climate change	$110,593		$1,549	$960,556	$6,385	$415,856
GHG emissions (direct energy savings)	$14,508		$978		$64	
GHG emissions (indirect energy savings)	$4,405		$113		$290	

[lxxiii] Solar PV payback after year 10, this model assumes "first cost" (i.e., financing payments) are net of electricity value (electricity value is zero for first 10 years after install), and therefore first cost is zero. Third-party financiers will bear the actual first cost and Baltimore system owners will not receive an electricity value benefit until year 11 after installation.

GHG emissions (energy generation)				$960,556		$415,856
Global cooling	$91,681		$458		$6,031	
Life extension	$86,261				$25,761	
Surface life extension	$86,261				$25,761	
Water		$549,322	$135,786			
Fee discounts		$12,195	$1,714			
SRC value		$537,127	$134,072			
Employment			$1,983	$80,202		$35,436
Welfare payments			$4	$3,981		$2,012
Employee pay			$1,979	$76,222		$33,424
Taxes			$519			
Federal taxes			$462	N/A to financed		N/A to financed
City taxes			$56	N/A to financed		N/A to financed
NET TOTAL	**$714,224**	**$449,931**	**$76,874**	**$7,002,282**	**$35,454**	**$3,127,060**
NPV (2% real discount rate)	**$513,050**	**$301,406**	**$45,631**	**$4,637,736**	**$27,834**	**$2,066,530**
Benefit-Cost Ratio	**9.4**	**5.5**	**1.9**	**22.9**	**2.4**	**21.2**

12.1.1.2 Pavement costs and benefits for 20-year scenario

Table 12.7. Costs and benefits summary of Smart Surface pavement targets (20-year scenario, dollar values in thousands of 2020 dollars)

Existing Surface	Parking Lots			Roads	Sidewalks
Smart Surface	Reflective Parking	Permeable Parking	Bioswale-managed Parking	Reflective Roads	Permeable Sidewalks
Adoption target (% of existing surface)	50%	5%	20%	15%	5%
Adoption timeframe (years)	20	20	20	20	20
Analysis timeframe (years)	30	30	30	30	30
COSTS	($43,881)	$48,452	($99,898,491)	($9,520)	($49,028)
First cost	($42,037)	$14,773	($68,744)	($651)	($42,435)
Operations and maintenance	($1,845)	($12,024)	($20,842)	($1,302)	($6,592)
Additional replacements		$45,703	($10,312)	($7,567)	
Employment training					
BENEFITS	$102,806	$112,644	$577,725	$27,197	$200,361
Energy	$5,611			$1,683	
Direct energy savings					
Indirect (UHI) energy savings	$5,611			$1,683	
Electricity value*					
Health	$34,270			$10,281	
Ozone	$11,824			$3,547	
PM2.5 (direct energy savings)					
PM2.5 (indirect energy savings)	$3,607			$1,082	
PM2.5 (energy generation)					
Heat-related mortality	$18,838			$5,651	
Climate change	$19,044			$5,713	
GHG emissions (direct energy savings)					
GHG emissions (indirect energy savings)	$802			$240	
GHG emissions (energy generation)					
Global cooling	$18,242			$5,473	
Life extension	$43,881			$9,520	
Surface life extension	$43,881			$9,520	
Water		$111,141	$577,725		$199,872
Fee discounts		$4,294	$12,826		$6,250

Reduced water use					
SRC value		$106,847	$564,899		$193,622
Other		$1,503			$490
Reduced salt use		$1,503			$490
NET TOTAL	**$58,925**	**$161,096**	**$477,827**	**$17,677**	**$151,334**
NPV (2% real discount rate)	**$43,213**	**$110,397**	**$320,637**	**$14,553**	**$98,511**
Benefit-Cost Ratio	**2.3**	**14.4**	**5.8**	**2.9**	**4.1**

As indicated in the summary table above (Table 12.7), Smart Surface pavements cost-benefit analysis does not include benefits for employment or taxes because roads and sidewalks are typically purchased and installed by the city. Reflective slurry seals for roads and reflective parking and sidewalks require no additional labor over what traditional resealing project for roads, refinishing parking lots, and replacing sidewalks would normally require.

Table 12.8. Costs and benefits Summary of Urban Trees (dollar values in millions of 2020 dollars unless otherwise specified)

Background Assumptions	
Existing Canopy (%)	29%
Future Target Canopy (%)[lxxiv]	40%
New Canopy Needed (SF)	248,243,213
Average Crown Size of Urban Tree (SF)[lxxv]	581
Number of trees needed to meet target	427,084
Cost per tree[lxxvi] (2020$)	($283.00)
Total cost	($121)
Total cost per SF canopy (2020$)	($0.49)
Adoption target (% of other surface)	18%
Adoption timeframe (years)	20
Analysis timeframe (years)	30
COSTS	($499)
First cost	($121)
Operations and maintenance	($241)
Additional replacements	($137)
BENEFITS	$1,330
Energy	$26
Direct energy savings	$10
Indirect (UHI) energy savings	$16
Health	$80
Ozone	$15
PM2.5 (direct energy savings)	$9
PM2.5 (indirect energy savings)	$10
Heat-related mortality	$46
Climate change	$35

[lxxiv] Full 40% canopy coverage will occur approximately 10 years after year 20 of adoption assuming O&M continues.
[lxxv] From Nowak field measurements in Baltimore.
[lxxvi] Includes 2yrs maintenance and/or possible additional construction needed

GHG emissions (direct energy savings)	$1
GHG emissions (indirect energy savings)	$3
Global cooling	$31
Water	$1,189
Fee discounts	$44
Pollution uptake	$83
SRC value	$1,063
NET TOTAL	**$831**
NPV (2% real discount rate)	**$560**
Benefit-cost ratio	**2.7**

12.1.2 Employment impact summary for 20-year scenario

Table 12.9. Employment impact for Smart Surface roofing targets (20-year scenario, dollar values in millions of 2020 dollars unless otherwise specified)

Direct Employment Impact: 20-year Adoption Scenario (30-year Analysis) – Direct Job Years Created				
Surface:	**Cool Roofs**	**Green Roofs**	**Solar PV**[lxxvii]	**Bioswale-managed Roofs**
Direct (install + O&M) labor intensity (as % of total cost)	80%	50%	40%	60%
Direct (materials) labor intensity (as % of total cost)	5%	30%	15%	10%
Avg. annual salary + benefits of 1 Smart Surface job (2020$)	($50,000)	($50,000)	($50,000)	($50,000)
Total cost (30-year timeframe)	($112)	($81)	($5,549)	($99)
Total direct install + O&M labor cost	($90)	($41)	($2,220)	($60)
Total direct install + O&M job years created	*1,792*	*812*	*44,394*	*1,193*
Total direct materials labor cost	($6)	($24)	($832)	($10)
Total direct materials job years created	*112*	*487*	*16,648*	*199*
Total job years created (30-year timeframe)	**1,904**	**1,300**	**61,042**	**1,391**
Direct Employment Impact During 20-year Adoption Timeframe – Direct Job Years Created				
Total install + O&M + materials labor cost (during 20-year adoption timeframe)	($56)	($59)	($2,920)	($58)
Total job years created (during 20-year adoption timeframe)	**1,120**	**1,176**	**58,391**	**1,152**

lxxvii Solar PV employment calculation based on full amount of principal (i.e., first cost, not net of electricity value, and not including interest).

Table 12.10. Employment impact for Smart Surface pavement targets (20-year scenario, dollar values in millions of 2020 dollars unless otherwise specified)

Direct Employment Impact: 20-year Adoption Scenario (30-year Analysis) – Direct Job Years Created				
Surface:	**Reflective Parking**	**Reflective Roads**	**Bioswale-managed Parking**	**Permeable Sidewalks**
Direct (install + O&M) labor intensity (as % of total cost)	80%	80%	80%	40%
Direct (materials) labor intensity (as % of total cost)	5%	5%	5%	15%
Avg. annual salary + benefits of 1 Smart Surface job (2020$)	($50,000)	($50,000)	($50,000)	($50,000)
Total cost (30-year timeframe)	($44)	($10)	($100)	($49)
Total direct install + O&M labor cost	($35)	($8)	($80)	($20)
Total direct install + O&M job years created	*702*	*152*	*1,598*	*392*
Total direct materials labor cost	($2)	($0.5)	($5)	($7)
Total direct materials job years created	*44*	*10*	*100*	*147*
Total job years created (30-year timeframe)	**746**	**162**	**1,698**	**539**
Direct Employment Impact During 20-year Adoption Timeframe – Direct Job Years Created				
Total install + O&M + materials labor cost (during 20-year adoption timeframe)	($36)	($3)	($69)	($26)
Total job years created (during 20-year adoption timeframe)	**727**	**52**	**1,371**	**514**

Table 12.11. Employment impact for urban trees and total Smart Surface employment impact (20-year scenario, dollar values in millions of 2020 dollars unless otherwise specified)

Surface:	**Urban Trees**	**TOTAL (ALL SURFACES)**
Direct (install + O&M) labor intensity (as % of total cost)	50%	
Direct (materials) labor intensity (as % of total cost)	50%	
Avg. annual salary + benefits of 1 Smart Surface job (2020$)	($50,000)	
Total cost (30 year timeframe)	($499)	
Total direct install + O&M labor cost	($250)	
Total direct install + O&M job years created	*4,991*	***56,027***
Total direct materials labor cost	($250)	
Total direct materials job years created	*4,991*	***22,737***
Total direct job years created (30-year timeframe)	**9,982**	**78,765**

Total install + O&M cost (during 20-year adoption timeframe)	($407)	
Total job years created from install and O&M during 20-year adoption timeframe	**8,137**	**72,638**

12.1.3 Emissions reduction impact summary for 20-year scenario

This analysis measures the emissions reduction impact of meeting reflective surface goals by first determining how much city area is to be become more reflective. We then determine the net increase in reflectivity (albedo) per surface replacement.

Table 12.12. The CO2 emissions offset from increasing surface albedo in the years following installation (cumulative v. single).

CO2EQ OFFSET FROM INCREASING SURFACE ALBEDO (REFLECTIVITY)		
Years from installation	Kg/m^2/0.01 albedo increase (cumulative)	Kg/m^2/0.01 albedo increase (single year)
0		
1	0.96	0.96
2	1.57	0.61
3	1.97	0.4
4	2.27	0.3
5	2.53	0.26
6	2.74	0.21
7	2.92	0.18
8	3.1	0.18
9	3.24	0.14
10	3.38	0.14
11	3.5	0.12
12	3.62	0.12
13	3.74	0.12
14	3.84	0.1
15	3.93	0.09
16	4.03	0.1

17	4.1	0.07
18	4.18	0.08
19	4.24	0.06
20	4.31	0.07
21-25	4.48	0.034
26-30	4.82	0.068
31-35	5.1	0.056
36-40	5.31	0.042
41-45	5.48	0.034
46-50	5.62	0.028
100	6.01	0.0078
200	6.66	0.0065
max	6.7	

12.1.3.1 Cool Roof Emissions Impact Summary for Goal Scenario

Table 12.13. 20-year adoption scenario emissions summary results (20-year adoption, 30-year analysis)

Smart Surface	20-Year Adoption Targets		Total Cumulative Emissions Reductions		Cumulative Total Reduction/Avoidance
Surface Type	Reflective (% of surface type)	Solar PV (% of surface type)	From Reflective (tonnes CO2eq)	From Solar PV (tonnes CO2 avoided)	Total CO2eq Emissions Reduction (tonnes, 30 years)
Low slope roofs	80%	40%	3,328,318	8,907,060	12,235,378
Steep slope roofs	20%	20%	246,231	3,491,547	3,737,778
Parking	50%		748,287		748,287
Streets	15%		216,400		216,400
		TOTAL	4,539,236	12,398,607	16,937,843

12.2 Baltimore Accelerated Adoption Scenario summary of findings

The Baltimore Accelerated Adoption Scenario was developed to frontload the reflective surface and Solar PV installation within the 20-Year Adoption Scenario for the purpose of providing greater assistance to the Baltimore 30% emissions reduction goal by 2030, as well as temperature reduction. For our emissions reduction model, the goals below are to be achieved by the end of 2030, with an assumed start year in 2022. For accelerated cost-benefit model, quantification of costs and benefits assume a 10-year adoption timeframe with 10-years of additional modeling of ongoing costs and benefits to arrive at a net present value. Please note this scenario serves as a snapshot for where the city could be after ten years of adoption of the accelerated surfaces. Estimated tourism loss is not included in NPV values and summary tables below.

12.2.1 Baltimore Accelerated Adoption Scenario summary of cost-benefit findings

Table 12.14. Roofing targets and NPV for Accelerated Adoption Scenario (dollar values in millions of 2020 dollars)

Surface Type	Cool Roofs	Solar PV[lxxviii]
Low slope roofs adoption	65%	25%
Steep slope roofs adoption	10%	12%
Adoption timeframe (yrs)	10	10

Table 12.15. Pavement targets and NPV for Accelerated Adoption Scenario (dollar values in millions of 2020 dollars)

Surface Type	Reflective
Parking	30%
Streets	5%
Sidewalk	0%
Adoption timeframe (yrs)	10

Table 12.16. Accelerated Adoption Scenario summary (dollar values in millions of 2020 dollars)

[lxxviii] Solar PV can be put on any roof (e.g., PV+ green, PV+ cool, or standard).

Total NPV	**$3,464**
Total Cost	**$(441)**
Total Benefit	**$4,957**
Benefit-Cost Ratio	**11.2:1**
Peak Summer Temp Reduction (in central/ hottest areas of city 1-4pm) degrees Fahrenheit (includes ½ tree adoption)[lxxix]	**2.9 °F**
Job Years Created	**38,083**

12.2.2.1 Roofing Costs and Benefits for Accelerated Scenario

Table 12.17. Costs and benefits summary for Smart Surface roofing targets (Accelerated Adoption Scenario, dollar values in thousands of 2020 dollars)

Existing Surface	***Low-slope Roofing***		***Steep-slope Roofing***	
Smart Surface	**Cool Roofs[lxxx]**	**Solar PV[lxxxi]**	**Cool Roofs[lxxx]**	**Solar PV[lxxxi]**
Adoption target (% of existing surface)	65%	25%	10%	12%
Adoption timeframe (years)	10	10	10	10
Analysis timeframe (years)	20	20	20	20
COSTS	($54,378)	($237,995)	($10,598)	($110,768)
First cost	($12,084)	-[lxxxi]	($4,891)	-[lxxxi]
Operations and maintenance	($42,294)	($215,506)	($5,707)	($101,301)
Additional replacements				
Employment training		($22,489)		($9,468)
BENEFITS	$511,315	$3,054,280	$24,737	$1,304,992
Energy	$83,534	$912,295	$1,056	$414,442
Direct energy savings	$66,024		$347	
Indirect (UHI) energy savings	$17,510		$709	
Electricity value[lxxxi]		$912,295		$414,442

[lxxix] Temperature reduction estimate includes half of 20-year adoption scenario tree canopy cover target met

[lxxx] Reflective surfaces have a large impact on city temperature. Local temperature reduction benefits from reflective surfaces are large but not included in the quantified benefits due to lack of input data.

[lxxxi] Solar PV payback after year 10, this model assumes "first cost" (i.e., financing payments) are net of electricity value (electricity value is zero for first 10 years after install), and therefore first cost is zero. Third-party financiers will bear the actual first cost and Baltimore system owners will not receive an electricity value benefit until year 11 after installation.

Health	$287,294	$1,650,163	$9,933	$685,817
Ozone	$164,958		$6,677	
PM2.5 (direct energy savings)	$52,808		$442	
PM2.5 (indirect energy savings)	$11,028		$446	
PM2.5 (energy generation)		$1,650,163		$685,817
Heat-related mortality	$58,500		$2,368	
Climate change	$86,109	$453,921	$3,149	$188,657
GHG emissions (direct energy savings)	$8,912		$24	
GHG emissions (indirect energy savings)	$2,706		$110	
GHG emissions (energy generation)		$453,921		$188,657
Global cooling	$74,490		$3,015	
Life extension	$54,378		$10,598	
Surface life extension	$54,378		$10,598	
Employment		$37,900		$16,076
Welfare payments		$1,881		$913
Employee pay		$36,019		$15,163
NET TOTAL	**$456,937**	**$2,816,285**	**$14,139**	**$1,194,224**
NPV (2% real discount rate)	**$372,347**	**$2,143,704**	**$12,157**	**$907,138**
Benefit-Cost Ratio	**9.4**	**12.8**	**2.3**	**11.8**

12.2.2.2 Pavement Costs and Benefits for Accelerated Scenario

Table 12.18. Costs and benefits summary of Smart Surface pavement targets (Accelerated Adoption Scenario, dollar values in thousands of 2020 dollars)

Existing Surface	**Parking Lots**	**Roads**
Smart Surface	**Reflective Parking**[lxxx]	**Reflective Roads**[lxxx]
Adoption target (% of existing surface)	30%	5%
Adoption timeframe (years)	10	10
Analysis timeframe (years)	20	20
COSTS	($26,003)	($1,427)
First cost	($25,222)	($217)
Operations and maintenance	($781)	($369)
Additional replacements		($841)
Employment training		
BENEFITS	$55,404	$6,327
Energy	$2,546	$424
Direct energy savings		
Indirect (UHI) energy savings	$2,546	$424

Electricity value*		
Health	$15,547	$2,591
Ozone	$5,364	$894
PM2.5 (direct energy savings)		
PM2.5 (indirect energy savings)	$1,636	$273
PM2.5 (energy generation)		
Heat-related mortality	$8,546	$1,424
Climate change	$11,309	$1,885
GHG emissions (direct energy savings)		
GHG emissions (indirect energy savings)	$364	$61
GHG emissions (energy generation)		
Global cooling	$10,945	$1,824
Life extension	$26,003	$1,427
Surface life extension	$26,003	$1,427
NET TOTAL	**$29,401**	**$4,900**
NPV (2% real discount rate)	**$24,463**	**$4,285**
Benefit-Cost Ratio	**2.1**	**4.4**

12.2.2 Employment impact summary for Accelerated Adoption Scenario

Table 12.19. Accelerated Adoption Scenario Impact on Employment (dollar values in thousands of 2020 dollars unless otherwise specified)

Direct Employment Impact: 20-year Adoption Scenario (30-year Analysis) – Direct Job Years Created					
Surface:	**Cool Roofs**	**Reflective Parking**	**Reflective Roads**	**Bioswale-managed Roofs**	**TOTAL**
Direct (install + O&M) labor intensity (as % of total cost)	80%	80%	80%	60%	
Direct (materials) labor intensity (as % of total cost)	5%	5%	5%	10%	
Avg. annual salary + benefits of 1 Smart Surface job (2020$)	($50,000)	($50,000)	($50,000)	($50,000)	
Total cost	($64,976)	($26,003)	($1,427)	($3,319,302)	
Total direct install + O&M labor cost	($51,981)	($20,803)	($1,141)	($1,327,721)	
Total direct install + O&M job years created	*1,040*	*416*	*23*	*26,554*	*28,033*
Total direct materials labor cost	($3,249)	($1,300)	($71)	($497,895)	
Total direct materials job years created	*65*	*26*		*9,958*	*10,050*
Total job years created	**1,105**	**442**	**24**	**36,512**	**38,083**
Timeframe (years)	20	20	20	20	

12.2.3 Emissions reduction impact summary for accelerated adoption scenario

Baltimore set an emissions reduction goal of 30% by 2030. The Smart Surfaces accelerated adoption scenario for Baltimore was therefore specifically developed in order to be aggressive on adoption of Smart Surfaces that contribute most rapidly to CO2 reduction—reflective surfaces and solar PV.

12.2.2.3 Baltimore 2030 emissions reduction goal summary

Table 12.20. Baltimore 2030 emissions reduction goal summary

Goal	%	Base Year (2017) Annual Emissions (tonnes)	Est. Current Annual Emissions (2021)	2030 Annual Emissions Goal	Difference (tonnes to reduce before 2030)	Projected 2030 emissions if accelerated adoption scenario targets met	% of 2030 emissions goal met if accelerated adoption scenario targets met
CO2 reduction (CO2eq) by 2030 (from base year)	30%	8,556,989	7,861,498	5,989,892	1,871,606	7,137,190	39%

12.2.2.4 Emissions impact summary for accelerated adoption scenario

Table 12.21. Accelerated adoption scenario emissions impact summary – 2030 goal summary results

Smart Surface	Targets (% by 2030)	Emissions Reduction (tonnes in 2030)	2030 Total

Surface Type	Reflective (% of surface type)	Solar PV (% of surface type)	From Reflective (single-year 2030, tonnes CO2eq)	From Solar PV (single-year 2030 tonnes CO2 avoided)	Total CO2eq Emissions Reduction (tonnes) in 2030	Percent of 2030 Goal Achieved
Low slope roofs	65%	25%	218,240	327,256	545,496	29%
Steep slope roofs	10%	12%	10,361	124,966	135,327	7%
Parking	30%		37,273		37,273	2%
Streets	5%		6,212		6,212	0%
		TOTAL	**272,086**	**452,222**	**724,308**	**39%**

12.3 Neighborhood specific cost-benefit breakdown

12.3.2 Cherry Hill

Table 12.22. Roofing targets for Cherry Hill

Surface Type	**Cool Roofs**	acres	**Bioswale-managed**[lxxxii]	acres	**Green Roofs**	acres	**Solar PV**[lxxxiii]	acres
Low slope roofs	80%	27	20%	7	2%	0.7	40%	14
Steep slope roofs	20%	6	N/A		N/A		20%	6
Adoption timeframe (yrs) & acres installed per year	20	1.7 acres/yr.	20	0.3 acres/yr.	20	0.03 acres/yr.	20	1 acre/yr.

Table 12.23. Pavement targets for Cherry Hill

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lxxxii Bioswales/bioretention can manage stormwater runoff from adjacent roofs or parking lots. Bioswale-managed roofs and parking lots are calculated using SF or % of the area managed by a bioswale, not SF of bioswale – the size of the bioswale is about 4.5% of the impervious area managed. I.e., a small area of bioswale or tree trench can manage the water runoff of a much larger hard surface.

lxxxiii PV Can be put on any roof (e.g., PV can go on a regular roof, green roofs, or reflective/cool roofs, and standard roofs).

Surface Type	Reflective	acres	Porous/Permeable[lxxxiv]	acres	Bioswale-managed[lxxxii]	acres
Parking	50%	31	5%	3	20%	12
Roads	15%	9	N/A			
Sidewalk	0%		5%	2		
Adoption timeframe (yrs) & acres installed per year	20	2 acres/yr.	20	0.25 acres/yr.	20	0.6 acres/yr.

Table 12.24. Urban tree target for Cherry Hill

Surface Type	Tree Canopy	acres (new canopy)
Area (% of total)	40%	144
Adoption timeframe (yrs)	20	

Table 12.25. Cherry Hill Smart Surface cost-benefit summary (dollar values in thousands of 2020 dollars)

Smart Surface	*Target*	*Costs*	*Benefits*	*NPV (2% real discount rate)*	*Benefit: Cost Ratio*	*Employment (job yrs)*	*Peak Summer Temp Reduction Estimate[lxxxv]*
Cool Roofs[lxxxv]	Low-slope roof area: 80% Steep-slope roof area: 20%	($886)	$6,816	$4,278	7.7	15	0.62 °F

[lxxxiv] Permeable parking only applied when a parking lot is ripped out and replaced, at which time it costs less to make the area permeable (grid-grass or grid-gravel) than to construct a new asphalt parking surface. Total Cost in this case is therefore positive number because it costs less to install permeable parking when the hard surface parking lot is replaced, reflecting a first cost savings.

[lxxxv] Reflective surfaces have a large impact on city temperature. Local temperature reduction benefits from reflective surfaces are large but not included in the quantified benefits due to lack of input data. Temperature reduction from increased tree canopy is from radiative shading only. It doesn't include temperature reduction from increased evapotranspiration or reduced heat ejection into the city by air conditioners due to lower ambient temperature or from shading of buildings by trees. These are substantial additional heat reduction benefits from expanding tree coverage, meaning that cooling benefits from trees are underestimated in this model.

Bioswale-managed roof[lxxxvi]	Low-slope roof area: 20%	($1,319)	$4,345	$1,964	3.3	18	Not included
Green Roofs	Low-slope roof area: 2%	($643)	$1,251	$361	1.9	10	Not included
Solar PV[lxxxvii]	Low-slope roof area: 40% Steep-slope roof area: 20%	($3,758)	$83,839	$53,012	22.3	486	Not included
Reflective Parking[lxxxv]	Parking area: 50%	($608)	$1,425	$599	2.3	10	0.27 °F
Permeable Parking[lxxxviii]	Parking area: 5%	$672	$1,561	1,530	14.4		Not included
Bioswale-managed Parking[lxxxvi]	Parking area: 20%	($1,385)	$8,008	$4,444	5.8	24	Not included
Reflective Roads[lxxxv]	Road area: 15%	($132)	$377	$202	2.9	2	0.08 °F
Permeable Sidewalks	Sidewalk area: 5%	($622)	$2,543	$1,250	4.1	7	Not included
Trees[lxxxix]	Land area: 40%	($12,604)	$33,590	$14,131	2.7	252	2.11 °F
TOTAL		**($21,285)**	**$143,754**	**$81,771**	**6.8:1**	**825**	**3.1 °F**

12.3.3 Brooklyn Curtis Bay

Table 12.26. Roofing targets for Brooklyn Curtis Bay

Surface Type	**Cool Roofs**	acres	**Bioswale-managed**[lxxxii]	acres	**Green Roofs**	acres	**Solar PV**[lxxxiiii xxxiv]	acres
Low slope roofs	80%	44	20%	11	2%	1	40%	22

[lxxxvi] Bioswales/bioretention can manage stormwater runoff from adjacent roofs or parking lots. Bioswale-managed roofs and parking lots are calculated using SF or % of the area managed by a bioswale, not SF of bioswale – the size of the bioswale is about 4.5% of the impervious area managed. I.e., a small area of bioswale or tree trench can manage the water runoff of a much larger hard surface.
[lxxxvii] Solar PV payback after year 10, this model assumes "first cost" (i.e., financing payments) are net of electricity value (electricity value is zero for first 10 years after install), and therefore first cost is zero. Third-party financiers will bear the actual first cost and Baltimore system owners will not receive an electricity value benefit until year 11 after installation.
[lxxxviii] Permeable parking only applied when a parking lot is ripped out and replaced, at which time it costs less to make the area permeable (grid-grass or grid-gravel) than to construct a new asphalt parking surface. Total Cost in this case is therefore positive number because it costs less to install permeable parking when the hard surface parking lot is replaced, reflecting a first cost savings.
[lxxxix] Actual canopy will reach 40% at an estimated 10 years after end of adoption timeframe assuming O&M, at that time tree temperature reduction benefits have accrued.

Steep slope roofs	20%	10	N/A		N/A		20%	10
Adoption timeframe (yrs) & acres installed per year	20	2.7 acres/yr.	20	0.5 acres/yr.	20	0.05 acres/yr.	20	1.6 acres/yr.

Table 12.27. Pavement targets for Brooklyn Curtis Bay

Surface Type	**Reflective**	acres	**Porous/Permeable**[lxxxiv]	acres	**Bioswale-managed**[lxxxii]	acres
Parking	50%	86	5%	9	20%	34
Roads	15%	26	N/A			
Sidewalk	0%		5%	3		
Adoption timeframe (yrs) & acres installed per year	20	5.6 acres/yr.	20	0.6 acres/yr.	20	1.7 acres/yr.

Table 12.28. Urban tree target for Brooklyn Curtis Bay

Surface Type	**Tree Canopy**	acres (new canopy)
Area (% of total)	40%	290
Adoption timeframe (yrs)	20	

Table 12.29. Brooklyn Curtis Bay Smart Surface cost-benefit summary (dollar values in thousands of 2020 dollars)

Smart Surface	***Target***	***Costs***	***Benefits***	***NPV (2% real discount rate)***	***Benefit :Cost Ratio***	***Employment (job yrs)***	***Peak Summer Temp Reduction Estimate***[lxxxv]
Cool Roofs[lxxxv]	Low-slope roof area: 80% Steep-slope roof area: 20%	($1,427)	$10,980	$6,892	7.7	24	0.62 °F
Bioswale-managed roof[lxxxvi]	Low-slope roof area: 20%	($3,542)	$7,000	$2,049	2.0	50	Not included
Green Roofs	Low-slope roof area: 2%	($1,035)	$2,015	$581	1.9	17	Not included
Solar PV[lxxxvii]	Low-slope roof area: 40% Steep-slope roof area: 20%	($6,043)	$135,117	$85,429	22.4	778	Not included

Reflective Parking[lxxxv]	Parking area: 50%	($1,674)	$3,921	$1,648	2.3	28	0.42 °F
Permeable Parking[lxxxviii]	Parking area: 5%	$1,848	$4,296	$4,210	14.4		Not included
Bioswale-managed Parking[lxxxvi]	Parking area: 20%	($3,810)	$22,034	$12,229	5.8	65	Not included
Reflective Roads[lxxxv]	Road area: 15%	($363)	$1,037	$555	2.9	6	0.13 °F
Permeable Sidewalks	Sidewalk area: 5%	($947)	$3,872	$1,904	4.1	10	Not included
Trees[lxxxix]	Land area: 40%	($25,387)	$67,657	$28,462	2.7	508	2.79 °F
TOTAL		**($42,381)**	**$257,929**	**$143,961**	**6.1:1**	**1,486**	**4 °F**

12.3.4 Madison East-End

Table 12.30. Roofing targets for Madison East-End

Surface Type	Cool Roofs	acres	Bioswale-managed[lxxxii]	acres	Green Roofs	acres	Solar PV[lxxxiii]	acres
Low slope roofs	80%	20	10%	2.5	2%	0.5	40%	10
Steep slope roofs	20%	0.4	N/A		N/A		20%	0.4
Adoption timeframe (yrs) & acres installed per year	20	1 acre/yr.	20	0.12 acres/yr.	20	0.02 acres/yr.	20	0.52 acres/yr.

Table 12.31. Pavement targets for Madison East-End

Surface Type	Reflective	acres	Porous/Permeable[lxxxiv]	acres	Bioswale-managed[lxxxii]	acres
Parking	50%	0.7	5%	0.07	20%	0.27

Roads	15%	1.8	N/A			
Sidewalk	0%		5%	0.17		
Adoption timeframe (yrs)	20	0.12 acres/yr.	20	0.012 acres/yr.	20	0.01 acres/yr.

Table 12.32. Urban tree target for Madison East-End

Surface Type	**Tree Canopy**	acres (new canopy)
Area (% of total)	40%	22.5
Adoption timeframe (yrs)	20	

Table 12.33. Madison East-End Smart Surface cost-benefit summary (dollar values in thousands of 2020 dollars)

Smart Surface	*Target*	*Costs (2020$)*	*Benefits (2020$)*	*NPV (2020$, 2% real discount rate)*	*Benefit: Cost Ratio*	*Employment (job yrs)*	*Peak Summer Temp Reduction Estimate*[lxxxv]
Cool Roofs[lxxxv]	Low-slope roof area: 80% Steep-slope roof area: 20%	($515)	$4,688	$2,999	9.1	9	4.39 °F
Bioswale-managed roof[lxxxvi]	Low-slope roof area: 10%	($55)	$1,598	$1,061	29.0	1	Not included
Green Roofs	Low-slope roof area: 2%	($473)	$920	$265	1.9	8	Not included
Solar PV[lxxxvii]	Low-slope roof area: 40%	($1,860)	$43,401	$27,560	23.3	244	Not included

	Steep-slope roof area: 20%						
Reflective Parking[lxxxv]	Parking area: 50%	($13)	$31	$13	2.3	0	0.05 °F
Permeable Parking[lxxxviii]	Parking area: 5%	$14	$34	$33	14.4		Not included
Bioswale-managed Parking[lxxxvi]	Parking area: 20%	($30)	$172	$95	5.8	1	Not included
Reflective Roads[lxxxxv]	Road area: 15%	($25)	$73	$39	2.9	0	0.14 °F
Permeable Sidewalks	Sidewalk area: 5%	($55)	$226	$111	4.1	1	Not included
Trees[lxxxix]	Land area: 40%	($1,970)	$5,250	$2,209	2.7	39	3.71 °F
TOTAL		**($4,981)**	**$56,392**	**$34,385**	**11.3:1**	**302**	**8.3 °F**

13 Summer Tourism

Tourism is a major industry for Baltimore and Maryland as is a large source of revenue and employment. In the calendar year 2019, visitor spending from tourism in Maryland accounted for $18.6 billion. In Baltimore specifically, this supported 86,827 jobs directly and indirectly and generated $312 million in city tax revenue.[496] In the state of Maryland, tourism accounted for 6.2% of total employment, as of 2016, and contributed over $1000 per household. Tourism revenue grew 2%-8% every year between 2008 and 2016.[497]

However, the Urban Heat Island effect, exacerbated by climate change is causing increasing extreme summer heat and poses growing risks to the tourism industry and the economic welfare of Baltimore and Maryland residents. July 2020 set a 148-year record for heat in Baltimore, as the city endured 25 days of 90-degree temperatures.[498] Researchers at the University of Maryland emphasized that Marylanders should expect more long and humid stretches in the years to come due to the effects of climate change.[499] How Baltimore and Maryland prepare—or don't prepare—for accelerating climate change impacts will determine not just the future livability of Baltimore in its hot summer months, but also the future of its critical and vulnerable tourism industry.

Employment and revenue from Baltimore's tourism industry is increasingly threatened by excess summer heat events accelerate in the coming years. This threat is documented and discussed in the sections above and below and demonstrates the need for Baltimore to adopt a city-wide Smart Surfaces strategy to protect its essential tourism industry. In addition, it is important that Maryland to support Baltimore in its transition to smarter and greener infrastructure solutions.

> ***Chris Riehl,*** *President of the Baltimore Tourism Association and owner of a local business Baltimore Rent-A-Tour:*
>
> "Sustainable design features are something that the people of Baltimore are proud of. In the long term, incorporating Smart Surfaces in Baltimore will overall improve the livability and appeal of the city; allowing the city to market itself as a more sustainable, energy efficient, and desirable tourism destination."

13.1 Maryland and Baltimore summer conditions

As the Maryland State government has noted, "the effects of climate change in Maryland are already apparent in rising seas, summer heat waves, and more frequent and violent thunderstorms."[500] The health risks and additional social and structural threats to Baltimore are extensively described and documented in a remarkable eight-part series titled "Code Red", which is the result of collaboration between the University of Maryland's Howard Center for Investigative Journalism, Capital News Service, NPR, Wide Angle Youth Media in Baltimore, and WMAR television.[501]

The "Code Red" series documents the disproportionate impact of climate change and summer heat on lower-income communities in Baltimore and the ways in which heat affects health and livability for city residents. The series examined factors such as ambient and surface temperatures in Baltimore. Additionally, it noted that neighborhoods in which dark and impervious surfaces are more prevalent tend to be significantly hotter. For example, one neighborhood examined had an ambient temperature of 87 degrees Fahrenheit, while the surface temperatures reached as high as 163 degrees.[502]

Visitation to Baltimore is the highest during the summer months. Considering the high summer surface temperature in areas with extensive dark and impervious surfaces, the tourism industry can expect impacts in the coming years as climate change accelerates heat events and temperatures increase in the summer months. In the state of Maryland, the most popular months for travel are June and July, according to data from Champion Traveler.[503] Over 40% of annual tourism occurs during the 3 hottest months of the year—June, July, and August.[504]

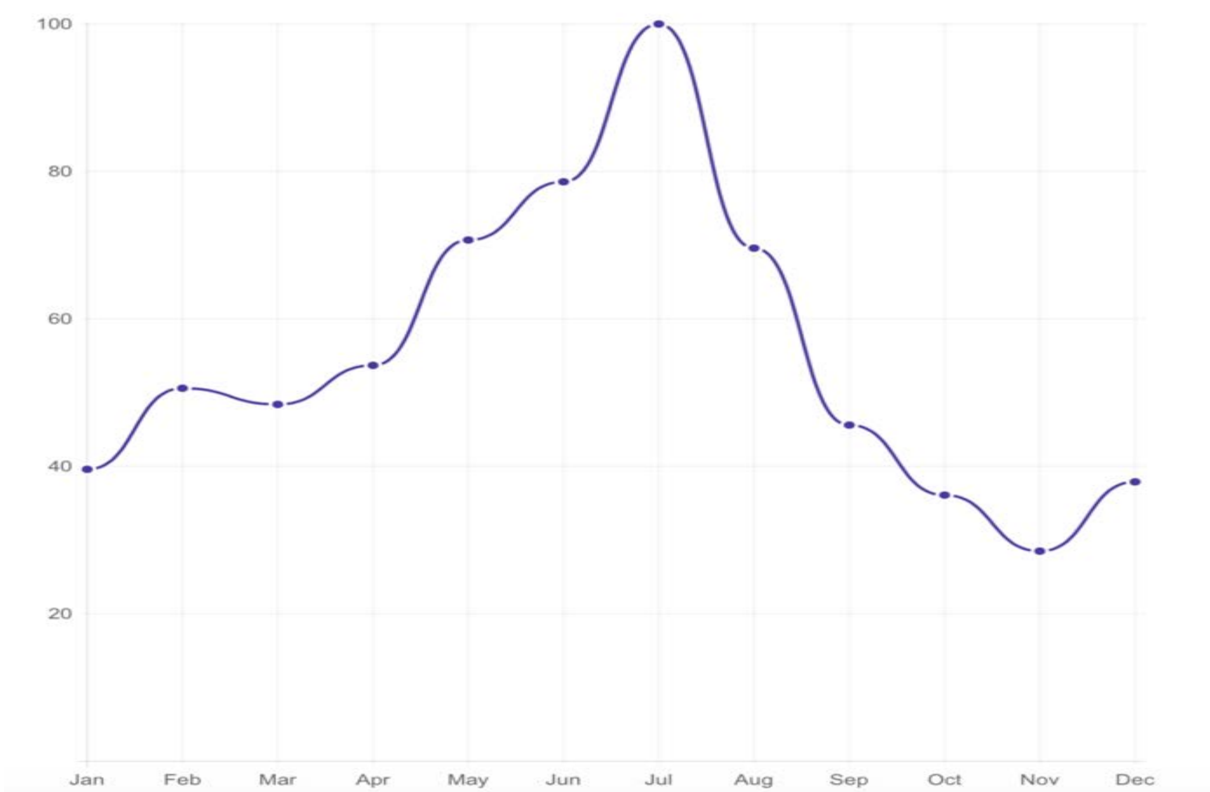


Figure 13.1. This tourism graph is based on Google searches for services used by tourists relative to the rest of the year. The summer months display the largest number of tourists.[505]

While June and July are the most popular months of tourism, the best times to visit Maryland for ideal weather and comfortable conditions based on average temperature and humidity data from NOAA is considered April 23rd to June 24th or August 27th to October 28th—which largely excludes the 3 summer months of June, July and August.[506] Therefore, while these summer months have traditionally been the most popular for tourism, sources such as US News already warn that "soaring temperatures" are a factor to consider while planning a trip to Baltimore in the summer months.[507] Climate change has put Baltimore's critical summer tourism industry on a collision course with rising summer heat.

13.2 Summer heat events and patterns

Average summer temperatures and the number of days in which heat exceeds dangerous levels are projected to increase drastically in Baltimore and Maryland in the coming decades. Currently, Maryland averages 10 days per year when the heat exceeds dangerous levels, and projections indicate that number will likely rise to 40 days each year by 2050.[508] Figure 13.2 below illustrates that in about 30 years, Baltimore's summer temperatures will be deemed unacceptable - "unfavorable" for tourists if no action is taken to address climate change and its impacts.

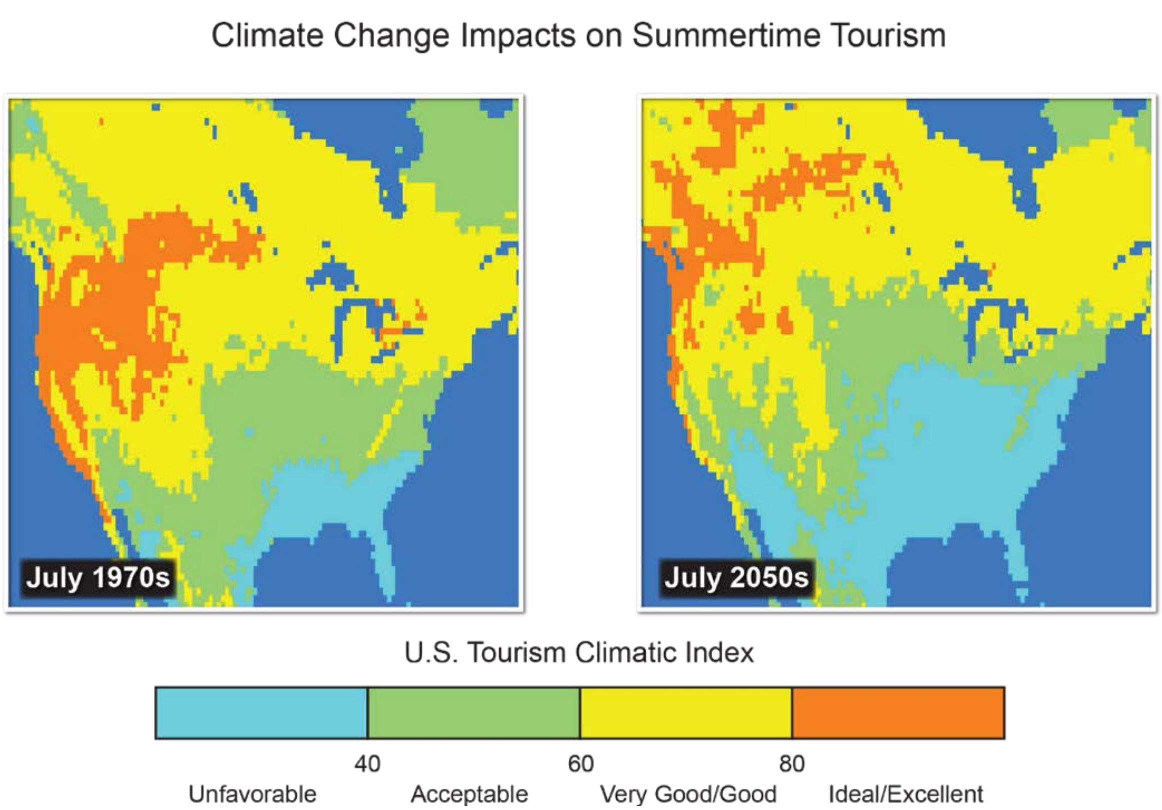


Figure 13.2. Climate change impacts on summer tourism under a high emissions scenario.[509]

A Baltimore Magazine's article entitled "Hell and High Water" discusses the threat of a projected steep increase in summer heat waves– defined as a heat index of over 105 degrees. The number of days with a heat index above 105 degrees is projected to rise from eight in 2020 to 30 in the year 2030, as Figure 13.3 shows below. This increase in extreme heat will increasingly deter tourists and could greatly reduce summer tourism.

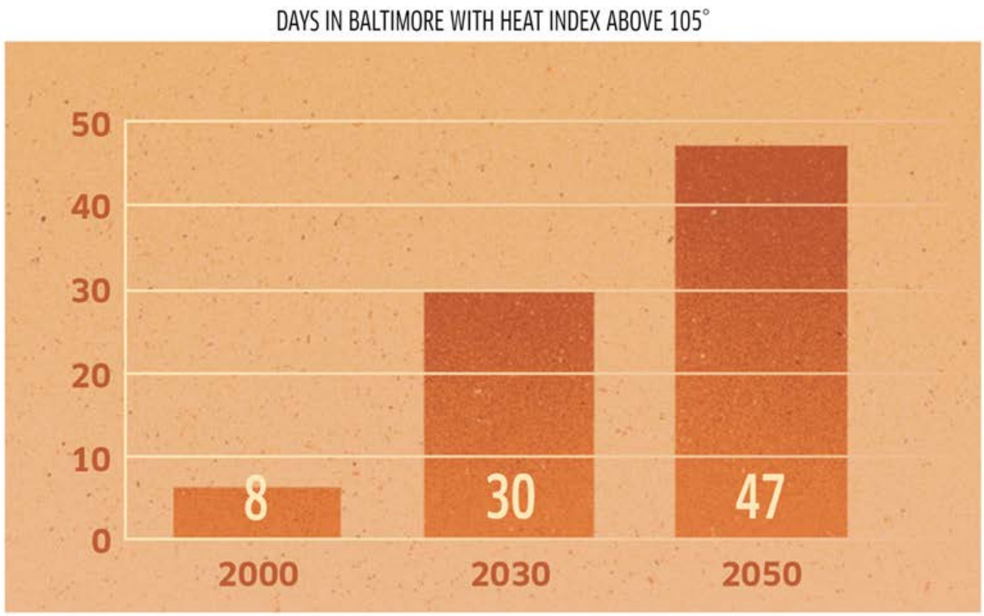
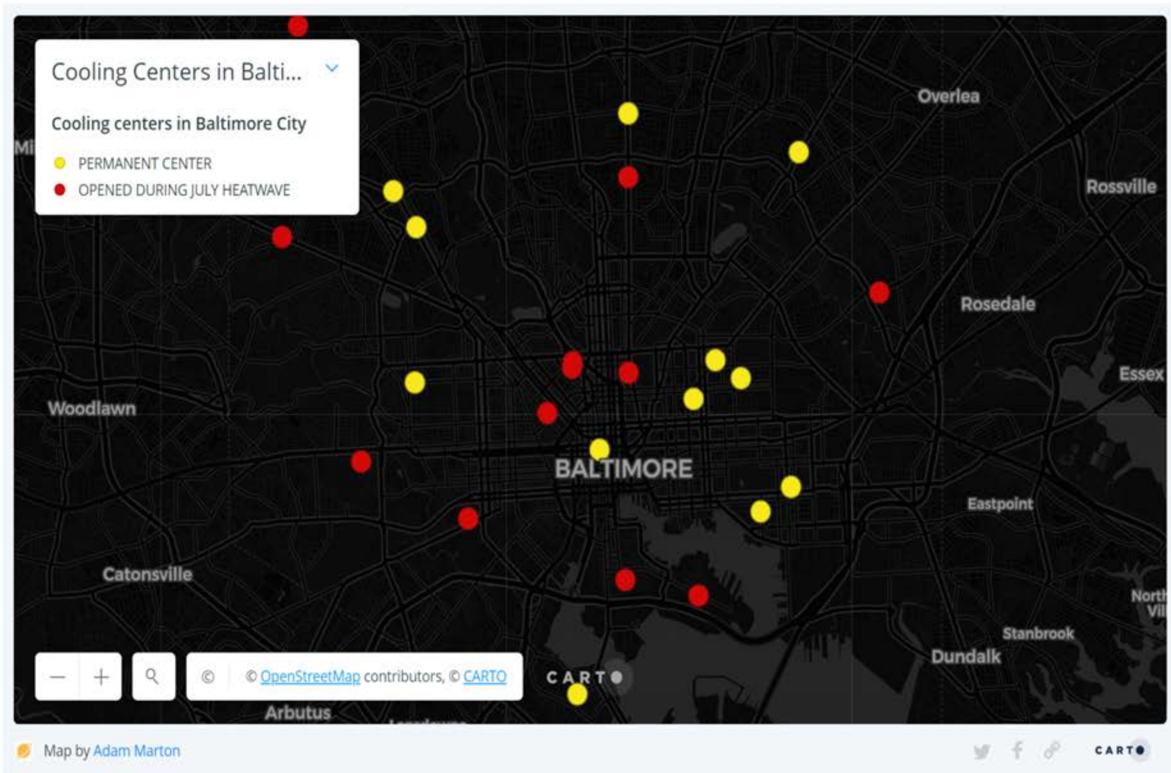


Figure 13.3. Days in Baltimore in which the heat index reaches above 105 degrees Fahrenheit.[510]

To deal with excess summer heat, Baltimore has established "cooling centers" scattered across the city to protect against excessive heat during summer months for vulnerable communities such as the elderly.[511] The cooling center locations in Baltimore are mapped below in Figure 13.4. And while these cooling centers save lives, they will not reduce summer tourism losses as heat rises. After all, sitting in a crowded cooling center or in air-conditioned hotel rooms is not an appealing vacation.



Source: Baltimore City Health Department

Figure 13.4. Cooling centers in Baltimore already in place to combat intense summer heat.[512]

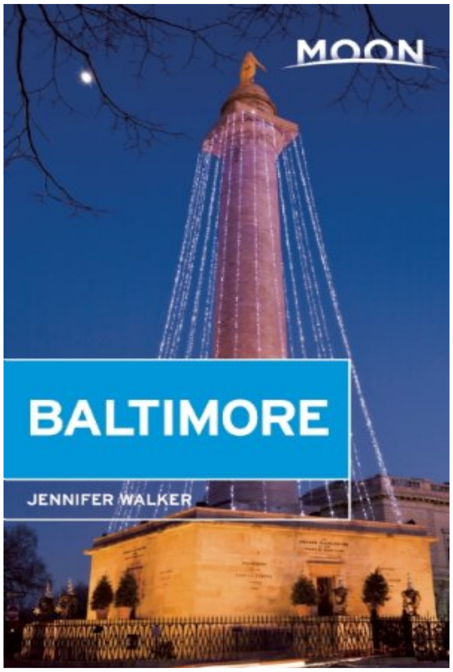
13.3 The impact of excess heat on tourism

Summer heat in Baltimore is already a problem for tourists, as illustrated by these quotes from popular tourism sources and sites:

- In the summer of 2016, the Baltimore Business Journal raised the concern, “what do people do when it is too hot to be outside for any extended period of time?”. The Journal noted the heat’s effect on tourism specifically, “that was the question Baltimore residents and tourists faced over the weekend and even into Monday as temperatures creeped around 100 degrees beginning Friday, and exceeding that point on Monday. The Baltimore Orioles hosted one of the biggest non-division matchups of the year…but the number of fans who came to see the action was down from what was expected.”[513]

- A TripAdvisor commentary responding to a question about summer conditions in Baltimore remarks, “it tends to be hot and very humid… I can’t say it’s comfortable in July, especially for someone who might not be used to heat and humidity,”[514] and “we have been facing record temperatures here in Baltimore, and today is supposed to reach 101 degrees. Many roads in our area have been "buckling" due to the extended heat wave we've been experiencing.”[515]

- A five-star rated tourist book on the city titled *Baltimore* points out the connection between Baltimore's surfaces and its excess summer heat, noting that Baltimore's "blacktop serve as a heat sink, absorbing more of the summer's relentless sun."[516]



"July is consistently the hottest month in Baltimore, with an average high of around 91°F. Note that temperatures in the center of Baltimore City will be significantly higher than in the less-dense regions as the swaths of concrete and blacktop serve as a heat sink, absorbing more of the summer's relentless sun." – *Baltimore* by Jennifer Walker

Figure 13.5. Image courtesy of Amazon.com and quote illustrates the problem of summer temperatures and conditions.[517]

Implementing the Smart Surfaces strategies described in this report would mitigate city-wide urban heat island (UHI) impacts and could fully offset the rising temperatures that are expected from climate change. Implementation of Smart Surfaces city-wide can reduce summer peak temperatures by over 3 degrees, with even larger reductions in the hottest areas, which are often lower-income and communities of color. At the end of our 30-year analysis period, Baltimore in the summer could be cooler than it is today despite rising global and regional temperatures—if Smart Surface strategies are adopted.[xc] This would protect Baltimore's critical tourism industry and could make Baltimore more livable and attractive to tourists than it is today.

[xc] This is based on the combination of our own analysis and calculations based on the work of Haider Taha, a leading expert on climate modeling in reflective surfaces.

13.4 Baltimore tourism numbers

As noted above, in 2019, tourism generated 10.7 billion dollars in business sales for Baltimore. Baltimore's tourism industry generated $312 million in city tax revenue in 2019 and sustained 86,827 total jobs directly and indirectly.[518]

40% of tourism dollars accrue in the three summer months (June, July, and August),[xci] which means that $4.28 billion in tourism driven revenue was generated for Baltimore in June, July and August, along with $171 million in revenue for Maryland and $122 million in tourism tax revenue accrues to Baltimore.[xcii]

Given the threat to tourism from heat today, we can conservatively assume that 3-4°F of additional climate heat and tripling of days at a heat index above 105 degrees Fahrenheit might reduce summer tourism in Baltimore by 10-20%. We model 5% and 10% summer heat related losses as a conservative estimate.

Research published in 2008 by the Chicago Climate Task Force concluded that expected increases in average summer temperatures due to climate change will make the city climate uncomfortable, resulting in fewer events being held in Chicago and making it harder to attract non-residents.[519] A similar effect can be expected for Baltimore. Additionally, a 2006 simulation study concluded that domestic tourism may decrease as much as 20% in warmer countries because of climate change.[520] A 2018 study on heat and urban tourism in Lisbon, Portugal notes: "tourists end up having a lower engagement with the destination by visiting fewer attractions, performing fewer activities or reducing the duration of their daytime visit to the city" due to uncomfortably high summer temperatures.[521]

To be clear, it is unreasonable to assume that tourists are indifferent to excess heat, or that tourist guidebooks and websites will not warn tourists of excess heat/pollution (they already do so), or that expanded cooling centers, will maintain the tourist industry in the face of rising heat waves (tourists will not be happy in crowded cooling centers or stuck in hotel rooms). After all, there is a large part of a continent of cooler alternative destinations in driving distance, especially for longer lasting summer family holidays. Elderly retirees and families with young children are especially likely to choose to avoid a hot city and instead travel further north to cooler areas during the summer holidays.[522]

Broad adoption of Smart Surfaces would allow Baltimore to entirely offset and avoid rising heat over the coming decades. That is, Baltimore could become cooler as the

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[xci] Because tourism in the summer is common due to school holidays.
[xcii] These calculations are based on the total business sales and tax revenue for Baltimore compared to peak visitation months.

world – and alternative tourism destinations - get hotter. Avoiding 10% loss of summer tourism through broad Smart Surfaces adoption would avoid $10 billion in lost tourism revenue, $1.2 billion in revenue to Maryland and $800 million in city revenue over 30 years. Even with just an avoided 5% tourism loss, the lowest end of the range suggested by research about potential tourism losses, the net present value to Baltimore over the 30-year analysis period would be ~ $5 billion in visitor spending, including $600 million in revenue to the state and ~$400 million in Baltimore tax revenue.[xciii] With a 10% avoided summer tourism losses would save $1.2 billion in State revenue over the 30-year period. This indicates that the State of Maryland should be very willing to invest substantially to support Baltimore adoption Smart Surfaces.

The 5% calculation are used in this report is a very conservative (e.g., very likely low) estimate of potential for summer tourism revenue losses that would be avoided by a broad adoption of Smart Surfaces and the resulting cooling of the city while the rest of the world gets hotter.

The above revenue impact estimates assume no future growth in tourism and tourism revenue, a conservative assumption given long term historic growth in Baltimore tourism and tourism revenue. If the historical growth in tourism revenue were to continue this would make avoided tourism losses larger. As a 2020 major tourism analysis of Maryland notes, Maryland visitor spending has grown for seven straight years, expanding by more than 35% since 2009, at an average rate of about 4% per year.[523]

Investing in city-wide adoption of Smart Surfaces to reduce summer heat, air pollution and the myriad of other benefits documented in this report is a low risk, prudent strategy for Baltimore. Investing in Smart Surfaces for Baltimore is also a smart strategy for Maryland. Maryland investment in state tourism averaged $1.2 billion per year in 2015 and 2016.[524] As noted above, Baltimore summer tourism revenue brings $418 million in revenue per year to the state coffers (in 2019). As noted above, it is therefore reasonable to expect that Maryland help pay for Baltimore to adopt Smart Surfaces city-wide to protect this critical state revenue source and employer.

Note: This kind of full, integrated analysis has not been done before in large part because of its complexity, and because existing analytic tools address only a small portion of the study scope. For example, we used EPA's BenMAP to value the health benefits that result from declines in ambient ozone concentration, but then solved a large set of other benefit estimation challenges including: estimating the indirect energy benefit of green roofs; developing simple, yet robust temperature-based methods to

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[xciii] Because we assume a linear installation rate and because the effects of UHI mitigation are approximately additive, we assume that the UHI mitigation impact on tourism is linear (i.e., halfway through the 40-year analysis period, in 2037, the Smart Surfaces solutions yield 1°F in UHI mitigation).

estimate city ozone concentration reductions; valuing health benefits of PM2.5 emissions reductions due to installing cool roofs, green roofs, solar PV, reflective pavements, and urban trees; valuing heat-related mortality reductions due to cool roofs, green roofs, reflective pavements, and urban trees; and combining new methods and existing methods to estimate costs and benefits at ward-level. This has involved guidance from a range of field specific experts. We wish to that the range of national and city partners, technology, stormwater, and energy experts who helped us gather data, develop analytic approaches, and build an integrated cost-benefit model for Baltimore.

14 Conclusions

Justin Bowers, *Assistant Director of the Baltimore Tree Trust:*

"The benefits that planting trees and other Smart Surfaces have on a community can be tremendous. Despite clear benefits for air, reduced urban temperatures, low-income communities, flood safety, and reduced energy burdens, a large number of benefits of trees are ignored in city policies. For Baltimore, trees deliver a large range of benefits, and the Smart Surface coalition cost-benefit tools allow us to really get at these and make a much better informed and more successful urban design choices. We have to do this if cities are to remain livable in a warming world."

This report provides an in-depth analysis of the costs and benefits of applying a set of roofing and surfacing solutions both at city-scale across Baltimore.

This report also provides an analysis of the impact of Smart Surfaces deployment on the three low-income neighborhoods of Brooklyn-Curtis Bay, Cherry Hill, and Madison East End. The low-income areas studied represent, in total, about 5 percent of Baltimore by population and over 8 percent of the city by area. These low-income neighborhoods have, on average, 90% higher family poverty rates and 55% higher unemployment rates than city-wide averages, according to Baltimore Neighborhood Indicators Alliance (BNIA)'s 2020 report. Not coincidentally, these low-income areas have less tree coverage than Baltimore as a whole. Cherry Hill's 21 percent, Brooklyn-Curtis Bay's 15 percent, and Madison East End's 6 percent tree coverage are all substantially less than the city-wide figure of 29 percent.

Long term underinvestment in trees and green solutions in urban low-income areas has resulted in higher summer temperatures, worse air quality, more health problems, and higher energy bills. This long-term structural inequality is both inimical to the City's commitment to equality of opportunity, as well as an unnecessary waste of money.

While more research remains to be done, the findings of this report are compelling. Low-income areas in Baltimore as part of a city-wide Smart Surfaces strategy would achieve large and very cost-effective improvements in health and comfort, lower energy bills, and reduced climate change by adopting Smart Surface solutions. Deployment of these solutions at scale in low-income areas can help redress systemic inequity in Baltimore's urban infrastructure. Reductions in energy bills matter much more to low-income residents than to wealthy city residents. Similarly, health benefits from the deployment of Smart Surface solutions would be greater for low-income than for wealthy city residents who already live in green cooler neighborhoods.

Overall, the Smart Surface solutions evaluated in this report provide a very large positive net benefit for Baltimore, with a net present value of over $9 billion and a compelling cost-benefit ration of 15:1 (assuming avoided 5% summer tourism losses).

The payback time for these solutions varies greatly: cool roofs offer very fast payback in all cases, while several other solutions offer the largest total net benefits. The report quantifies a large range of costs and benefits from adopting Smart Surface solutions, including detailed estimation of health impacts.

As discussed in the report, many additional benefits and a few costs were identified but not quantified due to lack of data and/or need to limit study scope. Unquantified benefits exceed unquantified costs, so the cost-benefit findings in this report underestimate the cost-effectiveness of these solutions. That is, the net benefits of scale deployment of Smart Surfaces are significantly larger than estimated here.

Furthermore, this analysis largely does not capture the regional comfort, health, and livability benefits. As deployment scales up, broader, shared urban cooling benefits also grow proportionally, reducing energy bills and smog, and improving health and livability in ways that bring reinforcing benefits, especially for low-income populations.

14.1 Low-income impact versus city-average impact

Low-income areas can achieve large gains in health, comfort and resilience, reducing energy bills, and mitigating climate change. Deployment of these solutions at scale in low-income areas can address systemic inequity in urban quality of life. For example, reductions in energy bills are a more significant portion of income saved for low-income residents than to wealthier city residents. Similarly, health benefits from the solutions analyzed in this report are generally larger for lower-income neighborhoods than for wealthier neighborhoods because these are already cooler and less polluted and with higher tree coverage. Job creation, if coupled with job training would also benefit low-income residents.

14.1.1 Comfort

Lower income city residents tend to live in areas with fewer trees and more impervious surface.[525] This was largely evident in the low-income regions we analyzed in this analysis. This indicates that the comfort benefit from Smart Surface adoption in low-income areas, which are currently less comfortable, hotter and more polluted in the summer than the city as a whole, would be greater than average city-wide.

Baltimore's average tree canopy is 29%, while the tree canopy for Brooklyn-Curtis Bay, Cherry Hill, and Madison East End is 15%, 21% and 6%, respectively. A goal should be set in the longer term, that all neighborhoods reach at least 40% tree coverage, requiring continued over-investment in low-income areas (to offset historic underinvestment) to achieve environmental parity and structural environmental justice with respect to urban surfaces.

14.1.2 Energy

Lower-income households in Baltimore spend about 10.5% of income on energy costs, while Baltimore households overall spend about 3% of income on energy costs.[526] Energy savings due to Smart Surface solution installation would therefore provide a much greater relative benefit to low-income residents.

If we assume that air conditioning accounts for 12% of energy costs for the average Baltimore household,[527] and if we suppose that Smart Surfaces reduce air conditioning use by 25%, this will free up about 0.3% of a low-income household's income that no longer has to be spent on air conditioning costs. For higher income households, this would only free up 0.09% of income. The benefit to lower income households in this case is at least three times larger than it is for higher income households. Regardless of percent energy saved, the benefit to low-income residents will be roughly three times larger, demonstrating the larger relative impact of Smart Surface solutions on low-income citizens.

14.1.3 Employment

In 2019, the low-income neighborhoods of Brooklyn-Curtis Bay, Cherry Hill, and Madison East End had, on average, an unemployment rate of 14.8% versus the Baltimore city-wide unemployment rate of 8.5%.[528] Given higher unemployment in these low-income areas, it is reasonable to assume a higher percentage of jobs created from Smart Surface solution installs could accrue to low-income residents if cities provide policy and training efforts to support employment in these communities.

Establishment of a nursery on city leased property for expanding tree nursery and green roof capacity would also be very job creative for Baltimore.

14.1.4 Health

Based on above ozone analysis, the health benefits for Baltimore's low-income neighborhoods are about 1.5 times greater per person than the benefits for the average city resident. If we assume the same multiplier (1.5) holds for the other air pollution related benefits (PM2.5 and heat-related mortality), this indicates that low- income residents would experience roughly 50% greater health benefit compared to the average city resident. City average impact per person includes low-income residents—removing low-income areas from the city-wide average would make income-linked differences even more stark.

This report identifies many additional benefits of city-wide adoption of Smart Surface technologies that we could not quantify due to insufficient data and/or peer reviewed studies, therefore, this report's findings generally underestimate the cost-effectiveness of these solutions—especially trees.

One large benefit of city-wide adoption of Smart Surface strategies we did not quantify (since it extends beyond the city) is that cooling of cities also means areas that are downwind in the summer would receive cooler airflow and improved air quality. This downwind cooling from city-wide adoption of Smart Surface options in Baltimore could be large. This downwind cooling would create additional energy, air quality, and livability benefits within each city as well as for the larger region.

The findings in this report demonstrate that city-wide deployment of the surface technologies is a viable and highly cost-effective strategy for cities generally and Baltimore specifically to protect their livability as well as key employment sectors such as tourism. Smart Surfaces would enhance the comfort and quality of life of every citizen.

The threats to Baltimore described by Baltimore officials (and quoted from above) are threats to every sector of the city from education to industry and livability. Protecting the city from rapidly increasing heat waves and extreme weather cannot be done overnight. It takes years and the sooner Baltimore begins the sooner it will see gains and the lower the risks it will face.

In adopting these Smart Surface strategies city-wide, Baltimore can also go a long way in redressing current deep structural inequality that consigns low-income citizens and people of color to less healthy, less green neighborhoods characterized by more severe heat and worse air pollution. This endemic urban structural inequality is both immoral and entirely unnecessary. Through city-wide Smart Surface strategies, Baltimore can provide a healthier place to work and live for all its citizens. The data on cost-effectiveness of these strategies is compelling.

This report demonstrates that city-wide adoption of Smart Surfaces creates very large net financial benefits for Baltimore. These findings should result in broad recognition of and support for these strategies as a city-wide standard practice. Comprehensive Smart Surface adoption would enable Baltimore to improve quality of life, address structural inequality, improve livability, cut costs, and contribute to slowing climate change. Baltimore leadership on Smart Surfaces can also be expected to accelerate Smart Surface adoption by the surrounding cities, in turn increasing city and region-wide cooling and health benefits.

The growing city-wide risks from extreme heat and climate change can be largely offset by Baltimore's adoption of these Smart Surface technologies. The city can become cooler as the world warms. Large net positive financial returns to the city as a whole constitute a strong financial, resilience and public policy-based case for rapid adoption of Smart Surface solutions city-wide as standard, baseline policy for Baltimore.

15 Endnotes

[1] Chi Xu, Timothy A. Kohler, Timothy M. Lenton, Jens-Christian Svenning, Marten Scheffer "Proceedings of the National Academy of Sciences", May 2020, 117 (21) 11350-11355, *SI Appendix, Fig. S12*, DOI: 10.1073/pnas.1910114117

[2] https://www.economicsandpeace.org/wp-content/uploads/2020/09/Ecological-Threat-Register-Press-Release-27.08-FINAL.pdf

[3] Pierre-Louis, Kendra, "The World Wants Air-Conditioning. That Could Warm the World", *New York Times*, May 15, 2018, https://www.nytimes.com/2018/05/15/climate/air-conditioning.html.

[4] Mayor and City Council of Baltimore v. BP P.L.C et al, No. 1:18-cv-02357, at 6 (Cir. Ct. Balt. City. filed Aug. 16, 2018), https://www.eenews.net/assets/2020/12/22/document_cw_01.pdf.

[5] Tord Kjellstrom et al, "Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts", Annual Review of Public Health, Vol. 37:97-112, March 2016, https://www.annualreviews.org/doi/abs/10.1146/annurev-publhealth-032315-021740.

[6] Kjellstrom T, et al. 2016. Annual Review of Public Health 37:97—112.

[7] Ibid.

[8] Baltimore Neighborhood Indicators Alliance (BNIA), "Cherry Hill Vital Signs," Jacob France Institute, https://bniajfi.org/community/Cherry%20Hill/; Baltimore Neighborhood Indicators Alliance (BNIA), "Brooklyn/ Curtis Bay/ Hawkins Point Vital Signs," Jacob France Institute, https://bniajfi.org/community/Brooklyn_Curtis%20Bay_Hawkins%20Point/; Baltimore Neighborhood Indicators Alliance (BNIA), "Madison/ East End Vital Signs," Jacob France Institute, https://bniajfi.org/community/Madison_East%20End/.

[9] New York Times, Heat Data Source: Vivek Shandas/CAPA Strategies

[10] Dan Novak et al, "Code Red Seeking Solutions: Global warming will be costly and neighborhoods must do more", *Howard Center for Investigative Journalism*, https://cnsmaryland.org/interactives/summer-2019/code-red/city-climate-future.html

[11] "Tourism Satellite Account Calendar Year 2016: The Economic Impact of Tourism in Maryland", Tourism Economics, https://industry.visitmaryland.org/wp-content/uploads/2020/04/MD-Visitor-Economic-Impact-20161.pdf.

[12] "Why Go to Baltimore," U.S News & World Report, https://travel.usnews.com/Baltimore_MD/.

[13] Fourth National Climate Assessment, USGCRP, November 23, 2018, https://nca2018.globalchange.gov/downloads/NCA4_2018_FullReport.pdf.

[14] Ibid.

[15] Richard Morin, "The Surprising Impact of Global Warming on Tourism," *Pew Research Center*, August 17, 2006, https://www.pewresearch.org/2006/08/17/the-surprising-impact-of-global-warming-on-tourism/.

[16]Greg Kats, "Here's How Cities Can Reduce Climate Change Risk", *Risk & Insurance*, https://riskandinsurance.com/how-cities-reduce-climate-change-risk/.

[17] Mayor and City Council of Baltimore v. BP P.L.C et al, No. 1:18-cv-02357.

[18] Baltimore Neighborhood Indicators Alliance (BNIA), "Cherry Hill Vital Signs"; Baltimore Neighborhood Indicators Alliance (BNIA), "Brooklyn/ Curtis Bay/ Hawkins Point Vital Signs"; Baltimore Neighborhood Indicators Alliance (BNIA), "Madison/ East End Vital Signs."

[19] "Urban Heat Island," National Geographic, https://www.nationalgeographic.org/encyclopedia/urban-heat-island/.

[20] Colleen et al., "Mapping Community Determinants of Heat Vulnerability," Environmental Health

Perspectives, June 10, 2009, doi:10.1289/ehp.0900683.
[21] Voelkel et al. "Assessing Vulnerability to Urban Heat: A Study of Disproportionate Heat Exposure and Access to Refuge by Socio-Demographic Status in Portland, Oregon," Int. J. Environ. Res Public Health 15, (March, 2018), 640. doi:10.3390/ijerph15040640.
[22] Takashi Asaeda, Vu Thanh Ca, and Akio Wake. "Heat storage of pavement and its effect on the lower atmosphere." Atmospheric Environment, 30 no.3 (1996): 413-27. doi:10.1016/1352- 249 2310(94)00140-5.
[23] Voelkel et al. "Assessing Vulnerability to Urban Heat: A Study of Disproportionate Heat Exposure and Access to Refuge by Socio-Demographic Status in Portland, Oregon," 640.
[24] Uejio et al. "Intra-urban societal vulnerability to extreme heat: the role of heat exposure and the built environment, socioeconomics, and neighborhood stability," Health & Place, 17, no.2 (2011): 498- 507, doi:10.1016/j.healthplace.2010.12.005.
[25] Hoffman, Shandas, and Nicholas Pendleton, "The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas," Climate, 8, no.1 (2020): 12. doi:10.3390/cli8010012.
[26] Popovich and Flavelle, "Summer in the City Is Hot, but Some Neighborhoods Suffer More."
[27] Mayor and City Council of Baltimore v. BP P.L.C., 46.
[28] Ernie Hood, "Dwelling Disparities: How Poor Housing Leads to Poor Health," Environmental Health Perspectives, May 2005.
[29] Alcock et al, "Land cover and air pollution are associated with asthma hospitalizations: A cross-sectional study." Environment International, 109, (December, 2017): 29–41.
DOI:10.1016/j.envint.2017.08.009.
[30] Uejio et al, "Intra-urban societal vulnerability to extreme heat" (2011).
[31] Mayor and City Council of Baltimore v. BP P.L.C., 47.
[32] Anderson and Bell. "Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities." Environmental Health Perspectives, 119, no.2 (February, 2011): 210-218. doi:10.1289/ehp.1002313; Hoffman et al, "The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat."
[33] Lu, Sarkar, and Yang Xiao. (2018). "The effect of street-level greenery on walking behavior: Evidence from Hong Kong." Social Science & Medicine, 208, (July, 2018): 41-49.
doi:10.1016/j.socscimed.2018.05.022.
[34] Abedi et al, "Racial, Economic, and Health Inequality and COVID-19 Infection in the United States." J. Racial and Ethnic Health Disparities (September, 2020).
doi:10.1007/s40615-020-00833-4.
[35] Wiemers et al, "Disparities in vulnerability to complications from COVID-19 arising from disparities in preexisting conditions in the United States," Research in Social Stratification and Mobility 69 (2020): 100553, https://doi.org/10.1016/j.rssm.2020.100553.
[36] Michael Carliner, "Reducing Energy Costs in Rental Housing: The Need and the Potential" (Joint Center for Housing Studies of Harvard University, December 2013).
[37] Bill M. Jesdale, Rachel Morello-Frosch, and Lara Cushing, "The Racial/Ethnic Distribution of Heat Risk–Related Land Cover in Relation to Residential Segregation," Environmental Health Perspectives ,121, no. 7 (May 14, 2013): 811–17,
doi:10.1289/ehp.1205919.
[38] Ariel Drehobl, Lauren Ross, and Roxana Ayala, "How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States," (Washington, D.C.: American Council for an Energy-Efficient Economy, September 10, 2020),

https://www.aceee.org/energy-burden.
[39] Ibid.
[40] Nicholas Kristof, “Temperatures Rise, and We’re Cooked,” The New York Times, September 10, 2016,
https://www.nytimes.com/2016/09/11/opinion/sunday/temperatures-rise-and-were-cooked.html.
[41] Greg Kats and Keith Glassbrook, “Delivering Urban Resilience,” Smart Surfaces Coalition, 2018, https://smartsurfacescoalition.org/analysis/delivering-urban-resilience-full-report.
[42] The 2019 Baltimore Sustainability Plan, Baltimore Commission on Sustainability (2019) https://www.baltimoresustainability.org/wp-content/uploads/2019/02/Sustainability-Plan_01-30-19-compressed-1.pdf.
[43] Baltimore Sustainability Plan, 7.
[44] Baltimore Sustainability Plan, 12.
[45] Baltimore Climate Action Plan, Baltimore Office of Sustainability, 2012
https://www.baltimoresustainability.org/wp-content/uploads/2015/12/BaltimoreClimateActionPlan.pdf.
[46] Baltimore Climate Action Plan, 5.
[47] Baltimore Sustainability Plan, 86.
[48] “Runoff pollution threatens the Chesapeake Bay”, Chesapeake Bay Foundation, 2010.
[49] American Public Health Association, “Medical Society Consortium on Climate and Health Launch”, March 15th, 2017,
https://www.apha.org/events-and-meetings/apha-calendar/2017/medical-society-consortium-on-climate-and-health.
[50] Mayor and City Council of Baltimore v. BP P.L.C., 40.
[51] Ibid, 46-47.
[52] Meg Anderson and Sean McMinn. “As Rising Heat Bakes U.S. Cities, The Poor Often Feel it Most,” NPR, September 3, 2019.
https://www.npr.org/2019/09/03/754044732/as-rising-heat-bakes-u-s-cities-the-poor-often-feel-it-most.
[53] American Lung Association. (2019). State of the Air 2019, 20th Anniversary.
https://www.stateoftheair.org/assets/sota-2019-full.pdf.
[54] Mayor and City Council of Baltimore v. BP P.L.C., 47.
[55] United States EPA. “Climate Impacts in the Northeast,” US EPA, 2017.
https://archive.epa.gov/epa/climate-impacts/climate-impacts-northeast.html#:~:text=Between%201958%20and%202012%2C%20the,northern%20parts%20of%20the%20region.
[56] Baltimore Office of Sustainability. ‘Protecting Yourself in the Floodplain.” City of Baltimore, 2020.
https://www.baltimoresustainability.org/floodplain/
[57] The Washington Post. “Baltimore experiences worst coastal flooding since 2003.” The Washington Post, May 1, 2020. https://www.washingtonpost.com/weather/2020/05/01/baltimore-annapolis-experienced-worst-coastal-flooding-over-5-years-thursday/.
[58] Mayor and City Council of Baltimore v. BP P.L.C., 42-43.
[59] Baltimore City Department of Public Works, City of Baltimore, & CleanWaterBaltimore. “Baltimore City MS4 Restoration and TMDL WIP.” City of Baltimore, August 2015.

http://publicworks.baltimorecity.gov/sites/default/files/Baltimore-City-MS4-and-TMDL-WIP-Rev-August-2015.pdf; "Stormwater Runoff/Non-Point Pollution Prevention," Baltimore Department of Planning.

[60] Baltimore City Department of Public Works, City of Baltimore, & CleanWaterBaltimore, "Baltimore City MS4 Restoration and TMDL WIP."

[61] Baltimore City Department of Public Works. "Regulatory Mandates, Plans, and Reports." City of Baltimore, 2018. https://publicworks.baltimorecity.gov/regulatory-mandates-plans-and-reports.

[62] Ibid.

[63] Ibid.

[64] Baltimore City Health Department, "Asthma," https://health.baltimorecity.gov/node/454.

[65] Ibid.

[66] Leah Kelly and Kira Burkhart (2017). Asthma and Air Pollution in Baltimore City. Environmental Integrity Project https://www.environmentalintegrity.org/wp-content/uploads/2017/12/Baltimore-Asthma.pdf.

[67] Maryland Asthma Control Program. (2011). Asthma in Baltimore City. https://phpa.health.maryland.gov/mch/documents/asthma_control/Profile_BaltimoreCity.pdf.

[68] Ibid.

[69] Kelly and Burkhart, Asthma and Air Pollution in Baltimore City, 11.

[70] Baltimore City Health Department. State of Health in Baltimore: White Paper (201), https://health.baltimorecity.gov/state-health-baltimore-winter-2016/state-health-baltimore-white-paper-2017.

[71] LaFave, S. (October, 2020). The Unequal Burden of Pediatric Asthma: A Call for An Equity-Driven, Multimodal, Public Health Approach to Asthma in Baltimore. 33(7). https://abell.org/sites/default/files/files/2020_Abell_pediatric%20asthma_FINAL-web%20(dr).pdf.

[72] Kelly and Burkhart, Asthma and Air Pollution in Baltimore City, 2.

[73] Ibid, 2.

[74] Ibid, 24.

[75] Ibid, 23.

[76] Maryland Department of Health. 2012. "Asthma in Maryland 2012," 35-38.https://phpa.health.maryland.gov/mch/Documents/Asthma%20in%20Maryland%202012.pdf.

[77] "Local Area Unemployment Statistics (LAUS) – Workforce Information & Performance," Maryland Department of Labor, accessed March 25, 2021, https://www.dllr.state.md.us/lmi/laus/.

[78] "Unemployment rates lower in January 2021 in 33 states," U.S. Bureau of Labor Statistics, March 19, 2021, https://www.bls.gov/opub/ted/2021/unemployment-rates-lower-in-january-2021-in-33-states.htm.

[79] "Solar Photovoltaic Installer; Salary," U.S. News & World Report, accessed March 25, 2021, https://money.usnews.com/careers/best-jobs/solar-photovoltaic-installer/salary.

[80] "Painter; Salary," U.S. News & World Report, accessed March 25, 2021, https://money.usnews.com/careers/best-jobs/painter/salary.

[81] "Tree Planter; Overview," Zippia, accessed March 25, 2021, https://www.zippia.com/tree-planter-jobs/.

[82] L.M. Sixel, "Wind, solar jobs pay more than average, study finds," Houston Chronicle, October 23, 2020, https://www.houstonchronicle.com/business/energy/article/Wind-solar-jobs-pay-more-than-average-15668642.php?.

[83] Josh Bivens, "Updated employment multipliers for the U.S. economy," Economic Policy

Institute, January 23, 2019, https://www.epi.org/publication/updated-employment-multipliers-for-the-u-s-economy/.
[84] Kristof, "Temperatures Rise, and We're Cooked".
[85] Lee, Cannon Hunter, and Namho Chung. "Smart City Tourism: Developments and Transformation". Sustainability, 12, no.10 (May, 2020). DOI: 10.3390/su12103958.
[86] Visit Baltimore. "About Us". https://baltimore.org/about-us/.
[87] Ibid.
[88] Visit Baltimore. "Annual Report and Business Plan FY 2020-2021," https://view.joomag.com/visit-baltimore-annual-report-fy-2020-2021-2020/0273960001601906190?short&.
[89] Amanda Yeager. "'They're staying home': Visit Baltimore CEO talks plans to bring back tourists from the Baltimore Suburbs," The Baltimore Business Journal, June 6, 2018. https://www.bizjournals.com/baltimore/news/2018/06/06/theyre-staying-home-visit-baltimore-ceo-talks.html.
[90] Jayne Miller. "Tourism officials: it will take years for Baltimore to recoup from coronavirus," WBALTV 1, September 2, 2020. https://www.wbaltv.com/article/coronavirus-tourism-officials-say-baltimore-will-take-years-to-recoup-from-pandemic/33864727#.
[91] Moody's Investors Service, "Climate change is forecast to heighten US exposure to economic loss placing short and long-term credit pressure on US states and local governments", https://www.moodys.com/research/Moodys-Climate-change-is-forecast-to-heighten-US-exposure-to--PR_376056.
[92] USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi:10.7930/NCA4.2018.
[93] Katz et al, "Here's How Cities Can Reduce Climate Change Risk." Risk and Insurance, June, 2019. https://riskandinsurance.com/how-cities-reduce-climate-change-risk/
[94] Ibid.
[95] Hood, "Dwelling Disparities: How Poor Housing Leads to Poor Health."
[96] Anderson and McMinn, "As Rising Heat Bakes U.S. Cities, The Poor Often Feel it Most."
[97] Ariel Drehobl, Lauren Ross, and Roxana Ayala, "How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States" (Washington, D.C.: American Council for an Energy-Efficient Economy, September 10, 2020), https://www.aceee.org/energy-burden.
[98] Ibid.
[99] U.S. Environmental Protection Agency (EPA), "Urban Heat Island Basics," Reducing Urban Heat Islands: Compendium of Strategies, 2008, 6, http://www.epa.gov/sites/production/files/2014-06/documents/basicscompendium.pdf; Houston Advanced Research Center, "Urban Heat Islands: Basic Description, Impacts, and Issues," 2009, http://www.harc.edu/sites/default/files/documents/projects/UHI_Basics.pdf.
[100] "Urban Heat Island.svg," TheNewPhobia, November 23, 2008, https://commons.wikimedia.org/wiki/File:Urban_heat_island.svg.
[101] U.S. Environmental Protection Agency (EPA), "Urban Heat Island Basics", 15
[102] James A. Voogt, "Urban Heat Islands: Hotter Cities," American Institute of Biological Sciences, 2004.
[103] U.S. Environmental Protection Agency (EPA), "Urban Heat Island Basics," 2.

[104] Ibid, 4.
[105] Nolan Freeney, "Pope Francis Says World Nearing Climate-Change 'Suicide.'" TIME, November 30, 2015, http://time.com/4129640/pope-francis-climate-change-paris/.
[106] James H. Butler and Stephen H. Montzka, "The NOAA Annual Greenhouse Gas Index," NOAA Earth System Research Laboratory, R/GMD, Spring 2020, https://www.esrl.noaa.gov/gmd/aggi/aggi.html.
[107] Mayor and City Council of Baltimore v. BP P.L.C., 38-40.
[108] U.S. Environmental Protection Agency (EPA), "What Climate Change Means for Maryland," August 2016, https://19january2017snapshot.epa.gov/sites/production/files/2016-09/documents/climate-change-md.pdf.
[109] Global Cool Cities Alliance (GCCA) and R20 Regions of Climate Action (R20), "A Practical Guide to Cool Roofs and Cool Pavements," January 2012, http://www.coolrooftoolkit.org/wp-content/pdfs/CoolRoofToolkit_Full.pdf.
[110] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings," May 2011, http://www.gsa.gov/portal/mediaId/158783/fileName/The_Benefits_and_Challenges_of_Green_Roofs_on_Public_and_Commercial_Buildings.action.
[111] Ibid.
[112] Ibid.
[113] Ibid.
[114] Ibid.
[115]"Maryland at a Glance: Energy," Maryland State Archives, November 19, 2020, https://msa.maryland.gov/msa/mdmanual/01glance/html/energy.html.
[116] U.S. Environmental Protection Agency (EPA), "Cool Roofs," Reducing Urban Heat Islands: Compendium of Strategies, 2008, http://www.epa.gov/sites/production/files/2014-06/documents/coolroofscompendium.pdf.
[117] National Conference of State Legislatures (NCSL), "State Renewable Portfolio Standards and Goals," ncsl.org, 2021, https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx.
[118] Baltimore County Government, "High Performance Homes Tax Credit," https://www.baltimorecountymd.gov/departments/budfin/taxpayerservices/taxcredits/performancehomes.html.
[119] American Lung Association (ALA), "Ozone Pollution," State of the Air 2015, accessed October 14, 2015, http://www.stateoftheair.org/2015/health-risks/health-risks-ozone.html.
[120] Michelle L. Bell et al., "Climate Change, Ambient Ozone, and Health in 50 U.S. Cities," Climatic Change 82, no. 1–2 (March 30, 2007): 61–76, doi:10.1007/s10584-006-9166-7; Howard H. Chang, Jingwen Zhou, and Montserrat Fuentes, "Impact of Climate Change on Ambient Ozone Level and Mortality in Southeastern United States," International Journal of Environmental Research and Public Health 7, no. 7 (July 14, 2010): 2866–80, doi:10.3390/ijerph7072866; Tracey Holloway et al., "Change in Ozone Air Pollution over Chicago Associated with Global Climate Change," Journal of Geophysical Research 113, no. D22 (November 29, 2008), doi:10.1029/2007JD009775; Ellen S. Post et al., "Variation in Estimated Ozone-Related Health Impacts of Climate Change due to Modeling Choices and Assumptions," Environmental Health Perspectives 120, no. 11 (July 12, 2012): 1559–64, doi:10.1289/ehp.1104271.

[121] Ulpiani, Giulia. "On the linkage between urban heat island and urban pollution island: Three-decade literature review towards a conceptual framework," Science of the Total Environment, 751 (2020). DOI: 10.1016/j.scitotenv.2020.141727.
[122] Louise Camalier, William Cox, and Pat Dolwick, "The Effects of Meteorology on Ozone in Urban Areas and Their Use in Assessing Ozone Trends," Atmospheric Environment 41, no. 33 (October 2007): 7127–37, doi:10.1016/j.atmosenv.2007.04.061; U.S. Environmental Protection Agency (EPA), "Final Ozone NAAQS Regulatory Impact Analysis," March 2008.
[123] U.S. Environmental Protection Agency (EPA), "Final Ozone NAAQS Regulatory Impact Analysis."
[124] Intergovernmental Panel on Climate Change, "Climate Change 2001: The Scientific Basis," (Geneva, CH: 2001), http://www.grida.no/publications/other/ipcc_tar/.
[125] U.S. Environmental Protection Agency (EPA), "Integrated Science Assessment for Ozone and Related Photochemical Oxidants," April 2020.
[126] Ibid.
[127] Bell et al., "Climate Change, Ambient Ozone, and Health in 50 U.S. Cities."
[128] Elizabeth M. Perera and Todd Sanford, "Climate Change and Your Health: Rising Temperature, Worsening Ozone Pollution," June 2011, http://www.ucsusa.org/assets/documents/global_warming/climate-change-and-ozone-pollution.pdf.
[129] Arthur H. Rosenfeld et al., "Cool Communities: Strategies for Heat Island Mitigation and Smog Reduction," Energy and Buildings 28, no. 1 (August 1998): 51–62, doi:10.1016/S0378-7788(97)00063-7; Akbari, Pomerantz, and Taha, "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas"; Haider Taha, "Meso-Urban Meteorological and Photochemical Modeling of Heat Island Mitigation," Atmospheric Environment 42, no. 38 (December 2008): 8795–8809, doi:10.1016/j.atmosenv.2008.06.036.
[130] American Lung Association (ALA), "Particle Pollution," State of the Air 2015.
[131] U.S. Environmental Protection Agency (EPA), "Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter," December 2012.
[132] Ibid.
[133] U.S. Environmental Protection Agency (EPA), "The 2011 National Emissions Inventory," EPA, September 26, 2014, http://www.epa.gov/ttnchie1/net/2011inventory.html.
[134] U.S. Environmental Protection Agency (EPA), "Basic Information," EPA, September 15, 2015, http://www.epa.gov/airquality/particlepollution/designations/basicinfo.htm.
[135] U.S. Environmental Protection Agency (EPA), "Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter," December 2012.
[136] Ibid.
[137] U.S. Environmental Protection Agency (EPA), "National Air Quality: Status and Trends Through 2007," November 2008.
[138] Ibid.
[139] U.S. Environmental Protection Agency (EPA). "Integrated Science Assessment (ISA) for Particulate Matter", December 2019, https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534.
[140] American Lung Association (ALA), "Particle Pollution."
[141] U.S. Environmental Protection Agency (EPA). "Integrated Science Assessment (ISA) for Particulate Matter."
[142] Ibid.

[143] Catherine Morehouse, “Legal experts, NGOs blast EPA move on air quality standards after higher pollution linked to COVID-19 deaths,” Utility Dive, April 15, 2020, updated December 8, 2020, https://www.utilitydive.com/news/groups-blast-epa-move-to-maintain-air-quality-standards-after-higher-pollut/576034/?utm_source=Sailthru&utm_medium=email&utm_campaign=Issue:%202020-12-08%20Utility%20Dive%20Newsletter%20%5Bissue:31293%5D&utm_term=Utility%20Dive; “National Ambient Air Quality Standards (NAAQS) for PM,” U.S. Environmental Protection Agency (EPA), Accessed December 10, 2020, https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm.

[144] Centers for Disease Control, “Climate Change and Extreme Heat Events,” 2011, https://www.cdc.gov/climateandhealth/pubs/climatechangeandextremeheatevents.pdf; David Mills et al., “Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States,” Climatic Change, June 13, 2014, doi:10.1007/s10584-014-1154-8; A. Scott Voorhees et al., “Climate Change-Related Temperature Impacts on Warm Season Heat Mortality: A Proof-of-Concept Methodology Using BenMAP,” Environmental Science &

Technology 45, no. 4 (February 15, 2011): 1450–57, doi:10.1021/es102820y; Roger D. Peng et al., “Toward a Quantitative Estimate of Future Heat Wave Mortality under Global Climate Change,” Environmental Health Perspectives 119, no. 5 (December 30, 2010): 701–6, doi:10.1289/ehp.1002430.

[145] Dan Li and Elie Bou-Zeid, “Synergistic Interactions between Urban Heat Islands and Heat Waves: The Impact in Cities Is Larger than the Sum of Its Parts,” Journal of Applied Meteorology and Climatology 52, no. 9 (September 2013): 2051–64, doi:10.1175/JAMC-D-13-02.1.

[146] Ibid.

[147] National Weather Service, ”Weather Related Fatality and Injury Statistics,” National Oceanic and Atmospheric Administration, 2019, https://www.weather.gov/hazstat/.

[148] Environmental Protection Agency (EPA), ”Climate Change Indicators: heat-Related Illnesses,” 2016, https://www.epa.gov/climate-indicators/heat-related-illnesses.

[149] National Research Council, “Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia,” (Washington, D.C: National Academies Press, 2011).

[150] Voorhees et al., “Climate Change-Related Temperature Impacts on Warm Season Heat Mortality.”

[151] Centers for Disease Control, “Climate Change and Extreme Heat Events.”

[152] Mark P. McCarthy, Martin J. Best, and Richard A. Betts, “Climate Change in Cities due to Global Warming and Urban Effects,” Geophysical Research Letters 37, no. 9 (May 2010): DOI:10.1029/2010GL042845.

[153] Laurence S. Kalkstein et al., “Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia,” 2013, http://www.coolrooftoolkit.org/wp-content/uploads/2013/12/DC-Heat-Mortality- Study-for-DDOE-FINAL.pdf.

[154] Ibid.; Jennifer Vanos et al., “Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York,” July 2014, http://www.coolrooftoolkit.org/knowledgebase/health- impacts-of-urban-cooling-strategies-in-baltimore-los-angeles-and-new-york-city/; Brian Stone et al., “Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three U.S. Cities,” ed. Igor Linkov, PLoS ONE 9, no. 6 (June 25, 2014): e100852, doi:10.1371/journal.pone.0100852.

[155] Vanos et al., “Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York.”
[156] DC Water, “Clean Rivers and Impervious Cover,” DC Water, October, 2017, https://www.dcwater.com/whats-going-on/blog/clean-rivers-and-impervious-cover.
[157] Department of Energy & Environment, “Changes to the District’s Stormwater Fee,” DC.gov, Accessed 7 Dec 2020, https://doee.dc.gov/service/changes-districts-stormwater-fee.
[158] Department of Energy & Environment, “Stormwater Fee Background,” DC.gov, Accessed 7 Dec 2020, https://doee.dc.gov/node/874782.
[159] Lucien Georgeson and Mark Maslin, “Estimating the scale of the US green economy within the global context,” Palgrave Commun 5, no. 121 (2019), https://www.nature.com/articles/s41599-019-0329-3.
[160] Robert Bacon and Masami Kojima, “Issues in estimating the employment generated by energy sector activities,” World Bank, Sustainable Energy Department, June 2011, http://documents1.worldbank.org/curated/en/627831468159915345/pdf/827320WP0emplo00Box379875B00PUBLIC0.pdf.
[161] Tom Konrad, “Not all Green Jobs were Created Equal,” Alt Energy Stocks, July 6, 2009, http://www.altenergystocks.com/archives/2009/07/not_all_green_jobs_were_created_equal_1/.
[162] Bivens, “Updated employment multipliers.”
[163] L. M. Sixel, “Wind, solar jobs pay more than average, study finds,” Houston Chronicle, October 23, 2020, https://www.houstonchronicle.com/business/energy/article/Wind-solar-jobs-pay-more-than-average-15668642.php?utm_campaign=Clean%20Energy%20News&utm_medium=email&_hsmi=98494850&_hsenc=p2ANqtz-8CA_c6CM97i8QIwz4zqhNUJKg0ngZ_amiOrEvu3Cg2dkflftt9XXDCkebeLtKLdLDLGHWNje53XFy1q8mAmrr8D-g8MA&utm_content=98494850&utm_source=hs_email.
[164] “Solar Photovoltaic Installer; Salary,” U.S. News & World Report, January, 2021, https://money.usnews.com/careers/best-jobs/solar-photovoltaic-installer/salary.
[165] “Tree Planter; Overview,” Zippia, January, 2021, https://www.zippia.com/tree-planter-jobs/.
[166] “The true cost of employees: How much does an employee *really* cost? (US),” BeeBole, January, 2021, https://beebole.com/blog/how-to-calculate-the-real-cost-of-an-employee/.
[167] Rory O’Sullivan, Konrad Mugglestone, and Tom Allison, “The Hidden Cost of Young Adult Unemployment” (Young Invincibles, January 2014), accessed June, 2019, https://www.voced.edu.au/content/ngv:63872
[168] Cool Roof Rating Council, “Cool Roof Rating Council,” January 25, 2016, http://coolroofs.org/.
[169] Global Cool Cities Alliance (GCCA) and R20 Regions of Climate Action (R20), “A Practical Guide to Cool Roofs and Cool Pavements.”
[170] Ibid.
[171] Personal communication with Richard Rast, CSO of Mantis Innovation Group and CEO of facility management consultant and pavement, roofing, and energy specialist BLUEFIN LLC, and with Paul Lanning, founder and Managing Director of cleantech firm Lightbox Energy, 2021, https://coolroofs.org/directory.
[172] Cool Roof Rating Council, “Rated Products Directory,” January, 2021, https://coolroofs.org/directory.
[173] Personal communication with Richard Rast and Paul Lanning, 2021.
[174] Bryan Urban and Kurt Roth, “Guidelines for Selecting Cool Roofs” (U.S. Department of Energy (DOE), July 2010), https://heatisland.lbl.gov/sites/all/files/coolroofguide_0.pdf.

[175] Ibid.; Personal communication with Paul Lanning of Bluefin LLC, 2014; Julian Sproul et al., “Economic Comparison of White, Green, and Black Flat Roofs in the United States,” Energy and Buildings 71 (March 2014): 20–27, doi:10.1016/j.enbuild.2013.11.058; Urban and Roth, “Guidelines for Selecting Cool Roofs”; Personal communication with Richard Rast and Paul Lanning, 2021; H. Gilbert et al, “Heat Island Mitigation Assessment and Policy Development for the Kansas City Region,” 2019, DOI:10.20357/B7JG61.
[176] Personal communication with Paul Lanning of Lightbox Energy
[177] Ibid.; Sproul et al., “Economic Comparison of White, Green, and Black Flat Roofs in the United States”; Gilbert et al., “Heat Mitigation Assessment and Policy Development.”
[178] Personal communication with Richard Rast and Paul Lanning, 2021.
[179] S R Gaffin et al., “Bright Is the New Black—multi-Year Performance of High-Albedo Roofs in an Urban Climate,” Environmental Research Letters 7, no. 1 (March 1, 2012): 014029, doi:10.1088/1748-9326/7/1/014029; Sproul et al., “Economic Comparison of White, Green, and Black Flat Roofs in the United States.”; Personal communication with Richard Rast and Paul Lanning, 2021.
[180] Personal communication with Richard Rast and Paul Lanning, 2021.
[181] Ronnen Levinson and Hashem Akbari, “Potential Benefits of Cool Roofs on Commercial Buildings: Conserving Energy, Saving Money, and Reducing Emission of Greenhouse Gases and Air Pollutants,” Energy Efficiency 3, no. 1 (March 2010): 53–109, doi:10.1007/s12053-008-9038-2.
[182] Ibid.
[183] P. Ramamurthy et al., “The Joint Influence of Albedo and Insulation on Roof Performance: An Observational Study,” Energy and Buildings 93 (April 2015): 249–58, doi:10.1016/j.enbuild.2015.02.040; P. Ramamurthy et al., “The Joint Influence of Albedo and Insulation on Roof Performance: A Modeling Study,” Energy and Buildings 102 (September 2015): 317–27, doi:10.1016/j.enbuild.2015.06.005.
[184] Levinson and Akbari, “Potential Benefits of Cool Roofs on Commercial Buildings.”
[185] Ibid.
[186] M. Santamouris, “Cooling the Cities – A Review of Reflective and Green Roof Mitigation Technologies to Fight Heat Island and Improve Comfort in Urban Environments,” Solar Energy 103 (May 2014): 682–703, doi:10.1016/j.solener.2012.07.003.
[187] Kalkstein et al., “Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia”; Stone et al., “Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three U.S. Cities”; Dan Li, Elie Bou-Zeid, and Michael Oppenheimer, “The Effectiveness of Cool and Green Roofs as Urban Heat Island Mitigation Strategies,” Environmental Research Letters 9, no. 5 (May 1, 2014): 055002, doi:10.1088/1748-9326/9/5/055002.
[188] Hashem Akbari and Steven Konopacki, “Calculating Energy-Saving Potentials of Heat-Island Reduction Strategies,” Energy Policy 33, no. 6 (April 2005): 721–56, doi:10.1016/j.enpol.2003.10.001.
[189] John Cook et al., “Quantifying the Consensus on Anthropogenic Global Warming in the Scientific Literature,” Environmental Research Letters 8, no. 2 (June 1, 2013): 024024, doi:10.1088/1748-9326/8/2/024024.
[190] Carnegie Mellon Center for Building Performance and Diagnostics, "Fully Assigning GHG Emissions to End Use Sectors for Decarbonization Policy & Action," 2020.
[191] Hashem Akbari, Surabi Menon, and Arthur Rosenfeld, “Global Cooling: Increasing World-Wide Urban Albedos to Offset CO2,” Climatic Change 94, no. 3–4 (June 2009): 275–86,doi:10.1007/s10584-008-9515-9; Surabi Menon et al., “Radiative Forcing and Temperature Response to Changes in Urban Albedos and Associated CO2 Offsets,” Environmental Research

Letters 5, no. 1 (January 2010): 014005, doi:10.1088/1748-9326/5/1/014005.
[192] Mark Z. Jacobson and John E. Ten Hoeve, "Effects of Urban Surfaces and White Roofs on Global and Regional Climate," Journal of Climate 25, no. 3 (February 2012): 1028–44, doi:10.1175/JCLI-D-11-00032.1; Dev Millstein and Surabi Menon, "Regional Climate Consequences of Large-Scale Cool Roof and Photovoltaic Array Deployment," Environmental Research Letters 6, no. 3 (July 1, 2011): 034001, doi:10.1088/1748- 9326/6/3/034001.
[193] Hannah Hoag, "How Cities Can Beat the Heat," Nature 524, no. 7566 (August 26, 2015): 402–4, doi:10.1038/524402a.
[194] Kalkstein et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia"; Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York"; Stone et al., "Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three U.S. Cities."
[195] Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York."
[196] Bivens, "Updated employment multipliers."
[197] U.S. Environmental Protection Agency (EPA), "Cool Roofs."
[198] Akbari and Konopacki, "Calculating Energy-Saving Potentials of Heat-Island Reduction Strategies."
[199] Portland State University, "Green Roof Energy Calculator," 2013, http://greenbuilding.pdx.edu/GR_CALC_v2/grcalc_v2.php#retain.
[200] Da-Lin Zhang et al., "Impact of Upstream Urbanization on the Urban Heat Island Effects along the Washington–Baltimore Corridor," Journal of Applied Meteorology and Climatology 50, no. 10 (October 2011): 2012–29, doi:10.1175/JAMC-D-10-05008.1.
[201] Matthew P. Jones and William F. Hunt, "Stormwater BMPs for Trout Waters: Coldwater Stream Design Guidance for Stormwater Wetlands, Wet Ponds, and Bioretention" (North Carolina Cooperative Extension, 2007), http://www.bae.ncsu.edu/stormwater/PublicationFiles/BMPsColdTemps2007.pdf.
[202] Ibid.
[203] Heat Island Group, "Cool Roofs."
[204] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings," May 2011, http://www.gsa.gov/portal/mediaId/158783/fileName/The_Benefits_and_Challenges_of_Green_Roofs_on_Publ ic_and_Commercial_Buildings.action.
[205] Ibid.
[206]Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States"; Hao Niu et al., "Scaling of Economic Benefits from Green Roof Implementation in Washington, D.C.," Environmental Science & Technology 44, no. 11 (June 2010): 4302–8, doi:10.1021/es902456x; Cynthia Rosenzweig, William D. Solecki, and Ronald B. Slosberg, "Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces," October 2006,http://www.nyserda.ny.gov/-/media/Files/EE/EMEP/Climate-Change/NYC-regional-heat-island-iniative.pdf; Corrie Clark, Peter Adriaens, and F. Brian Talbot, "Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits," Environmental Science & Technology 42, no. 6 (March 2008): 2155–61, doi:10.1021/es0706652; U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[207] Personal communication with Paul Lanning of Bluefin LLC; Sproul et al., "Economic

Comparison of White, Green, and Black Flat Roofs in the United States"; U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[208] Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States"; Personal communication with Paul Lanning of Bluefin LLC; U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[209] Ibid.
[210] "Green Roofs," in Reducing Urban Heat Islands: Compendium of Strategies, Draft, 2008, https://www.epa.gov/heatislands/heat-island-compendium.
[211] U.S. Environmental Protection Agency (EPA), "Green Roofs."
[212] "The EarthWord: Evapotranspiration," U.S. Geological Survey, September 28, 2015, https://www.usgs.gov/news/earthword-evapotranspiration; Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States."
[213] Ting Sun, Elie Bou-Zeid, and Guang-Heng Ni, "To Irrigate or Not to Irrigate: Analysis of Green Roof Performance via a Vertically-Resolved Hygrothermal Model," 127–37.
[214] R.L. Hanson, "Evapotranspiration and Droughts," in R.W. Paulson, E.B. Chase, R.S. Roberts, and D.W. Moody, Compilers, National Water Summary 1988-89--Hydrologic Events and Floods and Droughts: U.S. Geological Survey Water-Supply Paper 2375, 1991, p. 99-104.
[215] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[216] U.S. Environmental Protection Agency (EPA), "Green Roofs."
[217] Ibid.
[218] Ting Sun et al., "Hydrometeorological Determinants of Green Roof Performance via a Vertically-Resolved Model for Heat and Water Transport," Building and Environment 60, (February 2013) 211–24. doi:10.1016/j.buildenv.2012.10.018.
[219] Li, Bou-Zeid, and Oppenheimer, "The Effectiveness of Cool and Green Roofs as Urban Heat Island Mitigation Strategies."
[220] Ibid.
[221] Kyle Liu and Brad Bass, "Performance of Green Roof Systems" (National Research Council Canada, 2005); Rosenzweig, Solecki, and Slosberg, "Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces."
[222] Li, Bou-Zeid, and Oppenheimer, "The Effectiveness of Cool and Green Roofs as Urban Heat Island Mitigation Strategies."
[223] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[224] Kristin L. Getter et al., "Carbon Sequestration Potential of Extensive Green Roofs," Environmental Science & Technology 43, no. 19 (October 2009): 7564–70, doi:10.1021/es901539x; Leigh J. Whittinghill et al., "Quantifying Carbon Sequestration of Various Green Roof and Ornamental Landscape Systems," Landscape and Urban Planning 123 (March 2014): 41–48, doi: 10.1016/j.landurbplan.2013.11.015.
[225] Ibid.
[226] Kalkstein et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia"; Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York"; Stone et al., "Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three U.S. Cities."
[227] Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in

Baltimore, Los Angeles, and New York."; Antonino Marvuglia, Rembrandt Koppelaar, and Benedetto Rugani, "The Effect of Green Roofs on the Reduction of Mortality due to Heatwaves: Results from the Application of a Spatial Microsimulation Model to Four European Cities," Ecological Modelling 438 (2020), https://doi.org/10.1016/j.ecolmodel.2020.109351.
[228] District Department of the Environment (DDOE), "Stormwater Management Guidebook," January 2020, https://doee.dc.gov/swguidebook.
[229] U.S. Environmental Protection Agency (EPA), "What Climate Change Means for Maryland," August 2016, https://19january2017snapshot.epa.gov/sites/production/files/2016-09/documents/climate-change-md.pdf.
[230] Ibid.
[231] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[232] Ibid.
[233] Ibid.
[234]Ibid.
[235] Justyna Czemiel Berndtsson, "Green Roof Performance towards Management of Runoff Water Quantity and Quality: A Review," Ecological Engineering 36, no. 4 (April 2010): 351–60, doi: 10.1016/j.ecoleng.2009.12.014.
[236] "Green Roof Plants," Growing Green Guide, accessed January, 2021, http://www.growinggreenguide.org/technical-guide/design-and-planning/plant-selection/green-roofs/.
[237] Mia Taylor, "What a Green Roof Costs You on the Way to Saving Everything," The Street, May 22, 2015, https://www.thestreet.com/personal-finance/mortgages/what-a-green-roof-costs-you-on-the-way-to-saving-everything-13161050.
[238] "How Much Does a Green Roof Cost?," HomeAdvisor, accessed January, 2021, https://www.homeadvisor.com/cost/roofing/green-roof/#squarefoot; "An economic analysis of green roofs: Evaluating the costs and savings to building owners in Toronto and surrounding regions," Toronto and Region Conservation, July, 2007, http://roof-tek.com/wp-content/uploads/2016/02/GR_Econ.pdf.
[239] Don Moseley et al., "Green Roof Performance: A Cost-Benefit Analysis Based on Walmart's Chicago Store," January 2013, http://cdn.corporate.walmart.com/95/ab/ecb63ba44f51bec6f9aa42c73a9e/walmart-2013-green-roof-report.pdf.
[240] Personal communication with Sean Cahill of the District of Columbia Building Industry Association, 2015.
[241] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[242] Ralf Hansmann, Stella-Maria Hug, and Klaus Seeland, "Restoration and Stress Relief through Physical Activities in Forests and Parks," Urban Forestry & Urban Greening 6, no. 4 (November 2007): 213–25, doi:10.1016/j.ufug.2007.08.004; Kathy Wolf, "Urban Nature Benefits: Psycho-Social Dimensions of People and Plants," Human Dimensions of the Urban Forest (Center for Urban Horticulture, University of Washington, 1998); Urban and Roth, "Guidelines for Selecting Cool Roofs"; Francis E. Kuo, "Parks and Other Green Environments: Essential Components of a Healthy Human Habitat" (National Recreation and Parks Association, 2010), http://www.nrpa.org/uploadedFiles/nrpa.org/Publications_and_Research/Research/Papers/Ming Kuo- Research-Paper.pdf.

[243] R.S. Ulrich and R. Simmons, "Recovery from Stress during Exposure to Everyday Outdoor Environments, in The Costs of Not Knowing," Proceedings of the 17th Annual Conference of the Environmental Research Association (Washington, D.C.: Environmental Research Association, 1986).
[244] F. E. Kuo and W. C. Sullivan, "Environment and Crime in the Inner City: Does Vegetation Reduce Crime?," Environment and Behavior 33, no. 3 (May 1, 2001): 343–67, doi: 10.1177/0013916501333002.
[245] U.S. Environmental Protection Agency (EPA), "Green Roofs"; U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[246] Ibid.
[247] Nicholas S. G. Williams, Jeremy Lundholm, and J. Scott MacIvor, "FORUM: Do Green Roofs Help Urban Biodiversity Conservation?" ed. Richard Fuller, Journal of Applied Ecology 51, no. 6 (December 2014): 1643–49, doi:10.1111/1365-2664.12333.
[248] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[249] Williams, Lundholm, and Scott MacIvor, "FORUM."
[250] National Renewable Energy Laboratory (NREL), "PVWatts Calculator."
[251] D. Chemisana and C. Lamnatou, "Photovoltaic-Green Roofs: An Experimental Evaluation of System Performance," Applied Energy, 119, (2014): 246–256.
[252] Camalier, Cox, and Dolwick, "The Effects of Meteorology on Ozone in Urban Areas and Their Use in Assessing Ozone Trends."
[253] "Maryland Solar," Solar Energy Industries Association, January 2021, https://www.seia.org/state-solar-policy/maryland-solar.
[254] "Solar Financing," solar.com, https://www.solar.com/learn/solar-financing/.
[255] "Solar Panels in Baltimore (city) County, MD," EnergySage, January 23, 2021, https://www.energysage.com/local-data/solar-panel-cost/md/baltimore-city-county/.
[256] Feldman, David, et al. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020. National Renewable Energy Laboratory, Jan. 2021.
[257] Lazard. Levelized Cost of Energy and Levelized Cost of Storage—2020; Lazard: Hamilton, Bermuda, 2020; Available online: https: //www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/
[258] "Solar Loans vs. Solar Leases," EnergySage, July 7, 2020, https://www.energysage.com/solar/financing/comparing-solar-loans-vs-solar-leases/.
[259] "Solar Power Purchase Agreements (Solar PPA)," Sustainable Capital Finance, January, 2021, https://scf.com/solar-ppas/.
[260] Alison Knezevich, "Baltimore County seeking deal to put solar panels on government buildings and in parks," The Baltimore Sun, May 31, 2019, https://www.baltimoresun.com/maryland/baltimore-county/bs-md-co-solar-panels-20190523-story.html.
[261] "MD-PACE Facilitates C-PACE Financing for Baltimore City Property near The Johns Hopkins Hospital," Maryland, Commercial Pace, June 17, 2020, https://md-pace.com/md-pace-facilitates-solar-financing-for-baltimore-city-property/.

[262] "Solar Energy Questions and Answers for Maryland Residents," Maryland Energy Administration, November 17, 2016, https://news.maryland.gov/mea/2016/11/17/solar-energy-questions-and-answers-for-maryland-residents/.

[263] "Make Your Own Clean, Affordable Energy at Home with Sunrun Solar Panels in Maryland," sunrun, https://www.sunrun.com/solar-by-state/md.

[264] "Solar Panels in Baltimore (city) County, MD," EnergySage.

[265] "Commercial Clean Energy Rebate Program," Maryland Energy Administration, accessed April, 2021, https://energy.maryland.gov/business/Pages/incentives/cleanenergygrants.aspx.

[266] U.S. Department of Energy (DOE), "Third-Party Solar Financing," DOE, July 2, 2014, http://apps3.eere.energy.gov/greenpower/onsite/solar_financing.shtml.

[267] "Net Metering," DSIRE, November 19, 2018, https://programs.dsireusa.org/system/program/detail/363/net-metering.

[268] Kelly Pickerel, "Solar investment tax credit extended at 26% for two additonal years," Solar Power World, December 21, 2020, https://www.solarpowerworldonline.com/2020/12/solar-investment-tax-credit-extended-at-26-for-two-additional-years/.

[269] Jules Scully, "Solar ITC extension included in US coronavirus relief package," PV Tech, December 22, 2020, https://www.pv-tech.org/solar-itc-extension-included-in-us-coronavirus-relief-package/.

[270] "Levelized Cost of Energy and Levelized Cost of Storage," Lazard, October 19, 2020, https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/.

[271] Bivens, "Updated employment multipliers."

[272] Anthony Dominguez, Jan Kleissl, and Jeffrey C. Luvall, "Effects of Solar Photovoltaic Panels on Roof Heat Transfer," Solar Energy 85, no. 9 (September 2011): 2244–55, doi:10.1016/j.solener.2011.06.010.

[273] U.S. Energy Information Administration (EIA), "Sales and Revenue," Form EIA-826 Detailed Data, accessed May 4, 2016, http://www.eia.gov/electricity/data/eia826/.

[274] U.S. Energy Information Administration (EIA), "Commercial Buildings Energy Consumption Survey (CBECS)," 2012, http://www.eia.gov/consumption/commercial/data/2012/.

[275] David J. Sailor, "Energy Performance of Green Roofs," June 3, 2010, http://www.epa.gov/heatisland/resources/pdf/10June2010-DavidSailor.pdf.

[276] Adam Scherba et al., "Modeling Impacts of Roof Reflectivity, Integrated Photovoltaic Panels and Green Roof Systems on Sensible Heat Flux into the Urban Environment," Building and Environment 46, no. 12 (December 2011): 2542–51, doi:10.1016/j.buildenv.2011.06.012.

[277] Ibid.

[278] Ibid.

[279] Ibid.

[280] H. Taha, "Meteorological, Emissions and Air-Quality Modeling of Heat-Island Mitigation: Recent Findings for California, USA," International Journal of Low-Carbon Technologies 10, no. 1 (March 1, 2015): 3–14, doi:10.1093/ijlct/ctt010.

[281] U.S. Energy Information Administration (EIA), "How Much Electricity Is Lost in Transmission and Distribution in the United States?" July 10, 2015, https://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3.

[282] The World Bank, “Electric Power Transmission and Distribution Losses (% of Output),” 2014, http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

[283] Paul Denholm et al., “Methods for Analyzing the Benefits and Costs of Distributed Photovoltaic Generation to the U.S. Electric Utility System” (National Renewable Energy Laboratory (NREL), September 2014), http://www.nrel.gov/docs/fy14osti/62447.pdf; Rocky Mountain Institute, “A Review of Solar PV Benefit & Cost Studies, 2nd Edition,” September 2013, http://www.rmi.org/elab_empower.

[284] Cost of Solar, “Rooftop Solar Means Lower Peak Energy Prices for All,” June 1, 2015, http://costofsolar.com/rooftop-solar-means-lower-peak-hour-energy-prices/.

[285] Pomerantz et al., “Examples of Cooler Reflective Street for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals” (Berkeley, CA: Lawrence Berkeley National Laboratory, April 2003), https://heatisland.lbl.gov/publications/examples-cooler-reflective-streets-ur.

[286] Ibid.; Michael Ting, Jonathan Koomey, and Melvin Pomerantz, “Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements” (Berkeley, CA: Lawrence Berkeley National Laboratory, November 2001), http://www.osti.gov/scitech/biblio/791839.

[287] Pomerantz et al., “Examples of Cooler Reflective Street for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals”; Pomerantz et al., “The Effect of Pavements’ Temperatures on Air Temperatures in Large Cities” (Berkeley, CA: Lawrence Berkeley National Laboratory, April 2000), https://heatisland.lbl.gov/publications/effect-pavements-temperatures-air-tem; Ting, Koomey, and Pomerantz, “Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements.”

[288] Ibid.

[289] Pomerantz et al., “Examples of Cooler Reflective Street for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals”; Pomerantz et al., “The Effect of Pavements’ Temperatures on Air Temperatures in Large Cities.”

[290] Pomerantz et al., “Examples of Cooler Reflective Street for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals.”

[291] Ting, Koomey, and Pomerantz, “Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements.”

[292] Pomerantz et al., “Examples of Cooler Reflective Street for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals.”

[293] Pomerantz et al., “The Effect of Pavements’ Temperatures on Air Temperatures in Large Cities.”

[294] Li, “Evaluation of Cool Pavement Strategies for Heat Island Mitigation.”

[295] Thomas J. Van Dam et al., “Towards Sustainable Pavement Systems: A Reference Document” (Urbana, IL: Applied Pavement Technology, Inc., January 2015), https://www.fhwa.dot.gov/pavement/sustainability/ref_doc.cfm.

[296] Ibid.

[297] U.S. Environmental Protection Agency (EPA), “Cool Pavements,” Reducing Urban Heat Islands: Compendium of Strategies, 2008, http://www.epa.gov/sites/production/files/2014-06/documents/coolpavescompendium.pdf.

[298] Ibid.

[299] Ting, Koomey, and Pomerantz, “Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements.”

[300] Ibid.

[301] Ibid.
[302] Ibid.
[303] U.S. Environmental Protection Agency (EPA), "Cool Pavements."
[304] Ibid.
[305] Personal communication with Michael Heitzman of the National Center for Asphalt Technology, 2015.
[306] Mat Santamouris, Environmental Design of Urban Buildings: An Integrated Approach (London: Sterling, VA: Earthscan, 2006).
[307] Melvin Pomerantz, Hashem Akbari, and John T. Harvey, "Cooler Reflective Pavements Give Benefits beyond Energy Savings: Durability and Illumination" (Berkeley, CA: Lawrence Berkeley National Laboratory, June 1, 2000), https://www.aceee.org/files/proceedings/2000/data/papers/SS00_Panel8_Paper24.pdf
[308] Melvin Pomerantz et al., "Paving Materials for Heat Island Mitigation" (Berkeley, CA: Lawrence Berkeley National Laboratory, November 1997), https://heatisland.lbl.gov/publications/paving-materials-heat-island-mitigati; Akbari, Pomerantz, and Taha, "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas"; Personal communication with Ronnen Levinson of Lawrence Berkeley National Laboratory.
[309] Jeremey Deaton, "To guard against climate change, Lose Angeles is painting its street white," September 6, 2017, Popular Science, https://www.popsci.com/la-is-painting-its-streets-white-to-keep-city-cool/; Matt Hickman, How L.A. Is Beating the Heat with White-Painted Streets," July 3, 2019, Treehugger, https://www.treehugger.com/how-los-angeles-beating-heat-white-painted-streets-4868629.
[310] Akbari, Pomerantz, and Taha, "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas"; Pomerantz et al., "Paving Materials for Heat Island Mitigation."
[311] "CoolSeal by GuardTop," GuardTop, https://guardtop.com/coolseal/.
[312] "SUNSHIELD: Solar Reflective Coating," NEYRA, https://neyra.com/products/sealers/sunshield/.
[313] Personal communication with Richard Rast and Paul Lanning, 2021.
[314] Arthur H. Rosenfeld et al., "Mitigation of Urban Heat Islands: Materials, Utility Programs, Updates," Energy and Buildings 22, no. 3 (August 1995): 255–65, doi:10.1016/0378-7788(95)00927-P.
[315] Pomerantz et al., "The Effect of Pavements' Temperatures on Air Temperatures in Large Cities."
[316] H Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management," Environmental Research Letters, 8, no. 1 (March 1, 2013): 015023, doi:10.1088/1748-9326/8/1/015023.
[317] Pomerantz et al., "Examples of Cooler Reflective Street for Urban Heat-Island Mitigation: Portland Cement Concrete and Chip Seals."
[318] Personal communication with the District Department of Transportation (DDOT), 2015.
[319] Ibid.; Personal communication with the District Department of Transportation (DDOT).
[320] Personal communication with Thomas Van Dam of NCE.
[321] Pomerantz et al., "The Effect of Pavements' Temperatures on Air Temperatures in Large Cities."
[322] Tony Barboza, "L.A. takes climate change fight to the stress by pouring cooler pavement," Los Angeles Times, April 25, 2019, https://www.latimes.com/local/lanow/la-me-cool-pavement-

climate-change-20190425-story.html.
[323] Rosenfeld et al., "Cool Communities."
[324] Kalkstein et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia"; Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York"; Stone et al., "Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three U.S. Cities."
[325] Ibid.
[326] University of California San Diego, "Pavements Designed to Fight Climate Change Could Increase Energy Consumption in Surrounding Buildings," November 6, 2012, http://jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1281.
[327] Pomerantz, Hashem, and Harvey, "Cooler Reflective Pavements Give Benefits beyond Energy Savings: Durability and Illumination."
[328] ARA, Inc., ERES Consultants Division, "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Part 3. Design Analysis, Chapter 4. Design of New and Reconstructed Rigid Pavements" (Washington, D.C.: National Cooperative Highway Research Program, Transportation Research Board, National Research Council, March 2004), http://onlinepubs.trb.org/onlinepubs/archive/mepdg/guide.htm.
[329] U.S. Environmental Protection Agency (EPA), "Cool Pavements."
[330] Heat Island Group, "Cool Pavements."
[331] Lighting Research Center, Rensselaer Polytechnic Institute, "What Is Glare?" February 2007, http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightpollution/glare.asp.
[332] Akbari, Pomerantz, and Taha, "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas."
[333] U.S. Environmental Protection Agency (EPA), "Cool Pavements."
[334] U.S. Environmental Protection Agency (EPA), "Trees and Vegetation," Reducing Urban Heat Islands: Compendium of Strategies, 2008, www.epa.gov/sites/production/files/2014-06/documents/treesandvegcompendium.pdf.
[335] McPherson et al., "Piedmont Community Tree Guide: Benefits, Costs, and Strategic Planting."
[336] "Community Forestry," Blue Water Baltimore, https://bluewaterbaltimore.org/learn/programs-and-projects/forestry/.
[337] "Mission + History," Baltimore Tree Trust, https://www.baltimoretreetrust.org/about-us/why-baltimore-tree-trust/.
[338] Akbari, Pomerantz, and Taha, "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas"; U.S. Environmental Protection Agency (EPA), "Trees and Vegetation"; Casey Trees, "Reasons to Plant Trees," accessed June 23, 2016, http://caseytrees.org/resources/reasons/; "Why Trees," Casey Trees, https://caseytrees.org/tree-species/tree-benefits/.
[339] Hashem Akbari et al., "Peak Power and Cooling Energy Savings of High-Albedo Roofs," Energy and Buildings, 25, no. 2 (January 1997): 117–26, doi:10.1016/S0378-7788(96)01001-8.
[340] Yu Joe Huang, Hashem Akbari, and Haider Taha, "The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements," in Proceedings of the ASHRAE Winter Conference (ASHRAE Winter Meeting, Atlanta, GA, 1990), http://www.osti.gov/scitech/biblio/6839888.
[341] U.S. Environmental Protection Agency (EPA), "Trees and Vegetation."

[342] Ibid.
[343] Akbari, Pomerantz, and Taha, "Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas."
[344] J.R. Simpson and E.G. McPherson, "Simulation of Tree Shade Impacts on Residential Energy Use for Space Conditioning in Sacramento," Atmospheric Environment 32, no. 1 (January 1998): 69–74, doi:10.1016/S1352- 2310(97)00181-7.
[345] Huang, Akbari, and Taha, "The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements."
[346] U.S. Environmental Protection Agency (EPA), "Trees and Vegetation."
[347] H Taha, S Konopacki, and S Gabersek, "Modeling the Meteorological and Energy Effects of Urban Heat Islands and Their Mitigation: A 10-Region Study" (Berkeley, CA: Lawrence Berkeley National Laboratory, 1996).
[348] Rosenzweig, Solecki, and Slosberg, "Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces."
[349] David J. Sailor, "Streamlined Mesoscale Modeling of Air Temperature Impacts of Heat Island Mitigation Strategies," 2003.
[350] Wang, Chenghao, et al. "Cooling Effect of Urban Trees on the Built Environment of Contiguous United States." *Earth's Future*, vol. 6, no. 8, 2018, pp. 1066–1081., doi:10.1029/2018ef000891.

[351] Taha, Konopacki, and Gabersek, "Modeling the Meteorological and Energy Effects of Urban Heat Islands and Their Mitigation: A 10-Region Study."
[352] Akbari and Konopacki, "Calculating Energy-Saving Potentials of Heat-Island Reduction Strategies."
[353] Taha, Konopacki, and Gabersek, "Modeling the Meteorological and Energy Effects of Urban Heat Islands and Their Mitigation: A 10-Region Study."
[354] Rosenfeld et al., "Cool Communities."
[355] Ibid.
[356] Ibid.
[357] U.S. General Services Administration (GSA), "The Benefits and Challenges of Green Roofs on Public and Commercial Buildings."
[358] W.H. Smith, Air Pollution and Forests (New York, NY: Springer-Verlag New York Inc., 1990), http://www.osti.gov/scitech/biblio/7000629.
[359] David J. Nowak, Daniel E. Crane, and Jack C. Stevens, "Air Pollution Removal by Urban Trees and Shrubs in the United States," Urban Forestry & Urban Greening 4, no. 3–4 (April 2006): 115–23, doi:10.1016/j.ufug.2006.01.007.
[360] Ibid.; Rosenfeld et al., "Cool Communities."
[361] Kalkstein et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia"; Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York"; Stone et al., "Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three U.S. Cities."
[362] Vanos et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in Baltimore, Los Angeles, and New York."
[363] McPherson et al., "Northeast Community Tree Guide: Benefits, Costs, and Strategic Planting";

Ibid.
[364] Ibid.
[365] U.S. Environmental Protection Agency (EPA), "Trees and Vegetation"; McPherson et al., "Northeast Community Tree Guide: Benefits, Costs, and Strategic Planting."
[366] U.S. Environmental Protection Agency (EPA), "Trees and Vegetation"
[367] McPherson et al., "Northeast Community Tree Guide: Benefits, Costs, and Strategic Planting."
[368] Wiebke Klemm et al., "Street Greenery and Its Physical and Psychological Impact on Thermal Comfort," Landscape and Urban Planning 138 (June 2015): 87–98, doi:10.1016/j.landurbplan.2015.02.009; Loyde Vieira de Abreu-Harbich, Lucila Chebel Labaki, and Andreas Matzarakis, "Effect of Tree Planting Design and Tree Species on Human Thermal Comfort in the Tropics," Landscape and Urban Planning 138 (June 2015): 99–109, doi:10.1016/j.landurbplan.2015.02.008; Fazia Ali-Toudert and Helmut Mayer, "Effects of Asymmetry, Galleries, Overhanging Façades and Vegetation on Thermal Comfort in Urban Street Canyons," Solar Energy 81, no. 6 (June 2007): 742–54, doi:10.1016/j.solener.2006.10.007; Hyunjung Lee, Jutta Holst, and Helmut Mayer, "Modification of Human-Biometeorologically Significant Radiant Flux Densities by Shading as Local Method to Mitigate Heat Stress in Summer within Urban Street Canyons," Advances in Meteorology 2013 (2013): 1–13, doi:10.1155/2013/312572; Naveed Mazhar et al., "Thermal Comfort of Outdoor Spaces in Lahore, Pakistan: Lessons for Bioclimatic Urban Design in the Context of Global Climate Change," Landscape and Urban Planning 138 (June 2015): 110–17, doi:10.1016/j.landurbplan.2015.02.007.
[369] Wiebke Klemm et al., "Street Greenery and Its Physical and Psychological Impact on Thermal Comfort," Landscape and Urban Planning 138 (June 2015): 87–98, doi:10.1016/j.landurbplan.2015.02.009; Loyde Vieira de Abreu-Harbich, Lucila Chebel Labaki, and Andreas Matzarakis, "Effect of Tree Planting Design and Tree Species on Human Thermal Comfort in the Tropics," Landscape and Urban Planning 138 (June 2015): 99–109, doi:10.1016/j.landurbplan.2015.02.008; Fazia Ali-Toudert and Helmut Mayer, "Effects of Asymmetry, Galleries, Overhanging Façades and Vegetation on Thermal Comfort in Urban Street Canyons," Solar Energy 81, no. 6 (June 2007): 742–54, doi:10.1016/j.solener.2006.10.007; Hyunjung Lee, Jutta Holst, and Helmut Mayer, "Modification of Human-Biometeorologically Significant Radiant Flux Densities by Shading as Local Method to Mitigate Heat Stress in Summer within Urban Street Canyons," Advances in Meteorology 2013 (2013): 1–13, doi:10.1155/2013/312572; Naveed Mazhar et al., "Thermal Comfort of Outdoor Spaces in Lahore, Pakistan: Lessons for Bioclimatic Urban Design in the Context of Global Climate Change," Landscape and Urban Planning 138 (June 2015): 110–17, doi:10.1016/j.landurbplan.2015.02.007.
[370] Liang Chen and Edward Ng, "Outdoor thermal comfort and outdoor activities: A review of research in the past decade," Cities 29, No. 2 (2012): 118-125, https://doi.org/10.1016/j.cities.2011.08.006.
[371] Ali-Toudert and Mayer, "Effects of Asymmetry, Galleries, Overhanging Façades and Vegetation on Thermal Comfort in Urban Street Canyons."
[372] Lee, Holst, and Mayer, "Modification of Human-Biometeorologically Significant Radiant Flux Densities by Shading as Local Method to Mitigate Heat Stress in Summer within Urban Street Canyons."
[373] Ruey-Lung Hwang, Tzu-Ping Lin, and Andreas Matzarakis, "Seasonal Effects of Urban Street Shading on Long-Term Outdoor Thermal Comfort," Building and Environment 46, no. 4 (April 2011): 863–70, doi:10.1016/j.buildenv.2010.10.017; Tzu-Ping Lin, Andreas Matzarakis, and Ruey-

Lung Hwang, “Shading Effect on Long-Term Outdoor Thermal Comfort,” Building and Environment 45, no. 1 (January 2010): 213–21, doi:10.1016/j.buildenv.2009.06.002.
[374] Janina Konarska et al., “Transmissivity of Solar Radiation through Crowns of Single Urban Trees—application for Outdoor Thermal Comfort Modelling,” Theoretical and Applied Climatology 117, no. 3–4 (August 2014): 363– 76, doi:10.1007/s00704-013-1000-3.
[375] A. Troy, J. Grove, and J. O’Neil-Dunne, “The relationship between tree canopy and crime rates across an urban-rural gradient in the greater Baltimore region,” Landscape and Urban Planning 106 (2012): 262-270, https://www.sciencedirect.com/science/article/abs/pii/S0169204612000977.
[376] Ibid.
[377] Ibid.
[378] F. Kuo, “The role of arboriculture in a healthy social ecology,” Journal of Arboriculture 29, no. 3 (2003): 148-155, https://www.fs.usda.gov/treesearch/pubs/13860.
[379] F. Kuo and W. Sullivan, “Environment and crime in the inner city – Does vegetation reduce crime?,” Environment and Behavior 33, no. 3 (2001): 343-367, https://journals.sagepub.com/doi/abs/10.1177/0013916501333002.
[380] Jane Jacobs, The Death and Life of Great American Cities (Random House, 1961).
[381] B. Brown, and D. Bentley, “Residential burglars judge risk – The role of territoriality,” Journal of Environmental Psychology 13, no. 1 (1993): 51-61, https://www.sciencedirect.com/science/article/pii/S0272494405802142.
[382] Richard Conniff, “Trees shed bad rap as accessories to crime,” Yale School of Forestry & Environmental Studies, 2012, https://environment.yale.edu/envy/stories/trees-shed-bad-wrap-as-accessories-to-crime#gsc.tab=0.
[383] Jari Tiihonen, Pirjo Halonen, Laura Tiihonen, Hannu Kautiainen, Markus Storvik, and James Callaway, “The Association of Ambient Temperature and Violent Crime.” Scientific Reports 7 (2017): 6543, https://www.nature.com/articles/s41598-017-06720-z.
[384] Abigail Gates, Mitchel Klein, Fiorella Acquaotta, Rebecca M. Garland, and Noah Scovronick, “Short-term association between ambient temperature and homicide in South Africa: a case-crossover study.” Environmental Health 18 (2019): 109, https://ehjournal.biomedcentral.com/articles/10.1186/s12940-019-0549-4 .
[385] B. Sanz-Barbero, C. Linares, C. Vives-Cases, J. L. González, J. J. López-Ossorio, and J. Díaz, “Heat wave and the risk of intimate partner violence,” The Science of the Total Environment 644 (2018): 413–419, https://doi.org/10.1016/j.scitotenv.2018.06.368.
[386] D. M. Kurn, S. E. Bretz, B. Huang, and H. Akbari, “The potential for reducing urban air temperatures and energy consumption through vegetative cooling,” Lawrence Berkeley Laboratory, 1994, https://www.osti.gov/biblio/10180633.
[387] Safe Streets Baltimore, “Safe Streets,” Johns Hopkins University, 2012, https://www.jhsph.edu/research/centers-and-institutes/center-for-prevention-of-youth-violence/field_reports/Safe_Streets.html#:~:text=Safe%20Streets%20Baltimore%20is%20an,otherwise%20result%20in%20serious%20violence.

[388] David Nowak, “The effects of urban trees on air quality,” (USDA Forest Service: Syracuse, NY, 2002), https://www.nrs.fs.fed.us/units/urban/local-resources/downloads/Tree_Air_Qual.pdf.
[389] Michael T. Benjamin et al., “Low-Emitting Urban Forests: A Taxonomic Methodology for

Assigning Isoprene and Monoterpene Emission Rates," Atmospheric Environment 30, no. 9 (January 1996): 1437–52, doi:10.1016/1352-2310(95)00439-4; Michael T. Benjamin and Arthur M. Winer, "Estimating the Ozone-Forming Potential of Urban Trees and Shrubs," Atmospheric Environment 32, no. 1 (January 1998): 53–68, doi:10.1016/S1352-2310(97)00176-3.

[390] U.S. Environmental Protection Agency (EPA), "Trees and Vegetation."

[391] David J. Nowak and John F. Dwyer, "Understanding the Benefits and Costs of Urban Forest Ecosystems," in Urban and Community Forestry in the Northeast, ed. John E. Kuser (Dordrecht: Springer Netherlands, 2007), 25–46, http://link.springer.com/10.1007/978-1-4020-4289-8_2.

[392] Kuo and Sullivan, "Environment and Crime in the Inner City"; Austin Troy, J. Morgan Grove, and Jarlath O'Neil-Dunne, "The Relationship between Tree Canopy and Crime Rates across an Urban–rural Gradient in the Greater Baltimore Region," Landscape and Urban Planning 106, no. 3 (June 2012): 262–70, doi:10.1016/j.landurbplan.2012.03.010.

[393] Hansmann, Hug, and Seeland, "Restoration and Stress Relief through Physical Activities in Forests and Parks"; Wolf, "Urban Nature Benefits: Psycho-Social Dimensions of People and Plants."

[394] District Department of the Environment (DDOE), "Stormwater Management Guidebook"; William F. Hunt and Kelly A. Collins, "Permeable Pavement: Research Update and Design Implications" (Raleigh, NC: North Carolina Cooperative Extension, 2008), http://www.bae.ncsu.edu/stormwater/PublicationFiles/PermPave2008.pdf.

[395] District Department of the Environment (DDOE), "Stormwater Management Guidebook."

[396] U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement," Water: Best Management Practices, July 3, 2014, accessed in 2016, http://water.epa.gov/polwaste/npdes/swbmp/Porous-AsphaltPavement.cfm; U.S Department of Transportation (DOT), "Porous Asphalt Pavements with Stone Reservoirs," TechBrief, April 2015, https://www.fhwa.dot.gov/pavement/asphalt/pubs/hif15009.pdf.

[397] Ibid.

[398] District Department of the Environment (DDOE), "Stormwater Management Guidebook".

[399] Ibid.

[400] U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement."

[401] Stephen T. Muench et al., "Greenroads Manual v1.5" (Seattle, WA: University of Washington, 2011), https://www.greenroads.org/files/236.pdf.

[402] U.S. Environmental Protection Agency (EPA), "Pervious Concrete Pavement," Water: Best Management Practices, July 2, 2014, accessed in 2016, http://water.epa.gov/polwaste/npdes/swbmp/Pervious-Concrete-Pavement.cfm; Kenneth Justice,"Pervious Pavement Alternatives," U.S Environmental Protection Agency (EPA), https://archive.epa.gov/region02/njgiforum/web/pdf/08justice.pdf.

[403] District Department of the Environment, "Stormwater Management Guidebook," January, 2020, https://doee.dc.gov/swguidebook.

[404] Ibid.

[405] Muench et al., "Greenroads Manual v1.5."

[406] Hunt and Collins, "Permeable Pavement: Research Update and Design Implications"; Portland Cement Association (PCA), "What is Permeable Interlocking Concrete Pavement," https://www.cement.org/cement-concrete/paving/buildings-structures/concrete-homes/products/permeable-interlocking-concrete-pavement.

[407] District Department of the Environment, "Stormwater Management Guidebook."

[408] Portland Cement Association (PCA), "What is Permeable Interlocking Concrete Pavement."

[409] Muench et al., "Greenroads Manual v1.5."
[410] Hunt and Collins, "Permeable Pavement: Research Update and Design Implications"; U.S. Environmental Protection Agency (EPA), "Cool Pavements."
[411] Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management"; Portland Cement Association (PCA), "What is Permeable Interlocking Concrete Pavement."
[412] Hunt and Collins, "Permeable Pavement: Research Update and Design Implications."
[413] J.T. Kevern, L. Haselbach, and V.R. Schaefer, "Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems," Journal of Heat Island Institute International 7–2 (2012): 231–37; Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management."
[414] Kevern, Haselbach, and Schaefer, "Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems."
[415] Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management."
[416] Ibid.
[417] U.S. Environmental Protection Agency (EPA), "Cool Pavements," Reducing Urban Heat Islands: Compendium of Strategies, 2012, https://www.epa.gov/heatislands/heat-island-compendium.
[418] Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management."
[419] John Kevern, Vernon Schaefer, and Kejin Wang, "Temperature Behavior of Pervious Concrete Systems," Transportation Research Record: Journal of the Transportation Research Board 2098 (December 2009): 94–101, doi:10.3141/2098-10; Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management."
[420] Ibid.
[421] District Department of the Environment, "Stormwater Management Guidebook."
[422] Portland Cement Association (PCA), "What is Permeable Interlocking Concrete Pavement,"; U.S. Environmental Protection Agency (EPA), "Pervious Concrete Pavement"; U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement."
[423] Eban Z. Bean, William F. Hunt, and David A. Bidelspach, "Field Survey of Permeable Pavement Surface Infiltration Rates," Journal of Irrigation and Drainage Engineering 133, no. 3 (June 2007): 249–55, doi:10.1061/(ASCE)0733-9437(2007)133:3(249); Portland Cement Association (PCA), "What is Permeable Interlocking Concrete Pavement."
[424] District Department of the Environment, "Stormwater Management Guidebook."
[425] CTC & Associates LLC, "Transportation Synthesis Report: Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost," Department of Transportation (DOT) Research and Library Services, January 13, 2012, https://www.uni-groupusa.org/PDF/Wisconsin%20TSR-2011-permeable-pavements.pdf.
[426] U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement."
[427] Personal communication with Alan Dinges of Invisible Structures, Inc., 2016.
[428] District of Columbia Water and Sewer Authority, "Long Term Control Plan Modification for Green Infrastructure," May 2015, https://www.dcwater.com/education/gi-images/green-infrastructure-ltcpmodificaitons.pdf.
[429] ProMatcher, "Baltimore Sod Installation Costs & Prices - ProMatcher Cost Report," July 19, 2018, https://sod.promatcher.com/cost/baltimore-md-sod-costs-prices.aspx.
[430] King and Hagan, "Costs of Stormwater Management Practices in Maryland Counties."

[431] Communication with the District Department of Transportation (DDOT).
[432] King and Hagan, "Costs of Stormwater Management Practices in Maryland Counties."
[433] "Grasspave2 and Gravelpave2," Invisible Structures, March 20, 2015, https://www.invisiblestructures.com/wp-content/uploads/GPGV_brochure.pdf; "True Grid," True Grid Paver, https://www.truegridpaver.com.
[434] Interlocking Concrete Pavement Institute, "Durability," accessed July 7, 2016, https://www.icpi.org/pavingsystems/permeable-pavers/benefits/durability; Personal communication with Dan Bishop of EMCO Site Solutions, 2015.
[435] Kevern, Haselbach, and Schaefer, "Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems"; Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management."
[436] Kevern, Haselbach, and Schaefer, "Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems."
[437] U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement."
[438] District Department of the Environment (DDOE), "Stormwater Management Guidebook."; U.S. Environmental; Protection Agency (EPA), "Pervious Concrete Pavement"; U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement"; Portland Cement Association (PCA), "What is Permeable Interlocking Concrete Pavement."
[439] Center for Neighborhood Technology and American Rivers, "The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits."
[440] Houle, "Winter Performance Assessment of Permeable Pavements: A Comparative Study of Porous Asphalt, Pervious Concrete, and Conventional Asphalt in a North Climate."
[441] Kevern, Schaefer, and Wang, "Temperature Behavior of Pervious Concrete Systems."
[442] Husam Najm et al, "The Use of Porous Concrete for Sidewalks," Center for Advanced Infrastructure and Transportation, Rutgers, the State University of New Jersey, December, 2017, https://cait.rutgers.edu/wp-content/uploads/2019/01/fhwa-nj-2018-001-1.pdf.
[443] U.S. Environmental Protection Agency (EPA) "What is Green Infrastructure?: Permeable Pavements", January, 2021, https://www.epa.gov/green-infrastructure/what-green-infrastructure#permeablepavements.
[444] Kevern, Haselbach, and Schaefer, "Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems."
[445] Li et al., "The Use of Reflective and Permeable Pavements as a Potential Practice for Heat Island Mitigation and Stormwater Management."
[446] Andika Citraningrum, "The Impact of Permeable Pavement Utilization on Air Temperature above the Pavement and Building Energy Consumption" 2011.
[447] Hui Li, John Harvey, and David Jones, "Cooling Effect of Permeable Asphalt Pavement Under Dry and Wet Conditions," Transportation Research Record: Journal of the Transportation Research Board 2372 (December 2013): 97–107, doi:10.3141/2372-11.
[448] Ibid.
[449] Citraningrum, "The Impact of Permeable Pavement Utilization on Air Temperature above the Pavement and Building Energy Consumption."
[450] U.S. Environmental Protection Agency (EPA), "Porous Asphalt Pavement."
[451] Li, Bou-Zeid, and Oppenheimer, "The Effectiveness of Cool and Green Roofs as Urban Heat Island Mitigation Strategies."

[452] Kalkstein et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia."
[453] Sailor, "Streamlined Mesoscale Modeling of Air Temperature Impacts of Heat Island Mitigation Strategies."
[454] Akbari and Konopacki, "Calculating Energy-Saving Potentials of Heat-Island Reduction Strategies."; Ibid.
[455] Personal communication with El Paso Office of Resilience & Sustainability.
[456] U.S. Environmental Protection Agency (EPA), "Fact Sheet: Social Cost of Carbon," November 2013.
[457] Akbari, Menon, and Rosenfeld, "Global Cooling"; Menon et al., "Radiative Forcing and Temperature Response to Changes in Urban Albedos and Associated CO2 Offsets."
[458] Bryan J. Bloomer et al., "Observed Relationships of Ozone Air Pollution with Temperature and Emissions," Geophysical Research Letters 36, no. 9 (May 5, 2009), doi:10.1029/2009GL037308.
[459] Ben Machol and Sarah Rizk, "Economic Value of U.S. Fossil Fuel Electricity Health Impacts," Environment International 52 (February 2013): 75–80, doi:10.1016/j.envint.2012.03.003.
[460] Kalkstein et al., "Assessing the Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia."
[461] Ryan C. Bosworth, Alecia Hunter, and Ahsan Kibria, "The Value of a Statistical Life: Economics and Politics," Strata, March 2017.
[462] i-Tree, "References," I-Tree Landscape, https://landscape.itreetools.org/references/.
[463] Baltimore City Department of Public Works, City of Baltimore, and CleanWaterBaltimore. "Baltimore City MS4 Restoration and TMDL WIP."
[464] Baltimore Sustainability Plan, 99.
[465] Baltimore City Department of Public Works, City of Baltimore, and CleanWaterBaltimore. "Baltimore City MS4 Restoration and TMDL WIP."
[466] Baltimore City Department of Public Works & City of Baltimore. "Baltimore City MS4 Annual Report." City of Baltimore, June 2019. https://publicworks.baltimorecity.gov/sites/default/files/Baltimore%20City%20MS4%20Annual%20Report%20FY%202019.pdf.
[467] Ibid.
[468] Ibid.
[469] Ibid.
[470] Ibid.
[471] Ibid.
[472] Blue Water Baltimore. "Green Stormwater Infrastructure: Challenges and Opportunities in Baltimore." Blue Water Baltimore, December 2019. https://abell.org/sites/default/files/publications/FINAL_Green-Stormwater-Infrastructure-Report_Blue-Water-Baltimore_FINAL_December-2019_0.pdf.
[473] Ibid.
[474] Ibid.
[475] Baltimore Sustainability Plan, 49.
[476] Baltimore City Department of Public Works, City of Baltimore, and CleanWaterBaltimore. "Baltimore City MS4 Restoration and TMDL WIP."
[477] Baltimore City Department of Public Works & City of Baltimore. "Baltimore City MS4 Annual Report." City of Baltimore."

[478] Ibid.
[479] Baltimore Sustainability Plan, 7.
[480] DC Water, "Impervious Area Charge," DC Water, 2017, https://www.dcwater.com/impervious-area-charge.
[481] Department of Energy & Environment, "Stormwater Fee Background," DC.gov.
[482] Baltimore City Department of Public Works. "Stormwater Management." Department of Public Works. 2018. https://publicworks.baltimorecity.gov/pw-bureaus/water-wastewater/stormwater.
[483] Ibid.
[484] Baltimore City Department of Public Works. "SFP Stormwater Guidance Document." Department of Public Works. 2018. https://publicworks.baltimorecity.gov/sites/default/files/SFP%20Stormwater%20Guidance%20Document.pdf.
[485] Personal Communication with Jenn Aiosa, Executive Director at Blue Water Baltimore.
[486] The Baltimore Sun. "Baltimore officials approve $1.6 billion, 13-year sewer repair plan." The Baltimore Sun, Aug 2017. https://www.baltimoresun.com/maryland/baltimore-city/bs-md-ci-sewer-consent-decree-20170808-story.html.
[487] Chesapeake Bay Foundation. "Past Time to Fix the Pipes." Chesapeake Bay Foundation, 2019. https://www.cbf.org/about-cbf/locations/maryland/issues/baltimore-city-sewage-overflow.html.
[488] The Baltimore Sun, "Baltimore officials approve $1.6 billion, 13-year sewer repair plan."
[489] Baltimore Sustainability Plan, 58.
[490] Department of Energy & Environment. "FAQs: Generating and Selling SRCs." DC.gov, https://doee.dc.gov/node/130375.
[491] DC Department of Energy & Environment, "SRC and Offv Registry," DC Department of Energy & Environment, 2021, https://octo.quickbase.com/up/bjkxxcfcp/g/rb7/eg/va/levels.html?sitelevel=2&pagerecord=90&userrole=Everyone%20On%20the%20Internet.
[492] Rory O'Sullivan, Konrad Mugglestone, and Tom Allison, "The Hidden Cost of Young Adult Unemployment" (Young Invincibles, January 2014), http://younginvincibles.org/wp-content/uploads/2014/01/In-This-Together- The-Hidden-Cost-of-Young-Adult-Unemployment.pdf.
[493] Popovich and Flavelle, "Summer in the City Is Hot, but Some Neighborhoods Suffer More."
[494] New York Times, Heat Data Source: Vivek Shandas/CAPA Strategies
[495] "Vital Signs," Baltimore Neighborhood Indicators Alliance (BNIA), accessed April 2021, https://bniajfi.org/vital_signs/.
[496] "Annual Report & Business Plan FY2020-2021," Visit Baltimore, 2021, https://viewer.joomag.com/visit-baltimore-annual-report-fy-2020-2021-2020/0273960001601906190?short&; "Maryland: Fiscal Year 2020 Tourism Development Board Annual Report," visitmaryland.org, 2020, 6, https://industry.visitmaryland.org/wp-content/uploads/2020/12/MD_FY20_Annual-Report_v18.pdf.
[497] "Tourism Satellite Account: The Economic Impact of Tourism in Maryland," Tourism Economics, 2016, https://industry.visitmaryland.org/wp-content/uploads/2020/04/MD-Visitor-Economic-Impact-20161.pdf.
[498] Colin Cambell, "Baltimore's July heat wave set a nearly 150-year-old record. And 'it isn't going to get better.'" The Baltimore Sun, July 30, 2020, https://www.baltimoresun.com/news/environment/bs-md-hot-20200730-uao5nl34xfbf7p3py2ygtnl3jq-story.html.

[499] Ibid.

[500] "Climate Change Maryland," EmPower Maryland, https://climatechange.maryland.gov/science/#:~:text=The%20effects%20of%20climate%20change,more%20frequent%20and%20violent%20thunderstorms.&text=The%20combination%20of%20rising%20sea,more%20flooding%20in%20the%20future.

[501] Dan Novak et al, "Global Warming Will be Costly and Neighborhoods Must Do More," Code Red: Seeking Solutions, Howard Center for Investigative Journalism, September 3, 2019, https://cnsmaryland.org/interactives/summer-2019/code-red/city-climate-future.html.

[502] Ian Round et al, "In Urban Heat Islands, Climate Crisis Hits Harder," Code Red: Heat & Inequality, Howard Center for Investigative Journalism, September 3, 2019, https://cnsmaryland.org/interactives/summer-2019/code-red/neighborhood-heat-inequality.html.

[503] "The Best Time to Visit Maryland, United States for Weather, Safety, and Tourism," championtraveler.com, https://championtraveler.com/dates/best-time-to-visit-maryland-us/.

[504] Ibid.

[505] "The Best Time to Visit Maryland, United States for Weather, Safety, and Tourism."

[506] Ibid.

[507] "Why Go to Baltimore," U.S News & World Report, https://travel.usnews.com/Baltimore_MD/.

[508] "Maryland Extreme Heat – States at Risk," statesatrisk.org, https://statesatrisk.org/maryland/extreme-heat.

[509] Fourth National Climate Assessment, USGCRP, November 23, 2018, https://nca2018.globalchange.gov/downloads/NCA4_2018_FullReport.pdf.

[510] Ibid.

[511] "Code Red Extreme Heat," Baltimore City Health Department, https://health.baltimorecity.gov/coderedinfo.

[512] "Code Red Extreme Heat," Baltimore City Health Department, https://health.baltimorecity.gov/coderedinfo.

[513] Joshua Gordon, "Locals are Feeling the Heat – but Baltimore's Aquarium Isn't," July 25, 2016, https://www.bizjournals.com/baltimore/news/2016/07/25/locals-are-feeling-the-heat-but-baltimores.html.

[514] "Baltimore or Minnesota," TripAdvisor, https://www.tripadvisor.com/ShowTopic-g60811-i165-k3168042-Baltimore_or_Minnesota-Baltimore_Maryland.html#22426954.

[515] "July 16th Water Main Break May Affect Traffic for Days..." TripAdvisor, https://www.tripadvisor.com/ShowTopic-g60811-i165-k5596912-July_16th_water_main_break_may_affect_traffic_for_days-Baltimore_Maryland.html#42327513.

[516] Jennifer Walker, Baltimore, July 1, 2014, Moon Publications.

[517] Ibid.

[518] "Annual Report & Business Plan FY2020-2021," Visit Baltimore.

[519] Katharine Hayhoe and Donald Wuebbles, "Climate Change and Chicago Projects and Potential Impacts: Chapter Six - Infrastructure," Chicago Climate Action Plan, November, 7, 2007, https://www.chicago.gov/content/dam/city/progs/env/CCAP/Chicago_climate_impacts_report_Chapter_6_Infrastructure.pdf.

[520] Andrea Bigano, Jaqueline Hamilton, and Richard Tol, "The Impact of Climate Change on

Domestic and International Tourism: A Simulation Study," Fondazione Eni Enrico Mattei, June 2006, https://www.econstor.eu/bitstream/10419/74194/1/NDL2006-086.pdf.

[521] Ana Maria Caldeira and Elizabeth Kastenholz, "It's so hot: predicting climate change effects on urban tourists' time–space experience," Journal of Sustainable Tourism, Volume 26 Issue 9, 1532, 2018, https://doi.org/10.1080/09669582.2018.1478840.

[522] Linda Givetash, "Europe's heat wave shows how climate change could change tourism," NBC News, August 9, 2018, https://www.nbcnews.com/news/world/europe-s-heat-wave-shows-how-climate-change-could-change-n898586.

[523] Tourism Marketing and Development Plan: Fiscal Year 2015," Maryland Tourism Development Board and the Office of Tourism Development, https://industry.visitmaryland.org/wp-content/uploads/2020/04/marketing-plan-2015.pdf.

[524] "Tourism Satellite Account: The Economic Impact of Tourism in Maryland"

[525] Jesdale, Morello-Frosch, and Cushing, "The Racial/Ethnic Distribution of Heat Risk–Related Land Cover in Relation to Residential Segregation."

[526] Drehobl, Ross, and Ayala, "How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States."

[527] "Air conditioning accounts for about 12% of U.S. home energy expenditures," U.S. Energy Information Administration, July 23, 2018, https://www.eia.gov/todayinenergy/detail.php?id=36692.

[528] Baltimore Neighborhood Indicators Alliance (BNIA), "Cherry Hill Vital Signs"; Baltimore Neighborhood Indicators Alliance (BNIA), "Brooklyn/ Curtis Bay/ Hawkins Point Vital Signs"; Baltimore Neighborhood Indicators Alliance (BNIA), "Madison/ East End Vital Signs."