Achieving Urban Resilience: Washington DC

Actively managing sun and rain to improve District health and livability and slow global warming while saving billions of dollars

FUNDERS:

AUTHORS:

Greg Kats and Keith Glassbrook, Capital E

PARTNERS:

Comments on Report

Dan Tangherlini: former Washington DC City Administrator and Administrator of GSA
In my public work I gained a deep appreciation for the tremendous opportunities offered by and difficult challenges we face in making our buildings and communities greener and healthier. Achieving Urban Resilience is a critical, even transformative new analysis that provides a compelling case that DC should accelerate its greening by adopting the city wide technology and design practices documented here. What this report convincingly demonstrates is that there are cost effective technologies and strategies for managing sun and water that will deliver billions of dollars in financial benefits to the city and its residents. Delaying this transition would impose large financial and social costs particularly on places of lower economic opportunity, the elderly and children. We have the roadmap – now we must follow it.

David Bowers: Washington DC Minster, and Vice President, Enterprise Community Partners
This report Achieving Urban Sustainability is important for many reasons. It is the first rigorous analysis of the full cost and benefits of managing our city's sun and rain, and it shows how to make the city much more resilient, cleaner and more livable. As a District resident working for a company that develops and finances affordable, green and sustainable low-income residences in D.C., I am aware of the gross physical inequities in many low-income neighborhoods. Achieving Urban Sustainability demonstrates how the city can redress this inequity by making low-income neighborhoods more reflective and porous and green. The benefits would be dramatic: improved health, more jobs, and greater comfort.

Rick Fedrizzi: President and Founding Chairman, US Green Building Council
In his seminal work 14 years ago Kats provided the first and most influential analysis on the cost and benefits of green buildings. That work has had a transformative impact in the US and globally in greatly expanding recognition of the financial rational for building green and in accelerating adoption of green design. In Achieving Urban Resilience Kats provides an enormously important step for US cities to understand and quantify the large range of health, livability and climate change benefits from adopting a range of cost effective strategies now available to manage sun and rainfall. The work is so important because it is the first to rigorously document, quantify and explain these benefits and benefit pathways. As such it provides a powerful and compelling analysis and framework for the District and other cities to take a huge step to achieve climate resilience while securing very broad health benefits.

Will Wynn: two term mayor of Austin
As a two term mayor of Austin, I had the opportunity to lead our city's rapid transition toward a much more sustainable future, including a dramatic expansion of renewable energy and green buildings. Kats's work documenting costs and benefits of green buildings was a fundamental component in our understanding the cost and benefits, and a powerful driver for green design adoption and policy initiatives. Achieving Urban Resilience provides an entirely convincing case that city-wide adoption of cooling and greening roof and surface technologies is cost effective and essential to ensure that our cities remain livable in a warming world. The case has been made - and proven. We must now act.

Acknowledgments

We are deeply grateful to the Department of General Services and the Department of Energy & Environment for funding this work and to our Partners, Advisors, and the 100 or so experts who provided guidance and feedback. Any errors in the report and appendix are our own. This report draws on and benefits from parallel work by Capital E for the JPB Foundation that focuses on impact on low income areas and lower income city residents. Relevant findings from our work for JPB are included in this report in Box 2.

We are grateful to our Partners and Advisors who provided guidance and feedback throughout the development of this report. Our Advisors include:

- Sean Cahill (Senior VP of Development, Property Group Partners; Immediate Past President, DC Building Industry Association),
- Dr. John Davies-Cole (State Epidemiologist, Center for Policy, Planning & Evaluation, DC Department of Health);
- Dr. Lynn Goldman (Dean, Milken Institute School of Public Health (GWU); Epidemiologist; former EPA Assistant Administrator);
- Dr. Ronnen Levinson (Deputy Leader, Heat Island Group, Lawrence Berkeley National Laboratory);
- Dr. Art Rosenfeld (Lawrence Berkeley National Laboratory; former Commissioner at the California Energy Commission; co-founder of the American Council for an Energy-Efficient Economy (ACEEE));
- Kurt Shickman (Executive Director of Global Cool Cities Alliance);
- Dan Tangherlini (former Administrator of GSA; former City Administrator of Washington, DC).

Special thanks are due to:

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- Nicole Ferrini, Chief Resilience Officer, City of El Paso;
- Andrew Aurbach and John Settles of Capital Sustainability;
- Frank Loy (formerly of Department of State and Environmental Defense Fund);
- Will Wynn (formerly Mayor of Austin);

Advisors on past reports include David Bowers (VP & Market Leader, Mid-Atlantic, Enterprise Community Partners; Ordained Minister), Brendan Shane (Chief, Office of Policy & Sustainability, District Department of the Environment (now Regional Director for North America, C40 Cities)) Tom Osdoba (VP, Green Initiatives, Enterprise Community Partners), and Chris Pyke (VP of Research at USGBC and Chief Operating Officer at GRESB).

Our Partners provided guidance and reviewed sections of the report. Partners are: American Institute of Architects, Casey Trees, Chesapeake Bay Foundation, Department of Energy & Environment, Department of General Services, DowntownDC BID, EcoDistricts, Enterprise Community Partners, Global Cool Cities Alliance, National Housing Trust, National League of Cities, Rock Creek Conservancy, and U.S. Green Building Council.

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Author Bios

Greg Kats is President of Capital E, which works with large institutions on scaling greening, and partners with national organizations to research and document the cost-effectiveness of green policy and technology. He Is a Managing Director of ARENA Investments, LCC, a fund that invests in clean energy growth firms. Greg serves on the DC Mayor's Green Ribbon Task Force. Greg led the development of IPMVP—the global energy and water efficiency design, measurement, and verification standard that has served as the design basis for $50 billion in energy efficiency financing. He helped found LEED, the international green building standard, and was the first recipient of the USGBC Lifetime Achievement Award. Greg served as the Director of Financing for Energy Efficiency and Renewable Energy at the US Department of Energy. Greg also served as Managing Director for the multi-billion-dollar global clean energy VC/PE firm Good Energies, where he led investments in energy efficiency, smart grid, and green building technologies. Greg served as the Principal Advisor in designing and developing Enterprise Green Communities, the national green affordable housing design standard, the design basis for over 50,000 units of green affordable housing to date. He regularly testifies before and advises governmental entities on clean energy, green cities and financing issues, including recently the US Congress, the World Bank, the Israeli Knesset, and the National Academy of Sciences. He is a founder of the country's first green bank, is a founder of the American Council on Renewable Energy (ACORE), and Chairs the Congressionally established advisory board guiding the greening of 430,000 federal buildings. Greg earned an MBA from Stanford University, an MPA from Princeton University, and a BA from UNC as a Morehead Scholar. He is a LEED AP and a Certified Energy Manager. A solar PV system powers his DC family home and electric car. His prior work on cost-benefit analysis includes:

- March 2016 testimony on the cost effectiveness of DOE's $50 billion loan guarantee program to the joint Subcommittees on Energy and Oversight of the House Committee on Science, Space & Technology
- Greening Our Built World: Costs, Benefits, and Strategies (Island Press, 2010). The book was extensively excerpted by the National Academy of Sciences in its 2011 publication "Achieving High-Performance Federal Facilities"
- Primary Author, Green Office Buildings: A Practical Guide to Development (Urban Land Institute, 2005)
- "The Costs and Financial Benefits of Green Buildings." 2003. Written for a dozen California state agencies. Report findings cited as rationale for 2004 California Executive order requiring all future state public construction and retrofits to be green, for New York City legislation requiring all future public construction to be green, for Boston legislation requiring all private and public construction to be LEED certifiable, etc.
- Co-author, "International Greenhouse Gas Trading Programs: Measurement and Accounting" (Energy Policy, 2003)

Keith Glassbrook is Graduate Associate at Capital E. He has extensive experience in environmental analysis and life cycle assessment. Recently, his life cycle assessment and feasibility study of small wind power in Thailand was published in the journal Energy for Sustainable Development. He supported EPA's biogenic CO2 emissions ruling and analyzed the environmental impacts of biofuels while at RTI International. His background is rounded out with experience supporting solar renewable energy credit documentation at a VC funded solar firm in Washington, DC and securing funding and supporting the launch of a campus-wide bikeshare program at UNC-Chapel Hill. Keith holds a BS in Environmental Science from UNC-CH, where he graduated Phi Beta Kappa with highest distinction. He is currently pursuing an MEM at the Nicholas School of the Environment at Duke University and an MBA at Kenan–Flagler Business School at UNC-CH.

Executive Summary

How cities manage the sunlight and rain that falls on them has a huge impact on inhabitants' health and quality of life. But city leaders and planners generally do not manage or even think about their city's rain and sun in a systematic way and, as a result, mismanage or undermanage these two great natural gifts. This mismanagement costs cities billions of dollars in unnecessary health, energy-, and stormwater-related costs, degrades city comfort, livability and resilience, and contributes to climate change. These costs take the heaviest toll in low income areas, which are characterized by less greenery and greater unwanted summer absorption of sunlight, resulting in increased temperatures, worsened air pollution, and increased health costs.

This report provides an in-depth analysis of the costs and benefits of cool and green roofs, solar PV, cool and porous pavements, bioretention and expanded tree cover and combinations of these solutions at scale across Washington, DC (the District). Table E1 below summarizes the report's main findings about the cost-effectiveness of these surfacing solutions. The District could reap net benefits of at least 5 billion dollars over 40 years by widely adopting cool roofs, green roofs, solar PV, bioretention, rainwater harvesting, reflective pavements, permeable pavements, and urban trees. Benefits valued include energy cost savings, improved air quality and public health, reduced stormwater runoff, climate change mitigation, and increased resilience and employment.

Table E1. Summary of the present value of costs and benefits for the District

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015$)
COSTS	**$890,546,000**
BENEFITS	**$2,942,239,000**
NET PRESENT VALUE	**$2,051,693,000**

In addition to the above rigorous estimates, a first order estimate of the impact of climate change on tourism indicates that District adoption at scale of these technologies can avoid about $3.1 billion in lost tourism spending (including $335 million in city tax revenue). This indicates total net present value for the District of adopting the technologies described in the report of about $5 billion. Because there are a large number of additional benefits that would result from broad adoption of these technologies but that we could not quantify due to lack of data, $5 billion NPV can be considered a conservative estimate. That is, the net benefits of large scale deployment are almost certainly substantially larger than presented here.

Urban resilience includes anticipation of threats from climate change and investments to make a city less vulnerable and more able to handle and recover from threats. And because most of the world's population lives in cities, and cities are responsible for most global warming, urban resilience necessarily also means sharply reducing the causes of climate change - specifically reducing greenhouse gas emissions. This includes increased energy efficiency and generating renewable energy to displace fossil fuel usage. It also means making urban surfaces more reflective so incoming sunlight and heat is bounced back into space rather than absorbed and released as heat

The set of measures analyzed in this report are complementary and provide greater resilience benefits in combination and when deployed at scale city-wide and region-wide. For example, high albedo surfaces bounce incoming heat/sunlight back into space, both reducing global warming and reducing urban temperature directly. Lower urban temperature increases electricity output from solar PV panels. PV panels on roofs shade roofs, so less heat reaches buildings, reducing air conditioning related energy use and improving indoor comfort. Locating PV systems on green roofs reduces PV panel temperature, thus increasing output of renewable electricity, while partial shading of green roofs by PV panels improves growth of green roofs, in turn making green roofs work better at water management and lowering risk and cost of extreme rain events.

While this work can and should be expanded on, the findings are compelling. The District can achieve large gains in improving resilience, health and comfort, lower energy bills, and mitigating climate change with large financial paybacks. The opportunity cost for DC, already a national and international sustainability leader, for not acting promptly and comprehensively would be large.

The opportunity and need

The District's 61 square miles of surface is comprised of almost 16% roofs and over 24% paved area. As a result, the District, like most cities, suffers from higher summer temperatures and lower air quality[1] than surrounding suburban and rural areas. The impacts of higher summer temperatures and air pollution are particularly acute in low income urban areas where residents tend to live in inefficient buildings (sometimes without air conditioning) and disproportionately suffer from respiratory and other health problems (often exacerbated by poor air quality). In 2005, science writer Ernie Hood noted in *Environmental Health Perspectives* 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."[2] Research shows that the urban poor suffer disproportionally from the urban heat island effect because they have a higher likelihood of residing in inefficient homes.[3]

Some cities have begun programs supporting adoption of cool roofs and reflective pavements to cool the urban environment and lower energy bills, promotion of green roofs and trees to reduce stormwater runoff and cool the city, and investment in rooftop solar PV to generate electricity and reduce air pollution. Washington DC has been a national leader on a broad range of sustainability efforts and commitments, including in the areas of green buildings, an innovative city-wide stormwater program, purchasing of solar power, and relatively aggressive green and climate change targets that touch almost every aspect of the District. But even in progressive cities like Washington D.C., adoption of cool and green roofs and porous or high albedo roads and parking and similar measures is fragmented and very limited.

Limited adoption reflects limited understanding of costs and benefits. Until this analysis, there has been no established methodology for estimating the full costs and benefits for cool roofs, green roofs, solar PV, reflective pavements, and urban trees. And therefore there has been no way for cities to evaluate the cost-effectiveness of deploying these solutions. A large and poorly quantified part of the benefits of these surface solutions relates to health. This analysis draws on multiple methods, studies, and models to develop an integrated methodology for understanding and estimating the health impacts of surface solutions. This report shows that these solutions could go a long way towards cost-effectively reducing health and energy costs while increasing employment, resilience, and livability.

Summary of findings

The payback time for different surface solutions varies a great deal: cool roofs offer very fast payback in all cases, while several other solutions offer the largest net benefit on a per square foot basis. Overall, the net present value that can be rigorously quantified of the District deploying these solutions broadly is about two billion dollars over 40 years (see Table E2). When societal benefits are included, all technologies analyzed have a benefit-to-cost ratio greater than one (see Table E3). This analysis does not capture the full set of comfort, health, and livability benefits.

Table E2. Detailed summary of the present value of costs and benefits for the District

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015$)
COSTS	**$890,546,000**
First cost	$583,879,000
Operations and maintenance	$206,523,000
Additional replacements	$98,600,000
Employment training	$1,546,000
BENEFITS	**$2,942,239,000**
Energy	$346,754,000
Financial incentives	$65,604,000
Stormwater	$1,438,893,000
Health	$524,131,000
Climate change	$454,110,000
Reduced portable water use	$15,868,000
Reduced salt use	$693,000
Employment	$112,056,000
NET PRESENT VALUE	**$2,051,693,000**

Table E3. Benefit-to-Cost Ratio summary for each solution in the District

TECHNOLOGY	BENEFIT-TO-COST RATIO
Cool Roofs	7.3
Cool Roofs + Bioretention	3.4
Cool Roofs + Rainwater Harvesting	3.9
Green Roofs	2.0
PV (Direct Purchase)	1.8
PV (PPA)	Immediate payback/no out of pocket cost
Reflective Pavements	2.6
Permeable Pavements	14.2 (Reflects high DC water fees for new impervious surfaces)
Urban Trees	3.4

In addition to the rigorously (and somewhat conservatively) estimated NPV of $2.05 billion dollars, a first order estimate of the avoided cost due to lowered heat impact on tourism indicates that the District can avoid an additional $3.1 billion in lost tourism spending (including $335 million in tax revenue for the city). This indicates total net present value for the District of adopting the technologies described in the report of about $5 billion. Because there are a large number of additional benefits that would result from broad adoption of these technologies that we could not quantify due to lack of data, $5 billion NPV can be considered a conservative estimate. That is, the net benefits of deployment are almost certainly substantially larger than presented here.

This report quantifies a large range of cost and benefits from these solutions, many of which have never been rigorously quantified before. This includes detailed mapping of financial savings from health benefits. This is an area that is beginning to get attention in the general press. For example, a recent New York Times editorial entitled “Temperatures Rise, and We’re Cooked” reports recent 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”.[4] Clearly the consequences of excess urban heat is large, but integrated cost-benefit analysis of smart surface solutions on urban productivity and on measurable quality of life and economic impact has not been done to date. To address this, we worked with and consulted with national and city partners, epidemiologists, technology, stormwater, and energy experts and others to assemble the data and methods to build an integrated and rigorous cost-benefit model. While this work can and should be expanded on, the findings are compelling. The District can achieve large gains in improving health and comfort, reducing energy bills, and mitigating climate change with very attractive economic paybacks. And as smart surface strategies spread to adjacent areas, the urban cooling benefits will also grow proportionally and impact energy bills, smog, health and livability in ways that bring expanded benefits, especially to low income areas.

This report starts with a brief overview of the Phase 1 report on building level impact conducted for DGS on DC owned buildings. This is followed by an introduction to the report findings on solutions and impacts and then a dive into the cost and performance attributes of each individual solution. Following the solution descriptions, this report reviews methods—which are detailed more comprehensively in the Appendix—and then summarizes and discusses the results. The report concludes with key findings. The findings should enable, motivate, and guide District policies that support and enable city-wide adoption of the most cost-effective mix of these solutions to achieve broad livability, environmental, equity, and economic benefits. We have included detailed methodology for each component of the analysis to help other cities understand, evaluate, and estimate the full costs and benefits of smarter city surface solutions to promote city-wide policies that can achieve large health, livability, economic, and environmental benefits.

More broadly, as the District adopts these technologies as a city-wide strategy for all built surfaces it will motivate adjacent cities and jurisdictions to follow suit, and the lower urban heat in adjacent regions will in turn lower air temperature in DC. Thus both within the District and across the larger region broad adoption of these technologies brings additional and compounding benefits. In this report we were able to quantify only some of the compounding benefits from DC deployment. For example, we did not calculate the secondary benefits to DC of region-wide adoption of these technologies accelerated because of DC leadership. The financial benefits to the District would be large – on the order of billions of dollars – and are not calculated in this report.

All costs and benefits in this report are presented in present value, with explicit assumptions on term and discount rate. Assumptions are explicit throughout the text, and in all cases, this report provides references and, where available, links. All dollar values are presented in 2015 dollars unless otherwise noted. The Appendix includes net present value per square foot estimates that should enable solution and policy choices to be compared to each other and/or be aggregated into neighborhood-wide or city-wide estimates so that the District can make informed decisions about deploying these solutions at scale.

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 city-wide design choices in the District—and help drive these choices across the larger region.

Report genesis and aspiration

This report grows out of discussions on the Mayors Green Ribbon Task Force. [5] Capital E developed this work scope with DC and initially started with an analysis that demonstrated the cost- effectiveness of smart surface solutions for DC owned buildings and then extended to this city-wide analysis - which has broader implications. The Chesapeake Bay Foundation's "Save the Bay" fall 2016 edition 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"[6]. (The article, entitled "Polluted Runoff" elegantly describes the use of porous vs nonporous surfaces as a contrast between using landscape as a filter to recharge groundwater vs as a gray funnel channeling pollution into our waterways.) The benefits of adopting these technology options on a region-wide basis is far larger for the region and for DC if these practices are adopted region-wide. Similarly, other areas in the region would greatly benefit when DC and their other neighbors also adopt city or jurisdiction-wide smart surfaces and roofing options.

This report is intended to help the District and the larger DC region better understand and value the large range of benefits resulting from city wide deployments of these strategies. Put differently, the findings of this report should enable recognition of a far fuller set of net benefits and the compelling cost effectiveness of most of these technologies, and enable a rapid adopting of these technologies as city wide standard practice. This report quantifies over a dozen financial benefits for the first time. Comprehensive adoption would enable the District and other cities to greatly improve quality of life, address structural inequality challenges, improve livability, cut costs, contribute to slowing climate change, cleanup the Chesapeake and become more resilient. The opportunity cost for DC - already a national sustainability leader - of not acting would be large. As DC seeks to build on its green leadership this regional impact aspect of its decisions should be an important factor in motivating broad and rapid adoption of these technologies on a city wide basis for all built surfaces.

Will Baker, President of the Chesapeake Bay Foundation observes that this report… "demonstrates that these strategies have large health, resilience, livability and financial benefits that have to date been very poorly understand and largely ignored. These strategies should be adopted city-wide by all cities including those that border or drain into the Chesapeake. Doing so would provide enormous net benefits for the cities and for the Chesapeake Bay. This report demonstrates that these strategies are extremely cost effective and should be rapidly adopted throughout the entire Chesapeake Bay region as a matter of prudence, good policy and common sense.” [7]

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1 Introduction

Cities suffer from worse air pollution and higher summer temperatures than surrounding suburban and rural areas. Residents of Washington, DC (the District), who are already suffering through hotter and more humid summers due to climate change,[8] are projected to experience substantial increases in the number of days above 90°F, 95°F, and 100°F.[9] The number of days above 100°F is expected to increase four- to nine-fold (see Figure 1.1).[10] Summer daytime maximum temperature will rise from 87°F now by 2.5-3 degrees by the 2020s and by 5-7 degrees by the 2050s. The heat index, which combines relative humidity with ambient air temperature to determine how hot it feels, will rise sharply. From a baseline of 29 days per year from 1981-2000 with heat index over 95°F, is projected to rise to 50 days by the 2020s and 70 or 80 days by 2050. [11] This would make outdoor DC essentially unlivable for many people in the summer months. Under business as usual carbon dioxide emissions, the District is projected to be 10.3°F hotter by 2100, the equivalent of current summers in the Mexican border town of Pharr, Texas.[12] Higher temperatures will threaten summer tourism and will increase smog formation and cooling energy use, further threatening District livability in the summer. The impacts of air pollution and higher summer temperatures are particularly acute in low income urban areas where residents tend to live in inefficient buildings (sometimes without air conditioning) and disproportionately suffer from respiratory and other health problems (often exacerbated by poor air quality).

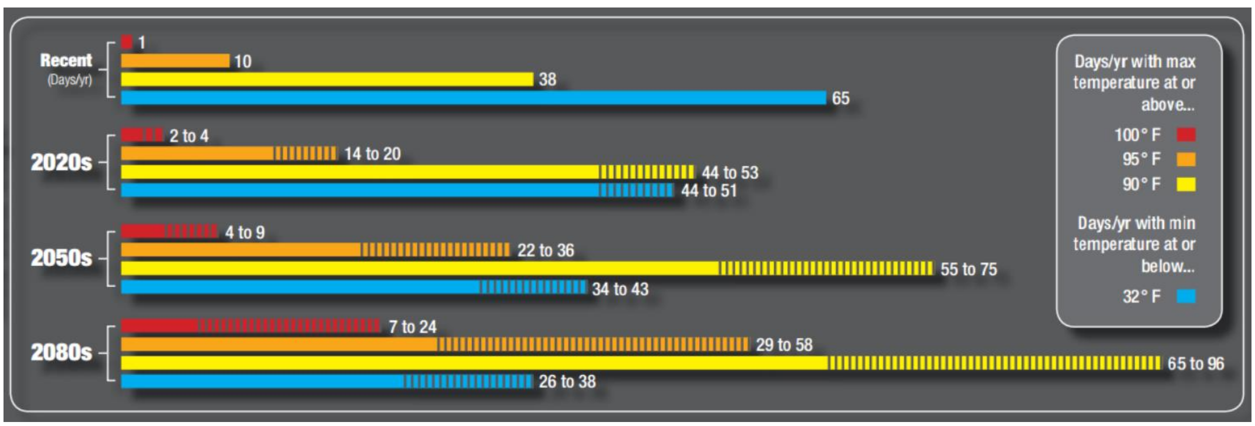

Figure 1.1. Project increase in hot and cold days in the District[13]

Fortunately, the last few decades have seen the emergence of a set of roof and surfacing solutions that could go a long way to reducing these environmental, health, and energy costs. These solutions include: cool (reflective) roofs to cool the urban environment and lower energy bills; green (vegetated) roofs to reduce stormwater runoff, cool the urban environment, and lower energy bills; and rooftop solar photovoltaics (PV) to generate electricity and reduce air pollution. These smart surface solutions can be installed together to achieve large benefits. Urban trees, usually thought of primarily as a way to beautify cities, are increasingly being recognized for their ability to help manage stormwater runoff, cool the urban environment, reduce smog, and lower energy bills. Cool (reflective) pavements, a technology still in its infancy, can also be used to cool the urban environment. Permeable pavements are already being used to manage stormwater runoff and may cool the urban environment.

These solutions are increasingly being deployed in pilot and subsidized programs by cities, including the District, to reduce the cost of stormwater treatment, cut utility bills, lower summer ambient air temperatures, improve air quality, and reduce CO_2 emissions. However, these initiatives tend to be standalone or pilot projects limited in application and scope, reflecting the very incomplete current understanding of their benefits.

Until this analysis, there has been no established methodology for estimating the full costs and benefits (including health benefits) for these roof and surface solutions. This report is intended to fill this critical industry and policy knowledge gap and to enable smarter and more cost-effective and comprehensive building and community policy, design, and investment choices as a way to address widespread health and environmental issues, as well as issues of affordability and climate change.

The District Department of General Services (DGS) hired Capital E in 2013 to undertake a cost-benefit analysis for the District's Smart Roof Program. Smart Roof was an initiative to improve the sustainability and durability of more than 400 District-owned and operated buildings. In this report, funded by DGS and then the Department of Energy & Environment (DOEE), we analyzed District public buildings and pavements city-wide. Based on current climate change projections, the District risks becoming intolerably hot for several months each summer. This report maps a cost-effective pathway to mitigate much of this projected heat gain while cutting energy bills, reducing stormwater management costs, reducing greenhouse gas emissions, increasing employment, and making the city greener and more livable. This work reflects and builds on the District's commitment to serve as an urban sustainability leader for cities globally.

1.1 Overview of report structure

A note on benefits estimation

To convey sometimes complex impact pathways, we have developed a visual representation approach that illustrates directionality of the impact (i.e., increase or decrease) and the sequential, causal steps that lead to the impact. Each element is labeled in these figures. Figure 1.2 shows a simple example for the thermal comfort impacts of urban trees, discussed in Section 10.2.7.

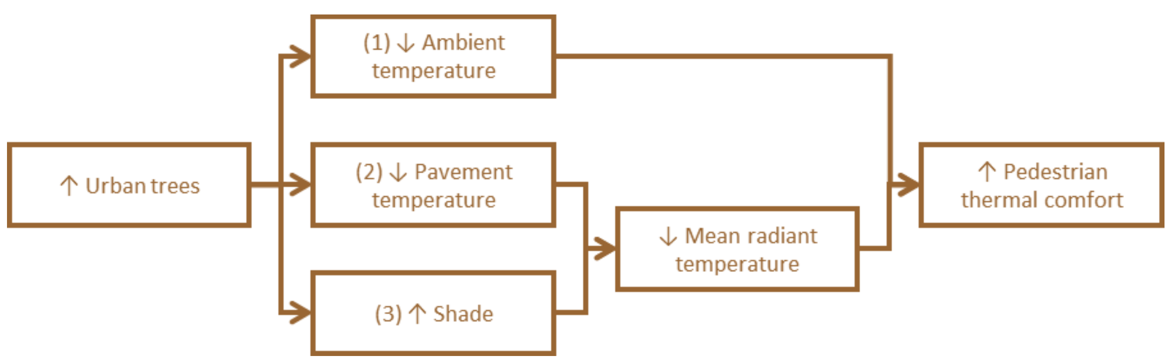

Figure 1.2. Example of simplified, illustrated impact pathway (up arrow indicates increase, down arrow indicates decrease)

Health impacts are generally large and complex, and have generally not been estimated or valued for the roof and surface solutions analyzed in this report. 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 the health impacts.

This report provides a preliminary estimate of the employment impact of the roof solutions. Due to the relatively small scale (i.e., city scale) compared to typical employment analyses that are on the scale of states or countries, this report makes conservative assumptions about how many jobs actually accrue to District residents.

As detailed and documented in this report, the net present value of adopting this set of solutions city-wide can be fairly rigorously estimated to be $2 billion over a forty-year period (see **Error! Reference source not found.**).

Table 1.1. Detailed summary of the present value of costs and benefits for the District

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD
COSTS	**$890,546,000**
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Climate change	$454,110,000
Reduced portable water use	$15,868,000
Reduced salt use	$693,000
Employment	$112,056,000
NPV	**$2,051,693,000**

Many additional benefits are not included in this analysis, including potential for cooling and shading to reduce economic losses from excess heat. To begin to get at the scale of potential value of reducing the costs of increasingly extreme summer heat, this report includes an assessment of the avoided summer tourism losses that could result from adoption of smart surface solutions. A first order estimate of just the avoided loss of summer tourism revenue from adopting the smart surfaces solutions is in excess of $3 billion in visitor spending and $335 million in District tax revenue over forty years. This is a much less exact estimate than the cost-benefit values developed in the rest of the report, but it represents a reasonable, first order estimate. Combined, the net present value is about $5 billion for the District over 40 years.

There are a set of additional benefits and impacts, some of which are significant, that this report does not estimate due to insufficient data and/or lack of existing rigorous studies. Most of the impacts excluded from cost-benefit calculations are benefits, so this report's estimates tend to underestimate the overall value of cool roofs, green roofs, rooftop PV, reflective pavements, permeable pavements, and urban trees. In this sense, the report findings are conservative—they tend to underestimate the net value of the solutions reviewed.

Box 1. Overview of Phase 1

From 2013 to 2014 Capital E worked with DGS to evaluate the costs and benefits of cool roofs, green roofs, and solar PV on District-owned properties—over 400 buildings in the District including office buildings, schools, and hospitals totaling over 28 million SF, with approximately $62 million in annual energy expenditures. The report is available on our website.

Why focus on roofs?

In general, roofs are great candidates for achieving health, energy, and equity policy goals. Roofs typically make up 15 to 25 percent of a cities' surface area. Because roofs get replaced or retrofitted more frequently than buildings, developers and building owners can achieve energy cost savings and other goals relatively quickly.

Results and conclusion

This worked provided the first rigorous and (relatively) comprehensive model to estimate the full costs and benefits of cool roofs, green roofs, and rooftop PV. Its development involved a range of leading health and policy advisors and the development of a multi-level health and benefits valuation model to quantify the full set of costs and benefits of the roof technologies. The analysis provided a powerful approach to understand, integrate, and prioritize city-wide design, demonstrating that a city-wide strategy of adoption of these technologies would have private and public benefits, including providing energy savings for building owners, reducing city peak summer temperatures, improving livability, and providing large public health benefits.

Table B1.1. Present value summary of costs and benefits for the three technologies on all low slope DGS roofs (Notes: all PV is financed with a PPA so there are no upfront or ongoing costs to DGS; results may not sum due to rounding)

COMPARISON	Cool compared to Conventional	Green compared to Conventional	Conventional w/ PV (PPA) compared to Conventional
COSTS	$5,580,000	$203,000,000	$0
BENEFITS	$52,100,000	$538,000,000	$294,000,000
Energy	$17,100,000	$21,100,000	$34,500,000
Stormwater	N/A	$482,000,000	N/A
Health	$32,900,000	$31,600,000	$205,000,000
Climate change	$2,110,000	$3,310,000	$54,700,000
NET TOTAL	$46,500,000	$335,000,000	$294,000,000

We recommended an expanded analysis to extend from District owned buildings to all public and private buildings in the District and incorporate residential as well as commercial buildings. We believed an expanded study could address additional benefits including quantifying benefits of resilience and increased employment. As temperature extremes continue to rise, the District will be faced with increasingly severe heat and weather events and increased pressure to make building and systems resilient. The potential for reductions in peak temperature, ozone concentration, and other health related costs indicates that a city-wide policy of extending cooling strategies (e.g., cool pavements, street trees) to other built areas, including roads, pavement and sidewalks, could yield large financial and health benefits at relatively low cost. This led to this analyses at the city-level in the District.

2 Background

This section provides an overview of the solutions analyzed as well as general background information relevant to understanding cost-benefit assumptions and calculations. For more detailed descriptions and discussions, please refer to the solution-specific sections and to the Appendix.

2.1 Urban heat islands

Urban areas commonly experience higher temperatures than their rural surroundings. This temperature difference is called an urban heat island (UHI) and is caused by several factors. The primary cause of UHIs is the replacement of natural, vegetated land with dark, impervious 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 air conditioners and urban morphology (the dimension and spacing of buildings that tend to trap urban heat).[14]

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 day and in the summer, though still persist during the night.[15] 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) but can also be significant during the day, especially in the afternoon when cities typically experience peak temperatures.[16] Figure 2.1 shows a simple atmospheric UHI profile and Figure 2.2 shows a more sophisticated illustration with surface and atmospheric UHIs and differences between day and night.

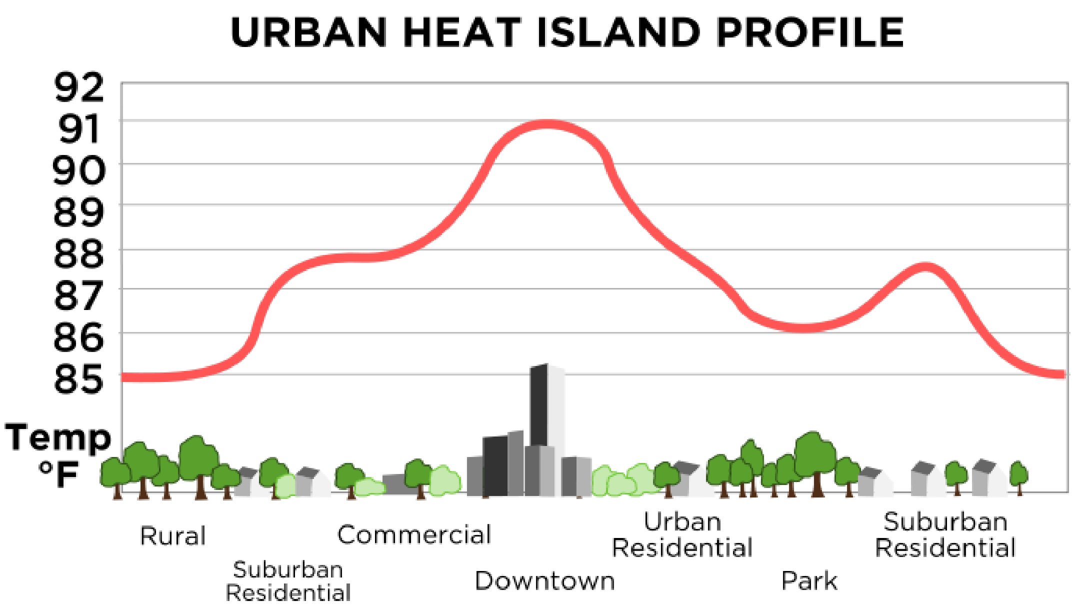

Figure 2.1. Simple illustrative example of urban heat island profile[17]

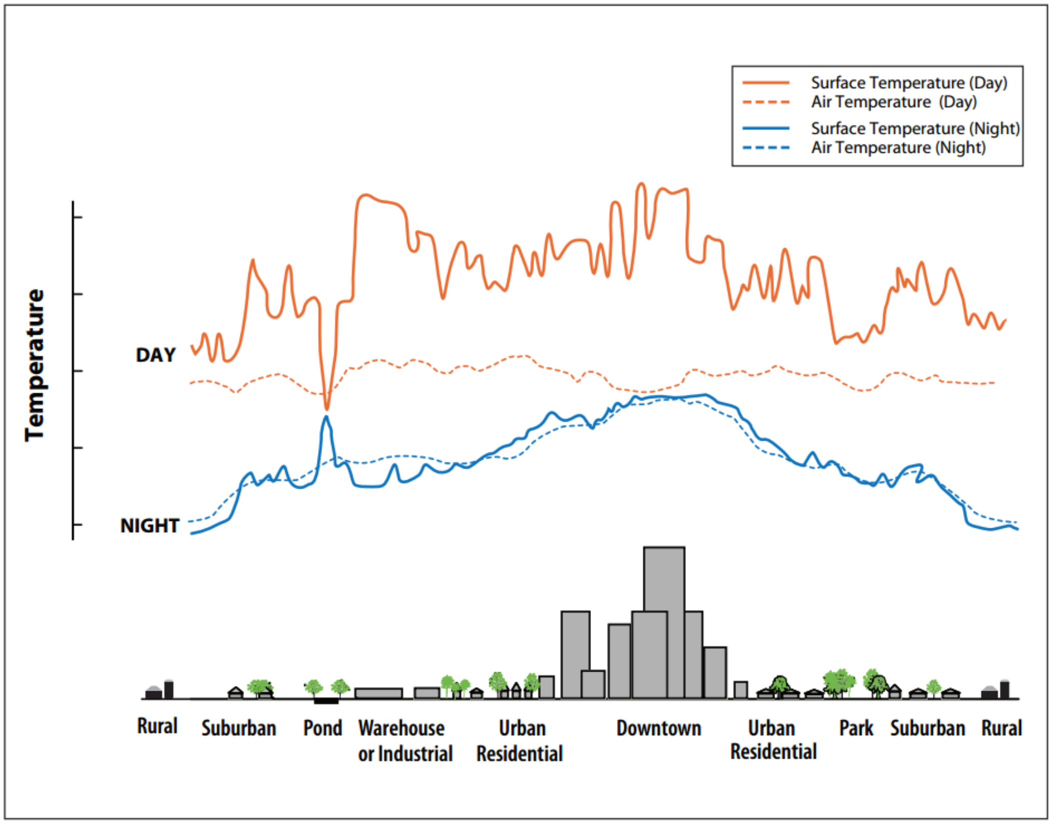

Figure 2.2. More sophisticated illustrative example of urban heat island profile[18]

There are two types of atmospheric UHIs: canopy layer (or near-surface) and boundary layer.[19] Boundary layer UHIs extend from the tops of trees and buildings to where the urban environment no longer effects 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.

A recent analysis by Climate Central studied the summertime UHI in 60 U.S. cities.[20] Using data from 2004 to 2013, Climate Central found the average summer daytime UHI in the District is 4.7°F. Climate Central also analyzed the average decadal change in UHI from 1970 through 2013 and found that the District's UHI is increasing at a rate of 0.42°F per decade.[i]

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 2.4, in the solution-specific sections, and in the Appendix.

2.2 Climate change projections

In 2015, weather.com released "The weather.com Climate Disruption Index" that ranks the 25 U.S. cities that will be most impacted by climate change.[21] The Index is based on six factors, with sea-level rise given

[i] Note this is not measuring the average decadal change in temperature, it is measuring the average decadal change in the temperature difference between the urban environment and rural surroundings.

the greatest weight and average temperature and precipitation changes given the least weight.[ii] The District is ranked 9th on this list (i.e., the 9th most impacted). In general, the District can expect to become warmer and wetter.

Even under low GHG emissions scenarios, the District can expect increases in temperature, precipitation, and sea level rise due to climate change.[22] Compared to the baseline (1981-2000) daytime summer maximum temperature of 87°F, DOEE predicts the District will warm by 2.5°F to 3°F by the 2020s and 5°F to 7°F by the 2050s (see Figure 2.3). DOEE predicts the same warming trends for summer nighttime minimum temperatures, where the baseline is 66°F (e.g., summer nighttime minimum temperatures will be above 70°F by the 2050s).[iii]

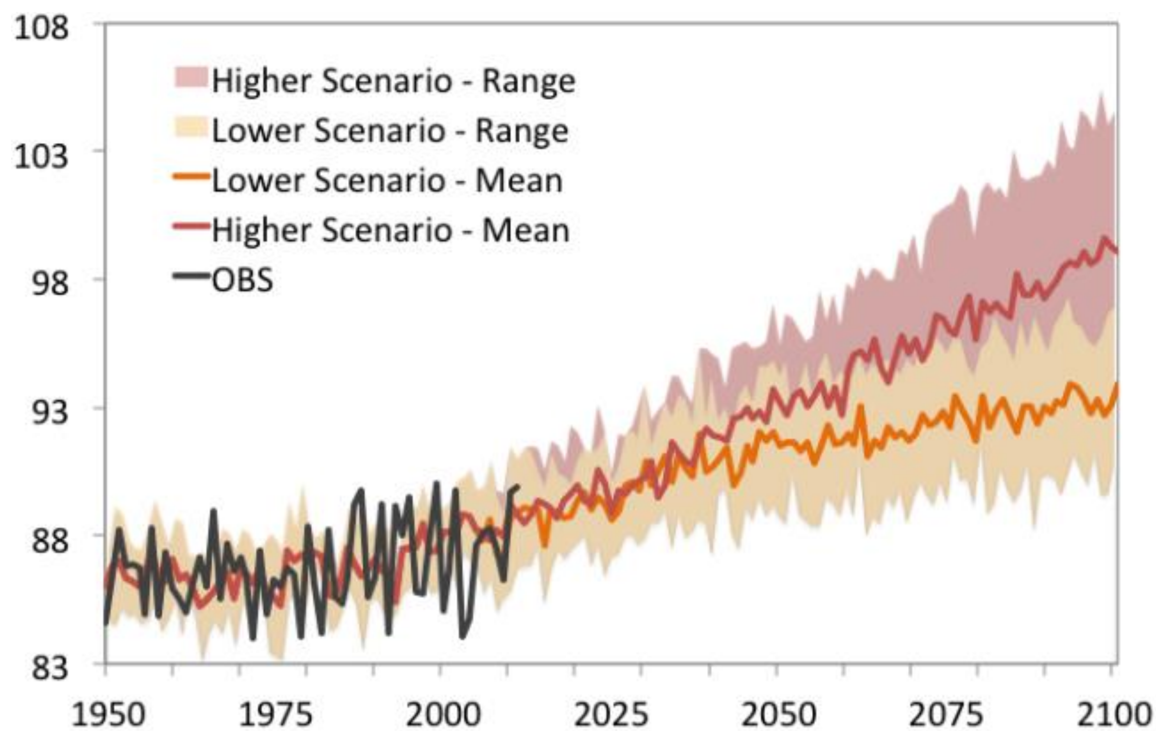

Figure 2.3. Average summer daytime high temperature in the District ("OBS" stands for "observed", "CMIP5 lower" and "CMIP5 higher" designate low and high carbon emissions scenarios, respectively; error bars encompass the range of projections from the nine different global climate models used in 23) [24]

In addition to higher temperatures, the District's Climate Projections and Scenario Development report predicts longer and more intense heat waves.[iv] Extreme heat days (when air temperature exceeds 95°F) will become much more common, with the number of days per year with air temperature above 95°F increasing from a baseline of 11 days to between 18 and 20 days by the 2020s and between 30 and 45

[ii] The weather.com Climate Disruption Index factors include (weights in parentheses): sea-level rise (2.0 with an additional multiplier for cities along the Atlantic and Gulf coasts, to account for potential effects from hurricanes), extreme precipitation (1.0), extreme drought (1.0), urban heat islands/extreme heat (1.0 with an additional multiplier for inland cities, to account for land-sea breeze effect), average temperatures changes (0.5), and average precipitation changes (0.5). Note that different weights could yield a different ranking.
[iii] For an illustrated view of temperature projections, see Climate Central's *1001 Blistering Future Summers*, which predicts the District will feel like South Texas by 2100.
[iv] Recent modeling studies show that heat waves exacerbate UHIs (e.g., Li and Bou-Zeid, 2013).

days by the 2050s (see Figure 2.4). In other words, the number of extreme heat days in the District is expected to at least triple by the middle of the century. The heat index, which combines ambient air temperature and relative humidity into a value that represents how hot the air feels, will also increase. DOEE predicts the number of days per year with a heat index above 95°F will increase from a baseline of 29 to around 50 by the 2020s and between 70 and 80 by the 2050s (see Figure 2.4). And under business as usual emissions, Climate Central predicts the number of days per year with a heat index above 105°F will increase almost five-fold, from 10 in 2000 to 49 in 2050.[25]

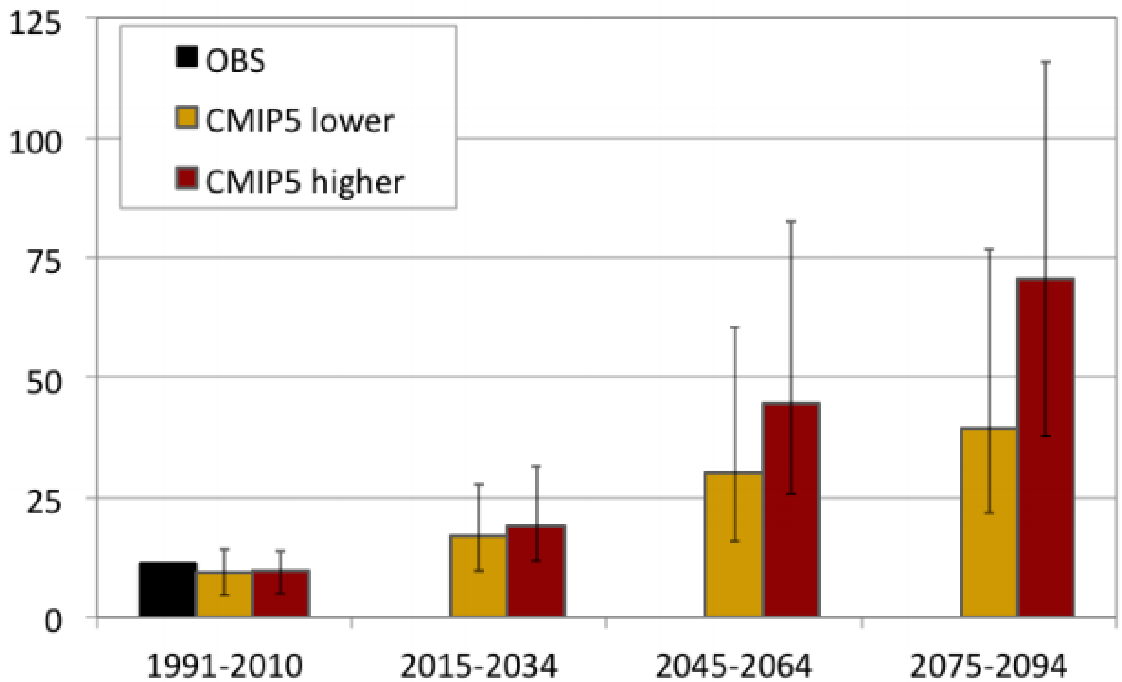

Figure 2.4. Number of days per year with maximum temperature above 95°F ("OBS" stands for "observed", "CMIP5 lower" and "CMIP5 higher" designate low and high carbon emissions scenarios, respectively; error bars encompass the range of projections from the nine different global climate models used in 26)

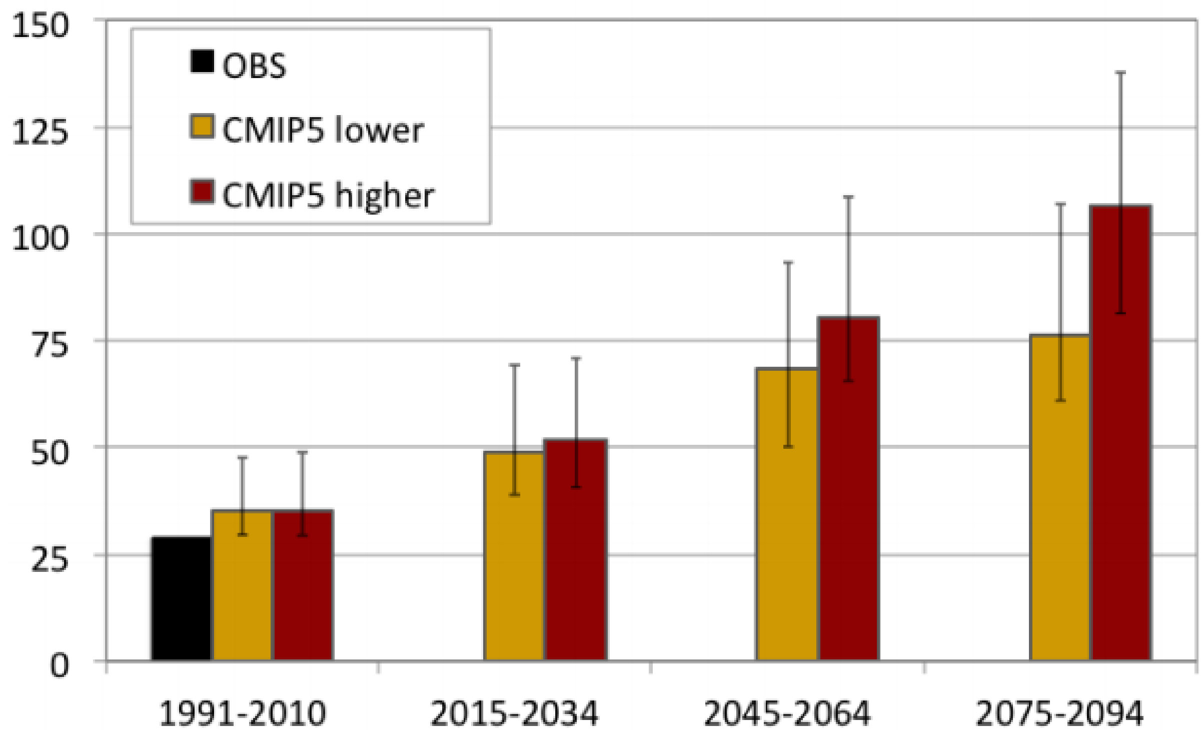

Figure 2.5. Number of days per year with maximum heat index above 95°F ("OBS" stands for "observed", "CMIP5 lower" and "CMIP5 higher" designate low and high carbon emissions scenarios, respectively; error bars encompass the range of projections from the nine different global climate models used in 27)

These temperature increases will severely strain the city's infrastructure, including increasing cooling energy use, reducing comfort, and increasing risk of heat-related deaths. This underlines the need to prioritize urban cooling measures (like those analyzed in this report) in policy making and planning. The District must do so if the city is to continue to be tolerable during the summer.

DOEE predicts that extreme precipitation events will increase in frequency and intensity and that sea level rise will continue and even accelerate.[28] DOEE predicts that the average number of days per year with total precipitation greater than 2 inches in a 24-hour period will increase from 1 day a year to 3.5 days per year by the 2050s. Perhaps more importantly, the size and frequency of "design" storms, which engineers and designers use to appropriately size stormwater infrastructure, will increase form 5.3 inches now to 6.8 inches by the 2020s and 7.1 inches by the 2050s. [29] Coupled with the projected sea level rise (see Figure 2.6),[30] this will put an enormous burden on the city's stormwater infrastructure. The District of Columbia Water and Sewer Authority (DC Water) is already investing $2.6 billion in the Clean Rivers Project to largely eliminate the roughly 2 billion gallons of sewage that the District releases into its rivers each year.[31] Part of this is a nationally leading effort expanding use of green infrastructure to cut water runoff. But rising severity and frequency of storm size and rainfall means that these infrastructure investments will be increasingly unlikely to be able to handle stormwater runoff and sewage overflow, resulting in continued river contamination and requiring further water infrastructure investment.

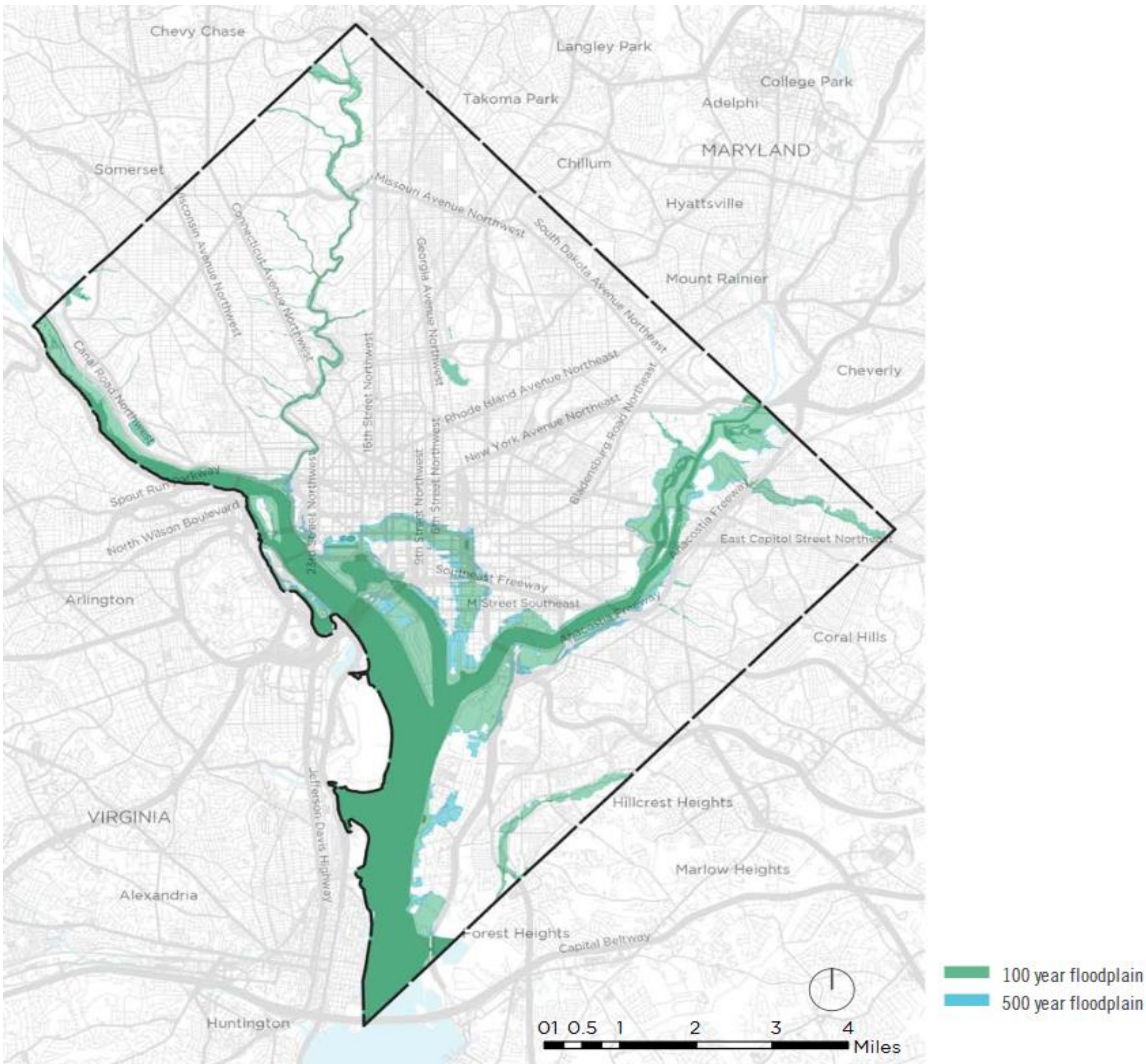

Figure 2.6.FEMA flood insurance rate maps, 100-yr and 500-yr Floods (FEMA map overlaid on GIS map base, Kleinfelder, 2015 From: Perkins + Will and Kleinfelder, 2016

2.3 Overview of solutions

This section provides an overview of the solutions analyzed in this report, including a summary of the major benefits each solution provides. More detailed descriptions of each solution and their impacts can be found in the solution-specific chapters.

Roofs

Most conventional roofs are dark and absorb a large majority of solar radiation that falls on them. Reflective roofs (commonly referred to as "**cool**" **roofs**) are roofs with a higher solar reflectance than conventional roofs. Because of their higher solar reflectance, cool roofs 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, resulting in lower air conditioning use and reduced summer ambient air temperatures. Cool roofs also reflect more sunlight back into space, effectively avoiding global warming. For a more in-depth discussion of cool roofs, refer to Section 3.

The vegetated extensive roofs (commonly referred to as "**green**" **roofs**) analyzed in this report generally have a similar underlying structure as conventional roofs but, importantly, differ in the addition of plants, soil (called "growing media" or "growing medium"), and more robust waterproofing and drainage. Green roofs stay cool through evapotranspiration and shading. They also have higher thermal mass than traditional roofs, meaning green roofs take longer to heat up and cool down. Together this means that buildings with green roofs have lower summer air conditioning loads and lower winter heating loads. Evapotranspiration on green roofs also cools the air, resulting in lower ambient air temperatures and reduced air conditioning use. The plants and growing medium soak up some of the rain that falls on a green roof, which reduces stormwater runoff volumes and results in reduced runoff peaks and delayed peak runoff times, reducing the burden on city stormwater management systems and reducing pollution of local water bodies. For a more in-depth discussion of green roofs, refer to Section 4.

In addition to cool roofs and green roofs, this report examines the costs and benefits of cool roofs combined with ground-level stormwater management: bioretention and rainwater harvesting systems. **Bioretention** systems are depressed areas with native plant cover on top of a layer of special soil (called "filter media") and a gravel layer (sometimes referred to as a "storage layer"). Bioretention can take many forms including streetscape bioretention, engineered tree pits, stormwater planters, and residential rain gardens. Stormwater planters are particularly useful for managing runoff from rooftops. In addition to the obvious stormwater benefits, bioretention can also cool the air through evapotranspiration, lowering ambient air temperature, air conditioning use, and associated energy costs. For a more in-depth discussion of bioretention, refer to Section 5.

Figure 2.7. Traditional bioretention (top left); streetscape bioretention (top right); engineered tree pit (bottom left); stormwater planter (bottom middle); residential rain garden (bottom right)[32]

Rainwater harvesting systems have several components, most prominent of which is the storage tank, or cistern. Rainwater harvesting systems collect and store rainwater, most commonly from roofs, for future use. They can be located inside or outside. Stored rainwater is generally used for non-potable uses, such as irrigation, toilet flushing, and cooling. Rainwater harvesting can also be combined with other stormwater management practices that infiltrate the stored rainwater. In addition to reducing the volume and time of peak stormwater runoff, rainwater harvesting can reduce a building's use of potable water, reducing water bills. Moreover, lowerd building water use reduces the energy used by the water utility to treat, transport, and deliver potable water. For a more in-depth discussion of rainwater harvesting, refer to Section 6.

Figure 2.8. An outdoor rainwater harvesting system[33]

Rooftop solar photovoltaics (commonly referred to as **rooftop** "**PV**") are photovoltaic (PV) panels mounted on a roof. PV panels are made up of photovoltaic cells that convert sunlight directly into electricity. Combined with an inverter and/or battery system that converts this electricity into a usable form, rooftop PV allows buildings and cities to become less reliant on the grid for electricity needs. For a more in-depth discussion of rooftop PV, refer to Section 7.

Figure 2.9. Cool roof (top left);[34] *green roof (top right);*[35] *solar PV (bottom)*[36]

Other surfaces

Reflective pavements (sometimes referred to as "cool" pavements) are similar in concept to cool roofs. That is, they have a higher solar reflectance than conventional pavement (i.e., asphalt and concrete), and thus absorb less solar energy. This means they stay cooler and so transfer less heat to the surrounding air, resulting in ambient cooling and reduced summer cooling loads. For a more in-depth discussion of reflective pavements, refer to Section 8.

Figure 2.10. Reflective pavement on a parking lot[37]

Impervious pavements are designed to shed water quickly and to prevent water from infiltrating to layers beneath the surface layer as this can damage the pavement and cause it to fail. **Permeable, pervious, and porous pavements** (hereafter referred to simply as permeable) are designed to do the opposite. The surface of permeable pavement allows water to infiltrate to subsurface layers and be slowly conveyed to the stormwater system and/or infiltrated into the underlying soils, reducing and delaying peak stormwater runoff. Beyond stormwater management, other benefits of permeable pavement are less well understood. For example, when moisture is in the surface layer, evaporative cooling can occur, cooling the air. However, when dry, there is some evidence that permeable pavement's surface is hotter than the impervious equivalent, possibly leading to warming.

Common types of permeable pavements are porous asphalt, pervious concrete, and permeable interlocking concrete pavers (often simply called "permeable pavers"). In theory, permeable pavements can be used in all the same applications as impervious pavements, but typically are used for sidewalks, driveways, patios, parking lots, parking lanes, alleys, and low traffic roads. This report focuses on permeable sidewalks. For a more in-depth discussion of permeable sidewalks, refer to Section 9.

Urban trees also help cool cities. Trees shade pedestrians and buildings and can provide wind block to nearby buildings, reducing summer cooling loads and winter heating loads, respectively. Similar to green roofs, trees also cool the air through evapotranspiration, reducing summer ambient air temperature and cooling load. Also like green roofs, trees and the surrounding soil absorb rain water, which reduces stormwater runoff volumes, delays peak runoff time, and decreases peak runoff volume, reducing cost of water treatment. For a more in-depth discussion of urban trees, refer to Section 10.

Figure 2.11. Permeable concrete sidewalk[38]

Figure 2.12. Urban street trees[39]

2.4 Overview of impacts

Each solution has different costs and benefits that vary by location, and each has their advocates. But until this analysis the District's government and other organizations have not had a way to evaluate the cost-effectiveness of any of these solutions, either as standalone investments, in comparison with each other, or installed in combination. Perhaps the single largest gap in understanding and quantifying the benefits of these approaches—especially cool roofs and green roofs—is the health-related benefits. Neal Fann of the Environmental Protection Agency (EPA), Lynn Goldman of George Washington University School of Public Health, and John Davies-Cole and Rowena Samala of the District of Columbia Department of Health (DOH) provided invaluable guidance in the development of the health components of this report.

In comparison to the other solutions evaluated in this report, reflective pavements are in their infancy. The science and understanding of the impact of reflective pavements is still evolving. This report uses the available data and literature on reflective pavements to estimate their costs and benefits. As noted earlier, this report details assumptions and identifies remaining uncertainties surrounding the data and impacts of reflective pavements and the other solutions.

2.4.1 A note on direct and indirect impacts

The impacts of modifying the urban environment (e.g., installing reflective pavements, cool and green roofs, and urban trees) may be best understood as falling into two main categories: (1) direct impacts and (2) indirect impacts. Akbari et al. (2001) provides an excellent description of these impact categories.[40]

Direct effects occur at the individual building level. For example, the direct effect of installing a cool roof on a building is a change in the energy balance of the building, reducing cooling load and cooling energy costs. City climate-related indirect effects result from city-wide changes in climate. Significant city-wide cooling requires widespread deployment of smart surfaces. One example of an indirect benefit is the reduced cooling load for buildings that results from ambient cooling.

2.4.2 Energy and greenhouse gases

In the District, grid electricity sources are relatively dirty[41] because the power sources include a lot of fossil-fuel-based electricity generation, especially coal. City greenhouse gas (GHG) emission reductions can be large from the combination of cutting electricity use by expanding cool and green roof areas, reflective pavement area, tree area, and generating power from solar PV. Cool and green roofs directly reduce energy used for space conditioning by reducing building heat gain and,[v] lowering energy bills. Rooftop PV reduces grid electricity purchases, lowering energy bills. For cool roofs and green roofs, much of cooling energy reductions occur during periods of peak electricity demand and can reduce the use of the least efficient and often dirtiest generation.[42] Rooftop PV substantially offsets grid electricity use during peak demand periods (sunny summer afternoons when air conditioning is greatest) thereby reducing utility need to build, maintain, and run peaking power plants. Large scale deployment of cool and green roofs, reflective pavements, and urban trees can reduce urban heat islands. Lower ambient air temperature means lower cooling energy consumption reduced peak electricity demand. Buildings that are more energy efficient maintain comfort longer than less efficient buildings, while buildings that produce their own energy are also more resilient. With rapid growth of building level storage, green buildings powered with PV will be able to operate when the grid is down.

2.4.3 Financial incentives

The District, along with 29 states, has a renewable portfolio standard that requires that a specific percentage of its energy generation come from renewable sources.[43] The District also has a specific solar target.[44] In the District, solar PV system owners and lessees may be credited with renewable energy credits that can be sold by the owner or installer to generate income. In addition to renewable energy credit income, there are other types of financial incentives for solar systems at the federal, state, and local levels (e.g., tax credits).

2.4.4 Health

Ozone

Widespread deployment of cool and green roofs, reflective pavements, and urban trees has large but diffuse health benefits.[vi] Ground-level ozone formation generally increases with higher air temperature, so lower summer air temperatures mean lower levels of ground-level ozone and decreased incidence of ozone-related health impacts—asthma, heart disease, and premature death.[45] Modeling studies demonstrate that ozone concentrations worsen with the higher temperatures caused by climate change.[46] Ozone reductions from ambient cooling due to deployment of these solutions can help offset climate change-related increases. Green roof vegetation and urban trees can also scrub the air of particulates, ozone, and other pollutants.

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[v] Reduced heat loss only applies to green roofs.
[vi] In other words, small risk reductions for lots of people.

Ozone basics

Ozone is a secondary pollutant formed when its two primary precursors, volatile organic compounds (VOCs) and nitrogen oxides (NO_x), combine in the presence of sunlight. Ambient ozone concentration depends on a number of factors, including but not limited to temperature, relative humidity, solar radiation, and wind speed.[47] As temperature increases, the rates of chemical reaction 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.[48]

Ozone concentration is also dependent on the level of VOCs and NO_x in the atmosphere—the rate of ozone production can be limited by the scarcity of VOCs or by NO_x. Ozone precursors are emitted directly into the atmosphere by biogenic (natural) and anthropogenic (human) sources. The largest source of anthropogenic VOCs is motor vehicles.[49] At the regional and global scales, VOC emissions from vegetation are significantly larger than VOC emissions from anthropogenic sources. Combustion processes are the largest source of anthropogenic NO_x emissions—electric power generation and motor vehicles are the two largest sources. Biogenic sources of NO_x are typically much less significant than anthropogenic sources.

Health impacts of ozone

The Clean Air Act of 1963 requires EPA to review the science for ozone, including health effects. In 2013, EPA released its most recent ozone review.[50] In the review, a panel of experts concluded that ozone pollution can cause serious health harm through multiple pathways. The American Lung Association produced a useful summary of EPA's findings (see Figure 2.13). The Appendix to this report provides additional references.

EPA Concludes Ozone Pollution Poses Serious Health Threats

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

—U.S. Environmental Protection Agency, *Integrated Science Assessment for Ozone and Related Photochemical Oxidants*, 2013. EPA/600/R-10/076F.

Figure 2.13. The American Lung Association's summary of the EPA's findings on the health impacts of ozone[51] (Note: COPD stands for chronic obstructive pulmonary disease.)

Ozone and temperature

Climate change is expected to result in increased ozone pollution and consequent negative human health effects. For example, 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.[52] Perera and Sanford (2011) analyzed the ozone-related health costs of climate change in 40 U.S. states and found that a 1 part per billion (ppb) and 2 ppb increase in ozone concentration would increase 2020 health costs by $2.7 billion and $5.4 billion, respectively.[53,vii] Few studies have examined the relationship between UHI mitigation and ozone concentration, and most focus on California.[54] In general, these studies find reductions in ozone concentrations due to UHI mitigation.

$PM_{2.5}$

Reductions in fossil fuel energy use from using any of the solutions analyzed also contribute to reductions in fine particle pollution from power plants and reductions in related health impacts (e.g., heart disease, asthma, and death).[55] Green roof vegetation and urban trees can also scrub the air of PM2.5 pollution.

$PM_{2.5}$ basics

There are two types of fine particles ($PM_{2.5}$). Primary particles are emitted directly into the atmosphere (most commonly from burning fossil fuels); secondary particles are formed through atmospheric chemical reactions of precursors.[56] Primary $PM_{2.5}$ largely consists of carbonaceous materials (elemental carbon, organic carbon, and crustal materials like soil and ash).[57] 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).[58] Secondary particles make up most of the $PM_{2.5}$ pollution in the U.S.[59] Secondary $PM_{2.5}$ is mainly made up of sulfates (formed from sulfur dioxide emissions), nitrates (formed from NO_x emissions), ammonium (formed from ammonia emissions), and organic carbon (formed from VOCs).[60] 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).[61] In the Northeast, the main components of fine particle pollution are organic carbon and sulfates.[62] Coal-fired power plants in the Ohio River Valley release a large amount of sulfates that contribute to $PM_{2.5}$ pollution in the District. This has a significant health cost to the city.

Health impacts of $PM_{2.5}$

The Clean Air Act of 1963 requires EPA to review the science for $PM_{2.5}$, including health effects. In 2009, EPA released its most recent review of $PM_{2.5}$.[63] In the review, EPA's panel of experts concluded that $PM_{2.5}$ pollution can cause serious health harm through multiple pathways. This is described in more detail in the appendix). The American Lung Association summarized EPA's findings (see Figure 2.14). The Appendix to this report provides additional references.

[vii] These cost increases are in 2008$.

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 2.14. The American Lung Association's summary of the EPA's findings on the health impacts of $PM_{2.5}$[64] (Note: COPD stands for chronic obstructive pulmonary disease.)

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.[65] Furthermore, heat waves, which are projected to become more common globally with climate change, including in the District, exacerbate urban heat islands (UHI).[66] 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.[67] Extreme heat was the leading cause of weather-related deaths in the U.S. from 2000 through 2009, accounting for 24 percent of weather-related deaths.[68] Extreme heat events are projected to be more frequent, longer lasting, and more severe as the climate warms.[69] 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.[70] Furthermore, UHIs and climate change together are expected to further increase the number of extreme heat events in cities.[71]

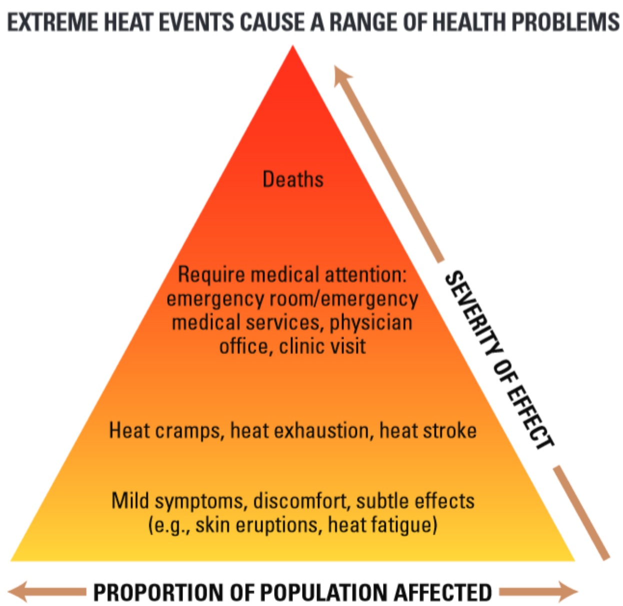

Figure 2.15. The health problems related to extreme heat[72]

In addition to elevated daytime temperatures due to UHIs, cities take longer to cool off at night and do not cool as much compared to rural areas. This means that urban populations often cannot recover from daytime heat and are thus more vulnerable to elevated temperatures in subsequent days.[73]

There are two ways the solutions analyzed in this study can impact heat-related mortality: by improving outdoor conditions (e.g., decreasing outdoor temperatures) and by improving indoor conditions (e.g., by reducing indoor temperatures). Modeling studies have shown that UHI mitigation technologies can decrease urban heat-related mortalities by improving outdoor conditions.[74] However, this report could not find sufficient data/studies to quantify the heat-related mortality impact of changes in indoor conditions from the solutions analyzed in this report, although some reports indicate significant indoor temperature benefits and the impact on indoor conditions appear likely to be significant.[75] This impact is particularly important for District residents in homes without air conditioning (not uncommon in low-income populations) and residents that live on the top floor of buildings.

2.4.5 Stormwater

Many cities, including the District, have stormwater management requirements and incentives to reduce stormwater runoff, especially peak runoff that can result in localized flooding, sewage system overflows, and local water body damage and contamination. DCs Stormwater Credit program makes the district a national and international leader in this area. Green roofs and urban trees stand out as effective managers of stormwater. Peak runoff rate reduction, delayed time of peak runoff, and decreased total runoff from green roofs and urban trees all relieve pressure on aging stormwater infrastructure and reduce water pollution. These types of stormwater management practices are being incentivized in the District's pathbreaking Stormwater Retention Credit Trading Program (discussed more in Section 11.7 and the Appendix) and are being adopted relatively aggressively by DC Water as part of a $2.6 billion investment to largely eliminate sewage overflow into District rivers. But as noted earlier, increasing extreme rainfall events from climate change means these investments will likely be increasingly inadequate.

2.4.6 Employment

Building and sustaining green infrastructure such as cool roofs, green roofs, solar PV, reflective pavements, and urban trees has the potential to create significant new "green collar" employment. Responding to the growth of the green economy, in 2010 the Bureau of Labor Statistics began an effort to define and measure green jobs. They estimated 3.1 million jobs in the green goods and services sectors in the United States in 2011, representing 2.3 percent of the private sector workforce and 4.2 percent of the public sector workforce.[viii] The DC Office of Planning commissioned a green collar job demand analysis for the District that very optimistically predicted 169,000 green jobs would be created between 2009 and 2018 from existing and proposed District green policies.[76] More recently, a more sober and realistic 2014 analysis by the American Council for an Energy Efficient-Economy (ACEEE) estimated that a city-wide commitment to 26% energy use reduction could create 600 net new jobs in the District by 2020 and 1,400 net jobs by 2030.[77]

Labor intensity of green energy is generally much higher than from conventional energy sources. In synthesizing 15 existing studies, Wei et al. (2010) found that all non-fossil fuel energy technologies they studied (including solar PV and energy efficiency) create substantially more jobs per unit energy than coal and natural gas power plants.[78,ix] Another advantage of green energy is that they create more installation, operations, and maintenance jobs than conventional power generation. Unlike centralized coal and natural gas plants, clean energy sources provide local "distributed" employment, including installation and maintenance jobs in the District.

For the District to realize the potentially large employment benefits of an expanded green economy, green jobs would need to go to city residents. Employment studies generally assume that all jobs created go to the state or other jurisdiction where installation occurs. However, this is not a good assumption at a city level because many jobs can be expected to go to people who reside outside the city. This report therefore adopts a more conservative assumption that only half of the District green jobs actually go to city residents. District policies around employment, such as training and District employment incentives and requirements would increase the portion of green jobs going to District residents.

Expanding the deployment of smart surfaces in the District would further expand the growth of green jobs. This is something the District recognizes in its Sustainable DC Plan.[79] For example, DC Water, along with the Water Environment Foundation, is leading development of the National Green Infrastructure Certification Program, which aims to set national certification standards for green infrastructure construction, inspection, and maintenance workers.[80] The city and DC Water have also set a goal that at least 51% of new jobs created from third party employers who work with DC Water as it implements green infrastructure in the District go to District residents.[81]

[viii] Green goods and services jobs are defined as jobs found in business that primarily produce goods and services that benefit the environment or conserve natural resources or jobs in which worker's duties involve making their establishment's production processes more environmentally friendly or use fewer natural resources. In 2013, the BLS eliminated the Green Goods and Services Occupations program due to budget cuts. Therefore, green goods and services jobs numbers for 2011 are the most recent ones available from the BLS.

[ix] For instance, they found average direct employment multipliers of 0.11 job-years per GWh on coal versus 0.87 on solar PV. A job-year is the equivalent of full time employment for one person for the duration of one year.

2.5 Region of analysis

This report analyzes the entire District. Figure 2.16 shows a satellite image of the study area, and Table 2.1 present a map of the District and selected characteristics of the region, respectively.

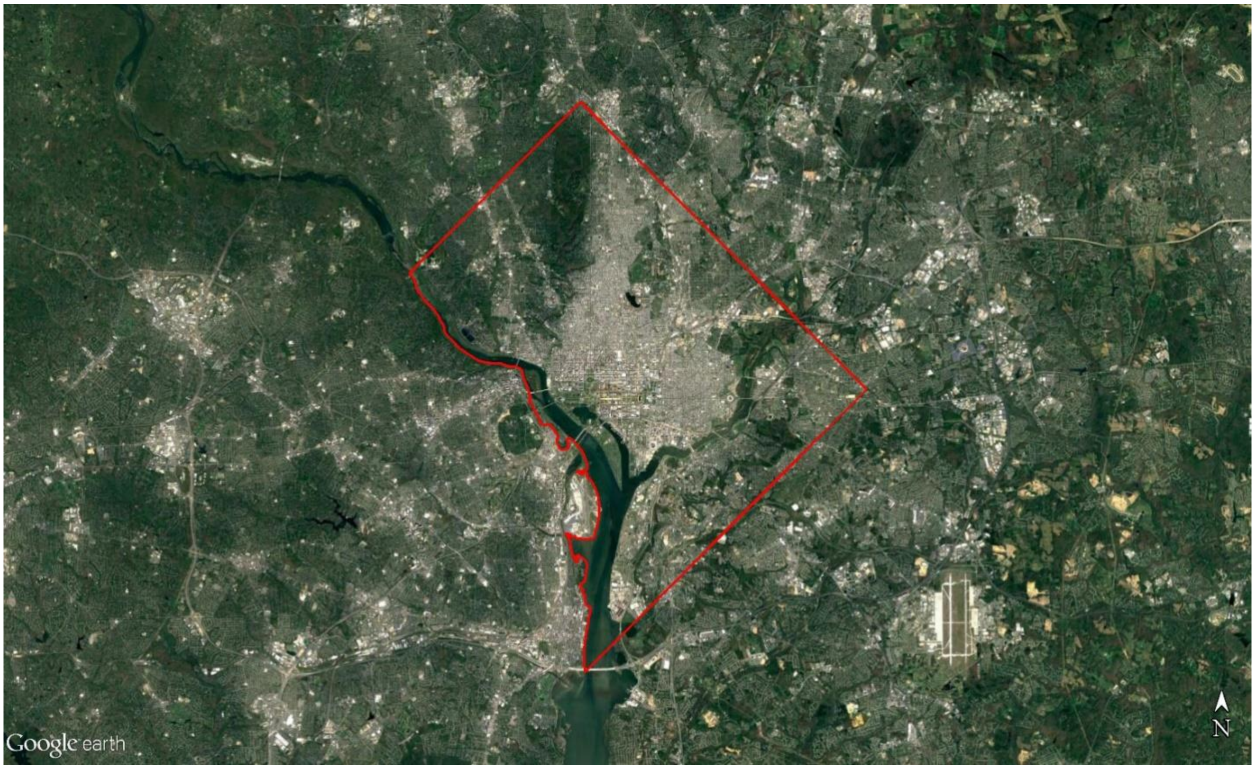

Figure 2.16. Aerial imagery of study area (the study area is outlined in red)

Table 2.1. Selected Washington, DC characteristics

Characteristic	**Washington, DC**
Population (2014)[82]	659,836
Income[83]	
Median income	$69,325
Percent of population below poverty line	18.2%
Unemployment rate	10.6%
Land use	
Area (square miles)[84]	61.05
Building footprint (% region)[85]	15.9%
Paved area (roads, parking, sidewalks) (% region)[86]	24.1%
Tree canopy (% region)[87]	37.2%

3 Cool roofs

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

3.1 Cool roof basics

Cool roofs are roofs with a higher solar reflectance[x] (often called albedo) than conventional dark roofs, which have a low solar reflectance. Because of their higher solar reflectance, cool roofs reflect more sunlight and so 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 3.1 below illustrates these concepts.[xi]

As illustrated in Figure 3.1 below, 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. In contrast, dark roofs absorb the large majority of solar radiation that reaches their surface and become hotter as a result. Compared to a cool roof, the higher temperature of a dark roof results in increased city and atmospheric warming and greater heat transfer to the building below.

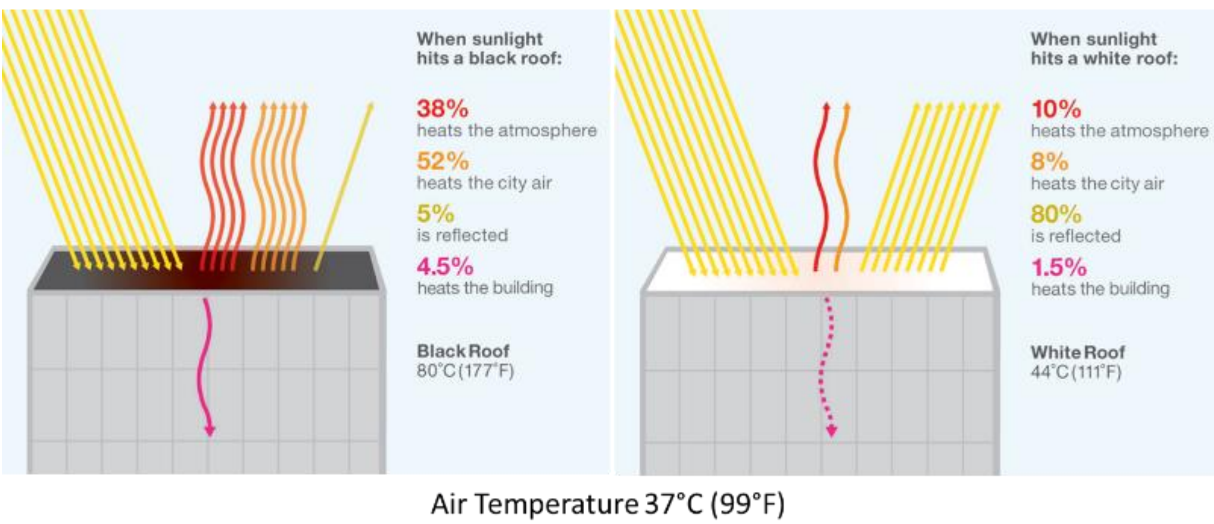

Figure 3.1. Comparison of a black roof and white roof on a summer afternoon (numbers do not sum due to rounding)[88]

3.1.1 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[xii] are common on commercial buildings, multifamily housing, and are also used on row homes. Common

[x] 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.
[xi] The solar reflectance of the black roof in Figure 3.1 is 0.05 and that of the white roof is 0.80.
[xii] No more than 2 inches of vertical rise over 12 inches of horizontal run.

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.[xiii] Steep slope roofs[xiv] 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, particulates, and sometimes, biological growth. 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,[89] a nonprofit membership organization that maintains credible, independent roof surface characteristic ratings and data and that provides industry-wide product testing and rating. All major building codes (e.g., American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and International Code Council (ICC)) reference Cool Roof Rating Council standards.

Conventional roofs have solar reflectances ranging from 0.05-0.20, depending on type.[90] This report assumes a solar reflectance of 0.15 for conventional low slope roofs in the District. Low slope cool roof solar reflectance also depends on roof type. Low slope cool roof products are available that have aged albedos above 0.7. This report assumes that low slope cool roofs have an aged albedo of 0.65. In 2030, this report assumes solar reflectance of newly installed and replaced roofs is 0.75, reflecting continued innovation of low slope cool roof materials. Table 3.1 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 ranges from 0.05-0.15.[91] This analysis assumes a conventional steep slope roof albedo of 0.10 (i.e., it absorbs 90% of sunlight). 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 3.2). Currently, most cool colored steep slope products achieve aged albedos around 0.25.[xv] However, it is possible to achieve higher albedos (e.g., roof tile aged albedos of 0.35, a white steep slope roof with albedo similar to low slope white roofs).[92] Based on review of existing green building codes (e.g., International Green Construction Code),[93] this analysis assumes an aged albedo of cool steep slope roofs of 0.25. As above for low slope roofs, this analysis assumes the albedo of new and replaced steep slope cool roofs is 0.40 starting in 2030, reflecting continued innovation of steep slope cool roof materials (see Figure 3.2 below showing cool-colored roof tiles measured by Lawrence Berkeley National Laboratory). Cool steep slope roofs experience a greater albedo increase in 2030 (0.15) compared to cool low slope roofs (0.10) because cool steep slope roof options are currently earlier in development than cool low slope roof options and thus have more room for improvement. Table 3.1 below presents the solar reflectance values used in this analysis.

Table 3.1. Conventional and cool roof albedos used in this report

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[xiii] For more detailed descriptions and pictures see ref 42 and ref 88.
[xiv] Greater than 2-inch rise over 12-inch run.
[xv] Based on analysis of Cool Roof Rating Council rated product database in October 2015.

Roof slope	Solar reflectance		
	Conventional roof	*Cool roof Pre-2030*	*Cool roof Post-2030*
Low slope	0.15	0.65	0.75
Steep slope	0.10	0.25	0.40

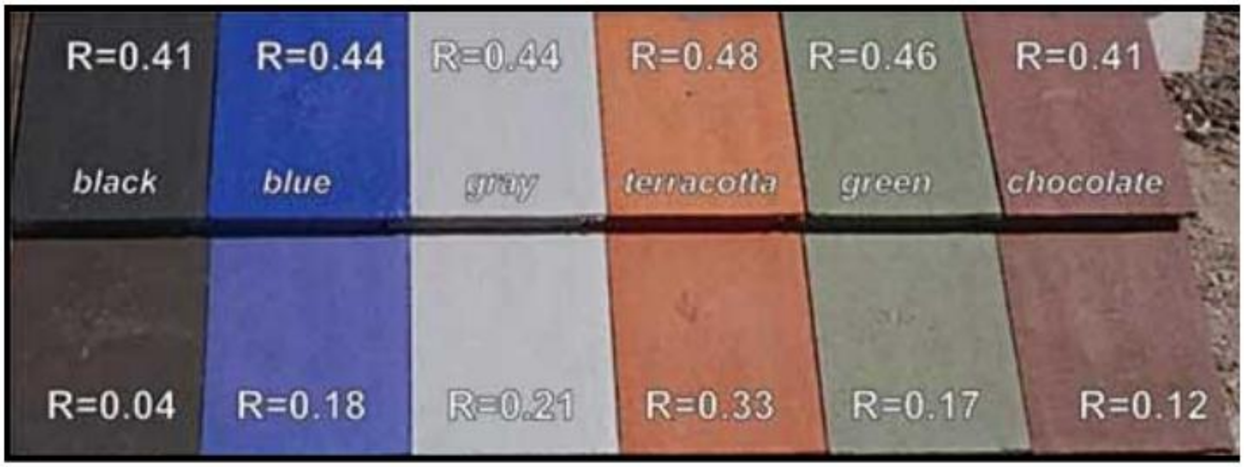

Figure 3.2. Cool-colored tiles (top row) look like conventional roof tiles (bottom row) but have higher solar reflectance (R)[94]

3.1.2 Installation and maintenance costs

Cool roof installation and maintenance costs presented in this report are based on recent literature and on guidance from roofing professionals.[95] Roof replacement, rather than restoration, is the norm when a roof needs repair (e.g., when there is a leak).[96] Low slope cool roofs have been around long enough that they typically are the same or only marginally higher cost than their conventional equivalent.[97] This report assumes a low slope cool roof cost premium of $0.15 per square foot, reflecting the need for a cost premium to drive more rapid technology development and adoption. This is also a conservative assumption. There is typically a higher cost premium for steep slope cool roofs. Based on a Department of Energy report, this report assumes the steep slope cool roof cost premium of $0.55 per square foot.[98] For both roof slopes, this report assumes a constant cost premium to drive sustained albedo improvements. Table 3.2 summarizes cool roof installation cost premiums.

High albedo roofs experience less thermal expansion and contraction than conventional roofs, and so likely have longer lives.[99] However, this report conservatively assumes cool roofs have the same lifetime as conventional roofs (20 years). This assumption is consistent with assumed values in the literature (e.g., see ref 99) and reflects a lack of studies on impact of albedo on roof life. For simplicity, we assume low slope and steep slope roofs have the same lifetime. At the end of a conventional or cool roof's life, the roof can be replaced or restored (e.g., patched, repaired). The choice between replacement and restoration depends on a number of factors including the condition of the existing roof and insulation.[xvi] A common practice is to replace a roof at the end of its life, so we assume that after 20 years each cool roof is replaced with a new cool roof. For all roof replacements, we assume the same cool roof cost premiums as noted above.

[xvi] For example, the manufacturer or installer of a new roof may not grant a warranty to the new roof if the existing roof is not in good enough shape.

The maintenance requirements for cool roofs are similar to those of conventional roofs, so there is generally no maintenance premium for cool roofs. Nevertheless, cool roofs can occasionally be washed to maintain a higher albedo. There are two cleaning options for cool roofs: power washing and mop cleaning (or equivalent). This report does not include roof cleaning in the cost-benefit estimates because it is rarely used and generally not cost-effective, so aged albedo is assumed in this report.[xvii] Table 3.2 summarizes cool roof maintenance cost premiums.

Table 3.2. Cool roof cost premiums

Roof type	Low slope	Steep slope
Installation premium	$0.15/SF	$0.55/SF
Maintenance premium	$0.00/SF-yr	$0.00/SF-yr

3.2 Impacts of cool roofs

3.2.1 Cool roof impact summary

Table 3.3 below summarizes the costs and benefits of cool roofs included this report. There are more benefits than costs excluded from cost-benefit results, and excluded benefits very likely have a higher value in aggregate than excluded costs, so our findings tend to underestimate the net value of cool roofs.

Table 3.3. Cool roof 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	
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
Downstream cooling (+)		X
Downstream warming (-)		X
Reduced stormwater runoff temperature (+)		X
Glare (-)		X

[xvii] For example, ref 99 conclude that power washing is not cost-effective.

3.2.2 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 somewhat more energy for heating in the winter. The reduced solar heat gain in the winter (called the "heating penalty") in the District far less than cooling energy savings[100] because there is less solar radiation during the winter due to lower sun position, shorter days, increased cloudiness, and the potential for winter snow coverage.[xviii] Furthermore, peak demand for heating typically occurs around sunrise—which is when conventional and cool roofs are roughly the same temperature.[xix] Section 11.2 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

In addition to direct energy use impacts, cool roofs reduce peak electricity demand, which benefits utilities because it reduces peak loads and some utility customers because it reduces peak electricity and demand charges.[xx] Cool roofs may also impact 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 3.2.7.

Factors that impact direct energy savings

The size of direct energy savings/penalties depends on a number of factors, including the thermal properties of the roof assembly, the operating schedule of a building, and HVAC equipment efficiencies.[101] Savings/penalties will be different in residential and commercial properties because of differences in design, occupancy, and HVAC schedules.[xxi]

Heat transfer through the roof is reduced by additional insulation, so buildings with well insulated roofs experience lower heat transfer than buildings with less well insulated roofs and thus lower cooling energy savings and penalties. Recent 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.[102]

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.[103] Therefore, the more floors a building

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[xviii] In northern climates, such as Alaska, the heating penalty commonly exceeds the cooling benefits.

[xix] This report does not directly model factors that impact the winter heating penalty. These factors are implicitly addressed in the calculators used to estimate direct energy benefits.

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

[xxi] 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.

has, the smaller 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 (typically further south), while heating penalties generally increase in cooler climates (typically further north).[104] 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 the District.[xxii] As the city gets warmer with climate change, the heating penalty will drop and the cooling benefits will increase. The load change ratio is typically higher for residential properties for reasons discussed in Footnote xxi.

3.2.3 Ambient cooling and indirect energy

Ambient cooling

Because of their higher reflectivity, cool roofs stay cooler than conventional roofs, which reduces heat transfer to the urban environment. At large scale, this can materially reduce urban air temperatures, helping to mitigate the UHI, effectively offsetting some of the warming expected from climate change. A recent 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).[105] The relationship between urban albedo and average air temperature is much better defined than the relationship between urban albedo and peak air temperature.[xxiii]

UHIs are highly location specific, so it is preferable to have a location specific ambient cooling analysis. Fortunately, two recent studies examined UHI mitigation in the District. Both studies found albedo increases are effective at reducing UHI in the District, with one finding 100% cool roof[xxiv] coverage would decrease maximum daytime temperatures by a little over 0.5°C (0.9°F) during the heat event studied[106] and the other finding that a 0.1 increase in average city albedo would decrease temperatures at 5PM by an average of 0.27°F across the four heat events studied.[107] These studies, which are used in developing this report's cost-benefit calculations, are discussed in more detail in Section 11 and the Appendix.

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

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[xxii] Note this is an energy comparison, *not* a cost comparison

[xxiii] The R^2 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 R^2 for the relationship between urban albedo and peak air temperature.

[xxiv] The albedo increase for all roofs was 0.4.

reductions (Section 3.2.4), improvements in air quality (Section 3.2.5), and declines in heat-related mortality (Section 3.2.5).

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.[xxv] 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, while indirect gas penalties are approximately one fifth of combined direct and indirect gas penalties.[108,xxvi]

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.[xxvii] Section 11.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

3.2.4 Climate change mitigation

Greenhouse gas emissions reductions
Anthropogenic (human-caused) greenhouse gas (GHG) emissions are the dominant factor driving global climate change.[109] One of the main sources of anthropogenic GHG emissions is energy use in buildings. In 2009, buildings accounted for about 40% of U.S. carbon dioxide emissions.[110] According to the District's most recent GHG inventory (2013), buildings represent about 74% of District GHG emissions.[111] Reducing energy used for space conditioning from cool roof installation reduces building-related GHG emissions.

Global cooling
Cool roofs reflect more sunlight back into space than conventional roofs, thereby causing negative radiative forcing[xxviii] on the earth and reducing global warming. Studies have found that increasing the albedo of one square foot of roof by 0.25 is equivalent to a onetime GHG offset of between 5.8 and 7.6 kg CO2e.[112] Because the global cooling impact can be significant, this analysis includes this impact.

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.[113] However, clouds are one of the most complex aspects to climate modeling, with no clear conclusions, so

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[xxv] Cooling energy savings as well as smaller heating penalties.
[xxvi] Electric heating penalties are included in the electricity savings calculations.
[xxvii] 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.
[xxviii] Radiative forcing is the difference between the radiant energy received by the Earth (from the Sun) and the energy Earth radiates to space.

some urban-climate scientists discount the impact of urban albedo changes on cloud formation.[xxix,114] 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 11.5. Further detail is provided in the Appendix. Figure 3.3 shows cool roof climate change mitigation pathways.

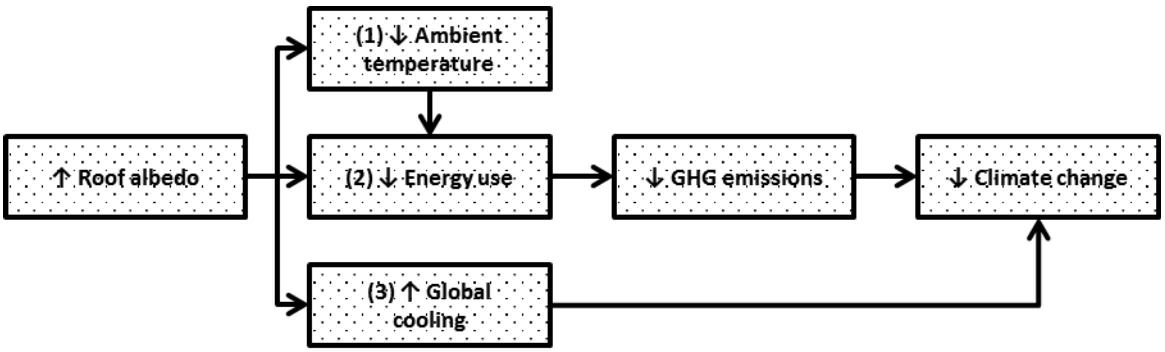

Figure 3.3. Cool roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

3.2.5 Improved air quality and health

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 2.4.4, 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 (see more in Section 3.2.2 above). Decreased summertime building energy use leads to decreased emissions of ozone precursors. In general, as ozone precursor emissions decline, ozone formation declines as well. Figure 3.4 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 11.6 and in the Appendix.

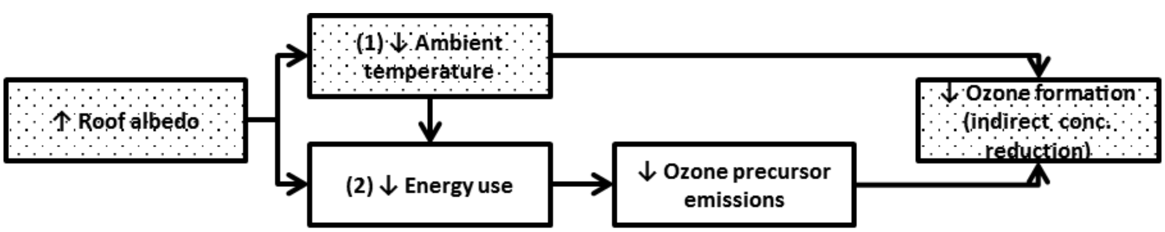

Figure 3.4. Cool roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Cool roofs and $PM_{2.5}$

Cool roofs reduce $PM_{2.5}$ pollution indirectly by decreasing building energy use and indirectly by decreasing ambient temperature, which in turn reduces building energy use. Reducing building energy use results in

xxix And note that urban areas already increase cloud formation because of particulates they produce.

decreased emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors, decreasing primary and secondary $PM_{2.5}$ pollution. Figure 3.5. shows the $PM_{2.5}$ concentration reduction pathways of cool roofs. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 11.6 and in the Appendix.

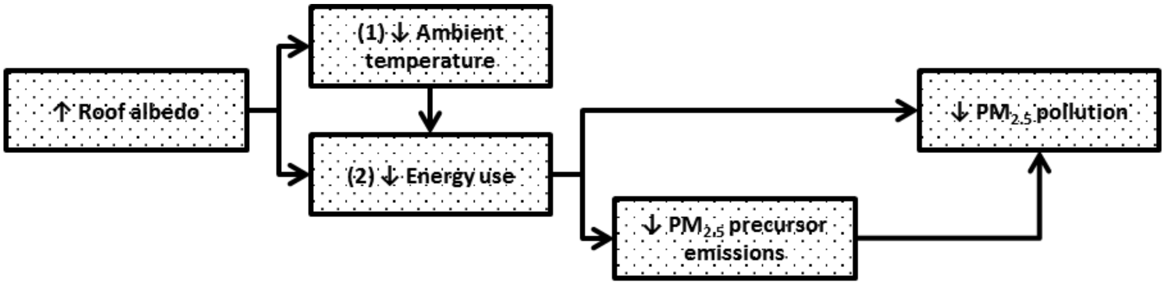

Figure 3.5. Cool roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Heat-related mortality

Modeling studies show that UHI mitigation technologies (e.g., cool roofs and green roofs) can decrease urban heat-related mortalities by reducing air temperature.[115] As noted in Section 2.4.4, there are two pathways by which cool roofs can reduce heat-related mortality: by (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 benefits is not estimated in this report. However, this benefit is probably significant[116] and warrants further research.[xxx] 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 (i.e., to underestimate the likely benefits). This report describes heat-related mortality benefit estimation methods and assumptions in Section 11.6 and in the Appendix.

3.2.6 Cool roofs and employment

The net employment impact of cool roof installation is negligible because cool roofs and conventional roofs have similar installation requirements.[xxxi] For this reason, the net employment impact of cool roofs is not included in costs-benefit results. However, cities (e.g., New York City[117]) are using cool roofing and training to bring people into the job market (i.e., jobs readiness).

For a more detailed discussion of cool roof employment impacts, see the Appendix.

3.2.7 Other impacts of cool roofs

Increased roof life

It is reasonable to assume that cool roofs generally last longer than conventional roofs due to reduced thermal expansion and contraction and reduced UV radiation absorption.[118] However, in the absence of

[xxx] 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.

[xxxi] The exception is cool coatings, which can create employment opportunities. However, we do not include this employment benefit because it would be small.

sufficient data, this report does not include this benefit in cost-benefit estimates. Increased cool roof life could be a significant benefit.

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 result in increased air conditioning efficiency and decreased energy use because the air conditioner does not need to remove as much heat from cooler incoming air. This potential benefit is little studied and not well quantified. The only peer-reviewed study available on this topic, estimated a cool roof reduced energy use of a test roof-top air conditioner by between 0.3% and 0.6%.[119]

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 relative impacts of air intake temperature and HVAC unit temperature on energy consumption would impact an entire buildings' energy consumption. This benefit should be included in future estimates of the energy consumption impact of cool (or green) roofs and deserves further research.

Reduced peak electricity demand

Peak roof surface temperatures generally coincide with peak electricity demand, which generally occurs on weekday afternoons during the cooling season (summer).[120] Because cool roofs have lower peak roof surface temperatures, buildings with cool roofs experience reduced peak electricity demand.[xxxii] Lower ambient temperatures also contributes to peak electricity demand reductions.[121] Pepco, the dominant utility in the District, has demand charges for large commercial customers,[122] providing a larger financial incentive for commercial peak load reduction. Pepco does not have mandatory time of use rates,[123] but customers with cool roofs could opt into the voluntary time of use rates for additional savings. However, because of limitations in the Green Roof Energy Calculator (GREC)[124] this analysis does not quantify the benefits of peak electricity demand reductions, and energy benefit calculations are therefore conservative.[xxxiii] Time of use rate and capacity may be adopted more broadly in the District, which would increase the financial benefit of cool roof peak load reduction.

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.[125] Their model results showed that hot air from upwind urbanization (i.e., in the District and the areas between the District and Baltimore) contributed to as much as 25% of Baltimore's UHI, equal to 1.25°C for the event modeled. The authors note that the contribution of the District and other urban areas to Baltimore's UHI partially depends on wind direction. Downwind cooling from city-wide adoption of smart surface options in the District is likely to be material, including some cooling impact in eastern and northeastern parts of the

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[xxxii] Based on a sample of nine cool roof studies, EPA found that peak demand for cooling energy was reduced by 14 to 38 percent after cool roof installation. It is important to note, however, that most of these buildings were one story and/or single family residences, so the peak demand savings would be proportionally smaller for multifamily affordable housing properties.

[xxxiii] We do not include peak demand savings in our direct energy savings estimates for cool roofs or green roofs due to limitations in the Green Roof Energy Calculator.

city—areas that tend to be low income. 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 would be large, and this benefit merits further research and analysis.

Reduced stormwater runoff temperature

Because conventional roofs absorb more solar radiation than most natural surfaces, they reach much higher temperatures. During a storm event, heat is transferred to rain, increasing initial stormwater runoff temperatures. Stormwater runoff temperatures spike at the beginning of storm events.[126] Increased stormwater runoff temperatures can cause temperature spikes in local water bodies, though this impact is hard to value. Cold-water aquatic ecosystems (e.g., cold-water streams home to trout) can be particularly sensitive to heated runoff.[127] Given the large uncertainty and the difficulty in valuing reduced stormwater runoff temperature in the district and its likely limited impact, this analysis does not include this potential benefit in cost-benefit calculations.

Increased PV efficiency

Cool roofs may enhance performance of solar PV systems installed on them. PV panel efficiency degrades slightly with higher panel temperature,[xxxiv] so lower near-roof air temperatures on cool roofs may 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 4.2.8 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. Although the benefits may be material, there is to date insufficient work quantifying the impact of cool roofs on PV power output to include this benefit in cost-benefit calculations.

Glare

Glare from roofs that reflect a large fraction of visible light (e.g., bright white roofs) might disturb occupants of nearby taller buildings.[128] In situations where this is a concern, cool-colored roofs (discussed in Section 3.1.1) that reflect less visible light are a good alternative. This should not be a concern for most current and near-future steep slope cool roofs as the vast majority are cool-colored[xxxv] already. This is likely a not significant impact and is also highly location specific, so it is not included in cost-benefit calculations in this analysis.

[xxxiv] All else equal, higher PV efficiency means greater electricity generation.

[xxxv] Cool-colored roofs have to have the same color as standard-colored roofs, but have high solar reflectance in the near-infrared band of sunlight, which makes up more than half of sunlight. This is discussed in Section 3.1.1.

4 Green roofs

The sections below explore the basic principles of green roofs and their potential impacts. Major benefits include reduced cooling and heating 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. Potential drawbacks include ambient warming if the green roofs are not well maintained and increased humidity.

4.1 Green roof basics

Put simply, a green roof is a vegetative layer on a rooftop. More specifically, green roofs typically consist of drainage layer and soil layer (where the plants grow) on top of conventional roofing and water proofing systems.[129] Figure 4.1 below shows conventional roofing structure and two green roof structures (one without a drainage system and one with a drainage system).[xxxvi] 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.

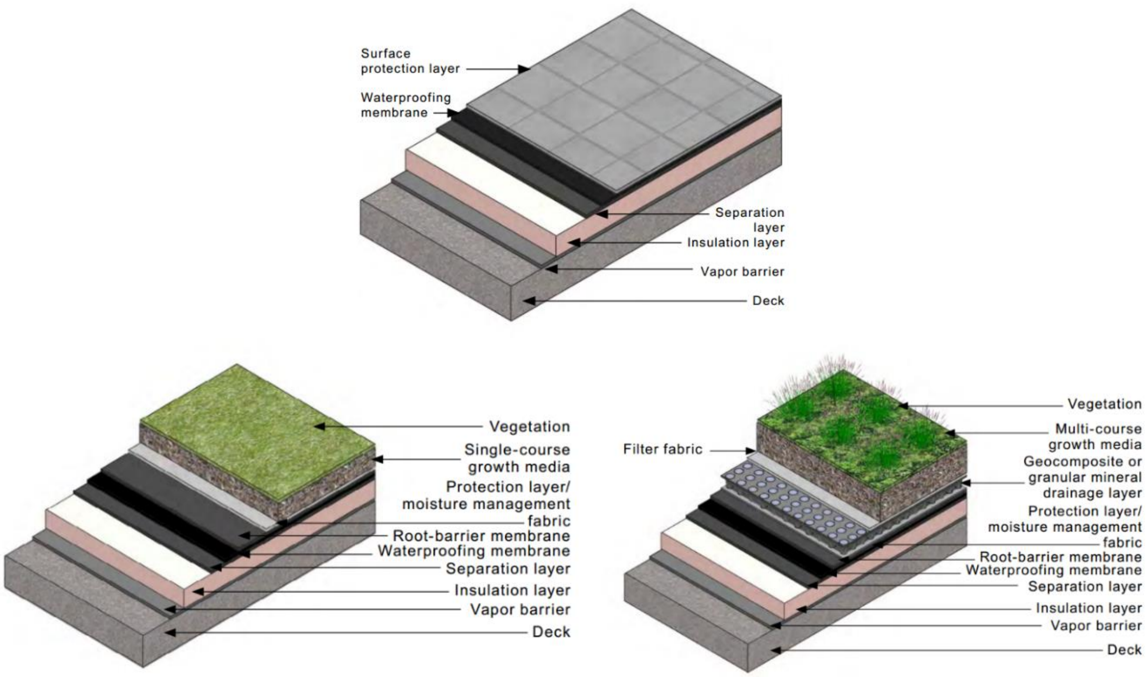

Figure 4.1. Examples of a conventional roof structure (top), green roof structure without a drainage layer (bottom left), and green roofs structure with a drainage layer (bottom right)[130]

There are two general approaches to installing green roof systems: (1) built-in place and (2) modular.[131] 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).[132] There is limited research into the performance

[xxxvi] For more discussion on green roof systems, EPA and GSA have good resources.

differences between the two green roof system installation methods,[133] so this this report does not make a distinction between the two in cost-benefit analysis calculations below.

4.1.1 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 6 inches, able to support a wider variety of and larger plants (like shrubs and sometimes small trees), and often accessible to the public. However, they are heavier and more expensive to install and maintain. Extensive green roofs, typically have soil depths between 3 inches to 6 inches, support herbaceous groundcover plants (sedums are common), and are usually not accessible to the public. Extensive green roofs are lighter and less expensive to install and maintain compared to intensive green roofs.[xxxvii] Extensive green roofs are by far the most common green roof type.[134] Figure 4.2 below shows examples of an extensive and intensive green roof.


Figure 4.2. Example of extensive green roof (left) and intensive green roof (right)[135]

4.1.2 Installation and maintenance costs

We assume that all green roofs modeled for the District are of the extensive type and have a life of 40 years. This assumption is consistent with other published cost-benefit analyses.[136] Because the cost-benefit analysis runs for 40 years, green roofs are assumed to be installed once and are not replaced with a new green roof during this report's analysis period.

Green roof installation and maintenance costs are based on current literature and on guidance from roofing professionals.[137] This report assumes that the additional cost of a green roof compared to a conventional roof is $15 per square foot.[xxxviii] This report assumes that starting in 2025 the green roof cost premium decreases to $10 per square foot reflecting a larger, more competitive green roof market.

Maintenance of green roofs is more involved than that for conventional or cool roofs and can include weeding, spot planting to cover bare spots, maintaining growth medium, and checking for other potential problems. The green roof establishment period—the first two to three years of green roof life—is critical

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[xxxvii] For more discussion on the types of green roofs EPA and GSA have good resources.

[xxxviii] 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.

for the success of a green roof and requires more involved maintenance than post-establishment.[xxxix] Irrigation is typically required during the establishment period. After the establishment period, irrigation should not be necessary because the plants selected for an extensive green roof are adapted to the conditions they will experience. Permanent irrigation can be installed on extensive green roofs but would increase the initial cost and annual maintenance cost.[xl] Irrigation can also increase benefits, however (as discussed in Sections 4.2.2 and 4.2.3). Because plants on an extensive green roof are selected to survive without permanent irrigation, and long term irrigation on extensive green roofs is rare in the District, only long term non-irrigated green roofs are analyzed in this report.

This report assumes establishment period maintenance premiums of $0.46 per square foot per year.[138] After the establishment period, this report assumes the overall maintenance cost reduces by 30 percent because less work is required to maintain the roof,[139] yielding a post-establishment period maintenance cost of $0.31 per square foot per year. This report assumes the establishment period lasts three years, so the post-establishment period maintenance takes effect in year four of the cost-benefit analysis. Furthermore, this report assumes maintenance premiums remain constant throughout the analysis. The maintenance and replacement premiums are summarized in Table 4.1.[xli]

Table 4.1. Green roof cost premiums

Period	Pre-2025	Post-2025
Installation premium	$15/SF-yr	$10/SF-yr
Maintenance premium, establishment	$0.46/SF-yr	$0.46/SF-yr
Maintenance premium, post-establishment	$0.31/SF-yr	$0.31/SF-yr

4.2 Impacts of green roofs

4.2.1 Green roof impact summary

Table 4.2 below summarizes 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 4.2. Green roof 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	
Direct cooling energy reduction (+)	X	

[xxxix] GSA notes that a minimum of three visits per year is recommended during the establishment period. After establishment period, the number of maintenance visits decreases to a minimum of two per year.

[xl] Permanent irrigation is typically required for intensive green roofs because the plants (ornamental herbaceous plants, shrubs, and trees) require more water than the growing medium will hold from average rainfall.

[xli] 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.

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

4.2.2 Direct energy

There are three mechanisms by which green roofs reduce direct energy consumption: (1) by increasing roof surface evapotranspiration rates, (2) by shading the roof surface, and (3) by increasing the thermal mass and thermal resistance of the roof.[140] Figure 4.3 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[xlii]—leading to cooling energy savings. The thermal mass and thermal resistance provided by green roofs help reduce heating energy costs in the winter as well. Section 11.2 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

[xlii] 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. (EPA, 2008)

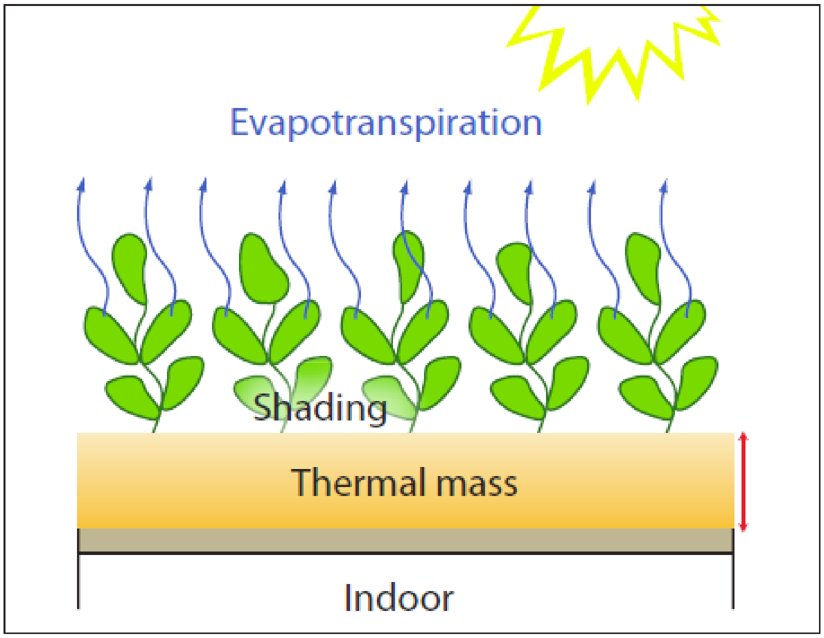

Figure 4.3. Green roof direct energy benefit features[141]

Like cool roofs, green roofs reduce total and peak electricity demand, which provides 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 impact air intake temperature of HVAC systems, potentially reducing cooling and heating 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 4.2.8.[xliii]

Evapotranspiration

Evapotranspiration, the combination of evaporation and transpiration, increases heat transfer from the green roof, keeping green roofs cooler than conventional roofs and yielding cooling energy savings for the building below. Some of the water absorbed by green roof vegetation and soil is converted into water vapor by energy from the sun (and to a lesser extent heat in the soil and the surrounding air).[xliv] Increased evapotranspiration means that the latent heat (energy released or absorbed in a phase change process) transfer from a green roof is greater than that from a conventional roof, so green roofs tend to stay cooler. This means that less heat is transferred to the building below, so building cooling energy needs decrease.

[xliii] Similar to 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.

[xliv] 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 through its stems and flowers). In evapotranspiration, heat from the sun and roof surface (e.g., vegetation, and soil) leads to the evaporation of water from the vegetation and soil, cooling the vegetation and soil. In other words, evapotranspiration converts sensible heat into latent heat. (USGS, 2015 and Sproul et al., 2014)

The evaporation benefit from a green roof depends on the type of plants used on the green roof, moisture availability, season, and air movement.

This report analyzes extensive green roofs, which can typically only support succulents (e.g., sedums) because of their shallow growing media. Succulents can survive and thrive in harsh environments (like those found on an extensive green roof) because they transpire little and store significant amounts of water in their tissues. Consequently, the evapotranspiration benefit from an extensive green roof is smaller than that from an intensive green roof, which typically can support plants that transpire more than succulents.

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 benefit, but only up to a point. In general, irrigating green roofs increases evapotranspiration rates—and thus the latent heat transfer away from the roof—increasing the cooling energy benefit.[142] However, the cooling energy use benefit plateaus above a certain soil moisture content.[xlv]

Seasons and air movement also play a role in the direct 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 an 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.[xlvi] This greatly reduces the winter cooling potential of green roofs, so the winter heating penalty caused by evapotranspiration is minimal. The evapotranspiration benefit also increases with air movement because humid air is moved away, making way for drier air, thus increasing evapotranspiration potential.

Shading

Green roof vegetation shades the growing medium (soil), which reduces the solar energy absorbed by the growing medium 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. The size of the shading impact depends on the type of green roof. Extensive green roof plants provide less shade than intensive green roof plants, and thus less shading benefit.

Roof surface shading has the potential to increase heating requirements if green roof vegetation does not dieback or if plants lose their leaves during the heating season, but any potential increase is more than offset by the heating savings due to the thermal mass and insulating properties of the green roof (discussed below).

[xlv] 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."
[xlvi] In the northern part of the U.S., evapotranspiration typically begins in April, reaches a peak in June/July, and decreases in October. (Hanson, 1991)

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.

Because of their higher thermal mass,[xlvii] green roofs store more heat and take longer to absorb and release heat than most conventional roofs. One consequence of this is decreased and delayed heat transfer down 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.[xlviii] This means that less heat is transferred through the roof to the building below, so during the cooling season air conditioning needs are lower than for a similar building with a conventional roof. In the heating season, less heat is lost through the roof, but less heat is gained as well. The net effect is reduced heating energy needs.[143]

Green roofs also provide a small insulation benefit to the building below.[144] 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 media—as moisture content increases, insulation value decreases.[145] 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.

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.

4.2.3 Ambient cooling and indirect energy

Ambient cooling

Because of evapotranspiration and shading, green roofs are typically cooler than conventional roofs, reducing heat transfer to the urban air. Green roofs are 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.[146] As solar radiation increases, the green roof ambient cooling benefit decreases, but is not eliminated. Generally, as soil moisture increases, sensible (what we feel) heat transfer to the urban air decreases—i.e., green roof ambient cooling benefit increases.[xlix] The

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

[xlviii] 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 a conventional roofs, reducing peak cooling loads.

[xlix] A recent modeling study demonstrates the importance of green roof soil moisture content. Ref 149 found very dry green roofs covering 50 percent of the roof space in the Washington, DC and Baltimore area may enhance the daytime UHI. As the goal of UHI mitigation technologies is not to enhance the UHI, 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.

study also found that relative humidity does not show a strong impact on green roof ambient cooling benefit.[147]

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.[148] As mentioned in the cool roof section, UHIs are location specific, so it is best to have a location-specific ambient cooling analysis when performing a cost-benefit analysis. Fortunately, a recent study examines the impact of green roofs on urban temperatures in the District and found that increasing green roof coverage generally reduces ambient temperatures.[149] Green roof installation may also increase urban humidity, which potentially has negative effects that are discussed in more detail in Section 4.2.8.

This report does not directly estimate the value of ambient cooling from green roofs, rather it estimates the benefits of ambient cooling through energy use reductions (this section) and related GHG emissions reductions (Section 4.2.4), improvements in air quality (Section 4.2.5), and declines in heat-related mortality (Section 4.2.5).

Indirect energy

The cooling effect of green roofs is apparent during both the cooling season (summer) and the heating season (winter), but is much smaller during the heating season because the sun is at a lower angle in the sky and is above the horizon for fewer hours and evapotranspiration is minimal in the heating season.[l] Section 11.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

4.2.4 Climate change mitigation

Reducing energy use for space cooling and heating from green roof installation also 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.[150] 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 low, 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,[151] but the amount of carbon sequestered is minimal and much less than the amount reduced by green roofs from energy use reductions and slightly increased reflectivity.[152] For this reason, this report does not include carbon sequestration in green roof cost-benefit analysis results.

The methods and assumptions used to estimate green roof climate change mitigation impact are described in Section 11.5. Figure 4.4 shows green roof climate change mitigation pathways.

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[l] Because winter days are shorter, the sun is at a lower angle in the sky, and there is often more cloud cover. Moreover, the evapotranspiration rate is lower during the heating season, so ambient air temperatures are reduced less.

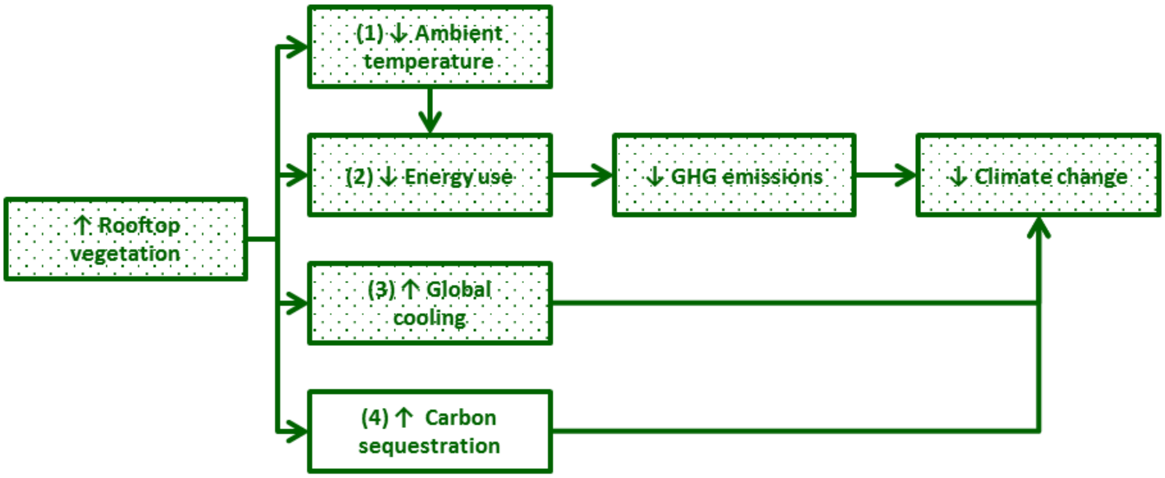

Figure 4.4. Green roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

4.2.5 Air quality and health

Green roofs and ozone

Compared to cool roofs, green roofs have two additional ozone reduction pathways. 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 NO_2 (an ozone precursor) from the air and (4) directly removing ozone from the air. Green roofs directly remove NO_2 and ozone through dry deposition (pollution removal during non-rainy periods). Figure 4.5 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. In addition, direct removal of pollutants from the air by extensive green roofs tends to be small, so this benefit is excluded from cost-benefit calculations as well. This report discusses the methods, assumptions, and pathways in more detail in Section 11.6 and in the Appendix.

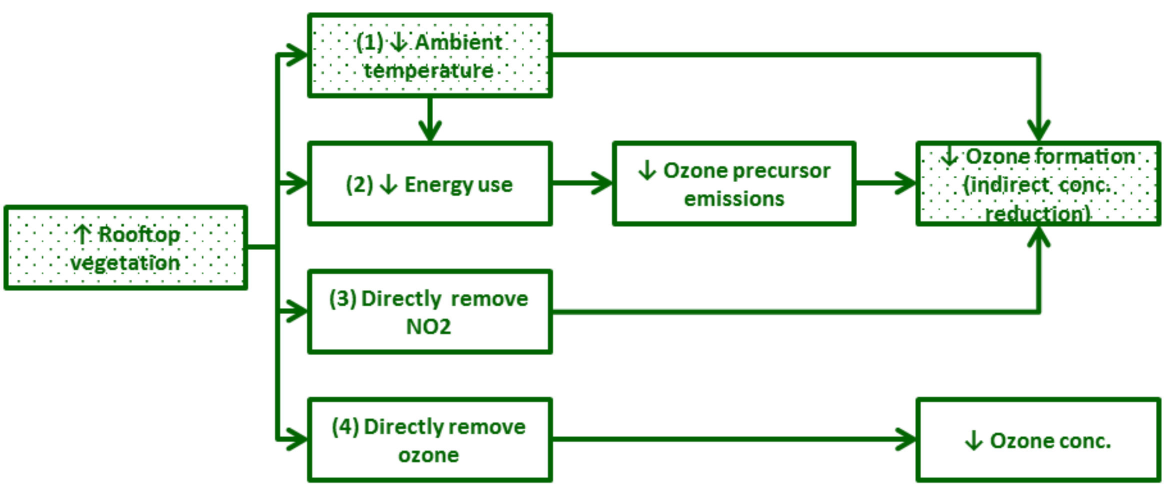

Figure 4.5. Green roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Green roofs and $PM_{2.5}$

Green roofs reduce concentration of $PM_{2.5}$ in four ways. Green roofs plants directly remove $PM_{2.5}$ from the air by dry deposition (pathway (1) in Figure 4.6). Green roof plants also directly remove $PM_{2.5}$ precursors from the air through dry deposition thereby decreasing secondary $PM_{2.5}$ pollution (pathway (4) in Figure 4.6). Similar to cool roofs, green roofs reduce $PM_{2.5}$ pollution by decreasing ambient temperature (pathway (2) in Figure 4.6), and decreasing building energy use (pathway (3) in Figure 4.6). Figure 4.6 shows green roof $PM_{2.5}$ 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 $PM_{2.5}$ impact estimation methods and assumptions in Section 11.6 and in the Appendix.

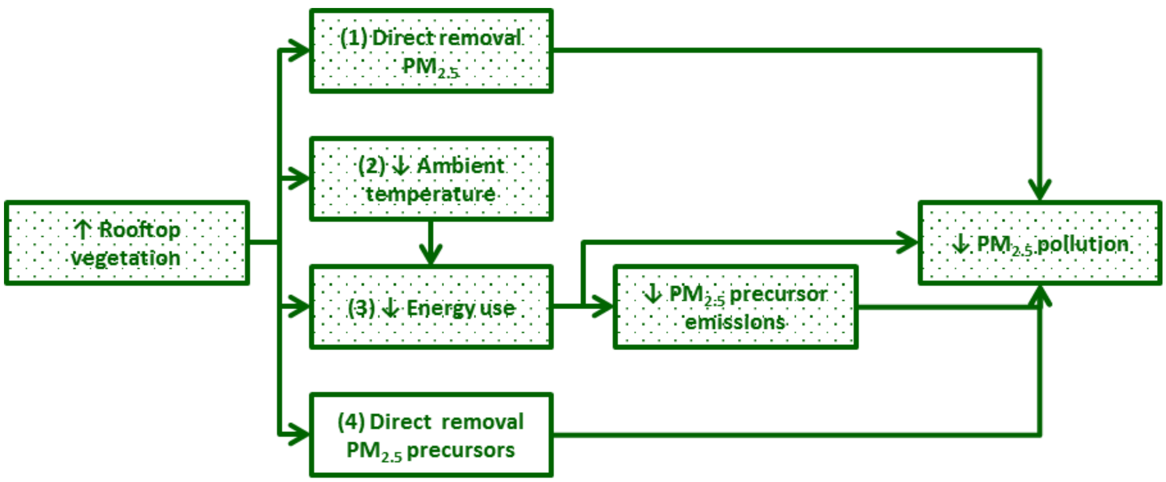

Figure 4.6. Green roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Heat-related mortality

Modeling studies have shown that UHI mitigation technologies (e.g., cool roofs and green roofs) can decrease urban heat-related mortalities through changes in ambient air temperature.[153] As noted in Section 2.4.4, 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 did not find work documenting the potential for green roofs to reduce heat-related mortality by improving indoor conditions, but these reductions could be significant.[154] 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 underestimate the likely benefits of mitigation. This report outlines methods and assumptions to estimate green roof heat-related mortality impact in Section 11.6 and in the Appendix.

4.2.6 Stormwater

As noted, the District surface is 40% percentage impervious (eg about 24 square miles of impervious area), resulting in larger volumes of stormwater runoff during rain events compared to natural land. Managing this runoff is a major cost for most cities, including for the District. 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.[155] And climate change is predicted to bring more extreme rainfall to the District, increasing river pollution and stormwater management costs.

There are three types of stormwater management: treatment, detention, and retention.[156] Treatment focuses on water quality control through removal of pollutants, while detention focuses on quantity control through controlling the peak discharge rate of stormwater. Retention effectively provides both treatment and detention by holding stormwater onsite.

Green roofs are useful tools for stormwater management because they provide stormwater retention and can help meet water quality treatment and detention requirements. The green roof growing medium captures and stores rainfall.[li] 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 4.7). 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 4.8 illustrates these stormwater benefits of green roofs.

Section 11.7 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

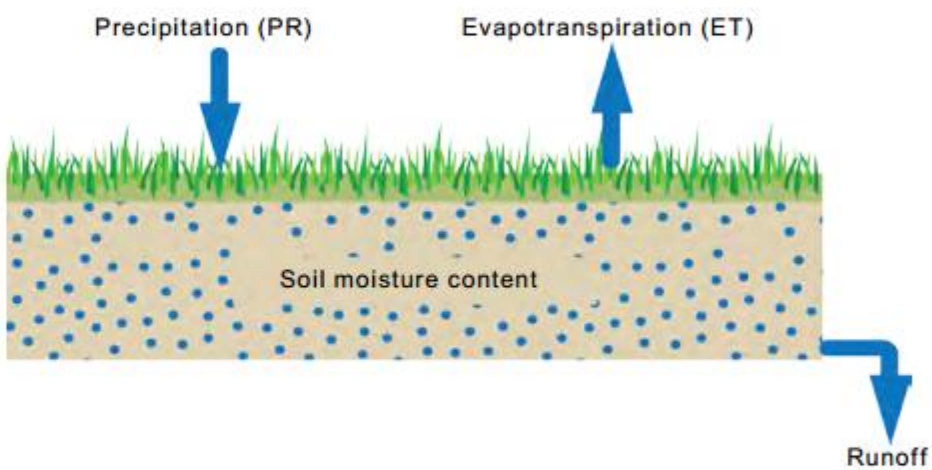

Figure 4.7. Green roof water budget[157]

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

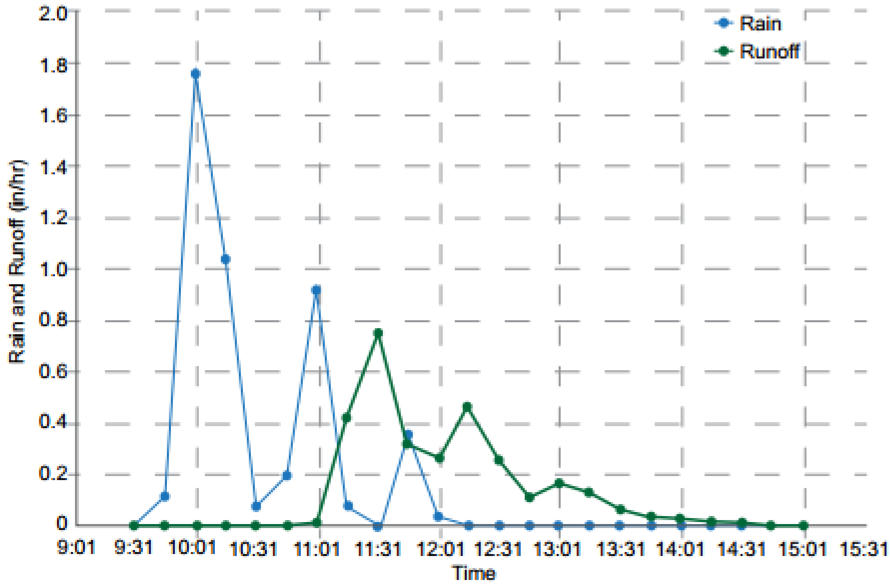

Figure 4.8. Example timeline of rainfall and green roof runoff[158]

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 (which increases as temperature increases) is at its peak.[159] The amount of water a green roof retains depends on the amount of rain that falls, the rate of rainfall, and the time since the previous rainfall.[160] As a green roof becomes more saturated, its ability to absorb rainfall decreases. Therefore, a green roof will retain less rainfall and reduce peak runoff rates to a lesser extent as (1) the amount of rainfall in a storm increases, (2) the rate of rainfall increases, and (3) the length of time between storms decreases.

4.2.7 Green roofs and employment

Green roofs generate jobs during installation and maintenance. Green roofs can be installed at a rate of approximately 54 square feet per hour.[161] Assuming one job-year is equivalent to 2000 hours of work, this translates to 8.8 job-years per million square feet of green roof installed. This number is for extensive green roofs and includes planning, travel, and on-site construction. GSA projects an annual maintenance requirement of 4 person hours per 1,000 square feet per year, assuming three annual site visits.[162] This drops to 2.7 yearly person hours after the establishment period, when only two annual site visits are needed. Green roofs usually last at least twice as long as conventional roofs. This limits the net job creation of green roofs since re-roofing of a conventional roof is a labor-intensive process.

This report considers only direct job creation, which underestimates the total jobs that green roof installation could create.[lii] All labor intensity estimates for installation in this report include planning, transportation, installation, and maintenance. We ignore manufacturing employment because these jobs

[lii] This report ignores both indirect and induced jobs. Indirect jobs are those created to support the industry of interest. Induced jobs result from indirect or direct employees of the given industry spending their paychecks in the community.

would likely occur outside of the District. Estimates are based on commercial buildings with a footprint between 10,000 to 20,000 square feet. Installing green roofs on small residential buildings would be more labor intensive while installing green roofs on large commercial buildings would typically be less labor intensive. Thus, estimates in this report provide an average labor intensity.

As noted in Section 2.4.6, employment impact studies generally assume that all jobs created go to residents in the area where installations occur. This assumption is incorrect for cities because many installation jobs go to people living outside cities. Based on discussions with local businesses, as a baseline, this report assumes 50 percent of employment remains in the District. This percent could be increased by incentives or coordinated city training and employment policies.

Section 11.8 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

4.2.8 Other impacts of green roofs

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.[163] Walmart 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.[liii] However, Walmart did not study the impact of increased humidity on the HVAC systems, which may decrease the projected cooling energy savings as air conditioning units may have to remove more moisture from the air to meet occupant comfort requirements. This potential benefit is little studied and not well quantified, especially compared to conventional roofs, so it is not included in this analysis. Nevertheless, as noted in the cool roof benefits section (Section 3.2.7), this benefit may be significant, particularly for multistory buildings that make up the large majority of buildings in cities, so deserves future research.

Reduced peak electricity demand

Compare with conventional roofs, green roofs reduce peak electricity demand and reduce electricity consumption during periods of peak electricity rates (e.g., summer afternoons).[164] As mentioned above, this report does not quantify the benefits of peak electricity demand and consumption reductions because of limitations in the Green Roof Energy Calculator (GREC). Energy benefits are conservative as a result.

Downwind cooling

As discussed in the cool roof benefits section (Section 3.2.7), hot air from urbanization can heat cities and towns downwind because of heat transfer by air movement (called "advection"). The ambient cooling

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[liii] Note that the results of 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 5 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.

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.

Reduced stormwater runoff temperature

Like cool roofs, green roofs can reduce stormwater runoff temperature because they are typically cooler than conventional roofs. There is some research on the phenomenon and it is designated a pollutant of concern by the EPA. However, given the limited analysis on the economic impact of thermal shock, this potential impact is not included as a quantified benefit.

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 could charge more for rent and might, for example, earn revenue from hosted events on the roof.[165] The GSA estimated the "real estate effect" (the market's value of a green roof") at $13 per square foot of roof per year.[166] For green roof installations that include building tenant access and use, this amenity value could be included, and would significantly increase green roof value. However, given that the applicability of this benefit varies (e.g., because extensive green roofs are typically not accessible to building occupants), amenity value is not included in cost-benefit calculations.

Aesthetic value

Green space and vegetation have been shown to reduce stress,[167] lower blood pressure,[168] and decrease crime.[169] These benefits could accrue to a green roof if it were accessible or more visible, but extensive green roofs analyzed in this study are not typically accessible to building occupants and are usually not visible by building occupants or pedestrians. Green roofs may still provide aesthetic benefits to occupants of neighboring buildings who can see the roof.[170] However, because these studies are not specific to green roofs, are very site-specific and, the GSA view is that their "methodology is open to debate,"[171] this analysis does not value aesthetic benefits of green roofs.

Increased biodiversity

Biodiversity refers to the variety of life in an area. Green roofs can increase biodiversity compared to conventional roofs.[172] 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.[173] 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,[174] so this analysis does not include biodiversity benefits in cost-benefit results.

Increased PV efficiency

Like cool roofs, green roofs may enhance PV performance. However, unlike cool roofs, there is some work studying 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),[175] meaning that for each additional degree PV panel temperature rises above 25°C (77°F), PV power output decreases by 0.35% (0.19%).[liv] For example, at 30°C, PV power output would decrease by 1.8%.

[liv] 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.

A study of the green roof on Chicago's city hall found that on a sunny August afternoon air temperature one meter above the green roof was 3.9°C lower than the air temperature one meter above a nearby black roof. Applying the PVWatts temperature coefficient yields a power output increase of 1.4% on the green roof compared to the black roof.[lv] Assuming a PV efficiency of 18%, installing the PV system over a green roof would be similar to installing panels with an efficiency of 18.2%.[lvi] If annual solar output is 1300 kWh per kW, this power output increase is approximately yields an additional 18 kWh per kW of output per year. Assuming an electricity cost of $0.15/kWh, a 5kW system over a green roof would earn about $14 more per year than the same system over a black roof.

A recent study from Carnegie Mellon University found that when air temperatures were at or above 77 °F, PV panel efficiency for panels over green roofs increased slightly compared to PV panels over black roofs.[176] The authors developed statistical relationships between roof type and PV output based on field data collected in Pittsburgh and used these relationships to estimate the impact of green roofs on PV power output in four cities (Pittsburgh, San Diego, Huntsville, and Phoenix). They found that PV power output over a green roof increased by between 0.8% and 1.5% compared to a black roof.[lvii] The largest power output increase was in Phoenix and the smallest was in Pittsburgh. Overall, the authors of the study conclude that the potential economic benefit of the temperature and power output interaction is minor. Given the limited data on the effect of green roofs on PV power output and because this benefit does not appear to be significant, it is not included in cost-benefit calculations.

Increased humidity

While green roofs can decrease city air temperature, they can also increase the moisture content of air, increasing humidity and apparent temperature (how hot it feels).[lviii] Higher moisture content in the air can increase cooling energy consumption[lix] and heat-stress.[lx] 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,[177] 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. with Kalkstein showed that increasing vegetation reduced actual temperature but left Apparent temperature about the same (slightly lower) due to increased humidity. Recent work by the Global Cool City Alliance with Kalkstein showed that increasing vegetation reduced actual temperature but left apparent temperature about the same (slightly lower) due to increased humidity. The benefit is small and little other data on impact is available so this impact is excluded it from cost-benefit calculations.

[lv] Based on the formula for calculating nominal operating cell temperature at PVEducation.org.
[lvi] This is optimistic because the air temperature on a green or black roof will not always be greater than 25°C.
[lvii] This is a relative efficiency increase, not an absolute efficiency increase.
[lviii] How hot air feels is based on both temperature and moisture content.
[lix] Because air conditioning systems may have to do more work to deliver air within the set humidity range.
[lx] Because it is more difficult for humans to cool their bodies in more humid conditions.

5 Bioretention

The sections below explore the basic principles of bioretention systems and their potential benefits. Major benefits of bioretention systems include reduced stormwater runoff, ambient cooling, and the associated benefits of reduced cooling energy use, reduced greenhouse gas emissions, improved air quality, and reduced heat-related mortality. Other benefits include increased aesthetic value and increased biodiversity. Potential drawbacks include increased humidity and increased winter heating energy use due to ambient cooling.

5.1 Bioretention basics

Bioretention systems are ground-based, vegetated areas designed to capture rainfall from roofs and other impervious surfaces. Captured rainfall is stored, evaporated, transpired, and depending on the design, conveyed to the existing stormwater infrastructure and/or infiltrated into the underlying soil.

The main components of a bioretention system are the surface layer, the filter media layer, and the stone base layer. The surface layer consists of vegetation (typically native plants) and mulch, and has sloped or vertical sides to allow for ponding. The next layer is the filter media, which is specially engineered soil. In its *Stormwater Management Guidebook*, DOEE notes that this layer is at least 18 inches thick.[178] The final layer consists of small stones and is sometimes called the storage layer. This layer also often contains an underdrain that is connected to the city stormwater system. DOEE notes that the stone layer is at least 9 inches thick.[179] Between the filter media and storage layer is a layer of smaller stones or permeable membrane that prevents the filter media and stone layer from mixing. Figure 5.1 shows a cross-section of a bioretention system.

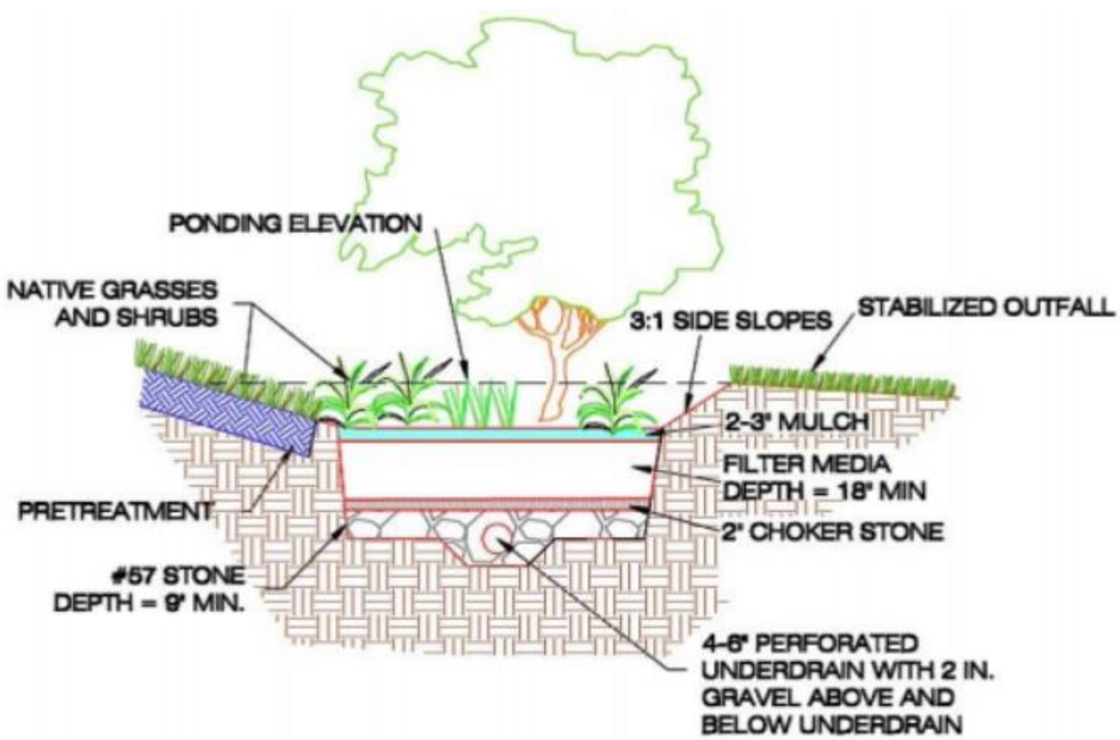

Figure 5.1. Example cross-section of a bioretention system[180]

There are many different types of bioretention systems including traditional bioretention, streetscape bioretention, engineered tree pits, stormwater planters, and residential rain gardens. Traditional bioretention, streetscape bioretention, and engineered tree pits are most useful for managing stormwater runoff from adjacent pavements (e.g., roads, parking lots, and sidewalks). Stormwater planters, on the other hand, are most useful for managing runoff from roofs. Residential rain gardens are useful for handling runoff from both roofs and pavements. Traditional bioretention and residential rain gardens are common on low- to medium-density land, whereas street scape bioretention, engineered tree pits, and stormwater planters are common in urban and space-constrained areas.[181]

Figure 5.2. Examples of bioretention systems in space-constrained areas[182]

As mentioned, we only examine bioretention systems installed in combination with cool roofs. Because this analysis examines green roofs only on commercial and multifamily low slope roofs, the most useful cool roof with bioretention system for comparison purposes is low slope cool roofs with a bioretention system on commercial and multifamily properties. We also focus on the bioretention system most useful for managing runoff from these types of roofs: stormwater planters.

5.1.1 Installation and maintenance costs

The area of the bioretention system relative to roof area is an important factor to consider when determining cost. DOEE recommends the surface area of bioretention systems be 3%-6% of the contributing drainage area (the roof in this case).[183] This report uses the average (4.5%), so stormwater runoff from a 10,000 square feet cool roof is managed by 450 SF of bioretention—0.045 SF of bioretention manages stormwater runoff from one SF of cool roof.

This report assumes a bioretention system (stormwater planter) lifetime of 25 years,[184] after which it is upgraded at half the cost of a new system. This report assumes installation costs are $74.00 per square foot of stormwater planter, based on an analysis prepared for the Maryland Department for the Environment.[185] We base the cost difference between standard and enhanced bioretention designs[lxi] on

[lxi] For costing purposes, the major difference between standard and enhanced designs is that enhanced designs typically have thicker stone layers, all else equal. For more discussion of this difference, see the Appendix.

the additional stone layer depth needed for enhanced design. We approximate the install cost for installing additional stone base is $4.66 per square foot (see the Appendix for more detail).

Maintenance for bioretention includes many of the same practices used to maintain traditional landscaping (e.g., weeding, pruning, removing and replacing dead or diseased plants). Additional maintenance needs for bioretention include removing sediment buildup from inflow and outflow points and ensuring proper stormwater functionality. This report assumes annual maintenance costs of $0.60/SF ($2011), based on an analysis prepared for the Maryland Department for the Environment.[186]

5.2 Impacts of bioretention

5.2.1 Bioretention impact summary

Table 5.1 below summarizes the costs and benefits of bioretention 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 higher value in aggregate than excluded costs, so the findings of this analysis will tend to underestimate the net value of bioretention.

Table 5.1. Bioretention 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	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
GHG emissions reduction (+)	X	
Carbon sequestration (+)		X
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Heat-related mortality reduction (+)	X	
Reduced stormwater runoff (+)	X	
Employment (+)	X	
Downstream cooling (+)		X
Downstream warming (-)		X
Aesthetic benefit (+)		X
Increased property value (+)		X
Biodiversity (+)		X
Increased humidity (+/-)		X

5.2.2 Ambient cooling and co-benefits

Like green roofs, bioretention can cool the air through evapotranspiration. At large scale, this can reduce urban air temperatures, which has a range of benefits, including reduced cooling energy use, climate change mitigation, and improved air quality and public health.

We found no studies that specifically examine the ambient cooling impact of bioretention. Studies on the urban temperature impact of vegetation almost always focus on green roofs, urban trees, or unspecified vegetation. Of these better-studied types of vegetation, green roofs appear most similar to bioretention on the surface (e.g., herbaceous plants close to the planting surface). The stormwater planters examined in this analysis typically have slightly larger plants than green roofs, like shrubs, but given their close proximity to buildings are unlikely to contain trees. Thus, one would expect the ambient cooling potential of stormwater planters to be similar to that of green roofs. That said, in contrast to green roofs, the plants in bioretention systems are selected to survive in dry and wet conditions and are not succulents, so transpire more. Furthermore, the filter media in a bioretention system is thicker than the growing media on a green roof and thus will likely hold more water. These two facts indicate that bioretention systems will evapotranspire substantially more than green roofs, thus cooling the air to a greater extent. As a result, this report assumes bioretention has twice the cooling benefit of a green roof per square foot.

This report does not directly estimate the benefit value of ambient cooling from bioretention systems, rather it estimates the benefits of ambient cooling through energy use reductions, GHG emissions reductions, air quality improvements, and heat-related mortality declines.

Indirect energy

The cooling effect of bioretention is apparent during both the cooling season (summer) and the heating season (winter). However, it is far smaller during the heating season because the sun is at a lower angle in the sky and is above the horizon for fewer hours and because evapotranspiration is minimal during the heating season.

No studies estimate the indirect energy saving potential of city-wide bioretention installations, but one study estimated urban cooling from greater tree canopy would lead to between $1.50 and $4.50 in annual indirect energy savings per 1000 SF of roof (values adjusted for inflation) in the District.[187] The ambient cooling impact of bioretention is likely less than that from trees, as noted, so we expect energy cost savings to be less. This report discusses the estimation methods and assumptions in more detail in Section 11.4 and in the Appendix.

Climate change mitigation

Bioretention systems reduce atmospheric carbon concentrations directly through carbon sequestration and indirectly through energy use reductions. Reducing energy used for space cooling through bioretention installation reduces building-related GHG emissions. The carbon sequestration potential of bioretention systems is likely larger than that of extensive green roofs because of the larger plants and greater soil depth but less than that of urban trees. However, for both extensive green roofs and urban trees, the carbon sequestration potential is small (see Section 3.2.4 on green roofs and Section 10.2.4 on urban trees for more), so we do not include the carbon sequestration benefit of bioretention in this analysis.

Unlike green roofs, which typically have higher albedos than the conventional roofs they replace, bioretention systems (with a likely albedo of between 0.25 and 0.30) often replace grass, concrete, or brick, which all have albedos in the range of 0.20 and 0.30.[188] Consequently, on average, bioretention likely does not have a material global cooling impact.

Figure 5.3 shows the climate change mitigation pathways of bioretention. This report discusses the estimation methods, assumptions, and pathways in more detail in Section 11.5 and in the Appendix.

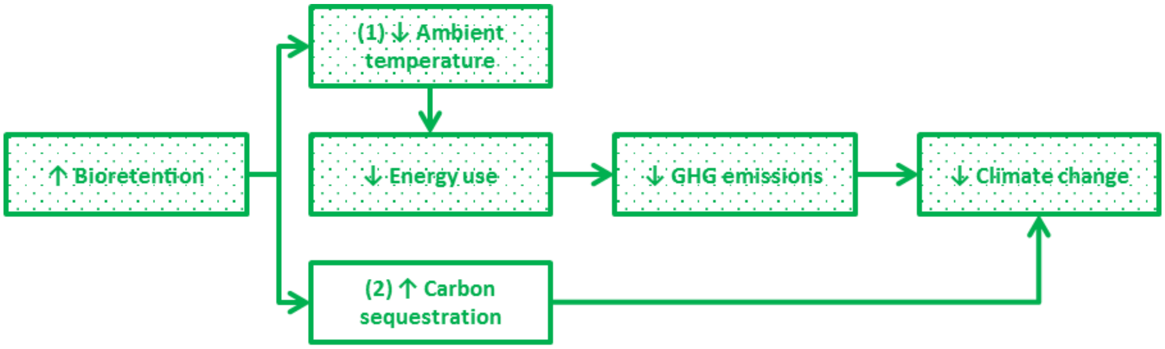

Figure 5.3. Bioretention climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Bioretention and ozone

Bioretention systems have similar ozone concentration reduction pathways as green roofs: ambient temperature reduction and direct removal of ozone and ozone precursors from the air.[189] The exception is that bioretention systems do not lead to direct energy reductions.

As noted in the green roof section, this report does not include the benefit of precursor emissions reductions in cost-benefit analysis calculations. Based on the type and size of plants typically planted in bioretention, we expect the pollution removal benefit to be smaller than that for trees and larger than that for green roofs. This report does not include the benefit of direct removal of pollutants from the air by bioretention vegetation due to lack of rigorous work quantifying pollution removal by bioretention vegetation.

Figure 5.4 illustrates the ozone concentration reduction pathways of bioretention. This report discusses the estimation methods, assumptions, and pathways in more detail in Section 11.6 and in the Appendix.

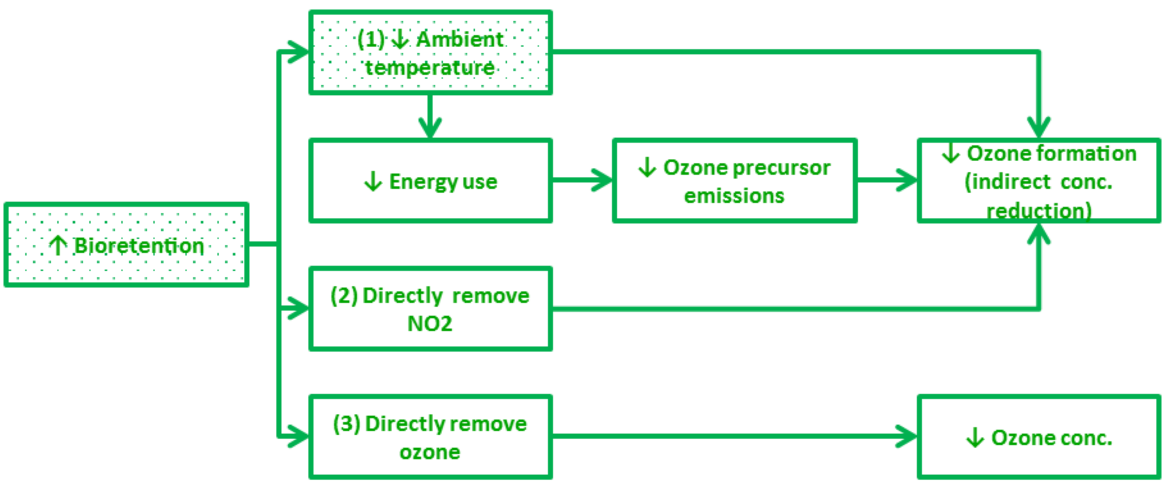

Figure 5.4. Bioretention ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Bioretention and PM2.5

Bioretention systems reduce the concentration of $PM_{2.5}$ in three of the four ways of green roofs: direct removal of $PM_{2.5}$ and its precursors and reduced energy use through ambient cooling. As with ozone, the $PM_{2.5}$ removal benefit of bioretention is likely small, so it is not included in cost-benefit calculations.

Figure 5.5 shows bioretention $PM_{2.5}$ concentration reduction pathways. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 10.2.5 and in the Appendix.

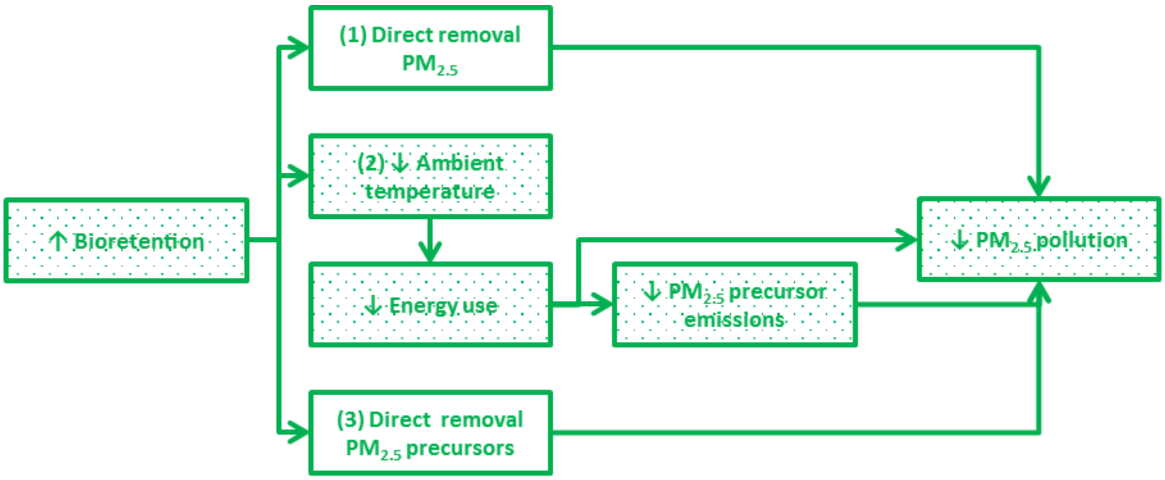

Figure 5.5. Bioretention $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Heat-related mortality

As noted above, published modeling studies show that UHI mitigation can decrease urban heat-related mortalities through changes in ambient air temperature. Unlike cool roofs and green roofs, there is only one significant pathway by which bioretention reduces heat-related mortality: by improving outdoor temperature conditions. However, while research examples general vegetation, no research specifically examines the impact of bioretention. This report estimates the heat-related mortality impact of bioretention by scaling up the impact of green roofs. Refer to Section 11.6 and the Appendix for an overview of methods and assumptions.

5.2.3 Stormwater

Bioretention systems are useful tools for stormwater management because they provide stormwater retention and are effective at removing pollutants from stormwater.[190] Bioretention manages stormwater through evapotranspiration and infiltration. Stormwater runoff from the connected roof and intercepted rainfall evaporates from the soil surface and infiltrates the engineered soil. Bioretention vegetation absorbs some infiltrated stormwater and releases it through transpiration. The remaining stormwater then infiltrates to the stone layer where it either infiltrates the underlying soil and/or flows to the stormwater system. Figure 5.6 illustrates these mechanisms. Refer to Section 11.7 for an overview of methods and assumptions. The Appendix provides further detail.

Important factors that influence stormwater retention

Plant selection, filter media characteristics, layer thicknesses, the infiltration rate of the underlying soil, and whether the practice has an underdrain all impact stormwater retention potential of bioretention. If properly sized and designed, bioretention can manage all of the rain that falls or drains into it.

Figure 5.6. Illustration of bioretention with stormwater flow[191]

5.2.4 Bioretention and employment

Green infrastructure, such as bioretention systems, is a great way to create long term jobs. Installation is labor intensive and bioretention systems require ongoing maintenance to ensure health of the plants and proper system function. The job creation potential of green infrastructure is something the District has recognized, and as noted in Section 2.4.6, DC Water is working to create a national certification for green infrastructure jobs.

This report estimates the employment impact of bioretention systems using employment multipliers from the Bureau of Economic Analysis.[192] Based on these multipliers, $1 million of spending on bioretention systems in the District creates 8.08 direct jobs. However, as noted, this report assumes only 50 percent of employment remains in the District. This percent can increase as a result of incentives or coordinated city training and employment policies.

Section 11.8 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

5.2.5 Other impacts of bioretention

Bioretention has a range of other benefits that are not well documented—many of these are the same as for green roofs. These benefits include: downwind cooling, aesthetic and property values, and increased biodiversity (e.g., butterflies).

As discussed in the cool roof and green roof benefits section, hot air from urbanization heats cities and towns downwind because of heat advection. The ambient cooling provided by bioretention systems could help alleviate a portion of this downwind warming. However, this analysis does not include this benefit due to limited available research.[lxii]

As noted in the green roof section (Section 4.2.8), green space and vegetation have been shown to reduce stress, lower blood pressure, and decrease crime. However, the studies cited focus on large, continuous spaces of vegetation (e.g., parks) or trees and in specific settings such as hospitals, so the benefits may not accrue to small scale vegetation spaces like bioretention. Furthermore, as noted, the studies' methods are not fully accepted. For these reasons, this analysis does not include these potential benefits of bioretention systems.

Bioretention systems may also increase property value. However, studies of property value have similar spatial limitations to those of aesthetic value. Moreover, all studies reviewed focus on residential (typically single-family) property values, and as the bioretention systems examined in this report are combined with commercial or multifamily low slope cool roofs, single-family residential property value increases are not specifically applicable. For these reasons, increased property value from bioretention is not included in this analysis.

Like green roofs, bioretention systems can increase biodiversity. Bioretention systems are typically planted with native species—they perform best when planted with native species[193]—so they provide a greater biodiversity benefit than green roofs, which are typically planted with a small range of non-native plants. However, there is limited research valuing the benefits of increased biodiversity, and existing research focuses on small scale measures like bioretention. Thus, biodiversity benefits are not included in this analysis.

Like other vegetation solutions examined in this analysis, bioretention systems can increase the moisture content of urban air, increasing humidity and apparent temperature. As mentioned, higher moisture content in the air can increase cooling energy consumption and heat-stress but decrease ozone concentrations. Because we found no research on the magnitude of or the negative or positive impacts of increased humidity from bioretention systems, we do not include it in our cost-benefit calculations.

[lxii] As with cool and green roofs, large scale deployment of biotention could lead to small pockets of warming downwind. However, this effect is small so it is not included in this analysis.

6 Rainwater harvesting

The sections below explore the basic principles of rainwater harvesting and its potential impacts. Major benefits of rainwater harvesting include reduced stormwater runoff and reduced use of potable water.

6.1 Rainwater harvesting basics

Rainwater harvesting systems are designed to store rainfall and gradually release it for future use. Stored rainfall is most often used for non-potable uses, such as irrigation, toilet flushing, and car washing, though with filtering and additional cleaning it can be used for potable uses. This analysis focuses on rainwater harvesting used for non-potable uses.

Rainwater harvesting systems can be placed underground, indoors, adjacent to buildings, or on rooftops.[194] Common cistern materials are metal (e.g., steel), fiberglass, concrete, and plastic. Preventing leaks is important for systems located adjacent to buildings and in or on top of buildings.

In its *Stormwater Management Guidebook*, DOEE notes that there are seven main components of a rainwater harvesting system: (1) contributing drainage area, (2) collection and conveyance system, (3) pretreatment, (4) cistern, (5) water quality treatment, (6) distribution system (including the pump), and (7) overflow, filter path, or secondary stormwater retention path.[195] The cistern is the "most important and typically the most expensive component of a rainwater harvesting system."[196]

Cisterns come in many sizes and materials and typically range from 250 to 30,000 gallons.[197] Residential rain barrels can be even smaller—rain barrels from DOEE's RiverSmart Homes are 132 gallons.[198] Cisterns used for commercial purposes are typically tens of thousands of gallons.[199]

As noted, we examine the cost-effectiveness of rainwater harvesting in combination with cool roofs to compare its cost-effectiveness with green roofs. Because we examine green roofs only on commercial and multifamily low slope roofs the most useful cool roof with rainwater harvesting combination for comparison purposes is low slope cools roofs with rainwater harvesting on commercial and multifamily properties. We examine these types of rainwater harvesting in this report.

6.1.1 Installation and maintenance costs

We estimate cistern size assuming a 10,000 SF roof and a design storm of 1.7 inches. Based on 10,060 gals of runoff, we assume the resultant cistern size is 10,100 gallons.

We adapt cistern cost calculations from the Water Environment Research Foundation's (WERF) *BMP and LID Whole Life Cost Models*.[200] Using an average[lxiii] cistern cost of $1.91 /gal, the 10,100-gallon cistern costs about $19,260. We assume a pump size of 5 HP, which costs $4,493. We use WERF's installation-cost-to-cistern-cost scale factor of 0.6 to estimate installation cost, and design-cost-to-system-base-cost sale factor of 0.08 to estimate design cost. The sum of cistern cost, pump cost, install cost, and design cost is the total rainwater harvesting install cost (about $38,139 or $3.78/gal).

Cisterns and their components can range in life between 20 and 50 years, depending on location and material.[201] Because we assume cisterns are built of durable materials, we assume cisterns last the full 40 years of this analysis.

[lxiii] An average of steel, fiberglass, concrete, and high-density polyethylene cistern unit costs.

Rainwater harvesting maintenance includes routine activities, such as system cleaning and inspection, and corrective/infrequent activities, like sediment removal and pump replacement.[202] Based on WERF's default assumptions, we assume an annual maintenance cost of $0.14/gal per year.

6.2 Rainwater harvesting impacts

6.2.1 Rainwater harvesting impact summary

Table 6.1 below summarizes the costs and benefits of rainwater harvesting 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 higher value in aggregate than excluded costs, so the findings of this analysis will tend to underestimate the net value of rainwater harvesting.

Table 6.1. Rainwater harvesting 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 potable water costs (+)	X	
Employment (+)	X	
GHG emissions reduction (+)		X
Ozone concentration reduction (+)		X
PM2.5 concentration reduction (+)		X

6.2.2 Stormwater

In all cases, cisterns are used to harvest runoff from impervious surfaces. Roof surfaces are the typical contributing drainage area, but rainwater from paved surfaces can also be harvested with appropriate treatment.[203] In addition to cistern size, one of the most important factors determining the stormwater management potential of a rainwater harvesting system is the frequency with which harvested water is used—a full cistern provides no immediate additional stormwater retention benefit.[204] Overflow can be conveyed directly to existing grey infrastructure (e.g., the sewer system) or to other on-site stormwater management practices (e.g., bioretention).[205] For simplicity, this analysis assumes excess stormwater is conveyed directly to existing grey infrastructure. Refer to Section 11.7 for an overview of methods and assumptions. The Appendix provides further detail.

6.2.3 Reduced potable water use

Harvested rainwater is used for non-potable applications that typically otherwise use potable water. Thus, rainwater harvesting reduces use of potable water and reduces the associated costs to the building owner.[lxiv]

[lxiv] This can also be thought of as lost revenue to the local water utility.

Reduced use of potable water also reduces energy to treat, transport, and deliver potable water, thus reducing the local water utility's costs.[lxv] This cost is typically built into the potable water costs[206] and so is already accounted for.

Benefits from reduced GHG emissions and reduced emissions of other air pollutants, such as $PM_{2.5}$, its precursors, and ozone precursors are not significant, and therefore are not included in cost-benefit calculations.

Methods and assumptions to estimate this benefit are summarized in Section 11.9. The Appendix provides further detail

6.2.4 Rainwater harvesting and employment

Green infrastructure, such as rainwater harvesting systems, is a great way to create long term jobs. Installation is labor intensive and rainwater harvesting systems require ongoing maintenance to ensure proper system function. The job creation potential of green infrastructure is something the District has recognized and is taking seriously (e.g., see the national certification for green infrastructure jobs being developed by DC Water referenced in Section 2.4.6).

This report estimates the employment impact of bioretention systems using employment multipliers from the Bureau of Economic Analysis.[207] Based on these multipliers, $1 million of spending on rainwater harvesting systems in the District creates 8.08 direct jobs. However, as noted, this report assumes only 50 percent of employment remains in the District. This percent can increase as a result of incentives or coordinated city training and employment policies.

Section 11.8 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

[lxv] Energy used to move water around a building with a cistern will be essentially the same that used to move water around a building without a cistern.

7 Solar PV

The sections below explore the basic principles of rooftop PV systems and their potential impacts. Major benefits include electricity generation, reduced greenhouse gas emissions, and improved air quality. Other impacts include a shading benefit and the potential for UHI mitigation.

7.1 PV basics

Solar PV panels are an assembly of solar cells that convert sunlight into electricity. Combined with an inverter and other hardware (e.g., racking), PV panels provide electricity to the grid or to homes and buildings they are installed on to offset electricity purchases from the grid.[lxvi]

There are three commonly cited PV sectors: residential, commercial, and utility-scale. Figure 7.1 illustrates PV systems from each sector. Utility-scale is large scale PV power plants and is typically the least expensive on a unit basis (largely due to the lower cost of installation and economies of scale). This report focuses on PV on single-family residential properties and PV on commercial or multifamily residential properties. Commercial PV is typically more expensive than utility-scale PV and less expensive than residential PV (see Figure 7.2). Commercial and residential PV are considered distributed generation, meaning they produce electricity at the point of consumption. 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.

Figure 7.1. Residential PV (top left),[208] commercial PV (top right),[209] and utility-scale PV (bottom)[210]

[lxvi] Batteries are increasingly being deployed with PV systems, allowing owners to use electricity produced by PV systems when the sun goes down.

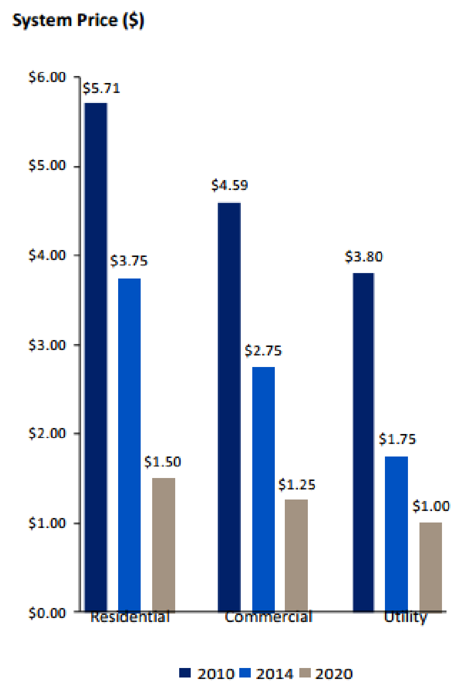

Figure 7.2. Installed solar PV system price[211]

7.1.1 Installation and maintenance costs

There are three common options for financing a PV system: direct purchase, loan purchase, and third-party financing.

Direct purchase

Direct purchase has a simple structure: the system owner pays for the PV systems' installation and any maintenance needs[lxvii] and receives all electricity generated by the system and any tax credits or rebates, but is typically responsible for the required paperwork.

The standard measure for estimating PV system install cost is cost per watt. System install costs have come down dramatically in the last decade[212] and are expected to continue to fall. Table 7.1 shows residential and commercial installation and maintenance costs used in this report. This report assumes pre-2020 install costs of $3.20 per watt and $2.60 per watt for residential and commercial systems, respectively. For simplicity, this report assumes one cost decline for the entire analysis period. Starting in 2020 and for the remainder of the analysis period, this report assumes install costs of $2.20 per watt and $1.80 per watt for residential and commercial systems, respectively. The "post-2020" cost assumptions are higher than U.S. Department of Energy (DOE) SunShot targets.[lxviii,213] Rationale for PV cost assumptions are provided in the Appendix.

This report conservatively assumes a system life of 20 years for direct purchase PV systems with an annual system electricity output degradation rate of 0.5% of total output per year. This report assumes the PV system has no residual value (or liability) at end of life.

[lxvii] Solar installers often provide maintenance services for a fee.
[lxviii] DOE SunShot targets are $1.50 per watt and $1.25 per watt for residential and commercial systems, respectively.

Table 7.1. Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems

System type	Pre-2020 installation cost	Post-2020 installation cost	Maintenance cost[214]
Residential	$3.20/W	$2.20/W	$0.21/kW-yr
Commercial	$2.60/W	$1.80/W	$0.19/kW-yr

Loan purchase

Loan purchase is similar to direct purchase except that the home or building owner uses a loan to finance some or all of the installation cost. This report does not model loan purchase systems due to the many possible term and rate combinations and because it is not a common financing approach used in the Distirct.

Third-party financing

Third-party financing is a popular option for home and building owners interested in rooftop PV who view the up-front cost of rooftop PV as too high, lack capital to fund a solar investment, and/or who cannot take advantage of certain solar incentives (e.g., tax credits). Third-party solar financing involves solar installers or developers funding installation and providing solar electricity to a customer without requiring that the customer own a PV system. The two most popular forms of third-party financing are leasing and power purchase agreements (PPAs).[215] 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.

For simplicity, this analysis only analyzes PPAs. For both commercial and residential PV, this analysis assumes 20 year PPAs with electricity rate savings of 5% below utility rates. After the initial PPA term is over, this report assumes the home or building owner enters into another 20 year PPA with the same savings profile as before. This report uses the same annual degradation rate (0.5%) as discussed above. This report assumes the PV systems has no residential value at the end of the PPA term.

7.2 Impacts of solar PV

7.2.1 Solar PV impact summary

Table 7.2 below summarizes 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 likely have a substantially higher aggregate value than excluded costs, meaning the findings tend to underestimate the net value of solar PV.

Table 7.2. Rooftop PV 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	
Energy generation (+)	X	
Tax credits (+)	X	
Depreciation (+)	X	
SRECs (+)	X	
GHG emissions reduction (+)	X	

Ozone concentration reduction (+)		X
PM2.5 concentration reduction (+)	X	
Employment (+)	X	
Direct energy reduction/penalty (+/-)		X
UHI mitigation & related benefits (+)		X
Increased home value (+)		X
Avoided peak transmission and distribution losses (+)		X

7.2.2 Energy generation

Rooftop PV substitutes PV-generated electricity for grid-purchased electricity. The District has a net metering law recognizing the value of PV electricity generation at the same price as electricity purchased from the utility; any unused electricity produced by the PV system is sent to the grid and credited towards the building's next electricity bill. Net metering means that utility customers with PV systems on their roofs are only charged for the difference between what they consume and what their PV system generates (i.e., their net consumption) on an annual basis. Energy users with PPAs pay the system owner for electricity generated by the PV system. The PV energy generation value for an energy user with a PPA is the difference between the utility retail electricity rate and the PPA rate for electricity generated by the PV system.[lxix] Refer to Section 11.3 and the Appendix for a review of methods and assumptions.

7.2.3 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 feed-in tariffs) and tax credits. In a third-party financing arrangement, the customer typically does not receive these incentives. Refer to the Appendix for details in addition to that provided below.

Tax credits

There are two federal tax credits available to PV system owners: the residential renewable energy tax credit[216] and the business energy investment tax credit (ITC).[217]

The residential tax credit is a personal income tax credit for 30% of the cost of installation. Any unused tax credit can generally be carried forward to the next year. For simplicity, this report assumes all tax credits are used in the year of installation. The residential tax credit drops to 26% in 2020, 22% in 2021, and 0% thereafter.[218]

The ITC is a corporate tax credit and is for 30% of the cost of installation. Similar to the residential tax credit, unused tax credit can generally be carried forward to following years. For simplicity, this report assumes all tax credits are used in the year of installation. The ITC drops to 26% in 2020, 22% in 2021, and 10% thereafter.[219]

[lxix] An exception is when PV generation exceeds on-site consumption. Rapid growth of community solar (i.e., shared PPAs) means that participants typically receive the same net metering pricing benefits as a single customer PPA. Community solar allows excess generation to be credited to other buildings or utility customers.

Depreciation

Businesses may recover the cost of an investment in solar PV using tax depreciation deductions through the federal Modified Accelerated Cost-Recovery System (MACRS).[220] PV systems are generally eligible for a cost recovery period of five years. For systems that use the ITC, the depreciable basis must be reduced by half the value of the ITC (e.g., for a 30% ITC, the depreciable basis is reduced by 15%, to 85% of the install cost).[221]

In December 2015, Congress extended the deadline for bonus depreciation.[222] Under bonus depreciation, companies can elect to depreciate a portion of the depreciable basis specified by Congress and depreciate the remaining percentage under the normal MARCS period.[223] Under the new rules, projects placed in service before the end of 2018 qualify for 50% bonus depreciation.[224] Those projects placed in service during 2018 and 2019 qualify for 40% and 30% bonus depreciation, respectively. [225]

For simplicity, this report assumes that businesses installing PV have enough tax appetite to deduct against. For more details, see the Appendix.

Solar renewable energy credits (SRECs)

Solar renewable energy credits (SRECs) are equivalent to one MWh of electricity derived from a solar system. (In the District, solar PV and solar thermal (solar hot water) are eligible to generate SRECs.)[226] Energy suppliers (e.g., electric utilities) use SRECs to meet their legally mandated requirements for solar generation under state renewable portfolio standards (RPS).

SREC price is determined by the market, but is capped at what is called the alternative compliance price (ACP). An energy supplier has to pay the ACP if it does not meet its RPS requirement. In the District, SRECs typically trade near the ACP. As of June 2016, the District had the highest SREC prices in the country.[227] We base SREC price assumptions on 5-year annuity contracts from one of the largest SREC aggregators in the country. For more on SREC price assumptions used in this analysis, see the Appendix.

7.2.4 Climate change mitigation

Unlike the two technologies discussed thus far, rooftop PV has only one significant climate change mitigation pathway: reducing building-related GHG emissions by offsetting grid electricity with GHG-free solar electricity. Figure 7.3 shows the rooftop PV climate change mitigation pathway. This benefit is included in cost benefit calculations. For more on methods and assumptions, see Section 11.5 and the Appendix.

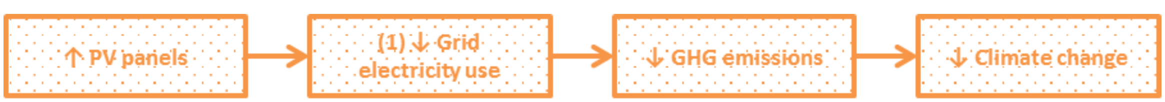

Figure 7.3. Rooftop PV climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

7.2.5 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 $PM_{2.5}$, $PM_{2.5}$ precursors, and ozone precursors. Therefore, installing PV panels reduces ozone concentrations by decreasing electricity-related ozone precursor emissions and reduces $PM_{2.5}$ concentrations by reducing emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors.

Figure 7.4 shows the ozone reduction pathway of rooftop PV. 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 7.5 shows the $PM_{2.5}$ reduction pathways of rooftop PV. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 11.6 and in the Appendix.

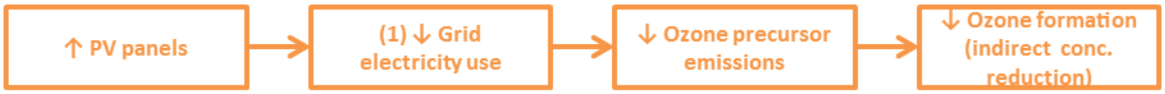

Figure 7.4. Rooftop PV ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

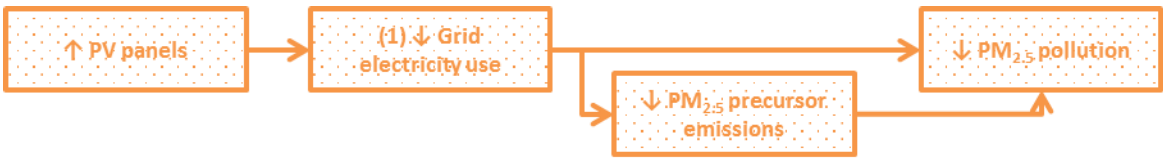

Figure 7.5. Rooftop PV $PM_{2.5}$ concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

7.2.6 PV and employment

According to NREL's Jobs and Economic Development Impact (JEDI) model, 1 kW of solar PV in the District at the prices noted in Section 7.1.1 requires about 16 hours of project development and on-site labor.[228] This works out to about 7.8 job years per MW of solar PV installed. The JEDI model estimates that approximately 0.2 annual operations and maintenance jobs are created for each MW of installed capacity in the District.

Learning curves play a significant role in employment factors over time. For instance, Germany experienced an 8% yearly decrease in operations and maintenance employment intensity for solar PV from 2007 to 2011.[229] While almost all new technologies exhibit some learning curve, solar PV has generally shown a faster learning rate than other renewable energy sources.[230] Therefore, the District should expect some reduction in its employment factors over time as city contractors become more efficient at installing and maintaining solar PV.

The JEDI model partly captures this learning curve through the impact of different PV install costs on employment creation. Using the post-2020 install costs in Table 7.1 yields a smaller employment impact for installation—about 11.2 hours of project development and on-site labor per installed kW of solar PV. Operations and maintenance job creation is held constant through the analysis for simplicity, but there will likely be operations and maintenance employment intensity declines as well. Further explanation of solar PV employment impact and assumptions can be found in Section 11.8 and the Appendix.

7.2.7 Other impacts

Reduced cooling energy consumption

When PV panels are installed on a roof they shade the roof surface and reduce the roof surface temperature, providing modest cooling energy savings. As discussed earlier in the cool roof and green roof sections, lower roof surface temperatures result in decreased cooling energy use during the cooling season and slightly increased heating energy use during the heating season. The magnitude of the cooling energy or heating energy impact depends on many factors, including climate and the characteristics of the roof below the panels (e.g., level of insulation), but the cooling benefit in the District likely greatly outweighs the potential heating penalty. 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.[231] In the District, assuming an electricity price of $0.12 per kWh,[232] a cooling energy intensity of 2.5 kWh per square foot,[233] and a reduction in annual cooling load of 20% (because of lower solar insolation in the District), PV shading could lead to annual cooling energy savings of about $0.06 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 the District, we do not include this benefit in cost-benefit calculations. This is a topic that warrants further research.

On a green roof, PV shading can have the added benefit of enhancing vegetation health and allowing for greater vegetation diversity.[234] 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.

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.[235] Putting PV panels on a white or green roof, increases the total sensible heat flux away from these roofs (decreasing their UHI benefit).[236] 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.[237] As the study notes, its results cannot be directly translated to changes in temperature,[238] but a recent study did examine the impact of large scale deployment of solar PV on urban temperatures.

A 2015 study of Los Angeles modeled “reasonably high” levels of solar PV deployment in the Los Angeles area and found either no temperature benefit or a slight temperature benefit from installing PV.[239] The cooling benefit of PV increased with increasing PV efficiency.[lxx] 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 18%, indicating a slight cooling benefit.

Reductions in ambient temperature from large scale PV installation could reduce energy use, reduce GHG emissions, and improve air quality and health. However, this will become less true as conventional roofs in the city are covered to cool or green roofs. Due to limited amount of research in this area and lack of results specific to the District, this benefit is not included in cost-benefit calculations.

Increased housing value

Two recent studies from Lawrence Berkeley National Laboratory provide evidence of a sales price premium for homes with owned solar PV systems. The first, which analyzed sales of almost 4,000 homes that included PV, found a sales premium of $4 per watt of installed PV capacity.[240] This equates to a sales premium of about $20,000 for a 5 kW solar PV system. The second and smaller study worked with a team

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[lxx] 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.

of appraisers to determine the value of solar PV systems in six states. This study found a similar premium to the previous study.[241] The first study notes a sharp decline in sales premium as systems age,[242] and the second study notes that the effect of system and market characteristics on price premium.[243]

Due to the relatively limited amount of research on this benefit, the need for location-specific methods, and the fact that value has only been shown for owned solar PV systems (most PV systems are installed as part of a third-party financing agreement), the benefit of increased home sales price with solar PV is not included in the cost-benefit calculations.

Avoided transmission and distribution losses

The U.S. Energy Information Administration estimates average transmission and distribution losses of 6% in the US.[244] These losses include losses between sources of supply and locations of distribution (transmission losses) and losses in distribution to customers (distribution losses).[245] Rooftop solar PV coverage generally avoids transmission and distribution losses.[246] Transmission losses rise during peak periods (e.g., summer afternoons in the District), and PV (especially west- and southwest-facing systems) reduces demand during this peak summer city electricity consumption period.[247] This increases PV value. This value is also not included in this analysis.

8 Reflective pavements

The sections below explore the basic principles of reflective pavements and their potential 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 include increased heating costs, glare, and reduced thermal comfort.

8.1 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.[248] 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.[249] Concrete is the composite of aggregate and binder.[250] 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.[251] The base course is built on top of the subgrade, or soil.

The two most common types of pavement are asphalt concrete and Portland cement concrete. Asphalt concrete consists of asphalt binder (which is black in color and is derived from petroleum) and aggregate.[252] Asphalt concrete is predominately aggregate by weight.[253] Asphalt concrete (commonly called "asphalt") is the most common roadway pavement—about 90% of roads are asphalt concrete.[254] 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 rouhgly 11 percent Portland cement binder, 33 percent sand, and 56 percent coarse aggregate by weight.[255] 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).[256]

8.1.1 Thermal performance

There are three ways heat transfers from one medium to another: conduction, convection, and radiation. Figure 8.1 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).[257]

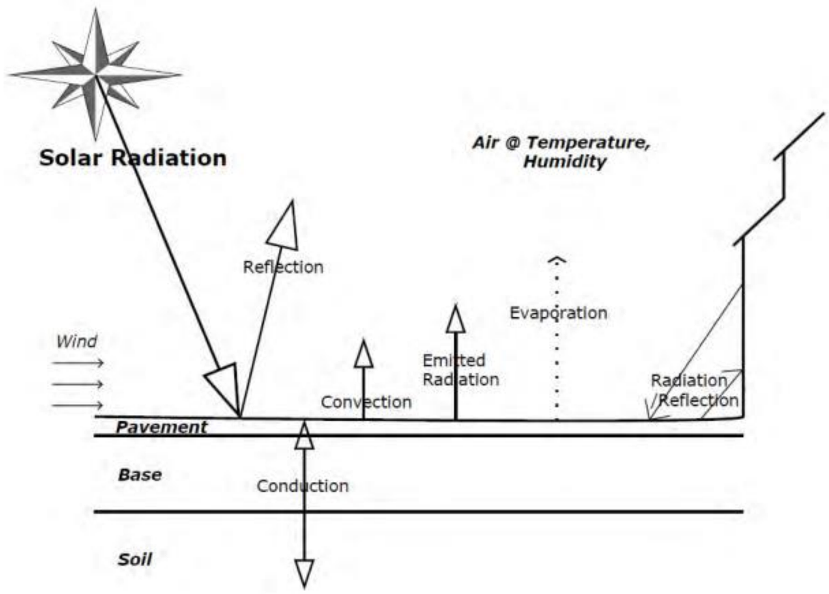

Figure 8.1. Pavement surface energy balance[258]

The size of these heat transfers are determined by several pavement properties: solar reflectance (albedo); thermal emittance;[lxxi] thermal conductivity;[lxxii] and specific heat.[lxxiii,259] The Federal Highway Administration (FWHA) notes that thermal emittance, thermal conductivity, and specific heat of asphalt and concrete pavements are very similar, so albedo is the most important material property in determining differences in thermal performance between pavements.[260] As a result, this analysis focuses on pavement albedo.

There are several other 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 wear and increased convection due to traffic movement.[261] Pedestrians, vehicles, and nearby vegetation and structures also shade pavements[262] more than roofs. If pavement is shaded for the majority of the day, it may not make sense to increase its solar reflectance.

8.1.2 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.[263] Rehabilitation, which typically occurs one or two times during a pavement's lifetime, are major repairs. Examples of rehabilitation techniques for asphalt

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

[lxxii] 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.

[lxxiii] 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.

pavement include patching, surface milling (i.e., removing the top few inches of asphalt), and overlays of a new asphalt (or potentially concrete) surface.[264] The combination of surface milling and overlays is often called "mill and fill". Examples of rehabilitation techniques for concrete pavement include full-/partial-depth repair (i.e., replacing sections of the pavement at the full-/partial-depth of the surface layer),[265] diamond grinding, and overlays of a new concrete or asphalt surface.[266]

Maintenance consists of minor repairs and can happen as often as annually or biannually. Maintenance also includes preservation techniques. Surface treatments are a common preservation technique for asphalt pavements and include techniques like chip seals,[lxxiv] asphalt emulsion sealcoats,[lxxv] slurry seals,[lxxvi] and bituminous crack sealants.[lxxvii,267] Surface treatments extend pavement life and improve water proofing and skid resistance.[268] Chip seals, asphalt emulsion sealcoats, and slurry seals typically impact the entire surface area of asphalt pavement being preserved. Bituminous crack sealants impact only a small fraction of the asphalt pavement surface. The type of surface treatment used and its frequency of application depends on the local transportation department and condition of pavement (see Section 8.1.4 for specifics in the District). Maintenance of concrete pavements can consist of joint resealing, slab stabilization, and load transfer restoration.[269] These techniques do not involve charges to large areas of the concrete pavement surface.

Reconstruction is necessary when pavement can no longer be repaired. The two types of reconstruction are surface reconstruction and total reconstruction. Surface reconstruction involves removing the existing pavement surface layer and replacing it with a new pavement surface layer. Total reconstruction, as the name suggests, is total replacement of the pavement surface and its underlying structure.

8.1.3 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.

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.[270] 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.[271] Albedo will vary to some extent by geography because of different pavement mix design standards.[lxxviii,272] This analysis uses the median of the aged solar reflectances, 0.15 and 0.30, respectively, as described above in cost-benefit calculations (see Table 8.1).

[lxxiv] For a description of chip seals, see https://en.wikipedia.org/wiki/Chipseal
[lxxv] For a description of emulsion sealcoats, see http://www.pavementinteractive.org/article/emulsified-asphalt/
[lxxvi] For a description of slurry seals, see http://www.pavementinteractive.org/article/slurry-seals/
[lxxvii] For a description of bituminous crack sealants, see http://www.pavementinteractive.org/article/bituminous-surface-treatments/
[lxxviii] For example, choice of aggregate is highly dependent on local geology (because aggregate is heavy and thus expensive to transport).

Brick is an important material for sidewalks, especially in older cities like the District. Red brick has an albedo between 0.20 and 0.30.[273] For simplicity this report assumes brick sidewalks have an albedo of 0.25.

Table 8.1. Solar reflectance of conventional pavement used in this analysis

Pavement type	Albedo
Asphalt	0.15
Concrete	0.30
Brick	0.25

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 8.2.5).

The most cost-effective way to increase existing road and parking lot reflectivity is through surface treatments or overlays, essentially adding a thin reflective layer to the existing pavement surface.[274] This is because the better that application of reflective pavements can fit into existing pavement installation and maintenance practices, the less expensive reflective pavements are and the more likely they are to be adopted at scale.[lxxix] Thinner pavement layers are also less expensive because they require less material.[275] 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 8.1.4, this report models reflective slurry seals on roads and parking lots.[lxxx] Reflective option for slurry seals (the resealing process used for many asphalt surfaced roads) are being developed but have not been piloted in any real-world conditions on trafficked roads. There are currently no reflective slurry seals on the market, so we model a hypothetical reflective slurry seal.[lxxxi]

Because it is better to fit pavement reflectance changes into existing installation and maintenance practices and because sidewalks are rarely maintained during their life, this report assumes sidewalk albedo is increased only when sidewalks are replaced. Options for higher albedo sidewalks are limited and can involve increasing albedo of the base material (e.g., concrete or brick) or applying a coating. Because coating sidewalks is uncommon, this report assumes more reflective concrete and brick sidewalks are achieved by increasing the albedo of the base material.

Based on discussions with Haley Gilbert and Ronnen Levinson of Lawrence Berkeley National Lab (see list of advisors at beginning of this report), this report assumes the solar reflectance of reflective roads and parking lots is 0.3 starting in 2020, and the solar reflectance of sidewalks is 0.35 starting in 2020.[276] This

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[lxxix] As noted previously, surface treatments and overlays are common maintenance practices of asphalt pavements.
[lxxx] Recall from Section 8.1.2 that slurry seals a common preservation technique for asphalt pavements.
[lxxxi] There are some pavement coatings available (e.g., from Emerald Cities Cool Pavement, from GAF) that can be used on parking lots. But there few examples of application and durability of these coatings—cool pavement coatings have not been piloted in any real-world conditions on trafficked roads. Given limited data availability, this report models a hypothetical slurry seal for parking lots.

report assumes pavements are made reflective starting in 2020 because of the limited number of existing reflective pavement options.

This report assumes that due to research, product development, and growing demand, albedo of reflective pavement in 2030 increases to 0.35 for roads, 0.40 for parking lots, and 0.45 for sidewalks. This report assumes the highest albedo for sidewalks because sidewalks typically experience the least wear, followed by parking lots and then roads.

Table 8.2. Solar reflectance of pavements used in this analysis

Pavement type	Conventional pavement albedo	Reflective pavement 2020-2030 albedo	Reflective pavement post-2030 albedo
Road	0.15	0.30	0.35
Parking lot	0.15	0.30	0.40
Sidewalk	0.30	0.35	0.45

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.[277] 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.[278] 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.[279] The similar relationship between albedo and surface temperature for both asphalt and concrete pavement reflects the similarity in thermal properties (discussed previously) of asphalt pavements and concrete pavements.[280]

8.1.4 Cost and timeline

Roads

Cost

This report focuses on reflective surface treatments—essentially changing the reflectivity of the topmost pavement layer when it is already scheduled and budgeted for resurfacing.

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 the District, the standard preservation surface treatment is a slurry seal,[lxxxii] with a unit cost of around $4 per square yard ($0.45 per square foot).[281] This analysis assumes a 5% cost premium for a reflective slurry seal to motivate research and development into higher albedo products, so the unit cost of a reflective slurry seal is about $4.27 per square yard ($0.47 per square foot). 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., $0.20 per square yard ($0.02 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.

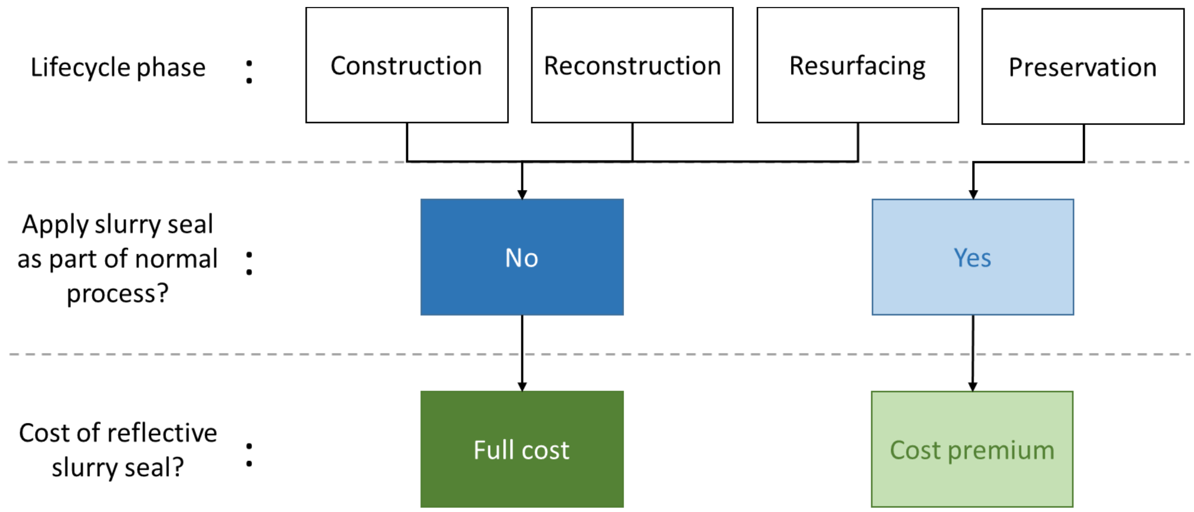

Figure 8.2. Flow chart to determine if pay full cost or cost premium for reflective slurry seal

As discussed above, increasing the reflectivity of asphalt pavement is a relatively new objective. A cost-effective way to increase pavement reflectivity during new construction, reconstruction, or resurfacing is to apply a reflective surface treatment. Because the District already uses slurry seals for preservation, adding a slurry seal during new construction, reconstruction, and resurfacing is a logical way to increase reflectivity during these lifecycle phases. However, during these lifecycle phases, the city will pay the full price (i.e., $4.27 per square yard ($0.47 per square foot)) for the reflective slurry seal because applying it is an additional process that would not normally occur during standard construction, reconstruction, or resurfacings (see Figure 8.2).[lxxxiii]

Timeline

The condition of the pavement will impact how often a slurry seal is needed. In general, the older or worse the condition of the pavement, the more frequently a new slurry seal needs to be applied to keep the road in condition for driving. Typically, slurry seals need to be reapplied every 5 to 7 years.[282] Commonly the time to the next application decreases with each additional application as pavement condition continues to decline with overall age (e.g., first it lasts 7 years, then 6 years, then 5 years).[283] This analysis assumes that a slurry seal is needed for pavement condition purposes 10 years after initial construction, reconstruction, or resurfacing.[284] Note that higher albedo surfaces will experience less thermal expansion

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

[lxxxiii] This analysis assumes no added labor cost because it is likely small (e.g., because the man power needed would already be on the construction site).

and contraction so are likely to last longer and may fully offset the cost premium of higher albedo products.

During new construction or reconstruction, the reflective slurry seal is applied at full cost (as noted above). During the three application slurry seal cycle after new construction or reconstruction, the reflective slurry seal is applied at the cost premium (as noted above). This analysis assumes slurry seals have a 6-year life. After the three-cycle slurry seal application, this analysis assumes the pavement is resurfaced and the reflective slurry seal is applied at full cost. After the 10-year resurfacing life, this analysis assumes a two application slurry seal cycle.[lxxxiv] During this period, the reflective slurry seal is applied at the cost premium.

For simplicity, this analysis assumes pavement timelines start in each of two instances: (A) at the beginning of a three-cycle slurry seal application phase and (B) at the beginning of a two-cycle slurry seal application phase.[lxxxv] Figure 8.3 shows the pavement timelines and costs associated with reflective road pavements in this analysis.

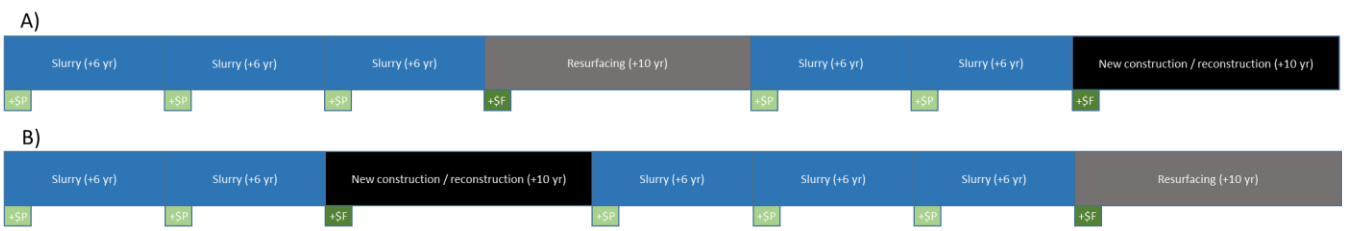

Figure 8.3. Road maintenance timelines and costs (dark green rectangles with "+$F" indicate the full cost (i.e., $4.27 per square yard) of the reflective slurry seal is paid and light green rectangles with "+$P" indicate only the cost premium (i.e., $0.20 per square yard) of the reflective slurry seal is paid)

Parking lots

Parking lots are typically privately owned and do not experience heavy traffic volume, so are not built to the same standard as public roads.[285] Therefore, this report assumes parking lots do not undergo preservation—any maintenance is likely crack sealing and filling potholes. Therefore, any reflectivity increase for parking lots will come at the full cost, only when the parking lot is upgraded or replaced due to wear. For simplicity, we assume the same costs for reflective surface treatments described in the previous section, or $4.27 per square yard. Because parking lots are not constructed to last as long as roads, this report assumes they have a lifetime of 15 years. Therefore, every 15 years the parking lot is reconstructed and a reflective surface treatment is added at a cost of $4.27 per square yard.

Figure 8.4. Parking lot maintenance timelines and costs (dark green rectangles with "+$F" indicate the full cost (i.e., $4.27 per square yard) of the reflective slurry seal is paid)

[lxxxiv] This report assumes just a two application slurry seal cycle after resurfacing, rather than a three application slurry seal cycle after new construction or reconstruction, because after the 10-year resurfacing life, the pavement is at a later stage in life and likely in worse condition and thus more likely to be replaced than pavement after the 10-year new construction or reconstruction life.

[lxxxv] 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.

Sidewalks

Sidewalks typically last for many decades.[286] This analysis assumes sidewalks are replaced every 40 years. Based on guidance from the District Department of Transportation (DDOT), this report assumes materials costs for concrete and brick sidewalks of $45 per square yard ($5.02 per square foot) and $97 per square yard ($10.78 per square foot), respectively.[287] This report assumes reflective sidewalks have a 5% cost premium compared to conventional sidewalks (i.e., $2.26 per square yard for concrete and $4.85 per square yard for brick) that is paid at the beginning of their 40-year lifetime.

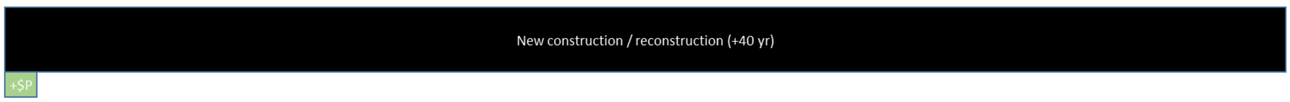

Figure 8.5. Sidewalk maintenance timelines and costs (light green rectangles with "+$P" indicate only the cost premium (e.g., $2.26 per square yard for concrete) of the reflective option is paid)

8.2 Impacts of reflective pavement

8.2.1 Reflective pavements impact summary

Table 8.3 below summarizes the costs and benefits of reflective pavements included in the cost-benefit results of this report. A lot of research still needs to be done to understand the full impacts of reflective pavements. As cities like the District become more serious about health, UHI mitigation, and climate change mitigation, reflective pavements can be a part of the solution, but need to be studied further.

Table 8.3. Reflective pavement 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	
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	
Direct cooling energy reduction (+)		X
Direct heating energy penalty (-)		X
Increased pavement life (+)		X
Enhanced nighttime visibility (+)		X
Downstream cooling (+)		X
Downstream 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

8.2.2 Ambient cooling and indirect energy

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 will heat up less and transmit less heat to urban air, reducing ambient temperatures.

As noted in the cool roof section (Section 3.2.3), there is a general relationship between urban albedo increase and air temperature decreases. Unlike for cool roofs, we have found only one study that examines the impact of city-scale reflective pavement installation on air temperature. The 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.[288] They estimate that in typical cases,[lxxxvi] increasing just pavement albedo from 0.10 to 0.35[lxxxvii] in the entire city[lxxxviii] will reduce peak air temperatures by up to 1 °F (0.6 °C). All 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). There are several small scale modeling studies (e.g., multiple city blocks) that specifically examine the impact of reflective pavements, but their findings vary widely.[lxxxix] Given the inconsistency of pavement temperature impacts at small-scale, this report focuses on impacts of average urban albedo changes. This report recommends pilot studies at the scale of multiple city blocks with temperatures measured before and after reflective pavement installation to assess reflective pavements effectiveness at cooling the air at small deployment scales.

As noted previously, UHIs are location specific, and fortunately, a recent study examined UHI mitigation in the District and found albedo increases are effective at reducing the District's UHI, though the study did not examine reflective pavements in isolation.[289]

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 8.2.2) and improvements in air quality and declines in heat-related mortality (Section 8.2.4).

Indirect energy

The cooling effect of reflective pavements is apparent in both the cooling season (summer) and the heating season (winter), but is much smaller during the heating season because the sun is at a lower angle in the sky and is above the horizon for fewer hours. Any ambient cooling that results from reflective pavement installation leads to net energy savings city-wide. Few studies have simulated the indirect energy effects of ambient cooling from reflective pavements. A modeling study of Los Angeles estimated that increasing the albedo of all 1250 km^2 of pavement in Los Angeles by 0.25 would lead to a temperature

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[lxxxvi] 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.
[lxxxvii] This is approximately equivalent to replacing asphalt pavements with concrete pavements.
[lxxxviii] In the District, roads make up about 12% of city area.
[lxxxix] For example, a modeling study of Phoenix found increasing pavement albedo by 0.4 decreased air temperature by 0.4°C and a study of Athens found increasing pavement albedo by 0.5 decreased air temperature by 6°C.

change of 0.6°C (about 1°F) and indirect energy savings of $15 million (1998$) per year ($0.01 per square foot of pavement per year).[290,xc] As with cool roofs, the scale of any net indirect energy savings depend on the building stock in a city, but cooling energy savings dominate in the District.

Section 11.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

8.2.3 Climate change mitigation

Reflective pavements reduce building space conditioning energy consumption through ambient cooling, reducing GHG emissions at power plants. Like cool roofs, much of the light reflected by reflective pavements is reflected back to space, altering the Earth's radiation balance and helping to counter global warming. As noted in the cool roof section (Section 3.2.4), the global cooling impact of reflective surfaces is an area of ongoing research. However, 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 11.5. Figure 8.6 shows the climate change mitigation pathways of reflective pavements.

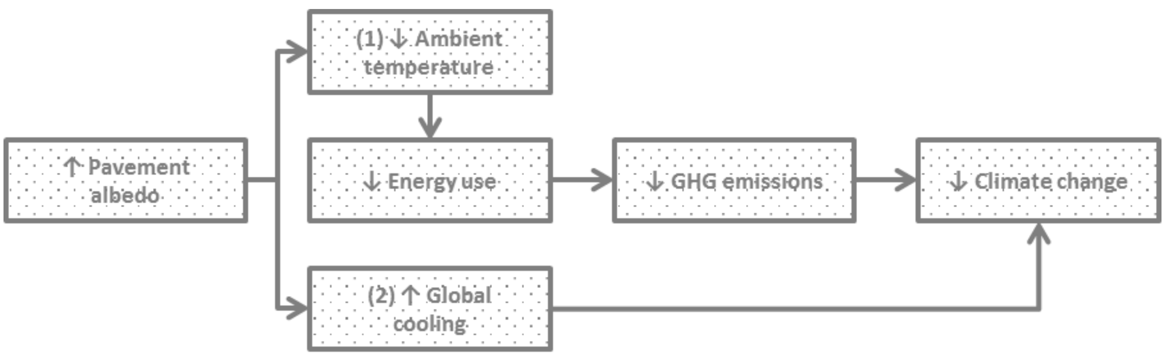

Figure 8.6. Climate change mitigation pathways of reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

A forthcoming study from Lawrence Berkeley National Lab, the University of Southern California, and the University of California Pavement Research Center generally indicates positive life cycle GHG emissions of currently available reflective coatings (i.e., GHGs emitted during production are higher than GHG emissions saved during the use phase).[291] GHG emissions that occur outside the use phase of smart surfaces are outside the scope of this analysis, so this does not impact the cost-benefit calculations for reflective pavements. However, if reflective pavements are to be an integral part of the District's climate change and UHI mitigation plans, this issue needs to be addressed in future technologies.

8.2.4 Air quality and health

Reflective pavements and ozone

Increasing pavement albedo indirectly reduces ozone concentrations by decreasing ambient air temperature. The chemical reactions that form ozone are dependent on temperature, so decreasing ambient temperature decreases ambient ozone concentration. Decreasing ambient temperature also indirectly reduces summertime building energy use, leading to decreased ozone precursor emissions. In

[xc] This is equivalent to about $22 million today, or about $0.002 per square foot.

general, as precursor emissions decline, ozone formation declines as well. Figure 8.7 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 11.6 and in the Appendix.

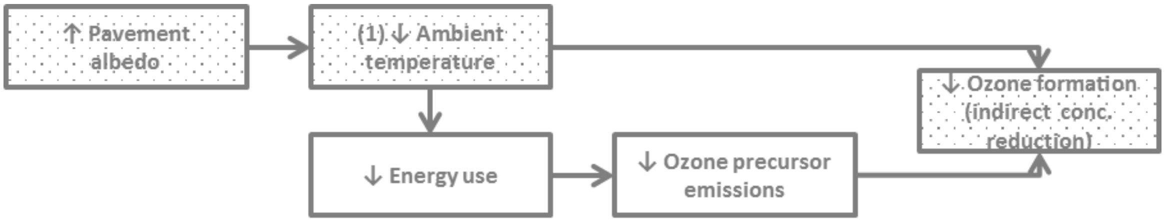

Figure 8.7. Ozone concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Reflective pavements and PM2.5

Reflective pavements reduce $PM_{2.5}$ pollution indirectly by decreasing ambient temperature, which in turn reduces building energy use. Reducing building energy use results in decreased power plant emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors, decreasing primary and secondary $PM_{2.5}$ pollution. Figure 8.8 shows the $PM_{2.5}$ concentration reduction pathways of reflective pavements. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 11.6 and in the Appendix.

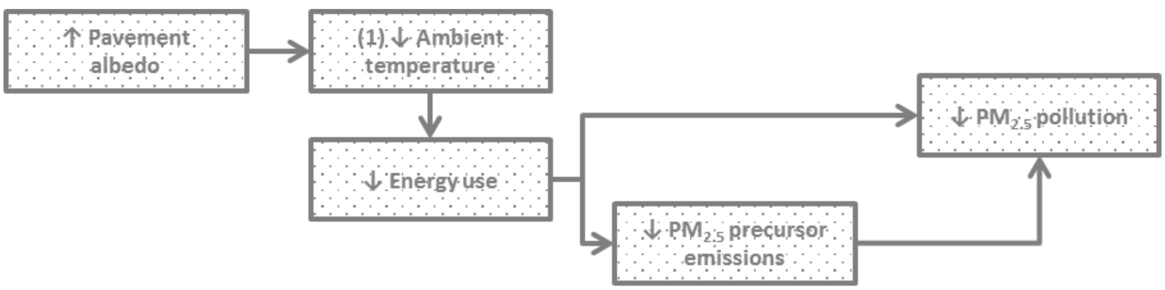

Figure 8.8. $PM_{2.5}$ concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

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.[292] This report describes heat-related mortality benefit estimation methods and assumptions in Section 11.6 and in the Appendix.

8.2.5 Other impacts of reflective pavements

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.[xci] This slightly increases building heat gain,[293] which in turn increases building cooling energy use in the summer.[294] (The increase in building heat gain also decreases building heating load in the winter, though this effect appears much smaller.)[295] The increased amount of reflected sunlight from reflective pavements can also slightly reduce nearby buildings' artificial lighting needs, which has two direct energy benefits.[296] Reducing a buildings artificial lighting needs not only reduces energy used for lighting, but also reduces the amount of heat given off by internal lighting, which could reduce cooling energy requirements in the summer (and increases heating requirements in the winter). The energy savings related to reduced artificial lighting needs depend on the type of lighting (e.g., incandescent, fluorescent, LED) a building has, with a smaller benefit for more efficient lighting.

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. This impact warrants further research—real-world pilot studies would be particularly useful.

Increased pavement life

Increasing pavement albedo can lead to increased pavement life because the lower temperatures of reflective pavements mean less thermal expansion and contraction, slowing the aging process. For instance, 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).[297] For concrete, lower daytime surface temperature reduces the temperature-related stresses that contribute to cracking.[298] However, there is limited research demonstrating the link between pavement reflectivity and increased life, so this benefit is excluded from cost-benefit calculations. However, this benefit could be substantial and warrants continued research, perhaps offsetting the cost premium (assumed to be 5% in this report).

Enhanced nighttime visibility

Increasing pavement reflectivity can enhance nighttime visibility.[299] This can increase driver and pedestrian safety and reduce street lighting needs because reflective pavements better reflect street and vehicle lights.[300] When new light fixtures are installed, fewer street lights 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 LBNL has analyzed potential lighting reduction impact form light colored road surfaces, there is probably not yet a sufficient body of research to include the economic benefit of reduced street lighting from reflective pavements, so this benefit, which may be significant, is 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.

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, given the

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[xci] Because reflective pavements are cooler than conventional pavements, they will emit less upward longwave radiation, which would decrease nearby building energy use. However, this impact appears to be much smaller than the increased reflected shortwave radiation.

large uncertainty and lack of research on its economic impact, this analysis does not include the potential benefit of reduced stormwater runoff temperature in cost-benefit calculations.

Downwind cooling

As discussed in the cool roof benefits section (Section 3.2.7), 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 District metro area), downwind cooling benefits could be large.

Glare

Glare is caused by excessive brightness and can be uncomfortable or disabling—glare is also subjective.[301] 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.[302] However, this report models reflective pavements with albedo higher than that of concrete (i.e., higher than 0.3), so this report includes a brief discussion of glare from reflective pavements.

Figure 8.9 below shows the solar energy intensity of the wavelengths of light present in sunlight. About 5% of solar energy is ultraviolet (UV) light (blue in Figure 8.9), about 43% is visible light (green in Figure 8.9), about 52% is near-infrared light (orange in Figure 8.9).[303] Lawrence Berkeley National Laboratory, a leader in cool roof and reflective pavement research, notes that it is possible to achieve albedo increases up to 0.40 without affecting a surfaces appearance[304] by installing a cool-colored surface material in place of standard-colored surface materials. Cool-colored materials reflect strongly in the near-infrared spectrum, which makes up about 52% of sunlight.[xcii] Adopting cool-colored pavements—essentially low-brightness pavements, or pavements that do not reflect much visible light—helps address the potential problem of increased glare that comes with installation of reflective pavements.[xciii]

This report found no studies that examine the relationship between increased pavement reflectivity and glare, so the impacts of glare are not included in cost-benefit calculations. The potential effects of glare from highly reflective pavements deserve further study.

[xcii] Cool colored materials are also described in the cool roof section (Section 3.1.1).

[xciii] Though limiting the amount of visible light reflected by reflective pavements will limit the potential for reduced lighting needs in buildings near reflective pavements.

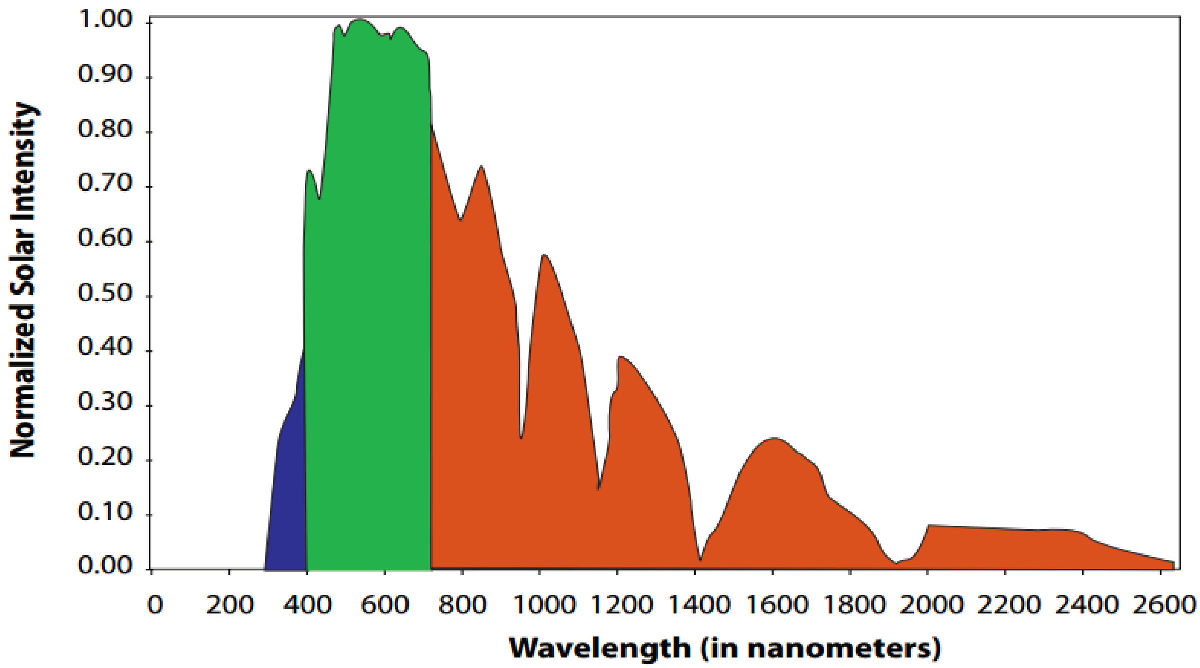

Figure 8.9. Solar energy versus wavelength reaching Earth's surfaces on a typical clear summer day (blue is ultraviolet wavelengths, green is visible wavelengths, and orange is near-infrared wavelengths)[305]

Thermal comfort

The impact of reflective pavements on thermal comfort may be best understood with a brief overview of the factors that impact thermal comfort. Several local microclimate factors commonly used in assessing thermal comfort are: **air temperature** (the temperature of the air surrounding an individual); **mean radiant temperature** (the weighted average of all temperatures from surfaces surrounding an individual; this accounts for the impact of radiation); relative humidity;[xciv] air speed; metabolic rate;[xcv] and clothing insulation.[xcvi,306] Air temperature and mean radiant temperature are the most important factors for understanding the thermal comfort impact of reflective pavements (see Figure 8.10).[xcvii] There is currently no clear consensus as to the impact of reflective pavements on outdoor thermal comfort.

One study of high albedo pavement coatings (with high reflectivity in the near-infrared spectrum) found that the majority of people surveyed felt cooler on the pavement with a high albedo coating than on uncoated pavement.[307] However, these results have limited value because the sample size was only six people. Two recent modeling studies found reflective pavements decreased pedestrian thermal comfort. The first, simulated a flat, paved area (e.g., a parking lot) and found that reflective pavements increased mean radiant temperature by 10-11°C because of the increased amount of reflected light from a reflective pavement (of albedo 0.5) compared to a conventional pavement (of albedo 0.1).[308] This increase in mean

[xciv] A measure of the amount of water vapor in the air compared to the maximum amount the air can hold at the same temperature and pressure.
[xcv] The energy generated by the human body.
[xcvi] The amount of thermal insulation provided by the clothing a person is wearing.
[xcvii] Reflective pavements will likely have little to no meaningful impact of relative humidity and air speed, and metabolic rate and clothing insulation are altogether unrelated to pavement reflectivity.

radiant temperature, however, was not enough to change a pedestrian's thermal sensation[xcviii] (e.g., from "hot" to "very hot").[xcix] The second study, simulated various urban canyon[c] configurations and found higher albedo surfaces decrease pedestrian thermal comfort.[309] The increased reflected radiation from the higher albedo surfaces counteracted any ambient air temperature reductions.[ci,310] As with the first study, only in a few circumstances did reflective pavements change the thermal sensation[cii] of pedestrians.

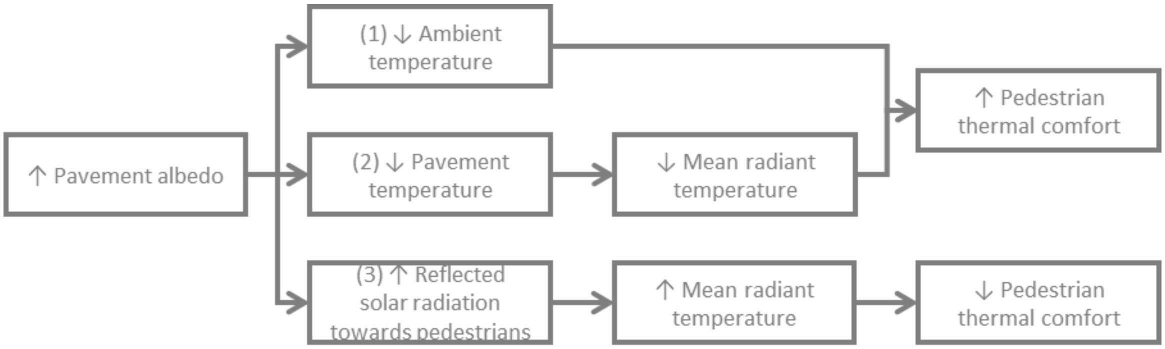

Figure 8.10. Impact of reflective pavements on summertime pedestrian thermal comfort

Given the lack of consensus and limited research on the impact of reflective pavements on thermal comfort, this impact is not included in cost-benefit calculations. The relationship between reflective pavements and thermal comfort warrants further research, particularly more experimentally robust real-world studies as well as modeling studies incorporating the ambient cooling impacts of city-wide reflective pavement installation.

UV light reflectance

Reflective pavements also increase the potential for upward UV light reflectance. This could be harmful to health[311]—because exposure to UV light can cause sunburn and increases risk of skin cancer. As with glare and visible light, increased reflectance of UV light can be largely designed out of reflective pavements.[312] And only about 4% of sunlight is in the UV spectrum (see Figure 8.9), so this will not have significant impact on goals to achieve high albedo pavements.[313] Given the lack of data on this impact and given its relatively simple solution, this repost does not include the impact of increased upward UV reflectance from reflective pavements in cost-benefit calculations.

[xcviii] Ref 306 modeled thermal sensation using the Physiological Equivalent Temperature. It is important to note that ref 306 did not include air temperature impacts in thermal comfort calculations, though this would have a minor effect if anything.

[xcix] There have been criticisms of this study surrounding the small size of the test bed. Many researchers felt that the test plot was too tiny to avoid influence from surrounding pavements (which were dark).

[c] Where the street is lined on both sides by buildings.

[ci] Though at large scale ambient temperature reductions will be larger and further counteract the declines in comfort from increased reflected radiation (i.e., increased mean radiant temperature).

[cii] Ref 309 modeled thermal sensation using the Index of Thermal Stress.

9 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.

Benefits of permeable sidewalks and parking lots include reduced stormwater runoff and reduced salt use due to less ice buildup. A benefit that needs to be studied more is ambient cooling, which leads to reduced cooling energy use, reduced greenhouse gas emissions, improved air quality and reduced heat-related mortality.

9.1 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.[314]

- The *surface layer* is the top layer that an observer sees. 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 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, which is common in the District.
- 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 9.1 shows an example cross section of a permeable pavement system

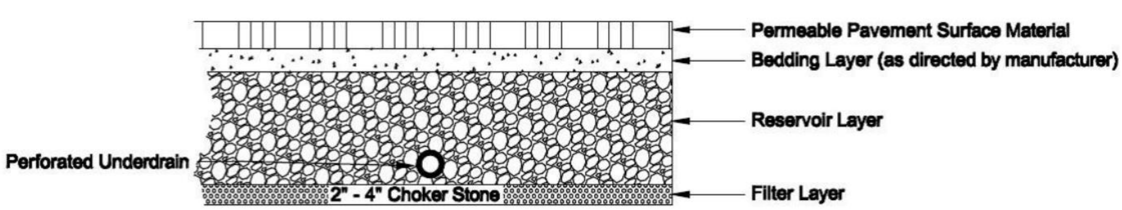

Figure 9.1. Example cross section of permeable pavement[315]

Porous asphalt

Porous and impervious asphalt have a very similar appearance and method of installation.[316] The main difference is that porous asphalt has reduced sand or fines that results in air voids for water to drain through.[317] Air voids typically make up 15 to 20 percent of the volume of porous asphalt.[318] The thickness of the porous asphalt surface layer depends on the expected traffic load and is typically 2 to 7 inches thick.[319] 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 reliably bear the high traffic load.[320]

Figure 9.2. Example of porous asphalt pavement[321]

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.[322] Air voids account for between 15 to 35 percent of the pervious concrete surface layer.[323] The thickness of the pervious concrete surface layer depends on the expected traffic load and typically ranges from 4 to 8 inches.[324]

Figure 9.3. Example of pervious concrete pavement surface layer, with quarter to for scale[325]

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.[326] These openings make up 5 to 20 percent of the pavement surface area and are typically filled with small gravel.[327] Permeable interlocking concrete pavers need to be at least 2.36

inches thick and tend to be thicker if they will support vehicle traffic.[328] 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.[329]

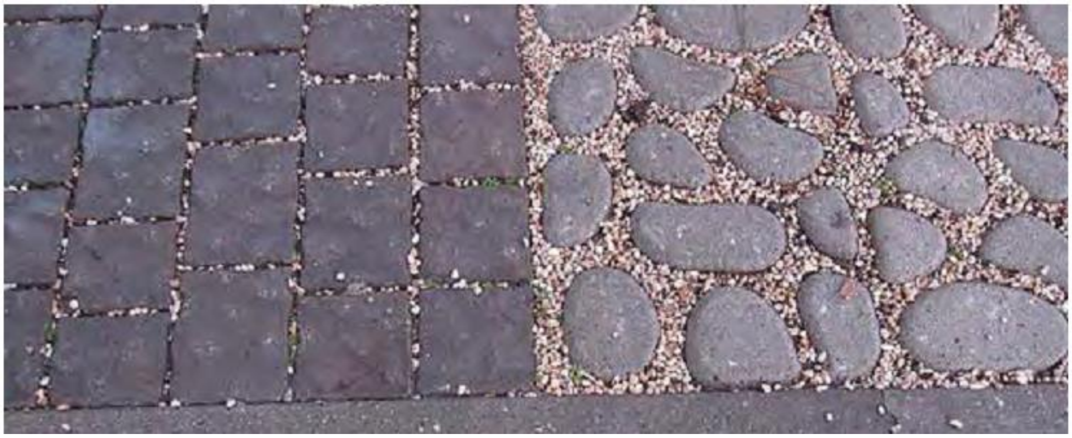

Figure 9.4. Examples of permeable pavers[330]

Grid pavements

Grid permeable pavements, a less common category of permeable pavement, 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.[331] 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 and are typically only used for areas that experience low traffic volume (e.g., alleys, side streets, parking lots, driveways, patios, and trails).[332] Grid pavements are generally not used for sidewalks.

Figure 9.5. Examples of grid pavements[333]

9.1.1 Permeable pavement thermal performance

To understand permeable pavement thermal performance, 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.[334] 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.[335]

The daytime and nighttime surface temperature of a wet permeable pavement tends to be less than that of the wet impervious equivalent.[336] 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.[337] Because energy in the pavement is used to evaporate surface moisture during evaporative cooling, there is less energy available to heat the air or surroundings. At large enough scales, evaporative cooling from permeable pavements could lead to air temperature reductions throughout a city.

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.[338] This may partly explain why permeable pavement surfaces are hotter than their impervious equivalent under dry conditions. However, there is little data on the solar reflectance of permeable pavements. Based on the limited information available, it seems porous asphalt has a similar initial albedo to impervious asphalt.[339] Pervious concrete may have a slightly lower initial albedo than impervious concrete,[340] and permeable pavers have a similar initial albedo to impermeable pavers.[341] Grid pavers' albedo is largely determined by the filler. High albedo filler, such as light-colored gravel, would provide a high albedo surface.

To date, there are 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).

9.1.2 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 effectiveness.[342] Sediment and particle sources include vehicles, the atmosphere, and runoff.[343] Tasks that can accelerate the clogging of the pores should be avoided on permeable pavements, including sanding, resealing and resurfacing, power washing, storage of snow piles containing sand, storage of mulch or soil materials.[344]

Clogging increases with age and use; however, permeable pavements are effective even when partially clogged.[345] Sediment and soil deposits should be removed as needed.[346] DOEE recommends vacuum sweeping in extreme circumstances and dry street sweeping multiple times per year.[347]

Freeze/thaw damage can be an issue for permeable pavements if they are not property constructed.[348] However, there is evidence that properly constructed permeable pavements can handle freeze/thaw stress better than their impermeable equivalent. For example, because of reduced freeze/thaw stress, a permeable asphalt parking lot in a northern climate can last 15 years longer than a traditional asphalt parking lot in the same conditions.[349]

Permeable pavements may even develop fewer cracks and potholes than traditional pavement. For instance, porous asphalt pavements tend to develop fewer cracks and potholes than impervious asphalt.[350] When cracks and potholes do occur, they can be patched with conventional asphalt as long as the patched area does not make up more than 10% of the total area of permeable pavement.[351] We have not found similar evidence for pervious concrete, but expect the similar results. For permeable pavers, individual pavers can be replaced as needed.

9.1.3 Cost and timeline

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

Costs

The cost of installing a permeable parking lot varies widely with the type of material. 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.[352] With a cost multiplier of 1.4 (from DC Water) to cover additional costs like construction management and design,[353] 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 $1.08 per square foot installed.[354] For gravel we assume a cost of $1.30 per square foot installed.[ciii] plastic grid with grass and plastic grid with gravel cost $3.88 per square foot and $4.10 per square foot, respectively.

The cost of permeable pavers averages about $10.50 per square foot.[355] For enhanced design, we assume an additional $2.24 per square foot to cover the cost of the gravel needed for an infiltration sump (see the appendix for more details).

Based on communication with DDOT, 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.

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.[356]

Timeline

Timeline assumptions for traditional asphalt parking lots are the same as discussed under reflective pavements (Section 8.1.4), with a complete replacement required every 15 years. Permeable alternatives have the ability to extend that timeline, depending on the material and the climate.

Little research has been done into 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).[357] 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 9.1. Permeable parking lot lifespans

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

[ciii] 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).

As noted in 8.1.4, we assume conventional sidewalks last for the full 40-year analysis period. Pavers typically last longer than conventional pavement,[358] so we assume permeable sidewalks last the full 40-year analysis period as well.

9.2 Impacts of permeable sidewalks and parking lots

9.2.1 Permeable sidewalk and parking lot impact summary

Table 9.2 below summarizes 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. However, additional research is needed to understand the full impacts of permeable sidewalks, and permeable pavements in general.

Table 9.2. 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

9.2.2 Stormwater

Permeable pavement is widely recognized as effective at helping to managing stormwater. Permeable pavement contains far more air voids than impervious pavement, 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.[359] The air voids in the surface layer also provide some water storage.[360]

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. The permeable pavement surface type generally does not have an impact on a permeable pavement's retention capabilities.[361] Refer to Section 11.7 for an overview of methods and assumptions. The Appendix provides further detail.

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.[362]

9.2.3 Sidewalk and parking lot salt use

Snow and ice melt faster on permeable pavements than impervious pavements, thus 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.[363] For example, research in New Hampshire found that permeable asphalt pavement required about 75% less salt than conventional asphalt.[364] There is no direct evidence showing that pervious concrete reduces salt use compared to traditional concrete. Research shows melted water immediately infiltrates pervious concrete, limiting the potential for refreezing.[365] Thus, it seems reasonable that pervious concrete requires less salting compared to traditional concrete. One would expect similar results for permeable pavers and lattice structures as well. Refer to Section 11.9 and the Appendix for an overview of methods and assumptions.

9.2.4 Additional impacts of permeable sidewalks and parking lots

Ambient cooling

Permeable pavements can have ambient cooling and other benefits. However, their UHI mitigation potential is less well 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. Also, permeable pavements are beneficial for treed sidewalks because they allow air and water to penetrate to the roots, rather than having the roots grow up to buckle the sidewalk.

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.[366] On the other hand, evaporative cooling can occur when water is present in the surface layer or on top of permeable pavements,[367] 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.

Few studies have modeled or measured impact of permeable pavements on air temperature. 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.[368] The exception is when switching from traditional concrete to porous asphalt, most likely because of the large difference in surface albedo. An empirical study in Davis, California found similar results for all seasons.[369] 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.[370] At night, the air temperature above permeable pavement was generally lower than that above impervious pavement under both dry and wet conditions.[371]

Current literature suggests permeable pavements are effective at mitigating nighttime UHIs and decreasing nighttime urban air temperatures. The size of this impact depends on the moisture available in the permeable pavement (e.g., dry vs. wet). The same is true of wet permeable pavements during the day. However, the available literature is less clear about the effect of dry permeable pavements during the day—some studies have found decreased air temperature and other have found increased air temperature. 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.

One way to enhance the UHI mitigation properties of permeable pavements is to keep moisture in the surface layer through continuous wetting. Some have suggested development and use of water-retentive pavements for this purpose[372] and others have suggested using landscaping water runoff.[373] The second option seems more practical. It could even be expanded to include collecting stormwater runoff from roofs to keep permeable pavements wet. This, too, is an area that merits further study.

We have not found compelling studies modeling the impact on air temperature of adding large areas of permeable pavements to a city. Converting conventional asphalt parking lots to plastic grid pavers with gravel or grass likely will have a small impact on urban temperatures because of the increased albedo and evapotranspiration. The impact on urban temperatures of converting conventional sidewalks (brick and concrete) to permeable pavers is less clear. Furthermore, 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. If the scale of permeable pavements is to increase, this modeling assumption would need to be changed.

Co-benefits of ambient cooling

Except under dry, daytime conditions, the available literature suggests that permeable pavements are effective at mitigating UHIs and reducing ambient air temperature. Co-benefits of ambient cooling, including reduced energy use, reduced pollutant emissions from power plants, improved air quality, and reduced heat-related mortality can be expected under the right conditions. 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. However, as with studies examining the impact of large-scale permeable pavement installations on UHIs, we have found no studies that examine the impact of permeable pavements on co-benefits of ambient cooling. This is an area that merits further study.

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. In fact, a study of Davis, California found that wet permeable pavements improve thermal comfort, though gross categories of thermal sensation did not change (e.g., still “hot” or “warm”).[374]

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.[375] 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. Unfortunately, this is the only study of permeable pavement under dry, daytime conditions. This is an area that deserves further study.

Water quality

Permeable pavements also improve urban water quality. EPA has summarized several studies that quantify pollutant removal by permeable pavements, including dirt, dust, heavy metals, and landscaping nutrients.[376] However, this benefit is difficult to quantify.

Pedestrian safety

The properties of permeable pavements that lead to reduced salt needs likely also mean that in the absence of salting, permeable pavements form ice less quickly and clear of ice more quickly. This means permeable pavements may be safer for pedestrians in the winter, potentially leading to fewer falling accidents, lower risk, lower insurance requirements. However, data to estimate this potential benefit is scarce, and data that does exist has limitations. The Royal Society for the Prevention of Accidents in England estimates that there were 2,919 hospital admissions in the winter of 2014/2015 as a result of falls on snow and ice.[377] Assuming the same incidence rate in the District as in England (population of about 55 million people),[378] this equates to about 34 hospital admissions per year for falls on snow and ice in the District. Averaged over the approximately 200 million square feet of parking lots and sidewalks in the District, this impact is negligible. Furthermore, injuries that would occur from these falls (e.g., sprains and broken bones) are much less costly than mortality and we do not know the extent to which these falls occur on pavements or the extent to which permeable pavements would actually reduce these falls. Given the significant uncertainty surrounding this benefit and that it appears negligible, we do not include it in cost-benefit calculations.

10 Urban trees

The sections below explore the basic principles of urban trees and their impacts. 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, aesthetic value, increased biodiversity, and improved thermal comfort. Potential drawbacks include increased humidity, increased emissions of biological volatile organic compounds, increased heating needs due to ambient cooling, and increased pollen production (increased contribution to allergies).

10.1 Urban tree basics

10.1.1 Planting and care considerations

Effective tree planting programs, such as those run by Casey Trees and DDOT, ensure trees have adequate soil volume and select species that can survive in the expected conditions. This ensures healthy, long-lived trees that provide full potential benefits.

Sufficient soil volume

Adequate soil volume is vital for the health and longevity of urban trees. Soil volume, or rooting space, is the area underground where tree roots grow. Without it, trees do not reach full size and can die prematurely, meaning trees with insufficient soil volume do not reach full benefit-providing potential.[379]

The appropriate soil volume depends on the expected tree size. The general rule of thumb is one to two cubic feet of soil per one square foot of crown spread (essentially the average canopy diameter of the full-grown tree).[380] Sufficient rooting space ensures better tree health, and minimizes damage to/extends life of paved surfaces.[381] Private land and park space are often best for increasing tree canopy because these areas tend to have most available soil volume.[382] The District Department of Transportation and Casey Trees each provide several design examples to enable adequate soil volume in space-constrained urban areas.[383]

Tree selection

Factors in tree selection include a tree's water needs, climate tolerance, preferred soil conditions,[civ] preferred light levels, salt tolerance,[cv] and pollution tolerance.[384] A tree's potential for creating litter (e.g., fruit droppings) is also important to secure the support of residents and local businesses.[cvi] Low maintenance, native trees with few or no droppings are typically preferred.

[civ] For example, can it handle the compacted soil common in urban settings?

[cv] To survive runoff from deiced roads and sidewalks

[cvi] We heard a few times of resistance to new tree planting programs because of tree selection in the past that create more cleanup for residents and local businesses.

Casey Trees has a valuable guide to tree selection in urban areas in the Mid-Atlantic that addresses each of considerations above and notes the best locations to plant specific tree species (streets, plazas, parking lots, bioretention/rain gardens, etc.).[385]

10.1.2 Costs

The initial cost of planting a tree includes purchasing the tree and the cost of planting. There is wide range of estimates for tree planting costs. This report assumes middle-of-the-road cost estimates: private trees cost $500 and public trees cost $220.[cvii,386] This report uses the average of these estimates for cost calculations (i.e., $360 per tree).

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.[387] A regional summary of the costs and benefits of trees by the U.S. Forest Service estimates trees cost between $5 and $21 per tree per year to maintain, depending on tree size and type (i.e., private or public).[388] Pruning is the costliest maintenance practice. This report assumes an average estimate of $13 per tree per year for maintenance. Table 10.1 shows planting and maintenance costs used in cost-benefit calculations for this report.

Table 10.1. Tree planting and maintenance costs used in this report ($2006)

Planting cost (per tree)	$360
Maintenance cost (per tree per year)	$13

Many cities offer free or discounted tree planting. Casey Trees is the leading organization in the District that offers free trees.[389]

10.2 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 CO_2, 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., CO_2, ozone precursors, $PM_{2.5}$ and $PM_{2.5}$ precursors) by reducing demand for electricity. Akbari et al., EPA, and Casey Trees provide excellent descriptions of the benefits of urban trees.[390] Much of the discussion and references cited below draw from these sources.

10.2.1 Urban tree impact summary

Table 10.2 below summarizes 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 reports findings will be conservative (i.e., underestimate the net value of urban trees).

[cvii] Both estimates include the cost of the tree and the cost of planting.

Table 10.2. Urban tree 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
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
Downstream cooling (+)		X
Downstream warming (-)		X
Reduced stormwater runoff temperature (+)		X
Amenity value (+)		X
Aesthetic benefits (+)		X
Biodiversity (+)		X
Reduced UV light exposure		X
Increased humidity (-)		X
Increased BVOC emissions (-)		X
Increased pollen production (-)		X

10.2.2 Direct energy

Urban trees can directly reduce energy use of adjacent buildings by shading building surfaces, decreasing the amount of solar radiation absorbed by the building surface or passed through windows. This reduces building surface temperatures[391] and thus the heat transferred into the building, which in turn reduces building cooling energy needs. Huang et al., (1990) estimate that during the summer 10% to 30% of solar energy reaches surfaces under a tree's canopy.[392] In the winter, up to 80% of incident solar energy reaches the surfaces below deciduous tree canopy. Deciduous trees are the norm in the District.

Trees can also serve as windbreaks (i.e., wind shields), reducing the wind speed in the vicinity of buildings.[393] This reduces 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 much larger than the effect of deciduous trees, which do lose foliage in the winter. In summer, the effect of a windbreak can be positive or negative,[394] but potential air conditioning use increases from windbreaks are generally less than savings due to shading.[395]

The extent of the direct energy benefits from urban trees depends on their placement. Direct energy benefits are greatest for trees planted on the west side of a building.[396] The east side and south side are also good options.[397] Tall trees protect from high southern sun in summer (low limbs should be removed to allow in low winter sun) and short trees to the east and west provide shade in the morning when the sun is lower in the sky.[398]

Estimates of direct energy savings vary. One study of a utility tree planting program in Sacramento found cooling energy savings in shaded buildings of between 7% and 47%.[399] Another study that examined the same utility program found cooling energy savings of 1% per tree and heating energy savings of 2% per tree. [400]A simulation study of trees in various US 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.[401]

Section 11.2 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

10.2.3 Ambient cooling and indirect energy

Evapotranspiration[cviii] and shading from urban trees leads to ambient cooling, reducing cooling energy use.[402]

The extent of ambient cooling varies by city. A modeling study simulated the impact of increasing the urban forest in 10 U.S. cities and found that, on average, more trees could reduce temperatures at 2pm between 0.3 and 1°C.[403] 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.[404] 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 the District.[405]

Indirect energy savings will also vary by city. The 10 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 ft^2 of roof in the District.[cix][406]

Section 11.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

10.2.4 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 CO_2,[407]and by global cooling (discussed in Section 3.2.4).

The greenhouse gas (GHG) emissions reductions at power plants depend on the magnitude of the direct and indirect energy savings that result from urban tree planting and on the carbon intensity of the

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[cviii] Evapotranspiration is described in the green roof section (Section 4.2.2).
[cix] 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.

electricity that is not used. A modeling study of CO_2 emissions reduction benefits of urban trees in Los Angeles found that each tree would reduce power plant CO_2 emissions by 18 kg of CO_2 per year.[cx,408]

In general, CO_2 sequestration depends on tree size and growth rate, with large, fast-growing trees sequestering more CO_2 than small, slow-growing trees.[409] EPA estimates that in 2013 urban trees in the continental U.S. sequestered 89.5 million metric tons of CO_2e.[410] Some of the carbon stored in a tree is released when it drop leaves or branches,[411] and 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.[412,cxi] 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).[413] Given the small size of the CO_2 sequestration benefit, this report does not include sequestration in cost-benefit calculations.[cxii]

Planting urban trees may also lead to global cooling (discussed in Section 4.2.4) because trees typically have a higher albedo than conventional roofs or pavements they cover—tree albedo ranges from 0.25 to 0.30.[414] Because global cooling can be a large 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 10.1 shows urban tree climate change mitigation pathways. Refer to Section 11.5 for an overview of methods and assumptions. The Appendix provides further detail.

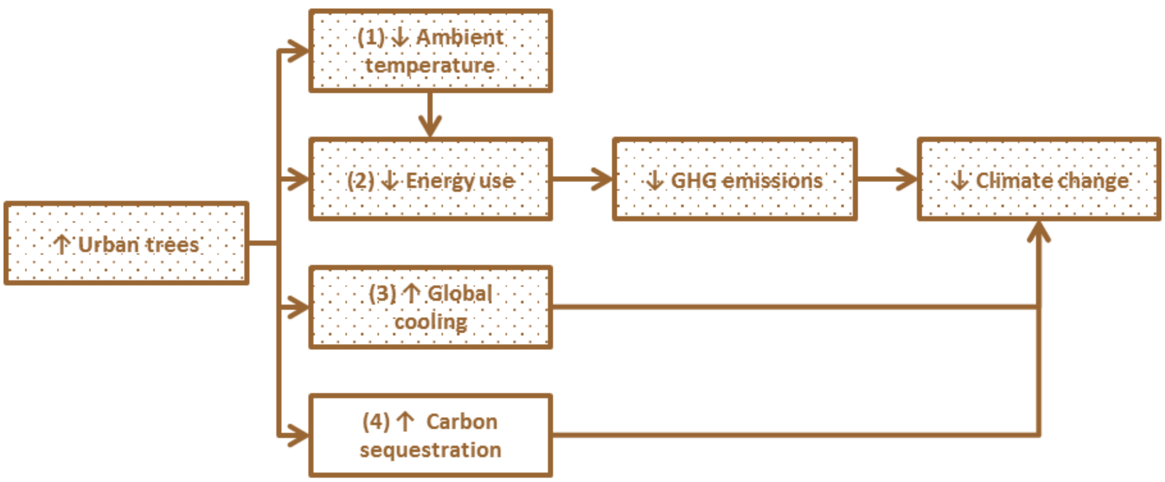

Figure 10.1. Urban tree climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

10.2.5 Air quality and health

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 NO_2 (an ozone precursor) from the air, and (4) directly removing ozone from the air. Urban trees directly remove NO_2 and ozone from the air through dry deposition (pollution removal during periods devoid of precipitation). Figure 10.2 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

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[cx] This includes emissions reductions due to direct and indirect energy savings.
[cxi] For example, mulching will release stored CO2 more quickly than using the wood to make furniture.
[cxii] This agrees with guidance we received from urban tree experts.

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 11.6 and in the Appendix.

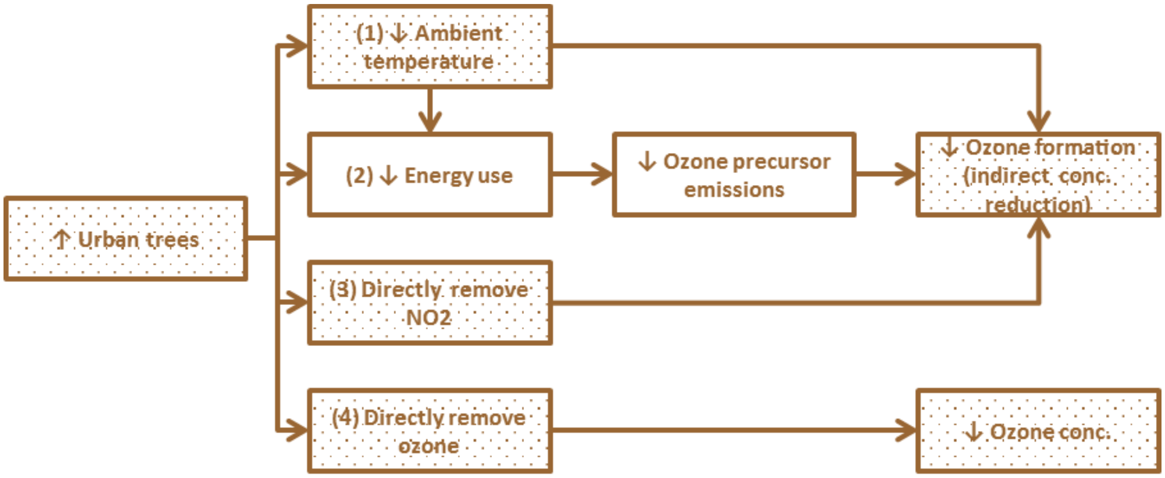


Figure 10.2. Urban tree ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Urban trees and PM2.5

Urban trees reduce $PM_{2.5}$ concentrations in the same four ways as green roofs. Urban trees remove $PM_{2.5}$ from the air by dry deposition (pathway (1) in Figure 10.3). Urban trees also remove $PM_{2.5}$ precursors from the air through dry deposition, thereby decreasing secondary $PM_{2.5}$ pollution (pathway (4) in Figure 10.3). Urban trees reduce $PM_{2.5}$ pollution by decreasing ambient temperature (pathway (2) in Figure 10.3), and decreasing building energy use (pathway (3) in Figure 10.3). Figure 10.3 shows urban tree $PM_{2.5}$ concentration reduction pathways. In contrast to the 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 $PM_{2.5}$ impact estimation methods and assumptions in Section 11.6 and in the Appendix.

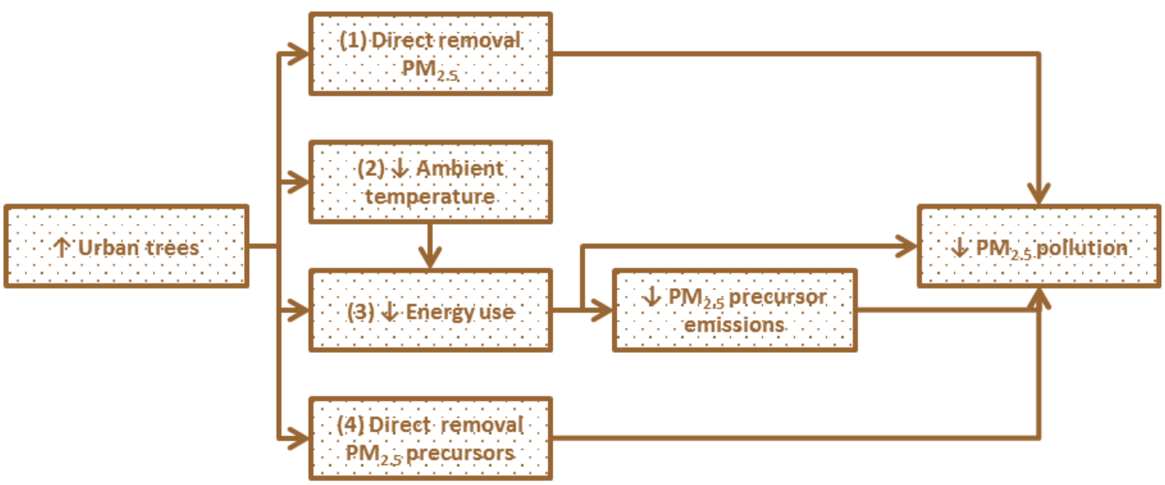


Figure 10.3. Urban tree $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease shaded boxes indicate pathways included in cost-benefit results)

Pollution uptake

In addition to removing CO_2 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, PM_{10} and $PM_{2.5}$, carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxides (NO_x). 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.[415] 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 (O_3, PM_{10}, NO_2, SO_2, CO), valued at $3.8 billion.[416] Despite the large value of pollutant removal, actual changes in local ambient air quality are modest and are typically less than 1%.[417] The impact of direct removal of pollutants, though modest, is well documented, so it is included in cost-benefit calculations. Refer to Section 11.6 and the Appendix for a description of methods and assumptions.

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.[418] 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.[419] This is an area that warrants further research. Because this analysis does not include the heat-related mortality impact of urban trees from improving indoor conditions it underestimates the likely benefits. This report describes methods and assumptions to estimate green roof heat-related mortality impact in Section 11.6 and in the Appendix.

10.2.6 Stormwater

Trees, like green roofs, also reduce stormwater runoff volumes and delay time of peak runoff.[420] Tree surfaces intercept rain as it falls. The soil around an urban tree also absorbs rain water, where it infiltrates into the ground, is absorbed by the tree through its roots, or evaporates. Figure 10.4 illustrates these and other stormwater runoff reduction pathways. Simulation studies estimate that urban trees reduce city-wide stormwater.[421]

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 washoff (e.g., vehicle oils).[422] During large rain events or extended periods of rain, an urban tree's capacity for interception and soil absorption will peak and the tree will no longer provide effective stormwater management.[423]

Refer to Section 11.7 for an overview of methods and assumptions. The Appendix provides further detail.

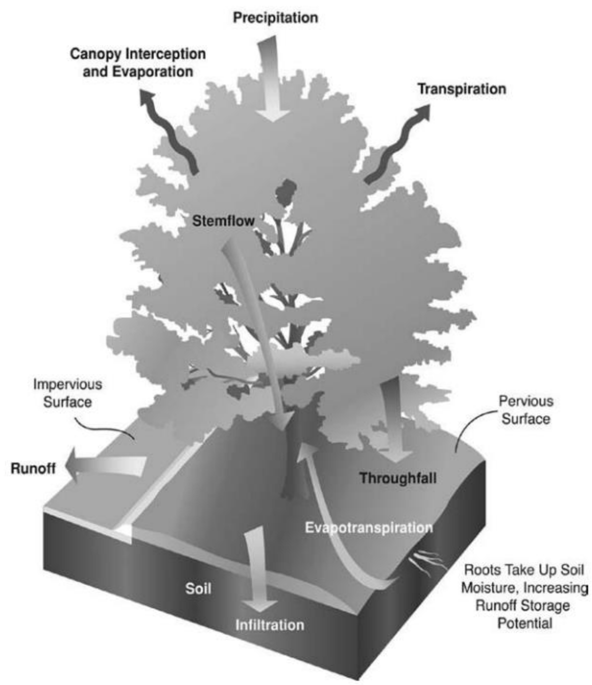


Figure 10.4. Illustration of tree stormwater runoff reduction pathways[424]

10.2.7 Other benefits of urban trees

Improved thermal comfort

Numerous modeling studies have demonstrated thermal comfort benefits from urban trees across different climates.[425] The most important local climate factor in the study of 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[426]—large scale tree planting is required to provide cities with significant 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 US simulation study of a hot-dry climate found planting trees in a street canyon reduced physiological equivalent temperature (PET)[cxiii] by over 20°C in summer conditions.[427] 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").[428] In a tropical climate (e.g., Brazil), shade from trees can reduce PET by up to 16°C in summer conditions.[429] The thermal comfort impacts described above likely serve as an upper bound because the impacts were estimated directly under tree canopy. In reality, pedestrian will only experience tree shade part of the time.

[cxiii] 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). 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.

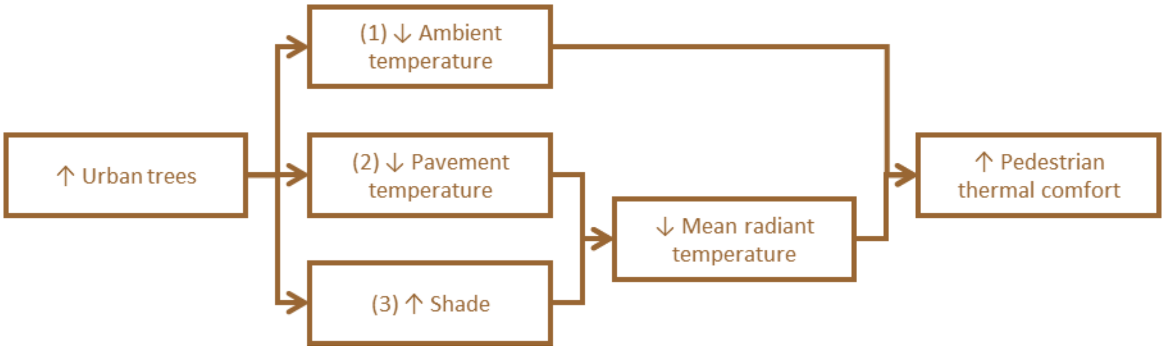


Figure 10.5. Impact of urban trees on summertime pedestrian thermal comfort

Adding trees can reduce thermal comfort in winter,[430] as deciduous trees block some solar radiation.[431] But in cities with subtropical climates and hot summers (like the District), 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 in cost-benefit calculations. However, we do include a discussion of thermal comfort on the impact of tourism, including an estimate of value from smart surface installations city-wide (see Section 13).

Increased humidity

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

Increased biological volatile organic compounds emissions (BVOCs)

Trees can also emit biologic volatile organic compounds (BVOCs), an ozone precursor, that in rare conditions could counteract the ozone reductions that result from reduced ambient air temperature.[cxv] However, this is a well-known risk of increasing urban tree canopy so researchers have compiled lists of tree species and the amount of volatile organic compounds they emit.[432] Trees with low ozone-forming potential typically are prioritized for urban tree programs, like in the District, avoiding the potential health costs. This potential health cost is not estimated in this analysis.

Increased pollen production

Increasing urban tree canopy can increase pollen production, exacerbating allergies.[433] As with biological volatile organic compounds, this potential drawback can be, and is generally, avoided with proper tree selection.

[cxiv] Because air conditioning units would have to remove more moisture.

[cxv] 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) 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.

Others

Urban trees can reduce human exposure to direct UV rays, which have adverse impacts on skin and eyes.[434] Urban trees that shade pavement may also reduce the need for pavement maintenance because lower levels of incident solar radiation and lower surface temperatures can increase pavement lifetime. However, tree roots can increase cost of pavement maintenance and repairs.[cxvi] Studies show that trees can increase residential and commercial property values.[435]

Urban trees can enhance quality of life in multiple ways. First, they increase habitat for birds, insects, and other living things.[436] In addition, trees reduce urban noise,[437] are linked to reduced crime,[438] and provide other psychological and social benefits that help reduce stress and aggressive behavior.[439]

As discussed in the cool roof benefits section (Section 3.2.7), hot air from urbanization can heat cities and towns downwind because of heat transfer by air movement (called "advection"). The ambient cooling benefit provided by urban trees can both reduce UHI and help alleviate a portion of this downwind warming.

Urban trees can reduce stormwater runoff temperature because they shade urban hardscape from solar radiation, reducing urban surface temperatures and thus runoff temperatures from these surfaces. Trees also stay cooler than conventional urban surfaces, so any rainfall that runs off tree surfaces will be cooler than runoff from conventional, non-porous urban surfaces.

Given the large uncertainties and limited research in these areas, this analysis does not include these potential benefits in cost-benefit calculations.

[cxvi] This cost is captured in the maintenance cost of trees used in this report.

11 Overview of methodology

The kind of full, integrated analysis presented in this report has not been done before in large part because of its complexity, and because there exists no analytic framework or tool that comes close to estimating full costs and benefits. We had to 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 $PM_{2.5}$ 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. This has involved a great deal of synthesis of existing studies and necessarily making informed choices. As a rule, we proceeded cautiously and conservatively in developing estimating methods. Report sources, assumptions, methodologies, and rationale are detailed in the 200-page appendix to this document.

The sections below provide an overview of the methods used to estimate the benefits included in cost-benefit calculations. A more detailed description of methods can be found in the Appendix.

11.1 New benefits valued in this report

Table 11.1 provides an overview of additions this report makes to the existing methodology in the literature.

Table 11.1. Overview of this report's additions to the existing methodology in the literature

Indirect energy	Estimating indirect energy benefit of green roofs
Climate change	Valuing emissions reductions from the solutions studied using the social cost of carbon
	Valuing global cooling impact of the solutions studied using the social cost of carbon
Ozone	Estimating ozone concentration reductions in Washington, DC using ozone-temperature relationship
	Estimating ozone concentration reductions due to green roofs
	Valuing health benefits of ozone concentration reductions from the solutions studied using BenMAP-CE
PM2.5	Valuing health benefits of PM2.5 emissions reductions due to installing cool roofs, green roofs, reflective pavements, and urban trees
Heat-related mortality	Valuing heat-related mortality reductions due to cool roofs, green roofs, reflective pavements, and urban trees
Employment	Assumption that only half of all jobs generated in the District go to city residents
Salt use reduction	Estimating and valuing salt use reductions for permeable sidewalks and parking lots
Combined analysis	Combining new methods above and the existing methods to estimate cost and benefits at region/city scale of all solutions studied
	Scenario development that models gradual implementation of all solutions at the same time

11.2 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[cxvii] 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.[cxviii]

Only trees near buildings provide direct energy benefits. This report uses results from the District's i-Tree Eco analysis to estimate direct energy impacts of trees. i-Tree Eco only estimates energy benefits for residential buildings.

11.3 Energy generation

This report estimates the energy output of rooftop PV systems using NREL's PVWatts Calculator. This report assumes that 25% of PV systems are directly purchased and 75% are purchased through a PPA. This report assumes more systems are purchased through PPAs because PPAs are the most common type of system purchase in the District.[cxix]

11.4 Ambient cooling and indirect energy

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 in the District.[440] Based on the discussion in Section 5.2.2, this report assumes bioretention performs 100% better per square foot in terms of ambient cooling compared to green roofs. For reflective pavements in the District, this report uses Kalkstein et al. (2013) as the basis for ambient cooling calculations.[441] For urban trees, this report uses Sailor (2003) as the basis for ambient cooling calculations.[442]

Estimating indirect energy impacts

The basis of our indirect energy calculations is from Akbari and Konopacki (2005).[443] Based on the discussion in Section 5.2.2, this report assumes bioretention performs 100% better per square foot in terms of indirect energy impacts compared to green roofs.

11.5 Climate change

Estimating climate change mitigation impacts of emissions reductions

For emissions intensities in the District, this report uses the most recent numbers available from Baltimore Gas & Electric (2014) that approximates the emission rate for electricity in the PJM Interconnection (which includes the District).[444]

[cxvii] This report assumes green roofs are not installed on steep-slope roofs.
[cxviii] GREC only provides annual energy savings/penalties estimates so its outputs are not resolved enough to estimate peak demand benefits.
[cxix] Solar leases are also common, but as described previously this report includes only PPAs for simplicity.

This report estimates the value of GHG emissions reductions from cool roofs, green roofs, bioretention, 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/decrease in CO_2 emissions.[445] 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.[cxx] The SCC estimates are built on three widely used climate impact models, and each are modelled with real discount rates of 2.5%, 3%, and 5%.

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).[446] 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 SCC for determining the value of the global cooling benefits of all solutions.

11.6 Health

Estimating ozone health impacts

This report estimates the ozone impact of cool and green roofs, bioretention, 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 11.4. 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.[447,cxxi] To estimate the health impact of ozone pollution reduction, this report uses EPA's Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) v1.1.[cxxii]

Estimating $PM_{2.5}$ health impacts

The basis of the $PM_{2.5}$ health benefits assessment in this report is Machol and Rizk (2013).[448] Machol and Rizk (2013) develop a method to determine the $PM_{2.5}$-related health benefits per kWh of electricity. This report utilizes their methodology for $PM_{2.5}$ benefit calculations. Put simply, this report multiplies the energy savings calculated using the methods in Section 11.1 by the health benefits factors from Machol and Rizk (2013) to estimate the $PM_{2.5}$-related health impacts.

Estimating heat-related mortality impacts

Kalkstein et al. (2013) forms the basis for the heat-related mortality impact assessment in this report.[449] Based on the discussion in Section 5.2.2, this report assumes bioretention performs 100% better per square foot in terms of heat-related mortality impact compared to green roofs.

[cxx] The SCC was recently reviewed by the U.S. Government Accountability Office (GAO). A report of GAO's findings, published in July, 2014, reaffirmed all SCC methodologies and findings.

[cxxi] OCPs relate a change in air temperature to a change in ozone concentrations.

[cxxii] 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.

There are several limitations to Kalkstein et al. (2013) mortality estimates that are discussed in more detail in the Appendix. This report estimates the value of avoided heat-related mortality using the Value of Statistical Life (VSL).

Estimating pollution uptake by urban trees

This report estimates the health impacts of pollution uptake by urban trees using results from city specific the i-Tree Landscape analyses.

11.7 Stormwater

The District has stormwater regulations that require building owners to pay stormwater fees. Revenue from stormwater fees is used for various aspects of stormwater management. These stormwater fees are calculated based on the impervious surface area of a property. If a property installs stormwater management practices (such as green roofs, bioretention, cisterns, permeable pavement, and trees), then it is eligible to receive discounts on its stormwater fee. The discounts reflect the decreased stormwater burden on a city's stormwater system from properties that install stormwater management practices. This report estimates stormwater benefits in the District using the city's own stormwater fee discounts.

In 2013, the District introduced stormwater regulations[450] that require many new and redeveloped properties to meet stormwater retention requirements. As part of these regulations, the District has developed an approach to incentivize stormwater management based on a stormwater retention credit (SRC) trading program. The SRC trading program provides a large financial incentive for green roof, bioretention, cistern, and permeable pavement installation and tree planting in the District. This report also estimates stormwater benefits in the District using the value of SRCs.

11.8 Employment

See Sections 4.2.7, 5.2.4, 6.2.4, and 7.2.6 for labor impact information for green roofs, bioretention, rainwater harvesting, and solar PV, respectively. This report values labor impacts using O'Sullivan et al. (2014).[451] This report also values labor impacts using an average annual income per job year of $40,000.

As noted, this report considers only direct job creation, which underestimates the total jobs that smart surface solutions would create.

11.9 Reduced potable water use

Based on average annual rainfall in Washington, DC of 39.74 inches per year,[452] a contributing drainage area of 10,000 square feet, and a collection efficiency of 90%, we estimate the rainwater harvesting system harvests 223,000 gallons (298.1 hundred cubic feet (Ccf)) of rainwater per year. We multiply this by current DC Water rates for multifamily ($12.31 per Ccf) and non-residential properties ($12.88 per Ccf).[453] See the Appendix for a breakdown of DC Water rates.

11.10 Sidewalk and parking lot salt use

To estimate the benefit of reduced salt application on permeable sidewalks and parking lots, we assume average salt application rates of 0.03 pounds per square foot of conventional pavement per year. We assume a 50% reduction in salting needs for permeable sidewalks—two-thirds of the 75% reduction found in empirical study of asphalt pavement summarized in Section 9.2.3. For permeable parking lots, which are gravel or grass, we assume a 100% salt reduction because salting gravel or grass in uncommon. We use a salt cost of $0.23 per pound, based on a review of DGS contracts.[454] See the Appendix for further explanation of methods.

Salt costs do not include labor cost or environmental cost, so estimated value for this benefit is likely much greater than estimated in this report.

11.11 Summary of key assumptions

Universal

Analysis year 1: 2017

Discount rate: 3% (real)

Dollar year: 2015 (adjusted using the historical consumer price index for all urban consumers)[455]

Table 11.2. Surface coverage by end of analysis (for a discussion of scenario development, see the Appendix)

Surface solution	Percent coverage by end of 40-year analysis
Cool roofs	50% of roofs (10% multifamily low slope cool roofs and 20% of commercial low slope cool roofs have bioretention; 5% multifamily low slope cool roofs and 10% of commercial low slope cool roofs have rainwater harvesting)
Green roofs	10% of roofs
Solar PV	50% of viable (~530 MW)
Reflective pavements	50% of pavements
Permeable pavements	4% of pavements (5% parking lots and 10% sidewalks)
Urban trees	Increase tree canopy by 10% absolute

Cool roofs

Table 11.3. Conventional and cool roof albedos used in this report

Roof slope	Solar reflectance		
	Conventional roof	*Cool roof Pre-2025*	*Cool roof Post-2025*
Low slope	0.15	0.65	0.75
Steep slope	0.10	0.25	0.40

Table 11.4. Cool roof cost premiums

Roof type	Low slope	Steep slope
Installation premium	$0.15/SF	$0.55/SF
Maintenance premium	$0.00/SF-yr	$0.00/SF-yr

Cool roof life: 20 years

Green roofs

Table 11.5. Green roof cost premiums

Period	Pre-2025	Post-2025
Installation premium	$15/SF-yr	$10/SF-yr

Maintenance premium, establishment	$0.46/SF-yr	$0.46/SF-yr
Maintenance premium, post-establishment	$0.31/SF-yr	$0.31/SF-yr

Green roof life: 40 years

Bioretention

Table 11.6.Bioretention cost summary

Type of cost	Cost per SF (standard)	Cost per SF (enhanced)
Install cost	$74.00	$78.66
Maintenance cost	$0.60 per year	

Bioretention system life: 25 years; assume upgraded at half cost after 25 years

Fraction enhanced design (with underdrain): 6%[cxxiii]

Fraction standard design: 94%[cxxiii]

Rainwater harvesting

Table 11.7. Rainwater harvesting cost summary

Type of cost	Cost per gallon
Install cost	$3.78
Maintenance cost	$0.14 per year

Rainwater harvesting system life: 40 years

Rooftop PV

Table 11.8. Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems

System type	Pre-2020 installation cost	Post-2020 installation cost	Maintenance cost
Residential	$3.20/W	$2.20/W	$0.21/kW-yr
Commercial	$2.60/W	$1.80/W	$0.19/kW-yr

PPA savings: 5% below utility rates

PPA duration/system life: 20 years

Direct purchase system life: 20 years

[cxxiii] Computed based on values from DOEE. See the Appendix for more details.

PV system purchase breakdown: 25% direct purchase vs. 75% PPA

PV Efficiency: 18%

Annual electricity degradation rate: 0.5% (compounded annually)

Reflective pavements

Table 11.9. Solar reflectance of pavements used in this analysis

Pavement type	Conventional pavement albedo	Reflective pavement 2020-2030 albedo	Reflective pavement post-2030 albedo
Road	0.15	0.30	0.35
Parking lot	0.15	0.30	0.40
Sidewalk	0.30	0.35	0.45

Reflective pavement cost premium: 5%

Time after new road construction/reconstruction to slurry seal: 10 years

Time after road resurfacing to slurry seal: 10 years

Slurry seal life: 6 years

Parking lot life: 15 years

Sidewalk life: 40 years

Permeable pavements

Plastic grid parking lot cost: $4.10 per square foot (gravel); $3.88 per square foot (grass)

Plastic grid parking lot life: 25 years (gravel); 40 years (grass)

Permeable paver sidewalk cost: $10.50 per square foot (plus $2.44 per square foot if enhanced design)

Permeable paver sidewalk life: 40 years

Fraction sidewalks enhanced design (with underdrain): 20%[cxxiv]

Fraction sidewalks standard design: 80%[cxxiv]

Urban trees

Table 11.10. Tree planting and maintenance costs used in this report ($2006)

Cost	Value per tree
Planting cost	$360
Maintenance cost	$13 per year

[cxxiv] Computed based on values from DOEE. Not applicable to parking lots. See the Appendix for more details.

Urban tree life: 30 years

12 Results

This report finds that in general cool roofs, cool roofs with stormwater retention, green roofs, rooftop PV, reflective pavements, permeable pavements, and urban trees are cost-effective surface solutions for the District. Below are scenario summary results tables for the District. All results are presented in 2015 dollars. More detailed tables are in the Appendix (including costs and benefits per square foot).

The cost-effectiveness of green roofs in the District is highly dependent on the value attributed to stormwater runoff reductions. For example, without SRC value, green roofs are not cost-effective in any scenario. (Green roofs are often the most cost effective solution for regulated projects that must meet stormwater retention performance standards). As green roof installation costs decline, green roof benefit-to-cost ratio increases. For example, if green roof installation premium begins at $10 per square foot and drops to $8 per square foot (instead of $15 per square foot to $10 per square foot), the benefit-to-cost ratio of green roofs increases by 0.43. Maintenance costs are also important. For example, if maintenance costs decrease by 25%, the benefit-to-cost ratio of green roofs increases by 0.19.

The cost-effectiveness of reflective pavements is highly dependent on the reflective pavement price premium. For example, doubling the premium to 10% reduces the Benefit-to-Cost ratio of reflective pavements by 0.65. In addition, with a 10% cost premium, reflective parking lots and sidewalks have a negative net present value per square foot.

Permeable pavements can have high benefit-to-cost ratio (14.19) because of negative net cost of grid pavers (that are cheaper to install and maintain than regular parking lots) for permeable parking lots modeled (plastic grid pavers with grass or gravel). While still relatively high, the benefit-to-cost ratio of just permeable plastic grid paver sidewalks is 6.50. That said, as with green roofs, if stormwater value is lower, this drops substantially. Permeable pavement is still 2-3 times more expensive than traditional pavement, so this is far less cost effective option.

Cool roofs with stormwater retention outperform green roofs. However, of the solutions analyzed, green roofs have the most unquantified benefits, some of which we expect are large (e.g., amenity value). This means, green roofs may have more unquantified benefits than other solutions.

Though not modeled, a good option might be to combine cool roofs, stormwater retention, and solar PV. Cool roofs benefits will be reduced with the additional of solar PV, but would get benefit in virtually all categories analyzed.

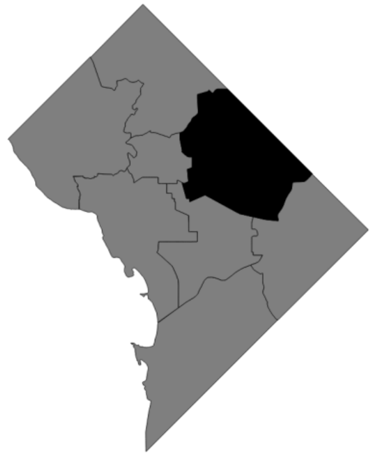
Table 12.1. Net present value (NPV) of costs and benefits for the District through 2056 (results are additive)

SOLUTION	Cool Roofs	Cool Roofs + Bioretention	Cool Roofs + Rainwater Harvesting	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Permeable Pavements	Urban Trees	TOTAL
COSTS	**$32,318,000**	**$23,351,000**	**$16,752,000**	**$282,957,000**	**$242,487,000**	**$499,000**	**$43,802,000**	**$13,538,000**	**$234,846,000**	**$890,546,000**
First cost	$23,827,000	$18,169,000	$10,312,000	$194,607,000	$163,019,000	--	$23,537,000	$13,936,000	$136,475,000	$583,879,000
Operations and maintenance	$0	$2,289,000	$6,026,000	$88,214,000	$25,112,000	--	--	$7,263,000	$77,622,000	$206,523,000
Additional replacements	$8,491,000	$2,425,000	$140,000	--	$54,192,000	--	$20,265,000	-$7,661,000	$20,750,000	$98,600,000
Employment training	$0	$469,000	$276,000	$138,000	$167,000	$499,000	--	--	--	$1,546,000
BENEFITS	**$236,960,000**	**$80,048,000**	**$65,751,000**	**$563,636,000**	**$443,693,000**	**$450,611,000**	**$112,377,000**	**$192,130,000**	**$797,038,000**	**$2,942,239,000**
Energy	$30,658,000	$5,674,000	$2,802,000	$22,103,000	$238,953,000	$33,202,000	$5,014,000	--	$8,352,000	$346,754,000
Financial incentives	--	--	--	--	$65,604,000	--	--	--	--	$65,604,000
Stormwater	--	$32,415,000	$41,482,000	$478,786,000	--	--	--	$191,437,000	$694,775,000	$1,438,893,000
Health	$114,544,000	$14,282,000	$6,669,000	$38,978,000	$65,824,000	$197,472,000	$29,734,000	--	$56,631,000	$524,131,000
Climate change	$91,758,000	$23,349,000	$11,573,000	$11,159,000	$50,341,000	$151,022,000	$77,630,000	--	$37,282,000	$454,110,000
Reduced portable water use	--	--	$15,868,000	--	--	--	--	--	--	$15,868,000
Reduced salt use	--	--	--	--	--	--	--	$693,000	--	$693,000
Employment	--	$4,330,000	$3,227,000	$12,611,000	$22,973,000	$68,917,000	--	--	--	$112,056,000
NPV	**$204,642,000**	**$56,697,000**	**$49,000,000**	**$280,679,000**	**$201,206,000**	**$450,113,000**	**$68,575,000**	**$178,592,000**	**$562,193,000**	**$2,051,693,000**

Table 12.2. Benefit-to-Cost Ratio summary for each solution in the District

SOLUTION	Cool Roofs	Cool Roofs + Bioretention	Cool Roofs + Rainwater Harvesting	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Permeable Pavements	Urban Trees
Benefit-to-Cost Ratio	7.33	3.43	3.93	1.99	1.83	Very high	2.57	14.19	3.39

Box 2. Impacts in Ward 5



In 2016, Capital E was funded by the JPB Foundation to evaluate the costs and benefits of city-wide adoption of cool roofs, green roofs, solar PV, reflective pavement and urban trees on low income areas in three cities: Washington, DC, Philadelphia, and El Paso. In the District, we focused on Ward 5 (black in the map above) because it has a large low income population and high unemployment rate compared to the District as a whole (see table below).

Table B2.1. Selected Ward 5 characteristics compared to Washington, DC

Characteristic	Washington, DC	
	Ward 5	City
Population (2014)	80,399	659,836
Income		
Median income	$57,886	$69,325
Percent of population below poverty line	20.8%	18.2%
Unemployment rate	16.5%	10.6%
Land use		
Area (square miles)	10.4	61.4
Building footprint (% region)	14.4%	15.9%
Paved area (roads, parking, sidewalks) (% region)	23.1%	24.1%
Tree canopy (% region)	27.7%	31.2%

Why focus on low income areas?

The impacts of air pollution and higher summer temperatures are particularly acute in low income urban areas where residents tend to live in inefficient buildings (sometimes without air conditioning) and disproportionately suffer from respiratory and other health problems (often exacerbated by poor air quality).

Results and conclusion

The work for JPB provides an in-depth analysis of the Ward 5 benefits of applying cool roofs, green roofs, solar PV, reflective pavements, and urban trees at city-scale (see Table B2.2 for application assumptions). It shows these solutions could go a long way towards cost-effectively reducing health and energy costs for low income areas while increasing employment, resilience, and livability. Overall, the cumulative economic impact of deploying these solutions broadly is about $352 million in Ward 5 (see Table B2.3). The analysis, however, does not capture the full set of comfort, health, and livability benefits. As in the city-wide analysis detailed in this report, many additional benefits and some costs were identified but not quantified due to lack of data and/or need to limit study scope.

Table B2.2. Surface coverage city-wide by end of analysis

Surface solution	Percent coverage by end of 40-year analysis
Cool roofs	50% of roofs
Green roofs	10% of roofs
PV	50% of viable
Reflective pavements	50% of pavements
Urban trees	Increase tree canopy by 10%

Table B2.3. Present value of cumulative economic impact in Ward 5

COSTS	**$95,250,000**
BENEFITS	**$446,840,000**
NET PRESENT VALUE	**$351,590,000**

The work for JPB estimates a large range of benefits from adopting these technologies, including detailed analysis of health impacts. While this work is far from complete, the findings are compelling. Low income areas can achieve large gains in improving health and comfort, reducing energy bills, and mitigating climate change with policies and solutions that offer compelling paybacks. Deployment of these solutions at scale can address systematic inequity in urban quality of life. Reductions in energy bills matter much more to low income residents than to wealthy city residents. Similarly, health benefits of the solutions analyzed are larger for low income than for wealthy city residents.

As noted in this report, downwind cooling from city-wide adoption of smart surface options in the District is likely to be material, including some cooling impact in eastern and northeastern parts of the city. The eastern and northeastern parts tend to have lower income residents than the central and western parts of the city. In the summer, winds often blow from the south or southwest, so cooling of the downtown and western parts of

13 Impact of excess heat on summer tourism

Tourism is common during the summer months due to school holidays, but the heat in the summer is a recurring concern for tourists. The four quotes below from popular District tourism sites illustrate this:

- HotelsNearDCMetro.com notes, "If you can stand the heat, the crowds thin out in August making pre-back-to-school vacations a better time for visiting with kids;"[456]
- National Geographic's site promoting tourism in the District comments, "Summer heat can sneak up on even the healthiest individual, and heat exhaustion is a risk on long days touring the Mall's two-mile length of monuments separated by expanses of near-treeless green;"[457]
- A TripAdvisor commentary remarks, "Actually, in my opinion, August is worse than July; July is hot and humid, August is so hot and so humid you can't stand it;"[458]
- A Frommer's review of the District writes that "Anyone who has ever spent July and August in D.C. will tell you how hot and steamy it can be. Though the buildings are air-conditioned, many of

Washington's attractions, like the memorials and organized tours, are outdoors and unshaded, and the heat can quickly get to you."[459]

With 20 million visitors in 2014, the District is one of the country's top destinations for both American and international tourists.[460] In 2014, tourists spent $6.8 billion dollars in the District on a range of services such as hotels, restaurants, etc, representing more than $725 million in new tax dollars for the District of Columbia.[461] Tourism revenue rose again in 2015 to more than $7 billion, and this figure does not include tourists from Canada or Mexico. For the purposes of quantifying potential revenue losses from summer tourism this report uses the smaller 2014 $6.8 billion number.

Revenue from summer tourism is at risk from rising temperatures and increasing heat waves driven by climate change and exacerbated by the UHI effect. As climate change continues, temperatures will become more extreme, including a higher number of days above 90°F, 95°F, and even 100°F. The number of days with temperatures above 100°F is predicted to increase by between four- and nine-fold by 2050). Higher temperatures from climate change also increase smog formation. The combination of higher average heat, greater frequency of extreme heat, and more air pollution will make the District less attractive for tourists in the summer. Figure 13.1 shows the projected impact of climate change on summertime tourism in the United States. In fact, as illustrated in the quotes above, high summer temperatures and humidity already adversely impact summer tourism in the District.

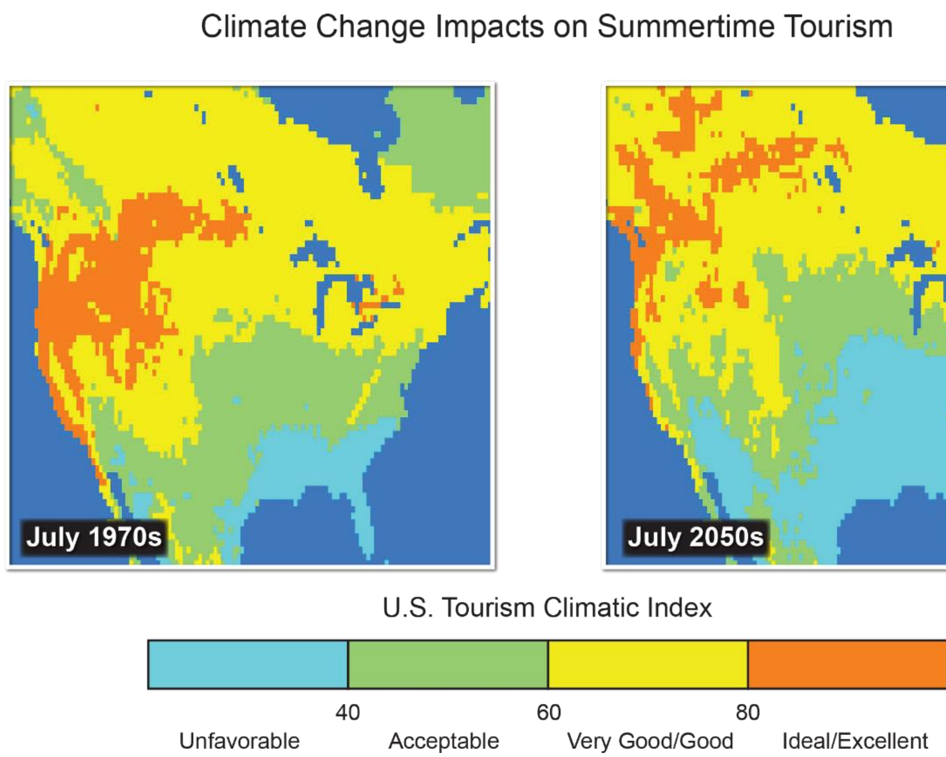


Figure 13.1. Climate change impacts on summertime tourism under a high emissions scenario[462]

City-wide UHI mitigation using the solutions described in this report would reduce the higher temperatures expected with climate change, though full implementation would take several decades. At the end of our 40-year analysis period, we assume the coverage achieved as described Table 13.1. We also assume that implementation occurs on a linear basis over the 40-year analysis period. Based on analysis in this report, we estimate that approximately 1°C (1.8°F) of the UHI would be mitigated by

2057—about half of the 2°C climate change target laid out at COP21. [463] 1C is an approximate number but is on balance probably more likely to be low than high. (Please see footnote for 1°C (1.8°F) estimate.)

Table 13.1. Surface coverage by end of analysis (this is a reproduction of Table 11.2)

Surface solution	Percent coverage by end of 40-year analysis
Cool roofs	50% of roofs (10% multifamily low slope cool roofs and 20% of commercial low slope cool roofs have bioretention; 5% multifamily low slope cool roofs and 10% of commercial low slope cool roofs have rainwater harvesting)
Green roofs	10% of roofs
Solar PV	50% of viable (~530 MW)
Reflective pavements	50% of pavements
Permeable pavements	4% of pavements (5% parking lots and 10% sidewalks)
Urban trees	Increase tree canopy by 10% absolute

If we assume that 40% of tourism dollars accrue in the three summer months (June, July, and August),[cxxv] $2.72 billion in total visitor spending and $290 million in city revenue are at risk. We assume that 2°C of climate change (projected to occur before the 2050 [464]) would reduce summer tourism in the District by 10% and that 1°C of UHI mitigation from smart surface installation could limit this loss to only 5%. This would avoid an annual loss of $136 million in visitor spending and $14.5 million in District tax revenue. The net present value of this avoided loss to the District over the 40-year analysis period would be $3.1 billion in visitor spending and $335 million in District tax revenue.[cxxvi]

Arguments can be made for faster deployment of UHI mitigation solutions, increased tourism revenue as population grows (hence larger avoided losses), and a larger or smaller tourism impact from excess heat from climate change. However, the assumptions above provide a reasonable, first order estimate of potential avoided tourism loss benefits associated with adoption of city-wide strategies described and documented in this report.

14 Emerging technologies and issues

There are a range of emerging technologies and issues that can enhance and/or impact urban benefits. Several of these are discussed below.

All the technologies described in this report are evolving, with improvements in performance such as increased power output from solar PV panels, typically combined with declining costs. These continue improvements open up new areas for cost effective potential applications, such as widespread use of solar PV to shade parking lots and pedestrian pathways. In a city like DC that is very hot in the summer with many tourists following common pathways, the deployment of solar PV, in combination with expanded

[cxxv] Because tourism in the summer is common due to school holidays.

[cxxvi] 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).

tree coverage, offers an effective way to reduce sun/heat exposure for summer tourists and to make the city more livable in the summer for residents and tourists alike.

In addition to green roofs, the city could employ green walls. Using hanging plants planted in matting, building owners can use outdoor wall space to plant vegetation that can decrease energy use and reduce the urban heat island effect through evapotranspiration. Green walls also decrease the temperature of the external walls of a building, decreasing need for cooling in the summer, reducing emissions from air conditioning.[465]

14.1 Carbon sequestration in concrete aggregate road and building products

Pollution sequestering products have the potential to offset carbon emissions or reuse byproducts of oil refinement while simultaneously providing a high albedo paving and construction material. Companies such as Blue Planet [466] (Disclosure: Kats is a Board Member of and an investor in Blue Planet) are producing high albedo aggregates and concrete from emissions from fossil fuel burning power plants (coal plant emissions are about 14% CO_2). Another company, Sulfcrete, is creating products from sulfur left over after oil refinement processes. These products can be used as high albedo gravel in plastic grid pavers as a permeable pavement or as a more traditional concrete.

Blue Planet precipitated calcium carbonate aggregate is far more reflective than natural and commercial aggregate, and has been measured to be as reflective as titanium dioxide (TiO_2). Recent work by the urban heat island group at Lawrence Berkeley National Laboratory “indicates that we would be able to make high albedo pavements using a grey concrete mix design, with preliminary results showed a SR=.54 for concrete that included [Blue Planet’s] CarbonMix aggregate as a coarse component.” [467]

The LBNL project on cool shingles Phase 1 study undertaken with Blue Planet (LBNL, Levinson et al. 2015) is developing a high albedo shingle for a residential high slope roof with a solar reflectance of 0.40 or above Current national solar reflectance average is about 0.15 so this would roughly triple residential steep roof albedo. Since these type of shingles are about 80% of the residential steep roof (most homes) market, the impact of this kind of broad albedo improvement on city temperature, comfort and air conditioning bills could be very large.

Sean Cahill, past President of the DC Building Industry Association and the SVP of Property Group Partners has expressed strong interest in using high albedo and carbon sequestering products such as those of Blue Planet in the Capital Crossing project he is leading, involving developing 3 new, extremely green city blocks on top of the 395 highway spur in downtown DC.[468] With greater awareness of concrete's harmful environmental effects, carbon sequestering cement and concrete products being developed by firms like Blue Planet could be used to both sequester carbon and substantially improve city albedo, lowering temperature and energy bills and improving urban and suburban livability and health.

Figure 14.1. Blue Planet Carbon sequestering (carbon negative) aggregate in concrete being poured at San Francisco airport, May 2016

These and other greener/higher performance products could be included as part of road and pavement surfacing and resurfacing, but only if markets emerge to demand and reward higher albedo and carbon sequestering solutions. Widespread adoption of carbon sequestering concrete could prevent a large portion of current CO2 emissions from entering the atmosphere, while making concrete carbon neutral or carbon negative, and thus new roads, parking lots and even buildings net carbon negative at the time of construction. Cities such as DC are uniquely positioned to create and drive these markets through mandates and incentives for enhanced albedo and sequestration performance on city surfaces roads and sidewalks.

According the DC consultant Jason Turner, this fall, Georgetown University will fund a research coalition of academia, sustainability experts, DC Department of Energy and Environment, and the private sector, to accelerate both the scientific and social-media driven adoption of "green(er)" concrete. Entitled "*Reducing the Environmental Impact of Concrete*," the effort will culminate in a global Symposium co-sponsored by the MIT Concrete Sustainability Hub, hosted at Georgetown in March of 2017 [469] and is intended, in part, to help cities accelerate adoption of lower carbon and carbon sequestering products.

Integration of these technologies also have the potential to increase benefits. Mounting PV panels on green roofs and cool roofs can increase energy generation due to lowered panel temperature. And PV shading can improve performance of green roofs. More generally, roofs should be thought of for multiple purposes, eg power generation and air quality and stormwater management. The performance, potential and cost effectiveness of these types of integrated solutions are little studied and documented, but benefits are potentially large in cities such as DC.

Figure 14.2. Solar PV installed on a green roof 470

14.2 Historic preservation issues

Many proposals for clean energy upgrades such as solar PV systems on structures in historic districts have been blocked, either by residents in the affected neighborhoods, or the Historic Preservation Office staff. A narrow reading of the Secretary of Interior Standards for historic structures can prevent solar PV and other smart roof and road surfaces, so it's worth commenting on the issue.

Visible television antennas and satellite dishes have been common on houses and buildings in historic districts. Similarly, many alterations which have been approved because they are easily reversible. Solar PV should be considered similarly reversible – and most systems in fact are just leased for finite period. (In contrast antenna or dish are typically owned permanently by building owners).

Rising global temperature will increase demand for air conditioning, driving addition of larger air conditioning systems and related internal and external infrastructure. Solar PV typically provides an extra skin over part of or all of a roof, thus protecting it from the sun and providing substantial cooling to the roof below. This allows buildings - despite rising temperatures to avoid expansion of unsightly air conditioning systems – potentially an important consideration for historic districts.

Solar PV has evolved significantly since the installations of even a few years ago. The panels of 2016 are thinner, less clunky and less visually intrusive than even a few years ago. The solar PV system on author Kats home in DC is uniformly black with no aluminum/silver trim and is relatively elegant and unintrusive – see figure 14.3. And like most current PV systems it does not alter the roofline.

Figure 14.3. DC solar PV installation: elegant, not clunky!

Historic preservation is an expression of responsibility and competing values. DC Historic Preservation Board member Andrew Aurbach has posed a relevant question: "Does responsibility include responsibility for the future quality of life, and if rising temperatures and related worsening in ozone, air quality and excess heat makes a historic areas increasingly unlivable should that be a concern for historic preservation boards?" 471 Historic preservation board responsibility in a time of climate change can balance traditional historic preservation concerns with a broader responsibility for keeping districts livable and enabling incorporation of PV, green roofs, energy efficiency, and high albedo roofs and road and parking surfaces to protect the livability of districts and viability of historic structures and neighborhoods. Recent approval of a few solar PV projects in historic District areas is encouraging.

15 Conclusion

This report provides an in-depth analysis of the costs and benefits of applying a set of roofing and surfacing solutions at city-scale in Washington, DC. These solutions are cost-effective and generally provide large positive net benefits. The payback times for these solutions vary: cool roofs offer very fast payback, while several other solutions offer the largest net benefit.

This report quantifies a large range of costs and benefits, including detailed mapping of health impacts, from broad District adoption of a range of smart surface solutions. Because integrated cost-benefit analysis of these solutions has not been done before, we worked with and consulted with national and city partners, epidemiologists, technology, stormwater, and energy experts and others to build the data and integrated cost-benefit model. While more needs to be done (this report identifies multiple areas that warrant further research), the findings are compelling.

Table 15.1Summary of the present value of costs and benefits for the District

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015$)
COSTS	**$890,546,000**
BENEFITS	**$2,942,239,000**
NET PRESENT VALUE	**$2,051,693,000**

The net present value of $2 billion in costs and benefits was rigorously valued. Higher summer temperatures will have a range of additional costs, including a reduction in comfort. One way to estimate part of this impact is by evaluating the potential costs of reduced summer tourism and to evaluate how the strategies reviewed in this report could mitigate these potential losses. Our preliminary estimates are that District-wide smart surfaces could prevent a $3.1 billion reduction in tourism spending in the District over 40 years, with $335 million in District tax revenue.

Until this analysis, there has been no established methodology for quantifying the full costs and benefits for these technologies. And therefore there has been no way for cities to evaluate the cost-effectiveness of deploying these solutions. A large and poorly quantified part of the benefits of these solutions relates to health. Health impacts are large and complex, and have generally not been quantified or valued for these roof and surface solutions. This report describes 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 quantifying the health impacts. To convey sometimes complex impact pathways, we developed figures that indicate directionality of the impact (i.e., increase or decrease) and the steps that lead to the impact.

Many additional benefits identified and described in the report lack adequate data to allow financial impact estimation, but collectively these additional non-quantified benefits to the District and its residents are large. Low income areas can achieve large gains in improving health, comfort and resilience, reducing energy bills, and mitigating climate change with policies and solutions that generally offer compelling paybacks. Deployment of these solutions at scale in low income areas can address systematic inequity in urban quality of life. For example, reductions in energy bills matter much more to low income residents than to wealthy city residents. Similarly, health benefits from the solutions analyzed in this report are generally larger for low income residents than for wealthy city residents. Job creation would also generally have greater benefits for low income residents.

This kind of full, integrated analysis has not been done before in large part because of its complexity. We used EPA's BenMAP to value the health benefits of declines in ambient ozone concentration. We had to 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. This has involved a comprehensive literature review, analysis, synthesis, and, necessarily, making informed choices to develop reasonable, conservative, and useful valuation estimates for a dozen benefits that – based on a comprehensive literature search and very extensive work with area experts - have not been quantified before. These findings provide an economically compelling basis for city-wide adoption.

As discussed in the report, many additional benefits and some costs were identified but not quantified due to lack of data and/or need to limit study scope. Unquantified benefits exceed unquantified costs, so overall the cost-benefit findings in this report underestimate the cost-effectiveness of these solutions.

Of particular interest for the region's future is downwind cooling and the impact of climate change on livability and tourism. Downwind cooling from city-wide adoption of smart surface options in the District would be large, including cooling impact in eastern and northeastern parts of the city. In addition, because summer winds in the District often blow from the south or southwest,[472] urban cooling in Arlington and Alexandria could lead to material cooling in the District. These examples of downwind cooling, which are in addition to the city average cooling approximated by our model, would create additional energy, air quality, and livability benefits in the District and in places to the NW, such as Baltimore.

The examples of downwind cooling and tourism show that smart surfaces would have larger benefits to the District than estimated in this report, indicating the need for coordinated adoption of smart surfaces in the broader region. Reflecting the Districts ongoing leadership on climate change, the DC government is developing a plan entitled Climate Ready DC [473] that provides an overview and roadmap of the District plan to adopt to climate change

The District has set out ambitious goals in its Sustainable DC Plan, and has made significant progress in meeting many of the goals. But there is still a lot of work to do to weave together and integrate many elements of DCs policies and incentives. Jeff Seltzer, Associate Director District Department of Energy and Environment DC notes that: "Many of the District's environmental challenges, including pollution from stormwater runoff and heat island is directly related to the vast area of impervious surface that has been created in our dense urban environment. To meet our environmental goals, much of these impervious surfaces on both public and private property will need to be retrofitted with green practices. The scale and cost of this work will require the District to leverage public funds and policy to accelerate implementation of green infrastructure. This leveraging includes DOEE's RiverSmart subsidy programs, stormwater fee discount program, progressive regulations that will retrofit the city through redevelopment and the stormwater retention credit trading program that provides incentives for private investment of voluntary retrofits." 474

The smart surface solutions analyzed in this report can help meet the District's ambitious sustainability goals, contributing to meeting the goals in 8 of the District's 11 action categories, summarized in Table 15.1.

Table 15.2. Smart surface solutions and Sustainable DC Plan

Sustainable DC Plan action category	Smart surface solutions impacts
Jobs & Economy	• Create 2,403 well-paying direct green jobs to District residents over 40 years • Provide an entry point into the emerging green workforce
Health & Wellness	• Improve air quality and public health (18% of benefits are from health), creating a healthier environment for District residents and visitors
Equity & Diversity	• Improve livability, particularly in low income areas that tend have less green cover and have less efficient buildings
Climate & Environment	• By full implementation, emissions reductions equivalent to 5.5% of 2013 emissions, assuming constant emissions through the 40-year analysis • Enhance resilience to climate change by reducing city temperature through UHI mitigation
Built Environment	• Improve sustainability performance of new and existing buildings; • Create higher quality of life through improved design
Energy	• When fully implemented, reduce electricity purchases from the grid by 8.5% and slightly increase natural gas purchases by 0.9% relative to 2013 consumption • Counter the rise in energy consumption due to rising temperatures from climate change
Nature	• Expand tree canopy and other green landscapes to create a District-wide ecosystem
Water	• Reduce stormwater runoff to protect local water bodies; • Reduce potable water use

Washington DC is already a national and international leader in sustainability. City-wide, integrated adoption of the technologies detailed in this report would greatly strengthen DCs sustainability leadership and would provide strong protection against continued climate change. This report describes the importance of working with other cities to establish albedo and other requirements for purchasing specification over the next decade or two to create a multi jurisdiction product performance specification market to drive innovation. Large opportunities include at least tripling the standard residential shingles (which now absorb 85% of sunlight), sequestering carbon in roads, sidewalks and parking lots to make them carbon negative, developing very reflective porous surfacing materials, and developing integrated PV+green roofing solutions.

The data on cost effectiveness of these strategies is now compelling. Delays in city-wide adoption would impose real costs. Former Washington DC City Administrator and former Administrator of the General Services Administration Dan Tangherlini notes that; "Achieving Urban Resilience is a critical, even transformative new analysis that provides a compelling case that DC should accelerate its greening by adopting the city wide technology and design practices documented here... Delaying this transition would impose large financial and social costs particularly on places of lower economic opportunity, the elderly and children. We have the roadmap – now we must follow it."

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Appendices

16 Appendix: Install cost

16.1 Bioretention

We base the cost difference between standard and enhanced bioretention designs on the additional stone layer depth needed for enhanced design. Based on our calculations in Section 20.1.2, we estimate an additional 2.25 feet of aggregate base is needed for enhanced design.

We assume aggregate is $20 per ton.[475] To convert aggregate layer depth into tons we use a "rule of thumb" (see Equation 16.1).[476] Using Equation 16.1 and the cost of aggregate at $20 per ton, we find that the cost of aggregate of depth d (ft) for 1 ft^2 of pavement is \$1.48d. So, 1 ft^2 of aggregate at a depth 2.25 ft (27 in) would cost $3.33.

Equation 16.1. Convert aggregate base dimensions into tons

$$\text{Weight aggregate (tons)} = \text{pavement surface area (ft}^2) \times \text{aggregate depth (ft)} \times \left(\frac{1\ \text{yd}^3}{27\ \text{ft}^3}\right) \times \left(\frac{2\ \text{tons}}{1\ \text{yd}^3}\right)$$

Next, we multiply by factor of 1.4 from DC Water to account for design costs, project management costs, etc.[477] We approximate the cost for installing additional stone base is $4.66 per square foot.

16.2 Solar PV

1) Basis: Barbose et al. (2015)[478]
2) Barbose et al. present prices for 2014 installs for various states

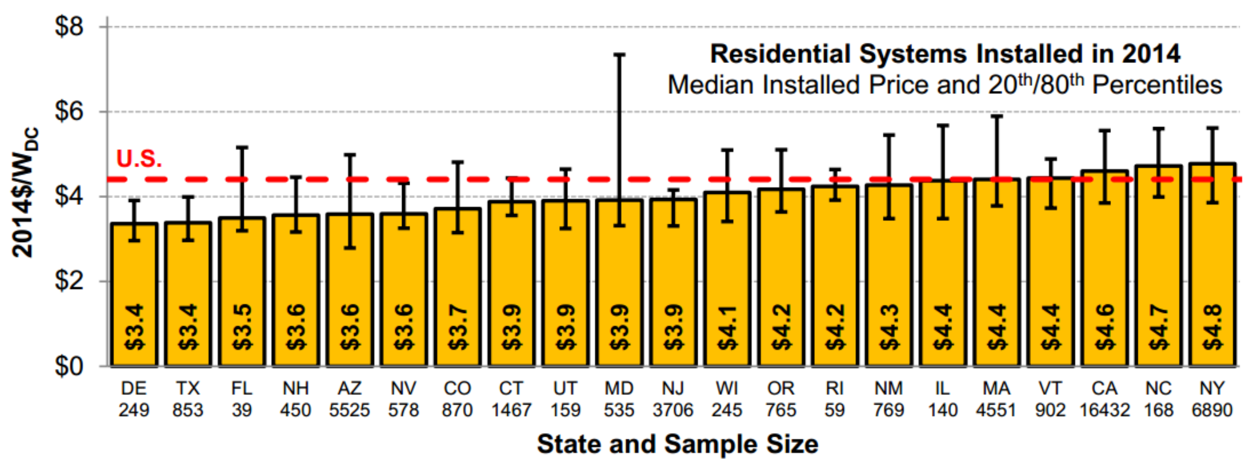

Figure 16.1. Installed price of residential PV systems by state[479]

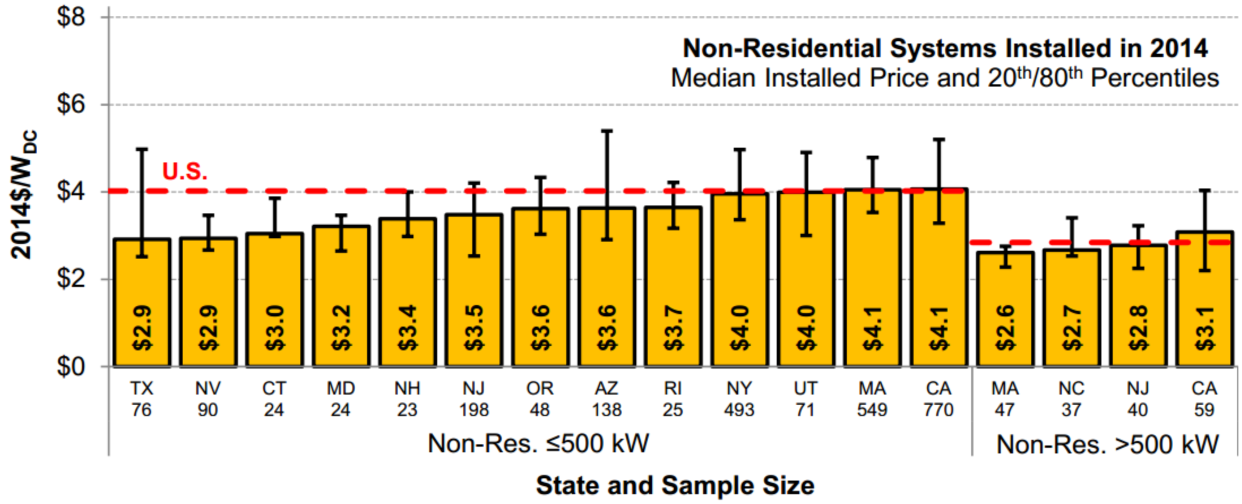

Figure 16.2. Installed price of non-residential PV systems by state[480]

- a) Multifamily residential systems are included in each figure due to conventions of data providers that provided data to Barbose et al.
  - i) For simplicity, we assume multifamily residential systems are same cost as non-residential systems.

3) Pre-2020
   - a) 2006 – 2014 PV cost per W fell on average 8.8% and 9.4% year-on-year for residential systems and non-residential systems less than 500kW, respectively (see Table 16.1)
   - b) Geographically closest state in Figure 16.1 and Figure 16.2 to DC is MD → use MD $/W numbers in analysis under assumption that DC and MD have similar PV markets
   - c) Extrapolate cost declines identified above through 2016 → residential $/W = 3.2 and non-residential <= 500kW $/W = 2.6
     - i) Use these values for pre-2020 solar PV costs

Table 16.1. National median installed price overtime[481]

Year	$/W	
	Residential	Non-Residential <= 500 kW
2006	9.1	8.8
2007	9.2	8.9
2008	8.8	8.7
2009	8.4	8.6
2010	7.1	6.9
2011	6.3	5.8
2012	5.4	5.0
2013	4.7	4.3
2014	4.3	3.9

4) Post-2020
   a) Use MD $/W
   b) Extrapolate trend identified above through 2020 → residential $/W = 2.2 and non-residential <= 500kW $/W = 1.8
      i) Uses these values for post-2020 solar PV costs

16.3 Permeable pavements

We base the cost difference between standard and enhanced bioretention designs on the additional stone layer depth needed for enhanced design. Based on our calculations in Section 20.1.4, we estimate an additional 13 inches of aggregate base is needed for enhanced design. Using the same methods as in Section 16.1, we approximate the cost for installing additional stone base is $2.24 per square foot.

17 Appendix: Estimating energy impact

17.1 Direct energy

17.1.1 Low slope cool and green roofs

We use the Green Roof Energy Calculator (GREC) v2.0 to determine direct energy savings/penalties for low slope cool and green roofs. The Green Roof Energy Calculator (GREC) was developed by researchers and staff at Portland State University, the University of Toronto, and Green Roofs for Healthy Cities, and was funded by the U.S. Green Building Council.[482] The developers created GREC because they recognized the need for an online tool that allowed non energy modeling experts to estimate the effects of green roofs and green roof design decisions on building energy use and energy costs.

GREC is based on building energy simulations performed using the U.S. Department of Energy's (DOE) EnergyPlus versions 3 and 6.[483] EnergyPlus includes a green roof module that was developed by Dr. David Sailor of Portland State University (Dr. Sailor also helped spearhead the development of GREC). The module allows users to simulate the impact of shading, sensible heat flux, thermal and moisture transport in the growing medium, and evapotranspiration on building energy consumption.[484] A total of 8,000 simulations were conducted for the calculator. Simulations were conducted for 95 U.S. cities and 5 Canadian cities, two building vintages, two building categories, and twenty roof types.[cxxvii]

The user can select from "old" (pre ASHRAE 90.1-2004; essentially 1980s vintage) and "new" (ASHRAE 90.1-2004) construction vintages and residential (four-story midrise apartment) and commercial (three-story medium office) building categories.[cxxviii] Dark (albedo 0.15) and white (albedo 0.65) roofs were modeled as controls, and nine different green roofs were modeled with and without irrigation. Energy and cost savings/penalties are estimated per square foot of roof and then multiplied by the roof area and green roof extent.[cxxix] Users can compare the energy impact of a green roof to that of a dark roof or a cool (white) roof. The albedos of the dark (0.15) and white roof (0.65) cannot be altered in the calculator but users can select the growing media depth (between 2 and 11.5 inches), leaf area index (between 0.5 and 5),[cxxx] and whether the green roof is irrigated. Users also select the roof area, the percent of the roof that is vegetated, and the characteristics of the roof area that is not vegetated (dark or white).

This analysis calculated direct green roof energy benefits using a growing media depth of 4.5 inches—approximately in the middle of extensive green roof growing media depths (3 inches to 6 inches). We hold

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[cxxvii] The building simulations were conducted using building benchmark models that were developed by DOE and three of its national laboratories for building professionals to analyze the energy performance across the commercial building stock. (U.S. Department of Energy (DOE), "Commercial Reference Buildings," *Energy.gov*, 2011, http://energy.gov/eere/buildings/commercial-reference-buildings.)

[cxxviii] Only the top floor of a building will experience measurable direct energy consumption impacts, so any differences in building height between actual buildings and DOE benchmark buildings is not material. 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.)

[cxxix] I.e., GREC assumes a linear relationship between roof area and energy use impact.

[cxxx] Leaf area index is the ratio of upper leaf area divided by growing medium area on which the vegetation grows. It generally ranges from 0 (bare ground) to 6 (dense forest). (Portland State University, "Green Roof Energy Calculator Information," 2013, http://greenbuilding.pdx.edu/GR_CALC_v2/CalculatorInfo_v2.php.)

leaf area index constant at 2, which is consistent with the standard value used by Sailor et al. (2011) to model green roof design decisions.[cxxxi] In addition, we assume that green roofs cover 100 percent of the roof.[cxxxii] Washington, DC was not one of the cities simulated for GREC development so we model the energy savings/penalties of green roofs for Washington, DC using Baltimore (geographically the closest of the modeled cities to Washington, DC).[cxxxiii] We calculate the energy saving for a 10,000 ft^2 roof and scale the results down to energy savings on per ft^2 basis. We average the energy savings of old and new commercial buildings and old and new residential buildings for simplicity.

Why did we choose GREC?

GREC is the best online calculator available for estimating the direct energy benefits of installing cool and green roofs. Other online calculators either do not include green roofs as a roofing option or do not allow important green roof characteristics, such as growing media depth and leaf area index, to be modified. One drawback of GREC is that users cannot modify the albedos of the dark roof or the cool roof that the green roof is compared to. However, the albedo options in GREC are consistent with our assumptions. And, given the importance of a green roof's characteristics in estimating the potential energy savings of its installation and the complexities that accounting for these characteristics generate, we chose to forgo albedo level customization in the calculator in lieu of green roof characteristic customization.

17.1.2 Steep slope cool roofs

We use GAF's Cool Roof Energy Savings Tool (CREST) to estimate the energy savings potential of cool roofs on steep slope roofs. We do not include steep slope green roofs in this analysis because they are uncommon. The Cool Roof Energy Savings Tool (CREST) calculates energy savings using the Department of Energy (DOE)'s Cool Roof Calculator and DOE's Steep Slope Roof Calculator. CREST allows users to estimate cool roof direct energy savings for commercial and residential buildings based on user inputs such as building zip code, HVAC efficiency, and roof insulation level.

We estimate energy savings for cool roofs in CREST using the same inputs as GREC. The CREST inputs for "old" and "new" buildings are shown in Table 17.1. The HVAC equipment efficiencies and roof insulation levels are set as close as possible to the respective values used in GREC.[cxxxiv,cxxxv] Similarly, GREC does not provide roof emissivity values for baseline or cool roofs so we assume a value of 0.90 for baseline and cool roofs, which is typical for most conventional and cool roofs.[485] We calculate the energy saving for a 10,000

[cxxxi] The leaf area index for extensive green roofs is generally between 1 and 3 (Tabares-Valesco, 2011). We use a midpoint value of 2, which is consistent with baseline leaf area index for green roofs as noted by Sailor et al. (2011). (Paulo Cesar Tabares-Velasco, "Leaf Area Index Values for Roof Vegetation," *Energy-Models*, May 11, 2011, http://energy-models.com/forum/leaf-area-index-values-roof-vegetation#comment-18914.)

[cxxxii] All of our cost and benefit estimates are calculated per square foot of roof, so this assumption does not impact the results. If instead we assumed that green roofs cover 80 percent of the roof, then the energy benefits and roof area would both decrease by 20 percent compared to a 100 percent green roof. Because both the energy benefits and roof area decrease by the same amount, the results are the same.

[cxxxiii] Based on a comparison of heating degree days (HDD) and cooling degree days (CDD) in Washington, DC and Baltimore, this should lead to conservative overall energy savings estimate for low slope roofs.

[cxxxiv] CREST only accepts whole numbers for cool roof insulation R-value. Because we assume insulation levels for cool roofs are the same as those for baseline roofs, we round the baseline roof insulation R-value to the nearest whole number for cool roof insulation levels.

[cxxxv] We derive the building characteristics used to develop GREC from DOE's Commercial Reference Buildings. (U.S. Department of Energy (DOE), "Commercial Reference Buildings.")

ft^2 roof and scale the results down to energy savings on per ft^2 basis. We average the energy savings of old and new commercial buildings and old and new residential buildings for simplicity.

Table 17.1. CREST inputs

CREST input	Old Office	New Office	Old Residence	New Residence
Building use	Normal	Normal	Normal	Normal
Cooling equip. efficiency (SEER)	9.52	10.98	10.68	12.52
Heating equip. efficiency (AFUE)	80%	80%	80%	80%
Roof area (ft2)	10,000	10,000	10,000	10,000
Baseline roof insulation R-value	17	16	17	16
Baseline solar reflectance	0.1	0.1	0.1	0.1
Baseline infrared emissivity	0.9	0.9	0.9	0.9
Cool roof insulation R-value	17	16	17	16
Cool solar reflectance	0.25	0.25	0.25	0.25
Cool infrared emissivity	0.9	0.9	0.9	0.9

17.1.3 Urban trees

1) Use results from Washington, DC i-Tree Eco analysis[486]
    a. i-Tree Eco assumes only residential buildings receive direct energy benefits, but don't have way to determine tree canopy that provides this benefit
    b. Use average across tree canopy from i-Tree report (29.2% or 497 million SF) → results conservative for trees that provide direct energy, and over estimate for those that don't
        i. Cooling savings = 15,552 MWh
            1. 0.03 kWh per SF tree canopy
        ii. Heating penalty = 66,888 MBTU + 973 MWH
            1. 0.001 therm + 0.002 kWh per SF tree canopy

17.2 Indirect energy use

17.2.1 Cool roofs and green roofs

The work performed by Akbari and Konopacki (2005) form the basis of our methods used to estimate the indirect energy impacts of cool roofs and green roofs.[487] One of the stated goals of Akbari and Konopacki

(2005) is to “develop a simple method to estimate the indirect effects [of UHI mitigation] on energy use and peak demand in the US.” Savings estimates are categorized by heating-degree-days or cooling-degree-days and presented per 1000 ft2 of roof area. Akbari and Konopacki (2005) analyze three building types: a single-family residence; an office; and a retail store.[cxxxvi] Variations of each building type were analyzed based on building age (i.e., pre-1980 building or 1980+ building) and heating fuel (i.e., natural gas or electricity). The 1980+ variant has more energy efficient HVAC equipment and better insulation than the pre-1980 variant (see Table 17.2 through Table 17.4 for the characteristics of each building and its variants), so savings/penalties will tend to be smaller for the 1980+ variant.

[cxxxvi] Akbari and Konopacki (2005) chose these buildings types because an earlier analysis (Konopacki et al., 1997) showed that these building types offer the most savings potential. (Steven Konopacki et al., “Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 US Metropolitan Areas,” May 1, 1997, http://heatisland.lbl.gov/publications/cooling-energy-savings-potential-ligh.)

Table 17.2. Residential building characteristics for indirect energy analysis (from Akbari and Konopacki (2005))

	Pre-1980	**1980+**
Single-family Residence		
Single-storey, non-directional		
Roof& floor area (ft2)	1600	
Zones		
Living (conditioned)		
Attic (unconditioned)		
Basement (unconditioned		
Roof Construction		
20° slope		
1/4" asphalt shingle		
3/4" plywood deck w/ 2" × 6" rafters		
Naturally ventilated attic		
3/4" plywood deck w/ 2" × 6" rafters (15%)		
Fiberglass insulation (85%)	R-11	R-30
1/2" drywall		
Roof Solar Reflectance		
Pre	0.2	
Post	0.5	
Roof Thermal Emittance	0.9	
Wall Construction		
Brick exterior		
Wood frame (15%)		
Fiberglass insulation (85%)	R-5	R-13
1/2' drywall interior		
Windows		
Clear with operable shades		
Number of panes	1	2
Window to wall ratio	0.18	
Fractional Leakage Area (in2/100 ft2)		
Living	4	2
Attic	8	4
Air-conditioning Equipment		
Central a/c, direct expansion, air-cooled		
Energy efficiency ratio (EER)	8.5	20
Coefficient of performance (COP)	2.5	2.9
Cooling setpoint (°F)	78	
Natural ventilation available		
Heating Equipment		
(1) Central forced air gas furnace		
Efficiency (%)	70	78
Heating setpoint (°F)	70	
11pm-7am setback (°F)	60	
(2) Central electric heat pump		
Heating season performance factor (HSFP)	5	7
Duct Air Leakage (%)	20	10

Table 17.3 Office building characteristics for indirect energy analysis (from Akbari and Konopacki (2005))

	Pre-1980	**1980+**
Single-story office		
Non-directional		
5 zones (conditioned)		
Roof & floor area (ft2)	4900	
Roof Construction		
Built-up roofing		
3/4" plywood decking (0° slope)		
Plenum (unconditioned)		
Roof Solar Reflectance		
Pre	0.2	
Post	0.6	
Roof Thermal Emittance	0.9	
Ceiling Construction		
2" × 6" studded frame (15%)		
Fiberglass insulation (85%)	R-11	R-30
1/2" drywall		
Wall Construction		
Brick exterior		
Wood frame (15%)		
Fiberglass insulation (85%)	R-6	R-13
1/2" drywall		
Foundation		
Slab-on-grade with carpet and pad		
Windows		
Clear with operable shades		
Number of panes	1	2
Window to wall ratio	0.5	
Air-conditioning Equipment		
Packaged a/c, direct expansion, air-cooled		
Energy efficiency ratio (EER)	8	10
Coefficient of performance (COP)	2.3	2.9
Heating Equipment		
(1) Gas furnace		
Efficiency (%)	70	74
(2) Electric heat pump		
Heating season performance factor (HSFP)	5	7
Distribution		
Constant-volume forced air system		
Economizer	Fixed	Temperature
Duct Leakage (%)	20	10
Duct temperature drop (°F)	2	1
Thermostat		
Weekday operation (6am-7pm)		
Cooling setpoint (°F)	78	
Heating setpoint (°F)	70	
Interior Load		
Infiltration (air-change/hour)	0.5	
Lighting (W/ft2)	1.9	1.4
Equipment (W/ft2)	1.7	1.5
Occupants	25	

Table 17.4 Retail store building characteristics for indirect energy analysis (from Akbari and Konopacki (2005))

	Pre-1980	1980+
Single-story retail store		
Non-directional		
Single-zone (conditioned)		
Roof & floor area (ft2)	8100	
Roof Construction		
Built-up roofing		
3/4" plywood decking (0° slope)		
Plenum (unconditioned)		
Roof Solar Reflectance		
Pre	0.2	
Post	0.6	
Roof Thermal Emittance	0.9	
Ceiling Construction		
2" × 6" studded frame (15%)		
Fiberglass insulation (85%)	R-11	R-30
1/2" drywall		
Wall Construction		
Brick exterior		
Wood frame (15%)		
Fiberglass insulation (85%)	R-4	R-13
1/2" drywall		
Foundation		
Slab-on-grade with carpet and pad		
Windows		
Clear with operable shades		
Number of panes	1	2
Window to wall ratio	0.17	
Air-conditioning Equipment		
Packaged a/c, direct expansion, air-cooled		
Energy efficiency ratio (EER)	8	10
Coefficient of performance (COP)	2.3	2.9
Heating Equipment		
(1) Gas furnace		
Efficiency (%)	70	74
(2) Electric heat pump		
Heating season performance factor (HSFP)	5	7
Distribution		
Constant-volume forced air system		
Economizer	Fixed	Temperature
Duct Leakage (%)	20	10
Duct temperature drop (°F)	3	1
Thermostat		
Weekday operation (8am-9pm)		
Weekend operation (10am-5pm		
Cooling setpoint (°F)	78	
Heating setpoint (°F)	70	
Interior Load		
Infiltration (air-change/hour)	0.5	
Lighting (W/ft2)	2.4	1.7
Equipment (W/ft2)	0.7	0.6

Occupants	16

We model the District using the building type estimates in Table 17.5. We base the District estimates on building footprint data and land use data from the District.[488] Due to data limitations, we model all retail space as office buildings. This is conservative because retail store indirect energy savings are generally higher than those for office buildings (see Table 17.6 and Table 17.7). For simplicity we assume an equal four part split for building vintage and heating fuel within each building type.

Table 17.5. Washington, DC city-wide building assumptions for indirect energy estimates

Building Type	Residence		Office		Retail Store	
Age	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+
Building roof area stock with gas heating (%)	15.3%	15.3%	9.7%	9.7%	0.0%	0.0%
Building roof area stock with heat pump system (%)	15.3%	15.3%	9.7%	9.7%	0.0%	0.0%

A&K categorize savings estimates based on heating-degree or cooling-degree day ranges. To estimate the savings for a prospective city, one finds the correct HDD or CDD range for the prospective city and extracts the results from the table. The energy savings estimates for each building type in each HDD or CDD category are shown in Table 17.6 and Table 17.7. We take the average of the HDD and CDD energy impact estimates.

Table 17.6. Estimated indirect energy savings per 1,000 ft^2 of roof based on HDD for the District[489]

City	**Washington, DC HDD**					
Building Type	**Residence**		**Office**		**Retail Store**	
Building Age	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+
Estimated total indirect electricity savings with gas heating system (kWh)	131	60	256	91	260	89
Estimated total indirect electricity savings with heat pump system (kWh)	89	42	241	82	247	86
Estimated total indirect peak power demand reduction (W)	127	53	167	58	101	45
Estimated total indirect gas penalties with gas heating system (Therm)	-6	-2	-2	-1	-1	0

Table 17.7. Estimated indirect energy savings per 1,000 ft² of roof based on CDD for the District[490]

City	**Washington, DC CDD**					
Building Type	**Residence**		**Office**		**Retail Store**	
Building Age	Pre-1980	1980+	Pre-1980	1980+	Pre-1980	1980+
Estimated total indirect electricity savings with gas heating system (kWh)	142	65	250	93	266	88
Estimated total indirect electricity savings with heat pump system (kWh)	102	51	234	86	255	86
Estimated total indirect peak power demand reduction (W)	112	51	142	56	107	34
Estimated total indirect gas penalties with gas heating system (Therm)	-6	-2	-2	-1	-5	0

The UHI mitigation methods Akbari and Konopacki (2005) analyze are urban reforestation and reflective surfaces (roofs and pavements). The number of deciduous shade trees modeled were 4, 8, and 10 for the residence, office, and retail store, respectively. The trees were placed outside the south and west walls of the buildings near the windows. The albedo changes analyzed were 0.2 to 0.5 (an albedo change of 0.3) for the residence and 0.2 to 0.6 (Δ of 0.4) for office and for the retail store.

The savings estimates from Akbari and Konopacki (2005) are calculated with the assumption that "all surfaces would be modified to the levels discussed above [100 percent implementation in a city]," so their results provide an upper boundary for estimates of indirect savings. However, A&K (2005) note that "Although we have not performed any analysis of partial or gradual implementation of HIR [UHI mitigation] measures, we assume that savings, once normalized per square foot of roof area, can be linearly scaled." Therefore, we can and do scale the energy impact estimates of Akbari and Konopacki (2005) to fit the roof areas analyzed in this cost-benefit analysis.[cxxxvii]

In our analysis, we do not analyze the same change in reflectance as that in Akbari and Konopacki (2005), so we need some way to scale the results. Akbari and Konopacki (2005) when they note that "Linear interpolation can be used to estimate savings or penalties for other net changes in roof reflectance ($\Delta\rho_2$) than presented in the tables ($\Delta\rho_1$).[491] Therefore, these results can simply be adjusted by the ratio $\Delta\rho_2/\Delta\rho_1$ to obtain estimates for other reflective scenarios." We use linear interpolation to scale results based on albedo change.

We use Equation 17.1 to scale the energy impact results of Akbari and Konopacki (2005) to fit the assumptions for this analysis. In Equation 17.1, ΔE_{CB} is the scaled energy use impact used in this analysis,

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[cxxxvii] Recent research from Li et al. (2014) shows that this assumption is reasonably accurate. Li et al. (2014) modeled the effect of cool roof or green roof installation in Washington, DC and Baltimore and found that the ambient temperature change that results from installing cool or green roofs in a city is roughly linearly related to the installation extent of cool or green roofs. For example, if installing cool roofs on 100 percent of roof area in a city results in an ambient temperature change of x °F, then installing cool roofs on 50 percent of roof area in a city results in an ambient temperature change of about $\frac{x}{2}$ °F.

ΔE_{AK} is the ratio to account for less than 100% deployment of UHI mitigation options, and $\frac{\Delta \rho_2}{\Delta \rho_1}$ is the ratio to account for difference in albedo changes between this study and Akbari and Konopacki (2005).

Equation 17.1. Scaling of Akbari and Konopacki (2005) results to match cost-benefit analysis assumptions

$$\Delta E_{CB} = \Delta E_{AK} \times \frac{\Delta \rho_2}{\Delta \rho_1}$$

We also have to account for the fact that Akbari and Konopacki (2005) estimated energy impacts of cool roofs and urban reforestation together. Based on personal correspondence with the authors, we assume there is a 50-50 split in indirect energy benefits between reflective roofs and urban reforestation, so we cut the results of Equation 17.1 in half to determine the indirect energy savings from cool roof implantation.[492]

No studies have estimated the indirect energy impacts of installing green roofs, so we estimate using our own method described below. Akbari and Konopacki (2005) only model the indirect energy impact of installing cool roofs and planting shade trees so we have to determine a workaround to account for green roofs. Li et al. (2014) modeled the impact of different coverages of cool roofs or green roofs on surface and near-surface air UHIs in Washington, DC and Baltimore.[493] They found that green roofs and cool roofs had roughly the same impact on near-surface UHI. Because ambient air temperature changes are what account for any indirect energy savings/penalties in Akbari and Konopacki (2005), we assume that green roofs have the same indirect energy savings/penalties impact as cool roofs (i.e., Equation 17.1divided by two).[cxxxviii]

Some considerations for using A&K (2005)

Depending on the age of the building stock in the city and the typical building height, the results taken from Akbari and Konopacki (2005) may somewhat overestimate or underestimate the indirect savings from UHI mitigation, but generally provide a reasonable estimate of savings. In A&K's estimates, all buildings are one story, so the indirect energy savings estimates provided by Akbari and Konopacki (2005) will tend to underestimate the indirect savings for taller buildings. Furthermore, if building stock in a city is old, then estimates will be approximately correct. However, if building stock is newer, then the estimates from A&K will tend to overestimate indirect energy savings.

17.2.2 Reflective pavements

We estimate the indirect energy impact of reflective pavements by scaling the indirect energy impact of cool roofs by the ratio of albedo change for reflective pavements compared albedo change for roofs. For example, the albedo change for a low slope cool roof pre-2025 is 0.50 and the albedo change for a pre-2030 road is 0.15. Therefore, to estimate the indirect energy impact of a reflective road, we multiple the

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[cxxxviii] The albedo change used in Li et al. (2014) does not match that used in Akbari and Konopacki (2005). Furthermore, other roof thermal properties used in Li et al. (2014), such as emissivity, heat capacity, and thermal conductivity, cannot be compared to those used in Akbari and Konopacki (2005) because Akbari and Konopacki do not list them. As a result, we cannot know for sure if cool roof-related indirect energy savings/penalties from Akbari and Konopacki (2005) would equal green roof-related indirect energy savings/penalties without performing a new analysis. Nevertheless, we intend to keep this analysis simple as it is targeted at non experts, so we assume that the indirect energy impacts of green roofs are equal to those of cool roofs.

estimated energy impact of a low slope cool roof by the ratio of albedo change for a reflective road compared to albedo change of a low slope cool roof (i.e., 0.15 divided by 0.50).

17.2.3 Urban trees

We estimate indirect energy benefits of urban tress using similar methods to cool roofs, green roofs, and reflective pavements. We use a version of Equation 17.1 without an albedo scaling factor. Based on the description of trees modeled in Akbari and Konopacki (2005), we assume canopy area per tree used for indirect energy calculations is 150 square feet. We divide this number by the total potential tree canopy area in each city to determine the correct scaling ratio (ΔE_{AK} in Equation 17.1). As described above in Section 17.2.1, this method likely underestimates the indirect energy benefits of trees.

17.3 PV energy generation

1) Use NREL's PVWatts Calculator (later referred to as PVWatts) to estimate energy output of rooftop PV systems
2) System parameter and annual energy output (based on Optony, 2014 methods and NREL, 2009 methods):[494]
    a. Single-family residential
        i. Assume average residential system size of 5 kW
        ii. Housing stock (detached vs attached)
            1. Collect single-family housing stock numbers from American Community Survey: 1-unit attached and 1-unit detached

Table 17.8. Housing units in the city (from American Community Survey)[495]

Housing type	Number of housing units
1-unit, detached	35,925
1-unit, attached	76,489

            2. Roof type for different housing types (from Optony, 2014)

Table 17.9. Housing type and roof type (from Optony, 2014)

Housing type	Flat	4-sided	2-sided
1-unit, detached	10%	45%	45%
1-unit, attached	50%	0%	50%

        iii. Structural integrity
            1. Assumption from Optony (2014) and A Solar Rooftop Assessment for Austin[496]
            2. 99% of single-family residences are capable of holding a rooftop PV system
        iv. Shading

1. Based on Denholm et al. (2009) Table C-2
    a. DC in South Atlantic EIA Census Region
        i. Shading fraction: 55% (i.e., the fraction of roofs that are shaded)

v. System orientations
    1. From Denholm et al. (2009) Table C-1

Table 17.10. Single-family residential tilt and azimuth assumptions for different roof types

Orientation reference in model	Tilt	Azimuth	Flat	4-sided	2-sided
1	0	0	100%		
2	25	-90			14%
3	25	-60			14%
4	25	-30		33%	14%
5	25	0		33%	14%
6	25	30		33%	14%
7	25	60			14%
8	25	90			14%

vi. Multiply Table 17.8 by factors presented above to determine the number of housing units in each region that can support solar

Table 17.11. Example result for Washington, DC 1-unit detached

Orientation	Tilt	Azimuth	Flat	4-sided	2-sided
1	0	0	1601	0	0
2	25	-90	0	0	1029
3	25	-60	0	0	1029
4	25	-30	0	2401	1029
5	25	0	0	2401	1029
6	25	30	0	2401	1029
7	25	60	0	0	1029
8	25	90	0	0	1029

Table 17.12. Example result for Washington, DC 1-unit attached

Orientation reference in model	Tilt	Azimuth	Flat	4-sided	2-sided
1	0	0	17038	0	0
2	25	-90	0	0	2434
3	25	-60	0	0	2434
4	25	-30	0	0	2434
5	25	0	0	0	2434
6	25	30	0	0	2434
7	25	60	0	0	2434
8	25	90	0	0	2434

vii. Multiply above by the average residential system size (5 kW) to determine maximum viable residential PV potential

Table 17.13. Example result for Washington, DC 1-unit detached

Orientation reference in model	Total kW
1	8005
2	5145
3	5145
4	17150
5	17150
6	17150
7	5145
8	5145

Table 17.14. Example result for Washington, DC 1-unit attached

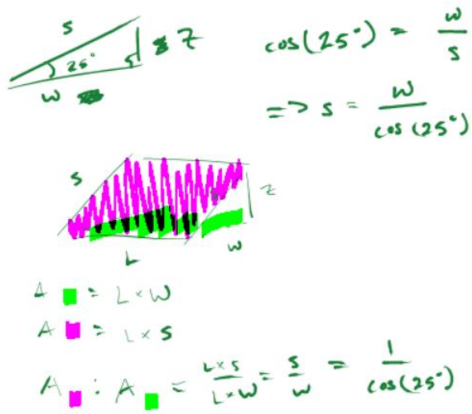
Orientation reference in model	Total kW
1	85190
2	12170
3	12170
4	12170
5	12170
6	12170
7	12170
8	12170

b. Commercial
    i. Roof slope
        1. Based on the 2012 Commercial Building Energy Consumption Survey from EIA[497]
        2. Two pathways to determine slope breakdown (i.e., % low slope and % steep slope): (1) based on floorspace and (2) based on number of buildings
            a. Take average
                i. South Atlantic (which includes DC):
                    1. 81% low slope
                    2. 19% steep slope
    ii. Commercial building footprint
        1. Based on publicly available data from each city processed for the regions of analysis; for commercial solar, we assume everything not described as residential is commercial
        2. Results

Table 17.15. Commercial building footprint

Analysis region city	Washington, DC
Commercial building footprint (SF)	99,479,908

        3. Multiply by above roof slope fractions above to determine the area of low slope and steep slope roof
            a. Revise steep slope area up to account for roof pitch
                i. Divide calculated are by cos(25°)



iii. Roof orientations
    1. We assume non-flat roofs are two-sided and that two-sided orientations are distributed evenly N, S, E, and W because of the gridded street structures that dominate in DC, Baltimore, and Philadelphia.
    2. Tilt assumptions are from NREL, 2009 Table C-3

Table 17.16. Commercial tilt and azimuth assumptions for different roof types

Orientation reference in model	Tilt	Azimuth	Flat	2-sided
1	0	0	100%	
2	25	-90		25%
5	25	0		25%
8	25	90		25%
9	25	180		25%

iv. Roof shading
    1. Unshaded
        a. Assume 80% of roofs are unshaded based on Denholm et al. (2009)
    2. Regional shading
        a. Assume those roofs that are shaded are shaded using the same shaded fractions described above for single-family residential (based on Denholm et al. (2009))

v. Multiply roof orientation factors and shading factors to get percent of roof space available for solar

vi. PV density per square foot of roof
    1. Based on Denholm and Margolis (2008)[498]
    2. We assume PV density per square foot of roof for sloped roofs is 16.7 watts per square foot (assuming 18% panel efficiency)

3. For flat roofs, to account for spacing between panels (e.g., because of shading by PV panels), we assume a density of 13.6 watts per square foot (assuming 18% panel efficiency)

vii. Multiply the result of roof area by the power density to determine the maximum viable PV potential for commercial buildings

Table 17.17. Example maximum commercial PV capacity for Washington, DC

Orientation reference in model	Tilt	Azimuth	Flat (kW)	2-sided (kW)	Total kW
1	0	0	435,132	0	435,132
2	25	-90	0	36,338	36,338
5	25	0	0	36,338	36,338
8	25	90	0	36,338	36,338
9	25	180	0	36,338	36,338

c. Multi-family residential

i. Roof slope

1. Same fractions as for commercial roofs

ii. Building footprint

Table 17.18. ***Multifamily residential*** *building footprint*

Analysis region city	Washington, DC
Multifamily residential building footprint (SF)	13,657,922

iii. Roof orientation

1. Same fractions as for commercial roofs

iv. Roof shading

1. Same fractions as for commercial roofs

v. PV density per square foot of roof

1. Same fractions as for commercial roofs

vi. Multiply the result of roof area by the power density to determine the maximum viable PV potential for multifamily residential buildings

Table 17.19. Example maximum multifamily residential PV capacity for Washington, DC

Orientation reference in model	Tilt	Azimuth	Flat (kW)	2-sided (kW)	Total kW
1	0	0	16,582	0	16,582
2	25	-90	0	1,317	1,317
5	25	0	0	1,317	1,317
8	25	90	0	1,317	1,317
9	25	180	0	1,317	1,317

3) Electricity output from PVWatts
    a. For all sloped roofs, use 25% tilt as described in the tables above.
    b. For low slope roofs, use 10% tilt based on discussion with solar professionals[499]
    c. Use the azimuths shown in the tables above
    d. For steep slope roofs assume fixed, roof mount systems; for low slope roofs assume fixed, open rack systems
    e. Solar and weather data locations
        i. DC: WASHINGTON DC REAGAN AP, VA
    f. Otherwise, use default PVWatts inputs unless noted above
        i. PV efficiency: 15% (i.e., "Standard" module type)[cxxxix]
        ii. System losses: 14%
        iii. Inverter efficiency: 96%
        iv. DC to AC size ratio: 1.1

17.4 Utility rates

We use the most recent (2015) annual utility rates from EIA. See Table 17.20 for commercial rates and Table 17.21 for residential rates.

Table 17.20. Commercial utility rates; held constant through analysis

Fuel	Base price	Fuel unit	Year
Electricity[500]	$0.1222	kWh	2015
Natural Gas[501]	$1.19	therm	2015

Table 17.21. Residential utility rates; held constant through analysis

Fuel	Base price	Fuel unit	Year
Electricity[502]	$0.1278	kWh	2015
Natural Gas[503]	$1.27	therm	2015

[cxxxix] In model, linearly scale efficiency to 18%. In other words, annual output increases by a factor of 18%/15%.

18 Appendix: Estimating solar PV financial incentives

18.1 Tax credit

There are two federal tax credits available to PV system owners: the residential renewable energy tax credit[504] and the business energy investment tax credit (ITC).[505]

The residential tax credit is a personal tax credit for 30% of the cost of installation. Any unused tax credit can generally be carried forward to the next year. For simplicity, we assume all tax credits are used in the year of installation. The residential tax credit drops to 26% in 2020, 22% in 2021, and 0% thereafter.[506] Table 18.1 shows the residential solar tax credit schedule used in this analysis.

Table 18.1. Residential solar tax credit schedule

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027-end
Incentive (%)	30%	30%	30%	30%	30%	26%	22%	0%	0%	0%	0%	0%	0%

The ITC is a corporate tax credit and is also for 30% of the cost of installation. Similar to the residential tax credit, unused tax credit can generally be carried forward to following years. For simplicity, we assume all tax credits are used in the year of install. The ITC drops to 26% in 2020, 22% in 2021, and 10% thereafter.[507] In this analysis, we assume the ITC stays at 10% for five years (2022 through 2026) and is 0% for the remainder of the analysis. Table 18.2 shows the residential solar tax credit schedule used in this analysis.

Table 18.2. ITC schedule

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027-end
Incentive (%)	30%	30%	30%	30%	30%	26%	22%	10%	10%	10%	10%	10%	0%

18.2 Depreciation

Businesses may recover the cost of an investment in solar PV using tax depreciation deductions through the federal Modified Accelerated Cost-Recovery System (MACRS) and bonus depreciation.[508] PV systems are generally eligible for a cost recovery period of five years. For systems that use the ITC, the depreciable basis must be reduced by half the value of the ITC (e.g., for a 30% ITC, the depreciable basis is reduced by 15% to 85% of the install cost).[509] For simplicity, we assume businesses have enough tax appetite to deduct against. Table 18.3 shows the 5-year MACRS schedule used in this analysis. Table 18.4 shows the bonus depreciation timeline.

Table 18.3. 5-year MACRS schedule[510]

Year	1	2	3	4	5	6
Depreciation rate	20%	32%	19.20%	11.52%	11.52%	5.76%

Table 18.4. Bonus deprecation timeline[511]

Placed in service date	Before Jan 1, 2018	2018	2019	After 2019
Bonus depreciation	50%	40%	30%	0%

18.3 SRECs

We base SREC price assumptions on 5-year annuity contracts from one of the largest SREC aggregators in the country. After 2020, we assume systems receive no SREC value.[cxl] Table 18.5 below shows the SREC schedules used in this analysis.

Table 18.5. SREC schedules used in this analysis[512]

Year	2016	2017	2018	2019	2020
Value in DC ($/kWh)	$0.250	$0.250	$0.250	$0.250	$0.250

[cxl] This is a common assumption among PV developers, investors, etc. who typically assign no value to SRECs beyond year 5 of a PV project.

19 Appendix: Estimating climate change impact

19.1 Greenhouse gas emissions

We estimate the value of greenhouse gas (GHG) reductions from installing cool roofs, green roofs, solar PV, and reflective pavements and planting urban trees using the social cost of carbon (SCC). The SCC is an estimate of the economic damages/benefits associated with a small increase/decrease in CO_2 emissions.[513] Developed by a dozen U.S. Federal agencies, including the Department of the Treasury and the Environmental Protection Agency, the effort reflects best current science and economic analysis. The SCC estimates are built on three widely used climate impact models and each are modeled with discount rates of 2.5%, 3%, and 5%. First issued in 2010, the SCC was revised in 2013 and 2015. The 2013 update estimated a higher cost value associated with CO_2 emissions than the earlier analysis, reflecting the scientific recognition of greater severity and depth of impact and cost of climate change. The 2015 update estimated a slightly lower cost associated with CO_2 emissions than the 2013 update, reflecting small modeling corrections.[514] In this report we use the SCC to capture the benefits of net CO_2 reductions.

We use the following method to determine GHG emissions reduction impacts. First, we determine the emission factors for electricity and natural gas consumption in Washington, DC. We obtained the PJM "Residual Mix" emissions, which approximates the emission rate for electricity in the PJM (which includes DC) from BGE.[515] The emissions rate is 1,108 lbs CO_2 per MWh for 2014.[516] EPA (2014) provides a CO_2 factor, a methane (CH_4) factor, and a nitrous oxide (N_2O) factor for burning natural gas.[517] We combine these three factors to arrive at CO_2-equivalent (CO_2e) factor for natural gas using 100-year global warming potential (GWP) factors (see Equation 19.1).[cxli] The result is 5.3 kg CO_2e per therm of natural gas.

Equation 19.1. Calculating emissions factors in units of CO2e

$$EF_{e,CO_2e} = \left(EF_{e,CO_2} \times GWP_{CO_2}\right) + \left(EF_{e,CH_4} \times GWP_{CH_4}\right) + \left(EF_{e,N_2O} \times GWP_{N_2O}\right)$$

where:

$EF_{e,x}$ = emission factor for pollutant x for energy source e (kg x per unit e)
GWP_x = Global Warming Potential for pollutant x

To determine future electricity emission factors, we use CO_2 emissions rate indices from Lavappa and Kneifel (2015).[518] Lavappa and Kneifel (2015) emissions indices are based on an EPA analysis of Low,

[cxli] GHG emissions are typically reported in units of CO_2e. To convert to units of CO_2e, we multiply the emission factor for each GHG by its respective GWP. We use GWPs from AR4 to be consistent and comparable with other GHG estimations. EPA notes that:

While EPA recognizes that Fifth Assessment Report (AR5) GWPs have been published, in an effort to ensure consistency and comparability of GHG data between EPA's voluntary and non-voluntary GHG reporting programs (e.g. GHG Reporting Program and National Inventory), EPA recommends the use of AR4 GWPs. The United States and other developed countries to the UNFCCC have agreed to submit annual inventories in 2015 and future years to the UNFCCC using GWP values from AR4, which will replace the current use of SAR GWP values. Utilizing AR4 GWPs improves EPA's ability to analyze corporate, national, and sub-national GHG data consistently, enhances communication of GHG information between programs, and gives outside stakeholders a consistent, predictable set of GWPs to avoid confusion and additional burden.[517]

Default, and High pricing carbon policies. For this analysis we use indices for the Default pricing policy. Lavappa and Kneifel (2015) does not provide emissions indices beyond 2045. We hold emissions indices constant at the 2045 value for analysis years beyond 2045. Table 19.1 shows the emissions indices from Lavappa and Kneifel (2015).

Next, we multiply the calculated emissions factors by the SCC to obtain the SCC per unit of electricity or natural gas (see Equation 19.2). SCC values were obtained from Table A1 of Interagency Working Group on Social Cost of Carbon (IWGSCC) (2015).[519] There are SCC estimates for years 2010 through 2050 calculated using 5%, 3%, and 2.5% discount rates. For this analysis we use a SCC discount rate of 3%. For analysis years for which SCC values are not estimated by IWGSCC (2015), we increase the SCC at the average annual growth rate of the SCC from 2010 through 2050 (see Table 19.2).

Equation 19.2. Calculating SCC per unit energy

$$SCC_{e,y} = EF_e \times SCC_y$$

where:

$SCC_{e,y}$ = Social Cost of Carbon per unit of energy source e in year y
EF_e = emission factor for energy source e
SCC_y = SCC in year y

Finally, we multiply the SCC per unit electricity by the annual electricity savings/penalties and the SCC per unit natural gas by the annual natural gas savings/penalties and sum the result. Then we sum the CO_2 benefit for each analysis year to determine a total CO_2 benefit.

Equation 19.3. Annual CO2 benefit

$$B_{CO_2,y} = \left(SCC_{EL,y} \times \Delta E_{EL}\right) + \left(SCC_{NG,y} \times \Delta E_{NG}\right)$$

where:

$B_{CO_2,y}$ = total CO_2 benefit in year y
ΔE_e = change in annual energy consumption for source e (EL = electricity and NG = natural gas)

Table 19.1. Projected Carbon Dioxide Emissions Rate Indices for Electricity, by Carbon Policy Scenario[520]

Year	No Policy	Default Pricing	Low Pricing	High Pricing	Year	No Policy	Default Pricing	Low Pricing	High Pricing
2015	1	0.91	0.91	0.88	**2039**	0.96	0.39	0.38	0.32
2016	0.99	0.89	0.89	0.85	**2040**	0.96	0.37	0.36	0.29
2017	0.99	0.86	0.86	0.82	**2041**	0.96	0.34	0.33	0.26
2018	0.98	0.83	0.83	0.79	**2042**	0.97	0.32	0.31	0.23
2019	0.98	0.8	0.8	0.76	**2043**	0.97	0.3	0.29	0.19
2020	0.97	0.78	0.77	0.73	**2044**	0.97	0.27	0.26	0.16
2021	0.97	0.76	0.75	0.7	**2045**	0.97	0.25	0.24	0.12
2022	0.96	0.74	0.73	0.68					
2023	0.96	0.72	0.71	0.66					
2024	0.95	0.7	0.69	0.64					
2025	0.95	0.68	0.67	0.61					
2026	0.95	0.65	0.65	0.59					
2027	0.95	0.63	0.62	0.58					
2028	0.96	0.6	0.6	0.56					
2029	0.96	0.58	0.57	0.54					
2030	0.96	0.56	0.55	0.52					
2031	0.96	0.54	0.53	0.5					
2032	0.96	0.52	0.51	0.48					
2033	0.96	0.5	0.49	0.46					
2034	0.96	0.49	0.48	0.44					
2035	0.96	0.47	0.46	0.42					
2036	0.96	0.45	0.44	0.39					
2037	0.96	0.43	0.42	0.37					
2038	0.96	0.41	0.4	0.34					

*Table 19.2. Annual SCC Values 2010-2060 (2007$/metric ton CO2);[521] we calculated the values in **red** using linear extrapolation*

Discount Rate	5.00%	3.00%	2.50%	3.00%	Discount Rate	5.00%	3.00%	2.50%	3.00%
Year	Avg	Avg	Avg	95th	**Year**	Avg	Avg	Avg	95th
2010	10	31	50	86	**2036**	19	56	79	171
2011	11	32	51	90	**2037**	19	57	81	174
2012	11	33	53	93	**2038**	20	58	82	177
2013	11	34	54	97	**2039**	20	59	83	180
2014	11	35	55	101	**2040**	21	60	84	183
2015	11	36	56	105	**2041**	21	61	85	186
2016	11	38	57	108	**2042**	22	61	86	189
2017	11	39	59	112	**2043**	22	62	87	192
2018	12	40	60	116	**2044**	23	63	88	194
2019	12	41	61	120	**2045**	23	64	89	197
2020	12	42	62	123	**2046**	24	65	90	200
2021	12	42	63	126	**2047**	24	66	92	203
2022	13	43	64	129	**2048**	25	67	93	206
2023	13	44	65	132	**2049**	25	68	94	209
2024	13	45	66	135	**2050**	26	69	95	212
2025	14	46	68	138	**2051**	26	70	96	215
2026	14	47	69	141	**2052**	27	71	97	218
2027	15	48	70	143	**2053**	27	72	98	221
2028	15	49	71	146	**2054**	28	73	99	224
2029	15	49	72	149	**2055**	28	74	101	227
2030	16	50	73	152	**2056**	28	75	102	231
2031	16	51	74	155	**2057**	29	75	103	234
2032	17	52	75	158	**2058**	29	76	104	237
2033	17	53	76	161	**2059**	30	77	105	240
2034	18	54	77	164	**2060**	30	78	106	243
2035	18	55	78	168					

19.2 Global cooling

1) Akbari et al. (2009) and Menon et al. (2010) for the basis for our global cooling calculations[522]
   a. Both modeled the effect of roof and pavement albedo increases on Earth's radiative forcing[cxlii]
   b. Roofs
      i. Found increasing roof albedo by 0.25 is equivalent to a onetime GHG offset of
         1. 5.8 kg CO_2e per ft2 of roof (Akbari)
         2. 7.6 kg CO_2e per ft2 of roof (Menon)
   c. Pavement
      i. Found increasing pavement albedo by 0.15 is equivalent to a onetime GHG offset of

[cxlii] Radiative forcing is the difference between the radiant energy received by the Earth (from the Sun) and the energy Earth radiates to space.

        1. 3.6 kg CO_2e per ft2 of pavement (Akbari)
        2. 4.6 kg CO_2e per ft2 of pavement (Menon)

2) We take average
    a. Roofs: 6.7 kg CO_2e per ft2 of roof
    b. Pavement: 4.1 kg CO_2e per ft2 of pavement
3) Cool roofs
    a. Low slope albedo change in this analysis: 0.15 → 0.65 = 0.50[cxliii]
    b. Steep slope albedo change in this analysis: 0.10 → 0.25 = 0.15[cxliv]
    c. To determine onetime GHG offset
        i. Multiply ratio of albedo change (0.50 for low slope in this analysis divided by 0.25 for roofs in Akbari (2009) and Menon (2010)) by average offset described above for roofs
4) Green roofs
    a. Albedo change: 0.15 → 0.25 = 0.10
    b. To determine onetime GHG offset use same steps as above
5) Reflective pavements
    a. Albedo change
        i. Roads: 0.15 → 0.30 = 0.15[cxlv]
        ii. Parking: 0.15 → 0.30 = 0.15[cxlvi]
        iii. Sidewalks: 0.30 → 0.35 = 0.05[cxlvii]
    b. To determine onetime GHG offset
        i. Multiply ratio of albedo change by average offset described above for pavements
6) Urban trees
    a. Albedo change: 0.15 (typical albedo of pavement or roof being shaded) → 0.25 = 0.10
    b. To determine onetime GHG offset
        i. Multiply ratio of albedo change by average offset described above for pavements
7) Value onetime GHG offsets using SCC, discussed above

[cxliii] Albedo changes in this analysis increase as technology approves in future years.
[cxliv] Albedo changes in this analysis increase as technology approves in future years.
[cxlv] Albedo changes in this analysis increase as technology approves in future years.
[cxlvi] Albedo changes in this analysis increase as technology approves in future years.
[cxlvii] Albedo changes in this analysis increase as technology approves in future years.

20 Appendix: Estimating stormwater impact

Under the District's 2013 stormwater regulations, projects with 5,000 square feet or more of land-disturbing activity must retain the rainfall from a 1.2-inch storm. For renovation projects where the structure and associated land-disturbance exceed 5,000 square feet, and construction costs exceed 50 percent of the pre-project assessed value, the project must retain the rainfall from a 0.8-inch storm. Installing a cool roof, green roof, or rooftop PV as a renovation but will not trigger the stormwater regulations because none of the technologies will cost more than 50% of the pre-renovation value of the project.

Development and redevelopment projects must meet 50 percent of their required retention onsite. Any offsite retention can be met by purchasing stormwater retention credits (SRCs) or by paying the in-lieu fee (ILF). The ILF and SRC corresponds to 1 gal of retention for one year. The Department of Energy & Environment (DOEE)[cxlviii] determines the stormwater retention requirement based on Equation 20.1.[523] Equation 20.1 can also be used to determine the maximum retention volume that can be certified for SRCs for a given property.

Equation 20.1. Stormwater retention volume

$$SWRv = \left\{\frac{P}{12} \times [(Rv_I \times \%I) + (Rv_C + \%C) + (Rv_N \times \%N)] \times SA\right\} \times 7.48$$

where:

$SWRv$	= volume required to be retained (gal)
P	= selection of District rainfall event--e.g., 1.2-inch storm (in)
12	= conversion factor, converting inches to feet
Rv_I	= 0.95 (runoff coefficient for impervious cover)
$\%I$	= percent of site in impervious cover
Rv_C	= 0.25 (runoff coefficient for compacted cover)
$\%C$	= percent of site in compacted cover
Rv_N	= 0.00 (runoff coefficient for natural cover)
$\%N$	= percent of site in natural cover
SA	= surface area (ft2)
7.48	= conversion factor, converting cubit feet to gallons

20.1 Stormwater Fee

In the District, all customers of DC Water are charged a "DC Govt Stormwater Fee" and a "Clean Rivers Imperious Area Charge" (subsequently referred to as the Stormwater Fee and CRIAC, respectively). The Stormwater Fee is used to support the implementation of stormwater management practices as part of the District's Municipal Separate Storm Sewer Systems permit.[524] Similarly, the IAC is used to enable compliance with the federally mandated Clean Rivers Project, part of DC Water's Long Term Control Plan, which aims to steeply reduce the number of combined sewer overflows from the District's Combined Sewer System.[525] Through the RiverSmart Rewards program, DOEE offers property owners a discount of up to 55 percent on their Stormwater Fee when they install stormwater best management practices

[cxlviii] The Department of Energy & Environment (DOEE) is analogous to a state department of the environment for Washington, DC. DOEE was previously called the District Department of Environment (DDOE).

(BMPs) on their property. DC Water offers property owners up to a 4 percent discount on their IAC through the Clean Rivers CRIAC Inventive Program when they install BMPs on their property. The Stormwater Fee discount is available indefinitely, but the CRIAC discount is only available for the three years after it is granted. If a property is regulated under DC's stormwater regulations, it can still receive both discounts.

Green roofs and trees qualify as BMPs that can be used to apply for stormwater fee discounts and SRC generation.

20.1.1 Green roofs

Green roof stormwater retention volume is calculated using Equation 20.2.

Equation 20.2. Retention volume for green roofs[526]

$$Sv = \frac{SA \times [(d \times \eta_1) + (DL \times \eta_2)]}{12}$$

where:

Sv = storage volume (ft3)
SA = green roof area (ft2)
d = media depth (in) (minimum 3 in)
η_1 = media volume of voids
DL = drainage layer depth (in)
η_2 = drainage layer volume of voids

As noted in 17.1.1, we assume a growing media depth (d) of 4.5 inches. We assume the drainage layer depth is .875 inches for all green roofs (the midpoint of the low and high values in the DOEE's Stormwater Management Guidebook (SWMG)).[527]

Based on guidance from DOEE, we assume media volume of voids[cxlix] and drainage layer volume of voids are both equal to 30 percent.[528] The calculated retention volume for a 10,000 square foot green roof is shown in Table 20.1.

Table 20.1. Stormwater retention volume for a green roof

Retention volume	
ft3	gal
1,344	10,051

Both the Stormwater Fee and the IAC are charged based on the Equivalent Residential Unit (ERU). One ERU equals 1,000 square feet of impervious surface—this is the statistical median amount of impervious surface on a single-family residential property in Washington, DC.[529] Residential customers are charged based on a six-tiered structure. Commercial customers are charged based on the total area of impervious surface on the property. For simplicity, we base all discount calculations on the total area of impervious surface.

[cxlix] Void volume is empty space in the media or drainage layers that help retain stormwater.

DOEE's Discount Calculations Spreadsheet forms the basis of our discount estimates.[530] The discounts for a 10,000 square foot green roof estimates are shown in Table 20.2. The CRIAC used for this analysis is \$20.30 per ERU.[531] The Stormwater Fee used for this analysis is \$2.67.[532] We conservatively assume the CRIAC and Stormwater Fee are constant throughout the analysis period.

Table 20.2. Calculated and actual received Stormwater Fee and IAC discounts for green roof

Calculated Stormwater Fee discount	Actual Stormwater Fee discount received[cl]	Calculated CRIAC discount	Actual CRIAC discount received[cl]
78%	55%	6%	4%

20.1.2 Bioretention

Bioretention stormwater retention volume is calculated using Equation 20.3.

Equation 20.3. Bioretention stormwater retention volume[533]

$$Sv = \{SA_{bottom} \times [(d_{media} \times \eta_{media}) + (d_{gravel} + \eta_{gravel})]\} + (SA_{average} \times d_{ponding})$$

Where:

Sv = Storage volume (ft3)
SA_{bottom} = Bottom surface area (SF)
d_{media} = Depth of filter media (ft)
η_{media} = Filter media effective porosity (0.25)
d_{gravel} = Depth of gravel layer (ft)
η_{gravel} = Gravel layer effective porosity (0.4)
$SA_{average}$ = Average of top and bottom surface areas
$d_{ponding}$ = Maximum ponding depth (ft)

An important factor in bioretention sizing is the size of the contributing drainage area. DOEE notes that the (top) surface area of bioretention is typically 3% to 5% of the contributing drainage area.[534] For this report we use the average (4.5%). Assuming a 10,000 SF roof as above, this equates to a bioretention surface area of 450 SF.

Before moving on to SA_{bottom} we need to establish $d_{ponding}$. DOEE lists typical ponding depth as between 6 and 12 inches.[535] For this report we use the average (9 in).

With top surface area (SA_{top}), we can determine SA_{bottom}. Urban or space constrained bioretention typically has vertical walls,[536] so SA_{bottom} equals surface area top (450 SF) and $SA_{average}$ equals 450 SF.

There are two types of bioretention design configurations: Standard and Enhanced. Standard design is bioretention with an underdrain and less than 24 inches of filter media. Enhanced design is bioretention that infiltrates in 72 hrs (without an underdrain) or bioretention with an underdrain, greater than 24

[cl] The maximum Stormwater Fee discount is 55% and the maximum IAC discount is 4%

inches of filter media, and an infiltration sump. Most bioretention in the District will require an underdrain,[cli] so we constrain our analysis to practices with an underdrain.

For filter media depth (d_{media}), we assume the minimum values from the Stormwater Management Guidebook: 18 inches for Standard design and 24 inches for Enhanced design.[537] The filter media effective porosity (η_{media}) is the value given in the Stormwater Management Guidebook as well.

Gravel layer depth is slightly more complicated (d_{gravel}). For Standard design, there must be 2 inches of gravel above and below the underdrain, which is 4 to 6 inches in diameter. We assume an average diameter underdrain (5 in). Thus, the gravel layer of a Standard design is 9 inches.

For Enhanced design (with underdrain), the same underdrain requirements apply and there is additional gravel below the underdrain that acts as the infiltration sump. Infiltration sump depth is determined using Equation 20.4. For infiltration rate we use the average of 0.1 in/hr (the minimum allowed)[538] and 0.5 in/hr (the infiltration rate at which underdrains are required. The other values used in the equation are constants from the Stormwater Management Guidebook. Based on the above values, d_{sump} equals 27 inches. Combined with the 9 inches needed for the underdrain, the gravel layer depth of Enhanced design bioretention we use in 36 inches.

Equation 20.4. Infiltration sump depth[539]

$$d_{sump} = \frac{\left(\frac{i}{2} \times t_d\right)}{\eta_r}$$

Where:

d_{sump} = depth of infiltration sump (in)
i = field-verified infiltration rate for native soils (in/hr) (must exceed 0.1 in/hr)
t_d = drawdown time (hr) (72 hr)
η_r = gravel layer effective porosity (0.4)

Table 20.3 summarizes the values described above used in Equation 20.3. Using these values, we calculate the retention volume from bioretention. Standard design bioretention only receive credit for 60% of calculated retention volume. Table 20.4 summarizes credited retention values for the different bioretention designs.

[cli] Underdrains are required when field verified infiltration rates are less than 0.5 in/hr.

Table 20.3. Summary of values used in Equation 20.3

SA_{bottom} (SF)	
Urban/Space constrained	450
d_{media} (ft)	
Standard design	1.5
Enhanced design	2
η_{media}	0.25
d_{gravel} (ft)	
Standard design	0.75
Enhanced design	3
η_{gravel}	0.4
$SA_{average}$ (SF)	
Urban/Space constrained	450
$d_{ponding}$ (ft)	0.75

Table 20.4. Retention volumes for urban/space constrained Standard and Enhanced design bioretention

Urban/space constrained	Cubic feet	Gallons
Standard design	419	3,131
Enhanced design	1,103	8,247

The discounts for a 10,000 square foot cool roof with a 450 square foot bioretention system are shown in Table 20.5.

Table 20.5. Calculated and actual received Stormwater Fee and IAC discounts for bioretention

Bioretention type	Calculated Stormwater Fee discount	Actual Stormwater Fee discount received	Calculated CRIAC discount	Actual CRIAC discount received
Standard	23%	23%	2%	2%
Enhanced	61%	55%	4%	4%

Fraction standard design and standard design with underdrain

Fractions from DOEE in Table 20.6.

Table 20.6. Bioretention types in the District

Type of Bioretention	Total BMP area
Enhanced	14%
Enhanced with underdrain	5%
Standard	81%

As noted, only include enhanced with underdrain and standard in this analysis.

- New % enhanced w/ underdrain = original % enhanced w/ underdrain / (original % enhanced w/ underdrain + original % standard) = 5% / (81% + 5%) = 6%
- New % standard = original % standard / (original % enhanced w/ underdrain + original % standard) = 81% / (81% + 5%) = 94%

20.1.3 Rainwater harvesting

Contributing drainage area = 10K square feet

Design storm = 1.7-in

10,100 gallon tank

Assume 55% factor for available storage volume --> 5,555 gal available storage volume

Available storage volume takes into account incoming and outgoing water and is used by DOEE to denote the retention volume of the rainwater harvesting volume of the cistern.

The discounts for a 10,000 square foot cool roof with a 10,100 gal rainwater harvesting system are shown in Table 20.7.

Table 20.7. Calculated and actual received Stormwater Fee and IAC discounts for rainwater harvesting

Calculated Stormwater Fee discount	Actual Stormwater Fee discount received	Calculated CRIAC discount	Actual CRIAC discount received
43%	43%	3%	3%

20.1.4 Permeable pavements

Sidewalks

There are two types of permeable pavement design configurations: Standard and Enhanced. Standard design is standard underdrain design and no infiltration sump or water quality filter layer.[540] Enhanced design is standard underdrain design with water quality filter layer and infiltration sump (beneath the underdrain) size to drain in 48 hours or no underdrain and can infiltrate in 48 hours.[541] Most permeable pavement in the District will require an underdrain,[clii] so we constrain our analysis to practices with an underdrain.

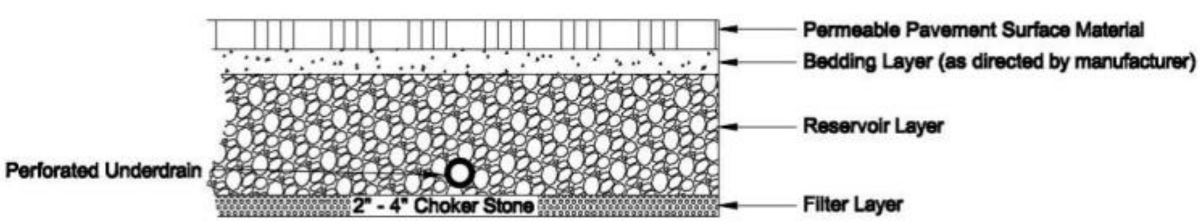


Figure 20.1. Cross section of a Standard permeable pavement design[542]

[clii] Underdrains are required when field verified infiltration rates are less than 0.5 in/hr.

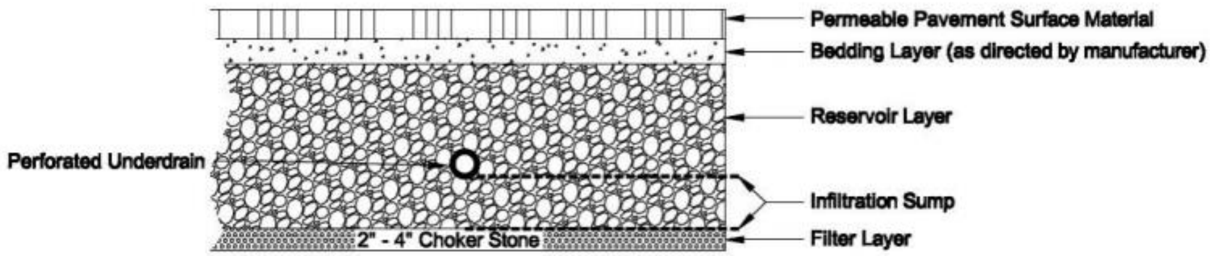


Figure 20.2. Cross section of an Enhanced permeable pavement design with underdrain[543]

Permeable pavement stormwater retention volume is calculated using Equation 20.5.

Equation 20.5. Permeable pavement retention volume[544]

$$Sv = A_p \times \left[\left(d_p \times \eta_r \right) + \left(\frac{i \times t_f}{2} \right) \right]$$

Where:

Sv = storage volume (ft^3)
A_p = permeable pavement surface area (ft^2)
d_p = depth of reservoir layer (or depth of infiltration sump) (ft)
η_r = effective porosity of reservoir layer (0.35)
i = field-verified infiltration rate for subgrade soils (ft/day)
t_f = time to fill reservoir layer (0.083 day)

As with bioretention, we assume an infiltration rate of 0.3 inches per hour (an average or 0.1 inches per hour and 0.5 inches per hour). For the purposes of example calculations, we assume a permeable pavement surface area of 5,000 SF.

Depth of reservoir layer

The depth of the reservoir layer or infiltration sump is calculated using Equation 20.6.

Equation 20.6. Reservoir layer or infiltration sump depth[545]

$$d_p = \frac{\left(\frac{P \times Rv_I \times DA}{A_p} \right) - \left(\frac{i}{2} \times t_f \right)}{\eta_r}$$

Where:

d_p = depth of reservoir layer (or depth of infiltration sump) (ft)
P = rainfall depth for design storm (ft)
Rv_I = runoff coefficient for impervious cover (0.95)
DA = total drainage area (contributing drainage area and permeable pavement area) (ft^2)
A_p = permeable pavement surface area (ft^2)
i = field-verified infiltration rate for subgrade soils (ft/day)
t_f = time to fill reservoir layer (0.083 day)

η_r = effective porosity of reservoir layer (0.35)

To determine d_p, we first need to determine the size of the contributing drainage area (CDA). DOEE notes that the CDA cannot be more than 5 times the size of the permeable pavement area; however, DOEE recommends the CDA be no more than 2 times the permeable pavement area.[546] For this analysis, we follow DOEE's recommendation that the CDA be no more than 2 times the area of the permeable pavement and assume the CDA is 10,000 SF (the maximum area following DOEE's recommendation and assuming 5,000 SF of permeable pavement).

We perform calculations for a 1.2-in design storm (the maximum for which stormwater reductions count towards fee reductions) and a 1.7-in design storm (the maximum for which stormwater reductions count towards SRCs). Table 20.8 presents the results.

Table 20.8. Reservoir or infiltration sump depth.

$\boldsymbol{P}$	1.2 in (0.10 ft)	1.7 in (0.14 ft)
$\boldsymbol{d_p}$	8.9 in (0.75 ft)	13 in (1.1 ft)

Captured stormwater volume must drain from the reservoir layer or infiltration sump in 36 to 48 hours. Drawdown time is calculated using Equation 20.7. Both depths satisfy this condition.

Equation 20.7. Drawdown time[547]

$$t_d = \frac{d_p \times n_r \times 2}{i}$$

Where:

t_d = drawdown time (day)
d_p = depth of reservoir layer (or depth of infiltration sump) (ft)
η_r = effective porosity of reservoir layer (0.35)
i = field-verified infiltration rate for subgrade soils (ft/day)

Stormwater retention volume

Standard design permeable pavement receives a retention value of 4.5 ft^3 per 100 SF of permeable pavement. So for our example, the 5,000 SF Standard design permeable pavement receives a retention value of 675 ft^3 (5,049 gal).

Retention value for Enhanced design permeable pavement is calculated with Equation 20.3. Table 20.9 shows the retention values for 5,000 SF of Enhanced design permeable based on the assumptions described above.

Table shows the retention values per SF of permeable pavement.

Table 20.9. Enhanced design permeable sidewalk retention volume

$\boldsymbol{P}$	1.2 in (0.10 ft)	1.7 in (0.14 ft)
Retention value	4,311 ft^3 (32,246 gal)	6,061 ft^3 (45,336 gal)

Table 20.10. Permeable sidewalk retention volume per SF of permeable sidewalk

P	1.2 in (0.10 ft)	1.7 in (0.14 ft)
Standard design retention value	0.045 ft^3 (0.34 gal)	
Enhanced design retention value	0.29 ft^3 (2.2 gal)	0.40 ft^3 (3.0 gal)

The discount values for permeable sidewalks are shown in Table 20.11.

Table 20.11. Calculated and actual received Stormwater Fee and IAC discounts for permeable sidewalks with P equal to 1.7 in

Permeable sidewalk type	Calculated Stormwater Fee discount	Actual Stormwater Fee discount received	Calculated CRIAC discount	Actual CRIAC discount received
Standard	9%	9%	1%	1%
Enhanced	78%	55%	6%	4%

Fraction standard design and standard design with underdrain

Fractions from DOEE in Table 20.6.

Table 20.12. Permeable pavement types in the District

Type of Permeable Pavement	Total BMP area
Enhanced	30%
Enhanced with underdrain	14%
Standard	56%

As noted, only include enhanced with underdrain and standard in this analysis.

- New % enhanced w/ underdrain = original % enhanced w/ underdrain / (original % enhanced w/ underdrain + original % standard) = 14% / (56% + 14%) = 20%
- New % standard = original % standard / (original % enhanced w/ underdrain + original % standard) = 56% / (56% + 14%) = 20%

Parking lots

Assume "native soil" under parking lots, i.e., no additional aggregate, because not heavy load parking lots (see Figure 20.3) → different stormwater calculations than traditional permeable pavement

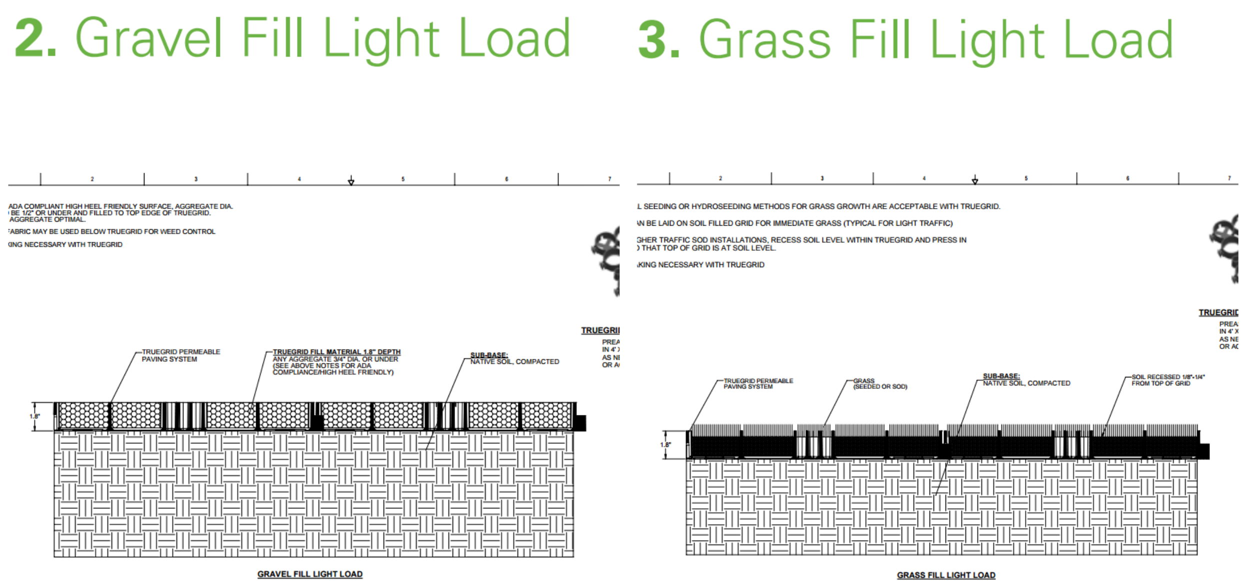


Figure 20.3. Light load parking lot examples for plastic grid pavers[548]

Treat grass paver as compacted cover, which has runoff coefficient of 0.25 (impervious surface has runoff coefficient of 0.95);[549] assume runoff coefficient of gravel paver is 0.5 based on review of various sources[550]

See Table 20.13 for stormwater retention calculations based on Equation 20.8.

Equation 20.8. Stormwater retention for parking lots (adapted from ref 523)

$$SW\ Retention = \left((1 - Runoff\ Coeff) \times Area\ (in\ ft^2)\right) \times \frac{1.7\ in}{12\ in\ per\ ft} \times \frac{7.48\ gal}{ft^3}$$

Table 20.13. Stormwater retention from 10K SF of surface from 1.7-in storm

Surface type	Compacted cover (e.g., grass)	Uncompacted gravel
Runoff coefficient	0.25	0.5
Stormwater retention from 1.7-in storm	7947.5	5298.3

The discount values for permeable parking lots are shown in Table 20.11.

Table 20.14. Calculated and actual received Stormwater Fee and IAC discounts for permeable parking lots

Permeable parking lot type	**Calculated Stormwater Fee discount**	**Actual Stormwater Fee discount received**	**Calculated CRIAC discount**	**Actual CRIAC discount received**
Gravel	41%	41%	3%	3%
Grass	61%	55%	5%	4%

20.1.5 Urban trees

Newly planted trees receive a retention value of 10 cubic feet (75 gallons).[551] To determine a stormwater fee discount value for urban trees, we convert urban tree retention volume into ERUs (one ERU is equivalent to 710.75 gallons of retention).[552] We multiply the result by the maximum possible discount allowable (55% for the Stormwater Fee and 4% for the CRIAC) to determine the number of ERU-based discount. We then multiply these values by the respective ERU-based charges as described in the previous section to determine the discount value (in dollars) per tree. Finally, we divide the per tree discount value by an assumed urban tree canopy area of 314 ft2 (i.e., the circular area of a tree with radius of 10 ft).[cliii]

20.2 Stormwater Retention Credits

Each of the technologies analyzed in this report does not trigger stormwater regulations when installed, so any retention volume generated by a technology (only green roofs in this case) up to that generated in a 1.7-in storm is eligible for SRC generation (i.e., all retention volume analyzed for this report is voluntary), see Figure 20.4.[553,cliv] Based on Equation 20.1, the retention volume needed to retain stormwater from 1.7-in storm from a 10,000 square foot roof is 10,067 gal, so any retention up to 10,067 gal provided by a green roof can be used to generate SRCs. All retention from the green roof modeled in this report is eligible to generate SRCs. Given the small retention value attributed to trees in the SWMG, it is unlikely planting trees will push any property over the SRC ceiling. Therefore, we assume all retention from newly planted trees is eligible to generate SRCs.

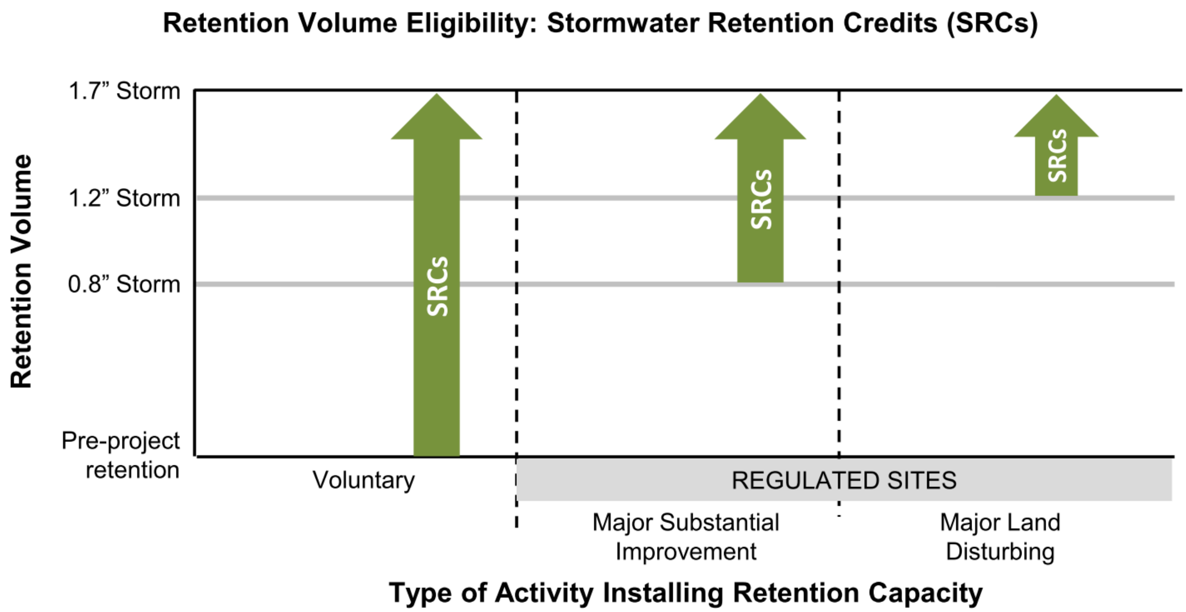


Figure 20.4. Retention volume eligible to earn stormwater retention credits[554]

[cliii] This is on the low end of values in Casey Trees' *Urban Tree Selection Guide*. (Casey Trees, "Urban Tree Selection Guide: A Designer's List of Appropriate Trees for the Urban Mid-Atlantic," 2015, http://caseytrees.org/wp-content/uploads/2015/07/150715-Urban-Tree-Selection-Guide-reduced-size.pdf.)

[cliv] Note: This does not mean a green roof will retain the retention volume from a 1.7-in storm.

Based on conversations with DOEE, we assume an SRC price of $1.75 per SRC (a conservative estimate).[555] DOEE does not expect SRC price to remain constant. For their analysis of SRC revenue, DOEE assumes an inflation rate of 3.38 percent per year, the 80-year average, through 2010, of the urban Consumer Price Index.[556] However, because we use a real discount rate in this analysis, we do not assume SRC prices rise with the rate of inflation. In other words, we hold SRC price constant at $1.75 throughout the analysis period.

20.3 Trees planted on property that do not pay stormwater fees or are not eligible to generate SRCs

For all trees planted on properties that do not pay stormwater fees and are not eligible to generate SRCs, we still value the stormwater benefits of trees with the methods above. Discounts on the Stormwater Fee and CRIAC are proxies for the stormwater benefits provided by BMPs because revenue from the Stormwater Fee and CRIAC are used to pay for stormwater management, the SRC program was designed to help the District meet its federal stormwater requirements, and SRCs can also be thought of as proxies for the stormwater benefits provided by BMPs. Therefore, we use the stormwater benefits calculations described above to value the stormwater benefit of trees planted on properties that do not pay stormwater fees or are not eligible to generate SRCs (e.g., parks). In other words, we use the methods described in Sections 20.1 and 20.2 to estimate the stormwater benefits of all trees in this analysis.

21 Appendix: Estimating health impact

21.1 BenMAP

For large parts of our health benefits analysis we use EPA's Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) v1.1.1. EPA developed the BenMAP program to facilitate the process of applying health impact functions and economic valuation functions to estimate and value the mortality and morbidity associated with changes in air quality. Health impact functions relate a change in concentration of a pollutant (e.g., ozone) to a change in the incidence of a health endpoint (e.g., Pneumonia Hospital Admissions). Equation 21.1 shows a typical log-linear health impact function.[557,clv] Economic valuation functions place a dollar value on estimated health incidence. Equation 21.2 shows a typical economic valuation function.

Equation 21.1. Typical log-linear health impact function

$$\Delta y = y_0\left(e^{\beta \Delta x} - 1\right)Pop$$

where:

Δy	= change in incidence of the health endpoint
y_0	= baseline incidence rate of health endpoint
β	= risk coefficient / effect estimate taken from an epidemiological study
Δx	= change in air quality
Pop	= population of interest

Equation 21.2. Typical economic valuation function

$$V_{\Delta y} = \Delta y \times V_y$$

where:

$V_{\Delta y}$	= value of change in incidence of the health endpoint
Δy	= change in incidence of the health endpoint
V_y	= value of incidence of health endpoint

The value of the incidence of a health endpoint (V_y) is typically expressed as an equation and determined from the economic literature.

21.1.1 Health impact and valuation function selection

We use the default EPA ozone BenMAP-CE compatible configuration and pooling setups as the basis for our health benefits analysis.[clvi] These configuration and pooling setups are a good alternative to creating a custom analysis because they are vetted by EPA experts and are used as the basis for EPA's own Regulatory Impact Assessments. As a result, they are generally comprehensive and represent the state of

[clv] Log-linear health impact functions make up the majority of health impact functions in the standard EPA configuration. However, several logistic and one linear health impact function are part of the EPA configuration.

[clvi] We downloaded the ozone and PM2.5 setup on May 15, 2014.

science.[clvii] Nevertheless, choosing to use EPA's default configuration will introduce some uncertainties because the concentration-response functions[clviii] used in EPA's default setups were developed with national, regional, or city-specific data and characteristics that do not necessarily represent DC. Greater accuracy could be achieved by developing city-specific concentration-response functions for ozone and $PM_{2.5}$. Note, we do not use BenMAP-CE to estimate the impact of $PM_{2.5}$-related health benefits; we discuss our methods to estimate PM2.5-benefits in Section 21.3. We include references to $PM_{2.5}$ in this section (21.1) in case a reader wants to perform a $PM_{2.5}$ health benefits analysis using BenMAP-CE.

The default setup for ozone allows the user to estimate the following ozone-related health impacts: premature mortality; respiratory hospital admissions and emergency department visits; minor restricted activity days; and school loss days. The default setup for $PM_{2.5}$ allows the user to estimate $PM_{2.5}$-related: premature mortality; non-fatal acute myocardial infarctions; respiratory hospital admissions and emergency department visits; cardiovascular hospital admissions; acute respiratory symptoms; asthma exacerbation; and minor restricted activity days. Figure 21.1 shows what we do and do not quantify in this analysis and Table 21.1 shows a complete list of the health endpoints and studies we use in this analysis.

We modified EPA's default setup to suit the constraints of a comprehensive cost-benefit analysis. Based on advice from EPA's expert reviewers and from the National Academy of Sciences, EPA estimates the impact of air pollution changes on mortality using multiple epidemiological studies and does not aggregate the resulting benefits.[558] Nonetheless, due to the constraints of a cost-benefit analysis (i.e., we need one estimate of mortality for ozone and one for $PM_{2.5}$), we aggregate mortality benefits. To simplify the health benefit analysis to fit our cost-benefit analysis, we select one study to analyze the impact of ozone and one study to analyze the impact of $PM_{2.5}$ concentration changes on mortality, respectively. Based on recommendations from EPA's Office of Air Quality Planning and Standards, we chose to use the most cited articles that examine all-cause mortality, are included in the EPA standard setup, and were published post 2000.[clix,clx] We focused on all-cause mortality rather than non-accidental mortality, lung cancer mortality, or cardiopulmonary mortality because all-cause mortality is the most comprehensive estimate of ozone- or $PM_{2.5}$-related premature mortality.

The value of reductions in the risk of premature mortality typically makes up the vast majority of financial benefits associated with air quality improvements (for examples, see EPA (2008) and EPA (2012b))[559]. We follow standard practice for health benefit analysis and do not place a dollar value on individual lives. We

[clvii] One alternative is to substitute DC-specific C-R functions where available.

[clviii] A concentration-response function is the relationship between a concentration of a pollutant and the population response. Concentration-response functions are estimated in epidemiological literature. Researchers choose a function form and estimate function parameters using pollutant and health response data (EPA, 2012a). The beta coefficient (β) of a health impact function is derived from a published concentration-response function.

[clix] Google Scholar is a commonly used tool to determine how many times an article has been cited. For each article, Google Scholar computes a "Cited by" entry. We searched the full title of each article to establish the most cited article in the ozone and PM2.5 setups, respectively.

[clx] Bell et al. (2005) for ozone-related all-cause mortality and Krewski et al. (2009) for $PM_{2.5}$-related all-cause mortality. (Michelle L. Bell, Francesca Dominici, and Jonathan M. Samet, "A Meta-Analysis of Time-Series Studies of Ozone and Mortality with Comparison to the National Morbidity, Mortality, and Air Pollution Study," *Epidemiology (Cambridge, Mass.)* 16, no. 4 (July 2005): 436–45; Daniel Krewski et al., "Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality," *Research Report (Health Effects Institute)*, no. 140 (May 2009): 5-114-136.)

base our monetized premature mortality benefits on how much people are willing to pay for small reductions in their risk of premature mortality; this is called the Value of Statistical Life (VSL).[560] We follow EPA recommendations and apply a VSL based on 26 value-of-life studies recommended by the EPA Science Advisory Board.[561] The VSL will increase as personal income increases because the willingness to pay to reduce premature mortality risk increases as personal income increases.[562] See Table 21.2 and Table 21.3 for details on economic valuation of health endpoints in addition to premature mortality.

Figure 21.1. What health benefits we do and don't quantify in our analysis[clxi,563]

Table 6.1: Human Health and Welfare Effects of Ozone and $PM_{2.5}$

Pollutant/Effect	Quantified and Monetized in Base Estimates[a]	Unquantified Effects[h]—Changes in:
PM/Health[b]	Premature mortality based on both cohort study estimates and on expert elicitation[c,d] Bronchitis: chronic and acute Hospital admissions: respiratory and cardiovascular Emergency room visits for asthma Nonfatal heart attacks (myocardial infarction) Lower and upper respiratory illness Minor restricted-activity days Work loss days Asthma exacerbations (asthmatic population) Respiratory symptoms (asthmatic population) Infant mortality	Subchronic bronchitis cases Low birth weight Pulmonary function Chronic respiratory diseases other than chronic bronchitis Non-asthma respiratory emergency room visits UVb exposure (+/-)[e]
PM/Welfare	Visibility in Southeastern, southwestern and California Class I areas	Visibility in northeastern and Midwestern Class I areas Household soiling Visibility in residential and non-Class I areas UVb exposure (+/-)[e]
Ozone/Health[f]	Premature mortality: short-term exposures Hospital admissions: respiratory Emergency room visits for asthma Minor restricted-activity days School loss days Asthma attacks Acute respiratory symptoms	Cardiovascular emergency room visits Chronic respiratory damage Premature aging of the lungs Non-asthma respiratory emergency room visits UVb exposure (+/-)[e]
Ozone/Welfare		Decreased outdoor worker productivity Yields for commercial crops Yields for commercial forests and noncommercial crops Damage to urban ornamental plants Recreational demand from damaged forest aesthetics Ecosystem functions UVb exposure (+/-)[e]

[a] Primary quantified and monetized effects are those included when determining the primary estimate of total monetized benefits of the alternative standards.

[b] In addition to primary economic endpoints, there are a number of biological responses that have been associated with PM health effects including morphological changes and altered host defense mechanisms. The public health impact of these biological responses may be partly represented by our quantified endpoints.

[c] Cohort estimates are designed to examine the effects of long-term exposures to ambient pollution, but relative risk estimates may also incorporate some effects due to shorter term exposures (see Kunzli, 2001 for a discussion of this issue).

[d] While some of the effects of short-term exposure are likely to be captured by the cohort estimates, there may be additional premature mortality from short-term PM exposure not captured in the cohort estimates included in the primary analysis.

[e] May result in benefits or disbenefits. Appendix 6d includes a sensitivity analysis that partially quantifies this endpoint. This analysis was performed for the purposes of this RIA only.

[f] In addition to primary economic endpoints, there are a number of biological responses that have been associated with ozone health including increased airway responsiveness to stimuli, inflammation in the lung, acute inflammation and respiratory cell damage, and increased susceptibility to respiratory infection. The public health impact of these biological responses may be partly represented by our quantified endpoints.

[g] The categorization of unquantified toxic health and welfare effects is not exhaustive.

[h] Health endpoints in the unquantified benefits column include both a) those for which there is not consensus on causality and b) those for which causality has been determined but empirical data are not available to allow calculation of benefits.

Table 21.1. Ozone- and PM2.5-related health endpoints and studies included

Endpoint	Pollutant	Study	Study Population
Premature Mortality			
All cause	Ozone	Bell et al., 2005[564]	All ages
All cause	PM2.5	Krewski et al., 2009[565]	>= 30 years
Chronic Illness			
Nonfatal acute myocardial infarction	PM2.5	Peters et al., 2001[566]	>= 18 years
Hospital Admissions			
All respiratory	Ozone	Burnett et al., 2001[567]	0 - 1 year
		Schwartz, 1995[568]	>= 65 years
		Schwartz, 1995[569]	>= 65 years
	PM2.5	Kloog et al., 2012[570]	>= 65 years
		Zanobetti et al., 2009[571]	>= 65 years
Chronic lung disease	Ozone	Moolgavkar et al., 1997[572]	>= 65 years
	PM2.5	Moolgavkar, 2000[573]	18 - 64 years
Chronic lung disease (less asthma)	Ozone	Schwartz, 1994[574]	>= 65 years
Pneuemonia	Ozone	Moolgavkar et al., 1997[575]	>= 65 years
		Schwartz, 1994[576]	>= 65 years
		Schwartz, 1994[577]	>= 65 years
Asthma	PM2.5	Babin et al., 2007[578]	0 - 17 years
		Sheppard, 2003[579]	0 - 17 years
All cardiovascular (less Myocardial Infarctions)	PM2.5	Bell et al., 2008[580]	>= 65 years
		Moolgavkar, 2000[581]	18 - 64 years
		Peng et al., 2009[582]	>= 65 years
		Peng et al., 2008[583]	>= 65 years
		Zanobetti et al., 2009[584]	>= 65 years
Asthma-related ER Visits	Ozone	Peel et al., 2005[585]	All ages
		Wilson et al., 2005[586]	All ages
		Wilson et al., 2005[587]	All ages
	PM2.5	Glad et al., 2012[588]	All ages
		Mar et al., 2010[589]	All ages
		Slaughter et al., 2005[590]	All ages
Other			
Acute bronchitis	PM2.5	Dockery et al., 1996[591]	8 - 12 years
Upper respiratory symptoms	PM2.5	Pope et al., 1991[592]	9 - 11 years
Lower respiratory symptoms	PM2.5	Schwartz and Neas, 2000[593]	7 - 14 years
Asthma exacerbations, Cough	PM2.5	Mar et al., 2004[594]	6 - 18 years
		Ostro et al., 2001[595]	6 - 18 years
Asthma exacerbations, Shortness of Breath	PM2.5	Mar et al., 2004[596]	6 - 18 years
		Ostro et al., 2001[597]	6 - 18 years
Asthma exacerbations, Wheeze	PM2.5	Ostro et al., 2001[598]	6 - 18 years
Work loss days	PM2.5	Ostro, 1987[599]	18 - 64 years
School loss days	Ozone	Chen et al., 2000[600]	5 - 17 years
		Gilliland et al., 2001[601]	5 - 17 years

[clxi] Note, we do not quantify visibility benefits for $PM_{2.5}$.

Minor Restricted Activity Days (MRADs)	Ozone	Ostro and Rothschild, 1989[602]	18 - 64 years
	PM2.5	Ostro and Rothschild, 1989[603]	18 - 64 years

Table 21.2. Ozone pooling and valuation

Health Endpoint	Study	Incidence Pooling Method			Valuation Method	Valuation Pooling Method
		Level 1	Level 2	Level 3		
Mortality, All Cause	Bell et al., 2005[604]	N/A	N/A	N/A	VSL, based on 26 value-of-life studies	None
Hospital Admissions, Respiratory	Burnett et al. 2001[605]	N/A	N/A	N/A	COI: med costs + wage loss	None
Emergency Room Visits, Respiratory	Wilson et al., 2005[606]	None	None	Random or Fixed Effects	COI:Smith et al. (1997);[607] COI: Stanford et al. (1999)[608]	User Defined Weights (0.5 and 0.5)
	Wilson et al., 2005[609]					
	Peel et al., 2005[610]					
School Loss Days	Chen et al., 2000[611]	None	None	Random or Fixed Effects	Use the only School Loss Days valuation function available in BenMAP-CE	None
	Gilliland et al., 2001[612]					
Acute Respiratory Symptoms	Ostro and Rothschild, 1989[613]	N/A	N/A	N/A	WTP: 1 day, CV studies	None
Hospital Admissions, Respiratory	Schwartz, 1994[614]	None	Sum Dependent	Random or Fixed Effects	COI: med costs + wage loss	None
	Schwartz, 1994[615]					
	Moolgavkar et al. 1997[616]	Sum Dependent	Fixed Effects			
	Moolgavkar et al. 1997[617]					
	Schwartz 1994[618]	None				
	Schwartz, 1995[619]	None	None			
	Schwartz, 1995[620]					

Table 21.3. PM2.5 pooling and valuation

Health Endpoint	Study	Incidence Pooling Method Level 1	Level 2	Valuation Method	Valuation Pooling Method Level 1	Level 2
Mortality, All Cause	Krewski et al. 2009[621]	N/A	N/A	VSL, based 26 value-of-life studies	N/A	N/A
Hospital Admissions, Respiratory	Zanobetti et al. 2009[622]	User Defined Weights	None	COI: med costs + wage loss	None	None
	Kloog et al. 2012[623]					
	Babin et al. 2007[624]	Random or Fixed Effects	None	COI: med costs + wage loss	None	None
	Sheppard 2003[625]					
	Moolgavkar 2000[626]	None	None	COI: med costs + wage loss	None	None
Hospital Admissions, Cardiovascular	Peng et al. 2009[627]	User Defined Weights	User Defined Weights	COI: med costs + wage loss	None	None
	Peng et al. 2008[628]					
	Zanobetti et al. 2009[629]	None				
	Bell et al. 2008[630]	None				
	Moolgavkar 2000[631]	None	None	COI: med costs + wage loss	None	None
Acute Respiratory Symptoms	Ostro and Rothschild 1989[632]	N/A	N/A	WTP: 1 day, CV studies	N/A	N/A
Lower Respiratory Symptoms	Schwartz and Neas 2000[633]	N/A	N/A	WTP: 1 day, CV studies	N/A	N/A
Upper Respiratory Symptoms	Pope et al. 1991[634]	N/A	N/A	WTP: 1 day, CV studies	N/A	N/A
Work Loss Days	Ostro 1987[635]	N/A	N/A	Median daily wage, county specific	N/A	N/A
Asthma Exacerbation	Mar et al. 2004[636]	Random or Fixed Effects	User Defined Weights	WTP: bad asthma day, Rowe and Chestnut (1986)[637]	None	None
	Ostro et al. 2001[638]					
	Mar et al. 2004[639]	Random or Fixed Effects				
	Ostro et al. 2001[640]					
	Ostro et al. 2001[641]	None				
Emergency Room Visits, Respiratory	Glad et al. 2012[642]	Random or Fixed Effects	None	COI: Smith et al. (1997);[643] COI: Stanford et al. (1999)[644]	User Defined Weights (0.5 and 0.5)	None
	Mar et al. 2010[645]					
	Slaughter et al. 2005[646]					
Acute Bronchitis	Dockery et al. 1996[647]	N/A	N/A	WTP: 6 day illness, CV studies	N/A	N/A
	Peters[648] 18-24	Sum Dependent	None	Not valued	Not valued	Not valued
	Peters[649] 25-44					

Acute Myocardial Infarction (Sum)[clxii]	Peters[650] 45-54					
	Peters[651] 55-64					
	Peters 65-99					
Acute Myocardial Infarction (3%)[clxii]	Peters[652] 18-24	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[653] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[654]	User Defined Weights (0.5 and 0.5)	Sum Dependent
	Peters[655] 25-44	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[656] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[657]	User Defined Weights (0.5 and 0.5)	
	Peters[658] 45-54	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[659] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[660]	User Defined Weights (0.5 and 0.5)	
	Peters[661] 55-64	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[662] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[663]	User Defined Weights (0.5 and 0.5)	
	Peters[664] 65-99	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[665] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[666]	User Defined Weights (0.5 and 0.5)	
Acute Myocardial Infarction (7%)[clxii]	Peters[667] 18-24	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[668] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[669]	User Defined Weights (0.5 and 0.5)	Sum Dependent
	Peters[670] 25-44	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[671] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[672]	User Defined Weights (0.5 and 0.5)	
	Peters[673] 45-54	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[674] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[675]	User Defined Weights (0.5 and 0.5)	
	Peters[676] 55-64	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[677] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[678]	User Defined Weights (0.5 and 0.5)	
	Peters[679] 65-99	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[680] COI: 5 yrs med,	User Defined Weights (0.5 and 0.5)	

[clxii] Peters XX-XX are found by changing the health impact function dataset under "Filter Dataset" in the top left of the HIF selection screen. Select the dataset called "AMI - Age-Dependent Survival Rates".

				5yrs wages, 7% DR, Wittels (1990)[681]		

21.1.2 Incidence/prevalence data

BenMAP-CE requires baseline incidence or prevalence rates to calculate the change in incidence of a health endpoint. National average incidence and prevalence data are included in BenMAP-CE. For this analysis, we utilize District-specific incidence and prevalence data wherever available.

The majority of the health data required to run a DC-specific health benefit analysis is not freely accessible online and must be requested from the DC Department of Health (DOH). Where possible, we collected health data for 2009, 2010, 2011, 2012, and 2013. We calculated the incidence/prevalence rate of each health endpoint for each year using the 2010 population. We used the 2010 population to calculate incidence/prevalence rates for all years because other population estimates lack the age resolution required to perform incidence/prevalence rate calculations.[clxiii] We then averaged the health endpoint-specific incidence/prevalence rates of each year together to determine the baseline incidence/prevalence rates for each health endpoint.

21.1.3 Air quality data

BenMAP-CE requires air quality monitoring or modeling data to perform health benefits calculations. Note, however, that BenMAP-CE does not perform air quality modeling; it simply calculates a change in air quality based on baseline and control data that are supplied by the user. The calculated change in air quality (Δx in Equation 21.1) is used in health impact functions to calculate changes in various health endpoint incidences.

We downloaded ozone and $PM_{2.5}$ air quality from EPA's AirData website, which allows users to access air quality monitoring data from EPA's Air Quality System Data Mart.[682][clxiv] If there were multiple monitors for ozone in a given year, we took the ozone season mean concentration for each monitor and then took the average of the monitor means to establish the given year's mean concentration. If there were multiple monitors for $PM_{2.5}$ in a given year, we took the mean (and quarterly mean) concentration for each monitor and then took the average of the monitor means to establish the given year's mean (and quarterly mean) concentration.

To establish a baseline scenario, we calculated the mean ozone season daily eight-hour maximum (D8HourMax) ozone concentration for 2010, 2011, and 2012.[clxv] Next, we calculated the three-year mean

[clxiii] If one has more resolved population data, then it is best to calculate incidence/prevalence rates based on incidence/prevalence data and population data from the same year.

[clxiv] EPA's Air Quality System stores air quality data from more than 10,000 monitors, 5000 of which are active. The data is collected and submitted by State, Local, and Tribal agencies. DC had three active ozone monitors in 2010 and two in 2011 and 2012, and three active PM2.5 monitors in 2010, 2011, and 2012.

[clxv] Air quality metrics are one of ways to measure air pollution. They are daily values calculated from daily observations or from hourly observations. A common metric used to measure daily ozone concentrations is the D8HourMax, or the highest eight-hour average concentration calculated between 12:00 AM and 11:59 PM of a given day. A common metric used to measure daily PM2.5 concentrations is the D24HourMean, or the average concentration of hours from 12:00 AM through 11:59 PM of a given day. Seasonal metrics allow aggregation of daily

ozone season D8HourMax based on the 2010, 2011, and 2012 means. The resultant three-year mean ozone value is our baseline ozone concentration. We perform a similar calculation for $PM_{2.5}$ but use a different air quality metric, the daily twenty four-hour mean (D24HourMean).[clxv] We calculated an annual mean D24HourMean and quarterly means for 2010, 2011, and 2012. Next, we calculated a three-year mean D24HourMean and three-year quarterly means (e.g., for Quarter 1, we took the mean of Q1 2010, Q1 2011, and Q1 2012). The resultant three-year means make up our baseline $PM_{2.5}$ concentration. Table 21.4 shows the baseline air quality concentrations used for this analysis for DC.

Table 21.4. Baseline ozone

Ozone D8HRMax (ppb)
Mean Summer Season
51.5

21.2 Ozone reduction

21.2.1 Cool Roofs

To fully capture the ozone reduction benefits of cool roof implementation requires complex air quality modeling that is outside the scope of this analysis. We use a simplified method ozone impact estimation method that utilizes the ozone-climate penalty (OCP). Our method provides a reasonably accurate estimate of ozone reduction from smart surface implementation.

The ozone-climate penalty (OCP) has varying definitions in the literature. In this analysis, the OCP refers to the direct increase in ambient ozone concentrations due to increasing temperature.[683] Several studies have modeled the impact of temperature on ozone formation either by examining the reductions in precursor emissions required to offset climate-induced ozone formation, or by modeling the effects of temperature perturbations on direct ozone formation.[684] Even though there are many studies that *model* the effect of temperature changes on ozone concentration, we use OCPs from Bloomer et al. (2009),[685] who determine OCP based on over two decades of *observational data*.[clxvi]

Bloomer et al. (2009) determined the OCP using co-located temperature and ozone concentration observations. They develop average OCPs for several regions of the U.S. and for the continental U.S.—excluding the Deep South and West Coast—for two periods of relatively stable precursor emissions[clxvii] (1995-2002 and 2003-2006).

The fact that the OCPs were developed over periods with relatively constant precursor emissions suggests that they would be most accurately applied to scenarios where precursor emissions are held constant.

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metrics. BenMAP-CE calculates a quarterly mean concentration for PM2.5, in which each quarter corresponds to three months of the year (e.g., Q2 is April 1 through June 30). BenMAP-CE only calculates ozone-related benefits during the ozone season (April 1 through September 30).

[clxvi] Perera and Sanford (2011), the only study we found that estimates the health impacts of increased ozone concentrations without using air quality modeling, makes this same decision. (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.)

[clxvii] Volatile organic compounds (VOCs) and nitrogen oxides (NO_x).

However, precursor emissions from energy production are expected to decrease in the future due to emissions control policies and due to a shift to a cleaner fuel mix. Reducing building energy use (from cooling, greening, or installing solar) will also cause precursor emissions reductions. Therefore, without modification, the OCPs from Bloomer et al. (2009) will tend to overestimate future ozone concentration reductions.

Another important factor that affects ozone precursor emissions is future increases in population.[clxviii] As more people move into the city, more cars will move into the city, so ozone precursor emissions will increase. Urban population increases also mean that the population impacted by ozone pollution will increase, likely increasing the prevalence of ozone-related health impacts. To simplify our analysis, we assume precursor emissions reductions that result from emissions controls and reduced building energy use will be offset by the effects of increased urban populations. Figure 21.2 reflects these simplifications.

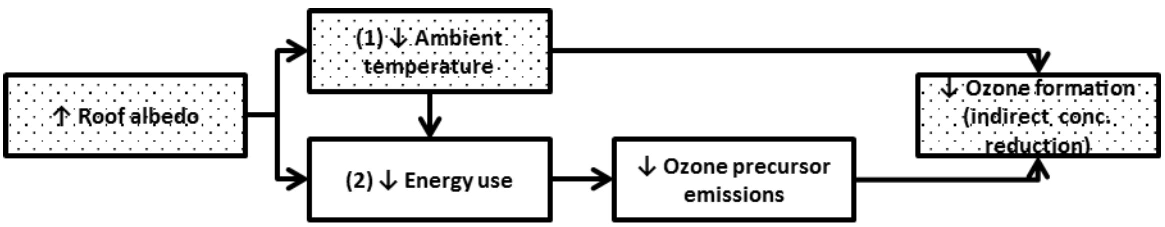

Figure 21.2. Cool roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

It is also important to consider that Bloomer et al. (2009) calculated their OCPs with data spanning a wide geographic area, so Bloomer et al.'s OCPs will tend to underestimate the intensity of urban ozone-temperature relationships (sometimes by as much as half)[686]. Nevertheless, we estimate the impact of ambient cooling on ozone concentrations in Washington, DC using Bloomer et al.'s OCPs, so we likely underestimate the impact of smart surface implementation on ozone concentration. Complex air quality modeling (which falls outside of the scope of this report) would refine these estimates.

21.2.2 Green Roofs

Following the same argument used to simplify the cool roof ozone reduction pathways, we can remove decreased energy use green roof ozone reduction calculations. We use the OCP from Bloomer et al. (2009) to estimate the impact of ambient temperature reductions on warm season ozone concentrations. Again, we assume that any reduction in precursor concentrations due to reduction in building energy use or power plant emissions reductions are offset by the effects of increased city populations. Note, in general, that we will tend to underestimate the impact of smart surface implementation on ozone concentration because we use regional, instead of urban, OCPs.

[clxviii] For example, the population of DC in 2040 is predicted to be about 280,000 greater than that in 2010, about 47 percent greater. (Personal communication with the DC Office of Planning, 2014.)

Green roofs can impact the ambient concentration of ozone precursors by other means than cool roofs. For example, green roofs can remove NO_2 from the air, yet they can also emit volatile organic compounds (VOCs).[687] Without performing air quality modeling to capture the complexities of ozone formation, it is not possible to accurately determine what impact a simultaneous decrease in NO_2 concentration and increase in VOC concentration would have on ozone concentration. Because the impact is likely small[clxix] and because we want this model to be user-friendly, we exclude green roof uptake of NO_2 from our ozone impact analysis. For the same reason, we exclude potential increases in VOC concentrations from the ozone impact analysis.[clxx] Based on these simplifications, we can our ozone benefits calculations even further. Figure 21.3 reflects these simplifications.

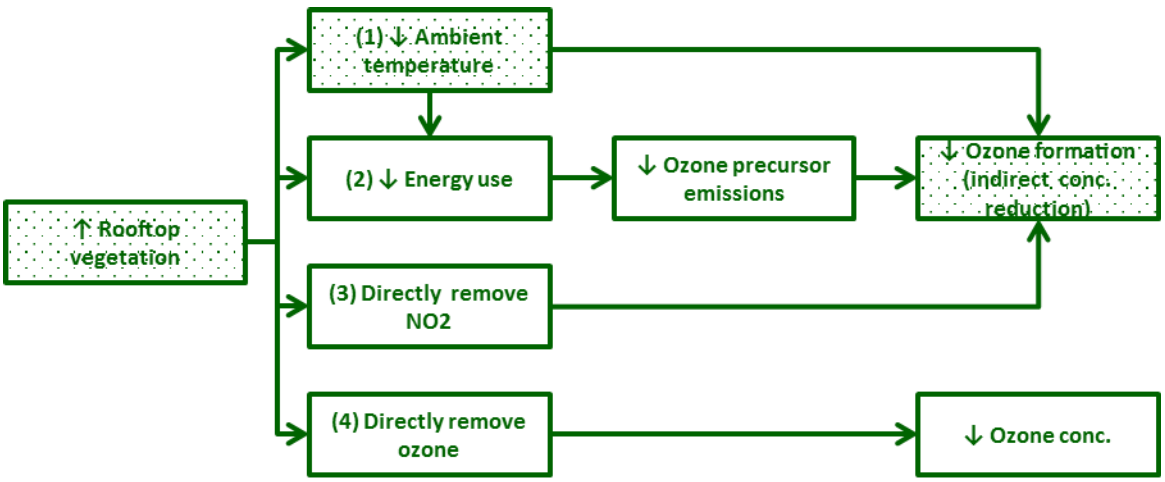

Figure 21.3. Green roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Ozone uptake

To estimate the ozone uptake of green roofs, we use the USDA Forest Service's Urban Forest Effects (UFORE) model. UFORE was developed by David Nowak at the Northern Research Station in Syracuse, NY and has recently been integrated into the i-Tree Eco tool. To date, at least 2,402 projects in the United States have used i-Tree to estimate the pollution removal benefits of urban forests.[688] In addition, two projects have used UFORE to estimate the pollution removal benefits of green roofs.[689] We utilize the

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[clxix] Previous work has shown that 74,970,000 square feet of green roofs in DC (~29% of building footprint) would remove 7.5 metric tons of NO2 annually (Deutsch et al., 2005)—0.085% of the roughly 8800 metric tons of NOx emitted in the borders of DC annually (EPA, 2014). The same area of green roofs would remove 2.9 metric tons of SO2 annually—0.17% of the roughly 1700 metric tons of SO2 emitted in DC annually. (Barbara Deutsch et al., "Re-Greening Washington, DC: A Green Roof Vision Based On Quantifying Storm Water and Air Quality Benefits," August 24, 2005; U.S. Environmental Protection Agency (EPA), "The 2011 National Emissions Inventory," *EPA*, September 26, 2014, http://www.epa.gov/ttnchie1/net/2011inventory.html.)

[clxx] This is a reasonable assumption because if green roofs are installed at city-scale, then effort should (and likely would) be made to select low VOC-emitting plants or plants that do not emit VOCs. However, this warrants further research.

UFORE-D model component, which estimates the air pollutant removal benefits of urban forests using pollution concentration data, meteorological data, and plant-specific air pollution removal rates. UFORE-D can calculate pollutant removal for O_3, SO_2, NO_2, CO, $PM_{2.5}$, and PM_{10}.

Pollutant removal depends on vegetation type. The UFORE-D model was designed for trees, shrubs, and grasses, so no removal rates exist for typical extensive green roof plants (e.g., sedum and other succulents). Based on previous work by Currie and Bass (2008) at the University of Toronto and discussions with David Nowak,[690] we chose to approximate pollutant removal by extensive green roofs using pollutant removal estimates from grasses. With the help of David Nowak, we first estimate the pollution removal of the high coverage scenario and then scale down the results of the maximum coverage analysis to determine pollution removal of a single roof.[clxxi] We use Equation 21.3 for scaling pollution removal for different coverage scenarios.

Equation 21.3. Green roof pollutant removal scaling

$$C_S = C_M \times \frac{S}{M}$$

where:

C_S	= Pollutant concentration reduction of scenario of interest (ppb, ug/m^3, etc.)
C_M	= Pollutant concentration reduction of maximum scenario (ppb, ug/m^3, etc.)
S	= Green roof area for scenario of interest (ft^2, m^2, etc.)
M	= Green roof area for maximum scenario (ft^2, m^2, etc.)

UFORE-D uses the D24HourMean air quality metric [clxxii] to estimate concentration changes for all pollutants. The typical air quality metric used to estimate the health impacts of ozone concentration BenMAP-CE is D8HourMax. To ensure the ozone concentration change estimates are in the optimal form for BenMAP-CE, we scale the estimates based on the average ratio of D8HourMax ozone concentrations to D24HourMean ozone concentrations for 2009, 2010, and 2011.[clxxiii] We found that the value of green roof uptake per ft^2 of roof is not significant, so we do not include it our cost-benefit analysis summary tables.

21.2.3 Rooftop PV

We do not examine the impact of PV on ozone concentration because of the offsetting discussed in the previous two sections. In other words, Figure 7.4 simplifies out of existence.

[clxxi] This process assumes there is a linear relationship between green roof coverage and pollutant removal. David Nowak, who developed the UFORE model, notes that this is generally a good assumption. (Personal communication with David Nowak of the U.S. Forest Service, 2014.)

[clxxii] See the BenMAP section above for more specifics on air quality metrics.

[clxxiii] For more on changing air quality metrics, see section F.6 of the Legacy BenMAP Appendices (EPA, 2012). (U.S. Environmental Protection Agency (EPA), "BenMAP User's Manual Appendices," October 2012.)

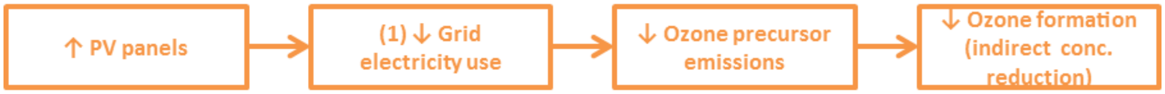

Figure 21.4. Rooftop PV ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

21.2.4 Reflective pavements

Using the same rationale as in Sections 21.2.1 and 21.2.2, we simplify our analysis by removing energy-related ozone concentrations reduction pathways. Figure 21.5 reflects these simplifications.

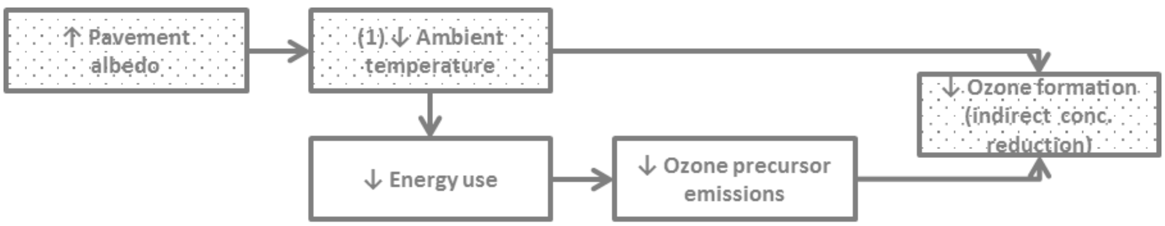

Figure 21.5. Reflective pavement ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

21.2.5 Urban trees

Using the same rationale as in Sections 21.2.1 and 21.2.2, we simplify our analysis by removing energy-related ozone concentrations reduction pathways. Figure 21.6 reflects the simplifications for the purposes of our ozone-temperature analysis. However, unlike green roofs, trees provide a significant pollution uptake benefit. We discuss this impact in Section 21.5 below.

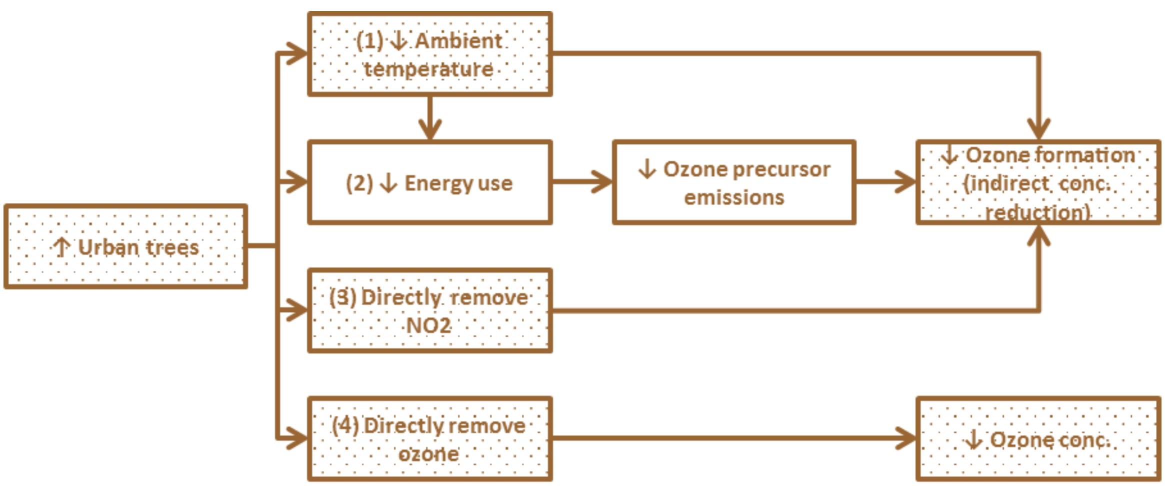

Figure 21.6. Urban tree ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

21.2.6 Ozone reduction calculation process

21.2.6.1 Cool roofs and green roofs

Determine temperature change

Li et al. (2014)[691] forms the basis for the cool roof and green roof ozone-specific temperature change analysis in this report. Li et al. (2014) models the cooling impacts of cool and green roof strategies in the Baltimore-Washington area during a heat wave period.[clxxiv]

We chose Li et al. (2014) for our analysis because it is the most robust analysis of its kind that focuses on the Washington-Baltimore region specifically *and* examines the ambient cooling impact of both cool and green roofs. Urban heat islands are highly location specific so the most important factor for us was a study that specifically analyzes the region. Li et al. (2014) and Kalkstein et al. (2013)[692] are the only UHI modeling studies that focus on the Washington, DC area. Kalkstein et al. (2013) do not explicitly model the cooling impact of cool roofs or green roofs, rather they model an overall urban albedo change and an overall urban albedo change combined with an increase in vegetation. In contrast, Li et al. (2014) explicitly models the cooling impact of cool roofs and green roofs. Given these considerations, we chose Li et al. (2014) for our ozone-specific temperature analysis.

Li et al. (2014) find that the relationship between cool roof or green roof coverage and change in near-surface UHI is roughly linear (see Figure 21.7). To utilize this relationship, we plot the data points taken from Figure 21.7 (for data points see Table 21.5 and Table 21.6) and perform a linear regression analysis (Figure 21.8 and Figure 21.9). We perform the linear regression analysis with the y-intercept set to zero for the most realistic fit line.[clxxv] The slope found with the linear regression analyses for cool/green roofs is the decrease in near-surface urban heat island (°C) per percent coverage of cool/green roof (Table 21.7).

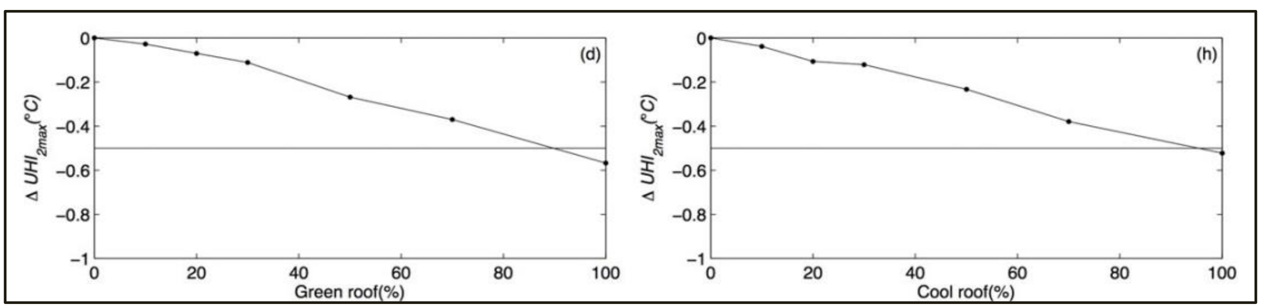

Figure 21.7. Reductions in near-surface urban heat islands from various green roof (right) and cool roof (left) coverage scenarios when the near-surface temperatures reach their maxima[clxxvi] (Source: Li et al., 2014)

[clxxiv] Because Li et al. (2014) assessed cool/green roof impact during a heat wave period, results may overestimate impact of cool roofs and green roofs during non-heat wave conditions. This is a potential source of overestimation for our analysis.

[clxxv] Without this constraint, the linear regression analysis may yield negative impacts on the urban heat island when cool/green roof percent is close to 0%. This phenomenon is unrealistic because 0% cool/green roofs (i.e., 100% conventional roofs, which is the baseline of roof characteristics contributing to the urban heat island) will not enhance the baseline urban heat island because it is part of what causes the baseline urban heat island.

[clxxvi] This does not necessarily coincide with the maximum UHI strength, especially for near-surface UHIs (Li et al., 2014). This figure shows the change in peak daytime temperature with cool roofs or green roofs.

Table 21.5. Reductions in near-surface urban heat islands when the near-surface temperatures reach their maxima from various green roof installation scenarios (compiled based on close visual examination of Figure 21.7)

Green roof (%)	ΔUHI_{2max} (°C)
0%	0.00
10%	-0.03
20%	-0.07
30%	-0.11
50%	-0.26
70%	-0.37
100%	-0.57

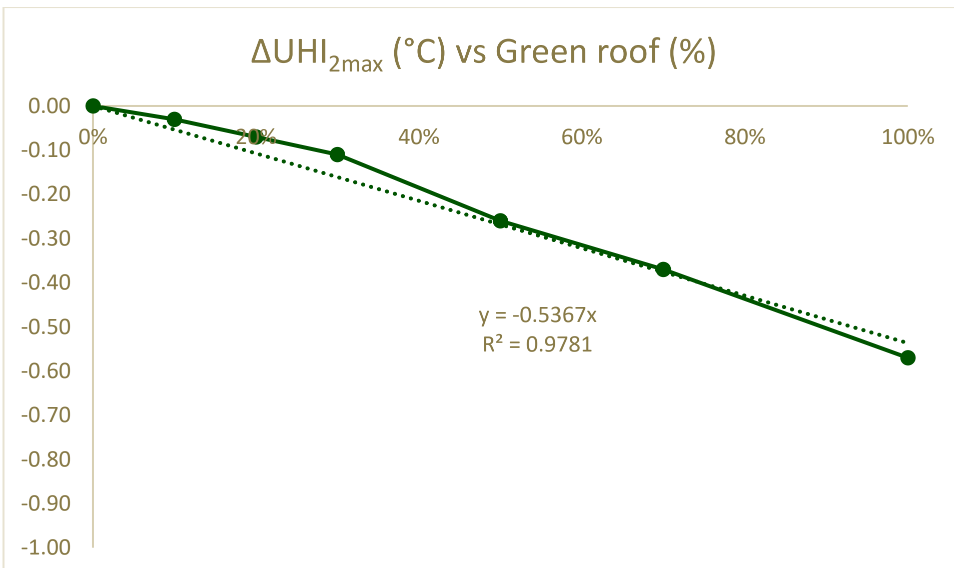

Figure 21.8. Plot of ΔUHI_{2max} (°C) vs Green roof (%) based on data points in Table 21.5

Table 21.6. Reductions in near-surface urban heat islands when the near-surface temperatures reach their maxima from various cool roof installation scenarios (compiled base on close visual examination of Figure 21.7)

Cool roof (%)	ΔUHI_{2max} (°C)
0%	0.00
10%	-0.04
20%	-0.10
30%	-0.11
50%	-0.23
70%	-0.37
100%	-0.52

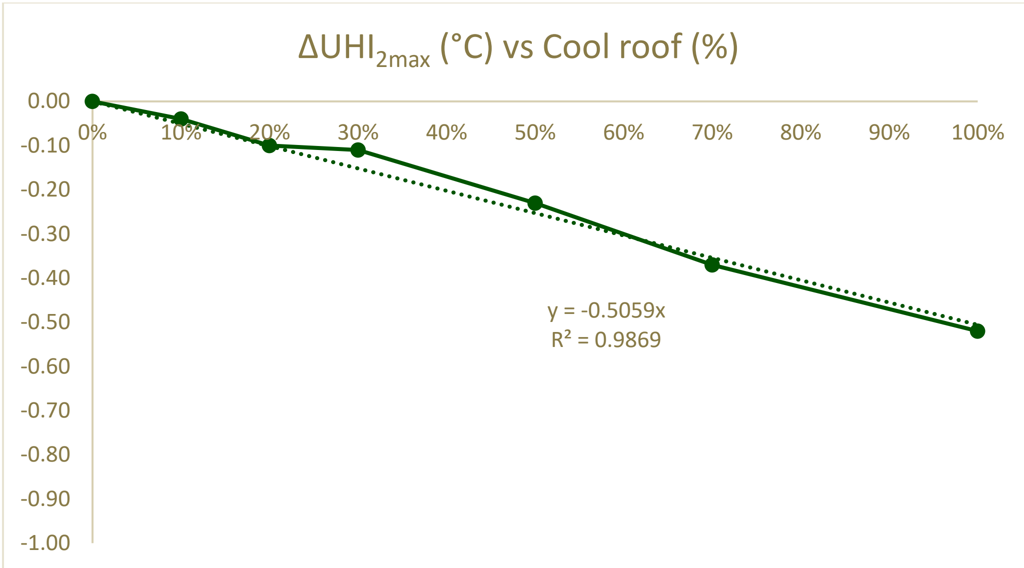

Figure 21.9. Plot of ΔUHI_{2max} (°C) vs Cool roof (%) based on data points in Table 21.6

Table 21.7. ΔUHI2max (°C) per % green roof or cool roof coverage

Roof type	Green roof	Cool roof
ΔUHI_{2max}/% roof type	-0.5367	-0.5059

Now that we have a temperature to roof coverage relationship, we need to scale the results to account for differences in roof properties between this analysis and Li et al. (2014). The characteristics of the roofs modeled in Li et al. (2014) are shown in Table 21.8.

For cool roofs, we scale the results based on albedo. Table 21.9 shows the albedo changes used for scaling. We calculate the weighted-average albedo change using Equation 21.4.[clxxvii] We do not consider the relationship between other cool roof properties (emissivity, heat capacity, thermal conductivity) and UHIs in this analysis, so we do not take them into account for scaling purposes. Based on these assumptions and the temperature to cool roof coverage relationship we describe above, we use Equation 21.10 to determine the cooling impact of cool roof installation.

[clxxvii] This value is specific to this analysis and will change if the albedo assumptions and roof slope-specific area assumptions change.

Table 21.8. Roof properties from Li et al. (2014)

Roof type	Green roof	Cool roof	Conventional roof
Albedo	0.30	0.70	0.30
Emissivity	0.95	0.95	0.95
Heat capacity (MJ m^{-3} K^{-1})	1.9	2.0	2.0
Thermal conductivity (W m^{-1} K^{-1})	1.1	1.0	1.0
Depth (cm)	40	20	20
Saturation soil moisture (m^3 m^{-3})	0.468	N/A	N/A
Wilting-point soil moisture (m^3 m^{-3})	0.15	N/A	N/A
Leaf Area Index	5	N/A	N/A

Table 21.9. Albedo changes for cool roof temperature scaling[clxxviii]

Cool to conventional albedo change in Li et al., 2014	0.40
Cool to conventional albedo change this analysis (weighted-average)	0.45
Low slope cool to conventional albedo change in this analysis	0.5
Steep slope cool to conventional albedo change in this analysis	0.15

Equation 21.4. Weighted-average albedo change

$$\Delta albedo_{weighted-average} = \left(\Delta albedo_{lowSlope} \times \frac{portfolio\ low\ slope\ roof\ area}{portfolio\ roof\ area}\right) + \left(\Delta albedo_{steepSlope} \times \frac{portfolio\ steep\ slope\ roof\ area}{portfolio\ roof\ area}\right)$$

Equation 21.5. UHI mitigation potential of cool roofs

$$\Delta UHI_{coolroof} = \frac{\Delta albedo_{this\ analysis}}{\Delta albedo_{Li\ et\ al.(2014)}} \times \frac{cool\ roof\ area}{roof\ area\ in\ DC} \times \frac{\Delta UHI_{coolroof}}{\%\ cool\ roofs}$$

Equation 21.6. UHI mitigation potential of green roofs

$$\Delta UHI_{greenroof} = \frac{green\ roof\ area}{roof\ area\ in\ DC} \times \frac{\Delta UHI_{greenroof}}{\%\ greeb\ roofs}$$

[clxxviii] Albedo changes in this analysis increase as technology approves in future years.

We assume that green roofs in this analysis have the same incremental impact as in Li et al. (2014). We use Equation 21.6 to estimate the cooling impact of green roof installation. There are several limitations to this assumption to consider. First, all else being equal, the difference in LAI between Li et al. (2014) (LAI = 5) and this study (LAI = 2) may result in us *overestimating* the cooling impact of green roofs. Second, conventional roof albedo is probably closer to 0.15 (the value we assume) than 0.3 (the valued Li et al. (2014) assume), so there is likely an increase in city albedo when green roofs are installed in place of conventional roofs.[clxxix] This means that, all else equal, our analysis will tend to *underestimate* the cooling impact of green roofs. It is outside the scope of this analysis to say what the combined impacted of this differences will have; nevertheless, it is important to understand that they exist.

The green roofs modeled in Li et al. (2014) are 20 cm (~8 in) thicker than a standard roof. In other words, there is 20 cm (~8 in) of green roof-specific material. This is at least 1 in thicker than any of the green roofs we consider. However, we do not have the resources, data, or expertise to accurately consider how this difference will impact the cooling impact of green roofs. Similarly, we do not have the resources, data, or expertise to accurately consider the difference between typical moisture content of green roofs in Washington, DC and those modeled in Li et al. (2014). This does not mean that green roof moisture content is not important. Li et al. (2014) modeled the impact of different green roof moistures on green roof cooling potential and found that if green roofs are very dry, they can enhance the UHI. Thus if Washington, DC plans to consider green roofs as a UHI mitigation technology at a large scale, it needs to seriously consider how moisture content is maintained.

Determine ozone concentration change

To estimate the ozone concentration change when cool roofs or green roofs are installed, we multiply the temperature change calculated using Equation 21.5 or Equation 21.6 by the OCP from Bloomer et al. (2009)[693] (see Equation 21.7). Figure 21.10 shows the OCPs for the Mid-Atlantic from Bloomer et al. (2009). We use the post 2002 OCP (2.2 ppbv O_3/°C) in this analysis.[clxxx] (From now on we will use ppb, or "parts per billion", in place of ppbv, "parts per billion by volume".)

[clxxix] Green roof albedo ranges from 0.25 to 0.3. (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.)

[clxxx] Note not all of the temperature data used by Bloomer et al. (2009) is peak temperature data. However, Kenward et al. (2014) use peak temperature to examine the relationship between ozone concentration and temperature and find a stronger relationship between peak temperature and ozone concentration than the OCP in Bloomer et al. (2009). This may be partly because Kenward et al. (2014) used urban data for their analysis where ozone concentrations tend to be more sensitive to temperature than rural areas. However, they also used more recent data (2004-2013) compared to Bloomer et al. (2009), suggesting Kenward et al. (2014) should find a weaker relationship due lower power plant and vehicle emission rates. It is hard to know exactly how the combined factors would impact the OCP, but they would likely balance each other in some way. This balancing, combined with the fact that we use OCP from Bloomer et al. (2009) that do not necessarily reflect the more extreme relationship between peak temperature and ozone concertation, suggests that the ozone reduction results of this analysis are conservative (i.e., an underestimate). (Alyson Kenward et al., "Summer in the City: Hot and Getting Hotter" (Princeton, NJ: Climate Central, 2014), http://assets.climatecentral.org/pdfs/UrbanHeatIsland.pdf.)

Equation 21.7. Ozone concentration reduction calculation

$$\Delta[O_3]_{rooftech} = OCP \times \Delta T_{rooftech}$$

where:

$\Delta[O_3]_{rooftech}$ = the change in ozone concentration due to the specific roof type
OCP = the OCP from Bloomer et al. (2009)
$\Delta T_{rooftech}$ = the temperature change due to the specific roof type

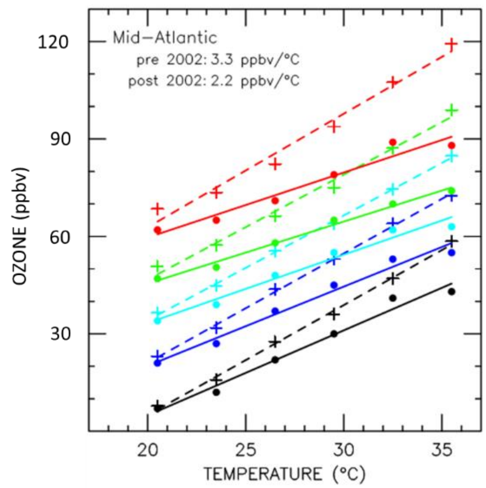

Figure 21.10. Relationship between ozone concentration and temperature. Dashed lines and plusses are for the pre 2002 linear fit of ozone as a function of temperature; solid lines and filled circles are for after 2002. (Bloomer et al., 2009)

We input the ozone concentration reductions from this analysis into BenMAP (described above) to determine the health incidence impact and value. See Figure 21.11 for a process map of which inputs go where.

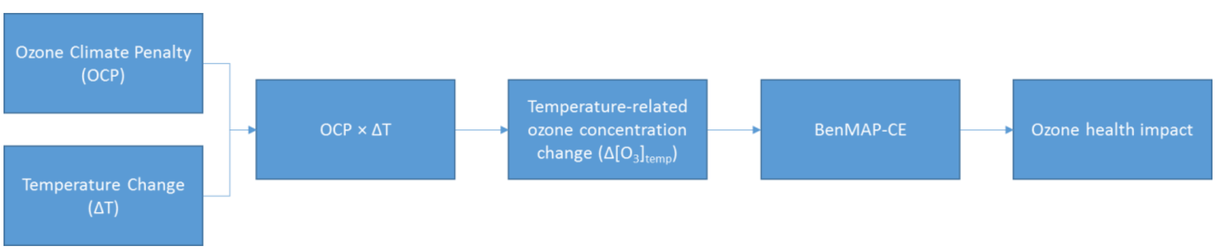

Figure 21.11. Process map for ozone benefits estimation

21.2.6.2 Reflective pavements

1) Basis is Kalkstein et al. (2013);[694]
2) Extract temperature change and city-wide albedo change relationship from K 2013
    a. DC: city-wide albedo change = 0.1 → average temperature reduction across 4 modeled heat events = 0.32°F (Table 7, K 2013)

3) Determine temperature change based on effect of pavement albedo change in this analysis on city-wide albedo
    a. Assume baseline road albedo is 0.15, parking albedo is 0.15, and sidewalk albedo is 0.30
    b. Assumed modified albedo for roads and parking is 0.30 and sidewalks is 0.35[clxxxi]
    c. Albedo change for roads and parking is 0.15 and sidewalks is 0.05
    d. Calculate the change in temperature for each pavement using the equations below

Equation 21.8. Equation used to calculate mortality change from cool roof installation in this analysis

$$\Delta T_{CB} = \Delta T_{KorV} \times \frac{\Delta albedo_{CB}}{\Delta albedo_{KorV}}$$

Equation 21.9. Equation used to calculate albedo change from cool roof installation

$$\Delta albedo_{CB} = (albedo_{new} - albedo_{old}) \times \frac{Pavement\ Area}{CityArea}$$

        i. DC
            1. Road = 14.7% city area[695]
            2. Parking = 7.7% city area[696]
            3. Sidewalk = 5.7% city area[697]
    e. Divide the result of Equation 21.9 by the total area of the pavement type to determine the per square foot temperature change
4) With this value, we follow the process in Figure 21.11 to determine the ozone benefit

21.2.6.3 Urban trees

1) Basis is Sailor (2003)[698]
    a. Sailor (2003) estimated impact on temperature of albedo increases and vegetation increases
    b. Examined DC
    c. Used larger land areas than actual city limits, so need to scale appropriately
2) Extract temperature change values from Table 1 of Sailor (2003); these are the temperature maximum temperature reductions that occur from increasing vegetative cover by 10%
    a. 0.18°F
3) Divide above numbers by 10% of city area (using areas from Sailor (2003)) to determine the temperature change from a square foot increase in vegetation
    a. 10% area in Sailor (2003) = 2.3 billion square feet
4) With this value, we follow the process in Figure 21.11 to determine the ozone benefit

21.3 $PM_{2.5}$ reduction

21.3.1 Cool roofs

$PM_{2.5}$ concentration reductions due to cool roof installation are from decreases in energy use (see Figure 21.12). We do not estimate the $PM_{2.5}$ concentration reduction or mass reduction that results from cool

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[clxxxi] Albedo changes in this analysis increase as technology approves in future years.

roof implementation because doing so would require complex photochemical air quality modeling that is outside the scope of this analysis. Instead, we go straight to calculating the health benefit of energy reductions using methods and per kilowatt hour $PM_{2.5}$-related health impacts values developed by Machol and Rizk (2013).[699]

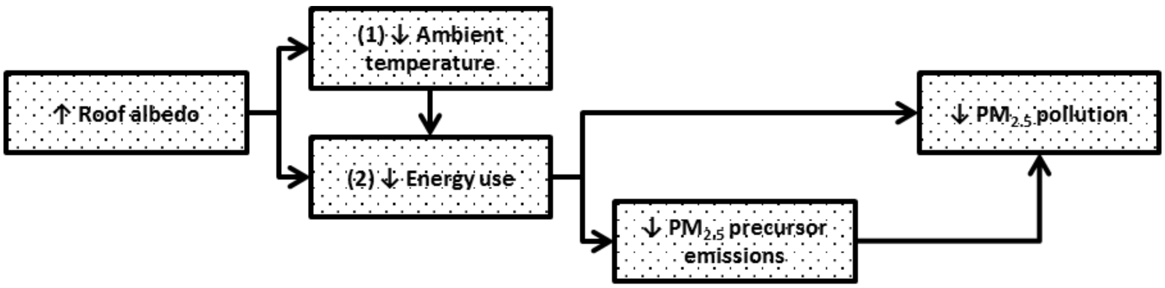

Figure 21.12. Cool roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

Machol and Rizk (2013) develop fuel-specific and state-level estimates of the economic value of $PM_{2.5}$-related health impacts due to fossil fuel use. We use the Machol and Rizk (2013) health impact estimates rather than other per kilowatt hour estimates because they are based on a photochemical air quality model that captures the nonlinearities in the photochemical reactions that form $PM_{2.5}$.[clxxxii] For more details on the calculation process we use, please see Section 21.3.6.

21.3.2 Green roofs

As with the green roof ozone concentration reduction analysis, we simplify the green roof $PM_{2.5}$ concentration reduction pathways. Because its impact is small and because we seek to ensure the usability of our methods for non-experts, we exclude the direct removal of $PM_{2.5}$ precursors from our analysis.[clxxxiii] Figure 21.13 reflects these simplifications.

[clxxxii] The value per kilowatt hour values provided in Machol and Rizk (2013) are based on $PM_{2.5}$ air quality modeling performed using the Community Multi-scale Air Quality (CMAQ) model (U.S. EPA uses for its own air quality modeling). Other studies (e.g., Muller et al., 2011; National Research Council, 2010) that provide economic values for the health impacts of electricity on a per kilowatt hour basis use a source-receptor model—called the Air Pollution Emissions Experiments and Policy model—that does not account for the nonlinearities in photochemical reactions. More research is needed to determine if source-receptor models accurately capture the non-linear chemistry governing $PM_{2.5}$ and other pollutants (Fann et al., 2012). (Nicholas Z Muller, Robert Mendelsohn, and William Nordhaus, "Environmental Accounting for Pollution in the United States Economy," *American Economic Review* 101, no. 5 (August 2011): 1649–75, doi:10.1257/aer.101.5.1649; National Research Council (U.S.), *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington, D.C: National Academies Press, 2010); Neal Fann, Kirk R. Baker, and Charles M. Fulcher, "Characterizing the PM2.5-Related Health Benefits of Emission Reductions for 17 Industrial, Area and Mobile Emission Sectors across the U.S.," *Environment International* 49 (November 2012): 141–51, doi:10.1016/j.envint.2012.08.017.)

[clxxxiii] Previous work has shown that 74,970,000 square feet of green roofs in DC (~29% of building footprint) would remove 7.5 metric tons of NO2 annually (Deutsch et al., 2005)—0.085% of the roughly 8800 metric tons of NOx

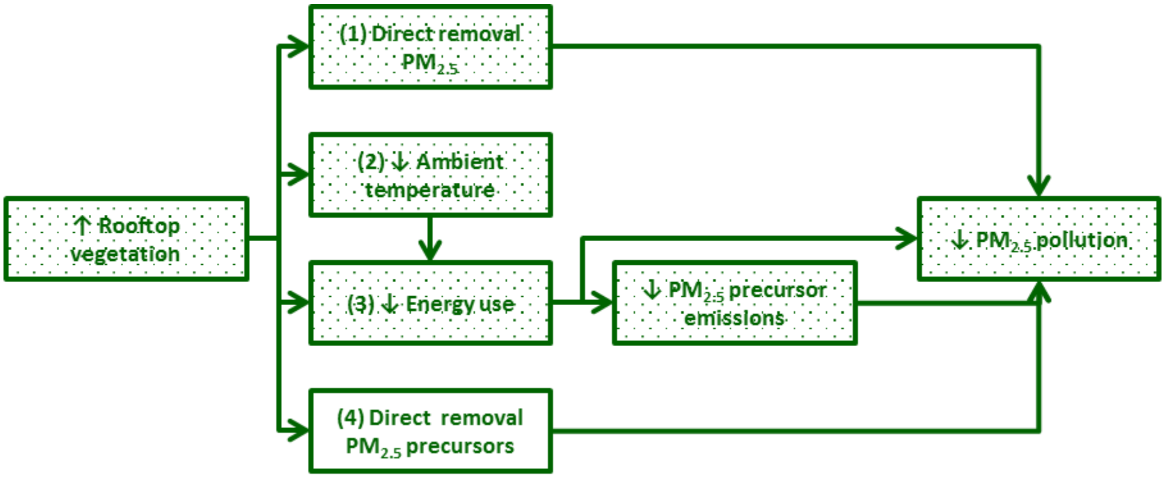

Figure 21.13. Green roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

We estimate the health impact of energy-related $PM_{2.5}$ reductions from green roof (pathways (2) and (3) in Figure 21.13) using the same methods as for cool roof. We estimate the direct removal of $PM_{2.5}$ by green roofs using the UFORE-D model discussed above in Section 21.2.2. The $PM_{2.5}$ concentration reductions that result from this analysis are input into BenMAP to determine the health incidence impact and value. We found that the value of green roof uptake per ft^2 of roof is not significant so we do not include it our cost-benefit analysis summary tables. Please see Section 21.3.6 for the calculation process.

21.3.3 Rooftop PV

Rooftop PV reduces $PM_{2.5}$ concentrations by reducing grid electricity use (which, in this case, is analogous to building energy use reductions), so we use benefit per kWh estimates from Machol and Rizk (2013) to calculate $PM_{2.5}$ benefits for rooftop PV. Please see Section 21.3.6 for the calculation process.

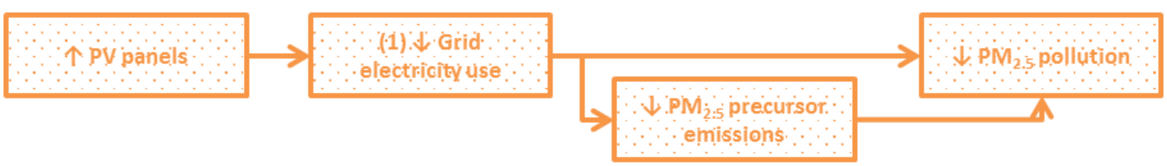

Figure 21.14. Rooftop PV $PM_{2.5}$ concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

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emitted in the borders of DC annually (EPA, 2014). The same area of green roofs would remove 2.9 metric tons of SO2 annually—0.17% of the roughly 1700 metric tons of SO2 emitted in DC annually. (Barbara Deutsch et al., "Re-Greening Washington, DC: A Green Roof Vision Based On Quantifying Storm Water and Air Quality Benefits," August 24, 2005; U.S. Environmental Protection Agency (EPA), "The 2011 National Emissions Inventory," *EPA*, September 26, 2014, http://www.epa.gov/ttnchie1/net/2011inventory.html.)

21.3.4 Reflective pavements

$PM_{2.5}$ concentration reductions due to reflective pavement installation are from decreases in energy use (see Figure 21.15). As noted above, we use a simplified $PM_{2.5}$ health benefits because complex air quality modeling is outside the scope of this report. To estimate the $PM_{2.5}$ health benefit of reflective pavements we use per kilowatt hour $PM_{2.5}$-related health impacts values developed by Machol and Rizk (2013). Please see Section 21.3.6 for the calculation process.

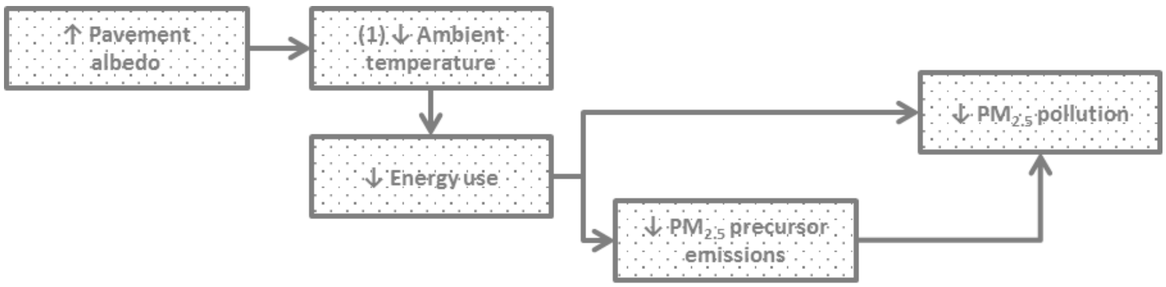

Figure 21.15. Reflective pavement $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

21.3.5 Urban trees

As with the urban tree ozone concentration reduction analysis, we treat direct removal of pollutants from the air in a different section. Please see Section 21.3.6 for the calculation process and Section 21.5 for discussion of pollution uptake by trees (i.e., pathways (1) and (4) in Figure 21.16).

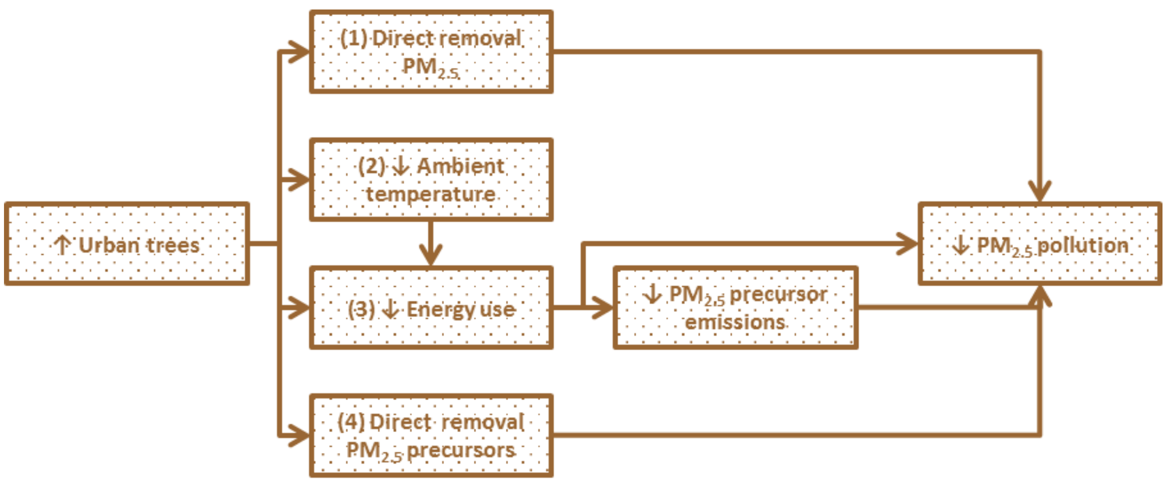

Figure 21.16. Urban tree $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

21.3.6 $PM_{2.5}$ benefits calculation process

To determine the value of $PM_{2.5}$-related health benefit that results from smart surface implementation we multiply the annual electricity savings (annual electricity output for PV) by a utility-specific health impact value calculated using methods from Machol and Rizk (2013) (see Equation 21.10). See Figure 21.17 for a process map of which inputs go where.

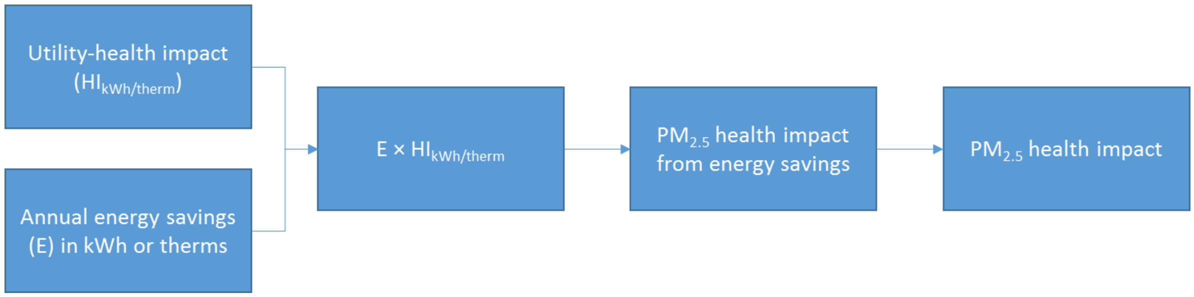

Figure 21.17. Process map for $PM_{2.5}$ benefits estimation

We use 2015 data from Pepco[700] to determine the fuel mix for Washington, DC (see Table 21.10) in order to calculate a utility-specific health impact value for energy reductions in Washington, DC. We then multiply the fuel mix percentage of each fuel by the low benefit-per-kWh estimates calculated by Machol and Rizk (2013) (Table 21.11).[clxxxiv] This method allows for a benefit-per-kWh estimate that is more specific to each city's electric utility than the values provided by Machol and Rizk (2013).

We perform a similar calculation for potential natural gas savings/penalties related to heating. The benefit-per-kWh estimates in Machol and Rizk (2013) are based on the emissions from electric generating units; however, using these benefit-per-kWh estimates to determine the $PM_{2.5}$-related health impact of natural gas heating is conservative.[clxxxv] We use Equation 21.10 for this calculation as well.

The benefit-per-kWh estimates from Machol and Rizk (2013) do not account for decreased $PM_{2.5}$ and $PM_{2.5}$ precursor emissions due to emissions standards or changes in population. To account for this reduction, we scale the $PM_{2.5}$ health impacts from Equation 21.10 using the carbon intensity index discussed in more detail in Section 19. As fossil fuel use decreases, carbon intensity decreases. Similarly, as fossil fuel use decreases, $PM_{2.5}$ health impacts from electricity use decrease, so scaling $PM_{2.5}$ impacts with carbon indices is approximately correct.

[clxxxiv] We use the low estimate of $PM_{2.5}$ benefit per kilowatt hour estimates because our intent is to be conservative.
[clxxxv] Electric generating units are typically located away from urban areas so electric generating unit benefit-per-ton estimates, which Machol and Rizk (2013) use to develop their benefit-per-kWh estimates, will tend to underestimate the health impact of natural gas used for heating (i.e., local burning of natural gas). Fann et al. (2012) find that benefits from directly emitted $PM_{2.5}$—the highest benefit-per-ton estimate for all sectors they analyzed—are greatest for sources closest to population centers. (Neal Fann, Kirk R. Baker, and Charles M. Fulcher, "Characterizing the PM2.5-Related Health Benefits of Emission Reductions for 17 Industrial, Area and Mobile Emission Sectors across the U.S.," *Environment International* 49 (November 2012): 141–51, doi:10.1016/j.envint.2012.08.017.)

Table 21.10. Pepco fuel mix

Energy source	**Percent of Pepco fuel mix**[clxxxvi]
Coal	39.4%
Gas	21.0%
Nuclear	34.9%
Oil	0.3%
Unspecified fossil	0.0%
Renewables	4.4%
Total	100%

Table 21.11. $PM_{2.5}$ health impact per kWh (Source: Machol and Rizk, 2013)

Generation Type	**LOW ($/kWh)**
COAL	$0.19
OIL	$0.08
NATURAL GAS	$0.01

Equation 21.10. Value of $PM_{2.5}$ health impact savings from fossil fuel electricity or natural gas

$$HI_{total} = E \times HI_{kWh/therm}$$

where:

HI_{total} = $PM_{2.5}$-related health impact ($)
E = Annual electricity savings (kWh) or annual natural gas savings (therm)
$HI_{kWh/therm}$ = $PM_{2.5}$-related health impact of electricity ($/kWh) or natural gas ($/therm)

Limitations of Machol and Rizk (2013)

There are several limitations to using the methods and benefit-per-kWh estimates from Machol and Rizk (2013). Machol and Rizk (2013) note these in their write-up (see Figure 21.18) and we discuss which apply to our analysis below.

[clxxxvi] Numbers may not sum to 100% due to rounding.

Table 1

Limitations. This table shows the limitations of the current work which represent areas ripe for improvement in future analyses. We provide estimates as to the magnitude and directionality of simplifications made relative to an idealized analysis which could provide complete and accurate assessments of health impacts.

Issue	Magnitude	Likely directionality
National benefit per ton used	High	Vary by location
Only include $PM_{2.5}$ precursors, not other environmental impacts	High	Underestimate
Benefits per ton estimates based on modeling of 2015 conditions	Medium	Overestimate
Incomplete information on energy imports is available	Medium	Uncertain
Benefits based on broad emission source categories	Medium	Uncertain
Do not account for transmission losses	Low	Underestimate
Only include power plant $PM_{2.5}$ data when NEI and acid rain data align	Low	Uncertain
Accept uncertainties from $PM_{2.5}$ benefits analysis methodology	Uncertain	Uncertain

Figure 21.18. Limitations as noted by Machol and Rizk (2013)

Machol and Rizk (2013) use national benefit-per-ton estimates to develop their fuel specific benefit-per-kWh factors. As Machol and Rizk (2013) note, this will have a large impact on the magnitude of the results. However, whether there is a larger or smaller impact compared to the national estimates (i.e., the direct of the impact) will vary direction by location. For example, in Washington, DC it is hard to tell the direction of the impact without doing extensive comparison between national and Washington, DC-specific population characteristics.[clxxxvii]

Machol and Rizk (2013) only include the impact of $PM_{2.5}$ and $PM_{2.5}$ precursors, not other environmental impacts, so the note that the likely highly underestimate the benefit of reduced electricity use. In our analysis we estimate some of the environmental impacts that Machol and Rizk (2013) leave out (ozone and CO_2), but there are still others we do not quantify (e.g., impact on wildlife) so we still underestimate the environmental impact of energy savings.

The benefits per ton estimates Machol and Rizk (2013) use are based on modeling of 2015 conditions, which they note will lead to a medium overestimate of impact. However, in our analysis 2015 is the first analysis year, so the benefits per ton modeling year will not result in an overestimate. It is possible that the 2015 modeling year Machol and Rizk (2013) use could lead to an underestimate of results because our analysis looks multi-year impacts, though we attempt to address this issue with the impacts offsetting described above (e.g., in Section 21.3.1).

The remaining limitations discussed by Machol and Rizk (2013)—that benefits are based on broad emissions source categories (uncertain), that transmission losses are not accounted for (underestimate), that they only include power plant $PM_{2.5}$ data when National Emissions Inventory (NEI) and acid rain data align (uncertain), and accepting the uncertainties from $PM_{2.5}$ benefits analysis methodology (uncertain)—all still apply to our analysis.

[clxxxvii] One reason for this is that different age groups are affected by $PM_{2.5}$ differently.

Based on the above discussion of limitations to Machol and Rizk (2013), it is clear which still apply to our analysis. However, it is unclear how these limitations impact the magnitude and directionality of our results relative to the most ideal $PM_{2.5}$ benefits analysis (which is outside the scope of our report).

21.4 Heat-related mortality

21.4.1 Cool roofs and green roofs

Kalkstein et al. (2013)[701] forms the basis for our estimation of heat-related mortality in Washington, DC. There are three parts to our methods for estimating heat-related mortality: (1) estimating the number of heat-related mortalities in Washington, DC; (2) using the results from (1) to estimate the change in heat-related mortality due to smart surface implementation; and (3) valuing this change. Below we describe the process used to estimate heat-related mortality impacts of cool roofs and green roofs.

Average number of heat-related mortality

To estimate the impact of smart surfaces on heat-related mortality, we first determine the average number of days in the warm season (the most oppressive period of the year) with Spatial Synoptic classifications (SSC)[clxxxviii] of Dry Tropical (DT) and Moist Tropical (MT+ or MT++ if extreme) from 2004 to 2013. Kalkstein et al. (2013) note that DT and MT+ (or MT++) days are associated with the greatest increase in heat-related mortality compared to other SSC day types (see Figure 21.19 for a full list of SSC day types). DT and MT+ (or MT++) days are the days Kalkstein et al. (2013) focus on, and thus the days we focus on. Further, Kalkstein et al. (2013) define the warm season as June, July, and August for their analysis; we use this definition for our heat-related mortality analysis as well.[clxxxix] Based on data maintained by Scott Sheridan at Kent State University, there were an average of 10 DT days and 6.3 MT+ days during the warm seasons in Washington, DC from 2004 through 2013.[702]

[clxxxviii] Kalkstein et al. (2013) state that the "SSC evaluates a broad set of meteorological conditions to place each day into one of a number of air mass types."

[clxxxix] Because we only include three months of the year in our analysis, our results should be conservative (e.g., our estimates exclude heat-related mortalities during other hot months of the year).

Air Mass	*Definition*
Generally Non-Oppressive Air Masses	
Dry Polar (DP)	Arrives from polar regions and is usually associated with the lowest temperatures observed in a region for a particular time of year as well as clear, dry conditions.
Dry Moderate (DM)	Consists of mild and dry air. It occurs when westerly winds warm the air as it descends the eastern side of mountain ranges.
Moist Polar (MP)	Typically cloudy, humid, and cool. MP air appears when air over the adjacent cool ocean is brought inland by an easterly wind, frequently during stormy conditions.
Moist Moderate (MM)	Considerably warmer and more humid than MP. The MM air mass typically appears in a zone south of MP air, near an adjacent stationary front (an area where warm air moves over a cooler air mass).
Moist Tropical (MT)	Warm and very humid. It is typically found in warm sectors of mid-latitude cyclones or in a return flow on the western side of a high-pressure area, such as the Bermuda High.
Transition (TR)	Defined as days in which one weather type yields to another, based on large shifts in pressure, dew point, and wind over the course of the day.
Oppressive Hot Air Masses	
Dry Tropical (DT)	Represents the hottest and driest conditions found at any location. There are two primary sources of DT: either it is transported from the desert regions, such as the Sonoran Desert, or it is produced by rapidly descending air.
Moist Tropical+ (MT+)	Hotter and more humid subset of MT. It is defined as an MT day where both morning and afternoon temperatures are above the MT averages, and thus captures the most "oppressive" subset of MT days. We have also identified an MT++ situation, which is even more extreme; in this case, both morning and afternoon temperatures are at least 1 standard deviation above MT averages.

Figure 21.19. Air mass types in the SSC (from Kalkstein et al. (2013))

Next we determine the daily increase in mortality during the warm season when DT and MT+ air mass days are present—this is the heat-related mortality. We use Table 3 from Kalkstein et al. (2013) (Figure 21.20 in this analysis) and find that DT and MT+ days are associated with a 0.9 (4%) and 1.7 (7%) increase in heat-related mortality in Washington, DC, respectively. Multiplied by the average number of DT and MT+ days during the warm season, respectively, we find there are typically 19.71 (9 associated with DT days and 10.71 associated with MT+ days) heat-related mortalities during the average warm season in Washington, DC (see Table 21.12).

City *(% frequency JJA)*	**DT Mortality** *(% Inc)*	**MT+ Mortality** *(% Inc)*
Washington (11%)	+0.9 (4%)	+1.7 (7%)
Seattle (6%)	+3.7 (8%)	+4.7[a] (10%)
New York (11%)	+16.6 (7%)	+16.9% (7%)
New Orleans (2%)	None	+3.7% (9%)
Phoenix (1%)	+2.7[b] (7%)	None
Rome (11%)	+6.2 (14%)	+5.0 (12%)
Shanghai (11%)	None	+42.4 (10%)
Toronto (7%)	+4.2 (11%)	+4.0 (10%)

Figure 21.20. Mortality responses in different cities when DT and MT+ air masses are present (from Kalkstein et al. (2013)

Table 21.12. Average number of heat-related mortalities associated with DT and MT+ air masses in typical Washington, DC warm season

Air mass type	DT	MT+	Combined
Heat-related mortalities	9	10.71	19.71

Estimating change in heat-related mortality

To estimate the change in heat-related mortality from smart surface implementation, we first need to determine the relationship between heat-related mortality and city-wide albedo change in Washington, DC. Kalkstein et al. (2013) found that the temperature effects of a city-wide albedo increase of 0.1 reduce heat-related mortality by 6.2% for Washington, DC.

We scale this result based on the roof albedo change in this analysis. To do this, we estimate the city-wide albedo change based on the properties of the surfaces discussed in this analysis. For example, as noted in the energy section, we assume the baseline roof albedo in Washington, DC is 0.15 and that cool roof albedo is 0.65 (a change of 0.5). We can calculate the impact of a roof albedo change on the average city albedo with Equation 21.11.[cxc] Once we know the change in average city albedo, we can use Equation 21.12 to relate the albedo change in this analysis to the change in heat-related mortality. The result is -4.8%. In other words, increasing albedo of roofs from 0.15 to 0.65 reduces warm season heat-related mortality in Washington, DC by 4.8%. To determine the absolute change in heat-related mortality we multiply ΔHM_{KG} (-4.8%) by the average number of warm season heat-related mortalities in Washington, DC (19.71; from Table 21.12); the result is -0.95 heat-related mortalities. We assume green roofs have the same mortality impact as cool roofs.

Equation 21.11. Equation to estimate the impact of roof albedo changes on average city-wide albedo

$$\Delta\alpha_{city,KG} = \left(\alpha_{new\ roof} - \alpha_{old\ roof}\right) \times \frac{A_{roofs}}{A_{city}}$$

where:

$\Delta\alpha_{city,KG}$	= city-wide albedo change, this analysis
$\alpha_{new\ roof}$	= cool roof albedo, this analysis
$\alpha_{old\ roof}$	= conventional roof albedo, this analysis
A_{roofs}	= area of roofs in the city
A_{city}	= total city area

Equation 21.12. Equation to estimate scaled changes in heat-related mortality

$$\Delta HM_{KG} = \Delta HM_{K} \times \frac{\Delta\alpha_{city,KG}}{\Delta\alpha_{city,K}}$$

where:

ΔHM_{KG}	= change in heat-related mortality, this analysis
ΔHM_{K}	= change in heat-related mortality, Kalkstein et al. (2013)
$\Delta\alpha_{city,K}$	= city-wide albedo change, Kalkstein et al. (2013)

[cxc] One can also use a similar equation to estimate the impact of reflective pavements on average city albedo.

Valuing change in heat-related mortality

We value the change in heat-related mortality using the value of statistical life (VSL), see the BenMAP section above for more details. The VSL we use is $7,400,000 (2006$) from EPA (2014).[703] We hold VSL constant for the 40 years of our analysis, making our results conservative. We calculate that the value of reduced heat-related mortality for the cool roofs described above is $0.26/ft2 per year. We use this value for green roofs as well.

Limitations to Kalkstein et al. (2013)

There are several limitations to using Kalkstein et al. (2013). First, Kalkstein et al. (2013) do not control for ozone or air quality-related mortality, so it is possible that we are double counting some heat-related mortalities with our ozone benefits analysis. Second, Kalkstein et al. (2013) estimates the change in heat-related mortality for extreme heat events. Because we use their estimate to estimate heat-related mortality throughout the warm season, we may be overestimating changes in heat-related mortality. Third, Kalkstein et al. (2013) only estimate mortality in relation to changes in ambient outdoor temperature, so their results do not reflect the complete impact of cool or green roofs on indoor air temperature (e.g., because of reduced heat transfer through the roof). This will tend to make our heat-related mortality estimates conservative. Further, Kalkstein et al. (2013) does not scale the average increase in heat-related mortality with future population growth. This too will tend to make our heat-related mortality estimates conservative.

A more robust analysis would use BenMAP because a BenMAP analysis eliminates many of the limitations from using Kalkstein et al (2013). In a BenMAP analysis, we can include extreme heat events and regular increased heat days, scaling with population growth, a changing VSL, correcting for the impact of ozone, and more days of the warm season. However, a BenMAP analysis requires many more inputs (e.g., more specific temperature data that is often generated from mesoscale meteorological modeling) that add complexities and potentially time to the analysis process. For an example or a heat-related mortality analysis that uses BenMAP, see Stone et al. (2014).[704]

21.4.2 Reflective pavements

We use the same process described in Section 21.4.1 to determine the heat-related mortality impacts of reflective pavements. The main differences are the albedo changes for pavements are lower and the area of pavements is generally larger than that of roofs. We discuss pavement albedo changes and areas in Section 21.2.6.1.

21.4.3 Urban trees

Kalkstein et al. (2013)[705] forms the basis of our urban tree heat-related mortality analysis. We use similar methods as described in Section 21.4.1. K 2013 estimate the heat-related mortality impact of increasing albedo by 0.1 and vegetation by 10% (e.g., 10% to 20%) for 4 heat events. As discussed in Section 21.4.1, K 2013 also estimate the heat-related mortality impact of only increasing albedo by 0.1 for the same 4 heat events. To determine the impact of trees on heat-related mortality, we subtract the heat-related mortality benefit of the albedo only scenario from the heat-related mortality benefit of the combined scenario. The result is an approximate benefit from a 10% increase in urban vegetation.[cxci] To determine the heat-related mortality impact per square foot of urban vegetation increase, we divide this difference by 10% of the city area and multiply by the VSL (as described previously).

21.5 Pollution uptake by urban trees

1) We scale down pollution uptake values from i-Tree Landscape to estimate the pollution uptake value per square foot of urban tree canopy
    a. i-Tree Landscape calculates county-specific health benefits based on procedures described in Nowak et al. (2014)[706]
        i. Nowak et al. (2014) calculates health benefits EPA's BenMAP
    b. i-Tree Landscape is web-based and allows users to estimate health benefits of removing CO, NO2, O3, $PM_{2.5}$, and $PM_{2.5-10}$.
2) Sample calculation
    a. Select Washington, DC in i-Tree Landscape web application
    b. Determine total canopy area base on values in -Tree Landscape
        i. 9078.1 acres ≈ 400 million sq ft
    c. Divide pollution benefit numbers for the current tree canopy by the total tree canopy area

Pollutant	$/yr for entire canopy	$/yr/ft2
CO	$17,864.00	$0.00005
NO2	$56,699.00	$0.00014
O3	$1,856,026.00	$0.00469
PM2.5	$4,179,627.00	$0.01057
SO2	$8,090.00	$0.00002
PM10	$304,804.00	$0.00077

[cxci] In other words, we assume an additive relationship between albedo increases and temperature increases, similar to our calculations for indirect energy benefits and ozone benefits.

22 Appendix: Reduced potable water use

Figure 22.1 shows the DC Water rates used to estimate the benefit of reduced potable water use. We hold water rates constant through the 40-year analysis period, a conservative assumption.

	Proposed FY 2017 (Effective 10/1/2016)	
Rate Class	**Ccf**	**1,000 Gallons**
Water Rate		
Residential - 0 - 4 Ccf	$3.23	$4.32
Residential - greater than 4 Ccf	$4.06	$5.43
Multi-Family	$3.62	$4.84
Non-Residential	$4.19	$5.60
Sewer Rate		
Residential	$5.71	$7.63
Multi-Family	$5.71	$7.63
Non-Residential	$5.71	$7.63
PILOT (Payment-In-Lieu Of Taxes) Fee*		
Residential	$0.48	$0.64
Multi-Family	$0.48	$0.64
Non-Residential	$0.48	$0.64
The Right-of-Way (ROW) Fee*		
Residential	$0.17	$0.23
Multi-Family	$0.17	$0.23
Non-Residential	$0.17	$0.23
Groundwater Sewer Charge		
Residential	$2.33	$3.11
Multi-Family	$2.33	$3.11
Non-Residential	$2.33	$3.11

Figure 22.1. DC Water Rates[707]

23 Appendix: Reduced sidewalk/parking lot salt use

Assume average salt application rates of 0.03 pounds per square foot of conventional pavement per year

- Based on 8.1 average snow events per year with snow total greater than 0.1 inches in the District[708] and on application rate of 4 pounds of salt per 1000 square feet (average of application rate for pavement temp greater than 30F (3 pounds) and pavement temp between 25-30F (5 pounds))[709]
- 8.1 events per year X 4 pounds of salt per event per 1000 square feet = 0.03 pounds of salt per square foot

We assume a 50% reduction in salting needs for permeable sidewalks (2/3 of the reduction found by the University of New Hampshire)[710]

For permeable parking lots, which are gravel or grass, we assume a 100% salt reduction because salting gravel or grass in uncommon.

We use a salt cost of $0.23 per pound ($11.50 per 50 lb bag), based on a review of DGS contracts.[711]

24 Appendix: Estimating employment impact

Building and sustaining roof technologies such as green roofs and solar PV has the potential to create significant new "green collar" employment. Responding to the growth of the green economy, the Bureau of Labor Statistics began an effort to define and measure green jobs in 2010.[712] They counted 3.1 million green goods and services jobs in the United States in 2011, representing 2.3 percent of private sector and 4.2 percent of the public sector workforce.[cxcii] The DC Office of Planning (2009) commissioned a green collar job demand analysis for Washington, DC that predicted 169,000 green jobs would be created between 2009 and 2018 from existing and proposed District green policies.[713] More recently, a 2014 analysis by the American Council for an Energy Efficient-Economy (ACEEE) estimated that a city-wide commitment to 26% energy use reduction could create 600 net new jobs in Washington, DC by 2020 and 1400 net jobs by 2030.[714,cxciii] Expanding the deployment of smart surfaces, particularly green roofs and solar PV, in DC would propel the growth of green jobs.

For the District to realize the potentially large employment benefits of an expanded green economy, green jobs must go to city residents. Employment studies usually leave this issue unaddressed. As follows, we estimate and characterize the job creation that would result from expanding the area of smart surfaces in the District.

24.1 Job Creation by Technology

24.1.1 Conventional Roofs

Conventional built-up roofs can be installed at 450 square feet per hour while conventional modified bitumen roofs can be installed at 550 square feet per hour.[715] Table 24.1 summarizes these values. We use conventional built-up roofs as our baseline to calculate net job increases because they are the most common on low-sloped roof type.[716] We do not include a baseline value for steep slope roofs because, as discussed below, cool roofs net employment impacts are negligible.

24.1.2 Cool roofs

The net employment impact of cool roof installation is negligible because cool roofs have very similar installation requirements to conventional roofs. For this reason, the net employment impact of cool roofs is not included in costs-benefit results.

24.1.3 Green Roofs

Green roofs can be installed at a rate of 53 square feet per hour.[717] Assuming one job year is equivalent to 2080 hours of work, this translates to 10.3 person-years of labor per million square feet. The estimate includes planning, travel, and on-site construction and is based on an extensive green roof.

[cxcii] Green goods and services (GGS) jobs are defined as jobs found in business that primarily produce goods and services that benefit the environment or conserve natural resources or jobs in which worker's duties involve making their establishment's production processes more environmentally friendly or use fewer natural resources. In 2013, the BLS eliminated the GGS Occupations program due to budget cuts. Therefore, GGS jobs numbers for 2011 are the most recent ones available from the BLS.

[cxciii] The ACEEE analysis took into account out-of-state purchases, using historic consumption patterns to adjust changes in state-level demand. They use the DEEPER model to estimate employment impacts. Jobs include those created through increased spending on goods and services due to energy bill savings. The analysis does not consider whether DC residents or commuters will take up the new jobs.

Maintenance needs vary depending on the age of the roof and the type of green roof installed. For extensive roofs, GSA (2011) projects an annual labor requirement of 4 person hours per 1,000 square feet per year, assuming three annual site visits.[718] This drops to 2.7 yearly person hours after the establishment period, when only annual two site visits are needed. Intensive roofs require more regular care. The GSA (2011) estimates a need for 6 person hours per 1,000 square feet per year during the establishment period, based on four annual site visits. They recommend that the rate of four site visits remain constant throughout the life of the intensive roof, though maintenance demands during each visit will decrease over time. In our analysis, we assume that only extensive roofs are installed and that the establishment period lasts three years. Given a green roof's 40-year life expectancy, an average of 1.33 jobs are needed annually to maintain one million square feet of green roof.

Green roofs usually last at least twice as long as conventional roofs. Studies estimate the life expectancy of a green roof at 40 years,[719] compared to 20 years for a conventional roof.[720] From an employment perspective, this reduces the net job creation of green roofs since re-roofing is a labor-intensive process.

Table 24.1 summarizes green roof labor requirements.

24.1.4 Solar PV

We use NREL's Jobs and Economic Development Impact (JEDI) model to estimate PV employment impact in this report.[721] The JEDI model generates employment impact estimates for U.S. states for five different systems applications (residential retrofit, residential new construction, small commercial, large commercial, and utility). We use the average of the estimated employment impacts of residential retrofit and residential new construction for single-family residential solar PV. For commercial and multifamily residential solar PV, we use the average of the estimated employment impacts of small commercial and large commercial.

Using the pre-2020 solar PV prices, 1 kW of single-family residential solar PV in the District requires about 18 hours of project development and on-site labor. This works out to about 8.6 jobs per MW of solar PV installed. The JEDI model estimates that approximately 0.2 annual operations and maintenance jobs are created for each MW of installed single-family residential solar PV capacity in the District.

Using the pre-2020 solar PV prices, 1 kW of commercial or multifamily residential solar PV in the District requires about 15 hours of project development and on-site labor. This works out to about 7.1 jobs per MW of solar PV installed. The JEDI model estimates that approximately 0.2 annual operations and maintenance jobs are created for each MW of installed commercial or multifamily residential solar PV capacity in the District.

Using the post-2020 solar PV prices, 1 kW of single-family residential solar PV in the District requires about 12 hours of project development and on-site labor. This works out to about 5.9 jobs per MW of solar PV installed. For commercial or multifamily residential solar PV, 1 kW requires about 10 hours of project development and on-site labor. This works out to about 4.9 jobs per MW of solar PV installed. We assume operations and maintenance job creation remains the same for simplicity.

Table 24.1 summarizes solar PV labor requirements per square foot of roof area. These values reflect the fact that PV systems take up more roof space on low slope roofs compared to steep slope roofs because of space. We arrive at these numbers using the PV power density estimates used previously in Section 17.3 (13.9 and 11.4 W per square foot of roof for steep slope and low slope roofs, respectively).

Table 24.1. Job-years of labor mentioned in the body of the report are calculated based on the following estimates for time to install and maintain different surface technologies (PV jobs are based on pre-2020 costs)

Technology	Labor requirement	
	Installation (ft^2/hour)	Operation & maintenance (ft^2/hour)
Conventional (built-up roof)	450	-
Conventional (modified bitumen)	550	-
Extensive green roofs	75	750 * (2 visits/yr)
Solar PV (single-family residential steep slope)	4.0	203 (total one year)
Solar PV (single-family residential low slope)	4.9	205 (total one year)
Solar PV (commercial or multifamily residential steep slope)	4.9	250 (total one year)
Solar PV (commercial or multifamily residential low slope)	6.0	252 (total one year)

24.1.5 Bioretention and rainwater harvesting

This report estimates the employment impact of bioretention systems and rainwater harvesting systems using employment multipliers from the Bureau of Economic Analysis.[722] Based on these multipliers, $1 million of spending on bioretention systems or rainwater harvesting systems in the District creates 8.08 direct jobs.

24.2 Job creation potential by technology

We only estimate direct job creation, which means that our figures underestimate the total jobs that smart surface installation could create in the District.[cxciv] For instance, the National Renewable Energy Laboratory (NREL)'s Jobs and Economic Development Impact (JEDI) model estimates that for every direct job created in solar PV installation in the District of Columbia, almost two indirect jobs are created in other sectors such as trade and professional services. For operation and maintenance of solar PV, four direct jobs are created for every indirect job, according to the NREL model.

All our labor intensity estimates for installation (see Table 24.2) include planning, transportation, and construction. We do not include manufacturing because these jobs would likely occur outside of the District. Roof estimates are based on commercial buildings with a footprint of roughly 10,000 to 20,000 square feet. Installing smart surfaces on small, residential buildings would require slightly higher labor intensities while very large commercial buildings would probably need fewer labor hours per square foot. Thus, our numbers provide a middle-of-the road scenario.

Net installation benefits will depend on the time horizon for installing the smart surface technologies and the period of the analysis because different technologies have different life cycles and will be need to be

[cxciv] We ignore both indirect and induced jobs. Indirect jobs are those created to support the industry of interest. Induced jobs result from indirect or direct employees of the given industry spending their paychecks in the community.

replaced at different frequencies. For instance, over the course of a 40-year analysis period, green roof (with a life expectancy of 40 years) will be replaced once, while a conventional roof (with a life expectancy of 20 years) will be replaced twice. However, if a 50-year time horizon were chosen, then a green roof would be replaced twice and a conventional roof would still be replaced twice. For results in Table 24.2, we select a 40-year time horizon and assume that all technologies are installed in year one.

We assume bioretention and rainwater harvesting systems are not built in place of something else. This means, net jobs are equivalent to the total jobs created each solution. Bioretention systems are upgraded at ½ cost 25 years into analysis.

Table 24.2. Labor requirement by technology (PV jobs are based on pre-2020 costs)

Technology	Labor requirement			
	Installation (job-years/ million ft^2)[cxcv]		Operation and maintenance (jobs/ million ft^2)[cxcv]	
	Total (1 install)	Net[cxcvi] (40 years)	Total	Net
Conventional (built-up roof)	1.07	-	-	-
Conventional (modified bitumen)	0.874	(0.389)	-	-
Extensive green roofs	10.3	8.16	1.3	1.3
Solar PV (single-family residential steep slope)	119	239	2.4	2.5
Solar PV (single-family residential low slope)	97.3	195	1.9	1.9
Solar PV (commercial or multifamily residential steep slope)	98.7	198	2.3	2.3
Solar PV (commercial or multifamily residential low slope)	80.5	161	1.9	1.9
Avg bioretention	617	926	4.9	4.9
Avg rainwater harvesting	31	31	1.8	1.8

24.3 Smart surface job characteristics

The green economy offers jobs across a wide range of skill levels. The DC Office of Planning (2009) estimates that 37 percent of green job opportunities in the city will require little to no preparation while 42 percent will require a moderate level, typically an associate's degree or specialized training.[723] The remaining jobs require a bachelor's degree or higher. The relatively low barriers to entry of many green jobs, including those discussed in this report, are especially important to city residents experiencing difficulty in finding work.

[cxcv] Rainwater harvesting is per million square feet of roof managed.

[cxcvi] Net means additional jobs compared to a conventional built-up roof (the most common type), taking into account the different life expectancies of conventional versus smart roofs.

Installing smart surfaces in DC would help provide the unemployed with relatively well-paid work. Expanding smart surface deployment in the District would help increase construction jobs.

The labor profiles of solar PV and green roof installation and maintenance showcase the educational requirements and median wages of jobs in smart surfaces. The Bureau of Labor Statistics (2015) reports that solar photovoltaic installers make a median hourly wage of $19.24 and only need a high school diploma plus on-the-job training.[724] For green roof jobs, 75 percent are taken up by construction, 60 percent of these going to roofers and landscapers.[725] Roofers do not need high school education and earn a median wage of $17.19 per hour in DC.[726] Smart surface jobs offer individuals without college educations access to living wages.

24.4 Costs and benefits of training

24.4.1 Costs

Jobs training programs typically cost several thousand dollars per student to run. The United Planning Organization's Building Careers Academy in DC costs $4000 per participant for a 14-week full-time program,[727] while longer programs that provide stipends to all participants can cost substantially more. For instance, BEST Academy, run by Sustainable South Bronx in New York City, costs $8,500 per participant for 17 weeks of full-time training.[728] We use the average of these costs per participant to estimate the costs of employment training.

We assume linear installation rates for all technologies. This means the number of installation jobs created each year remains constant, so we assume training for installation jobs occurs at the beginning of the analysis period. In years when a technology is replaced a second, third, fourth, etc. time, we assume no employment training costs for installation jobs because these extra replacements will occur in a well-developed market so installers will be more efficient and can train individuals on the job. In contrast to installation jobs, the number of maintenance jobs will increase as the area of green roofs and solar PV increases in our analysis. We assume these jobs require training and include the additional cost of training these new workers in employment cost calculations.

24.4.2 Benefits

While the costs of jobs training programs are significant, the cost of unemployment can be much higher. For example, an average unemployed 24-35 year-old in the District of Columbia costs the combined federal and state governments $15,093. This includes $2,949 in foregone state[cxcvii] income tax, $3,221 in foregone Federal Insurance Contributions Act (FICA) taxes, $8,530 in foregone federal taxes, and $293 in welfare payments.[729] An average 18-24 year-old in the District of Columbia costs the government $5,849, which includes $2,655 in foregone federal income tax, $2,012 in foregone FICA taxes, $1138 in foregone state[cxcvii] income taxes, and $44 in welfare payments.[730] We use an average of the values for each age group for benefits calculations.

The cost to the government of unemployment grows significantly when more costs are included. According to Belfield et al. (2012), each American aged 16-24 who is not in school or working costs taxpayers $13,900 annually in direct costs that involve lost tax payments, public criminal justice system

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[cxcvii] These can also be thought of as city income taxes.

costs, public health expenditures, welfare, and avoided education spending.[731] The report by Belfield et al. does not break out costs by state and federal governments.

In our analysis, we assume that all jobs created through investments in smart surfaces (relative to conventional surfaces) are net jobs. That is, we assume that these jobs go to city residents who would not otherwise be in the workforce, providing a net gain in employment to the economy. This is reasonable given that infrastructure investment dollars are mainly spent in the construction and landscaping industries, areas of the economy with high excess capacity.[732] Since we are interested in jobs in the city, we estimate costs and benefits based on 50% city employment. As discussed further on, our estimates fall short of the true expected costs based on two reasons: (a) they ignore the significant individual and social costs and benefits that go beyond direct government expenditures and (b) they are based on an average unemployed individual (whereas green jobs are usually targeted toward hard-to-employ individuals who typically contribute different costs and revenues to the government).

Our estimates ignore individual and social costs of unemployment that far exceed lost tax revenue and welfare payments. These include loss of social cohesion, increased crime rates, negative opinions about the effectiveness of democracy, and lower academic achievement by children of the unemployed.[733] Many effects are challenging to estimate and exceedingly hard to monetize, though some have tried. Using social security data for high-seniority males in Pennsylvania, Daniel Sullivan and Till von Wachter (2009) find that even 20 years after experiencing job loss, mortality is 10-15 years higher for those who lost their jobs, primarily due to reduced ability to invest in good health care and a healthy lifestyle.[734] Thus, workers in their study who were laid off at 40 lost 1-1.5 years of life expectancy, valued at $100,000.[cxcviii] Blanchflower and Oswald (2004), found that to 'compensate' men exactly for lost happiness due to one year of unemployment would take a rise in income approximately $60,000 per year.[735]

Additionally, costs to the government of unemployment associated with the target demographic for green jobs training tend to be higher than for other demographics. Green jobs training programs in the District of Columbia and other cities often recruit low-income, chronically unemployed, and hard-to-employ individuals. The United Planning Organization only accepts students into its Building Careers Academy who make up to 125 percent of the federal poverty line. Several students in their programs have experienced homelessness or are currently homeless.[736] According to the DC Auditor (2015), the District of Columbia spent $14,016 on homeless services per homeless individual in 2014. The Department of Human Services, which administers income assistance and homeless services, spent $361 million total in fiscal year 2014.[737] In fiscal year 2013, the last year for which complete data is available, a monthly average of 17,446 TANF recipients were transferred $250 million in benefits over the year by the state and federal government. In the same year, 145,707 people received $135.17 monthly in SNAP benefits, on average.[cxcix] Were more residents employed in stable jobs with family-supporting wages, jobs the green economy could help create and that training programs could help economically disadvantaged DC residents take up fewer of these services would be necessary. Considering these benefits and costs, the case for

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[cxcviii] Daniel Sullivan and Till von Wachter (2009) set the value of statistical life at $5 million, which is low compared to other studies. (In this report, we use the central estimate recommended by the US EPA: $7.4 million ($2006).) Also, the authors use data from high-seniority men in stable jobs, so the findings are not necessarily applicable to all workers. (Daniel Sullivan and Till von Wachter, "Job Displacement and Mortality: An Analysis Using Administrative Data [*]," *Quarterly Journal of Economics* 124, no. 3 (August 2009): 1265–1306, doi:10.1162/qjec.2009.124.3.1265.)
[cxcix] The District DHS already provides some job training through the TANF and SNAP programs.

implementing jobs training programs that successfully place people into employment becomes an easy one to make.

25 Appendix: Scenario development

Surface technology coverage for low income regions by end of analysis period are in Table 25.1.

Table 25.1. Surface coverage in low income region by end of analysis

Surface solution	Percent coverage by end of 40-year analysis
Cool roofs	50% of roofs (10% multifamily low slope cool roofs and 20% of commercial low slope cool roofs have bioretention; 5% multifamily low slope cool roofs and 10% of commercial low slope cool roofs have rainwater harvesting)
Green roofs	10% of roofs
Solar PV	50% of viable (~530 MW)
Reflective pavements	50% of pavements
Permeable pavements	4% of pavements (5% parking lots and 10% sidewalks)
Urban trees	Increase tree canopy by 10% absolute

Table 25.2. Selected Washington, DC characteristics compared to Washington, DC

Characteristic	**Washington, DC**
Population (2010)[738]	601,723
Income[739]	
Median income	$69,325
Percent of population below poverty line	18.2%
Unemployment rate	10.6%
Land use	
Area (square miles)[740]	61.05
Building footprint (% region)[741]	15.9%
Paved area (roads, parking, sidewalks) (% region)[742]	24.1%
Tree canopy (% region)[743]	27.7%

25.1 Cool roofs

1) Combine building footprint data[744] and land use data[745] to determine area detached single family, attached single family, multifamily, and "commercial"; conversions below based on DC land use codes,[746] personal communication w/ DC Gov't,[747] on crosschecking w/ aerial photography
    a. If usecode = detached single family → detached single family building
    b. If usecode = attached single family → attached single family building
    c. If usecode = multifamily → multifamily building
    d. If usecode = no residential or vacant → "commercial" building

Table 25.3. Washington, DC building class roof areas

City	Roof area (ft2)
Detached single-family	52,161,077
Attached single-family	90,924,800
Multifamily	13,657,922
Commercial	99,479,908

2) Determine roof slope
   a. Single family
      i. Based on slope assumptions used in PV analysis (table replicated below)

Table 25.4. Slope breakdown of single family residential buildings

Housing type	Flat	4-sided	2-sided
1-unit, detached	10%	45%	45%
1-unit, attached	50%	0%	50%

      ii. Detached: 10% flat, 90% sloped
      iii. Attached: 50% flat, 50% sloped
   b. Multifamily
      i. Based on slope assumptions in PV analysis (Section 17.3): 81% flat, 19% sloped
   c. Commercial
      i. Based on slope assumptions in PV analysis (Section 17.3): 81% flat, 19% sloped
3) Combine steps 1) and 2)

Table 25.5. Washington, DC building type + roof slope areas

Building type + roof slope	Roof area (ft2)
Commercial LS	80,578,725
Commercial SS	18,901,182
Residential LS	61,741,424
Residential SS	95,002,374

4) To determine installation rate
   a. Multiply values in Table 25.5 by corresponding coverage % from Table 25.1 (50% for cool roofs); i.e., we assume 50% of each building type + roof slope is cooled by end of analysis
   b. Divide by 40 to determine annual installation rate

25.1.1 Cool roof + bioretention

1) To determine installation rate
    a. 10% multifamily low slope cool roofs and 20% of commercial low slope cool roofs
    b. Divide by 40 to determine annual installation rate

25.1.2 Cool roof + rainwater harvesting

1) To determine installation rate
    a. 5% multifamily low slope cool roofs and 10% of commercial low slope cool roofs
    b. Divide by 40 to determine annual installation rate

25.2 Green roofs

1) To determine installation rate
    a. Green roofs only installed on commercial LS and residential LS
        i. To achieve 10% coverage this equals: 24% of commercial LS have green roof and 14% of residential LS have green roof
    b. Divide by 40 to determine annual installation rate

25.3 Solar PV

1) To determine installation rate
    a. To bring our maximum capacity calculations more in line with NREL's recent estimate of PV technical potential in the Distrcit of 1.3 GW,[748] we multiply our maximum capacity estimates by a factor of 1.25. The result is shown in column 2 of Table 25.6.
        i. This is a fair assumption because of:
            1. Future potential increases in PV panel efficiency
            2. Increase in canopy (e.g., use of parking canopies and PV overhangs on buildings)
    b. We multiply the values in column 2 of Table 25.6 by corresponding coverage % from Table 25.1 (50% for solar PV); i.e., we assume 50% of viable solar for each building type (single family detached, single family attached, multifamily, and commercial) by end of analysis. The result is shown in column 3 of Table 25.6.

Table 25.6. Maximum viable target PV capacity by system type in Washington, DC

Type	Maximum capacity (MW)	Target capacity (MW)
Commercial low slope	544	272
Commercial steep slope	182	91
Detached, single family low slope	10	5
Detached, single family steep slope	90	45
Attached, single family low slope	106	53
Attached, single family steep slope	106	53
Multifamily low slope	21	10
Multifamily steep slope	7	3

c. Divide by 40 to determine annual installation rate

25.4 Reflective pavements

1) Use pavement area data[749] to different pavement areas
    a. Roads = "Road" + "Intersection" classes in DC GIS data
    b. Parking = "Parking Lot" class in DC GIS data
    c. Sidewalk = "Sidewalk" in DC GIS data

Table 25.7. Washington, DC pavement areas

Type	Area (ft2)
Roads	217,636,905
Parking Lot	94,024,811
Sidewalk	99,253,945

2) To determine installation rate
    a. Multiply values in Table 25.7 by corresponding coverage % from Table 25.1 (50% for reflective pavements); i.e., we assume 50% of each pavement type is cooled by end of analysis
    b. Divide by 36 to determine annual installation rate
        i. Divide by 36 instead of 40 because start installing pavements until in yr 5 of analysis

25.5 Permeable pavements

1) Use pavement area data[750] to different pavement areas (see Table 25.7)

2) To determine installation rate
    a. Multiply values in Table 25.7 by corresponding coverage % from Table 25.1 (5% for parking lots and 10% for sidewalks)
    b. Divide by 40 to determine annual installation rate

25.6 Urban trees

1) To determine planting rate
    a. Add 10% to current tree canopy value in Table 2.1
    b. Divide by 40 to determine annual planting rate

26 Appendix: Detailed results

26.1 Scenario (NPV)

Table 26.1. Detailed net present value (NPV) of costs and benefits (through 2032)

SOLUTION	Cool Roofs	Cool Roofs + Bioretention	Cool Roofs + Rainwater Harvesting	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Permeable Pavements	Urban Trees	TOTAL
COSTS	**$13,572,000**	**$11,204,000**	**$7,579,000**	**$146,992,000**	**$104,164,000**	**$424,000**	**$11,179,000**	**$8,987,000**	**$97,685,000**	**$401,782,000**
First cost	$13,572,000	$10,349,000	$5,874,000	$122,921,000	$97,569,000	--	$10,904,000	$7,938,000	$77,736,000	$346,860,000
Operations and maintenance	$0	$589,000	$1,549,000	$23,985,000	$6,454,000	--	--	$1,867,000	$19,949,000	$54,390,000
Additional replacements	$0	$0	$0	--	$0	--	$276,000	-$817,000	$0	-$542,000
Employment training	$0	$267,000	$157,000	$88,000	$142,000	$424,000	--	--	--	$1,075,000
BENEFITS	**$56,938,000**	**$25,233,000**	**$19,346,000**	**$147,087,000**	**$156,282,000**	**$151,778,000**	**$18,632,000**	**$49,435,000**	**$206,020,000**	**$830,747,000**
Energy	$6,904,000	$1,458,000	$720,000	$5,681,000	$75,273,000	$8,648,000	$655,000	--	$2,147,000	$101,483,000
Direct energy savings	$5,162,000	$1,239,000	$620,000	$5,037,000	--	--	--	--	$842,000	$12,898,000
Indirect (UHI) energy savings	$1,742,000	$220,000	$101,000	$644,000	--	--	$655,000	--	$1,305,000	$4,665,000
Electricity value	--	--	--	--	$57,649,000	$8,648,000	--	--	--	$66,297,000
SRECs	--	--	--	--	$17,624,000	--	--	--	--	$17,624,000
Financial incentives	--	--	--	--	$33,300,000	--	--	--	--	$33,300,000
Tax Credit	--	--	--	--	$14,983,000	--	--	--	--	$14,983,000
Depreciation	--	--	--	--	$18,317,000	--	--	--	--	$18,317,000
Stormwater	--	$8,349,000	$10,683,000	$123,168,000	--	--	--	$49,257,000	$178,804,000	$370,259,000
Fee discounts	--	$217,000	$178,000	$1,457,000	--	--	--	$702,000	$2,972,000	$5,524,000
SRC value	--	$8,132,000	$10,505,000	$121,712,000	--	--	--	--	$175,832,000	$316,180,000
Health	$26,847,000	$4,171,000	$1,960,000	$10,977,000	$27,304,000	$81,911,000	$4,177,000	--	$14,554,000	$171,897,000
Pollution uptake	--	--	--	--	--	--	--	--	$6,818,000	6818000
Ozone	$16,483,000	$2,076,000	$953,000	$6,096,000	--	--	$1,376,000	--	$1,263,000	$28,245,000
PM2.5	$4,519,000	$1,360,000	$671,000	$2,722,000	$27,304,000	$81,911,000	$604,000	--	$2,644,000	$121,731,000
PM2.5 (direct energy savings)	$2,904,000	$1,139,000	$570,000	$2,075,000	--	--	--	--	$742,000	$7,428,000
PM2.5 (indirect energy savings)	$1,615,000	$222,000	$102,000	$648,000	--	--	$604,000	--	$1,903,000	$5,090,000
PM2.5 (electricity generation)	--	--	--	--	$27,304,000	$81,911,000	--	--	--	$109,214,000
Heat-related mortality	$5,845,000	$736,000	$338,000	$2,159,000	--	--	$2,198,000	--	$3,830,000	$15,103,000
Climate change	$23,189,000	$9,269,000	$4,587,000	$2,877,000	$11,916,000	$35,746,000	$13,801,000	--	$10,517,000	$111,897,000
GHG emissions	$1,070,000	$6,758,000	$3,332,000	$1,313,000	$11,916,000	$35,746,000	$252,000	--	$968,000	$61,352,000
GHG emissions (direct energy savings)	$454,000	$5,598,000	$2,799,000	$1,067,000	--	--	--	--	$189,000	$10,104,000
GHG emissions (indirect energy savings)	$617,000	$1,161,000	$533,000	$247,000	--	--	$252,000	--	$780,000	$3,588,000
GHG emissions (energy generation)	--	--	--	--	$11,916,000	$35,746,000	--	--	--	$47,662,000
Global cooling	$22,119,000	$2,511,000	$1,256,000	$1,564,000	--	--	$13,550,000	--	$9,549,000	$50,546,000
Reduced portable water use	--	--	$4,144,000	--	--	--	--	--	--	$4,144,000
Reduced salt use	--	--	--	--	--	--	--	$178,000	--	$178,000
Employment	--	$1,988,000	$1,397,000	$4,387,000	$8,492,000	$25,474,000	--	--	--	$41,737,000
Employee pay	--	$1,572,000	$1,107,000	$3,469,000	$7,406,000	$22,218,000	--	--	--	$35,770,000
Welfare payments	--	$4,000	$3,000	$10,000	$10,000	$28,000	--	--	--	$53,000
Tax revenue	--	$414,000	$288,000	$909,000	$1,077,000	$3,230,000	--	--	--	$5,915,000
Federal taxes	--	$369,000	$256,000	$812,000	$866,000	$2,597,000	--	--	--	$4,899,000
State taxes	--	$0	$0	$0	$0	$0	--	--	--	$0
City taxes	--	$45,000	$32,000	$97,000	$211,000	$633,000	--	--	--	$1,017,000
NPV	**$43,366,000**	**$14,030,000**	**$11,767,000**	**$95,000**	**$52,119,000**	**$151,355,000**	**$7,453,000**	**$40,448,000**	**$108,336,000**	**$428,966,000**

Table 26.2. Detailed net present value (NPV) of costs and benefits (through 2050)

SOLUTION	Cool Roofs	Cool Roofs + Bioretention	Cool Roofs + Rainwater Harvesting	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Permeable Pavements	Urban Trees	TOTAL
COSTS	**$28,963,000**	**$20,930,000**	**$14,817,000**	**$254,717,000**	**$216,228,000**	**$487,000**	**$36,886,000**	**$12,719,000**	**$200,664,000**	**$786,405,000**
First cost	$22,149,000	$16,890,000	$9,586,000	$182,879,000	$152,312,000	--	$21,471,000	$12,955,000	$126,866,000	$545,103,000
Operations and maintenance	$0	$1,848,000	$4,865,000	$71,708,000	$20,271,000	--	--	$5,863,000	$62,659,000	$167,212,000
Additional replacements	$6,814,000	$1,758,000	$112,000	--	$43,484,000	--	$15,416,000	-$6,099,000	$11,140,000	$72,622,000
Employment training	$0	$436,000	$256,000	$130,000	$163,000	$487,000	--	--	--	$1,469,000
BENEFITS	**$190,504,000**	**$66,732,000**	**$54,189,000**	**$455,521,000**	**$371,390,000**	**$375,698,000**	**$87,689,000**	**$155,116,000**	**$642,563,000**	**$2,399,398,000**
Energy	$24,129,000	$4,580,000	$2,262,000	$17,843,000	$196,597,000	$26,848,000	$3,747,000	--	$6,742,000	$282,744,000
Direct energy savings	$17,777,000	$3,891,000	$1,946,000	$15,821,000	--	--	--	--	$2,644,000	$42,078,000
Indirect (UHI) energy savings	$6,352,000	$689,000	$316,000	$2,022,000	--	--	$3,747,000	--	$4,098,000	$17,222,000
Electricity value	--	--	--	--	$178,973,000	$26,848,000	--	--	--	$205,821,000
SRECs	--	--	--	--	$17,624,000	--	--	--	--	$17,624,000
Financial incentives	--	--	--	--	$58,510,000	--	--	--	--	$58,510,000
Tax Credit	--	--	--	--	$14,983,000	--	--	--	--	$14,983,000
Depreciation	--	--	--	--	$43,528,000	--	--	--	--	$43,528,000
Stormwater	--	$26,174,000	$33,496,000	$386,539,000	--	--	--	$154,557,000	$560,942,000	$1,161,705,000
Fee discounts	--	$631,000	$518,000	$4,241,000	--	--	--	$2,044,000	$8,649,000	$16,081,000
SRC value	--	$25,543,000	$32,978,000	$382,299,000	--	--	--	--	$552,293,000	$993,111,000
Health	$90,540,000	$11,769,000	$5,501,000	$31,918,000	$57,982,000	$173,946,000	$22,429,000	--	$45,714,000	$439,797,000
Pollution uptake	--	--	--	--	--	--	--	--	$21,415,000	21415000
Ozone	$60,088,000	$6,519,000	$2,991,000	$19,148,000	--	--	$7,872,000	--	$3,966,000	$100,582,000
PM2.5	$9,141,000	$2,940,000	$1,452,000	$5,990,000	$57,982,000	$173,946,000	$1,980,000	--	$8,304,000	$261,732,000
PM2.5 (direct energy savings)	$5,474,000	$2,458,000	$1,229,000	$4,646,000	--	--	--	--	$2,329,000	$16,134,000
PM2.5 (indirect energy savings)	$3,667,000	$483,000	$223,000	$1,345,000	--	--	$1,980,000	--	$5,976,000	$13,671,000
PM2.5 (electricity generation)	--	--	--	--	$57,982,000	$173,946,000	--	--	--	$231,928,000
Heat-related mortality	$21,312,000	$2,310,000	$1,060,000	$6,781,000	--	--	$12,578,000	--	$12,030,000	$56,069,000
Climate change	$75,836,000	$20,414,000	$10,115,000	$8,620,000	$38,564,000	$115,692,000	$61,514,000	--	$29,166,000	$359,919,000
GHG emissions	$292,000	$12,895,000	$6,356,000	$4,700,000	$38,564,000	$115,692,000	$1,137,000	--	$5,215,000	$184,848,000
GHG emissions (direct energy savings)	-$1,642,000	$10,556,000	$5,278,000	$4,010,000	--	--	--	--	$1,015,000	$19,215,000
GHG emissions (indirect energy savings)	$1,934,000	$2,340,000	$1,078,000	$690,000	--	--	$1,137,000	--	$4,201,000	$11,379,000
GHG emissions (energy generation)	--	--	--	--	$38,564,000	$115,692,000	--	--	--	$154,256,000
Global cooling	$75,544,000	$7,519,000	$3,760,000	$3,921,000	--	--	$60,378,000	--	$23,951,000	$175,071,000
Reduced portable water use	--	--	$12,847,000	--	--	--	--	--	--	$12,847,000
Reduced salt use	--	--	--	--	--	--	--	$560,000	--	$560,000
Employment	--	$3,797,000	$2,817,000	$10,603,000	$19,738,000	$59,214,000	--	--	--	$96,167,000
Employee pay	--	$3,001,000	$2,231,000	$8,383,000	$17,214,000	$51,641,000	--	--	--	$82,468,000
Welfare payments	--	$7,000	$7,000	$26,000	$22,000	$66,000	--	--	--	$127,000
Tax revenue	--	$790,000	$580,000	$2,195,000	$2,503,000	$7,507,000	--	--	--	$13,573,000
Federal taxes	--	$704,000	$516,000	$1,964,000	$2,013,000	$6,038,000	--	--	--	$11,232,000
State taxes	--	$0	$0	$0	$0	$0	--	--	--	$0
City taxes	--	$86,000	$65,000	$232,000	$490,000	$1,470,000	--	--	--	$2,341,000
NPV	**$161,542,000**	**$45,802,000**	**$39,372,000**	**$200,805,000**	**$155,163,000**	**$375,212,000**	**$50,804,000**	**$142,398,000**	**$441,899,000**	**$1,612,993,000**

Table 26.3. Detailed net present value (NPV) of costs and benefits (through 2056)

SOLUTION	Cool Roofs	Cool Roofs + Bioretention	Cool Roofs + Rainwater Harvesting	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Permeable Pavements	Urban Trees	TOTAL
COSTS	**$32,318,000**	**$23,351,000**	**$16,752,000**	**$282,957,000**	**$242,487,000**	**$499,000**	**$43,802,000**	**$13,538,000**	**$234,846,000**	**$890,546,000**
First cost	$23,827,000	$18,169,000	$10,312,000	$194,607,000	$163,019,000	--	$23,537,000	$13,936,000	$136,475,000	$583,879,000
Operations and maintenance	$0	$2,289,000	$6,026,000	$88,214,000	$25,112,000	--	--	$7,263,000	$77,622,000	$206,523,000
Additional replacements	$8,491,000	$2,425,000	$140,000	--	$54,192,000	--	$20,265,000	-$7,661,000	$20,750,000	$98,600,000
Employment training	$0	$469,000	$276,000	$138,000	$167,000	$499,000	--	--	--	$1,546,000
BENEFITS	**$236,960,000**	**$80,048,000**	**$65,751,000**	**$563,636,000**	**$443,693,000**	**$450,611,000**	**$112,377,000**	**$192,130,000**	**$797,038,000**	**$2,942,239,000**
Energy	$30,658,000	$5,674,000	$2,802,000	$22,103,000	$238,953,000	$33,202,000	$5,014,000	--	$8,352,000	$346,754,000
Direct energy savings	$22,514,000	$4,821,000	$2,411,000	$19,599,000	--	--	--	--	$3,276,000	$52,618,000
Indirect (UHI) energy savings	$8,145,000	$853,000	$392,000	$2,504,000	--	--	$5,014,000	--	$5,077,000	$21,983,000
Electricity value	--	--	--	--	$221,329,000	$33,202,000	--	--	--	$254,531,000
SRECs	--	--	--	--	$17,624,000	--	--	--	--	$17,624,000
Financial incentives	--	--	--	--	$65,604,000	--	--	--	--	$65,604,000
Tax Credit	--	--	--	--	$14,983,000	--	--	--	--	$14,983,000
Depreciation	--	--	--	--	$50,622,000	--	--	--	--	$50,622,000
Stormwater	--	$32,415,000	$41,482,000	$478,786,000	--	--	--	$191,437,000	$694,775,000	$1,438,893,000
Fee discounts	--	$773,000	$634,000	$5,195,000	--	--	--	$2,505,000	$10,595,000	$19,700,000
SRC value	--	$31,643,000	$40,848,000	$473,592,000	--	--	--	--	$684,180,000	$1,230,261,000
Health	$114,544,000	$14,282,000	$6,669,000	$38,978,000	$65,824,000	$197,472,000	$29,734,000	--	$56,631,000	$524,131,000
Pollution uptake	--	--	--	--	--	--	--	--	$26,529,000	26529000
Ozone	$77,048,000	$8,076,000	$3,705,000	$23,720,000	--	--	$10,532,000	--	$4,913,000	$127,992,000
PM2.5	$10,168,000	$3,346,000	$1,652,000	$6,858,000	$65,824,000	$197,472,000	$2,372,000	--	$10,287,000	$297,977,000
PM2.5 (direct energy savings)	$5,941,000	$2,795,000	$1,398,000	$5,344,000	--	--	--	--	$2,885,000	$18,362,000
PM2.5 (indirect energy savings)	$4,228,000	$552,000	$255,000	$1,514,000	--	--	$2,372,000	--	$7,403,000	$16,320,000
PM2.5 (electricity generation)	--	--	--	--	$65,824,000	$197,472,000	--	--	--	$263,296,000
Heat-related mortality	$27,329,000	$2,861,000	$1,312,000	$8,401,000	--	--	$16,831,000	--	$14,902,000	$71,634,000
Climate change	$91,758,000	$23,349,000	$11,573,000	$11,159,000	$50,341,000	$151,022,000	$77,630,000	--	$37,282,000	$454,110,000
GHG emissions	-$1,053,000	$14,086,000	$6,942,000	$6,308,000	$50,341,000	$151,022,000	$1,519,000	--	$7,645,000	$236,806,000
GHG emissions (direct energy savings)	-$3,532,000	$11,481,000	$5,741,000	$5,453,000	--	--	--	--	$1,487,000	$20,628,000
GHG emissions (indirect energy savings)	$2,479,000	$2,605,000	$1,202,000	$855,000	--	--	$1,519,000	--	$6,158,000	$14,817,000
GHG emissions (energy generation)	--	--	--	--	$50,341,000	$151,022,000	--	--	--	$201,362,000
Global cooling	$92,812,000	$9,264,000	$4,632,000	$4,852,000	--	--	$76,111,000	--	$29,637,000	$217,305,000
Reduced portable water use	--	--	$15,868,000	--	--	--	--	--	--	$15,868,000
Reduced salt use	--	--	--	--	--	--	--	$693,000	--	$693,000
Employment	--	$4,330,000	$3,227,000	$12,611,000	$22,973,000	$68,917,000	--	--	--	$112,056,000
Employee pay	--	$3,422,000	$2,556,000	$9,970,000	$20,035,000	$60,103,000	--	--	--	$96,083,000
Welfare payments	--	$8,000	$8,000	$32,000	$26,000	$78,000	--	--	--	$150,000
Tax revenue	--	$900,000	$665,000	$2,611,000	$2,913,000	$8,738,000	--	--	--	$15,824,000
Federal taxes	--	$802,000	$591,000	$2,336,000	$2,343,000	$7,028,000	--	--	--	$13,098,000
State taxes	--	$0	$0	$0	$0	$0	--	--	--	$0
City taxes	--	$98,000	$74,000	$275,000	$571,000	$1,711,000	--	--	--	$2,727,000
NPV	**$204,642,000**	**$56,697,000**	**$49,000,000**	**$280,679,000**	**$201,206,000**	**$450,113,000**	**$68,575,000**	**$178,592,000**	**$562,193,000**	**$2,051,693,000**

26.2 NPV per square foot

26.2.1 Cool roofs

Table 26.4. Costs and benefits per square foot of cool roof (albedo and cost held constant)

TYPE	Commercial Low Slope	Commercial Steep Slope	Residential Low Slope	Residential Steep Slope
COSTS	$0.23	$0.83	$0.23	$0.83
First cost	$0.15	$0.53	$0.15	$0.53
Operations and maintenance	$0.00	$0.00	$0.00	$0.00
Additional replacements	$0.08	$0.30	$0.08	$0.30
Employment training	$0.00	$0.00	$0.00	$0.00
BENEFITS	$5.85	$1.16	$3.86	$1.13
Energy	$1.63	$0.11	$0.43	$0.09
Direct energy savings	$1.42	$0.05	$0.21	$0.03
Indirect (UHI) energy savings	$0.22	$0.06	$0.22	$0.06
Health	$3.38	$0.87	$3.00	$0.87
Ozone	$2.04	$0.61	$2.04	$0.61
PM2.5	$0.62	$0.05	$0.24	$0.04
PM2.5 (direct energy savings)	$0.54	$0.02	$0.16	$0.02
PM2.5 (indirect energy savings)	$0.08	$0.02	$0.08	$0.02
Heat-related mortality	$0.72	$0.22	$0.72	$0.22
Climate change	$0.84	$0.18	$0.43	$0.17
GHG emissions	$0.24	$0.00	-$0.17	$0.00
GHG emissions (direct energy savings)	$0.20	-$0.01	-$0.20	-$0.01
GHG emissions (indirect energy savings)	$0.03	$0.01	$0.03	$0.01
Global cooling	$0.60	$0.18	$0.60	$0.18
Employment	$0.00	$0.00	$0.00	$0.00
Welfare payments	$0.00	$0.00	$0.00	$0.00
Tax revenue	$0.00	$0.00	$0.00	$0.00
Federal taxes	$0.00	$0.00	$0.00	$0.00
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.00	$0.00	$0.00	$0.00
NPV	$5.45	$0.30	$3.52	$0.27

Table 26.5. Costs and benefits per square foot of cool roof + bioretention (albedo and cost held constant)

TYPE	Commercial Low Slope + Standard Bioretention	Multifamily Low Slope + Standard Bioretention	Commercial Low Slope + Enhanced Bioretention	Multifamily Low Slope + Enhanced Bioretention
COSTS	$4.72	$4.72	$4.96	$4.96
First cost	$3.23	$3.23	$3.43	$3.43
Operations and maintenance	$0.60	$0.60	$0.60	$0.60
Additional replacements	$0.82	$0.82	$0.86	$0.86
Employment training	$0.08	$0.08	$0.09	$0.09
BENEFITS	$14.51	$12.61	$27.87	$25.97
Energy	$1.58	$0.43	$1.58	$0.43
Direct energy savings	$1.36	$0.20	$1.36	$0.20
Indirect (UHI) energy savings	$0.23	$0.23	$0.23	$0.23
Stormwater	$7.74	$7.74	$21.09	$21.09
Fee discounts	$0.18	$0.18	$0.43	$0.43
SRC value	$7.56	$7.56	$20.66	$20.66
Health	$3.48	$3.12	$3.48	$3.12
Ozone	$2.12	$2.12	$2.12	$2.12
PM2.5	$0.60	$0.24	$0.60	$0.24
PM2.5 (direct energy savings)	$0.52	$0.16	$0.52	$0.16
PM2.5 (indirect energy savings)	$0.08	$0.08	$0.08	$0.08
Heat-related mortality	$0.75	$0.75	$0.75	$0.75
Climate change	$0.80	$0.42	$0.80	$0.42
GHG emissions	$0.23	-$0.16	$0.23	-$0.16
GHG emissions (direct energy savings)	$0.20	-$0.19	$0.20	-$0.19
GHG emissions (indirect energy savings)	$0.03	$0.03	$0.03	$0.03
Global cooling	$0.57	$0.57	$0.57	$0.57
Employment	$0.91	$0.91	$0.92	$0.92
Employee pay	$0.72	$0.72	$0.72	$0.72
Welfare payments	$0.00	$0.00	$0.00	$0.00
Tax revenue	$0.19	$0.19	$0.20	$0.20
Federal taxes	$0.17	$0.17	$0.18	$0.18
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.02	$0.02	$0.02	$0.02
NET TOTAL	$9.37	$7.53	$22.10	$20.25

Table 26.6. Costs and benefits per square foot of cool roof + rainwater harvesting (albedo and cost held constant)

TYPE	Commercial Low Slope + Rainwater Harvesting	Multifamily Low Slope + Rainwater Harvesting
COSTS	$7.25	$7.25
First cost	$3.85	$3.85
Operations and maintenance	$3.31	$3.31
Additional replacements	$0.08	$0.08
Employment training	$0.10	$0.10
BENEFITS	$38.98	$36.53
Energy	$1.63	$0.43
Direct energy savings	$1.42	$0.21
Indirect (UHI) energy savings	$0.22	$0.22
Stormwater	$22.81	$22.76
Fee discounts	$0.34	$0.34
SRC value	$22.47	$22.43
Health	$3.38	$3.00
Ozone	$2.04	$2.04
PM2.5	$0.62	$0.24
PM2.5 (direct energy savings)	$0.54	$0.16
PM2.5 (indirect energy savings)	$0.08	$0.08
Heat-related mortality	$0.72	$0.72
Climate change	$0.84	$0.43
GHG emissions	$0.24	-$0.17
GHG emissions (direct energy savings)	$0.20	-$0.20
GHG emissions (indirect energy savings)	$0.03	$0.03
Global cooling	$0.60	$0.60
Reduced portable water use	$8.87	$8.46
Employment	$1.44	$1.44
Employee pay	$1.14	$1.14
Welfare payments	$0.00	$0.00
Tax revenue	$0.30	$0.30
Federal taxes	$0.26	$0.26
State taxes	$0.00	$0.00
City taxes	$0.03	$0.03
NET TOTAL	$30.59	$28.22

26.2.2 Green roofs

Table 26.7. Costs and benefits per square foot of green roof (cost held constant)

TYPE	Commercial Low Slope	Residential Low Slope
COSTS	$21.83	$21.83
First cost	$14.56	$14.56
Operations and maintenance	$7.45	$7.45
Employment training	$0.03	$0.03
BENEFITS	$48.05	$47.75
Energy	$1.98	$1.71
Direct energy savings	$1.77	$1.49
Indirect (UHI) energy savings	$0.22	$0.22
Stormwater	$41.09	$41.09
Fee discounts	$0.43	$0.43
SRC value	$40.66	$40.66
Health	$3.49	$3.30
Ozone	$2.04	$2.04
PM2.5	$0.73	$0.55
PM2.5 (direct energy savings)	$0.65	$0.46
PM2.5 (indirect energy savings)	$0.08	$0.08
Heat-related mortality	$0.72	$0.72
Climate change	$0.51	$0.67
GHG emissions	$0.39	$0.55
GHG emissions (direct energy savings)	$0.36	$0.52
GHG emissions (indirect energy savings)	$0.03	$0.03
Global cooling	$0.12	$0.12
Employment	$0.98	$0.98
Employee pay	$0.77	$0.77
Welfare payments	$0.00	$0.00
Tax revenue	$0.20	$0.20
Federal taxes	$0.18	$0.18
State taxes	$0.00	$0.00
City taxes	$0.02	$0.02
NET TOTAL	$24.82	$24.53

26.2.3 Solar PV

Table 26.8. Costs and benefits per square foot of solar PV direct purchase (commercial and multifamily) (cost held constant)

TYPE	Commercial Low Slope	Commercial Steep Slope	Multifamily Low Slope	Multifamily Steep Slope
COSTS	$59.72	$73.18	$59.72	$73.18
First cost	$34.40	$42.21	$34.40	$42.21
Operations and maintenance	$5.98	$7.34	$5.98	$7.34
Additional replacements	$19.04	$23.37	$19.04	$23.37
Employment training	$0.47	$0.47	$0.47	$0.47
BENEFITS	$136.00	$140.91	$136.32	$162.77
Energy value	$77.27	$91.50	$77.60	$91.90
Electricity value	$54.46	$64.50	$54.80	$64.90
SRECs	$22.80	$27.00	$22.80	$27.00
Financial incentives	$26.62	$32.67	$26.62	$32.67
Tax Credit	$10.32	$12.66	$10.32	$12.66
Depreciation	$16.30	$20.00	$16.30	$20.00
Initial install depreciation	$9.97	$12.24	$9.97	$12.24
Replacement depreciation	$6.33	$7.76	$6.33	$7.76
Health	$20.09	$1.67	$20.09	$23.79
PM2.5	$20.09	$1.67	$20.09	$23.79
PM2.5 (electricity generation)	$20.09	$1.67	$20.09	$23.79
Climate change	$10.75	$12.73	$10.75	$12.73
GHG emissions	$10.75	$12.73	$10.75	$12.73
GHG emissions (energy generation)	$10.75	$12.73	$10.75	$12.73
Employment	$4.55	$5.59	$4.55	$5.59
Employee pay	$3.97	$4.88	$3.97	$4.88
Welfare payments	$0.00	$0.01	$0.00	$0.01
Tax revenue	$0.58	$0.71	$0.58	$0.71
Federal taxes	$0.46	$0.57	$0.46	$0.57
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.11	$0.14	$0.11	$0.14
NET TOTAL	$76.28	$67.73	$76.60	$89.59

Table 26.9. Costs and benefits per square foot of solar PV direct purchase (single family) (cost held constant)

TYPE	Single Family Detached Low Slope	Single Family Detached Steep Slope	Single Family Attached Low Slope	Single Family Attached Steep Slope
COSTS	**$72.66**	**$89.07**	**$72.66**	**$89.07**
First cost	**$42.33**	**$51.95**	**$42.33**	**$51.95**
Operations and maintenance	**$6.61**	**$8.12**	**$6.61**	**$8.12**
Additional replacements	**$23.44**	**$28.77**	**$23.44**	**$28.77**
Employment training	**$0.47**	**$0.47**	**$0.47**	**$0.47**
BENEFITS	**$129.90**	**$151.59**	**$129.90**	**$147.33**
Energy value	**$77.60**	**$95.62**	**$77.60**	**$92.48**
Electricity value	**$54.80**	**$67.53**	**$54.80**	**$65.31**
SRECs	**$22.80**	**$28.10**	**$22.80**	**$27.17**
Financial incentives	**$12.70**	**$15.59**	**$12.70**	**$15.59**
Tax Credit	**$12.70**	**$15.59**	**$12.70**	**$15.59**
Depreciation	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Health	**$24.65**	**$24.75**	**$24.65**	**$23.94**
PM2.5	**$24.65**	**$24.75**	**$24.65**	**$23.94**
PM2.5 (electricity generation)	**$24.65**	**$24.75**	**$24.65**	**$23.94**
Climate change	**$13.20**	**$13.25**	**$13.20**	**$12.81**
GHG emissions	**$13.20**	**$13.25**	**$13.20**	**$12.81**
GHG emissions (energy generation)	**$13.20**	**$13.25**	**$13.20**	**$12.81**
Employment	**$5.26**	**$6.46**	**$5.26**	**$6.46**
Employee pay	**$4.59**	**$5.64**	**$4.59**	**$5.64**
Welfare payments	**$0.01**	**$0.01**	**$0.01**	**$0.01**
Tax revenue	**$0.67**	**$0.82**	**$0.67**	**$0.82**
Federal taxes	**$0.54**	**$0.66**	**$0.54**	**$0.66**
State taxes	**$0.00**	**$0.00**	**$0.00**	**$0.00**
City taxes	**$0.13**	**$0.16**	**$0.13**	**$0.16**
NET TOTAL	**$57.23**	**$62.52**	**$57.23**	**$58.27**

Table 26.10. Costs and benefits per square foot of solar PV PPA (commercial and multifamily) (cost held constant)

TYPE	Commercial Low Slope	Commercial Steep Slope	Multifamily Low Slope	Multifamily Steep Slope
COSTS	**$0.47**	**$0.47**	**$0.47**	**$0.47**
First cost	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Operations and maintenance	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Additional replacements	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Employment training	**$0.47**	**$0.47**	**$0.47**	**$0.47**
BENEFITS	**$37.01**	**$44.02**	**$37.02**	**$44.04**
Energy value	**$2.72**	**$3.23**	**$2.74**	**$3.24**
Electricity value	**$2.72**	**$3.23**	**$2.74**	**$3.24**
SRECs	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Financial incentives	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Tax Credit	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Depreciation	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Initial install depreciation	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Replacement depreciation	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Health	**$20.09**	**$23.79**	**$20.09**	**$23.79**
PM2.5	**$20.09**	**$23.79**	**$20.09**	**$23.79**
PM2.5 (electricity generation)	**$20.09**	**$23.79**	**$20.09**	**$23.79**
Climate change	**$10.75**	**$12.73**	**$10.75**	**$12.73**
GHG emissions	**$10.75**	**$12.73**	**$10.75**	**$12.73**
GHG emissions (energy generation)	**$10.75**	**$12.73**	**$10.75**	**$12.73**
Employment	**$4.55**	**$5.59**	**$4.55**	**$5.59**
Employee pay	**$3.97**	**$4.88**	**$3.97**	**$4.88**
Welfare payments	**$0.00**	**$0.01**	**$0.00**	**$0.01**
Tax revenue	**$0.58**	**$0.71**	**$0.58**	**$0.71**
Federal taxes	**$0.46**	**$0.57**	**$0.46**	**$0.57**
State taxes	**$0.00**	**$0.00**	**$0.00**	**$0.00**
City taxes	**$0.11**	**$0.14**	**$0.11**	**$0.14**
NET TOTAL	**$36.54**	**$43.55**	**$36.55**	**$43.57**

Table 26.11. Costs and benefits per square foot of solar PV PPA (single family) (cost held constant)

TYPE	Single Family Detached Low Slope	Single Family Detached Steep Slope	Single Family Attached Low Slope	Single Family Attached Steep Slope
COSTS	$0.47	$0.47	$0.47	$0.47
First cost	$0.00	$0.00	$0.00	$0.00
Operations and maintenance	$0.00	$0.00	$0.00	$0.00
Additional replacements	$0.00	$0.00	$0.00	$0.00
Employment training	$0.47	$0.47	$0.47	$0.47
BENEFITS	$44.52	$46.45	$44.52	$45.13
Energy value	$2.74	$3.38	$2.74	$3.27
Electricity value	$2.74	$3.38	$2.74	$3.27
SRECs	$0.00	$0.00	$0.00	$0.00
Financial incentives	$0.00	$0.00	$0.00	$0.00
Tax Credit	$0.00	$0.00	$0.00	$0.00
Depreciation	$0.00	$0.00	$0.00	$0.00
Health	$24.65	$24.75	$24.65	$23.94
PM2.5	$24.65	$24.75	$24.65	$23.94
PM2.5 (electricity generation)	$24.65	$24.75	$24.65	$23.94
Climate change	$13.20	$13.25	$13.20	$12.81
GHG emissions	$13.20	$13.25	$13.20	$12.81
GHG emissions (energy generation)	$13.20	$13.25	$13.20	$12.81
Employment	$5.26	$6.46	$5.26	$6.46
Employee pay	$4.59	$5.64	$4.59	$5.64
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.67	$0.82	$0.67	$0.82
Federal taxes	$0.54	$0.66	$0.54	$0.66
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.13	$0.16	$0.13	$0.16
NET TOTAL	$44.05	$45.98	$44.05	$44.66

26.2.4 Reflective pavements

Table 26.12. Costs and benefits per square foot of reflective pavement (albedo and cost held constant)

TYPE	Road Lifecyle A	Road Lifecyle B	Parking Lot	Concrete Sidewalk	Brick Sidewalk
COSTS	$0.34	$0.39	$0.95	$0.24	$0.52
First cost	$0.02	$0.02	$0.46	$0.24	$0.52
Additional replacements	$0.33	$0.38	$0.50	$0.00	$0.00
BENEFITS	$0.63	$0.63	$0.63	$0.31	$0.32
Energy	$0.06	$0.06	$0.06	$0.03	$0.03
Indirect (UHI) energy savings	$0.06	$0.06	$0.06	$0.03	$0.03
Health	$0.38	$0.38	$0.38	$0.19	$0.19
Ozone	$0.14	$0.14	$0.14	$0.07	$0.07
PM2.5	$0.02	$0.02	$0.02	$0.01	$0.01
PM2.5 (indirect energy savings)	$0.02	$0.02	$0.02	$0.01	$0.01
Heat-related mortality	$0.22	$0.22	$0.22	$0.11	$0.11
Climate change	$0.19	$0.19	$0.19	$0.09	$0.10
GHG emissions	$0.01	$0.01	$0.01	$0.00	$0.01
GHG emissions (indirect energy savings)	$0.01	$0.01	$0.01	$0.00	$0.01
Global cooling	$0.18	$0.18	$0.18	$0.09	$0.09
NET TOTAL	$0.27	$0.22	-$0.33	$0.06	-$0.21

26.2.5 Permeable pavements

Table 26.13. Costs and benefits per square foot of permeable pavement (albedo and cost held constant)

TYPE	Plastic Grid + Gravel Parking Lot	Plastic Grid + Grass Parking Lot	Pervious Concrete Sidewalk Standard	Pervious Concrete Sidewalk Enhanced	Permeable Paver Sidewalk Standard	Permeable Paver Sidewalk Enhanced
COSTS	**-$3.97**	**-$5.63**	**$6.44**	**$8.62**	**$0.85**	**$3.03**
First cost	-$1.36	-$1.57	$5.32	$7.49	-$0.27	$1.91
Operations and maintenance	$1.16	$1.62	$1.16	$1.16	$1.16	$1.16
Additional replacements	-$3.73	-$5.63	$0.00	$0.00	$0.00	$0.00
BENEFITS	**$19.79**	**$30.61**	**$13.91**	**$123.55**	**$13.91**	**$123.55**
Energy	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Indirect (UHI) energy savings	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Stormwater	$19.61	$30.44	$13.82	$123.47	$13.82	$123.47
Fee discounts	$0.32	$0.43	$0.20	$1.30	$0.20	$1.30
SRC revenue	$19.29	$30.01	$13.62	$122.16	$13.62	$122.16
Health	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Ozone	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
PM2.5	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
PM2.5 (indirect energy savings)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Heat-related mortality	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Climate change	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
GHG emissions	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
GHG emissions (indirect energy savings)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Reduced salt use	$0.17	$0.17	$0.09	$0.09	$0.09	$0.09
NET TOTAL	**$23.18**	**$35.35**	**$7.06**	**$111.34**	**$12.65**	**$116.92**

26.2.6 Urban trees

Table 26.14. Costs and benefits per square foot urban tree canopy (albedo and cost held constant)

COSTS	**$2.91**
First cost	**$1.31**
Operations and maintenance	**$1.10**
Additional replacements	**$0.54**
BENEFITS	**$10.75**
Energy	**$0.12**
Direct energy savings	**$0.05**
Indirect (UHI) energy savings	**$0.07**
Stormwater	**$9.80**
Fee discounts	**$0.15**
SRC value	**$9.66**
Health	**$0.70**
Pollution uptake	**$0.38**
Ozone	**$0.07**
PM2.5	**$0.05**
PM2.5 (direct energy savings)	**$0.02**
PM2.5 (indirect energy savings)	**$0.03**
Heat-related mortality	**$0.21**
Climate change	**$0.13**
GHG emissions	**$0.01**
GHG emissions (direct energy savings)	**$0.00**
GHG emissions (indirect energy savings)	**$0.01**
Global cooling	**$0.12**
NET TOTAL	**$7.53**

27 Appendix: Potentially significant benefits not included not included in cost-benefit calculations

Impact	Impact Direction	Application Smart Surface
Peak energy reduction	Net Benefit	Cool roofs, green roofs, solar PV; to a lesser extent reflective pavements, permeable pavements and urban trees
HVAC air intake temperature reduction	Net Benefit	Cool roofs, green roofs
Regional cooling	Net Benefit	All (except rainwater harvesting)
Increase amenity/property value	Net Benefit	Green roofs, solar PV, bioretention, urban trees
Increased PV efficiency	Net Benefit	Green roofs
Reduced ozone concentrations	Net Benefit	Solar PV
Increased roof or pavement life	Net Benefit	Cool roof, reflective pavements
Improved thermal comfort	Net Benefit	All (except rainwater harvesting)
UHI mitigation	Net Benefit	Solar PV, permeable pavements

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[4] Nicholas Kristof, “Temperatures Rise, and We’re Cooked”, New York Times, September 11, 2016, p. 11
[5] In 2013 Capital E proposed to do this work for Washington, DC and separately, with a low income focus, to the JPB Foundation. Current work Capital E is leading for JPB focuses on low income areas and city wide for DC, El Paso and Philadelphia with a focus on low income impact. It is clear from this work that cities have physical characteristics that structurally burden and disadvantage their low income and minority citizens and that make it hard for them to fully participate in the educational and economic life of their cities. Some of the low income impact findings from work undertaken for JPB is included in this report. In effect, this work was developed in parallel for both clients, with differing but overlapping objectives. This parallel process has allowed iterative analysis and feedback that has proven useful.
6 “Polluted Runoff”, Save the Bay, Chesapeake Bay Foundation, fall 2016, p 7
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Li et al find that 100% cool roof coverage → ~0.5 C reduction in UHImax, and that 100% green roof coverage → ~0.5 C reduction in UHImax. UHI reductions from Li et al are estimated at the maximum daytime UHI; important to

note that maximum daytime UHI does not necessarily coincide with maximum temperature reductions from the roof modifications (which tends to underestimate peak temperature impact). Li et al assume albedo change of 0.40 for cool roofs; by end of our analysis we assume 0.5 for low slope roofs and 0.3 for steep slope roofs. Baseline albedo for Li et al is 0.3, high for conventional roofs → all else equal, underestimate cooling impact of green roof because a small cooling benefit of green roofs is albedo increase → assuming high conventional roof albedo minimizes or eliminates this cooling benefit. Li et al only looked at roofs, while this analysis looks at roofs, pavements, and trees. No studies exist for temp impact of trees in DC, but NYC study showed trees more effective than cool/green roofs at reducing city temperatures → greater impact on temp than roofs. Pavements, while don't necessarily have as great albedo change as roofs, are higher % of city area than roofs → approximately similar impact on temp. Albedo change roads = 0.2, parking = 0.25, sidewalk = 0.15. Pavement ~24% city area vs roofs ~16% city area.

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