DELIVERING URBAN RESILIENCE

Costs and benefits of city-wide adoption of smart surfaces across Washington, D.C., Philadelphia and El Paso to strengthen resilience, improve health and livability, reduce urban inequality, and slow global warming while saving billions of dollars.

BY GREG KATS AND KEITH GLASSBROOK

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EARLY REVIEWS OF "DELIVERING URBAN RESILIENCE"

Will Wynn, former Mayor of Austin

I was born September 10, 1961 during the emergency evacuation of my hometown of Beaumont, Texas during the onslaught of Hurricane Carla, the last Category 4 storm to hit the Texas coast until Hurricane Harvey inundated Texas. As Mayor of Austin, I was proud of our city's response in sheltering thousands of New Orleans evacuees from Hurricane Katrina in 2005. But as hurricanes Harvey and Irma demonstrate, cities must do more than react – they must become far more resilient to hurricanes and other severe weather events that are increasing in intensity and frequency due to climate change.

As two-term Mayor of Austin during a decade of unprecedented growth, I led our city's urban transformation promoting mixed-use density, renewable energy and green buildings. Kats's earlier work documenting costs and benefits of green buildings was a fundamental component in our understanding their advantages, and a powerful driver for our green design promotion and adoption. Delivering Urban Resilience provides an entirely convincing case that city-wide adoption of "smart surfaces" like green and cool roofs and porous pavements can make our cities far more resilient. This rigorous report demonstrates that these smart surfaces strategies are both cost-effective and essential for city resilience, and can help protect our citizens and ensure that our cities remain livable in a warming world. The case has been made - and proven. We must now act.

Mark Chambers, NYC Director of Sustainability

Like NYC with its 8.5 million residents, coastal cities nationally and around the globe are working hard to make themselves more resistant to the accelerating impacts of climate change. The Delivering Urban Resilience report is so critical because it is the first rigorous analysis of city wide surfacing options to manage sun and water at scale. This work quantifies for the first time many substantial benefits of what it calls "smart surfaces", and provides a compelling case that cites should move rapidly to adopt these inclusive and equitable climate solutions to design, upgrade and holistically manage our urban environments to deliver healthier, more resilient outcomes.

Mahesh Ramanujan, CEO, U.S. Green Building Council

As a society, we have no excuses for not improving how our built environment interacts with people and the planet we all rely on. Delivering Urban Resilience demonstrates how leveraging existing "smart surface" technologies will improve living conditions for all of us, and especially for those who live in urban low-income areas. By reducing heat island effects, increasing vegetation and green space, and using renewable energy, cities can make large and measurable improvements in how their cities perform. Just as importantly, this work shows that when health, productivity, jobs and energy benefits are tallied up across the city's economy, the financial benefits provide an impressive return on investment .

Reverend David Bowers, Minister

This report, Delivering Urban Resilience, is important for many reasons. It is the first rigorous analysis of the full cost and benefits of managing our cities' sun and rain, and it shows how to make the city much more resilient, cleaner and more livable. As a city resident working for a company that develops and finances affordable, green and sustainable low-income residences., I am aware of the gross physical inequities in many low-income neighborhoods. This report demonstrates how cities 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.

Dan Tangherlini, former Administrator of GSA, former Administrator (COO) of Washington D.C.

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. Delivering Urban Resilience is a critical, even transformative new analysis that provides a compelling case that cities should accelerate their 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. With this report, we have the roadmap – now we must follow it.

Terri Ludwig, President and CEO, Enterprise Community Partners, Inc.

Enterprise has been a national leader in developing quality, affordable housing and strong communities for several decades. The low-income areas in which we work are often hotter, less green and less healthy than wealthier neighborhoods. The report Delivering Urban Resilience documents – for the first time – the benefits of addressing how such physical disparities can be addressed by adopting a broad range of technologies, including green roofs, cool roofs, solar PV, porous and highly reflective (cooler) pavement and roads. This report rigorously and compellingly demonstrates how such technological investments can have enormous social, health and comfort benefits city wide, but especially in more vulnerable, low-income areas. Providing a cost-effective way to correct the chronic physical disadvantages that impact our low-income communities must be an urgent priority for our nation's cities, and this report demonstrates that such an approach is not only feasible, but that it would more than pay for itself.

Will Baker, President of the Chesapeake Bay Foundation

The report Delivering Urban Resilience provides the first comprehensive documentation of the full benefits associated with roof and surface technologies such as green roofs, porous surfaces, and rain gardens as well as cool roofs and solar PV. What this report demonstrates is 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.

Michael Bodaken, President, the National Housing Trust

This rigorous and comprehensive report for the first time explains, documents and quantifies the full financial cost and benefits of a large range of city surface options such as green roofs, cool roofs, porous and high albedo pavements. The work demonstrates the huge structural disparities and inequalities in low-income city neighborhoods and how these can be addressed in ways that save money as well as enhance health, livability and employment. This is a powerful and timely new tool for cites as they move toward climate responsibility because it provides a roadmap for doing so in a way that enhances citizen's lives, especially for low income seniors and families. And the report is a clarion call to affordable housing developers to deploy smart surfaces across all their developments to save money and to make their residents healthier and happier.

Rick Fedrizzi, Chairman and CEO, International WELL Building Institute, and Founding Chairman, U.S. 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 U.S. and globally, greatly expanding recognition of the financial rational for building green and in accelerating adoption of green design. In Delivering Urban Resilience Kats provides an enormously important step for U.S. 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.

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AUTHOR BIOS

Greg Kats is President of Capital E, which works with cities, companies and financial institutions to design, scale, and implement clean energy and low carbon strategies and technologies. Greg is also Managing Director of ARENA Investments, LCC, which invests in clean energy growth firms. Greg led the development of IPMVP—the global energy and water efficiency design, measurement, and verification standard that is 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 was also awarded the Lifetime Achievement Award from the Alliance to Save Energy. Greg served for six years as the Director of Financing for Energy Efficiency and Renewable Energy at the U.S. Department of Energy. He also served as Managing Director for the multi-billion-dollar global clean energy VC/PE firm Good Energies, investing $1.6 billion in renewable energy, energy efficiency, smart grid, and green building companies globally. Greg has served on the Boards of Directors of a dozen clean energy firms. He served as the Principal Advisor in designing and developing Green Communities, the national green affordable housing design standard that has served as the design basis for 50,000 units of green affordable housing to date. Greg served on the D.C. Mayor's Green Ribbon Task Force, 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 D.C. family home and electric car. His prior work on cost-benefit analysis includes:

- 2016, 2012 and 2011 Congressional testimony on the cost effectiveness of clean energy financing, including 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
- Member, Steering Committee on enhancing U.S. global competitiveness, National Academy of Sciences, findings published as Rising to the Challenge: U.S. Innovation Policy for the Global Economy, National Research Council, 2012
- Author, Greening Our Built World: Costs, Benefits, and Strategies (Island Press, 2010). Extensively excerpted by the National Academy of Sciences in its 2011 publication Achieving High-Performance Federal Facilities
- Principal Author, Green Office Buildings: A Practical Guide to Development (Urban Land Institute, 2005)
- Author, "The Costs and Financial Benefits of Green Buildings." Cited as primary 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 the EPA's biogenic CO_2 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, D.C., 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/MBA at Duke University's Nicholas School of the Environment and Fuqua School of Business.

OVERVIEW

This report provides an in-depth analysis of the costs and benefits of applying a set of smart surface solutions[1], including cool roofs, green roofs, solar PV, and permeable and reflective pavements and road surfaces across three cities: El Paso, Philadelphia and Washington, D.C. The report demonstrates that cities can strengthen resilience, improve health and comfort, expand jobs and slow global warming through smart surface strategies while securing billions of dollars in net financial benefits. Applied nationally, these strategies could potentially deliver half a trillion dollars in net financial benefits.

How cities manage the sun and rain that fall on them has a huge impact on city resilience and on residents' health and quality of life. Some cities have established programs supporting adoption of cool roofs, solar PV or reflective pavements, while others promote expansion of green roofs and trees. But even in a city like Washington, D.C. - which is a national leader in urban sustainability, or in Philadelphia - which is a leader in water management, adoption of these measures is fragmented and limited. This reflects very limited data and analysis to date on the costs and benefits of these solutions.

City leaders, planners and developers lack the data and tools needed to understand and quantify the costs and benefits of technologies such as cool roofs, green roofs and porous pavements that could allow them to manage their city's rain and sun far more effectively and cost-effectively. As a result, cities mismanage their two great natural gifts of sunshine and rain. This mismanagement costs billions of dollars in unnecessary health, energy, and stormwater-related costs, degrades city comfort, decreases livability and resilience, and contributes to climate change.

The costs are greatest in low-income areas, characterized by little greenery and dark impervious surfaces that result in excess summer heat and air pollution, excess respiratory illness, heat stress, and high health costs. Building on earlier work by Capital E for The JPB Foundation and for Washington DC, this report documents and quantifies large physical disadvantages of low-income neighborhoods relative to cities as a whole.[i] This typically includes more paved areas, fewer trees, and lower albedo (reflectivity), all of which means that more sunlight is absorbed, creating additional heat and heat stress and increased smog formation, and in turn worsening health. A broad review published in Environmental Health Perspectives examined heat risk–related land cover and found that, in U.S. cities, African Americans and Hispanics are 51% and 21% more likely, respectively, to live in high heat risk urban areas than non-Hispanic white Americans.[ii] The report found that the "extent of impervious surface is greater in neighborhoods with low socioeconomic status and a high proportion of minority residents", and cites multiple studies of extreme heat that show large racial disparities in heat-related deaths. This systematic structural inequity appears endemic to many US cities.

Even a modest city step such as adoption of a cool roof procurement policy for affordable housing would generate substantial net benefits. For example, changing a square foot of dark, low albedo roof to a higher albedo generates nearly $4/ft^2 in net energy and health benefits.[iii] Residents of these buildings benefit from lower energy bills and improved health due to better air quality, lower heat stress and cooler indoor conditions.

As summarized below, the calculated city-wide net present value (NPV) of city-wide adoption of these technologies ranges from $538 million for El Paso to $1.8 billion for Washington, D.C., and $3.6 billion for Philadelphia. If we include the estimated avoided summer tourism losses the expected NPV from city-wide adoption by our nation's capital rises to $4.9 billion, and for Philadelphia it rises to $8.4 billion.

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[i] *This work builds on two completed studies by Capital E for The JPB Foundation; an evaluation of low-income multi-unit buildings in Washington, D.C., Philadelphia, Baltimore and Los Angeles, and an analysis of costs and benefits of low-income ward-level adoption in Washington, D.C., Philadelphia and Baltimore.*
[ii] *Jesdale et al. (2013) can be accessed at: http://ehp.niehs.nih.gov/1205919/*
[iii] *Accessible at: https://cap-e.com/affordable-housing-smart-roof/*

Summary of the present value of costs and benefits for the three cities studied

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015)		
	Washington, D.C.	**Philadelphia**	**El Paso**
Costs	$838 M	$2.38 B	$1.62 B
Benefits	$2.65 B	$5.96 B	$2.16 B
Net Present Value	$1.81 B	$3.58 B	$538 M

This work tackles the full range of smart surface technologies and quantifies many of their benefits for the first time. In all cases, application of these smart surface technologies both city-wide and to low-income neighborhoods produce financial benefits that exceed costs. At a neighborhood level, such as Ward 5 in Washington, D.C., application of these smart surface technologies would provide a net present value of several hundred million dollars.

This report demonstrates that the growing city-wide risks from extreme heat and weather driven by climate change can be largely offset by city-wide adoption of these smart surface technologies while delivering large net financial benefits. Many of the physical inequalities that characterize and disadvantage low-income areas of most American cities can be greatly improved with smart surface with large net financial returns to the city as a whole. These large net positive financial returns constitute a strong financial, resilience and public policy case for rapid adoption of smart surface solutions city-wide as standard, baseline policy for most U.S. cities.

Note on report structure:

This report starts with an Executive Summary then dives into the cost and performance attributes of each smart surface solution, such as cool roofs, porous pavements and solar PV. The report then describes and documents the smart surfaces cost-benefit analysis, data, models and methods, then summarizes and discusses the results. The report includes key findings that can guide city policies to achieve the most cost-effective mix of these smart surface solutions. Detailed methodologies for each component of the analysis is included to help readers understand costs and benefits of each smart surface solution. This report is intended to enable cities to make more informed policy and design choices to deliver large and cost-effective resilience, health, equity, livability, and environmental benefits.

Note on terms used in this report:

Because this report seeks to rigorously document and quantify a set of technology and policy measures for the first time, we had to develop some new approaches, methodologies and even a few new terms. (See Table 9.1 for overview of this report's additions to the existing methodology in the literature.)

This work for the first time looks at technologies from the air, as it were - all city surfaces and how cities manage - or fail to manage – their sun and rain through their choice of surfaces. This report clusters and analyzes for the first time a set of technologies that are applied to the surfaces of cities – roofs, road, parking lots sidewalks etc and describes these collectively with a new term: "smart surfaces" because they cover surfaces and because they are engineered to deliver a range of measurable if sometimes complex benefits and enhancements relative to conventional surfaces. The large majority of these "smart surfaces" for most cities deliver positive net present value. The process we have developed to understand, quantify and compare these "smart surface" choices also demonstrates that these are, overwhelmingly, smarter choices than conventional design.

It is also clear that the urban heat island reduction strategies such as cool and green roofs and cool pavements if applied city -wide can have large cooling benefits both within the city but also on areas that are downwind in the summers. At the scale of cooling application envisaged – with smart surfaces adopted as baseline standard practice rather than in current limited applications - this downwind cooling impact is cumulative and can be large, potentially doubling peak cooling benefits. This concept is a new one and is potentially very large and so merits a new term - we call it "downwind cooling".

EXECUTIVE SUMMARY

Cities can increase resilience, improve health and comfort, expand jobs and slow global warming through smart surface strategies - such as cool and green roofs – while also achieving hundreds of millions of dollars in net financial benefits at a city level, and potentially deliver half a trillion dollars in net financial benefits from urban deployment nationally.

With more paved area, less greenery and more dark surfaces, cities experience what is called an urban heat island (UHI) effect – substantially higher summer temperatures and worse air pollution than the surrounding suburban and rural areas. The damage and cost of increased temperature and air pollution are particularly acute for urban low-income urban areas. In 2005, *Environmental Health Perspectives* noted 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]

Low income communities generally share some common attributes:

Greater population density	• more people at risk
Higher % children/elderly	• greater medical risk
Higher % impervious surfaces	• hotter, more smog and more stormwater runoff
Lower % tree cover	• hotter and more air pollution
Energy bills higher % of income	• larger relative energy cost savings
Higher % unemployed	• employment benefits potentially larger

Air and temperature conditions are worsened by less tree coverage, fewer reflective and porous surfaces, and more unwanted heat absorption than more affluent city neighborhoods. This results in higher summer temperatures, worse air quality, increased health problems, and higher energy bills than in more affluent areas. Urban low-income residents also suffer disproportionally from the urban heat island effect, and have a higher likelihood of residing in inefficient homes.[3] Health also suffers, and brings cascading costs relating to lost school and work days and reduced income.

The effects of excess heat from climate change on productivity is fast emerging as an area of public interest. A recent New York Times editorial entitled "Temperatures Rise, and We're Cooked" summarizes findings that "students who take New York State Residents exam on a 90-degree day have a 12 percent greater chance of failing than when the temperature is 72 degrees", and that in auto factories, "a week of six days above 90 degrees reduces production by 8 percent".[4] Low-income schools, neighborhoods, workplaces and homes are more likely to experience this kind of discomfort and productivity loss.[iv]

Many U.S. cities struggle with growing water quality and stormwater management issues and costs. Consider the Chesapeake Bay, a 200-mile estuary that receives water from 150 major rivers and streams from six states plus Washington, D.C. It is an enormously important watershed in terms of ecological diversity, quality of life, health, tourism and the economy. And like most watersheds, the health of the

[iv] *Analysis of greener schools with greater comfort, better light, etc., shows quantifiable improvements from reduced number of sick days, enhanced test scores and even lifelong income.*

Chesapeake depends on how urban and built areas upstream manage the rain that falls on them, whether city surfaces are porous and whether smart surface treatments are applied or ignored.[v] [5]

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

Lack of understanding on the cost and benefits of technology and policy options has severely limited urban responses. This report is intended to fill this critical gap by quantifying these costs and benefits in detail, including quantifying more than a dozen significant benefits for the first time. By providing in-depth look at three very different cities—Washington, D.C., Philadelphia and El Paso—this report demonstrates that deployment of smart surface solutions would deliver very large city-wide net benefits, including reducing health and energy costs, increasing employment, resilience and livability—while reducing contribution to global warming.

Because integrated cost-benefit analysis of these solutions has not been done before, this report reflects the guidance of national and city partners, epidemiologists, technology, stormwater, energy experts and others, to assemble and analyze U.S. and international data and studies to build a detailed, integrated cost-benefit analytic/financial model.

We also developed a flow chart for each impact pathway to provide a clear visual representation of causal links between each smart surface technology (such as a cool roof or green roof) and quantified impact (such as increased ozone or reduced CO_2). In order to simplify this representation and quantification of impacts, we include only impacts that are material. Figure 1 below is an example of an impact pathway diagram, in this case for the impact of increasing rooftop vegetation on ozone concentration.

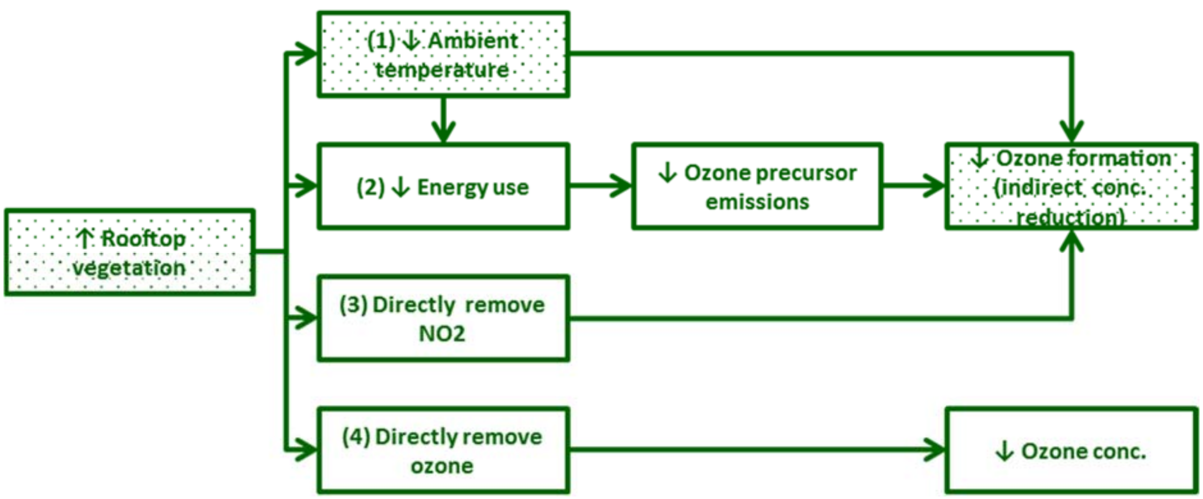

Figure 1: Example of Smart Surface Impact Pathway

(Note: vertical arrows indicate increase or decrease while horizontal arrows indicate direction of impact.)

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[v] *For example, 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."*

[vi] https://www.moodys.com/research/Moodys-Climate-change-is-forecast-to-heighten-US-exposure-to--PR_376056

Costs (such as operations and maintenance costs), and **benefits** (such as ozone reduction or job creation) are mapped and calculated for each smart surface technology. These costs and benefits are then aggregated based on modeled ward-wide or city-wide application of these technology solutions for each of the three cities analyzed: Washington, D.C., Philadelphia and El Paso. While we were able to quantify many benefits, additional significant benefits lack adequate data to allow quantification, so findings here substantially underestimate benefits and net present value of these smart surface solutions.

Low-income areas are characterized by higher poverty rates, worse health and higher unemployment. Deployment of smart surface solutions at scale in low-income areas can largely redress this systematic physical urban inequity. Energy costs make up a higher percentage of expenses for low-income residents. Recent research from the Joint Center for Housing Studies of Harvard University shows that for the lowest-income renters, tenant-paid household energy costs represent approximately 15% of income, while energy costs make up about 1% of total income for the highest-income renters.[i] ". With city training and job linking, a higher percent of jobs created from smart surface solution installations and maintenance could reduce unemployment in low-income areas. Although health benefits from adoption of the solutions analyzed in this report are greater for low-income than for wealthy city residents, these benefits also accrue city-wide. For example, excess summer heat in low income areas also heats up the city more generally. Excess heat in low income areas and worse air quality increase emergency room visits by low-income residents some of whom lack insurance and this imposes with large non-reimbursed hospital costs.

As smart surface deployment scales up, the urban cooling benefits would also grow proportionally, further reducing regional energy bills and smog, and improving health and livability in ways that bring compounding benefits, especially for low-income populations. Lower urban heat effects in adjacent regions that are upwind from Washington, D.C., such as Tysons Corner or Arlington would reduce summer excess heat and smog in those cities *and also* in Washington, D.C. This phenomenon that we call "downwind summer cooling" would bring very large comfort and health benefits both within cities and across larger regions, potentially doubling cooling compared with policies only within city limits. This report does not calculate these downwind summer cooling benefits from accelerating region-wide adoption of these technologies. Additional financial benefits to the cities would likely be large —but are not calculated in this report. However, it is worth noting that low-income neighborhoods are very commonly downwind in cities, so they suffer from excess heating and air pollution. These benefits and the policy implication and opportunities should be more broadly and better understood.

The tables below summarize the report's main findings on the cost-effectiveness of city-wide adoption of cool roofs, green roofs, solar PV, reflective pavements and urban trees. Benefits valued include energy cost savings, improved air quality and public health, reduced stormwater runoff, climate change mitigation, and increased employment.[vii] The three low-income areas studied would realize hundreds of millions of dollars in net benefits over 40 years (see Table B). All costs and benefits quantified in this report are in present value, with explicit assumptions on term and discount rate.

[vii] *Note that the cost and benefits for Washington, D.C., in this report are slightly lower than findings for Capital E analysis of and for Washington, D.C., in the report entitled* Achieving Urban Resilience: Washington DC*. The reason for this difference is that the D.C. report includes three additional surface options—permeable pavements, cool roof combined with bioretention, and cool roof combined with rain swales.*

Table A. Summary of the present value of costs and benefits for the three cities studied

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015)		
	Washington, D.C.	**Philadelphia**	**El Paso**
Costs	$838 M	$2.4 B	$1.6 B
Benefits	$2.6 B	$6.0 B	$2.2 B
Net Present Value	$1.8 B	$3.6 B	$538 M

Table B. Summary of the present value of the economic impact of city-wide smart surface deployment in the low-income areas studied

CATEGORY	TOTAL		
	Ward 5 (Washington. D.C.)	**North Philadelphia (Philadelphia)**	**El Paso Low-income area (El Paso)**
Costs	$95 M	$189 M	$205 M
Benefits	$450 M	$627 M	$340 M
Net Present Value	$355 M	$437 M	$135 M

The payback times for the surface solutions vary greatly: cool roofs offer very fast payback in all cases, while other solutions offer the largest net benefit on a per square foot basis. Overall, the net present value of deploying these solutions range from $540 million for El Paso to $3.5 billion for Philadelphia (see Table A and C). Including the value of avoided summer tourism revenue losses increases estimated net benefits to $4.9 billion and $8.4 billion, respectively. When societal benefits are included, most technologies analyzed have a benefit-to-cost ratio greater than one (see Table D). As noted above, this analysis does not capture the full set of comfort, health, and livability benefits that we were not able to quantify due to limited data.

Table C. Detailed summary of the present value of costs and benefits for each city studied

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015)		
	Washington. D.C.	**Philadelphia**	**El Paso**
Costs	**$838 M**	**$2.38 B**	**$1.62 B**
First Cost	$543 M	$1.56 B	$1.01 **B**
Operations And Maintenance	$191 M	$491 M	$412 M
Additional Replacements	$104 M	$334 M	$193 M
Employment Training	$803 K	$3.2 M	$1.4 M
Benefits	**$2.648 B**	**$5.959 B**	**$2.155 B**
Energy	$348 M	$1.33 B	$700 M
Financial Incentives	$65.6 M	$225 M	$85.5 M
Stormwater	$1.17 B	$185 M	$39 M
Health	$523 M	$2.28 B	$344 M
Climate Change	$434 M	$1.47 B	$806 M
Employment	$104 M	$471 M	$181 M
Net Present Value	**$1.81 B**	**$3.575 B**	**$538 M**

Table D. Benefit-to-Cost Ratio summary for each solution

SOLUTION	BENEFIT-TO-COST RATIO		
	Washington, D.C.	**Philadelphia**	**El Paso**
Cool Roofs	8.29	7.40	4.23
Green Roofs	1.99	0.39	0.19
PV (Direct Purchase)	1.83	1.94	1.72
PV (PPA)	Very high	Very high	Very high
Reflective Pavements	2.57	3.03	2.50
Urban Trees	3.39	1.34	0.66

Tourism revenue would also be affected by rising heat, and estimating this impact provides a way to quantify a portion of the comfort and livability costs of global warming. In Washington, D.C., the estimated 40 year avoided tourism loss due to lower urban temperatures from smart surface strategies is $3.1 billion (including $335 million in tax revenue for the city). Including the estimated NPV from avoided loss of tourism revenue would increase total NPV of city-wide adoption of smart surface technologies to $4.9 billion for Washington, D.C. For Philadelphia, with its huge summer tourism draw, limiting tourism losses from rising temperature would create large net financial benefits over 40 years. Including this benefit for Philadelphia increases NPV to $8.4 billion NPV from city-wide adoption of smart surfaces.

City management of water has a very big impact on downstream watersheds that are critical tourism destinations—such as the Chesapeake Bay—that enhance the regional attractiveness as tourist destination as well as enhancing quality of life for residents. The Chesapeake Bay Foundation notes that "pollution from urban and suburban runoff is the only major source of pollution that is continuing to grow in the Chesapeake Bay watershed…every four years an area of land the size of Washington, D.C., is paved or hardened in the Chesapeake Bay region."[6]

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

The complexity of accounting for benefits is illustrated below in Figure 2, using the example of increasing the albedo of a square foot of dark roof. The cost is $\$0.65/ft^2$, with a benefit of $\$1.34/ft^2$ to the building owner in the form of lower energy costs. There is also a set of benefits that accrue more broadly, including indirect energy savings, the health benefits of ozone and $PM_{2.5}$ reduction, a reduction in heat mortality due to reduced excess summer heat, and the value of CO_2 reductions based on the social cost of carbon.[ix]

[viii] *Costs of smart surface solutions are relatively simple to calculate and typically involve two elements: the upfront capital cost to buy and install, and ongoing operations and maintenance costs. In contrast, benefits are more complex and varied, and commonly include a large range of impacts related to health, stormwater, energy, climate change, and employment.*

[ix] *The present administration is reportedly disbanding its technical advisory board on carbon and moving away from a science and economics based approach for calculating SCC, so cities should rely on prior, more science-based estimates. Most states using a cost of carbon reportedly use a price of above $40 per ton.*
https://www.economist.com/news/united-states/21731395-reducing-social-cost-carbon-would-allow-epa-dispense-regulations-epa?fsrc=rss
https://insideclimatenews.org/news/11082017/states-climate-change-policy-calculate-social-cost-carbon

From the perspective of a building owner, the cost-benefit returns of this measure is attractive. Additional, city-wide and societal benefits are large but do not accrue to the building owner. However, most of these benefits, including improved citizen health and additional energy savings, generally result in lower health costs, lower water infrastructure and treatment costs, lower energy bills, etc., at a city level.

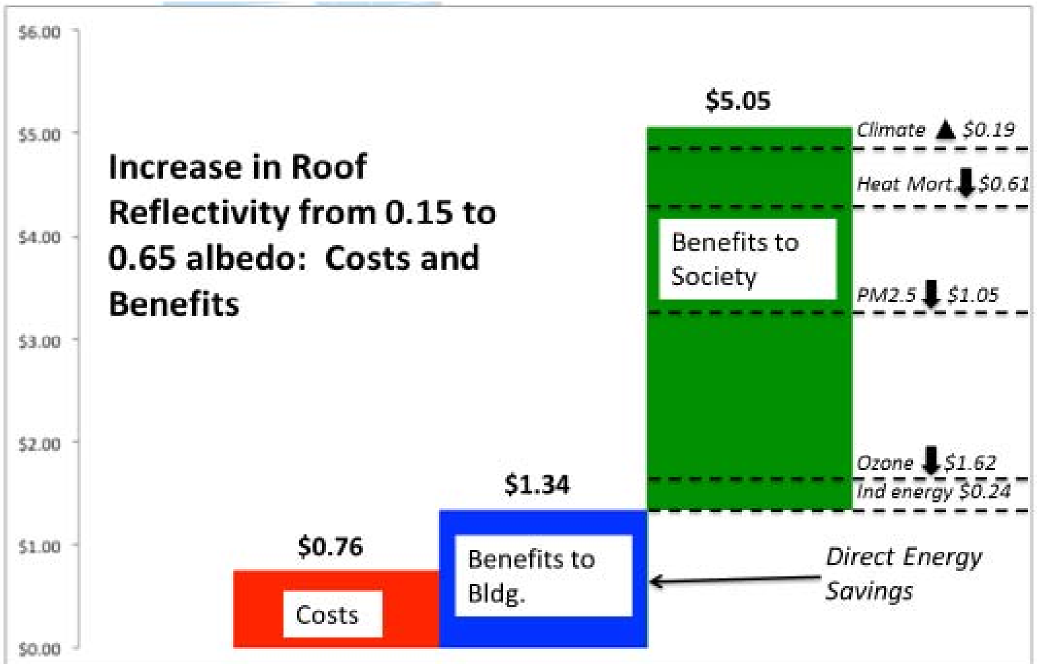

Figure 2. Costs and Benefits of making 1 square foot dark roof much more reflective (higher albedo)[x]

One area of benefits that is largely not monetized is contribution to slowing climate change. A 2017 report, by the Medical Society Consortium on Climate & Health, representing 11 major medical societies and more than 400,000 doctors, found that "climate change is already causing problems in communities in every region of our nation."[7] The report documents health impacts in three areas of health: direct harms from climate change-altered weather, increased spread of disease and contamination, and mental health effects.

Over 1,000 U.S. cities have committed to limiting or reducing their contribution to climate change. A growing number of cities take responsibility for their climate change impact and therefore—as a baseline assumption—this report includes in the cost-benefit analysis the benefits of greenhouse gas reductions, including from lower use electricity from utilities relying on fossil fuels for power generation. This dollar value assigned to CO_2 reductions (for example for energy efficiency from cool roofs) is based on the social cost of carbon, a cost per ton of carbon estimate developed and updated every three years by a dozen U.S. federal agencies, including the EPA and Treasury Department.

This report demonstrates that city-wide adoption of smart surfaces creates very large net financial benefits for the three varied cites of Washington, D.C., Philadelphia and El Paso. The smart surface strategies analyzed in this report have broad benefits for the city, especially for its low-income neighborhoods, as well as for the larger watersheds in which these cities sit. City leadership on smart

[x] *Please note that these values are from an earlier report by Capital E and are not identical to the costs and benefits of cool roofs estimated in this report.*

surfaces can also be expected to accelerate smart surface adoption by the surrounding cities, in turn increasing city and region-wide cooling and health benefits, including region-wide summer peak cooling. The findings of this report across three varied cities should encourage adoption of these technologies as city-wide standard practice.

Even with many benefits not included due to lack of data, this report's findings are compelling. Cities can secure large gains in resilience, health and comfort, reduce energy bills, and mitigate climate change and excess heat while saving money. Former Washington, D.C. COO Dan Tangherlini observes that, "This report convincingly demonstrates that there are cost-effective technologies and strategies for managing sun and water that will deliver billions of dollars in financial benefits to cities and their residents. Delaying this transition would impose large financial and social costs particularly on places of lower economic opportunity, the elderly and children."

Consistent findings of this report across three varied cities should encourage broad adoption of these technologies as city-wide standard practice. As two-term mayor of Austin Will Wynn notes, "Delivering Urban Resilience provides an entirely convincing case that city-wide adoption of "smart surfaces" like green and cool roofs and porous pavements can make our cities far more resilient. This rigorous report demonstrates that these smart surfaces strategies are both cost-effective and essential for city resilience, and can help protect our citizens and ensure that our cities remain livable in a warming world."

This report demonstrates that the growing city-wide risks from extreme heat and weather driven by climate change can be largely offset by city-wide adoption of these smart surface technologies while delivering large net financial benefits. Many of the physical inequalities that characterize and disadvantage low-income areas of many or most American cities can be greatly improved with smart surface while delivering large net financial returns to the city as a whole. These findings constitute a compelling financial, resilience and public policy case for rapid adoption of smart surface solutions city-wide as standard, baseline urban policy.

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1 INTRODUCTION

Cities suffer from worse air pollution and higher summer temperatures than surrounding suburban and rural 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 exacerbated by poor air quality. The last few decades have seen the emergence of a set of surface solutions that could contribute towards reducing these environmental, health, and energy costs. These smart surface solutions include cool (reflective) roofs to cool the urban environment and decrease energy bills, green (vegetated) roofs to reduce stormwater runoff, cool the urban environment, and decrease energy bills; and rooftop solar photovoltaics (PV) to generate electricity and reduce air pollution. Urban trees, though commonly seen as a way to beautify cities, are increasingly becoming recognized for their ability to help manage stormwater, cool the urban environment, reduce pollution, and decrease energy bills. Cool (reflective) pavements, a technology still in its infancy, can also be used to cool the urban environment. These solutions are deployed in pilot and subsidized programs by cities, developers, affordable housing organizations, and others 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.

Until this analysis, there was no established methodology for estimating the full costs and benefits, including health benefits, for these solutions. In earlier iterations of this work, we estimated the costs and benefits for individual buildings up to the scale of wards. There are tens of thousands of buildings and hundreds of millions of square feet of pavement in cities the size of Washington, D.C., ("the District"), Philadelphia, and El Paso, so it is important for these and other cities to understand the costs and benefits of deploying these solutions at large scale. This is particularly true for low-income areas which generally suffer from higher summer temperatures, worse air quality, more severe health problems, and greater energy bills per square foot than more affluent areas (see Figure 1.1). This analysis is intended to enable more informed, cost-effective city-wide decisions to make cities healthier, more equitable and affordable, and to reduce their contribution to climate change.

1.1 Overview of report structure

This report starts with a brief overview of the Phase 1 work on building-level smart surface costs and benefits, followed by a review of findings from low-income ward-level analysis. This is followed by an introduction to the smart surface solutions and their impacts. This report overviews methods of analysis used in cost benefit quantification, and then summarizes findings. The report concludes with key findings and a discussion of next steps. The intent is to provide analysis and documentation that enable readers to better understand, evaluate, and estimate the full costs and benefits of smarter city surface choices, and to then adopt and implement the most cost-effective solutions for their cities.

All financial costs and benefits in this report are presented in present value, with explicit assumptions on term and discount rate. All dollar values are presented in 2015 dollars unless otherwise noted. This report is designed to allow evaluation of the deployment of integrated options. This report estimates the cumulative impact of these solutions at the city-level and at the low-income, ward or neighborhood level. By quantifying a set of costs and benefits that is far broader and more complete than other work to date, this report is intended to inform wiser and more cost-effective city policy design choices. The Appendix includes net present value per square foot estimates that enable solution choices to be compared to each other and/or be aggregated into neighborhood-wide or city-wide estimates to enable informed city decisions about deploying these solutions at scale.

Health impacts are large and complex, and have generally not been estimated or valued for these surface solutions. This report describes the different health impact pathways and methodologies used to estimate these costs and benefits. Because this type of analysis is new, it draws on multiple methods, studies, and models to develop an integrated methodology for estimating health impacts.

This report also provides a preliminary estimate of the employment impact of solutions. Due to the relatively small scale (i.e., city and city-sub-region scale) of the employment analysis in this report compared to typical employment analyses that are on the scale of states or countries, this report assumes that even with city training and job-linking programs, only half the net new jobs in a city accrue to residents of that city. Assumptions are explicit throughout the text, and in all cases, this report provides references and, where available, links.

As detailed and documented in this report, the net present value of adopting this set of solutions city-wide is estimated to be $1.8 billion in Washington, D.C., $3.6 billion in Philadelphia, and $540 million in El Paso over a forty-year period (see Table 1.1). This report also addresses summer tourism. It includes an initial estimate of the avoided summer tourism losses that would result from city-wide adoption of smart surface solutions. This is a far less exact estimate than cost-benefit values developed in the rest of the report, but it represents a reasonable, first order estimate. With tourism included, the net present value of city-wide smart surface adoption is about $4.9 billion for the District and $8.4 billion for Philadelphia.[xi]

Table 1.1. Detailed summary of the present value of costs and benefits for the three cities studied

CATEGORY	PRESENT VALUE OVER 40-YEAR ANALYSIS PERIOD (2015)		
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Climate Change	$434 M	$1.47 B	$806 M
Employment	$104 M	$471 M	$181 M
Net Present Value	**$1.81 B**	**$3.575 B**	**$538 M**

Including the value avoided summer tourism losses increases the net present value to $4.9 billion for Washington D.C and to $8.4 billion for Philadelphia. We were not able to calculate tourism benefits for El Paso. There is 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. Virtually all of the impacts excluded from cost-benefit calculations are benefits, so this report underestimates the value of smart surfaces measures such as cool roofs, green roofs, rooftop PV, reflective pavements, and urban trees.

The below sections provide an overview of the first phase of this work, which evaluated the costs and benefits of cool and green roofs, solar PV, and solar thermal on affordable housing properties in each of four cities: Washington, D.C., Baltimore, Philadelphia, and Los Angeles.

[xi] *We did not include El Paso in the tourism analysis due to lack of data.*

1.2 Why a focus on low-income areas?

The importance of making smart roof choices, decreasing urban heat islands (UHI), and improving air quality is especially significant for low-income populations. The publication, *Environmental Health Perspectives* notes, "Substantial scientific evidence gained in the past decade has shown that various aspects of the built environment can have profound, directly measurable effects on both physical and mental health outcomes, particularly adding to the burden of illness among ethnic minority populations and low-income communities."[8] Many roofs in low-income city areas have low solar reflectance, meaning they absorb the majority of sunlight, which greatly increases the heat gain on the top floor of buildings and contributes to higher urban temperatures. In addition, urban low-income residents are more likely to live in areas with no tree canopy and/or greater than 50 percent impervious area.[9] The urban poor suffer disproportionally from UHIs (urban heat island) due to their increased likelihood of residing in inefficient homes and attending inefficient schools.

Deployment of these solutions at scale in low-income areas can address systematic inequity in urban quality of life from excess heat, worse air quality, and less greenery in low-income areas than in wealthier urban areas. This inequity is summarized in the figure below.

Greater population density	• more people at risk
Higher % children/elderly	• greater medical risk
Higher % impervious surfaces	• hotter, more smog and more stormwater runoff
Lower % tree cover	• hotter and more air pollution
Energy bills higher % of income	• larger relative energy cost savings
Higher % unemployed	• employment benefits potentially larger

Figure 1.1. Greater risk and larger potential benefit in low-income areas

Energy costs make up a higher percentage of expenses for low-income residents. Recent research from the Joint Center for Housing Studies of Harvard University shows that for the lowest-income renters, tenant-paid household energy costs represent approximately 15% of income, while energy costs make up about 1% of total income for the highest-income renters.[10] As a consequence, the impact of energy bill reductions is proportionally far larger for affordable housing properties. The April 2016 ACEEE report "Lifting the High Energy Burdens in America's Largest Cities: How Energy Efficiency Can Improve Low-Income and Underserved Communities" illustrates this disproportionate burden of energy bills on low-income and minorities. The report findings include the following:

- Low-income households experienced the highest median energy burden (7.2 percent), followed by African-American households (5.4 percent), and low-income households living in multifamily buildings (5.0 percent).
- In 17 cities —more than one-third of the cities studied — a quarter of low-income households experienced an energy burden four times higher than for all households.
- African-American households experienced a median energy burden 64 percent greater than white households.
- Latino households experienced a median energy burden 24 percent greater than white households.
- Cost and unreliability/poor energy services can increase financial stress, as well as incidence of asthma, respiratory problems, heart disease, arthritis, and rheumatism.[11]

The ACEEE report found that "the overwhelming majority of low-income and households of color in major U.S. cities experienced higher energy burdens when compared to the average household in the same city. Families who face higher energy burdens experience many negative long-term effects on their health and well-being. These families are at greater risk for respiratory diseases and increased stress, and they can experience increased economic hardship and difficulty in moving out of poverty."[12]

The greatest incidence of heat-related mortalities in cities occurs on the top floor of apartment buildings and in low-income areas.[13] Additionally, elevated urban temperatures due to urban heat islands (UHI) increase smog and related respiratory illness among the most vulnerable populations, including the poor, the elderly, minority communities, and children. Differences in proximate built environment contribute significantly to this health disparity, and the greening and cooling of roofs on urban buildings—specifically multi-unit affordable housing—represents a promising strategy for enhancing comfort, cutting energy bills, improving health, and creating local jobs for urban, low-income populations.

1.3 Report outline

In an earlier report (Affordable Housing Smart Roof Report), we describe each of the technologies, focusing on characteristics that affect the costs and benefits of each technology. We then describe how we estimated the costs and benefits of the technologies—including a description of how and why we arrived at each method. Our intent is to provide a complete description and documentation that enables readers to use data from their building(s) and city conditions to evaluate and estimate the full costs and benefits of these technologies.

All costs and benefits are quantified on a present value, dollars per square foot basis, with explicit and consistent assumptions on term and discount rate. This approach results in common net present value per square foot estimates that enable all costs and benefits to be compared to each other and/or aggregated into a single cost-benefit estimate for combined technologies. This allows for more informed policy and design choices. In the Phase 1 analysis, we included three cost-benefit estimates for each technology. The lower bound estimate assumes the lowest estimated benefits and the highest estimated costs, and the upper bound estimate assumes the highest estimated benefits and the lowest estimated costs. The middle estimate serves as the main cost-benefit estimate of our analysis and assumes the midpoint or average benefit and cost estimates.

Health impacts are substantial but complex, and have generally not been estimated or valued for these smart surface options. Because this kind of analysis has not been done before, we drew on multiple methods, studies, and models to develop new approaches for estimating the health impacts, including some costs and benefits that had not been quantified before. We made assumptions explicit throughout the text. And, in all cases, we provide references and, where available, links.

1.4 The multi-unit affordable housing properties

In the Phase 1 low-income building-level report, we analyzed the costs and benefits of installing cool roofs, green roofs, rooftop PV, or solar hot water on multi-unit affordable housing properties. Data for the properties in the District, Baltimore, MD, and Philadelphia, PA, was provided by our partner, the National Housing Trust. Data for the Los Angeles, CA property was provided by Enterprise Community Partners.

Table 1.2 includes select information for each property. Additional info can be found in the Appendix. Figure 1.2, Figure 1.3, and Figure 1.4 show example views of the District, Baltimore, and Philadelphia properties, respectively.

The properties in this analysis differ from one another. For example, the properties in the District and Philadelphia have gas heat, while the property in Baltimore has electric heat. Roof slope also differs. The District affordable housing property has low slope roofs. In contrast, the Baltimore affordable housing property is majority steep slope roofs and the Philadelphia affordable housing property has all steep slope roofs. These and other differences impact the results of the Phase 1 report. Table 1.3, 1.4, and 1.5 show cost-benefit results for the District, Baltimore, and Philadelphia properties, respectively. More detailed results and results for the Los Angeles property are provided in the Appendix.

Table 1.2. Property characteristics

LOCATION	WASHINGTON, D.C.	PHILADELPHIA, PA	BALTIMORE, MD
Number of floors	10 in Tower; 2 in Townhomes	2 to 3	2 to 3
Number of units	223	108	111
Number of units on top floor	16 in Tower; 56 in Townhomes	45	17
Total occupancy	557	270	278
Roof area (ft^2)	44820	38500	94000
Non-cool roof substrate material	Asphalt shingles	Asphalt shingles	Asphalt shingles
Roof slope	Low slope	Steep slope	10,000 ft^2 low slope; 84,000 ft^2 steep slope
Roof insulation (R-value)	R-15	R-18	R-18
Air conditioner efficiency	9.3 EER	6 to 13 EER	12.5 EER
Heating fuel	Natural gas	Natural gas	Electricity
Heating system efficiency	80% AFUE	70% to 80% AFUE	8.0 to 9.0 HSPF
Water heating fuel	Natural Gas	Natural gas	Electricity
Price of electricity ($/kWh)	0.13	0.16	0.12
Price of natural gas ($/therm)	1.10	1.42	N/A

Figure 1.2. Views of the District property tower (left) and townhomes (right)

Figure 1.3. Views of Baltimore property

Figure 1.4. Views of Philadelphia property

1.5 Phase 1 results

Table 1.3. Washington, D.C., property costs and benefits per ft² of roof occupied by each technology (NOTE: we assume all rooftop PV and solar hot water is financed through a PPA, so there is no upfront cost)

COMPARISON	COOL compared to conventional	GREEN compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional	CONVENTIONAL w/ shw (ppa) compared to conventional
Costs	**$0.62**	**$22.61**	**$0.00**	**$0.00**
First cost	$0.25	$15.00	N/A	N/A
Stormwater BMP review fee	N/A	$0.02	N/A	N/A
Operations and maintenance	$0.23	$7.59	N/A	N/A
Additional replacements	$0.14	$0.00	N/A	N/A
Benefits	**$4.60**	**$60.90**	**$69.20**	**$124.70**
Energy	$0.53	$2.48	$2.49	$48.70
Stormwater	N/A	$53.60	N/A	N/A
Health	$4.01	$4.03	$52.10	$27.88
Climate change	$0.06	$0.83	$14.58	$48.08
Net total	**$3.98**	**$38.30**	**$69.20**	**$124.70**

Table 1.4. Baltimore property costs and benefits per ft² of roof occupied by each technology (NOTE: we assume all rooftop PV is financed through a PPA, so there is no upfront cost; the cool roof and PV estimates are a weighted-average of the results for low slope and steep slope roofs, while the green roof estimates are only for the low slope roof portion of the property)

COMPARISON	COOL compared to conventional	GREEN compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional
Costs	**$1.31**	**$22.66**	**$0.00**
First cost	$0.70	$15.0	N/A
Stormwater bmp review fee	N/A	$0.07	N/A
Operations and maintenance	$0.23	$7.59	N/A
Additional replacements	$0.39	$0.00	N/A
Benefits	**$1.73**	**$5.34**	**$30.67**
Energy	$0.40	$1.80	$2.19
Stormwater	N/A	$0.80	N/A
Health	$1.28	$2.54	$22.67
Climate change	$0.05	$0.20	$5.81
Net total	**$0.42**	**-$17.32**	**$30.67**

Table 1.5. Philadelphia property costs and benefits per ft^2 of roof occupied by each technology (NOTE: we assume all rooftop PV is financed through a PPA, so there is no upfront cost)

COMPARISON	COOL compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional
Costs	**$1.40**	**$0.00**
First cost	$0.75	N/A
Stormwater BMP review fee	N/A	N/A
Operations and maintenance	$0.23	N/A
Additional replacements	$0.42	N/A
Benefits	**$1.96**	**$5.84**
Energy	$0.26	$0.00
Stormwater	N/A	N/A
Health	$1.73	$3.07
Climate change	-$0.02	$2.77
Net total	**$0.57**	**$5.84**

1.6 Phase 1 Conclusions

The Phase 1 report developed the first rigorous and comprehensive model to estimate the costs and benefits of cool roofs, green roofs, rooftop PV, and solar hot water for affordable housing developments. It involved a range of leading health and policy advisors and the development of a multi-level health and benefits valuation model to estimate a significant set of costs and benefits of these technologies on affordable housing developments.

For affordable housing projects in the District, Baltimore, Philadelphia, and Los Angeles, the Phase 1 report demonstrates cost-effective alternative roof design strategies that would have substantial net benefits and should be adopted as standard for affordable housing retrofit design.

The Phase 1 report's methodology provides a broadly useful new platform to understand and address affordable housing roof design opportunities. Its findings also indicated that a low-income area-wide strategy of adoption of the technologies analyzed would have large benefits, including significant energy savings, reduced area-wide peak summer temperature, improved livability, and large public health benefits.

The potential for reductions in average and peak daytime summertime temperatures and improvements in air quality and public health indicates that a policy of adopting cooling strategies on the roofs, roads and sidewalks of all low-income areas of cities would yield large financial and health benefits at relatively low cost. The costs of polluted air and contaminated water fall disproportionately on low-income residents. For low-income residents, the cost of paying utility bills in inefficient buildings is a larger burden than that for the wealthy, so the potential benefits include important equity benefits. Building on this report to undertake a low-income area-wide analysis, to include built surfaces in addition to roofs, appeared likely to demonstrate large, low net cost opportunities to improve the health, livability, and environmental footprint of low-income residents and neighborhoods while cutting energy bills. These findings led us to undertake, with JPB funding, analyses of the roof technologies, urban trees, and reflective pavements at the low-income ward-level in three cities: Washington, D.C., Baltimore, and Philadelphia.

2 OVERVIEW OF PHASE 2

Phase 2 of work for JPB involved a neighborhood/ward-wide cost-benefit analysis. In 2015, 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, D.C., Baltimore, and Philadelphia.

2.1 Why focus on low-income areas?

The impacts of air pollution and higher summer temperatures are 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.

2.2 Results and conclusions

The work for JPB provides an in-depth analysis of the benefits of applying cool roofs, green roofs, solar PV, reflective pavements, and urban trees at ward/neighborhood scale in low-income neighborhoods in Washington, D.C., Baltimore, and Philadelphia. It demonstrates that these solutions would cost-effectively reduce health and energy costs for low-income areas while increasing employment, resilience, and livability. The low-income areas studied are substantial, representing on average about one-tenth of city population. These areas are characterized by higher poverty rates, lower income, and higher unemployment than the rest of the cities. On average, the low-income areas studied have a 53% higher percent of population below the poverty line and 64% higher unemployment rates than the cities. Not coincidentally, these low-income areas also have on average 43% lower tree coverage relative to the cities as a whole. Underinvestment in trees and green technologies in urban low-income areas like these results in higher summer temperatures, worse air quality, more severe health problems, and higher energy bills per square foot than more affluent areas.

The tables below summarize the report's main findings on the cost-effectiveness of each of these technologies in the three low-income areas studied. To enable more informed and broad policy changes, all costs and benefits quantified in the report are in present value, with explicit assumptions on term and discount rate. Overall, these technologies are cost-effective and generally provide large positive net benefits.

The payback time for these technologies varies a great deal. Cool roofs offer very fast payback in all cases, while several other technologies offer the largest net benefit on a city by city basis. Overall, the net present value of deploying these technologies broadly is about $250 million each in the low-income areas studied in Washington, D.C., and in Philadelphia. In Baltimore, where the low-income population and area studied is smaller, net present value of deploying these technologies is about $75 million. The analysis, however, does not capture the full set of comfort, health, and livability benefits. As deployment scales up, the urban cooling benefits grow proportionally and impact energy bills, smog, health and livability in ways that bring reinforcing benefits, especially to low-income areas.

Table 2.1. Summary of the net present value (NPV) of costs and benefits for Ward 5 (Washington, D.C.)

TECHNOLOGY	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	$5.3 M	$68 M	$30.2 M	$14K	$10.2 M	$47.4 M	$161.1 M
Benefits	$47.4 M	$128.5 M	$49.4 M	$45.6 M	$18.2 M	$138.4 M	$427.4 M
NPV	$42.1 M	$60.5 M	$19.1 M	$45.6 M	$8.0 M	$91.0 M	$266.4 M

Table 2.2. Benefit-to-Cost Ratio summary for each technology in Ward 5 (Washington, D.C.)

TECHNOLOGY	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	8.94	1.89	1.63	Very high	1.79	2.92

Table 2.3. Summary of the net present value (NPV) of costs and benefits for Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights (Baltimore)

TECHNOLOGY	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	$2.86 M	$24.8 M	$16.1 M	$7K	$6.18 M	$14.1 M	$64.0 M
Benefits	$21.5 M	$26.5 M	$26.4 M	$28.9 M	$10.03 M	$25.9 M	$139.2 M
NPV	$18.6 M	$1.77 M	$10.3 M	$28.9 M	$3.85 M	$11.8 M	$75.2 M

Table 2.4. Benefit-to-Cost Ratio summary for each technology in Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights (Baltimore)

TECHNOLOGY	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	7.51	1.07	1.64	Very high	1.62	1.83

Table 2.5. Summary of the net present value (NPV) of costs and benefits for North Philadelphia (Philadelphia)

TECHNOLOGY	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	$8.24 M	$100.1 M	$55.7 M	$25 K	$12.4 M	$14.1 M	$190.6 M
Benefits	$70.8 M	$115.2 M	$92.7 M	$95.5 M	$26.8 M	$31.1 M	$432 M
NPV	$62.6 M	$15.1 M	$37.0 M	$95.4 M	$14.4 M	$17. M	$241.4 M

Table 2.6. Benefit-to-Cost Ratio summary for each technology in North Philadelphia (Philadelphia)

TECHNOLOGY	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	8.60	1.15	1.66	Very high	2.15	2.20

The report quantifies a large range of cost and benefits from adopting these technologies, including detailed mapping of health impacts. Because integrated cost-benefit analysis of these technologies had not been done before, we worked with and consulted with national and city partners, epidemiologists, stormwater, and energy experts and others to build the data and integrated cost-benefit model. 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 technologies that offer compelling paybacks.

Following this work, JPB Foundation funded Capital E to undertake this multi-city, city-wide analysis.

3 BACKGROUND

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

3.1 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, dry urban surfaces that absorb more solar energy than the natural surfaces they replace. Other factors that contribute to UHIs include heat given off by fuel combustion (e.g., in vehicles), 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 persistent 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 3.1 shows a simple atmospheric UHI profile. Figure 3.2 shows a more sophisticated illustration with surface and atmospheric UHIs and differences between day and night.

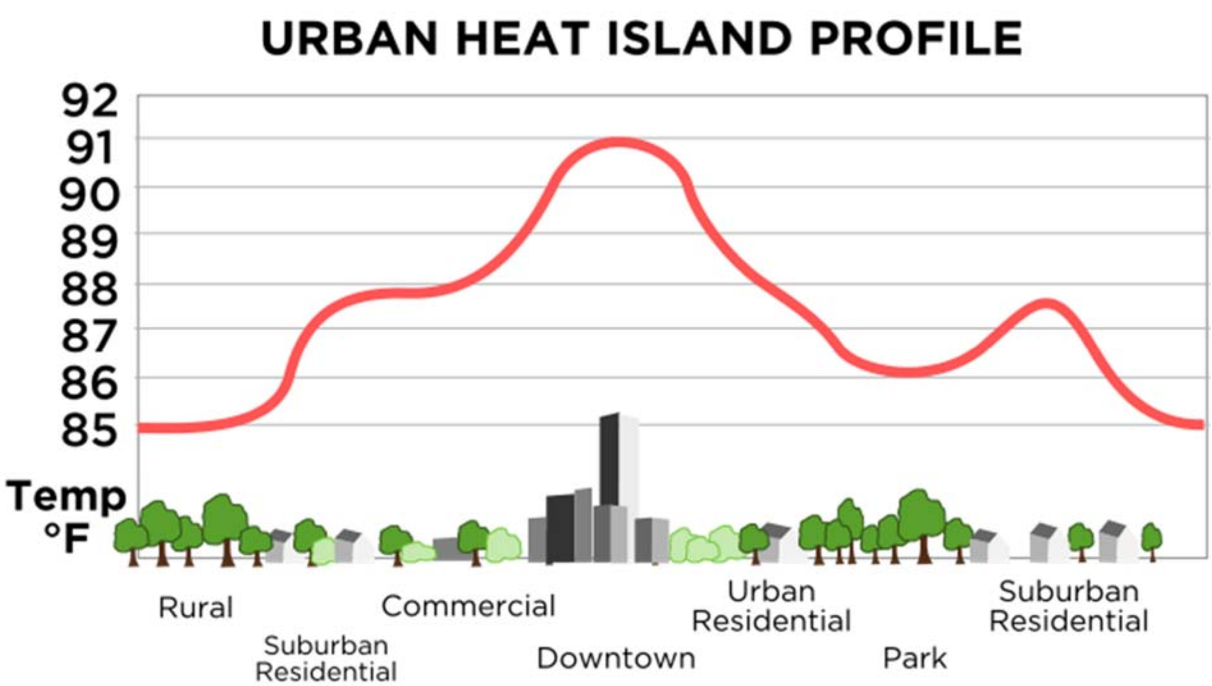

Figure 3.1. Simple illustrative example of urban heat island profile[17]

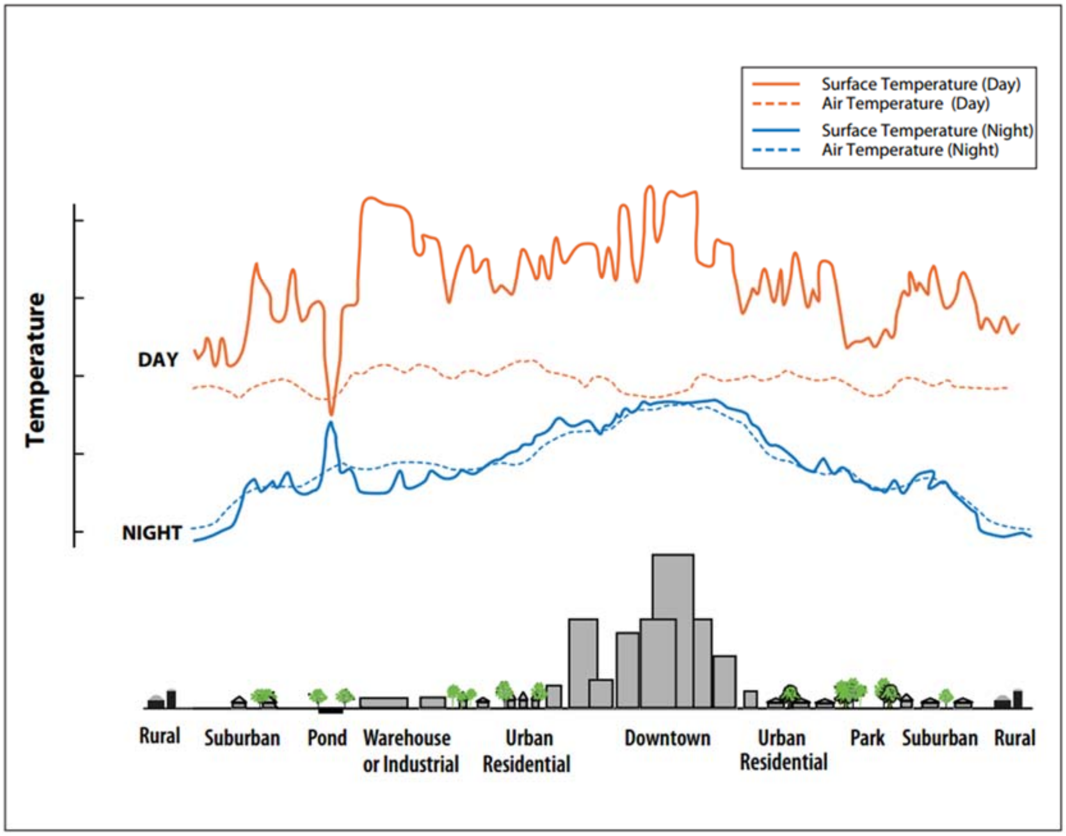

Figure 3.2. More sophisticated illustrative example of urban heat island profile[18]

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 affects the atmosphere. Canopy layer UHIs occur where people live, from the ground surface to the tops of trees and buildings. Canopy layer UHIs are the most common UHI discussed. Subsequently, when this report uses the term UHI, it refers to the canopy layer/near-surface UHI, unless otherwise specified.

A recent analysis by Climate Central studied the summertime UHI in 60 U.S. cities.[20] Using data from 2004 to 2013, it found the average summer daytime UHI in Washington, D.C., ("the District") is 4.7°F and in Philadelphia is 3.8°F. Climate Central also analyzed the average decadal change in UHI from 1970 through 2013.[xii] The District's UHI is increasing at a rate of 0.42°F per decade and Philadelphia's UHI is increasing at a rate of 0.53°F per decade. We found no data on El Paso's atmospheric UHI, though recent work from the University of Texas at El Paso shows a surface UHI, strongly suggesting presence of an atmospheric UHI.[21] Furthermore, the surface UHI appears to be increasing due to development, meaning the atmospheric UHI is likely increasing as well.[22]

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

[xii] 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.

3.2 Climate change projections

Climate change is accelerating, meaning peak temperatures are increasing globally. The Spring 2016 NOAA greenhouse gas index illustrates this trend (see Figure 3.3). This accelerating climate warming trend lead Pope Francis in November 2015 to state in an interview with Time Magazine, "Every year the problems are getting worse. We are at the limits. If I may use a strong word I would say that we are at the limits of suicide."[23]

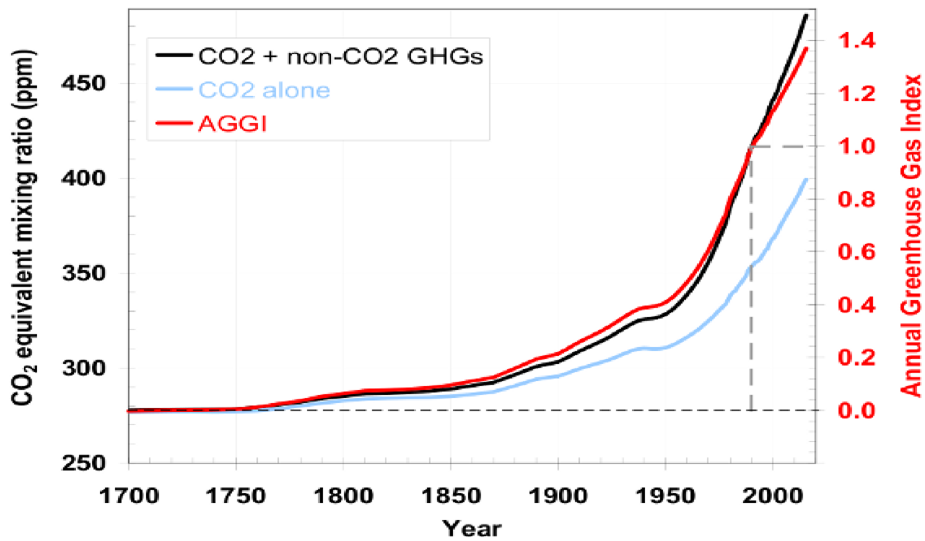

Figure 3.3. NOAA Annual Greenhouse Gas Index (updated Spring 2016)[24]

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.[25] The Index is based on six factors, with sea-level rise given the greatest weight and average temperature and precipitation changes given the least weight.[xiii] The District is ranked 9th and Philadelphia 10th—El Paso is not on the list.

The sections below provide more detail on the projected impacts of climate change in the three cities discussed in this report. All three cities can expect warmer conditions in the future. The District and Philadelphia can expect wetter conditions, while El Paso can expect drier conditions.

3.2.1 The District

Even under low emissions scenarios, the District will experience substantial increases in temperature, precipitation, and sea level rise due to climate change.[26]

3.2.1.1 Hotter

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 3.4). 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).

[xiii] 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.

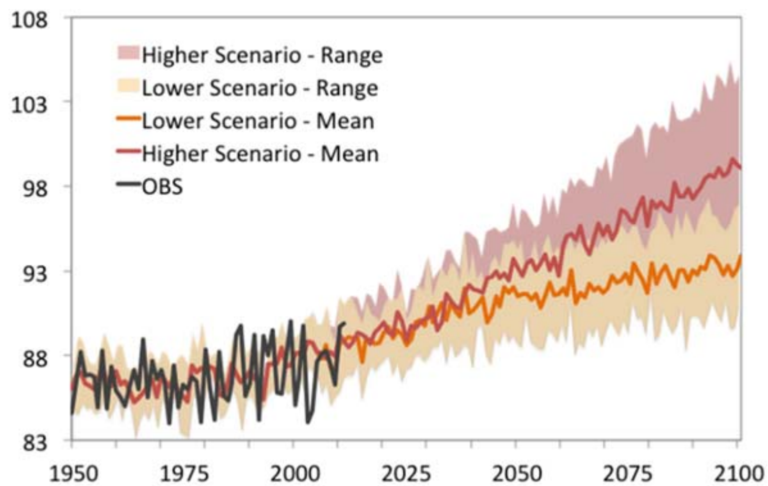

Figure 3.4. Average summer daytime high temperature in the District ("OBS" stands for "observed", "CMIP5 lower" and "CMIP5 higher" designate low and high carbon emissions scenarios, respectively; error bars encompass the range of projections from the nine different global climate models used in ref 27)

In addition to higher temperatures, the District's Climate Projections and Scenario Development report predicts longer and more intense heat waves.[xiv] Extreme heat days (when air temperature exceeds 95°F) will become more numerous, 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 days by the 2050s (see Figure 3.5). The number of extreme heat days in the District is expected to roughly triple by the middle of the century. Heat index, which combines ambient air temperature and relative humidity into a value that represents how hot the air feels, will also soar. DOEE predicts the number of days per year with a heat index above 95°F will increase from a baseline of 30 to around 50 by the 2020s and between 70 and 80 by the 2050s (see Figure 3.6). 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.[28]

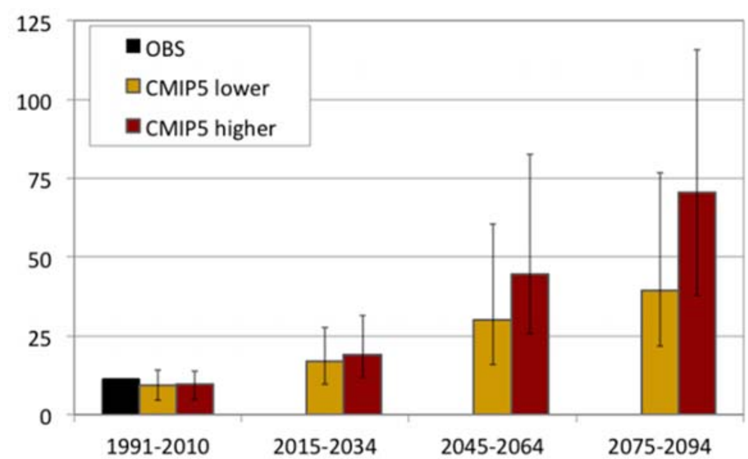

Figure 3.5. Number of days per year with maximum temperature above 95°F ("OBS" stands for "observed", "CMIP5 lower" and "CMIP5 higher" designate low and high carbon emissions scenarios, respectively; error bars encompass the range of projections from the nine different global climate models used in 29)

[xiv] *Recent modeling studies show that heat waves exacerbate UHIs (e.g. Li and Bou-Zeid, 2013)*

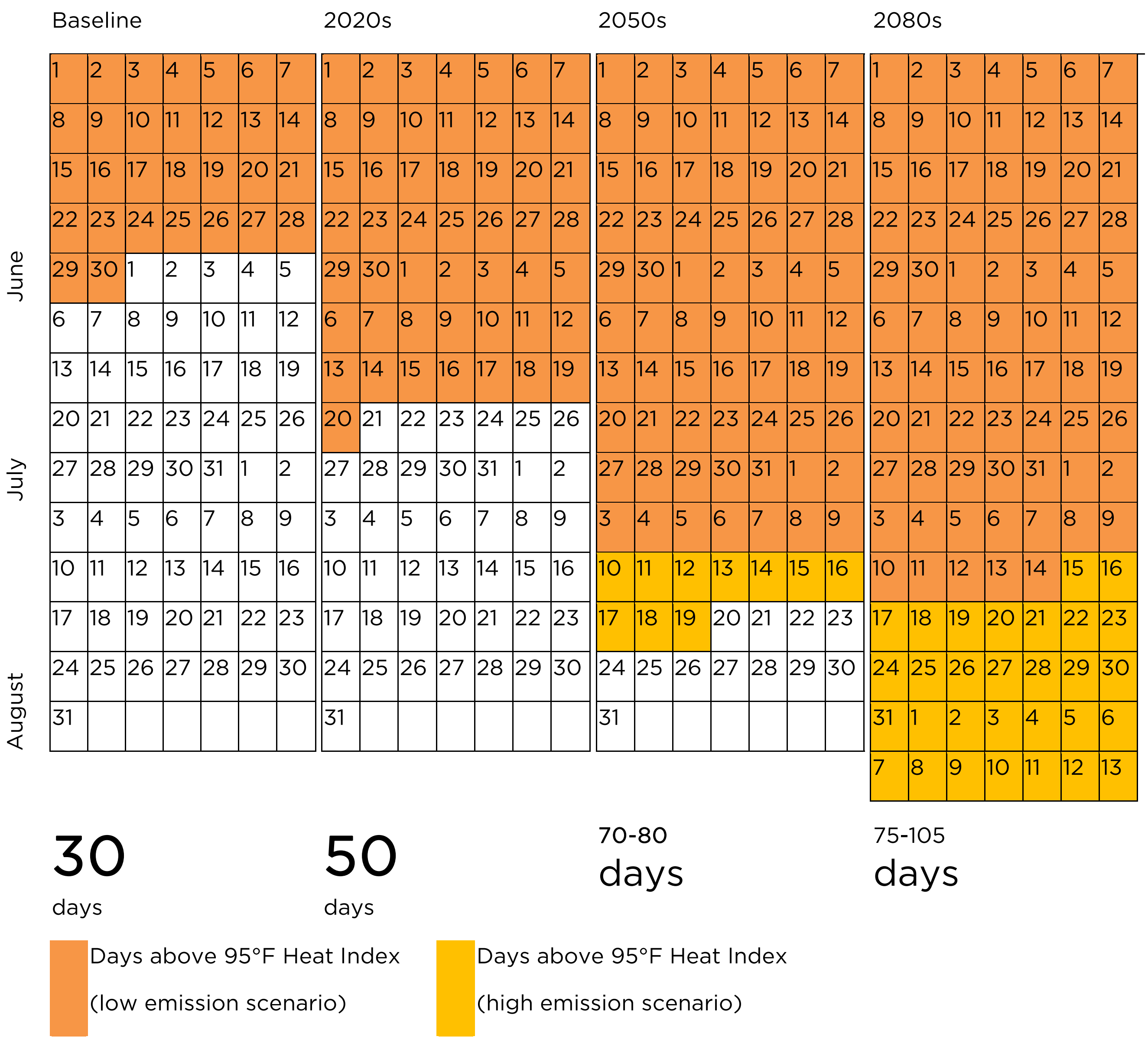

Figure 3.6. Days in Washington, D.C. with a heat index above 95°F[30]

These temperature increases will put a severe strain on the city's infrastructure, including increased energy use for cooling, reduced comfort, and increased risk of heat-related deaths. This underlines the need to prioritize urban cooling measures in policy making and planning.

3.2.1.2 Wetter

DOEE predicts that extreme precipitation events will increase in frequency and intensity, and that sea level will continue to rise at an accelerating rate.[31] 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. Coupled with the projected sea level rise (see Figure 3.7),[32] this will put an enormous burden on the city's stormwater infrastructure. The District of Columbia Water and Sewer Authority (D.C. 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.[33] But rising severity and frequency of storm size and rainfall means that these infrastructure investments will be increasingly unable to handle stormwater runoff and sewage overflow, resulting in continued river contamination and requiring further water infrastructure investment.

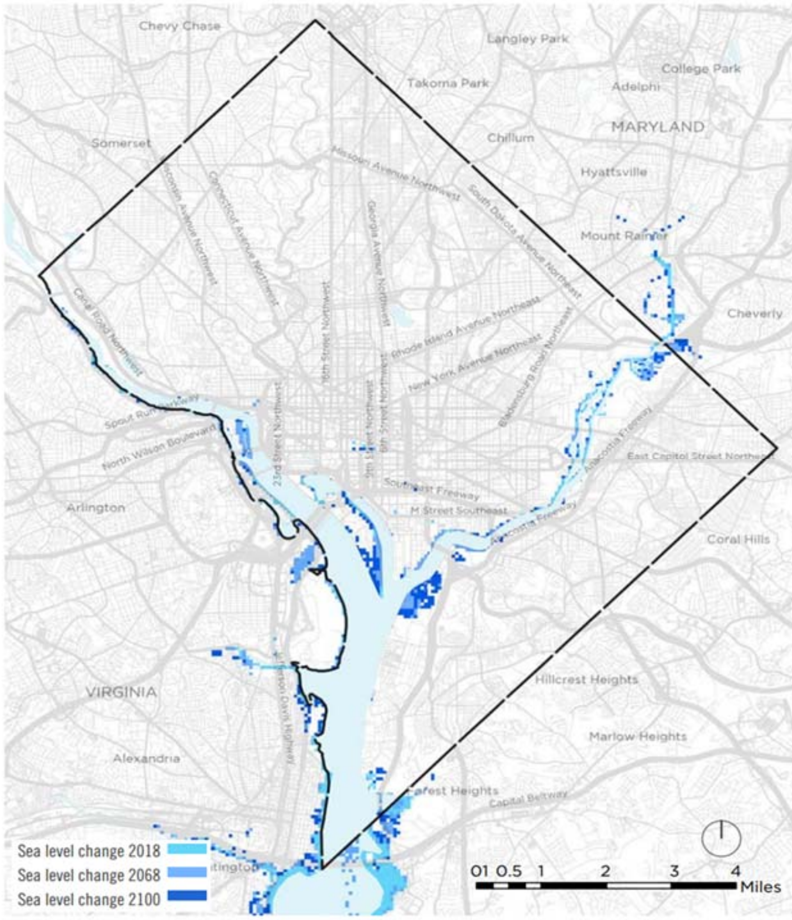

Figure 3.7. Relative sea level rise inundation mapping for high scenario from the U.S. Army Corp of Engineers (adapted from ref 34)

3.2.2 Philadelphia

Philadelphia is expected to get warmer and wetter with climate change under all projected emissions scenarios. A January 2016 report entitled "Options for Achieving Deep Reductions in Carbon Emissions in Philadelphia by 2050" prepared by Drexel University for the Philadelphia Mayor's Office of Sustainability describes a compelling rationale and pathways to achieve 80% city-wide CO2 reduction by 2050.[35]

3.2.2.1 Hotter

In the near term (2020-2039) and by mid-century (2045-2065), Philadelphia's average annual temperature is projected to increase between 2.9°F and 3.2°F and between 3.7°F and 5.8°F, respectively.[36]

Extreme heat will be more common in Philadelphia's future. The average number of days per year above 95°F and 100°F for the baseline period (1961 and 2000) was 3 days per year and 0 days per year, respectively.[37] In the near term, these counts will increase to between 9 and 10 days per year above 95°F (a 3-fold increase) and 1 day per year above 100°F. By mid-century, they will increase to between 13 and 23 days per year above 95°F (a 4- to 8-fold increase) and between 1 and 4 days per year above 100°F. Not surprisingly, what is defined "very hot" (95^{th} percentile temperatures) and "extremely hot" (99^{th} percentile temperatures) will increase by as much as 5.4°F and 5.3°F, respectively, by mid-century. In other words, the 95th percentile temperature could be as high as 95.6°F and the 99th percentile temperature could be as high as 100°F by mid-century.

Further adding to the increased heat burden, hot weather is predicted to persist for longer periods. For example, the maximum number of consecutive days above 90.2°F[xv] will increase from a baseline of 6 days to between 14 and 21 days by mid-century.[38] Moreover, the highest average sustained temperature for a seven-day period is projected to increase from a baseline of 92.2°F to between 96.4°F and 98.4°F by mid-century.

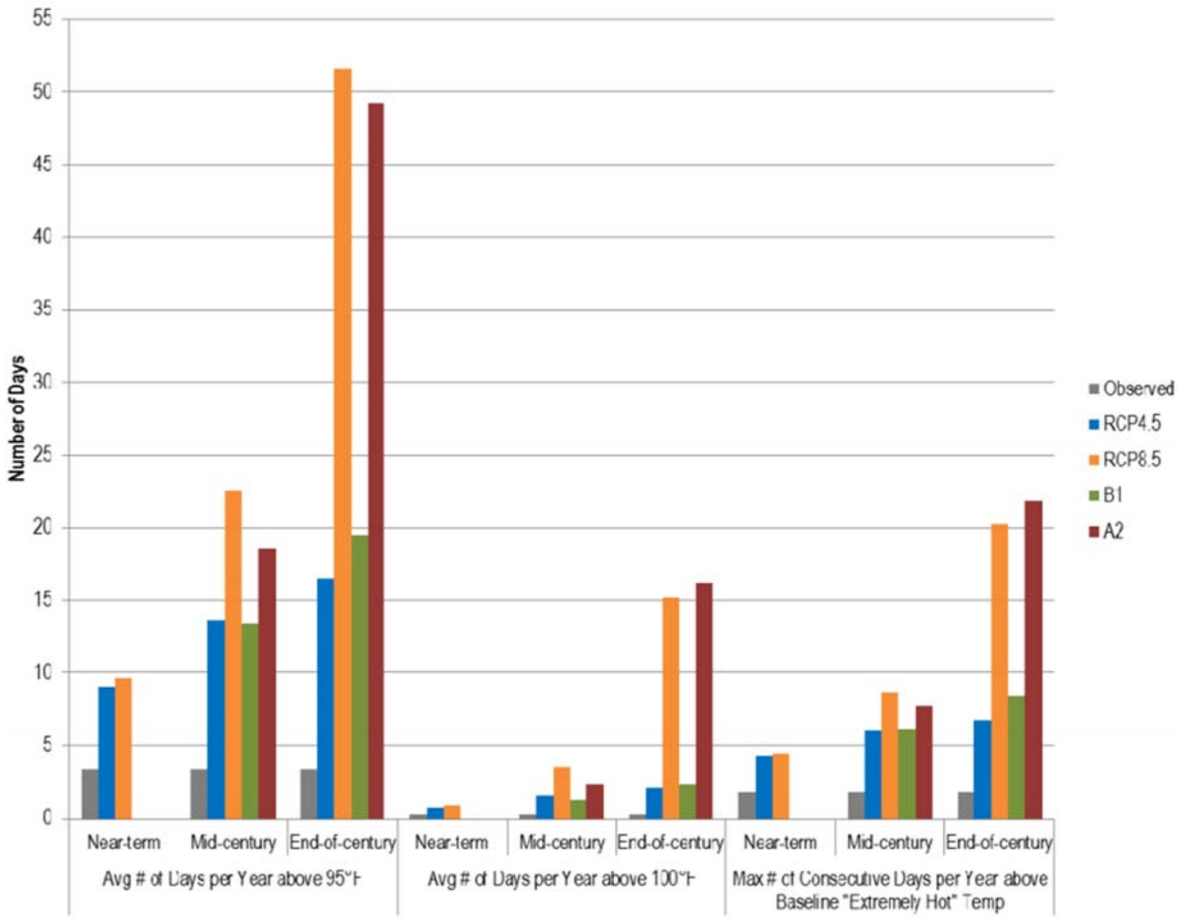

Figure 3.8. Projected temperatures extremes in Philadelphia (RCP4.5 and B1 are low emissions scenarios and RCP8.5 and A2 are high emissions scenarios)[39]

3.2.2.2 Wetter

Philadelphia is predicted to get wetter. The average annual amount of precipitation is projected to increase between 6% and 10% by mid-century, with the greatest increase expected in winter months.[40] The height of the Delaware River, a tidal river in Philadelphia, will also increase with climate change, bringing increased coastal flooding and negative impacts on water quality (e.g., from salt water intrusion). Compared to the period 2000-2004, Philadelphia is predicted to experience between 1 and 4.5 feet (12 and 54 inches) of sea-level rise by the 2080s.[41] 156,000 people or about 10% of Philadelphia's population live in areas that would be below high tide in the next century if carbon emissions continue on current

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[xv] *This is the baseline definition of "very hot," or the baseline 95th percentile temperature*

trajectory, but with large global cuts in CO_2 emissions that could decrease to about 14,000 people. Philadelphia appears to be one of cities with most to gain from CO_2 reductions based on sea level rise. Additional costs would be substantial from saltwater intrusion.[42]

The increased heat burden, precipitation, and river levels will severely strain the city's energy and water infrastructure. The potential consequences of a hotter and wetter urban environment underline the need for Philadelphia to prioritize urban cooling measures and stormwater management measures in policy making, planning, and investment.

3.2.3 El Paso

There is limited data available about El Paso's climate change future, but like the District and Philadelphia, El Paso is expected to get warmer. However, unlike the District and Philadelphia, it is expected to become drier as well.

3.2.3.1 Hotter

By mid-century (2041-2070), the average annual temperature in El Paso is expected to be between 2.5 and 3.5°F warmer than the historical average (1971-2000) under a lower emissions scenario. Under a higher emissions scenario, warming between 4.5 and 5.5°F is expected. See Figure 3.9 for additional average annual temperature changes under climate change.

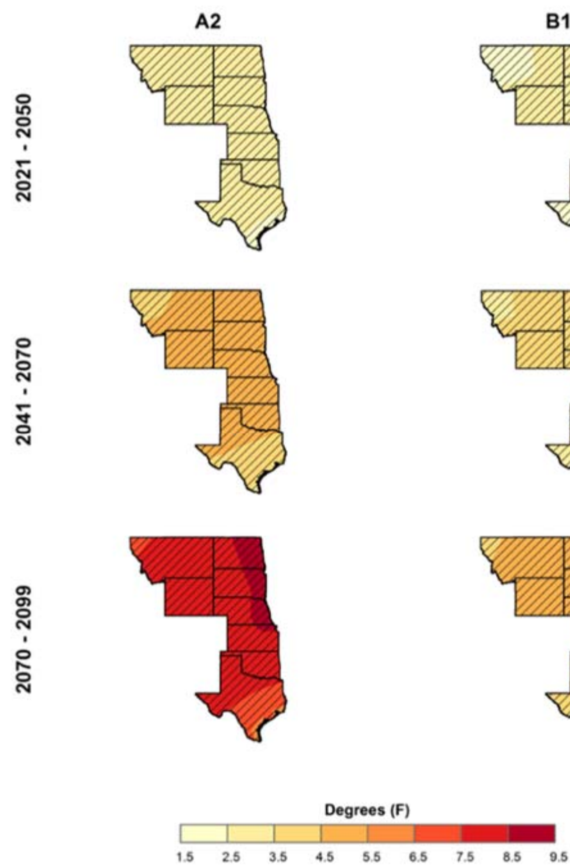

Figure 3.9. Simulated difference in annual mean temperature for the Great Plains (A2 is the higher emissions scenario and B1 is the lower emissions scenario from CMIP3 global climate simulations). (adapted from ref 43)

In addition to higher temperatures, the number of days above 100°F is expected to increase. Historically, there are about 7 days per year with temperatures above 100°F.[44] Under the lower emissions and higher emissions scenarios, this number will more than double to between 16 and 19 days and almost quadruple to between 25 and 28 days, respectively. Nights will get hotter as well, with the number of nights warmer than 80°F increasing from about 7 per year to between 30 and 35 per year or to over 45 per year under lower and higher emissions scenarios, respectively.

3.2.3.2 Drier

El Paso is projected to get even drier. Compared to the reference period (1971-2000), El Paso is expected to get between 3% and 9% less rain by mid-century. (See Figure 3.10 for additional average annual precipitation changes under climate change.) El Paso is also expected to experience longer dry spells, with the number of consecutive dry days (45) increasing by 1 to 2 days or by more than 4 days under the lower and higher emissions scenarios, respectively.[45] Extreme heat further exacerbate the drying of El Paso by increasing surface water losses.[46]

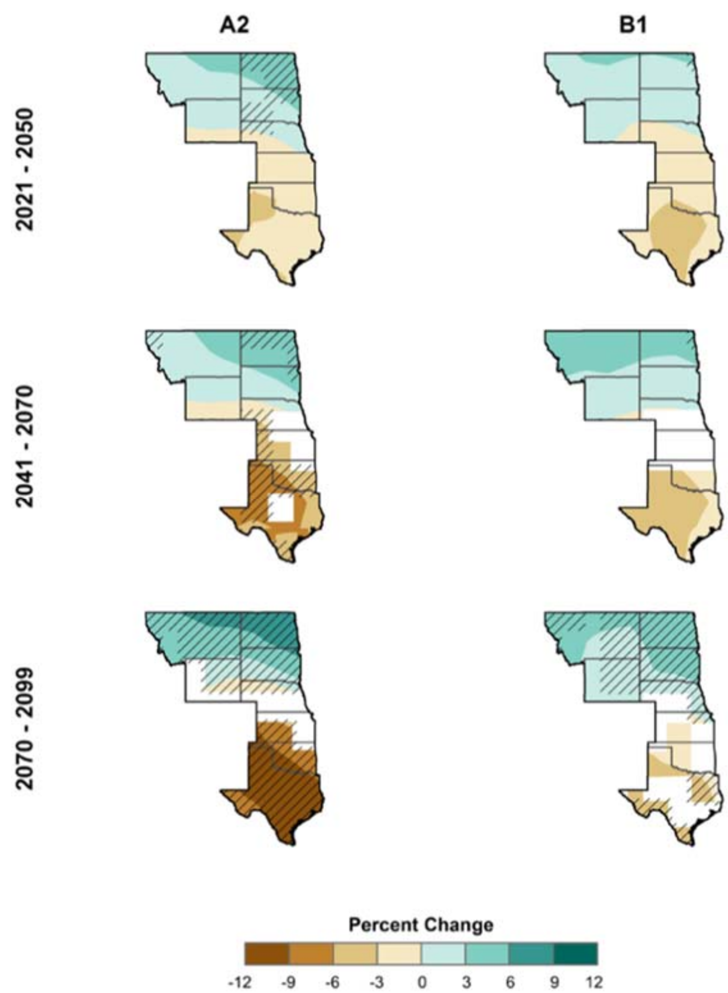

Figure 3.10. Simulated difference in annual mean precipitation for the Greg Plains (A2 is the higher emissions scenario and B1 is the lower emissions scenario from CMIP3 global climate simulations; color only indicates that less than 50% of the models show a statistically significant change in precipitation; and color with hatching indicates that more than 50% of the models show a statistically significant change in precipitation, and more than 67% agree on the sign of the change). (adapted from ref 47)

The increased heat burden and decreased precipitation will severely strain El Paso's energy and water infrastructure. The potential consequences of a hotter and drier urban environment highlight the need for El Paso to prioritize urban cooling measures in policy making, planning, and investment. Furthermore, incorporating more solutions to recharge groundwater (e.g., urban trees) could help lessen the impact of declining rainfall.

3.3 Overview of solutions

Below is a basic overview of the solutions analyzed in this report, including a summary of some benefits each solution provides. More detailed descriptions of each solution and their impacts can be found in the solution-specific chapters.

3.3.1 Roofs

Reflective roofs, commonly referred to as "cool" roofs, have higher solar reflectance than conventional roofs, which are dark and absorb most solar radiation. Because of the 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. This results in lower air conditioning use and reduced summer ambient air temperatures. For a more in-depth discussion of cool roofs, refer to Section 4.

Vegetated roofs (commonly referred to as "green" roofs) generally have a similar underlying structure to conventional roofs, but differ in the addition of plants, soil (called "growing media"), and more robust waterproofing and drainage. Green roofs stay cool through evapotranspiration and shading. They also have greater 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 cooling loads and lower winter heating loads. Evapotranspiration from green roofs cools the air, resulting in lower ambient air temperatures and air conditioner use, reducing energy costs. The plants and growing media soak up some of the rain that falls on a green roof, which reduces stormwater runoff volumes and results in smaller 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 5.

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 to electricity. Combined with an inverter and/or battery system that converts this electricity into a usable form, rooftop PV allows buildings and cities to reduce their use of grid electricity and become less reliant on the grid for electricity needs. For a more in-depth discussion of rooftop PV, refer to Section 6.

Figure 3.11. Cool roof (top left);[48] green roof (top right);[49] solar PV (bottom)[50]

3.3.2 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 7.

Figure 3.12. Reflective pavement on a parking lot[51]

The cooling value behind **urban trees**, though obvious, warrants explanation. Trees shade pedestrians and buildings and can provide wind block to nearby buildings, reducing summer cooling loads and winter heating loads. 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. For a more in-depth discussion of urban trees, refer to Section 8.

Figure 3.13. Urban street trees[52]

3.4 Overview of impacts

Four of the solutions this report analyzes are well established: cool roofs, green roofs, rooftop PV, and urban trees. Each solution has different costs and benefits, and each has their advocates. But city governments and affordable housing and other organizations, until this analysis, did not have a way to evaluate the cost effectiveness of any of these solutions completely, either as standalone investments, a combined investment, or in comparison with each other. The single largest gap in understanding and quantifying the benefits of these approaches—especially cool roofs and green roofs—is the health-related benefits, which involves complicated impact pathways. The authors of this report have been fortunate to be able to work with leading public health experts and institutions in developing this analysis.

In comparison to the other solutions evaluated in this report, reflective pavements are in their infancy. The science and understanding of the impacts of reflective pavements is still evolving, but they have similar impacts as the other four solutions, particularly cool roofs. 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.

3.4.1 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. 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. 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.

3.4.2 Energy and greenhouse gases

In the District, Philadelphia, and El Paso, grid electricity sources are relatively dirty,[53] because the power sources include fossil fuel based electricity generation.[xvi] Greenhouse gas (GHG) emission reduction benefits from cutting electricity use by expanding cool and green roof areas, reflective pavement area, tree area, and generating power from solar PV can therefore be substantial. Cool and green roofs directly reduce energy use for space conditioning by reducing heat gain and loss[xvii] to the building below, making buildings more efficient and lowering energy bills. Rooftop PV also reduces grid electricity purchases, lowering energy bills. For cool roofs and green roofs, a large portion of cooling energy reductions occurs during periods of peak energy demand and can reduce the use of the least efficient and often dirtiest generation.[54] Rooftop PV also generally offsets grid electricity use during peak demand periods, thereby reducing utility need to build 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 not only means lower cooling energy consumption, but also reduced peak electricity demand. Buildings that require less energy and/or produce their own energy are less dependent on the grid and more resilient.

3.4.3 Financial incentives

In many cities and states there are incentives for installing the roof technologies analyzed in this report. The District, along with 29 states, including Philadelphia (PA) and Texas (TX), have a renewable portfolio standard that requires that a specific percentage of its energy generation come from renewable sources—the District and PA also have specific solar targets.[55] In the District, PA, and TX, 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). There are various cool roof and green roof financial incentives as well, most of which are at the local level.

3.4.4 Health

3.4.4.1 Ozone

Widespread deployment of cool and green roofs, reflective pavements, and urban trees has large but diffuse health benefits.[xviii] Ground-level ozone formation generally increases with higher air temperature,

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[xvi] *This mix will change and generally become less CO2-intensive as coal plants close, renewables investments increase.*
[xvii] *Reduced heat loss only applies to green roofs.*
[xviii] *In other words, small risk reductions for lots of people*

so lower summer air temperatures results in lower levels of ground-level ozone and decreased incidence of ozone-related health consequences (e.g., asthma, heart disease, and premature death).[56] Modeling studies demonstrate that ozone concentrations worsen with the higher temperatures caused by climate change.[57] Ozone reductions from ambient cooling due to deployment of these five solutions can help offset climate change-related increases. Green roof vegetation and urban trees can also scrub the air of ozone pollution and ozone precursors.

3.4.4.1.1 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 temperature, relative humidity, solar radiation, and wind speed.[58] As temperature increases, the rates of chemical reactions that create ozone increase, leading to greater ozone formation. Ozone levels tend to be highest during summer afternoons. The ozone season is typically defined as the beginning of May through the end of September.[59]

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 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.[60] 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.

3.4.4.1.2 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.[61] 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 3.14). 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 3.14. The American Lung Association's summary of the EPA's findings on the health impacts of ozone[62] (Note: COPD stands for chronic obstructive pulmonary disease.)

3.4.4.1.3 Ozone and temperature

Climate change is expected to result in increased ozone pollution and consequent negative human health effects. Bell et al. (2007) analyzed the effects of climate change on ozone concentrations in 50 U.S. cities and found that climate change can be expected to increase ambient ozone concentrations and thus harm human health.[63] 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 health costs by $2.7 billion and $5.4 billion, respectively, in 2020.[64][xix] Few studies have examined the relationship between UHI mitigation and ozone concentration, and most focus on California.[65] In general, these studies find reductions in ozone concentrations resulting from UHI mitigation.

3.4.4.2 $PM_{2.5}$

Reductions in fossil fuel energy use from using any of the five solutions also contribute to reductions in fine particle pollution from power plants and reductions in related health impacts (e.g., heart disease, asthma, and death).[66] Green roof vegetation and urban trees can also scrub the air of $PM_{2.5}$ pollution.

3.4.4.2.1 PM2.5 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), and secondary particles are formed through atmospheric chemical reactions of precursors.[67] Primary $PM_{2.5}$ largely consists of carbonaceous materials (elemental carbon, organic carbon, and crustal materials like soil and ash).[68] 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).[69] Secondary particles make up most of the $PM_{2.5}$ pollution in the U.S.[70] 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).[71] 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).[72] In the Northeast, the main components of fine particle pollution are organic carbon and sulfates.[73]

3.4.4.2.2 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 $PM_{2.5}$.[74] In the review, EPA's panel of experts concluded that $PM_{2.5}$ pollution can cause serious harm through multiple pathways. The American Lung Association summarized EPA's findings (see Figure 3.15). The Appendix to this report provides additional references.

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 3.15. The American Lung Association's summary of the EPA's findings on the health impacts of $PM_{2.5}$[75] (Note: COPD stands for chronic obstructive pulmonary disease.)

[xix] *These cost increases are in 2008*

3.4.4.3 Heat stress

Heat stress has many negative health outcomes, including premature death, and is expected to become more common as the planet continues to warm.[76] Furthermore, heat waves, which are expected to become more common with climate change, exacerbate urban heat islands (UHI).[77] 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.[78] 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.[79] Extreme heat events are projected to be more frequent, longer lasting, and more severe as the climate warms.[80] 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.[81] Furthermore, UHIs and climate change together are expected to further increase the number of extreme heat events in cities.[82]

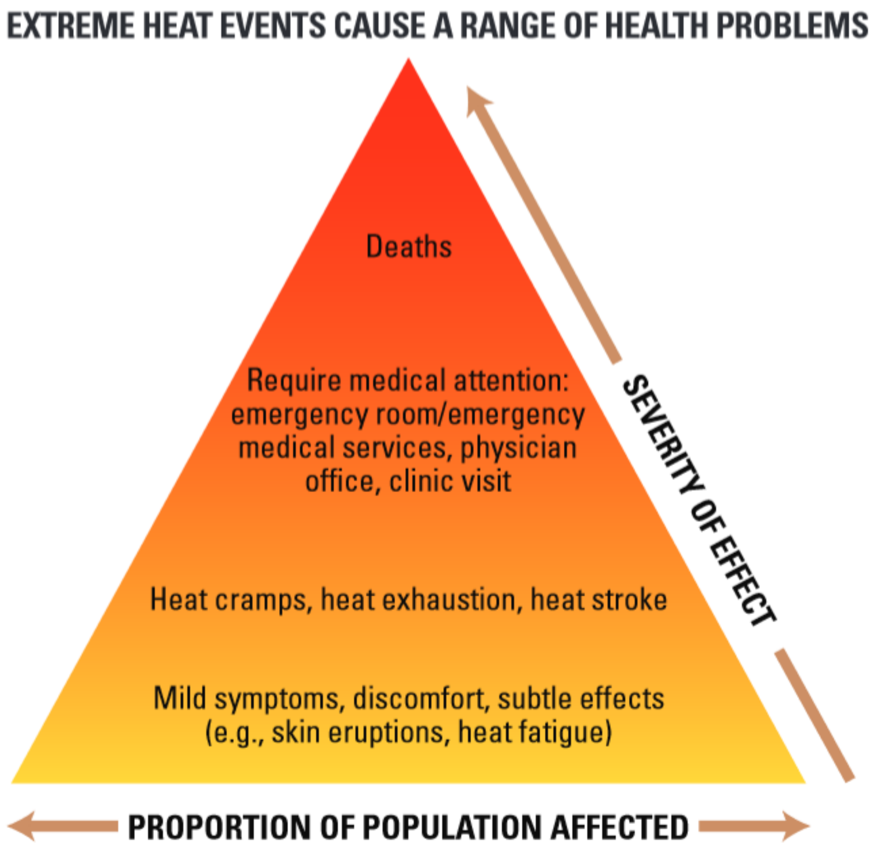

Figure 3.16. The health problems related to extreme heat[83]

In addition to elevated daytime temperatures due to UHIs, cities take longer to cool off at night and do not cool as much as rural areas. This means that urban populations often cannot recover from daytime heat and are thus more vulnerable to elevated temperatures in subsequent days.[84]

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 solutions can decrease urban heat-related mortalities by improving outdoor conditions.[85] However, this report could not find adequate data or studies to quantify the heat-related mortality impact of changes in indoor conditions from the solutions analyzed in this report, despite the fact that the impact of indoor conditions may be significant.[86] This impact is particularly important for residents in homes without air conditioning (not uncommon in low-income populations) and residents that live on the top floor of buildings.

3.4.5 Stormwater

Many cities, including the three analyzed in this report, 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. 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 expected to become even more important as average annual precipitation and the incidence of extreme rainfall events are expected to increase in many regions, including in the Mid Atlantic.

3.4.6 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, the Bureau of Labor Statistics began an effort to define and measure green jobs in 2010. They counted 3.1 million jobs in the green goods and services sectors in the United States in 2011, representing 2.3 percent of private sector and 4.2 percent of the public sector workforce.[xx] The D.C. Office of Planning commissioned a green collar job demand analysis for the District that optimistically predicted 169,000 green jobs would be created between 2009 and 2018 from existing and proposed District green policies.[87] More recently, a more conservative analysis conducted by the American Council for an Energy Efficient-Economy (ACEEE) in 2014 estimated that a city-wide commitment to 26 percent energy use reduction could create 600 net new jobs in the District by 2020 and 1,400 net jobs by 2030.[88]

Labor intensity of green energy tends to be higher than from conventional energy sources. There are a few good independent rigorous sources on job intensity of energy efficiency and renewable energy relative to other forms of energy. In synthesizing 15 existing studies, Wei et al. (2010) found that all non-fossil fuel energy solutions they studied (including energy efficiency) create more jobs per unit energy than coal and natural gas.[89][xxi] Another good example is from the World Bank (see Figure 3.17).

[xx] *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.*

[xxi] *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.*

Job creation per $ million of spending				
Energy source	Direct jobs	Indirect jobs	Induced jobs	Total jobs
Oil & natural gas	0.8	2.9	2.3	5.2
Coal	1.9	3.0	3.9	6.9
Building retrofits	7.0	4.9	11.8	16.7
Mass transit/freight rail	11.0	4.9	17.4	22.3
Smart grid	4.3	4.6	7.9	12.5
Wind	4.6	4.9	8.4	13.3
Solar	5.4	4.4	9.3	13.7
Biomass	7.4	5.0	12.4	17.4

Figure 3.17. Job creation by energy sector in the United States[90]

The World Bank estimates that wind and solar investment creates about 13.5 jobs per million dollars of spending, and that building retrofits—energy efficiency—creates 16.7 jobs per million dollars of spending. This is more than 3 times the 5.2 jobs per million dollars in spending for oil and natural gas, and more than 2 times the 6.9 jobs per million dollars in spending.[91]

A more detailed job analysis finds 5.3 jobs per million dollars of fossil fuel investment, and a bit over 3 times this—16.7 per million dollars—for clean energy (energy efficiency and renewable energy) investment. Importantly, this analysis also documents the substantially higher quality and higher pay nature of clean energy jobs relative to fossil fuel employment.[92]

U.S. state-level energy employment impact analyses also find large employment benefits from clean energy investments. For example, the Illinois Department of Commerce and Economic Opportunity found that an energy efficiency investment of $1 million creates 66 job years (this includes both direct and indirect jobs) in a 2015 review of state level energy efficiency programs.[93]

International studies also find large differences in labor intensity of clean energy relative to fossil fuels. For example, a 2014 United Kingdom Energy Research Center report found that the average employment creation for fossil fuels is 0.14 jobs per GWh (0.15 and 0.12 jobs per GWh for coal and gas, respectively), that the average across all renewable energy is 0.65 jobs per GWh, and that the average across both renewable energy and energy efficiency is 0.80 jobs per GWh. [94] This broad government study finds that renewable energy creates 4.3 times as many jobs as coal and 5.4 times as many as natural gas. It also finds that job creation from clean energy generally (renewables plus energy efficiency) is 5.3 greater than from coal and 6.7 times greater than from natural gas.

Renewable energy and energy efficiency clearly are more labor intensive than fossil fuels. Clean energy jobs are also more distributed and are largely higher quality jobs. For the District, Philadelphia, and El Paso to realize the large employment benefits of an expanded green economy, green jobs should largely go to city residents. Employment studies generally assume jobs created go to residents where installation occurs, but this is generally incorrect at a city level because many jobs can be expected to go to people who reside outside the city. This report therefore adopts more conservative assumptions about the percentage of jobs created that remain in the cities analyzed. For the purposes of this report we assume half the clean energy jobs in cities go the city residents, assuming that these programs include city resident training, job linking, in city hiring preferences—features that are common in larger city programs engaged in expanding clean energy. Without these specific efforts, expected job creation for in-city resident from in-city clean energy employment can be expected to be substantially less than 50%.

3.5 Regions of analysis

The low-income regions this report analyzes are Ward 5 in Washington, D.C., North Philadelphia in Philadelphia, and a low-income region of El Paso. Region selection rationale is explained in the Appendix. The following sections present maps and selected characteristics of each region.

3.5.1 Washington, D.C.: Ward 5

Table 3.1. Selected Ward 5 characteristics compared to Washington, D.C.

CHARACTERISTIC	WARD 5	WASHINGTON, D.C.
Population (2014)[95]	80,399	633,736
Income[96]		
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)[97]	10.4	61.05
Building footprint (% region)[98]	14.4%	15.9%
Paved area (roads, parking, sidewalks) (% region)[99]	23.1%	24.1%
Tree canopy (% region)[100]	27.7%	31.2%

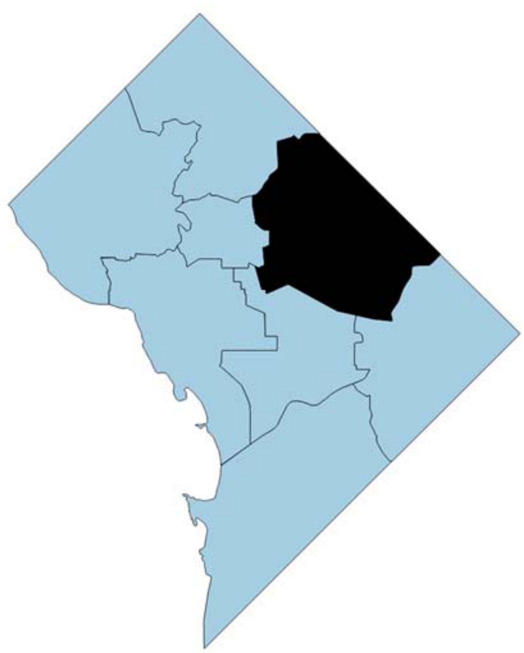

Figure 3.18. Washington, D.C., map; Ward 5 is black (base map from D.C. GIS Open Data,[101] map created with QGIS[102])

3.5.2 Philadelphia: North Philadelphia

Table 3.2. Selected North Philadelphia characteristics compared to Philadelphia

CHARACTERISTIC	NORTH PHILADELPHIA (2035 DISTRICT)	PHILADELPHIA
Population (2014) [103]	142,835	1,546,920
Income[104]		
Median income	$23,115	$37,460
Percent of population below poverty line	45.2%	26.7%
Unemployment rate	24.8%	14.9%
Land use		
Area (square miles)[105]	8.6	134.1
Building footprint (% region)[106]	27.6%	18.7%
Paved area (roads, parking, sidewalks) (% region)[107]	32.9%	26.6%
Tree canopy (% region)[108]	10.1%	20.0%

Note that the low-income neighborhood of Philadelphia (North Philadelphia) has 6 times as much of its surface impervious (eg roofs, road parking lots) as in tree canopy. In contrast, Philadelphia-wide that ratio is a little over 2 to 1.

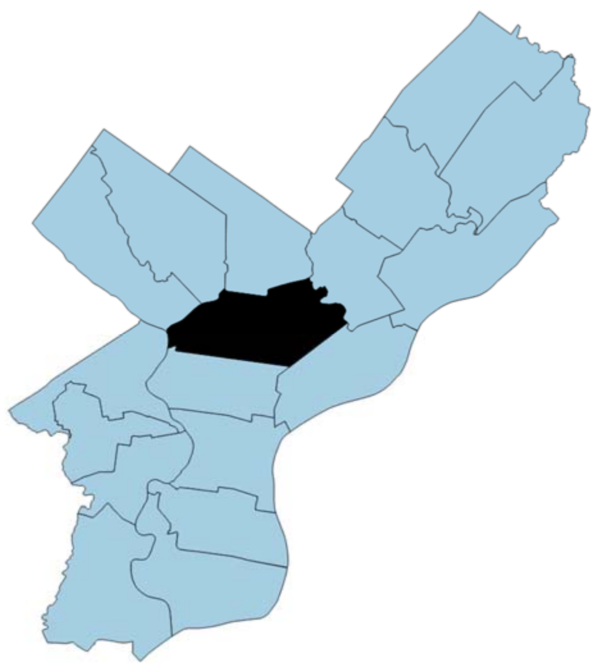

Figure 3.19. Philadelphia map; North Philadelphia is black (base map from OpenDataPhilly,109 map created with QGIS110)

3.5.3 El Paso: El Paso Low-income Region

Table 3.3. Selected El Paso Low-income Region characteristics compared to El Paso

CHARACTERISTIC	EL PASO LOW-INCOME REGION	EL PASO
Population (2014) [111]	76,982	669,771
Income[112]		
Median income	$21,789	$42,037
Percent of population below poverty line	41.5%	21.5%
Unemployment rate	12.7%	8.6%
Land use		
Area (square miles)[113]	19.2	256.3
Building footprint (% region)[114]	14.7%	8.4%
Paved area (roads, parking, sidewalks) (% region)[115xxii]	21.6%	12.3%
Tree canopy (% region)[116]	Not available, assume 0.8%	0.8%

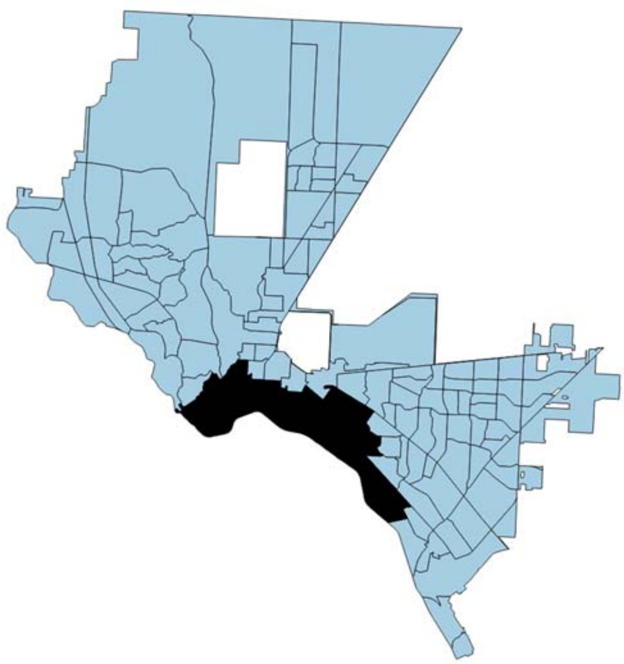

Figure 3.20. E Paso map; El Paso low-income region is black (base map from** Pasa Del Norte Map for Public Access,[117] **map created with QGIS[118])

[xxii] *Parking lot data in El Paso is limited, so approximated parking lot area using methods described in the Appendix.*

4 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.

4.1 Cool roof basics

Cool roofs have higher solar reflectance[xxiii] (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 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 4.1 below illustrates these concepts.[xxiv]

As illustrated in Figure 4.1 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.

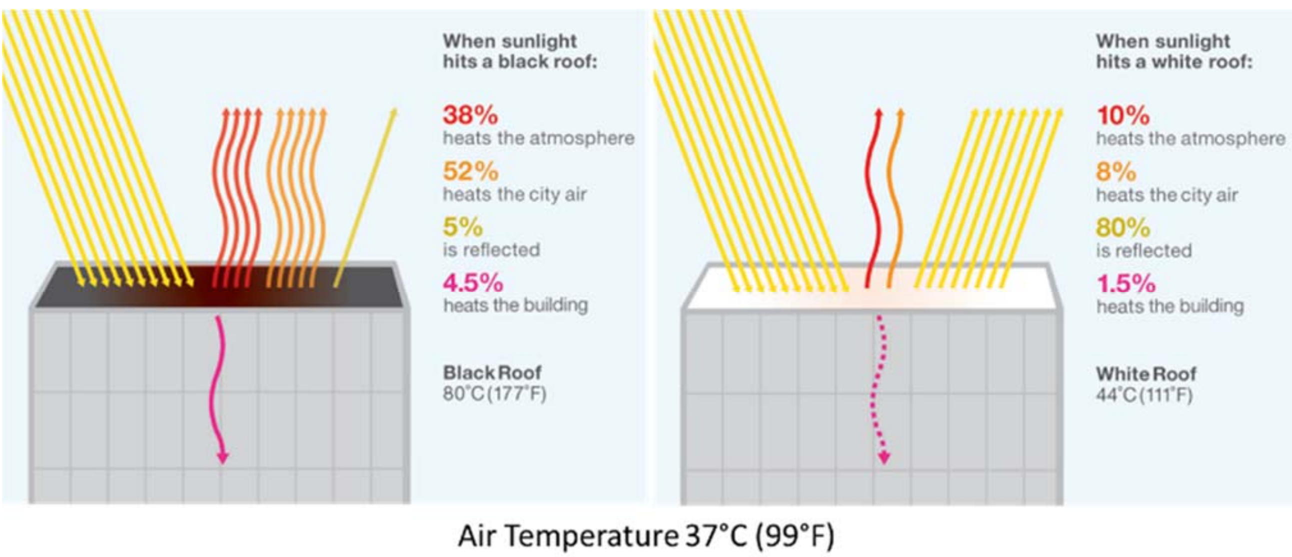

Figure 4.1. Comparison of a black roof and white roof on a summer afternoon (numbers do not sum due to rounding)[119]

4.1.1 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[xxv] are common on commercial buildings, multifamily housing, and row homes. Common types of low slope roofs are built-up roofing, modified bitumen, and single-ply membrane roofing. The most common cool

[xxiii] 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
[xxiv] The solar reflectance of the black roof in Figure 5.1 is 0.05 and that of the white roof is .80
[xxv] No more than 2 inches of vertical rise over 12 inches of horizontal run

roof options for low slope roofs are coatings and membranes.[xxvi] Steep slope roofs[xxvii] 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,[120] 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 such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and International Code Council (ICC)) reference Cool Roof Rating Council standards.

Conventional roofs have ranges of solar reflectance from 0.05-0.20, depending on type.[121] This report assumes a solar reflectance of 0.15 for conventional low slope roofs. 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 4.1 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.[122] 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 4.2). Currently, most cool steep slope products achieve aged albedos around 0.25.[xxviii] 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).[123] Based on review of existing green building codes (e.g., International Green Construction Code),[124] 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 4.2 below showing cool-colored roof tiles measured by Lawrence Berkeley National Laboratory). Cool steep slope roofs will have 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 4.1 below presents the solar reflectance values used in this analysis.

Table 4.1. Conventional and cool roof albedos used in this report

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

[xxvi] *For more detailed descriptions and pictures see ref 54 and ref 119*
[xxvii] *Greater than 2-inch rise over 12-inch run*
[xxviii] *Based on analysis of Cool Roof Rating Council rated product database in October 2015*

Figure 4.2. Cool-colored tiles (top row) look like conventional roof tiles (bottom row) but have higher solar reflectance[125]

4.1.2 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.[126] Roof replacement, rather than restoration, is the norm when a roof needs repair (e.g., when there is a leak).[127] Low slope cool roofs have been around long enough that they typically are the same or only marginally higher cost than their conventional equivalent.[128] This report assumes a low slope cool roof cost premium of $0.15 per square foot, which is 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.[129] For both roof slopes, this report assumes a constant cost premium necessary to drive continuous albedo improvements. Table 4.2 summarizes cool roof installation cost premiums.

High albedo roofs experience less thermal expansion and contraction than conventional roofs, and so likely have longer lives.[130] 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 (see ref 130), 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.[xxix] 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.

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.[xxx] Table 4.2 summarizes cool roof maintenance cost premiums.

[xxix] *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*
[xxx] *For example, ref 130 conclude that power washing is not cost-effective*

Table 4.2. 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

4.2 Impacts of cool roofs

4.2.1 Cool roof impact summary

The table 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 4.3. Cool roof cost-benefit impact table (A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact)

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

4.2.2 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") is less than cooling energy savings[131] 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.[xxxi] Furthermore, peak demand for heating typically occurs around sunrise—which is when conventional and cool roofs are roughly the same temperature.[xxxii] Section 9.2 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.[xxxiii] 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 4.2.7.

4.2.2.1 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.[132] Savings/penalties will be different in residential and commercial properties because of differences in design, occupancy, and HVAC schedules.[xxxiv]

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.[133]

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.[134] Therefore, the more floors a building 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, while heating penalties generally increase in cooler climates.[135] 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 or Philadelphia.[xxxv] Around El Paso, the load change ratio for office buildings ranged from 0.06 to 0.08. As the city gets warmer with climate change, the heating penalty will

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[xxxi] In northern climates, such as Alaska, the heating penalty commonly exceeds the cooling benefits.
[xxxii] 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.
[xxxiii] Demand charges are sometimes referred to as capacity charges.
[xxxiv] 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.
[xxxv] Note this is an energy comparison, not a cost comparison

drop and the cooling benefits will increase. The load change ratio is typically higher for residential properties.

4.2.3 Ambient cooling and indirect energy

4.2.3.1 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).[136] The relationship between urban albedo and average air temperature is much better defined than the relationship between urban albedo and peak air temperature.[xxxvi]

UHIs are highly location specific, so it is preferable to have a location specific ambient cooling analysis. Fortunately, a few recent studies examine UHI mitigation in the District and Philadelphia.[137] All studies found albedo increases are effective at reducing UHIs these two cities. El Paso's UHI is less well studied, so this report uses the UHI of Phoenix, AZ as a proxy for that in El Paso given similar desert climates. Studies of Phoenix's UHI find albedo increases are effect at mitigating the UHI.[138] These studies are discussed in more detail in Section 9.4 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 it estimates the benefits of ambient cooling by estimating 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).

4.2.3.2 Indirect energy

As noted above, a city-wide switch from conventional, dark roofs to cool roofs can have a substantial impact on urban summer air temperature, leading to city-wide net energy savings.[xxxvii] 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.[139, xxxviii]

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.[xxxix] Section 9.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

[xxxvi] 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.
[xxxvii] Cooling energy savings as well as smaller heating penalties.
[xxxviii] Electric heating penalties are included in the electricity savings calculations.
[xxxix] 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.

4.2.4 Climate change mitigation

4.2.4.1 Greenhouse gas emissions reductions

Anthropogenic (human-caused) greenhouse gas (GHG) emissions are the dominant factor driving global climate change.[140] 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.[141] Reducing energy used for space conditioning from cool roof installation reduces building-related GHG emissions.

4.2.4.2 Global cooling

Cool roofs reflect more sunlight back into space than conventional roofs, thereby causing negative radiative forcing[xl] 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 CO_2e.[142] 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.[143] However, clouds are one of the most complex aspects to climate modeling, with no clear conclusions, so some urban-climate scientists discount the impact of urban albedo changes on cloud formation.[144][xli] 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 9.5. Further detail is provided in the Appendix.

Figure 4.3 shows cool roof climate change mitigation pathways.

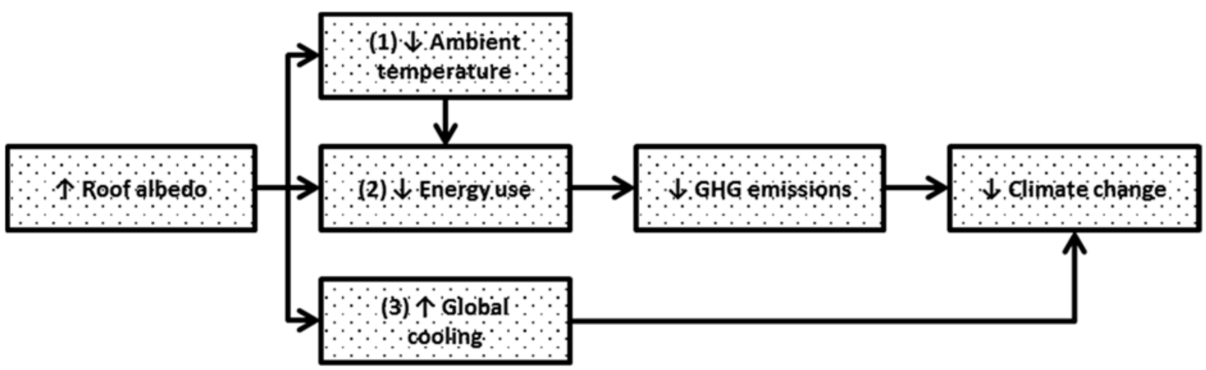

Figure 4.3. Cool roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

4.2.5 Improved air quality and health

4.2.5.1 Cool roofs and ozone

Increasing urban albedo indirectly reduces ambient ozone concentrations by: (1) decreasing ambient temperature; and (2) decreasing summertime building energy use. As discussed above in Section 3.4.4, the chemical reactions that form ozone are temperature dependent, so decreasing ambient temperature

[xl] Radiative forcing is the difference between the radiant energy received by the Earth (from the Sun) and the energy Earth radiates to space.
[xli] And note that urban areas already increase cloud formation because of particulates they produce.

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. 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 4.4 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 9.6 and in the Appendix.

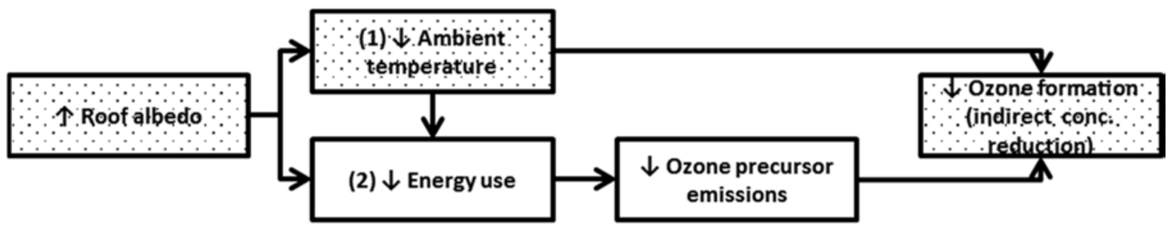

Figure 4.4. Cool roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

4.2.5.2 Cool roofs and $PM_{2.5}$

Cool roofs reduce $PM_{2.5}$ pollution directly by decreasing building energy use and indirectly by decreasing ambient temperature, which in turn reduces building energy use. Reducing building energy use results in decreased emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors, decreasing primary and secondary $PM_{2.5}$ pollution.

Figure 4.5. shows the $PM_{2.5}$ concentration reduction pathways of cool roofs. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 9.6 and in the Appendix.

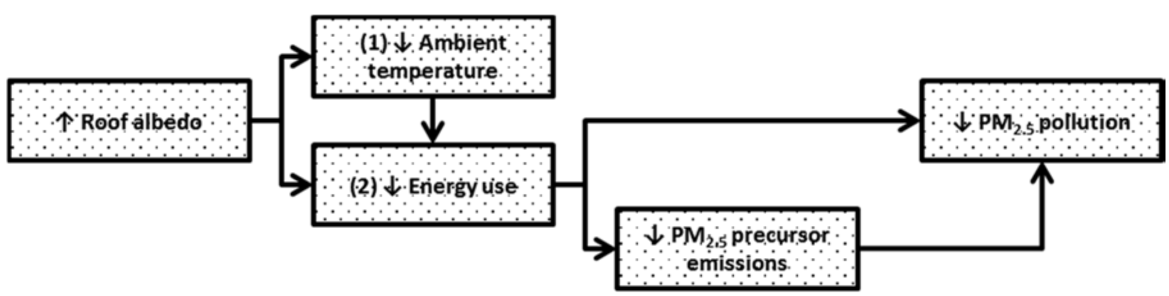

Figure 4.5. Cool roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

4.2.5.3 Cool roofs and heat-related mortality

Modeling studies show that UHI mitigation solutions like cool roofs can decrease urban heat-related mortalities by reducing air temperature.[145] As noted in Section 3.4.4, there are two pathways by which cool roofs can reduce heat-related mortality: (1) improving outdoor temperature conditions and (2) improving indoor temperature conditions. This report did not find sufficient rigorous work documenting the potential for cool roofs to reduce heat-related mortality by improving indoor conditions, so this benefit is not estimated in this report. However, this benefit is probably significant[146] and warrants further research.[xlii] Because this analysis does not include the heat-related mortality impact of cool roofs from improving indoor conditions, heat-related mortality benefit estimates in this report should be considered conservative. This report describes heat-related mortality benefit estimation methods and assumptions in Section 9.6 and in the Appendix.

4.2.6 Cool roofs and employment

The net employment impact of cool roof installation is negligible because cool roofs and conventional roofs have similar installation requirements.[xliii] For this reason, the net employment impact of cool roofs is not included in costs-benefit results. However, cities like New York City[147] are using cool roofing and training to bring people into the job market.

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

4.2.7 Other impacts of cool roofs

4.2.7.1 Increased roof life

It is reasonable to assume that cool roofs last longer than conventional roofs due to reduced thermal expansion and contraction and reduced UV radiation absorption.[148] However, in the absence of sufficient data, this report does not include this benefit in cost-benefit estimates. Increased cool roof life could be a significant benefit.

4.2.7.2 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.

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 roofs and deserves further research.

4.2.7.3 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).[149] Because cool roofs have lower peak roof surface temperatures, buildings with cool roofs experience reduced peak electricity demand.[xliv] Lower ambient temperatures also contribute to peak electricity demand reductions.[150] Peak electricity demand reductions mean reduced consumption during periods with higher electricity rates during which "time of use" rates apply, and reduced capacity charges (e.g., for large commercial and industrial buildings), so

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[xlii] 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.

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

[xliv] 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.

reduced peak demand can provide significant consumer savings. However, because of limitations in the Green Roof Energy Calculator (GREC)[151] this analysis does not quantify the benefits of peak electricity demand reductions, and energy benefit calculations are conservative as a result.

4.2.7.4 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.[152] The 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 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.

4.2.7.5 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.[153] 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 that support trout) can be particularly sensitive to heated runoff.[154] Given the large uncertainty and the difficulty in valuing reduced stormwater runoff temperature and its likely limited impact, this analysis does not include this potential benefit in cost-benefit calculations.

4.2.7.6 Increased PV efficiency

Cool roofs may enhance performance of solar PV systems installed on them. PV panel efficiency degrades slightly with higher panel temperature,[xlv] 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 5.2.8 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. Given that we did not find convincing work quantifying the impact of cool roofs on PV power output, we do not include this benefit is cost-benefit calculations.

4.2.7.7 Glare

Glare from roofs that reflect a large fraction of visible light (e.g., bright white roofs) might disturb occupants of nearby taller buildings.[155] In situations where this is a concern, cool-colored roofs (discussed in Section 4.1.1) 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[xlvi] 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.

[xlv] *All else equal, higher PV efficiency means greater electricity generation.*
[xliv] *Cool-colored roofs 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 4.1.1.*

5 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.

5.1 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 on top of conventional roofing and water proofing systems.[156] Figure 5.1 below shows conventional roofing structure and two green roof structures, one without a drainage system and one with a drainage system.[xlvii] 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.

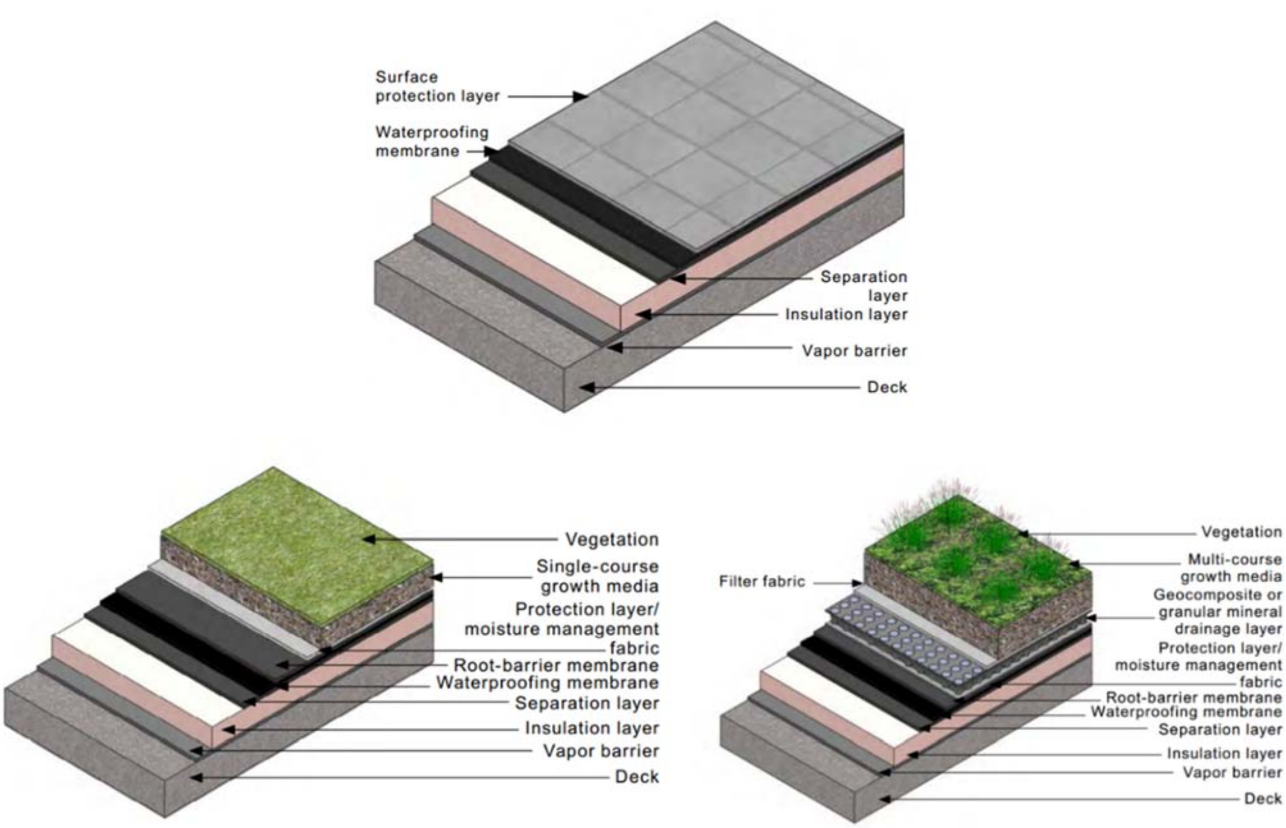

Figure 5.1. Examples of a conventional roof structure (top), green roof structure without a drainage layer (bottom left), and green roofs structure with a drainage layer (bottom right)[157]

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

There are two general approaches to installing green roof systems: (1) built-in place and (2) modular.[158] 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).[159] There is limited research into the performance differences between the two green roof system installation methods,[160] so this report does not make a distinction between the two in cost-benefit analysis calculations below.

5.1.1 Extensive and intensive green roofs

There are two major types of green roof: (1) intensive and (2) extensive. Intensive green roofs are thicker, typically with soil depths greater than six inches, able to support a wider variety of 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 three inches and six 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.[xlviii] Extensive green roofs are by far the most common green roof type.[161] Figure 5.2 below shows examples of an extensive and intensive green roof.

Figure 5.2. Example of extensive green roof (left) and intensive green roof (right)[162]

5.1.2 Installation and maintenance costs

We assume that all green roofs modeled are of the extensive type and have a life of 40 years. This assumption is consistent with other published cost-benefit analyses.[163] 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.[164] This report assumes that the additional cost of a green roof compared to a

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

conventional roof is $15 per square foot.[xlix] 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 for the success of a green roof and requires more involved maintenance than post-establishment.[l] 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.[li] Irrigation can also increase benefits, however (as discussed in Sections 5.2.1 and 5.2.3). Because plants on an extensive green roof are selected to survive without permanent irrigation, and long-term irrigation on extensive green roofs is uncommon, 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.[165] After the establishment period, this report assumes the overall maintenance cost reduces by 30 percent because less work is required to maintain the roof,[166] 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 5.1.[lii]

Table 5.1. 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

5.2 Impacts of green roofs

5.2.1 Green roof impact summary

[xlix] 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.
[l] 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
[li] 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.
[lii] 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.

Table 5.2Table 5.2 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 5.2. Green roof cost-benefit impact table (A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact)

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

5.2.2 Direct energy

There are three mechanisms by which green roofs reduce direct energy consumption: (1) increasing roof surface evapotranspiration rates, (2) shading the roof surface, and (3) increasing the thermal mass and thermal resistance of the roof.[167] Figure 5.3 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[liii]—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 9.2 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

[liii] *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)*

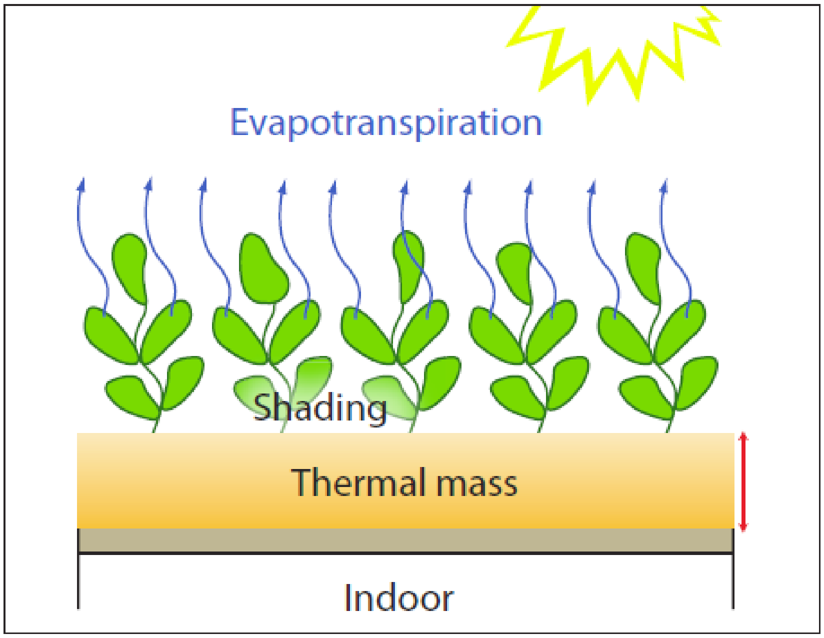

Figure 5.3. Green roof direct energy benefit features[168]

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 5.2.8.[liv]

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

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

[lv] 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)

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.[169] However, the cooling energy use benefit plateaus above a certain soil moisture content.[lvi]

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.[lvii] 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.

5.2.2.2 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 die back or if plants do not 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).

5.2.2.3 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,[lviii] 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.[lix] This

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[lvi] *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."*
[lvii] *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*
[lviii] *Thermal mass is the ability of a material to absorb and store heat energy.*
[lix] *Because they heat up slower than conventional roofs, the membrane of a green roof (where the heat transfer between the roof and building occurs) reaches peak temperature after conventional roofs, reducing peak cooling loads.*

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.[170]

Green roofs also provide a small insulation benefit to the building below.[171] The amount of thermal resistance (insulation) provided by green roofs depends on the thickness of the growing medium—a thicker growing medium generally means greater insulating properties—and the moisture content in the growing medium—as moisture content increases, insulation value decreases.[172] 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.

5.2.2.4 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.

5.2.3 Ambient cooling and indirect energy

5.2.3.1 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.[173] As solar radiation increases, the green roof ambient cooling benefit decreases, but is not eliminated. Generally, as soil moisture increases, sensible heat transfer to the urban air decreases—i.e., green roof ambient cooling benefit increases.[lx] The study also found that relative humidity does not show a strong impact on green roof ambient cooling benefit.[174]

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.[175] 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, there are a few recent studies that examine the impact of green roofs on urban temperatures in the District,[176] and Philadelphia,[177] all of which found that increasing green roof coverage generally reduces ambient temperatures. Green roofs are comparatively less well studied in El Paso. We found no studies examining the impact of green roofs on El Paso's UHI. However, studies of vegetation in similar climates (e.g., Phoenix) find vegetation is effective at mitigating the UHI, though generally not as effective as increases in albedo because of lack of soil moisture in desert climates.[178]

Green roof installation may also increase urban humidity, which potentially has negative effects that are discussed in more detail in Section 5.2.8.

[lx] *A recent modeling study demonstrates the importance of green roof soil moisture content. Ref 176 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.*

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 5.2.4), improvements in air quality (Section 5.2.5), and declines in heat-related mortality (Section 5.2.5).

5.2.3.2 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 evapotranspiration is minimal, and the sun is at a lower angle in the sky and is above the horizon for fewer hours.[lxi] Section 9.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

5.2.4 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.[179] 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,[180] but the amount of carbon sequestered is minimal and[181] so, 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 9.5. Figure 5.4 shows green roof climate change mitigation pathways.

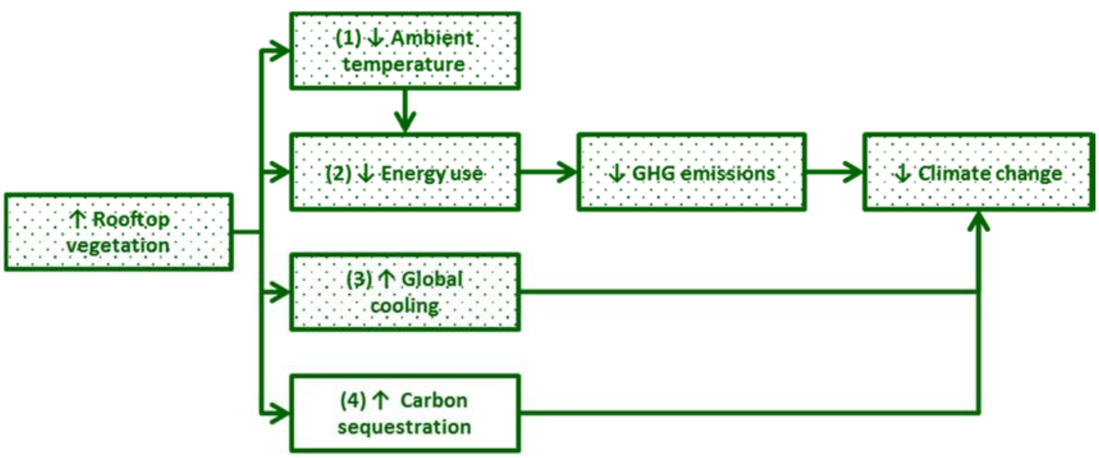

Figure 5.4. Green roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

[lxi] *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.*

5.2.5 Air quality and health

5.2.5.1 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 5.5 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 9.6 and in the Appendix.

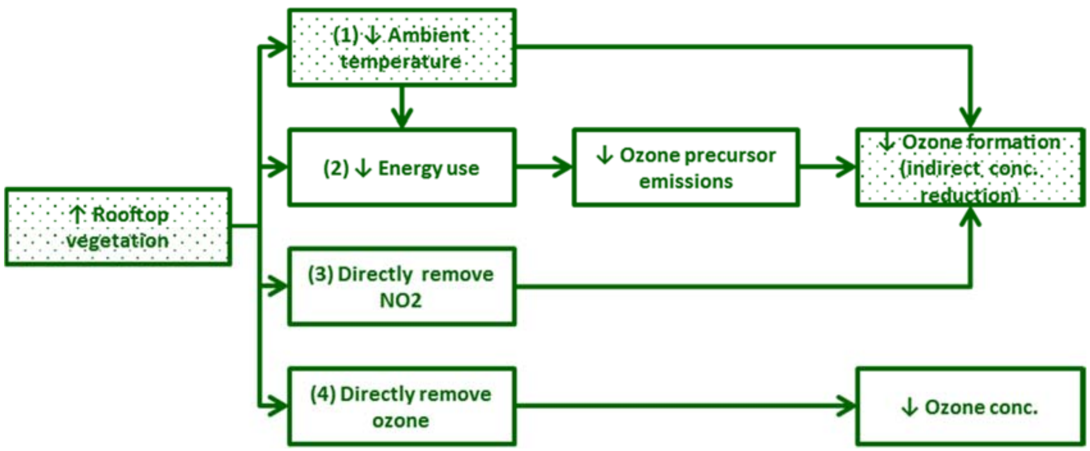

Figure 5.5. Green roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

5.2.5.2 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 5.6). 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 5.6). Similar to cool roofs, green roofs reduce $PM_{2.5}$ pollution by decreasing ambient temperature (pathway (2) in Figure 5.6), and decreasing building energy use (pathway (3) in Figure 5.6). Figure 5.6 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 9.6 and in the Appendix.

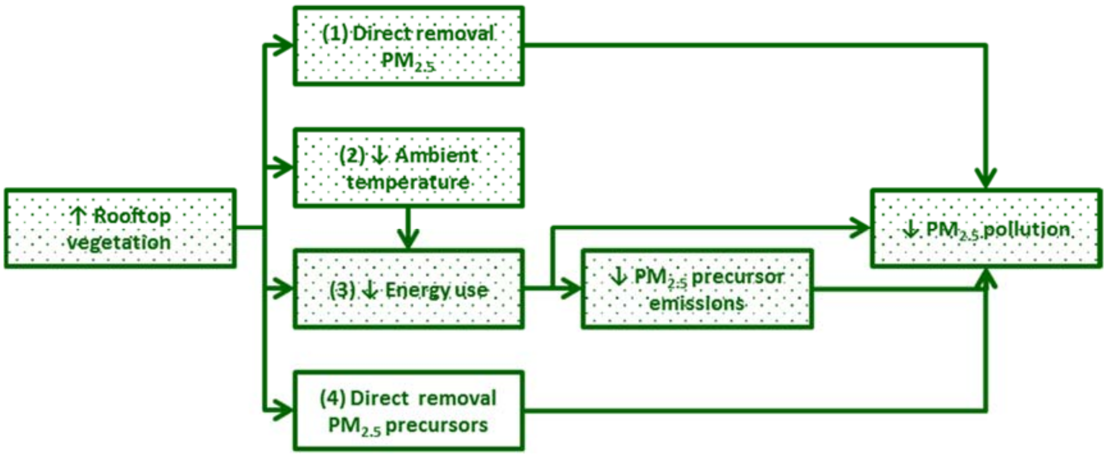

Figure 5.6. Green roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

5.2.5.3 Green roofs and heat-related mortality

Modeling studies have shown that UHI mitigation solutions (e.g., cool roofs and green roofs) can decrease urban heat-related mortalities through changes in ambient air temperature.[182] As noted in Section 3.4.4, 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.[183] 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 9.6 and in the Appendix.

5.2.6 Stormwater

As noted, the District, Philadelphia, and El Paso have high percentages of impervious surface 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. 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.[184] Climate change is predicted to bring more extreme rainfall to the District and Philadelphia, increasing river pollution and stormwater management costs.

There are three types of stormwater management: treatment, detention, and retention.[185] 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.[lxii] 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 5.7). Peak runoff rate reduction,

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

delayed peak runoff, and decreased total runoff from green roofs all relieve pressure on stormwater infrastructure and reduce water pollution. Figure 5.8 illustrates these stormwater benefits of green roofs.

Section 9.7 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

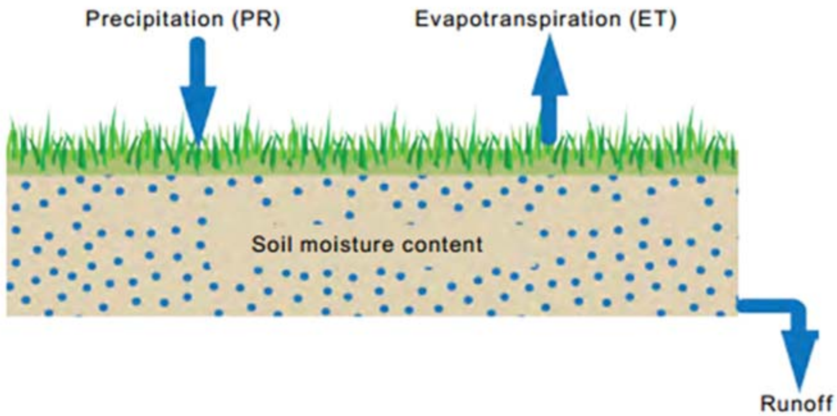

Figure 5.7. Green roof water budget[186]

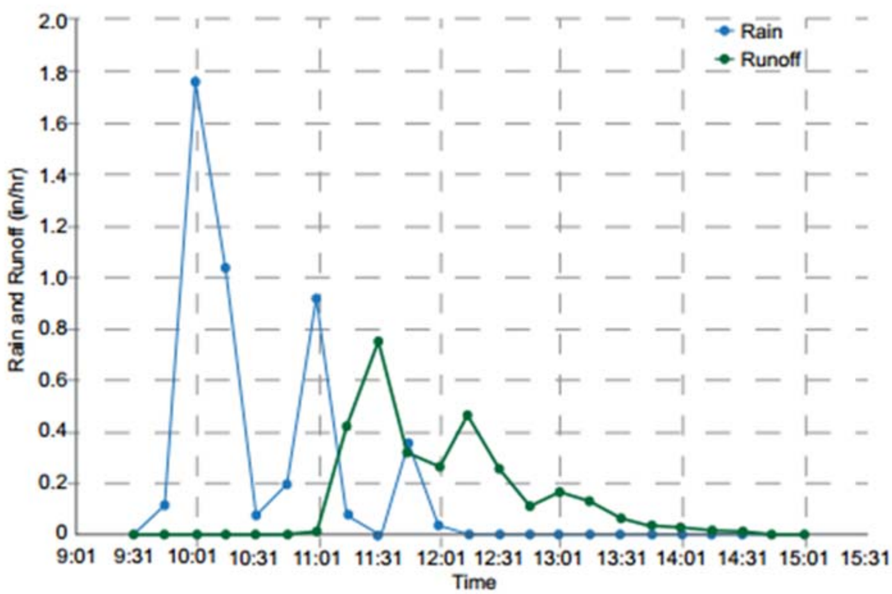

Figure 5.8. Example timeline of rainfall and green roof runoff[187]

5.2.6.1 Important factors that influence green roof stormwater retention

Green roof stormwater retention capacity depends on several factors. Plant selection, growing medium, drainage layer, and roof slope all affect green roof stormwater retention. Green roofs retain the most stormwater during the summer, because this is when plants are most active and evapotranspiration is at its peak.[188] 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.[189] 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.

5.2.7 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.[190] 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.[191] 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.[lxiii] All labor intensity estimates for installation in this report include planning, transportation, installation, and maintenance. We ignore manufacturing employment because these jobs would likely occur outside of the cities analyzed. 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 3.4.6, 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 city. This percent could be increased by incentives or coordinated city training and employment policies.

Section 9.8 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

5.2.8 Other impacts of green roofs

5.2.8.1 *Reduced HVAC air intake temperature*

Like cool roofs, green roofs may impact HVAC air intake temperature. Walmart compared a green roof to a white roof on a store in Chicago.[192] 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.[lxiv] As noted in the cool roof benefits section (Section 4.2.7), this benefit may be significant, particularly for multistory buildings that make up the large majority of buildings in cities, and deserves future research.

[lxiii] *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.*

[lxiv] *Note that the results of the Walmart study are based on the analysis of a single story building with an approximately 1-to-1 floor area to roof area ratio so it is difficult to draw general conclusions for all buildings sizes. Thought experiment: HVAC equipment draws in large volumes of air. Walmart HVAC system and HVAC system of 5 story building with same floor area as Walmart store will draw in approximately same amount of outside air to maintain comfortable building environment. The Walmart HVAC system will draw in more air that has been tempered by roof than the HVAC system of the five story building with same floor because the roof of the 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.*

5.2.8.2 *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).[193] 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.

5.2.8.3 *Downwind cooling*

As discussed in the cool roof benefits section (Section 4.2.7), 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 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.

5.2.8.4 *Reduced stormwater runoff temperature*

Like cool roofs, green roofs can reduce stormwater runoff temperature because they are typically cooler than conventional roofs. However, given the limited research on the economic impact of thermal shock, this analysis does not include this benefit.

5.2.8.5 *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.[194] The GSA estimated the "real estate effect" (the market's value of a green roof") at $13 per square foot of roof per year.[195] For green roof installations that include building tenant access and use, this amenity value can be added in, and could 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.

5.2.8.6 *Aesthetic value*

Green space and vegetation have been shown to reduce stress,[196] lower blood pressure,[197] and decrease crime.[198] 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.[199] 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,"[200] this analysis does not value aesthetic benefits of green roofs.

5.2.8.7 *Increased biodiversity*

Biodiversity refers to the variety of life in an area. Green roofs can increase biodiversity compared to conventional roofs.[201] 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.[202] 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,[203] so this analysis does not include biodiversity benefits in cost-benefit results.

5.2.8.8 *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),[204] meaning that for each additional degree PV panel temperature rises above 25°C (77°F), PV power output decreases by 0.35% (0.19%).[lxv] For example, at 30°C, PV power output would decrease by 1.8%.

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.[lxvi] 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%.[lxvii] If annual solar output is 1300 kWh per kW,[lxviii] 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.[205] 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.[lxix] 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.

5.2.8.9 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).[lxx] Higher moisture content in the air can increase cooling energy consumption[lxxi] and heat-stress.[lxxii] 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,[206] which would increase the ozone reduction benefit of green roofs. Both the negative and positive impacts of higher humidity vary by location and are condition dependent. This report found no research on the negative or positive impacts of increased humidity from green roofs, and this is excluded it from cost-benefit calculations.

[lxv] *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.*
[lxvi] *Based on the formula for calculating nominal operating cell temperature at PVEducation.org.*
[lxvii] *This is optimistic because the air temperature on a green or black roof will not always be greater than 25°C.*
[lxviii] *This is approximately right for the District and Philadelphia, but low for El Paso.*
[lxix] *This is a relative efficiency increase, not an absolute efficiency increase.*
[lxx] *How hot air feels is based on both temperature and moisture content.*
[lxxi] *Because air conditioning systems may have to do more work to deliver air within the set humidity range.*
[lxxii] *Because it is more difficult for humans to cool their bodies in more humid conditions.*

6 SOLAR PV

This section explores 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.

6.1 PV basics

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

There are three commonly cited PV sectors: residential, commercial, and utility-scale. Figure 6.1 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 6.2). 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 6.1. Residential PV (top left),[207] commercial PV (top right),[208] and utility-scale PV (bottom)[209]

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

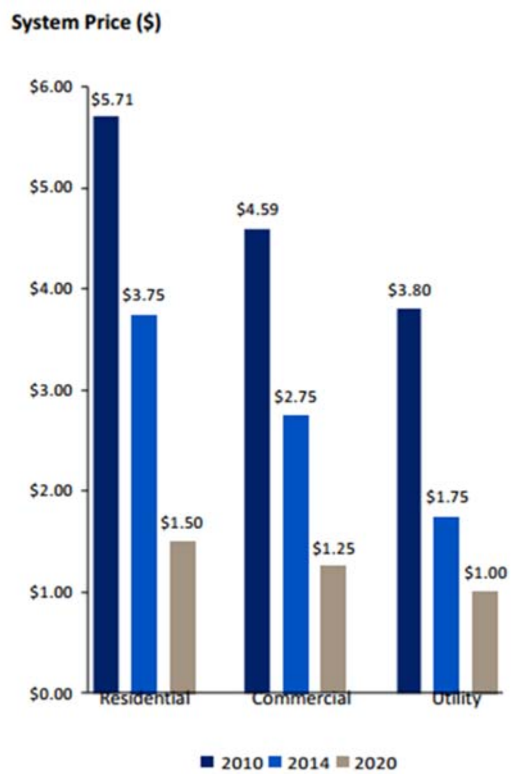

Figure 6.2. Installed solar PV system price[210]

6.1.1 Installation and maintenance costs

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

6.1.1.1 Direct purchase

Direct purchase has a simple structure: the system owner pays for the PV system's installation and any maintenance needs[lxxiv] 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[211] and are expected to continue to fall. Table 6.1, 6.2 and 6.3 show residential and commercial installation and maintenance costs used in this report in the District, Philadelphia, and El Paso, respectively. This report assumes one cost decline for the entire analysis period for simplicity. Starting in 2020 and for the remainder of the analysis period, the cost per watt drops from the "pre-2020" level to the "post-2020" level. The "post-2020" cost assumptions are higher than U.S. Department of Energy (DOE) SunShot targets.[lxxv,212] 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.

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

Table 6.1. Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems for Washington, D.C.

SYSTEM TYPE	PRE-2020 INSTALLATION COST	POST-2020 INSTALLATION COST	MAINTENANCE COST[213]
Residential	$3.20/W	$2.20/W	$0.21/kW-yr
Commercial	$2.60/W	$1.80/W	$0.19/kW-yr

Table 6.2 Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems for Philadelphia

SYSTEM TYPE	PRE-2020 INSTALLATION COST	POST-2020 INSTALLATION COST	MAINTENANCE COST[214]
Residential	$3.00/W	$2.10/W	$0.21/kW-yr
Commercial	$2.60/W	$1.70/W	$0.19/kW-yr

Table 6.3 Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems for El Paso

SYSTEM TYPE	PRE-2020 INSTALLATION COST	POST-2020 INSTALLATION COST	MAINTENANCE COST[215]
Residential	$2.80/W	$2.00/W	$0.21/kW-yr
Commercial	$2.40/W	$1.60/W	$0.19/kW-yr

6.1.1.2 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 that would create unnecessary complexity.

6.1.1.3 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 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).[216] 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.

6.2 Impacts of solar PV

6.2.1 Solar PV impact summary

Table 6.4 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 6.4. Rooftop PV cost-benefit impact table (A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact)

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Energy generation (+)	X	
Tax credits (+)	X	
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

6.2.2 Energy generation

Rooftop PV substitutes PV-generated electricity for grid-purchased electricity. The District, PA, and El Paso all have net metering laws 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.[lxxvi] Refer to Section 9.3 and the Appendix for a review of methods and assumptions.

6.2.3 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 those provided below.

[lxxvi] *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.*

6.2.3.1 Tax credits

There are two federal tax credits available to PV system owners: the residential renewable energy tax credit[217] and the business energy investment tax credit (ITC).[218]

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.[219]

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.[220]

6.2.3.2 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).[221] 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).[222]

In December 2015, Congress extended the deadline for bonus depreciation.[223] 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.[224] Under the new rules, projects placed in service before the end of 2018 qualify for 50% bonus depreciation.[225] Those projects placed in service during 2018 and 2019 qualify for 40% and 30% bonus depreciation, respectively. [226]

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

6.2.3.3 Solar renewable energy credits (SRECs)

Solar renewable energy credits (SRECs)[lxxvii] 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. In Pennsylvania (PA), only solar PV can generate SRECs.[227] 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).[lxxviii] 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. In PA, the ACP (or SACP) is determined after the compliance year ends and is largely a function of the average market price of SRECs. SRECs in PA are much less valuable than in the District. 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.

6.2.3.4 Texas solar and wind energy device franchise tax deduction

Texas has a state franchise tax deduction for solar PV systems. In Texas, franchise tax is the corporate tax. Under this deduction, Texas allows a company to deduct the cost of a solar PV project from its franchise tax in two ways: (1) total cost can be deduced from the company's taxable capital or (2) 10% of the

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[lxxvii] *SRECs are called solar alternative energy credits (SAECs) in PA.*
[lxxviii] *The solar alternative compliance price (SACP) in PA.*

amortized cost of the system can be deducted from the company's income.[228] As before, this report assumes businesses have enough tax appetite to deduct against. For more on Texas' solar franchise tax deduction, see the Appendix.

6.2.4 Climate change mitigation

Unlike the two solutions 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 6.3 shows the rooftop PV climate change mitigation pathway. This benefit is included in cost benefit calculations. For more on methods and assumptions, see Section 9.5 and the Appendix.

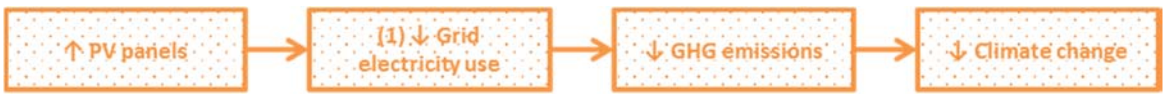

Figure 6.3. Rooftop PV climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

6.2.5 Air quality and health

Rooftop PV has one significant ozone reduction pathway and one significant $PM_{2.5}$ 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 6.4 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 6.5 shows the $PM_{2.5}$ reduction pathways of rooftop PV. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 9.6 and in the Appendix.

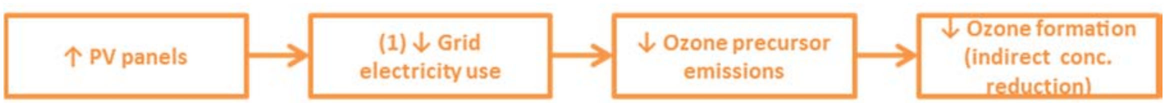

Figure 6.4. Rooftop PV ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

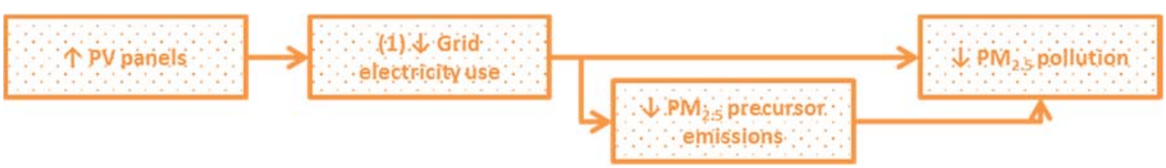

Figure 6.5. Rooftop PV $PM_{2.5}$ concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

6.2.6 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 6.1.1 requires about 16 hours of project development and on-site labor.[229] 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. In Pennsylvania, the JEDI model estimates about 20 hours of project development and on-site labor per 1 kW of installed solar PV (about 9.5 jobs per MW) and approximately 0.2 annual operations and maintenance jobs for each MW of installed solar PV capacity. In Texas, the JEDI model estimates about 18 hours of project development and on-site labor per 1 kW of installed solar PV (about 8.7 jobs per MW) and approximately 0.2 annual operations and maintenance jobs for each MW of installed solar PV capacity.

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.[230] While almost all new technologies exhibit some learning curve, solar PV has generally shown a faster learning rate than other renewable energy sources.[231] Therefore, the District, Philadelphia, and El Paso 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 Section 6.1.1 yields a smaller employment impact for installation—about 11.2 hours of project development and on-site labor per installed kW of solar PV in the District, 13.4 hours in Pennsylvania, and 12.5 hours in Texas. 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 9.8 and the Appendix.

6.2.7 Other impacts

6.2.7.1 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 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.[232] In the District, assuming an electricity price of $0.12 per kWh,[233] a cooling energy intensity of 2.5 kWh per square foot,[234] 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. We expect similar results for Philadelphia and El Paso. 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.[235] 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.

6.2.7.2 UHI mitigation

There is some modeling evidence that large scale deployment of solar PV can reduce urban air temperatures. A modeling study of the sensible heat flux from black roofs, white roofs, green roofs, and these three roof types with added PV panels found that putting PV panels on black roofs slightly reduces the contribution of black roofs to the UHI because total heat conduction away from the roof decreases.[236] Putting PV panels on a white or green roof, increases the total sensible heat flux away from these roofs (decreasing their UHI benefit).[237] 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.[238] As the study notes, its results cannot be directly translated to changes in temperature,[239] 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.[240] The cooling benefit of PV increased with increasing PV efficiency.[lxxix] 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 cities examined in this analysis, this benefit is not included in cost-benefit calculations.

6.2.7.3 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.[241] This equates to a sales premium of about $20,000 for a five kW solar PV system. The second and smaller study worked with a team of appraisers to determine the value of solar PV systems in six states. This study found a similar premium to the previous study.[242] The first study notes a sharp decline in sales premium as systems age,[243] and the second study notes that the effect of system and market characteristics on price premium.[244]

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.

6.2.7.4 Avoided transmission and distribution losses

The U.S. Energy Information Administration estimates average transmission and distribution losses of 6% in the U.S.[245] These losses include losses between sources of supply and locations of distribution (transmission losses) and losses in distribution to customers (distribution losses).[246] Rooftop solar PV coverage generally avoids transmission and distribution losses.[247] 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.[248] This increases PV value. This value is also not included in this analysis.

[lxxix] 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.

7 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.

7.1 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.[249] 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.[250] Concrete is the composite of aggregate and binder.[251] 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.[252] 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.[253] Asphalt concrete is predominately aggregate by weight.[254] Asphalt concrete (commonly called “asphalt”) is the most common roadway pavement—about 90% of roads are asphalt concrete.[255] Portland cement concrete consists of Portland cement binder (which is grey or whitish in color and is derived from calcium and silicon oxides) and aggregate. Portland cement concrete is roughly 11 percent Portland cement binder, 33 percent sand, and 56 percent coarse aggregate by weight.[256] 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).[257]

7.1.1 Thermal performance

There are three ways heat transfers from one medium to another: conduction, convection, and radiation. Figure 7.1 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).[258]

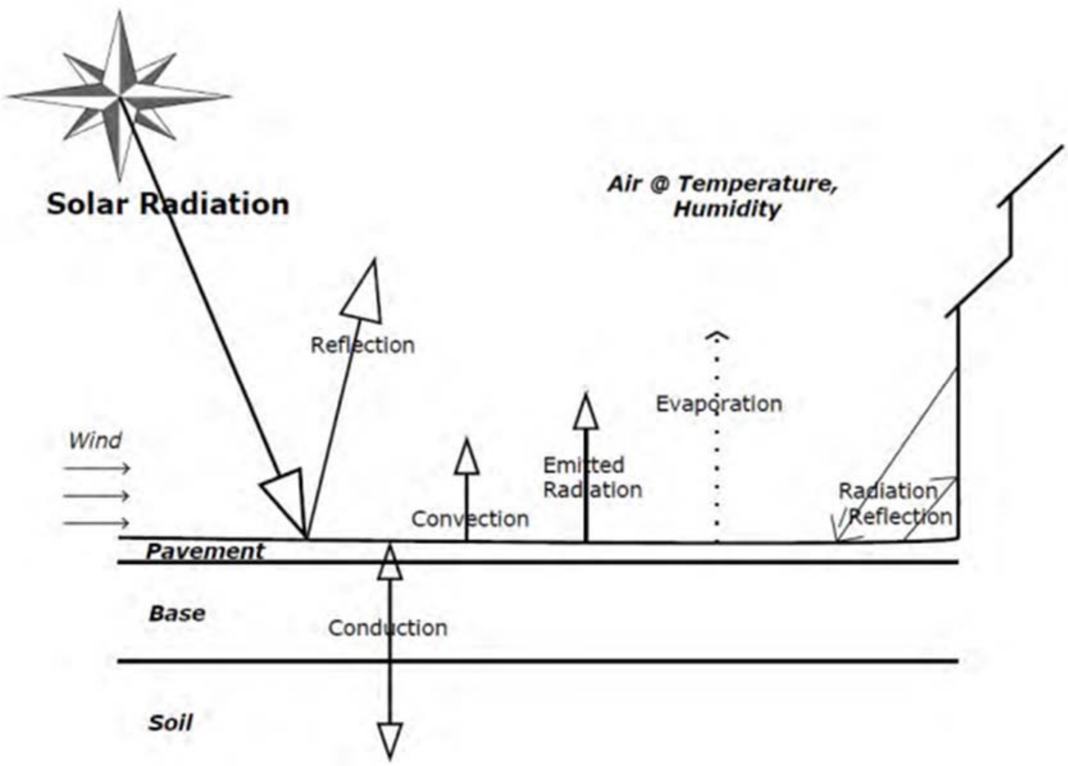

Figure 7.1. Pavement surface energy balance[259]

The size of these heat transfers are determined by several pavement properties: solar reflectance (albedo); thermal emittance;[lxxx] thermal conductivity;[lxxxi] and specific heat.[lxxxii,260] 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.[261] 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.[262] Pedestrians, vehicles, and nearby vegetation and structures also shade pavements[263] more than roofs. If pavement is shaded for the majority of the day, it may not make sense to increase its solar reflectance.

7.1.2 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.[264] Rehabilitation, which typically occurs one or two

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

times during a pavement's lifetime, are major repairs. Examples of rehabilitation techniques for asphalt pavement include patching, surface milling (i.e., removing the top few inches of asphalt), and overlays of a new asphalt (or potentially concrete) surface.[265] 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),[266] diamond grinding, and overlays of a new concrete or asphalt surface.[267]

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,[lxxxiii] asphalt emulsion sealcoats,[lxxxiv] slurry seals,[lxxxv] and bituminous crack sealants.[lxxxvi,268] Surface treatments extend pavement life and improve water proofing and skid resistance.[269] 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 7.1.4 for specifics in the District). Maintenance of concrete pavements can consist of joint resealing, slab stabilization, and load transfer restoration.[270] 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.

7.1.3 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.

7.1.3.1 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.[271] 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.[272] Albedo will vary to some extent by geography because of different pavement mix design standards.[lxxxvii,273] 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 7.1).

Brick is an important material for sidewalks, especially in older cities like the District and Philadelphia. Red brick has an albedo between 0.20 and 0.30.[274] For simplicity this report assumes brick sidewalks have an albedo of 0.25. Brick is uncommon as a sidewalk material in El Paso and is not modeled.

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

Table 7.1. Solar reflectance of conventional pavement used in this analysis

PAVEMENT TYPE	ALBEDO
Asphalt	0.15
Concrete	0.30
Brick	0.25

7.1.3.2 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 7.2.5).

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.[275] 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.[lxxxviii] Thinner pavement layers are also less expensive because they require less material.[276] 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 7.1.4, this report models reflective slurry seals on roads and parking lots.[lxxxix] There are currently no reflective slurry seals on the market, so we model a hypothetical reflective slurry seal.[xc]

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, 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.[277] This 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.

[lxxxviii] As noted previously, surface treatments and overlays are common maintenance practices of asphalt pavements.
[lxxxix] Recall from Section 7.1.2 that slurry seals a common preservation technique for asphalt pavements.
[xc] 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.

Table 7.2. 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

7.1.3.3 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.[278] 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.[279] 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.[280] 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.[281]

7.1.4 Cost and timeline

7.1.4.1 Roads

7.1.4.1.1 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,[xci] with a unit cost of around $4 per square yard ($0.45 per square foot).[282] 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.

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

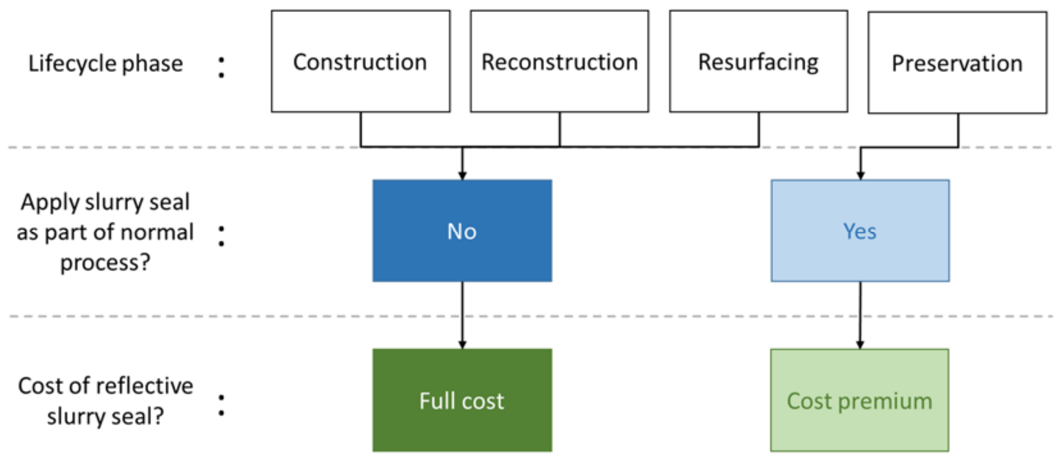

Figure 7.2. Flow chart to determine if pay full cost or cost premium for reflective slurry seal

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 7.2).[xcii]

For simplicity, this analysis uses these same reflective pavement cost assumptions for the District, Philadelphia, and El Paso pavements.

7.1.4.1.2 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.[283] 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).[284] This analysis assumes that a slurry seal is needed for pavement condition purposes 10 years after initial construction, reconstruction, or resurfacing.[285] Note that higher albedo surfaces will experience less thermal expansion 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-cycle slurry seal application phase 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-cycle slurry seal application phase.[xciii] During this period, the reflective slurry seal is applied at the cost premium.

[xcii] *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).*
[xciii] *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*

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.[xciv] This analysis assumes the same reflective road timelines in all three cities. Figure 7.3 shows the pavement timelines and costs associated with reflective road pavements in this analysis.

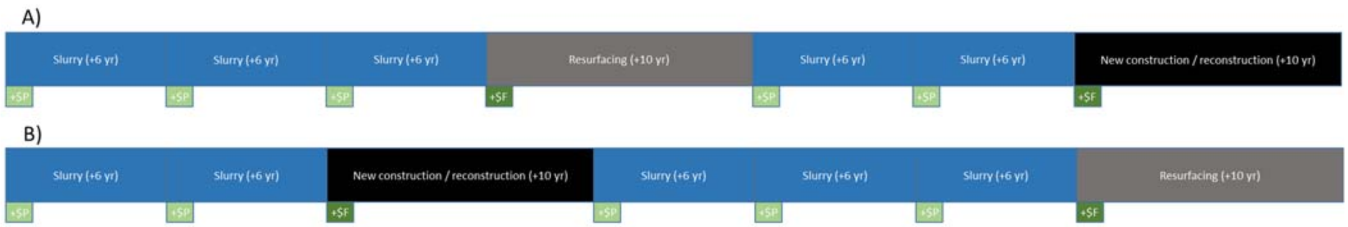

Figure 7.3. Road maintenance timelines and costs (dark green rectangles with "+$F" indicate the full cost (i.e., $4.27 per square yard) of the reflective slurry seal is paid and light green rectangles with "+$P" indicate only the cost premium (i.e., $0.20 per square yard) of the reflective slurry seal is paid)

7.1.4.2 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.[286] 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.

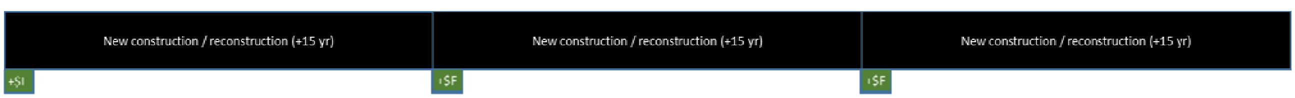

Figure 7.4. Parking lot maintenance timelines and costs (dark green rectangles with "+$F" indicate the full cost (i.e., $4.27 per square yard) of the reflective slurry seal is paid)

7.1.4.3 Sidewalks

Sidewalks typically last for many decades.[287] 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.[288] 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 7.5. 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)

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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.

[xciv] 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.

7.2 Impacts of reflective pavement

7.2.1 Reflective pavements impact summary

Table 7.3 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, Philadelphia, and El Paso 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 7.3. Reflective pavement cost-benefit impact table (A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact)

IMPACT	INCLUDED	NOT INCLUDED
Installation (-)	X	
Maintenance (-)	X	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
GHG emissions reduction (+)	X	
Global cooling (+)	X	
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Heat-related mortality reduction (+)	X	
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

7.2.2 Ambient cooling and indirect energy

7.2.2.1 Ambient cooling

The mechanism by which reflective pavements provide indirect energy benefits is similar to that of cool roofs. Reflective pavements (i.e., those with high albedo) absorb less solar energy than standard pavements, so they will heat up less and transmit less heat to urban air, reducing ambient temperatures.

As noted in the cool roof section (Section 4.2.3), 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.[289] They estimate that in typical cases,[xcv] increasing pavement albedo from 0.10 to 0.35[xcvi] in the entire city[xcvii] 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.[xcviii] 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.

As noted previously, UHIs are location specific, and fortunately, a few recent studies examined UHI mitigation in the District, Philadelphia, and desert climates similar to El Paso.[290] All studies found albedo increases are effective at reducing UHIs in the three cities, though the studies did not examine reflective pavements in isolation.

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 7.2.1) and improvements in air quality and declines in heat-related mortality (Section 7.2.4).

7.2.2.2 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 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).[291,xcix] 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 9.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

7.2.3 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 4.2.4), the global cooling impact of reflective surfaces

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[xcv] 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.
[xcvi] This is approximately equivalent to replacing asphalt pavements with concrete pavements.
[xcvii] In the District, roads make up about 1215% of the city area for example.
[xcviii] 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.
[xcix] This is equivalent to about $22 million today, or about $0.002 per square foot.

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 9.5. Figure 7.6 shows the climate change mitigation pathways of reflective pavements.

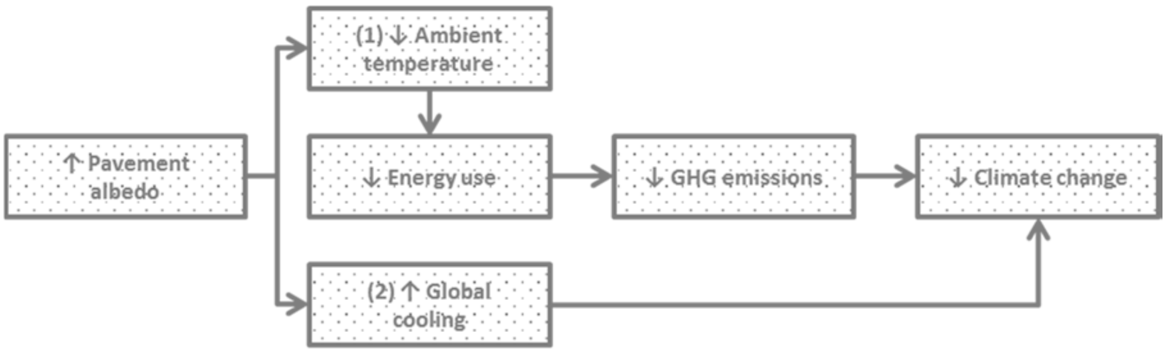

Figure 7.6. Climate change mitigation pathways of reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

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).[292] 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, Philadelphia's, and El Paso's climate change and UHI mitigation plans, this issue needs to be addressed in future technologies.

7.2.4 Air quality and health

7.2.4.1 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 general, as precursor emissions decline, ozone formation declines as well. Figure 7.7 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 9.6 and in the Appendix.

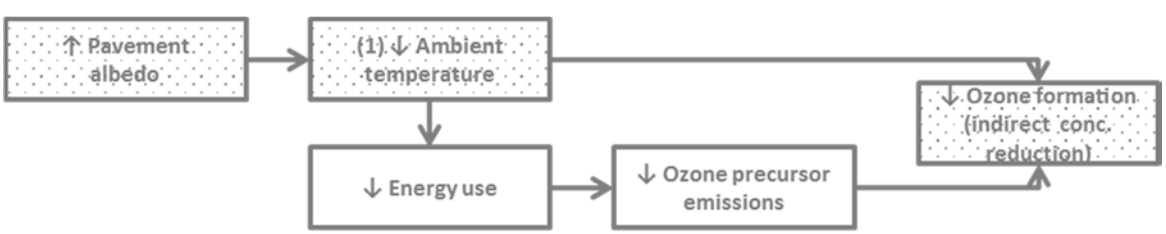

Figure 7.7. Ozone concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

7.2.4.2 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 7.8 shows the $PM_{2.5}$ concentration reduction pathways of reflective pavements. This report describes $PM_{2.5}$ impact estimation methods and assumptions in Section 9.6 and in the Appendix.

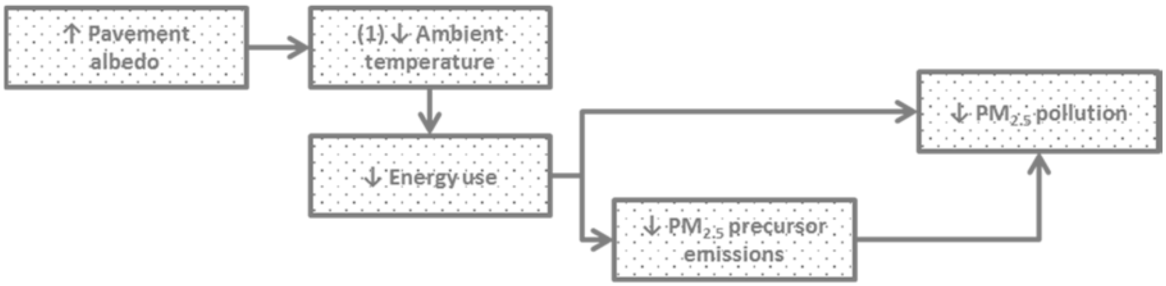

Figure 7.8. $PM_{2.5}$ concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

7.2.4.3 Reflective pavements and heat-related mortality

Unlike cool roofs and green roofs that can impact heat-related mortality by two pathways, reflective pavements reduce heat-related mortality by only one significant pathway: improving outdoor temperature conditions. Several modeling studies have found that city-wide increases in albedo can reduce heat-related mortality.[293] This report describes heat-related mortality benefit estimation methods and assumptions in Section 9.6 and in the Appendix.

7.2.5 Other impacts of reflective pavements

7.2.5.1 Direct energy

There are two mechanisms by which reflective pavements directly influence building energy consumption: (1) increased heat gain and (2) decreased artificial lighting requirements. Some of the sunlight reflected from reflective pavements is absorbed by surrounding buildings.[c] This slightly increases building heat gain,[294] which in turn increases building cooling energy use in the summer.[295] The increase in building heat gain also decreases building heating load in the winter, though this effect appears much smaller.[296] The increased amount of reflected sunlight from reflective pavements can also slightly reduce nearby buildings' artificial lighting needs, which has two direct energy benefits.[297] 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.

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[c] *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.*

7.2.5.2 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).[298] For concrete, lower daytime surface temperature reduces the temperature-related stresses that contribute to cracking.[299] 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). This is particularly true in El Paso where UV deterioration is a problem for roads.[300]

7.2.5.3 Enhanced nighttime visibility

Increasing pavement reflectivity can enhance nighttime visibility.[301] This can increase driver and pedestrian safety and reduce street lighting needs because reflective pavements better reflect street and vehicle lights.[302] 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. There is not a sufficient body of research to include a defensible assumption for the economic benefit of reduced street lighting with 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.

7.2.5.4 Reduced stormwater runoff temperature

As with cool and green roofs, reflective pavements would reduce initial summer stormwater runoff temperatures, helping reduce thermal shock to aquatic life in nearby water bodies. However, given the 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.

7.2.5.5 Downwind cooling

As discussed in the cool roof benefits section (Section 4.2.7), 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, Philadelphia, or El Paso metro area), downwind cooling benefits could be large.

7.2.5.6 Glare

Glare is caused by excessive brightness and can be uncomfortable or disabling, but glare is also subjective.[303] 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.[304] 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 7.9 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 7.9), about 43% is visible light (green in Figure 7.9), and about 52% is near-infrared light (orange in Figure 7.9).[305] 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 surface's appearance[306] 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.[ci] 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.[cii]

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.

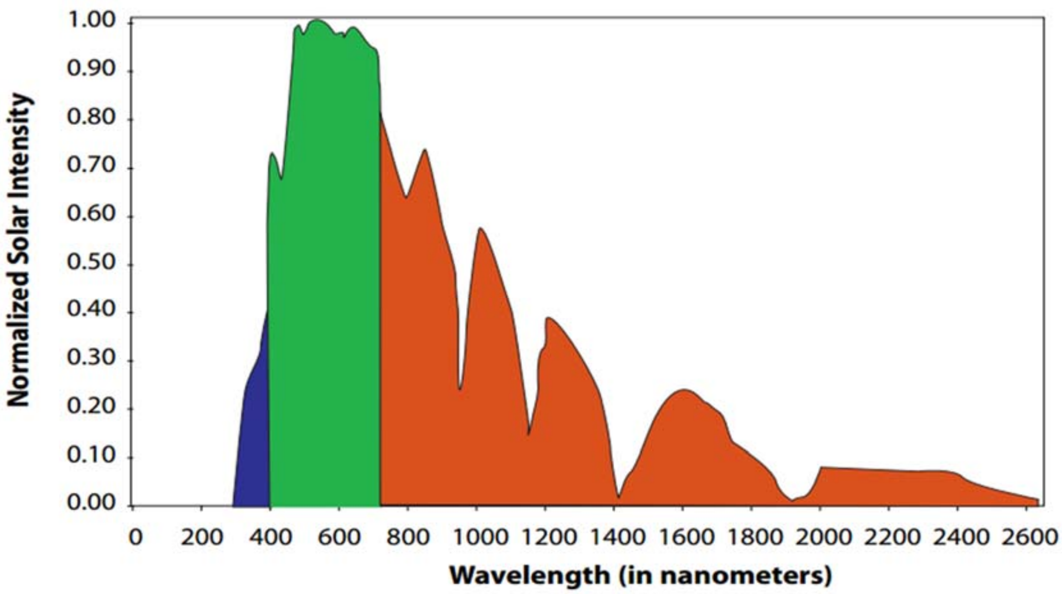

Figure 7.9. Solar energy versus wavelength reaching Earth's surfaces on a typical clear summer day (blue is ultraviolet wavelengths, green is visible wavelengths, and orange is near-infrared wavelengths)[307]

7.2.5.7 Reduced 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, mean radiant temperature (the weighted average of all temperatures from surfaces surrounding an individual; this accounts for the impact of radiation), relative humidity,[ciii] air speed, metabolic rate,[civ] and clothing insulation.[cv,308] Air temperature and mean radiant temperature are the most important factors for understanding the thermal comfort impact of reflective pavements (see Figure 7.10).[cvi] There is currently no clear consensus as to the impact of reflective pavements on outdoor thermal comfort.

[ci] Cool colored materials are also described in the cool roof section (Section 4.1.1).
[cii] Though limiting the amount of visible light reflected by reflective pavements will limit the potential for reduced lighting needs in buildings near reflective pavements.
[ciii] 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.
[civ] The energy generated by the human body.
[cv] The amount of thermal insulation provided by the clothing a person is wearing.
[cvi] 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.

One small sample size 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.[309] 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).[310] This increase in mean radiant temperature, however, was not enough to change a pedestrian's thermal sensation[cvii] (e.g., from "hot" to "very hot").[cviii] The second study, simulated various urban canyon[cix] configurations and found higher albedo surfaces decrease pedestrian thermal comfort.[311] The increased reflected radiation from the higher albedo surfaces counteracted any ambient air temperature reductions.[cx,312] As with the first study, only in a few circumstances did reflective pavements change the thermal sensation[cxi] of pedestrians.

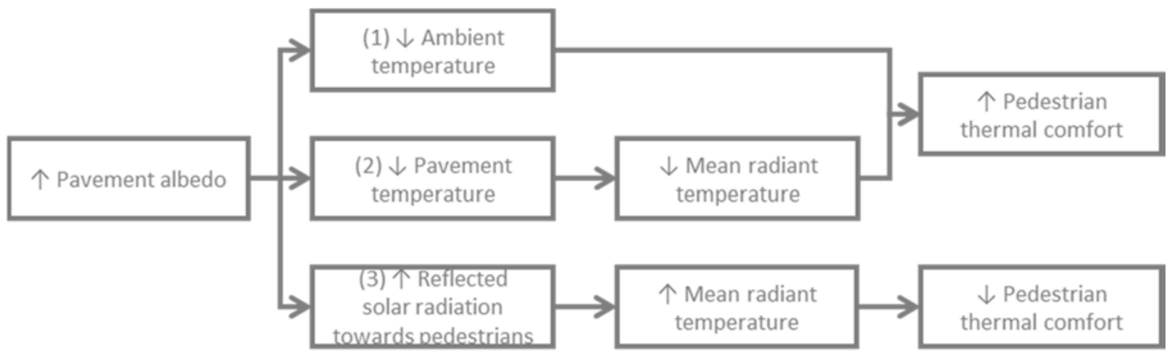

Figure 7.10. Impact of reflective pavements on summertime pedestrian thermal comfort

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.

7.2.5.8 UV light reflectance

Reflective pavements also increase the potential for upward UV light reflectance. This could be harmful to health,[313] 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.[314] Only about 4% of sunlight is in the UV spectrum (see Figure 7.9), so this will not have significant impact on goals to achieve high albedo pavements.[315] Given the lack of data on this impact and given its relatively simple solution, this report does not include the impact of increased upward UV reflectance from reflective pavements in cost-benefit calculations.

[cvii] Ref 3088 modeled thermal sensation using the Physiological Equivalent Temperature. It is important to note that ref 308 did not include air temperature impacts in thermal comfort calculations, though this would have a minor effect if anything.
[cviii] 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).
[cix] Where the street is lined on both sides by buildings.
[cx] 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).
[cxi] Ref 311 modeled thermal sensation using the Index of Thermal Stress.

8 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 and 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).

8.1 Urban tree basics

8.1.1 Planting and care considerations

Effective tree planting programs 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.

8.1.1.1 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.[316]

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).[317] Sufficient rooting space ensures better tree health, and minimizes damage to and extends the life of paved surfaces.[318] Private land and park space are often best for increasing tree canopy, because these areas tend to have the most available soil volume.[319] The District Department of Transportation and Casey Trees each provide several design examples to enable adequate soil volume in space-constrained urban areas.[320]

8.1.1.2 Tree selection

Factors in tree selection include a tree's water needs, climate tolerance, preferred soil conditions,[cxii] preferred light levels, salt tolerance,[cxiii] and pollution tolerance.[321] A tree's potential for creating litter (e.g., fruit droppings) is also important to secure the support of residents and local businesses.[cxiv] Low maintenance, native trees with few or no droppings are typically preferred.

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.).[322]

8.1.2 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. For the District and Philadelphia, this report assumes middle-of-the-road cost estimates from McPherson et al. (2006): private trees cost $500 and public trees cost $220.[cxv,323] This report uses the average of these estimates for cost calculations (i.e., $360 per tree). For El

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[cxii] *For example, can it handle the compacted soil common in urban settings?*
[cxiii] *To survive runoff from deiced roads and sidewalks*
[cxiv] *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.*
[cxv] *Both estimates include the cost of the tree and the cost of planting.*

Paso, this report assumes middle-of-the-road cost estimates from Vargas et al. (2007): private trees cost $150 and public trees cost $150.[324] This report uses the average of these estimates for cost calculations (i.e., $150 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.[325] A regional summary of the costs and benefits of trees by the U.S. Forest Service estimates trees in the District and Philadelphia cost between $5 and $21 per tree per year to maintain, depending on tree size and type (i.e., private or public).[326] Pruning is the costliest maintenance practice. This report assumes an average estimate of $13 per tree per year for maintenance. A separate regional summary of the costs and benefits of trees by the U.S. Forest Service estimates trees in El Paso cost between $4 and $13 per tree per year to maintain, depending on tree size and type (i.e., private or public).[327] This report assumes a middle-of-the-road estimate of $7 per tree per year for maintenance. Table 8.1 shows planting and maintenance costs used in cost-benefit calculations for the District and Philadelphia. Table 8.2 shows planting and maintenance costs used in cost-benefit calculations for El Paso.

Table 8.1. Tree planting and maintenance costs used for Washington, D.C. and Philadelphia ($2006)

TREE COSTS FOR WASHINGTON, D.C. AND PHILADELPHIA	
Planting cost (per tree)	$360
Maintenance cost (per tree, per year)	$13

Table 8.2. Tree planting and maintenance costs used for El Paso ($2006)

TREE COSTS FOR EL PASO	
Planting cost (per tree)	$150
Maintenance cost (per tree per year)	$7

Many cities offer free or discounted tree planting. Casey Trees in the District[328] and Tree Philly in Philadelphia[329] are examples of organizations that offer these programs in the cities examined in this report.

8.2 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.[330] Much of the discussion and references cited below draw from these sources.

8.2.1 Urban tree impact summary

Table 8.3 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 report's findings are underestimate the net value of urban trees.

Table 8.3. Urban tree cost-benefit impact table (A "minus" indicates a cost or negative impact, a "plus" indicates a benefit or positive impact)

IMPACT	INCLUDED	NOT INCLUDED
Planting (-)	X	
Maintenance and other expenses (-)	X	
Direct cooling energy reduction (+)	X	
Direct heating energy reduction (+)	X	
Indirect cooling energy reduction (+)	X	
Indirect heating energy penalty (-)	X	
GHG emissions reduction (+)	X	
Global cooling (+)	X	
Carbon sequestration (+)		X
Ozone concentration reduction (+)	X	
PM2.5 concentration reduction (+)	X	
Air pollution uptake (+)	X	
Heat-related mortality reduction (+)	X	
Reduced stormwater runoff (+)	X	
Improved thermal comfort (+)		X
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

8.2.2 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[331] and thus the heat transferred into the building, which in turn reduces building cooling energy needs. Huang et al. (1990) estimated that during the summer, 10% to 30% of solar energy reaches surfaces under a tree's canopy.[332] 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, Philadelphia, and El Paso.

Trees can also serve as windbreaks (i.e., wind shields), reducing the wind speed in the vicinity of buildings.[333] 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 lose foliage in the winter. In summer, the effect of a windbreak can be positive or negative,[334] but potential air conditioning use increases from windbreaks are generally less than savings due to shading.[335]

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.[336] The east side and south side are also good options.[337] 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.[338]

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%.[339] Another study that examined the same utility program found cooling energy savings of 1% per tree and heating energy savings of 2% per tree.[340] A simulation study of trees in various U.S. cities found 20% tree canopy cover over a home yielded between 8% and 18% savings on cooling energy use and between 2% and 8% savings on heating energy use.[341]

Section 9.2 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

8.2.3 Ambient cooling and indirect energy

Evapotranspiration and shading from urban trees leads to ambient cooling, reducing cooling energy use.[342]

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.[343] 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.[344] 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 and by 0.27°C in Philadelphia.[345] A recent study shows large-scale urban greening in the desert climate of Phoenix could reduce average summer temperature by about 0.07°C.[346] Vegetation is typically less effective at mitigating UHIs in desert climates because of lack of moisture.

8.2.3.1 Indirect energy

Indirect energy savings will also vary by city. The ten city modeling study cited above found that ambient cooling due to greater numbers of urban trees would lead to annual indirect energy savings between $1 and $3 per 1000 ft^2 of roof in the District and between $4 and $8 per 1000 ft^2 in Phoenix.[cxvi][347]

Section 9.4 provides an overview of methods and assumptions used to estimate this benefit, and the Appendix provides further detail.

8.2.4 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,[348] and by global cooling (discussed in Section 4.2.4).

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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[cxvi] *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.[cxvii,349]

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.[350] EPA estimates that in 2013 urban trees in the continental U.S. sequestered 89.5 million metric tons of CO_2e.[351] Some of the carbon stored in a tree is released when it drop leaves or branches,[352] and when a tree dies, most of the CO_2 it stored is released to the atmosphere through decomposition, though different disposal techniques can prolong the release.[353,cxviii] 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 CO_2 per year).[354] Given the small size of the CO_2 sequestration benefit, this report does not include sequestration in cost-benefit calculations.[cxix]

Planting urban trees may also lead to global cooling (discussed in Section 5.2.4), because trees typically have a higher albedo than conventional roofs or pavements they cover—tree albedo ranges from 0.25 to 0.30.[355] 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 8.1 shows urban tree climate change mitigation pathways. Refer to Section 9.5 for an overview of methods and assumptions. The Appendix provides further detail.

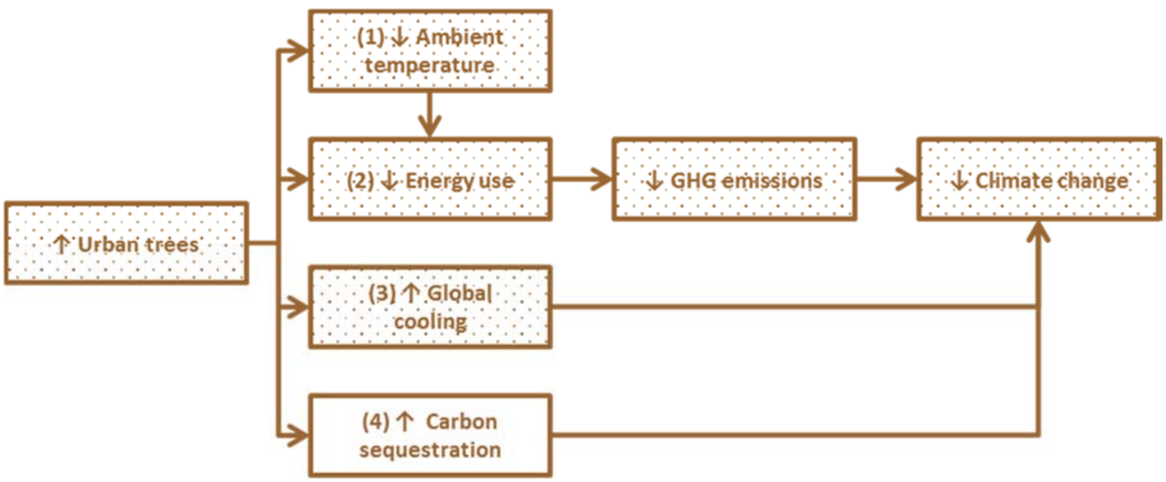

Figure 8.1. Urban tree climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

8.2.5 Air quality and health

8.2.5.1 Urban trees and ozone

Urban trees have the same ozone reduction pathways as green roofs. Urban trees reduce ambient ozone concentration by (1) decreasing ambient temperature, (2) decreasing building energy use, (3) directly removing 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 8.2 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 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

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

report includes this benefit for urban trees (see below). Methods and assumptions are discussed in more detail in Section 9.6 and in the Appendix.

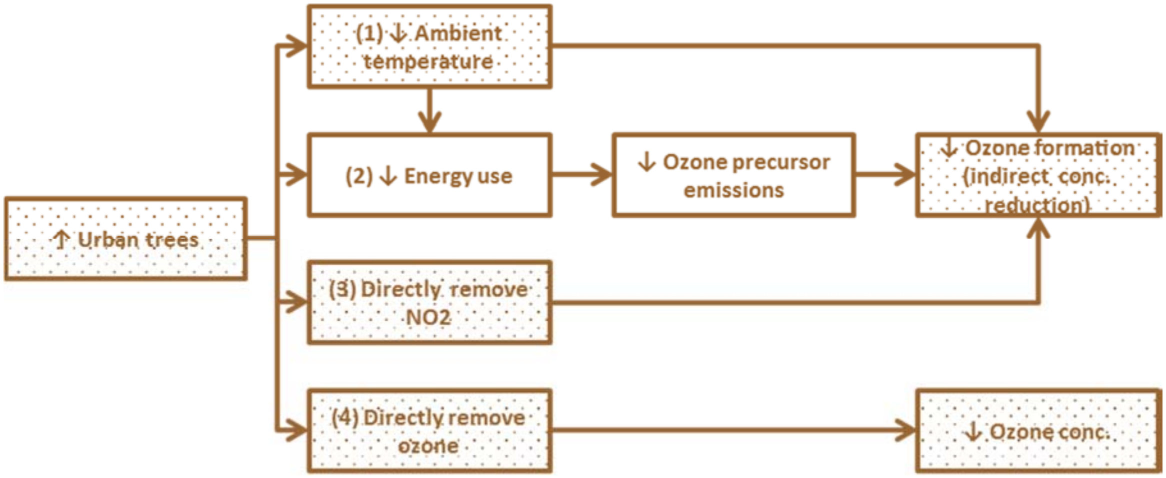

Figure 8.2. Urban tree ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

8.2.5.2 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 8.3). 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 8.3). Urban trees reduce $PM_{2.5}$ pollution by decreasing ambient temperature (pathway (2) in Figure 8.3), and decreasing building energy use (pathway (3) in Figure 8.3). 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 9.6 and in the Appendix.

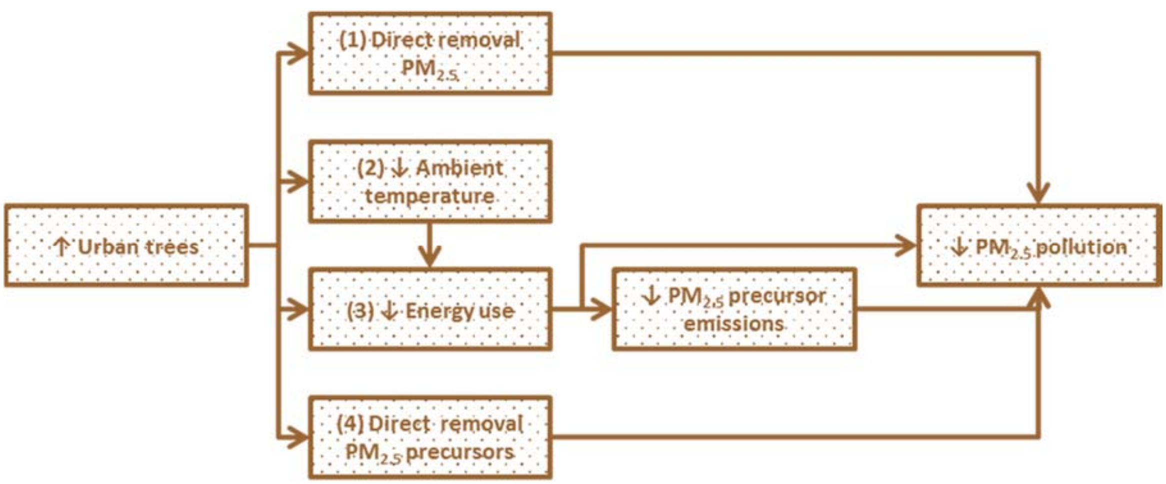

Figure 8.3. Urban tree $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease shaded boxes indicate pathways included in cost-benefit results)

8.2.5.3 Urban trees and 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.[356] 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.[357] Despite the large value of pollutant removal, actual changes in local ambient air quality are modest and are typically less than 1%.[358] The impact of direct removal of pollutants, though modest, is well documented, so it is included in cost-benefit calculations. Refer to Section 9.6 and the Appendix for a description of methods and assumptions.

8.2.5.4 Urban trees and heat-related mortality

Urban trees can reduce heat-related mortality through the same pathways as cool roofs and green roofs. Urban trees can reduce heat-related mortality by keeping buildings cooler through shading. In addition, urban trees can reduce heat-related mortality through ambient cooling. Modeling studies find that increasing urban vegetation reduces heat-related mortality.[359] 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.[360] 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 9.6 and in the Appendix.

8.2.6 Stormwater

Trees, like green roofs, also reduce stormwater runoff volumes and delay time of peak runoff.[361] 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 8.4 illustrates these and other stormwater runoff reduction pathways. Simulation studies estimate that urban trees reduce city-wide stormwater.[362]

Interception and soil capture are most effective at reducing stormwater runoff during small rain events, which account for most precipitation events and are responsible for most roadway pollution wash-off (e.g., vehicle oils).[363] 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.[364]

Refer to Section 9.7 for an overview of methods and assumptions. The Appendix provides further detail.

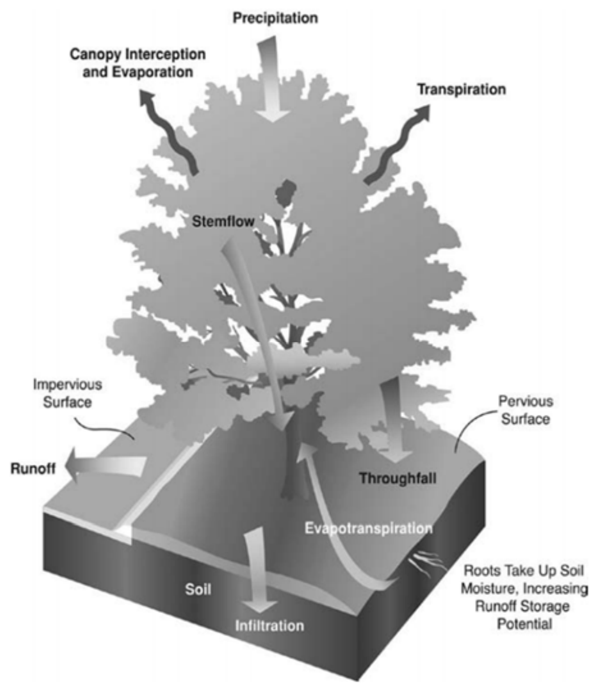

Figure 8.4. Illustration of tree stormwater runoff reduction pathways[365]

8.2.7 Other benefits of urban trees

8.2.7.1 Improved thermal comfort

Numerous modeling studies have demonstrated thermal comfort benefits from urban trees across different climates.[366] 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.[367] 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 U.S. simulation study of a hot-dry climate found planting trees in a street canyon reduced physiological equivalent temperature (PET)[cxx] by over 20°C in summer conditions.[368] 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").[369] In a tropical climate (e.g., Brazil), shade from trees can reduce PET by up to 16°C in summer conditions.[370] 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.

[cxx] 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.

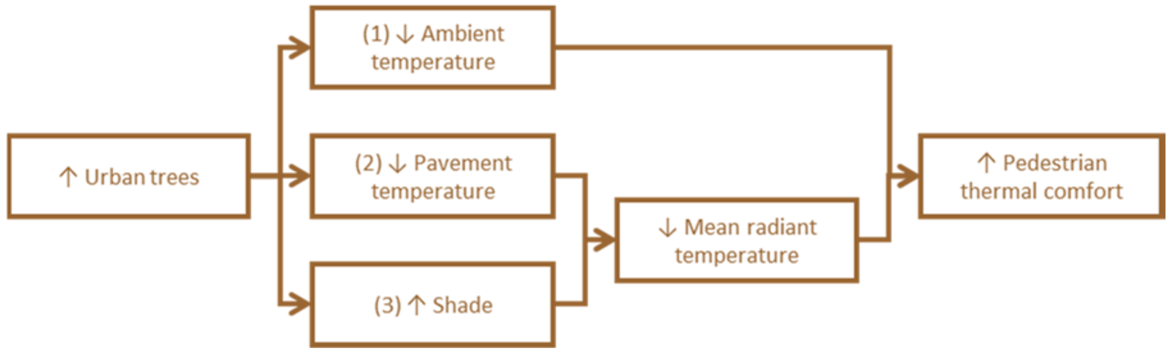

Figure 8.5. Impact of urban trees on summertime pedestrian thermal comfort

Adding trees can reduce thermal comfort in winter,[371] as deciduous trees block some solar radiation.[372] But in cities with subtropical or desert climates and hot summers (like those analyzed in this report), 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 11).

8.2.7.2 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.[cxxi] However, EPA notes both negative or positive impacts of increased humidity from urban trees, and net impact is unclear, so it is not included in cost-benefit calculations.

8.2.7.3 Increased biological volatile organic compounds emissions (BVOCs)

Trees can also emit ozone precursor biologic volatile organic compounds (BVOCs), that in rare conditions could counteract the ozone reductions that result from reduced ambient air temperature.[cxxii] 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.[373] Trees with low ozone-forming potential typically are prioritized for urban tree programs, avoiding the potential health costs. This potential health cost is not estimated in this analysis.

8.2.7.4 Increased pollen production

Increasing urban tree canopy can increase pollen production, exacerbating allergies.[374] As with biological volatile organic compounds, this potential drawback generally is avoided with proper tree selection.

8.2.7.5 Others

Urban trees can reduce human exposure to direct UV rays, which have adverse impacts on skin and eyes.[375] 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.

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

[cxxii] *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.*

However, tree roots can increase cost of pavement maintenance and repairs.[cxxiii] Studies show that trees can increase residential and commercial property values.[376]

Urban trees can enhance quality of life in multiple ways. First, they increase habitat for birds, insects, and other living things.[377] In addition, trees reduce urban noise,[378] are linked to reduced crime,[379] and provide other psychological and social benefits that help reduce stress and aggressive behavior.[380]

As discussed in the cool roof benefits section (Section 4.2.7), 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, impervious urban surfaces.

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

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

9 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.

9.1 New benefits valued in this report

Table 9.1 provides an overview of additions this report makes to the existing methodology in the literature.

Table 9.1. Overview of this report's additions to the existing methodology in the literature

ADDITIONS TO EXISTING METHODOLOGY	
Indirect energy	• Estimating indirect energy benefit of green roofs
Climate change	• Valuing emissions reductions from smart surface solutions studied using the social cost of carbon • Valuing global cooling impact of smart surface solutions studied using the social cost of carbon
Ozone	• Estimating ozone concentration reductions in Washington, D.C., Philadelphia, and El Paso 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 half of all jobs generated in the cities go to city residents if cities deploy training and job linking to increase city-based employment
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

9.2 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[cxxiv] 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.[cxxv]

Only trees near buildings provide direct energy benefits. This report uses results of i-Tree Eco analyses in Washington, D.C., Philadelphia, and El Paso to estimate direct energy impacts of trees. i-Tree Eco only estimates energy benefits for residential buildings.

9.3 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.

9.4 Ambient cooling and indirect energy

9.4.1 Estimating ambient cooling impacts

Based on a broad literature review, this report uses Li et al. (2014) as the basis for ambient cooling calculations for cool roofs and green roofs in the District.[381] For Philadelphia and El Paso, this report uses Stone et al. (2014) as the basis for ambient cooling calculations.[382] For reflective pavements in the District, this report uses Kalkstein et al. (2013) as the basis for ambient cooling calculations.[383] For Philadelphia and El Paso reflective pavements, this report uses Stone et al. (2014) as the basis for ambient cooling calculations. For urban trees, this report uses Sailor (2003) as the basis for ambient cooling calculations for the District and Philadelphia.[384] For El Paso urban trees, this report uses Stone et al. (2014).

9.4.2 Estimating indirect energy impacts

The basis of our indirect energy calculations is from Akbari and Konopacki (2005).[385]

9.5 Climate change

9.5.1 Estimating climate change mitigation impacts of emissions reductions

For emissions intensities in the District and Philadelphia, this report uses the most recent numbers available from Baltimore Gas & Electric that approximates the emission rate for electricity in the PJM Interconnection (which includes the District and Philadelphia).[386] For El Paso, we obtained emissions information for El Paso Electric, the dominant electricity provider in El Paso.[387]

This report estimates the value of GHG emissions reductions from cool roofs, green roofs, rooftop PV, reflective pavements, and urban trees using the social cost of carbon (SCC). The SCC is an estimate of the economic damages/benefits associated with a small increase/decrease in CO_2 emissions.[388] 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.[cxxvi] The SCC estimates are built on three widely used climate impact models, and each are modeled with real discount rates of 2.5%, 3%, and 5%.

[cxxiv] *This report assumes green roofs are not installed on steep-slope roofs.*
[cxxv] *GREC only provides annual energy savings/penalties estimates so its outputs are not resolved enough to estimate peak demand benefits.*
[cxxvi] *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.*

9.5.2 Estimating climate change impacts of global cooling

To estimate the CO_2-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).[389] 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.

9.6 Health

9.6.1 Estimating ozone health impacts

This report estimates the ozone impact of cool and green roofs, reflective pavements, and urban trees using the relationship between temperature and ozone formation. This report uses temperature reductions calculated using the work described in Section 9.4. 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.[390,cxxvii] 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.[cxxviii] This report uses scale-specific population breakdowns to estimate the ozone health impacts at the city-wide and low-income region scales.

9.6.2 Estimating $PM_{2.5}$ health impacts

The basis of the $PM_{2.5}$ health benefits assessment in this report is Machol and Rizk (2013).[391] 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 Sections 9.2, 9.3, and 9.4 by the health benefits factors from Machol and Rizk (2013) to estimate the $PM_{2.5}$-related health impacts.

9.6.3 Estimating heat-related mortality impacts

Kalkstein et al. (2013) and Stone et al. (2014) form the basis for the heat-related mortality impact assessment in this report.[392] Kalkstein et al. (2013) is used for the District estimate and Stone et al. (2014) for Philadelphia and El Paso. There are several limitations to Kalkstein et al. (2013) and Stone et al. (2014) 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).

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

9.6.4 Estimating pollution uptake by urban trees

This report estimates the health impacts of pollution uptake by urban trees using results from location-specific i-Tree Landscape analyses. i-Tree Landscape bases its health impact estimates on county- or city-level population data.[393] Therefore, for low-income regions we scale the county or city-wide health estimates by the ratio of low-income region population to county/city population in order to better approximate the pollution uptake impact in low-income regions.

[cxxvii] *OCPs relate a change in air temperature to a change in ozone concentrations.*
[cxxviii] *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.*

9.7 Stormwater

The District, Philadelphia, and El Paso have stormwater regulations that require building owners to pay stormwater fees. Revenue from stormwater fees is used for various aspects of stormwater management in these cities. These stormwater fees are calculated in different ways in each city, but all are based on the impervious surface area of a property. If a property installs stormwater management practices (such as green roofs or 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 a property that installs stormwater management practices. This report estimates stormwater benefits in the District and Philadelphia using the cities' own stormwater fee discounts. In El Paso, only stormwater ponds qualify for discounts. However, because green roofs and urban trees would reduce stormwater runoff in El Paso, we approximate their stormwater value using El Paso's stormwater fee. Refer to the Appendix for specifics.

In 2013, the District introduced stormwater regulations[394] 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 installation and tree planting in the District. This report also estimates stormwater benefits in the District using the value of SRCs.

The discounts/credits provided by Philadelphia do not fully capture the stormwater benefit of green roofs or urban trees. However, the combined value of stormwater runoff reductions shown through fee discounts and SRC revenue in Washington, D.C., is approximately right, though likely high. Philadelphia stormwater regulations are less ambitious than District stormwater regulations, including in value recognition. To more fully capture the stormwater benefits of green roofs and urban trees in Philadelphia, this report computes an alternative stormwater value in Philadelphia by assigning 50% of the SRC value for each solution in Washington, D.C., to the respective solution in Philadelphia. This is an area for further city-specific research for Philadelphia.

For El Paso, this report does not provide this additional value because of the much lower rainfall amounts compared to the District or Philadelphia. That said, because of declining groundwater sources in El Paso, there is likely additional value in El Paso to stormwater practices that enhance infiltration. Estimating this value is outside the scope of this report, but deserves further research.

9.8 Employment

See Sections 5.2.7 and 6.2.6 for labor impact information for green roofs and solar PV, respectively. This report values labor impacts in each analysis city using O'Sullivan et al. (2014).[395] This report also values labor impacts using an average annual income per job year of $40,000. [cxxix]

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

9.9 Summary of key assumptions

9.9.1 Universal

Analysis year 1: 2017

Discount rate: 3% (real)

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

Dollar year: 2015 (adjusted using the historical consumer price index for all urban consumers)[396]

Table 9.2. 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
Green roofs	10% of roofs
PV	50% of viable
Reflective pavements	50% of pavements
Urban trees	Increase tree canopy by 10% in D.C. and Philadelphia; 2% in El Paso

9.9.2 Cool roofs

Table 9.3. 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 9.4. 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

9.9.3 Green roofs

Table 9.5. 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

9.9.4 Rooftop PV

Table 9.6. Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems for Washington, D.C.

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

Table 9.7. Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems for Philadelphia

SYSTEM TYPE	PRE-2020 INSTALLATION COST	POST-2020 INSTALLATION COST	MAINTENANCE COST
Residential	$3.00/W	$2.10/W	$0.21/kW-yr
Commercial	$2.60/W	$1.70/W	$0.19/kW-yr

Table 9.8. Solar PV install cost per watt and maintenance cost per watt for residential and commercial systems for El Paso

SYSTEM TYPE	PRE-2020 INSTALLATION COST	POST-2020 INSTALLATION COST	MAINTENANCE COST
Residential	$2.80/W	$2.00/W	$0.21/kW-yr
Commercial	$2.40/W	$1.60/W	$0.19/kW-yr

PPA savings: 5% below utility rates

PPA duration/system life: 20 years

Direct purchase system life: 20 years

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

PV Efficiency: 18%

Annual electricity degradation rate: 0.5% (compounded annually)

9.9.5 Reflective pavements

Table 9.9. 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

9.9.6 Urban trees

Table 9.10. Tree planting and maintenance costs used for Washington, D.C., and Philadelphia ($2006)

TREE COSTS FOR WASHINGTON, D.C. AND PHILADELPHIA	
Planting cost (per tree)	$360
Maintenance cost (per tree, per year)	$13

Table 9.11. Tree planting and maintenance costs used for El Paso ($2006)

TREE COSTS FOR EL PASO	
Planting cost (per tree)	$150
Maintenance cost (per tree per year)	$7

Urban tree life: 30 years

10 RESULTS

This report finds that in general cool roofs, green roofs, rooftop PV, reflective pavements, and urban trees are cost-effective surface solutions in each city and low-income region. Below are scenario summary results tables for each city: Section 10.1 shows results for the Washington, D.C., scenario; Section 10.2 shows results for the Philadelphia scenario, and Section 10.3 shows results for the El Paso scenario. All results are presented in 2015 dollars. More detailed tables are in the Appendix.

10.1 Washington, D.C.

Table 10.1. NPV of building-level benefits from building specific installations in Ward 5 (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$5.2 M**	**$48.2 M**	**$41.9 M**	**$0**	**$0**	**$0**	**$95.3 M**
First cost	$3.8 M	$33.1 M	$28.2 M	--	--	--	$65.1 M
Operations and maintenance	$0	$15.0 M	$4.4 M	--	--	--	$19.4 M
Additional replacements	$1.4 M	--	$9.4 M	--	--	--	$10.7 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$5.4 M**	**$84.9 M**	**$53.2 M**	**$5.77M**	**$0**	**$118.8 M**	**$268.2 M**
Energy	$5.4 M	$3.4 M	$41.5 M	$5.77M	$0	$558 K	$56.7 M
Financial incentives	--	--	$11.7 M	--	--	--	$11.7 M
Stormwater	--	$81.5 M	--	--	--	$118.2 M	$199.8 M
Health	$0	$0	$0	$0	$0	$0	$0
Climate change	$0	$0	$0	$0	$0	$0	$0
Employment	--	$0	$0	$0	--	--	$0
NPV	**$271 K**	**$36.7 M**	**$11.3 M**	**$5.77 M**	**$0**	**$118.8 M**	**$172.9 M**

Table 10.2. NPV of cumulative economic impact in Ward 5 (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$5.17 M**	**$48.2 M**	**$41.9 M**	**--**	**$0**	**$0**	**$95.3 M**
First cost	$3.81 M	$33.14 M	$28.2 M	--	--	--	$65.1 M
Operations and maintenance	$0	$15.02 M	$4.36 M	--	--	--	$19.3 M
Additional replacements	$1.36 M	--	$9.37 M	--	--	--	$10.7 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$46.4 M**	**$95.5 M**	**$77.4 M**	**$78.2 M**	**$19.0 M**	**$133 M**	**$450 M**
Energy	$7.00 M	$3.77 M	$41.5 M	$5.77M	$864K	$1.38M	$60.3 M
Financial incentives	--	--	$11.7 M	--	--	--	$11.7 M
Stormwater	--	$81.5 M	--	--	--	$118 M	$200 M
Health	$22.1 M	$6.45 M	$11.5 M	$34.5 M	$5.16M	$7.6 M	$87.3 M
Climate change	$17.3 M	$1.86 M	$8.79 M	$26.4 M	$13.0M	$6.3 M	$73.6 M
Employment	--	$1.92 M	$3.85 M	$11.6 M	--	--	$17.3 M
NPV	**$41.3 M**	**$47.4 M**	**$35.5 M**	**$78.2 M**	**$19.0M**	**$133.5 M**	**$355 M**

Table 10.3. NPV of city-wide impact in Washington, D.C. (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$33.9 M**	**$283 M**	**$243 M**	**$499 K**	**$43.8 M**	**$234.8 M**	**$839 M**
First cost	$25.0 M	$195 M	$163 M	--	$23.5 M	$136.5 M	$543 M
Operations and maintenance	$0	$88.2 M	$25.1 M	--	--	$77.6 M	$191 M
Additional replacements	$8.9 M	--	$54.2 M	--	$20.3 M	$20.8 M	$104 M
Employment training	$0	$138K	$167 K	$499 K	--	--	$803 K
Benefits	**$281 M**	**$564 M**	**$444 M**	**$451 M**	**$112 M**	**$797.0 M**	**$2.65 B**
Energy	$34.0 M	$22.1 M	$239 M	$33.2 M	$5.01M	$8.35 M	$348 M
Financial incentives	--	--	$65.6 M	--	--	--	$65.6 M
Stormwater	--	$479 M	--	--	--	$695 M	$1.17 B
Health	$134 M	$39.0 M	$65.8 M	$198 M	$29.7 M	$56.6 M	$523 M
Climate change	$107 M	$11.2 M	$50.3 M	$151 M	$77.6 M	$37.3 M	$434 M
Employment	--	$12.6 M	$23.0 M	$68.9 M	--	--	$104 M
NPV	**$247 M**	**$281 M**	**$201 M**	**$450 M**	**$68.6 M**	**$562 M**	**$1.81 B**

Table 10.4. Benefit-to-Cost Ratio for each solution in Washington, D.C.

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	8.29	1.99	1.83	Very high	2.57	3.39

10.2 Philadelphia

Table 10.5. NPV of building-level benefits from building specific installations in North Philadelphia (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$7.97 M**	**$77.0 M**	**$104 M**	**$0**	**$0**	**$0**	**$189 M**
First cost	$5.87 M	$53.0 M	$70.1 M	--	--	--	$129 M
Operations and maintenance	$0	$24.0 M	$11.2 M	--	--	--	$35.2 M
Additional replacements	$2.09 M	--	$23.2 M	--	--	--	$25.3 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$8.27 M**	**$13.0 M**	**$133 M**	**$16.0 M**	**$0**	**$8.97 M**	**$179 M**
Energy	$8.27 M	$5.44 M	$107 M	$16.0 M	$0	$1.46	$139 M
Financial incentives	--	--	$25.7 M	--	--	--	$25.7 M
Stormwater	--	$7.51 M	--	--	--	$7.51	$15.0 M
Health	$0	$0	$0	$0	$0	$0	$0
Climate change	$0	$0	$0	$0	$0	$0	$0
Employment	--	$0	$0	$0	--	--	$0
NPV	**$307K**	**-$64.1 M**	**$28.7 M**	**$16.0 M**	**$0**	**$8.97 M**	**-$10.1 M**

Table 10.6. NPV of cumulative economic impact in North Philadelphia (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$7.97 M**	**$77.0 M**	**$104 M**	**--**	**$0**	**$0**	**$189 M**
First cost	$5.87 M	$53.0 M	$70.1 M	--	--	--	$129 M
Operations and maintenance	$0	$24.0 M	$11.2 M	--	--	--	$35.2 M
Additional replacements	$2.09 M	--	$23.2 M	--	--	--	$25.3 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$66.8 M**	**$28.5 M**	**$207 M**	**$238 M**	**$31.3 M**	**$54.4 M**	**$627 M**
Energy	$10.3 M	$5.97 M	$107 M	$16.0 M	$894K	$2.5 M	$143 M
Financial incentives	--	--	$25.7 M	--	--	--	$25.7 M
Stormwater	--	$7.51 M	--	--	--	$7.5 M	$15.0 M
Health	$29.6 M	$8.4 M	$35.0 M	$105 M	$15.4 M	$38.2 M	$232 M
Climate change	$26.8 M	$2.9 M	$24.5 M	$73.4 M	$15.1 M	$6.1 M	$149 M
Employment	--	$3.7 M	$14.6 M	$43.7 M	--	--	$61.9 M
NPV	**$58.8 M**	**-$48.5 M**	**$103 M**	**$238 M**	**$31.3 M**	**$54.4 M**	**$437 M**

Table 10.7. NPV of city-wide impact in Philadelphia (results are additive), shown in millions

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$93.5 M**	**$699 M**	**$956 M**	**$2.16 M**	**$118 M**	**$516 M**	**$2.38 B**
First cost	$69.0 M	$481 M	$641 M	--	$65.7 M	$300 M	$1.56 B
Operations and maintenance	$0	$218 M	$102 M	--	--	$171 M	$491 M
Additional replacements	$24.6 M	--	$212 M	--	$52.4 M	$45.6 M	$334 M
Employment training	$0	$340 K	$719 K	$2.16 M	--	--	$3.21 M
Benefits	**$692 M**	**$271 M**	**$1.86 B**	**$2.09 B**	**$357 M**	**$692 M**	**$5.96 B**
Energy	$91.9 M	$53.7 M	$984 M	$147 M	$9.44 M	$38.7 M	$1.32 B
Financial incentives	--	--	$225 M	--	--	--	$225 M
Stormwater	--	$68.1 M	--	--	--	$117 M	$185 M
Health	$329 M	$91.5 M	$316 M	$949 M	$156 M	$443 M	$2.29 B
Climate change	$272 M	$27.0 M	$221 M	$663 M	$192 M	$93. M	$1.47 B
Employment	--	$30.4 M	$110 M	$331 M	--	--	$471 M
NPV	**$599 M**	**-$428 M**	**$901 M**	**$2.09 B**	**$239 M**	**$176 M**	**$3.57 B**

Table 10.8. Benefit-to-Cost Ratio for each solution in Philadelphia

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	7.40	0.39	1.94	Very high	3.03	1.34

Table 10.9. NPV of building-level benefits from building specific installations in North Philadelphia (with ½ SRC value) (results are additive), shown in millions

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$7.97 M**	**$77.0 M**	**$104 M**	**$0**	**$0**	**$0**	**$189 M**
First cost	$5.87 M	$53.0 M	$70.1 M	--	--	--	$129 M
Operations and maintenance	$0	$24.0 M	$11.2 M	--	--	--	$35.2 M
Additional replacements	$2.09 M	--	$23.2 M	--	--	--	$25.3 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$8.27 M**	**$69.9 M**	**$133 M**	**$16.0 M**	**$0**	**$49.6 M**	**$277 M**
Energy	$8.27 M	$5.44 M	$107 M	$16.0 M	$0	$1.46 M	$139 M
Financial incentives	--	--	$25.7M	--	--	--	$25.7 M
Stormwater	--	$64.5 M	--	--	--	$48.1 M	$113 M
Health	$0	$0	$0	$0	$0	$0	$0
Climate change	$0	$0	$0	$0	$0	$0	$0
Employment	--	$0	$0	$0	--	--	$0
NPV	**$307 K**	**-$7.09 M**	**$28.7 M**	**$16.0 M**	**$0**	**$49.6 M**	**$87.5 M**

Table 10.10. NPV of cumulative economic impact in North Philadelphia (with ½ SRC value) (results are additive), shown in millions

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$7.97 M**	**$77.0 M**	**$104 M**	**--**	**$0**	**$0**	**$189.4 M**
First cost	$5.87 M	$53.0 M	$70.1 M	--	--	--	$129 M
Operations and maintenance	$0	$24.0 M	$11.2 M	--	--	--	$35.2 M
Additional replacements	$2.09 M	--	$23.2 M	--	--	--	$25.3 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$66.8 M**	**$85.5 M**	**$207 M**	**$238 M**	**$31.3 M**	**$95.0 M**	**$724 M**
Energy	$10.3 M	$5.97 M	$107 M	$16.0 M	$894 K	$2.53 M	$143 M
Financial incentives	--	--	$25.8 M	--	--	--	$25.8 M
Stormwater	--	$64.47 M	--	--	--	$48.1 M	$113 M
Health	$29.6 M	$8.41 M	$35.1 M	$105 M	$15.4 M	$38.2 M	$232 M
Climate change	$26.9 M	$2.91 M	$24.5 M	$73.4 M	$15.1 M	$6.15 M	$149 M
Employment	--	$3.70 M	$14.6 M	$43.7 M	--	--	$61.9 M
NPV	**$58.8 M**	**$8.46 M**	**$103 M**	**$238 M**	**$31.3 M**	**$95.0 M**	**$535 M**

Table 10.11. NPV of city-wide impact in Philadelphia (with ½ SRC value) (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$93.5 M**	**$699 M**	**$956 M**	**$2.16 M**	**$118 M**	**$516 M**	**$2.38 B**
First cost	$69.0 M	$481 M	$641 M	--	$65.7 M	$300 M	$1.56 B
Operations and maintenance	$0	$218 M	$102 M	--	--	$171 M	$491 M
Additional replacements	$24.6 M	--	$212 M	--	$52.4 M	$45.6 M	$334 M
Employment training	$0	$340 K	$719 K	$2.16 M	--	--	$3.21 M
Benefits	**$692 M**	**$787 M**	**$1.86 B**	**$2.09 B**	**$357 M**	**$1.33 B**	**$7.11 B**
Energy	$91.9 M	$53.7 M	$984 M	$147 M	$9.44 M	$38.7 M	$1.32 B
Financial incentives	--	--	$225 M	--	--	--	$225 M
Stormwater	--	$585 M	--	--	--	$751 M	$1.34 B
Health	$329 M	$91.5 M	$316 M	$949 M	$156 M	$443 M	$2.29 B
Climate change	$272 M	$27.0 M	$221 M	$663 M	$192 M	$93.2 M	$1.47 B
Employment	--	$30.4 M	$110 M	$331 M	--	--	$471 M
NPV	**$599 M**	**$88.6 M**	**$901 M**	**$2.09 B**	**$239 M**	**$811 M**	**$4.73 B**

Table 10.12. Benefit-to-Cost Ratio for each solution in Philadelphia (with ½ SRC value)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	7.40	1.13	1.94	Very high	3.03	2.57

10.3 El Paso

Table 10.13. NPV of building-level benefits from building specific installations in the El Paso low-income area (results are additive), shown in millions

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$11.1 M**	**$129 M**	**$64.3 M**	**$0**	**$0**	**$0**	**$205 M**
First cost	$8.21 M	$88.9 M	$42.3 M	--	--	--	$140 M
Operations and maintenance	$0	$40.3 M	$7.40 M	--	--	--	$47.7 M
Additional replacements	$2.93 M	--	$14.1 M	--	--	--	$17.1 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$15.7 M**	**$9.84 M**	**$92.4 M**	**$11.0 M**	**$0**	**$6.18 M**	**$135 M**
Energy	$15.7 M	$8.23 M	$73.1 M	$11.0 M	$0	$3.81 M	$112 M
Financial incentives	--	--	$19.3 M	--	--	--	$19.3 M
Stormwater	--	$1.61 M	--	--	--	$2.37 M	$3.98 M
Health	$0	$0	$0	$0	$0	$0	$0
Climate change	$0	$0	$0	$0	$0	$0	$0
Employment	--	$0	$0	$0	--	--	$0
NPV	**$4.58 M**	**-$119 M**	**$28.2 M**	**$11.0 M**	**$0**	**$6.18 M**	**-$69.5 M**

Table 10.14. NPV of cumulative economic impact in the El Paso low-income area (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$11.1 M**	**$129 M**	**$64.3 M**	**--**	**$0**	**$0**	**$205 M**
First cost	$8.21 M	$88.9 M	$42.7 M	--	--	--	$140 M
Operations and maintenance	$0	$40.3 M	$7.40 M	--	--	--	$47.7 M
Additional replacements	$2.93 M	--	$14.1 M	--	--	--	$17.1 M
Employment training	--	$0	$0	$0	--	--	$0
Benefits	**$67.3 M**	**$21.3 M**	**$115 M**	**$78.6 M**	**$31.3 M**	**$26.3 M**	**$340 M**
Energy	$18.9 M	$9.15 M	$73.1 M	$11.0 M	$1.98 M	$5.87 M	$120 M
Financial incentives	--	--	$19.3 M	--	--	--	$19.3 M
Stormwater	--	$1.61 M	--	--	--	$2.37 M	$3.98 M
Health	$15.4 M	$2.04 M	$4.74 M	$14.2 M	$6.74 M	$6.23 M	$49.3 M
Climate change	$33.1 M	$4.53 M	$11.1 M	$33.3 M	$22.6 M	$11.9 M	$117 M
Employment	--	$3.95 M	$6.69 M	$20.1 M	--	--	$30.7 M
NPV	**$56.2 M**	**-$108 M**	**$50.7 M**	**$78.6 M**	**$31.3 M**	**$26.3 M**	**$135 M**

Table 10.15. NPV of city-wide impact in El Paso (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$103 M**	**$605 M**	**$362 M**	**$829 K**	**$96.2 M**	**$450 M**	**$1.62 B**
First cost	$75.8 M	$416 M	$241 M	--	$45.4 M	$232 M	$1.01 B
Operations and maintenance	$0	$189 M	$40.8 M	--	--	$183 M	$412 M
Additional replacements	$27.0 M	--	$79.9 M	--	$50.8 M	$35.3 M	$193 M
Employment training	$0	$295 K	$277 K	$829 K	--	--	$1.40 M
Benefits	**$443 M**	**$116 M**	**$620 M**	**$437 M**	**$241 M**	**$298 M**	**$2.15 B**
Energy	$103 M	$46.1 M	$410 M	$61.5 M	$14.1 M	$65.3 M	$700 M
Financial incentives	--	--	$85.5 M	--	--	--	$85.4 M
Stormwater	--	$7.55 M	--	--	--	$31.6 M	$39.2 M
Health	$121 M	$14.0 M	$25.7 M	$77.1 M	$54.5 M	$51.4 M	$344 M
Climate change	$219 M	$23.1 M	$60.4 M	$181 M	$172 M	$150 M	$806 M
Employment	--	$24.8 M	$39.1 M	$117 M	--	--	$181 M
NPV	**$340 M**	**-$489 M**	**$258 M**	**$436 M**	**$145 M**	**-$152 M**	**$539 M**

Table 10.16. Benefit-to-Cost Ratio for each solution in El Paso

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES
Benefit-to-Cost Ratio	4.31	0.19	1.72	Very high	2.50	0.66

11 IMPACTS OF HEAT ON SUMMER TOURISM

11.1 Washington, D.C.

Tourism is most common during the summer months due to school holidays and family travel. Excess summer heat is a recurring concern for tourists as illustrated by the four quotes below from popular District tourism sites:

- 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;"[397]
- 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;"[398]
- 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;"[399]
- A Frommer's review of the District writes, "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."[400]

With 20 million visitors in 2014, the District is one of the country's top destinations for both American and international tourists.[401] In 2014, tourists spent $6.8 billion in the District, representing more than $725 million in new tax dollars for the District of Columbia.[402]

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 increases in the number of days above 90°F, 95°F, and even 100°F (Figure 11.1 shows that the number of days with temperatures above 100°F is predicted to increase by between four- and nine-fold by 2050). Higher temperatures will also increase smog formation, all else equal. 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. Under high emissions scenarios, the District is expected to be unfavorable for tourism in the summer by the 2050s (see Figure 11.2). We expect the same is true of low emissions scenarios as well. In fact, as illustrated in the quotes above, high summer temperatures and humidity may already impact summer tourism in the District.

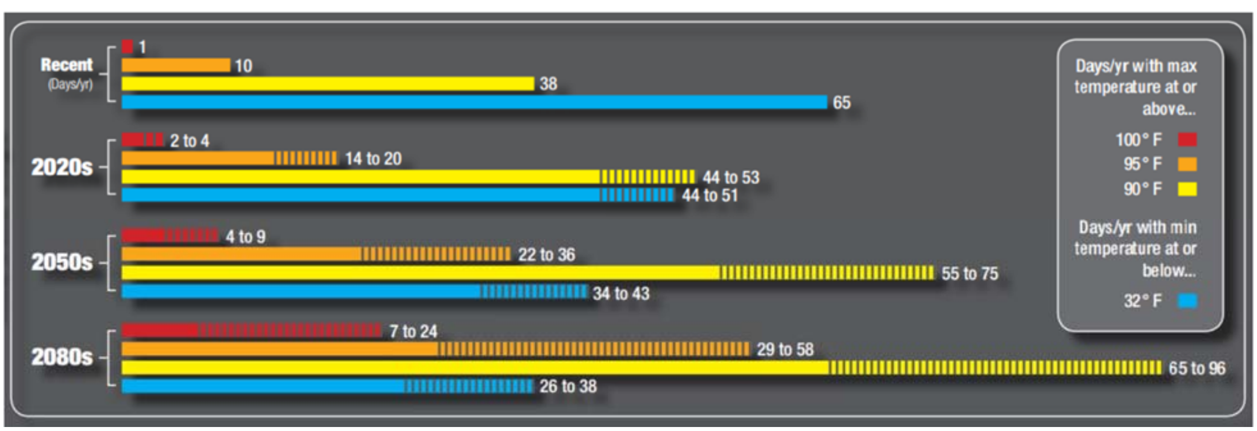

Figure 11.1. Project increase in hot and cold days in the District[403]

Climate Change Impacts on Summertime Tourism

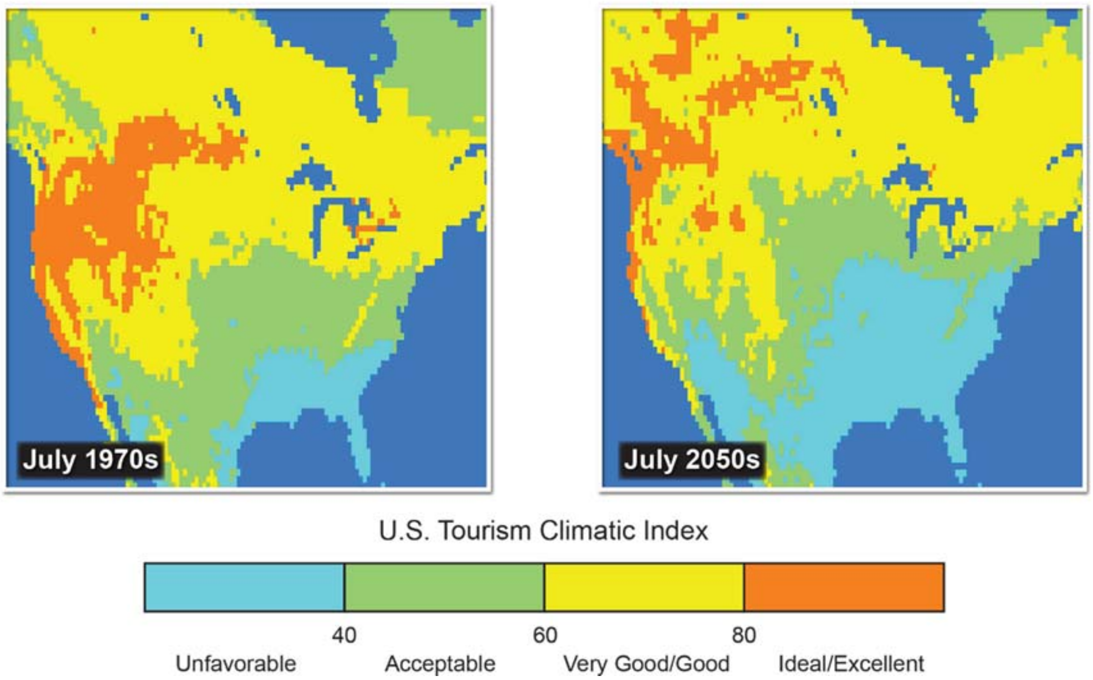

Figure 11.2. Climate change impacts on summertime tourism under a high emissions scenario[404]

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 in Table 11.1. We also assume that implementation occurs on a linear basis over the 40-year analysis period. Based on analysis in this report, we assume 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.

Table 11.1. Surface coverage by end of analysis (this is a reproduction of Table 9.2)

SURFACE SOLUTION	PERCENT COVERAGE BY END OF 40-YEAR ANALYSIS
Cool roofs	50% of roofs
Green roofs	10% of roofs
Solar PV	50% of viable (~530 MW)
Reflective pavements	50% of pavements
Urban trees	Increase tree canopy by 10% absolute

If we assume, conservatively, that 40% of tourism dollars accrue in the three summer months (June, July, and August),[cxxx] $2.72 billion in total visitor spending and $290 million in city revenue are at risk. Let us also assume that 2°C of climate change will reduce summer tourism in the District by 10%, meaning the 2°F of UHI mitigation from smart surface installation could limit this loss to only 5%, or $136 million in visitor spending and $14.5 million in District tax revenue. The net present value of this avoided loss to the

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

District over the 40-year analysis period would be $3.1 billion in visitor spending and $335 million in District tax revenue.[cxxxi]

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 climate change. However, the assumptions above provide a reasonable, first order estimate of potential avoided tourism loss benefits associated with strategies described and documented in this report.

11.2 Philadelphia

Tourism in Philadelphia also spikes during the summer during school vacations, and some tourism websites already express concerns about summer heat. They say that the summer gets “muggy,” and that spring and fall are the ideal times to visit.[405] These testimonies along with Figure 11.2 indicate a warming city with increased summer peak may repel some summer tourists. Increases in summer heat could cause losses to the tourism industry.

As in the District, tourism significantly contributes to the economy of Philadelphia. In 2015, tourists generated $10.4 billion in economic impact, according to a Philadelphia tourism report. With that economic impact comes an additional $655 million in state and local tax revenue. 88% of tourists coming to Philadelphia were there for leisure, not on a required trip, meaning that increased summer temperature has the potential to deter tourists.

Philadelphia already experiences an average of 10 days in July and 6 days in August that are above 90°F. The number of summer days above 90 degrees could quadruple, and 100°F days, which currently only occur once every few years could become a regular summer occurrence. These rising temperatures, created by climate change and exacerbated by urban heat island effects could significantly decrease summer tourism.

Assuming, as we did in Section 11.1, that 40% of tourism occurs during the summer months, there is $4.16 billion in generated economic revenue and $262 million in tax revenue from summer tourism a year, a portion of which is at risk of being lost from increasing summer temperatures. If we assume that 10% of Philadelphia summer tourism revenue is at risk, a city-wide smart surface strategy might enable Philadelphia to avoid half of these tourism losses. 5% avoided summer tourism losses would be $208 million per year tax revenue and about $5 million in revenue to the city. This would be a larger avoided loss than Washington, D.C., and would have a NPV of about $4.8 billion over 40 years. As with the District, these estimates are very rough but provide a reasonable first order estimate of potential value from smart surface strategies to prevent summer tourism loss in Philadelphia. Combining rough estimate of avoided tourism losses with the earlier rigorously calculated NPV indicates a total NPV to Philadelphia on the order of $8.4 billion from a city-wide smart surfaces strategy.

It is worth noting that a city-wide smart surfaces strategy that would benefit tourism would also have large comfort and livability benefits for residents and potentially on property value that are not calculated and included here. These additional benefits from avoided losses may be substantially larger than avoided tourism losses and merit further research.

[cxxxi] *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).*

12 CONCLUSIONS

"This rigorous and comprehensive report for the first time explains, documents and quantifies the full financial cost and benefits of a large range of city surface options such as green roofs, cool roofs, porous and high albedo pavements. The work demonstrates the huge structural disparities and inequalities in low-income city neighborhoods and how these can be addressed in ways that save money as well as enhance health, livability and employment. This is a powerful and timely new tool for cites as they move toward climate responsibility because it provides a roadmap for doing so in a way that enhances citizen's lives, especially for the less well off. And the report is a clarion call to affordable housing developers to deploy smart surfaces across all their developments to save money and to make their residents healthier and happier." ***- Michael Bodaken, President, the National Housing Trust***

This report provides an in-depth analysis of the costs and benefits of applying a set of roofing and surfacing solutions at city-scale across three cities: Washington, D.C., Philadelphia, and El Paso.

This report also provides an analysis of the impact of smart surface deployment on a low-income neighborhood/ward in each of the three cities. The low-income areas studied are substantial, representing, on average, about one-tenth of the entire city. These low-income areas have an average of 59% more of their populations below the poverty line and 57% higher unemployment rates than city-wide averages. Not coincidently, these low-income areas have about 30% lower tree coverage relative to the cities as a whole. Underinvestment in trees and green solutions in urban low-income areas results in higher summer temperatures, worse air quality, more health problems, and higher energy bills per square foot. This structural inequality is both inimical to the country's foundational commitment to equality of opportunity, as well as a waste of money.

Until this analysis, there had been no established methodology for quantifying the full costs and benefits for smart surface solutions, so cities have been unable to financially quantify these options. While more research remains to be done, the findings of this report are compelling. Low-income areas can achieve large and very cost-effective improvements in health and comfort, lower energy bills, and reduced climate change by adopting smart surface solutions. Deployment of these solutions at scale in low-income areas can largely redress systematic inequity in urban infrastructure. Reductions in energy bills matter much more to low-income residents than to wealthy city residents. Similarly, health benefits from the deployment of smart surface solutions are greater for low-income than for wealthy city residents.

Overall, the smart surface solutions evaluated in this report are cost-effective and generally provide large positive net benefits. The payback time for these solutions varies greatly: cool roofs offer very fast payback in all cases, while several other solutions offer the largest net benefit in one or more city. The report quantifies a large range of cost and benefits from adopting smart surface solutions, including detailed estimation of health impacts. Because integrated cost-benefit analysis of these solutions has largely not been done before, we have worked and consulted with national and city partners, epidemiologists, technology, stormwater, and energy experts and others to build the data, develop analytic approaches, and an integrated cost-benefit model.

This kind of full, integrated analysis has not been done before in large part because of its complexity, and because existing analytic tools address only a small portion of the study scope. For example, we used EPA's BenMAP to value the health benefits that result from declines in ambient ozone concentration. We had to solve a large set of other benefit estimation challenges including: estimating the indirect energy benefit of green roofs; developing simple, yet robust temperature-based methods to estimate city ozone concentration reductions; valuing health benefits of $PM_{2.5}$ emissions reductions due to installing cool roofs, green roofs, solar PV, reflective pavements, and urban trees; valuing heat-related mortality reductions due to cool roofs, green roofs, reflective pavements, and urban trees; and combining new methods and existing methods to estimate costs and benefits at ward-level. This has involved a great deal of synthesis of existing studies and necessarily making informed choices, with guidance from a range of field specific experts.

As discussed in the report and its Appendix, many additional benefits and a few costs were identified but not quantified due to lack of data and/or need to limit study scope. Unquantified benefits exceed unquantified costs, so the cost-benefit findings in this report underestimate the cost-effectiveness of these solutions. That is, the net benefits of scale deployment are significantly larger than estimated here.

Furthermore, this analysis largely does not capture the regional comfort, health, and livability benefits. As deployment scales up, the urban cooling benefits also grow proportionally, reducing energy bills and smog, and improving health and livability in ways that bring reinforcing benefits, especially for low-income populations. The following sections discuss how this report's findings enable and reinforce each city's sustainability goals and incorporates direct guidance and language from each city. As a result, the objectives discussed below are broader than the focus of this report.

12.1 Washington, D.C.

(This section is drawn in part from the Capital E report for the District entitled *Achieving Urban Resilience: Washington D.C.*)

Reflecting the District's ongoing leadership on climate change, the District government developed a plan entitled Climate Ready D.C. that provides an overview and roadmap of the District plan to adapt to climate change.[cxxxii]

The District has set out ambitious goals in its Sustainable D.C. Plan, and has made significant progress in meeting many of the goals. But there is still a lot of work to do in order to integrate many elements of the Districts policies and incentives. Jeff Seltzer, Associate Director of District Department of Energy & Environment notes, "Many of the District's environmental challenges, including pollution from stormwater runoff and heat island are 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."[406] 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 12.1.

Table 12.1. Smart surface solutions and Sustainable D.C. Plan

SUSTAINABLE D.C. 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

[cxxxii] *Accessible at http://doee.dc.gov/climateready*

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, D.C., is already a national and international leader in sustainability. City-wide, integrated adoption of the solutions detailed in this report would greatly strengthen the District's sustainability leadership and would provide strong protection against continued climate change.

12.2 Philadelphia

Philadelphia has 14 primary sustainability goals in four categories, all of which can be helped by adoption of the smart surface strategies detailed in this report. The first sustainability goal is to reduce energy use. This report provides a structure and economic analysis to enable Philadelphia to adopt smart surface measures like solar PV, green roofs for insulation, and technologies to mitigate the urban heat island effect and reduce air conditioning use.

Philadelphia's second and third goals are bettering the environment and promoting equity. As documented in this report, these two goals go hand in hand. As environmental conditions are improved and spaces become more livable, low-income communities benefit. One important way to accomplish this goal is to improve stormwater management. This report outlines stormwater management practices that can improve livability of the city in a cost-effective way.

Creating a more walkable environment is also key for creating a more livable environment. For low-income communities, greater walkability means easier access to parks and recreation spaces and food sources. It means that citizens can choose to walk or cycle more frequently. As this report demonstrates, increased greenery, shade, and reduced heat can be cost-effectively achieved and would make the city more walkable.

Encouraging economic growth in a sustainable way is Philadelphia's fourth goal. Implementing the practices recommended by this report would save the city money, create jobs, and increase tourism, all while improving quality of life and the environment.

12.3 El Paso

El Paso's Office of Sustainability and Resilience has specified four areas that will "define El Paso's resilience" for the future, of which two are most relevant: (1) build a sustainable city that sets the standard for quality of life and quality of place, and (2) position El Paso as the model for building resilience in an arid urban environment.[407] The solutions analyzed in this report can help El Paso achieve these objectives. A key finding is that most smart surface options evaluated have a positive NPV for individual building owners as well as city-wide. In fact, this report demonstrates that there is a significant opportunity cost (e.g. unnecessary costs) to businesses and residents if El Paso, Washington, D.C., or Philadelphia do not implement smart surface solutions. The longer El Paso waits, the larger its opportunity cost.

The climate shocks El Paso is most vulnerable to are extreme heat and flash flooding.[408] The solutions studied in this report can help El Paso reduce the risk of and mitigate the effects of these shocks. Installation of cool and green roofs, reflective pavements, and urban trees can lessen El Paso's vulnerability to extreme heat through UHI mitigation. Stormwater management services provided by installation of green roofs and urban trees increase city permeability, reducing the risk of flash flooding and increase groundwater recharging.

These solutions would also address El Paso's climate adaptation priorities. The amount of water El Paso receives from surface water bodies is declining, and the two main groundwater supplies that serve El Paso are predicted to become unusable by the middle of this century.[409] Increasing urban tree canopy, one of the actions prioritized in El Paso's Climate Resilience report as well as in this report, can help keep rainwater in the city and recharge groundwater supplies.

Improving air quality, another of El Paso's climate adaptation priorities, would be supported by scale deployment of several of the solutions analyzed in this report. Reducing energy use by installing cool and green roofs, solar PV, and urban trees will also reduce pollution emitted by power plants. Cooling the city would slow ozone formation and indirectly reduce power plant emissions. Green roofs and trees would directly remove pollutants from the air. Given that limited access to health care and lack of health insurance is a stressor in El Paso[410] and that bronchitis and asthma are the number one general pediatric diagnosis in El Paso,[411] adopting smart surface solutions could substantially improve health in El Paso—while also addressing a wide range of other city concerns.

Urban tree canopy may be particularly valuable for low-income residents in or near downtown El Paso because many of have no alternative to walking.[412] The shade provided by trees would be a reprieve from summer sun. A significant concern in low-income areas of El Paso is energy costs. For about 10% of El Paso households, up to 30% of household income goes towards electricity purchases.[413] Installing cool and green roofs and urban trees to reduce solar heat gain, and solar PV would reduce energy costs for these low-income residents. Ambient cooling, through city-wide installation of these solutions, would also contribute to reduced energy costs.

Unemployment, low wages, and workforce skills gaps are additional concerns for El Paso.[414] The roof and surface solutions analyzed in this report are labor intensive to install and require annual maintenance. Solar PV and green roof jobs are also relatively well-paying jobs, and the skills gained on the job could be broadly useful. This is important employment pathway for unemployed residents to build a valuable skillset through green roof and solar PV installation and maintenance.

12.4 Low-income impact versus city-average impact

Low-income areas can achieve large gains in health, comfort and resilience, reducing energy bills, and mitigating climate change 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 are a more significant portion of income saved for 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, if coupled with city job linking and training would also benefit low-income residents.

12.4.1 Comfort

Lower income city residents tend to live in areas with fewer trees and more impervious surface.[415] This was evident in the low-income regions we analyzed in this analysis.[cxxxiii] This indicates that the comfort benefit

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[cxxxiii] *For example, Ward 5 in Washington, DC has 27.7% tree canopy and the city average is 31.2%. North Philadelphia has a tree canopy of 10.1% and the city average is 20.0%. In El Paso, the city average tree canopy*

from smart surface adoption in low-income areas – which are currently less comfortable, hotter and polluted in the summer than the city as a whole, would be greater than average city-wide.

Philadelphia's average tree canopy is 20.0%, while North Philadelphia's (the low-income area studied for Philadelphia) tree canopy is 10.1%. If the city were to increase tree canopy by an absolute 10% in both regions (as analyzed in this report), tree canopy in Philadelphia would rise to 30% and tree canopy in North Philadelphia would be 20.1%. The relative change Philadelphia-wide would be 50%, and 100% in North Philadelphia (see Figure 12.1). Using tree canopy as a proxy for shade, this means the amount of shade in North Philadelphia would increases twice as much as for city-wide. Many low-income residents do not own cars, so unless there is convenient public transportation, they may have no option but to walk even during hot summer months, so the shading from trees would create greater comfort and health benefits for low-income areas, helping reduce summer heat stress.

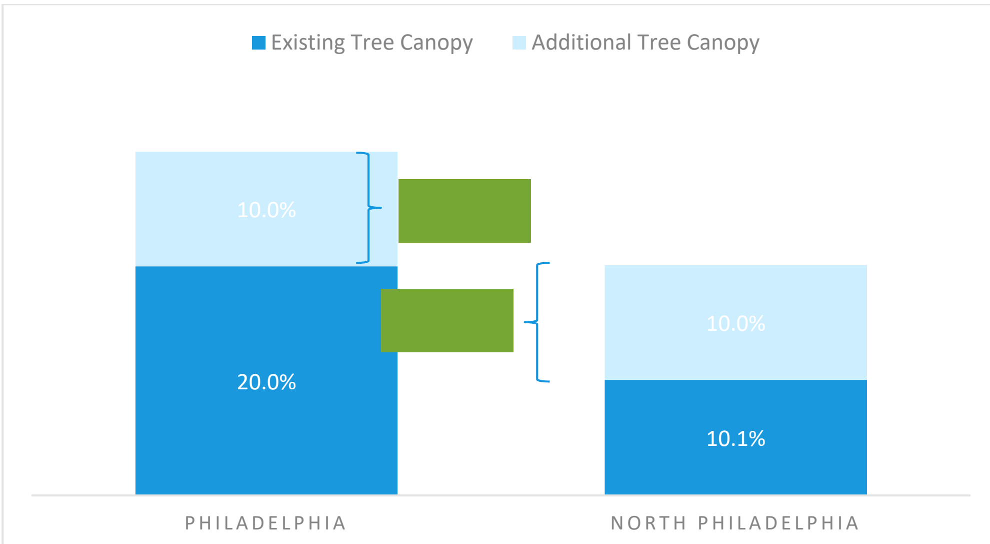

Figure 12.1. Tree canopy in Philadelphia vs North Philadelphia

12.4.2 Energy

Lower income renters spend about 10% of income on energy costs, while higher income renters spend about 2% of income on energy costs.[416] Energy savings due to smart surface solution installation would therefore provide a much greater relative benefit to low-income renters.

Based on EIA's Residential Energy Consumption Survey covering Washington, D.C., and El Paso, air conditioning accounts for about 16% of energy expenditures for renters.[417] If we assume smart surfaces reduce air conditioning use by 25%, this would free up 0.4% of a low-income renter's income that no longer has to be spent on air conditioning costs. For higher income renters, this would only free up 0.08% of income. The benefit to lower income renters in this case is five times larger than it is for higher income renters. We do not have data for homeowners, but expect comparable results. Regardless of percent energy saved, the benefit to low-income residents will be roughly 5 times larger, demonstrating the larger relative impact of smart surface solutions on low-income citizens.

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is 5.1%. The El Paso low income area does not have tree canopy data, but a scan of Google Maps and a recent study indicates less tree coverage than other areas of the city. The El Paso low income area in this analysis is predominantly located in El Paso's urban core, where higher density makes tree planting more difficult. Comparing the building footprint and pavement area in the low income regions to the city yields similar results.

12.4.3 Employment

Lower income areas of cities tend to have higher unemployment than more affluent neighborhoods. This is evident in the regions analyzed in this report. For example, low-income North Philadelphia has an unemployment rate of 24.8% versus the Philadelphia city-wide unemployment rate of 14.9%. Given higher unemployment in low-income areas, it is reasonable to assume a higher percentage of jobs created from smart surface solution installs could accrue to low-income residents if cities provide policy and training efforts to support employment in low-income communities.

To get a sense of scale of potential employment impact, we assume that with strong city training and job linking policies, two-thirds of jobs accrue to low-income residents. In this case, 3,000, 13,560, and 5,250 direct jobs-years would be created for low-income residents over 40 years in Washington, D.C., Philadelphia, and El Paso, respectively. Assuming an average income of $40K per job-year, this would equate to $120 million, $542 million, and $210 million of additional income for low-income residents over 40 years in Washington, D.C., Philadelphia, and El Paso, respectively. This illustration is not a prediction, but rather serves to indicate potential scale of employment and income gains from well structured, city-wide smart surface programs.

12.4.4 Health

Based on our ozone analysis for Washington, D.C., the ozone health benefit in Ward 5 is about 1.5 times greater per person than the benefit for the average city resident. If we assume same multiplier (1.5) holds for the other air pollution related benefits ($PM_{2.5}$ and heat-related mortality), this indicates that low-income residents would experience roughly 50% greater health benefit compared the average city resident. This is likely conservative because the city average impact per person includes low-income residents—removing low-income areas from the city-wide average would make income-linked differences even more stark.

This report identifies many additional benefits of city-wide adoption of smart surface technologies that we could not quantify due to insufficient data and/or studies, so this report's findings underestimate the cost-effectiveness of these solutions.

One large benefit of city-wide adoption of smart surface strategies we were not able to quantify is that cooling of cities also means that cities that are downwind receive cooler airflow and cooling benefits. This downwind cooling from city-wide adoption of smart surface options in the District, for example could be large, including cooling impact in the poorer eastern and northeastern parts of the city. In addition, because summer winds in the District generally blow from the south or southwest,[418] urban cooling in Arlington, Annandale and Tysons Corner, for example, would lead to summer cooling in the District. This downwind cooling, would create additional energy, air quality, and livability benefits within each city as well as for the larger region.

The findings in this report demonstrate that city-wide deployment of the surface technologies is an urgent, viable and highly cost- effective strategy for cities to protect their livability and resilience. In adopting these smart surface strategies city-wide, cities can go a long way in redressing current deep structural inequality that consigns low-income and minority citizens to less healthy, less green neighborhoods characterized by more severe heat and worse air pollution. This endemic urban structural inequality is both immoral and entirely unnecessary. Terri Ludwig, President and CEO, Enterprise Community Partners, Inc. observes that;

"This report rigorously and compellingly demonstrates how such technological investments can have enormous social, health and comfort benefits city-wide, but especially in more vulnerable, low-income areas. Providing a cost-effective way to correct the chronic physical disadvantages that impact our low-income communities must be an urgent priority for our nation's cities, and this report demonstrates that such an approach is not only feasible, but that it would more than pay for itself."

Through city-wide smart surface strategies, cities can provide a healthier place to work and live for all their citizens. The data on cost-effectiveness of these strategies is compelling.

This report demonstrates that city-wide adoption of smart surfaces creates very large net financial benefits for the three varied cites of Washington, D.C., Philadelphia and El Paso. These findings should result in broad recognition of a far fuller set of costs and benefits of these technologies and the rationale for adoption of these technologies as city-wide standard practice. Comprehensive smart surface adoption would enable cities to improve quality of life, address structural inequality, improve livability, cut costs, and contribute to slowing climate change. City leadership on smart surfaces can also be expected to accelerate smart surface adoption by the surrounding cities, in turn increasing city and region-wide cooling and health benefits.

Delays in city-wide adoption would impose real costs. Former Washington, D.C., City Administrator and former Administrator of the General Services Administration Dan Tangherlini observes that:

"Delivering Urban Sustainability, Equity and Resilience is a critical, even transformative new analysis that provides a compelling case that cities should accelerate their 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."

APPENDICES

13 APPENDIX: SOLAR PV INSTALLATION COSTS

1) Basis: Barbose et al. (2015)[419]
2) Barbose et al. present prices for 2014 installs for various states

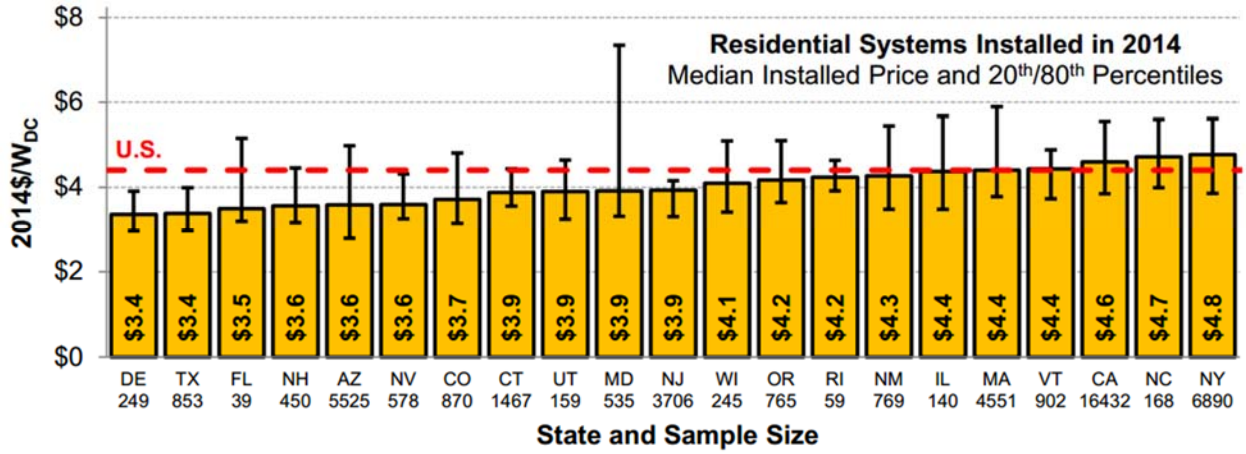

Figure 13.1. Installed price of residential PV systems by state[420]

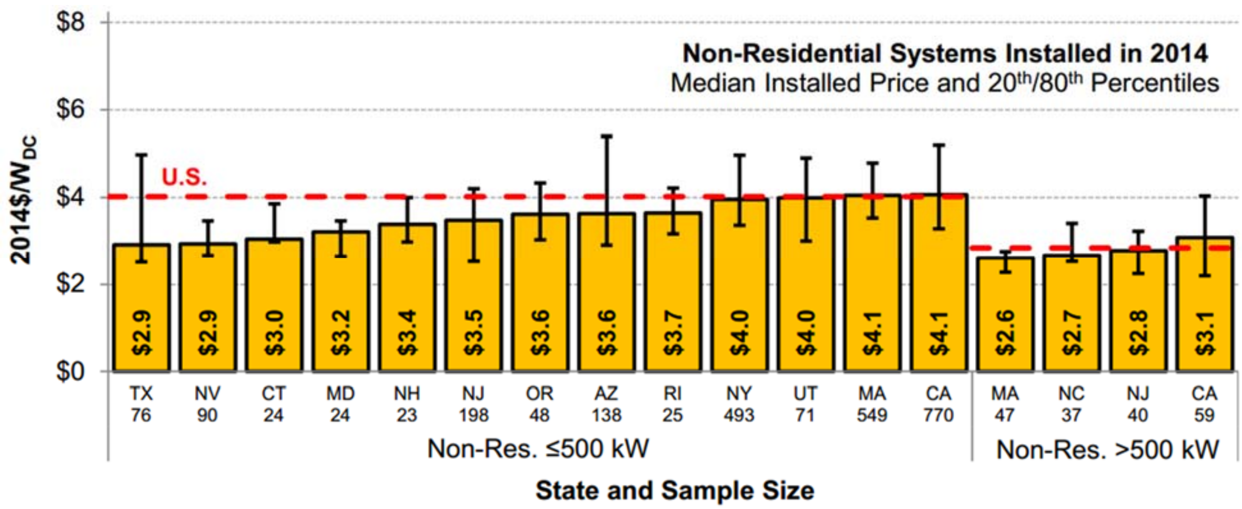

Figure 13.2. Installed price of non-residential PV systems by state[421]

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%, 9.4%, and 11.7% year-on-year for residential systems, non-residential systems <= 500kW, and non-residential systems > 500kW, respectively (see Table 13.1)

Table 13.1. National median installed price overtime[422]

YEAR	$/W		
	Residential	Non-Residential <= 500 kW	Non-Residential > 500 kW
2006	9.1	8.8	7.8
2007	9.2	8.9	7.5
2008	8.8	8.7	7.4
2009	8.4	8.6	7.6
2010	7.1	6.9	5.7
2011	6.3	5.8	4.7
2012	5.4	5.0	4.3
2013	4.7	4.3	3.5
2014	4.3	3.9	2.8

b) Washington, D.C.
   i) Geographically closest state in Figure 13.1 and Figure 13.2 to D.C. is MD → use MD $/W numbers in analysis under assumption that D.C. and MD have similar PV markets
   ii) Extrapolate cost declines identified above through 2016 → residential $/W = 3.2 and non-residential <= 500kW $/W = 2.6
      (1) Use these values for pre-2020 solar PV costs in the District
c) Philadelphia
   i) Geographically closest states in Figure 13.1 and Figure 13.2 to Philly are MD, DE, and NJ → use average of the $/W in these states under assumption that Philly have similar PV markets
   ii) Extrapolate cost declines identified above through 2016 for each state, then average → residential $/W = 3.0 and non-residential (<= 500kW and > 500kW) $/W = 2.6
      (1) Use these values for pre-2020 solar PV costs in the Philly
d) El Paso
   i) Use TX $/W values from Figure 13.1 and Figure 13.2
   ii) Extrapolate cost declines identified above through 2016 → residential $/W = 2.8 and non-residential <= 500kW $/W = 2.4
      (1) Use these values for pre-2020 solar PV costs in El Paso

4) Post-2020
   a) Washington, D.C.
      i) Use MD $/W as before
      ii) Extrapolate trend identified above through 2020 → residential $/W = 2.2 and non-residential <= 500kW $/W = 1.8
         (1) Uses these values for post-2020 solar PV costs in the District
   b) Philadelphia
      i) Use average of MD, DE, and NJ as before
      ii) Extrapolate cost declines identified above through 2020 for each state, then average → residential $/W = 2.1 and non-residential (<= 500kW and > 500kW) $/W = 1.7
         (1) Use these values for post-2020 solar PV costs in the Philly
   c) El Paso
      i) Use TX $/W as before
      ii) Extrapolate trend identified above through 2020 → residential $/W = 2.0 and non-residential <= 500kW $/W = 1.6
         (1) Uses these values for post-2020 solar PV costs in El Paso

14 APPENDIX: ESTIMATING ENERGY IMPACT

14.1 Direct energy

14.1.1 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.[423] 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.[424] 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.[425] 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.[cxxxiv]

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.[cxxxv] 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.[cxxxvi] 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),[cxxxvii] 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 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.[cxxxviii] In addition, we assume that green roofs cover 100 percent of

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[cxxxiv] *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.)*

[cxxxv] *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.)*

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

[cxxxvii] *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.)*

[cxxxviii] *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.)*

the roof.[cxxxix] Washington, D.C., was not one of the cities simulated for GREC development so we model the energy savings/penalties of green roofs for Washington, D.C., using Baltimore (geographically the closest of the modeled cities to Washington, D.C.).[cxl] For Philadelphia and El Paso, we use results for Philadelphia and El Paso, respectively. 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.

14.1.1.1 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.

14.1.2 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 in the District and Philadelphia are shown in Table 14.1 and the same for El Paso are shown in Table 14.2. The HVAC equipment efficiencies and roof insulation levels are set as close as possible to the respective values used in GREC.[cxli,cxlii] 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.[426] 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.

Table 14.1. CREST inputs for the District and Philadelphia.

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%

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

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

Table 14.2. CREST inputs for El Paso.

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	21	16	21	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	21	16	21	16
Cool solar reflectance	0.25	0.25	0.25	0.25
Cool infrared emissivity	0.9	0.9	0.9	0.9

14.1.3 Urban trees

14.1.3.1 Washington, D.C.

1) Use results from Washington, D.C., i-Tree Eco analysis[427]
    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

14.1.3.2 Philadelphia

2) Use preliminary results from Philadelphia i-Tree Eco analyses[428]
    a. i-Tree Eco assumes only residential buildings receive direct energy benefits → conservative
3) Sample calculation using Philadelphia data
    a. Residential area = 36370.5 acres (1.6 million square feet)
    b. % Residential area that is tree canopy = 14.9%
    c. Multiply together to determine residential tree canopy area = 240 thousand square feet
    d. Divide energy savings by canopy area
        i. Cooling = 0.13 kWh per ft2 canopy
        ii. Heating = 0.008 therm + 0.013 kWh per ft2 canopy

4) Determine percent of trees that provide direct energy benefits
    a. Determine low and medium density residential land use fraction for each region
        i. Philadelphia[429]
            1. City-wide: 26.8%
            2. North Philadelphia: 21.5%
            3. LU classes: low density residential, medium density residential

14.1.3.3 El Paso

1) Use results from El Paso i-Tree Eco analysis[430]
    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 (5.1% or 364 million SF) → results conservative for trees that provide direct energy, and over estimate for those that don't
        i. Cooling savings = 28,864 MWh
            1. 0.08 kWh per SF tree canopy
        ii. Heating penalty = 47,303 MBTU + 1,194 MWH
            1. 0.001 therm + 0.003 kWh per SF tree canopy

14.2 Indirect energy use

14.2.1 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.[431] 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 U.S." 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.[cxliii] 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 14.3 through Table 14.5 for the characteristics of each building and its variants), so savings/penalties will tend to be smaller for the 1980+ variant.

Table 14.3. 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		

cxliii 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.)

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 14.4 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 14.5 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, Philadelphia, and El Paso using the building type estimates in Table 14.6 through 14.11. We base the District estimates on data from the Government of the District of Columbia.[432] We base the Philadelphia estimates on data from the City of Philadelphia.[433] We base the El Paso estimates on data from the City of El Paso. 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 14.12 and Table 14.13).

For simplicity we assume an equal four part split for building vintage and heating fuel within each building type.

Table 14.6. Washington, D.C., 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%

Table 14.7. Ward 5 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 (%)	13.7%	13.7%	11.3%	11.3%	0.0%	0.0%
Building roof area stock with heat pump system (%)	13.7%	13.7%	11.3%	11.3%	0.0%	0.0%

Table 14.8. Philadelphia 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 (%)	16.5%	16.5%	8.5%	8.5%	0.0%	0.0%
Building roof area stock with heat pump system (%)	16.5%	16.5%	8.5%	8.5%	0.0%	0.0%

Table 14.9. North Philadelphia 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 (%)	14.1%	14.1%	10.9%	10.9%	0.0%	0.0%
Building roof area stock with heat pump system (%)	14.1%	14.1%	10.9%	10.9%	0.0%	0.0%

Table 14.10. El Paso 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 (%)	19.0%	19.0%	6.0%	6.0%	0.0%	0.0%
Building roof area stock with heat pump system (%)	19.0%	19.0%	6.0%	6.0%	0.0%	0.0%

Table 14.11. El Paso Region X 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 (%)	14.0%	14.0%	11.0%	11.0%	0.0%	0.0%
Building roof area stock with heat pump system (%)	14.0%	14.0%	11.0%	11.0%	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 14.12 and Table 14.13. We take the average of the HDD and CDD energy impact estimates.

Table 14.12. Estimated indirect energy savings per 1,000 ft² of roof based on HDD for the District, Philadelphia, and El Paso[434]

CITY	WASHINGTON, D.C., 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
CITY	PHILADELPHIA 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)	88	38	256	85	273	87
Estimated total indirect electricity savings with heat pump system (kWh)	44	22	237	72	262	82
Estimated total indirect peak power demand reduction (W)	128	73	182	74	129	58
Estimated total indirect gas penalties with gas heating system (Therm)	-11	-5	-2	-1	-1	0
CITY	EL PASO 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)	168	78	276	107	295	101
Estimated total indirect electricity savings with heat pump system (kWh)	140	70	266	104	289	101
Estimated total indirect peak power demand reduction (W)	120	61	157	72	129	48
Estimated total indirect gas penalties with gas heating system (Therm)	-3	-1	-1	0	-1	0

Table 14.13. Estimated indirect energy savings per 1,000 ft^2 of roof based on CDD for the District, Philadelphia, and El Paso[435]

CITY	WASHINGTON, D.C., 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
CITY	PHILADELPHIA 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)	115	51	250	89	256	85
Estimated total indirect electricity savings with heat pump system (kWh)	60	33	228	75	243	79
Estimated total indirect peak power demand reduction (W)	97	53	162	58	116	47
Estimated total indirect gas penalties with gas heating system (Therm)	-7	-3	-3	-1	-2	-1
CITY	EL PASO 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)	202	95	257	122	263	105
Estimated total indirect electricity savings with heat pump system (kWh)	191	92	252	121	261	105
Estimated total indirect peak power demand reduction (W)	102	60	127	86	90	47
Estimated total indirect gas penalties with gas heating system (Therm)	-1	0	0	0	0	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.[cxliv]

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 ($\Delta\rho_1$).[436] 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 14.1 to scale the energy impact results of Akbari and Konopacki (2005) to fit the assumptions for this analysis. In Equation 14.1, ΔE_{CB} is the scaled energy use impact used in this analysis, 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 14.1. 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 14.1 in half to determine the indirect energy savings from cool roof implantation.[437]

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, D.C., and Baltimore.[438] 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 14.1 divided by two).[cxlv]

14.2.1.1 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

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[cxliv] 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 °F, then installing cool roofs on 50 percent of roof area in a city results in an ambient temperature change of about °F.

[cxlv] 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.

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.

14.2.2 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 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).

14.2.3 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 14.1 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 14.1). As described above in Section 14.2.1, this method likely underestimates the indirect energy benefits of trees.

14.3 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):[439]
    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 14.14. Housing units in the District (from American Community Survey)[440]

HOUSING TYPE	NUMBER OF HOUSING UNITS
1-unit, detached	35,925
1-unit, attached	76,489

Table 14.15. Housing units in Ward 5 (from American Community Survey)[441]

HOUSING TYPE	NUMBER OF HOUSING UNITS
1-unit, detached	5,322
1-unit, attached	12,574

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

Table 14.16. 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[442]
   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. D.C. in South Atlantic EIA Census Region
         i. Shading fraction: 55% (i.e., the fraction of roofs that are shaded)
      b. Philadelphia is in Middle Atlantic EIA Census Region
         i. Shading fraction: 55%
      c. El Paso is Texas EIA Census Region
         i. Shading fraction: 35%
v. System orientations
   1. From Denholm et al. (2009) Table C-1

Table 14.17. 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
vii. Table 14.15 by factors presented above to determine the number of housing units in each region that can support solar

Table 14.18. Example result for Washington, D.C., city-wide 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 14.19. Example result for Ward 5 1-unit detached

ORIENTATION	TILT	AZIMUTH	FLAT	4-SIDED	2-SIDED
1	0	0	238	0	0
2	25	-90	0	0	153
3	25	-60	0	0	153
4	25	-30	0	356	153
5	25	0	0	356	153
6	25	30	0	356	153
7	25	60	0	0	153
8	25	90	0	0	153

Table 14.20. Example result for Washington, D.C., city-wide 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

Table 14.21. Example result for Ward 5 1-unit attached

ORIENTATION REFERENCE IN MODEL	TILT	AZIMUTH	FLAT	4-SIDED	2-SIDED
1	0	0	2801	0	0
2	25	-90	0	0	401
3	25	-60	0	0	401
4	25	-30	0	0	401
5	25	0	0	0	401
6	25	30	0	0	401
7	25	60	0	0	401
8	25	90	0	0	401

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

Table 14.22. Example result for Washington, D.C., 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 14.23. Example result for Ward 5 1-unit detached

ORIENTATION REFERENCE IN MODEL	TOTAL KW
1	1190
2	765
3	765
4	2545
5	2545
6	2545
7	765
8	765

Table 14.24. Example result for Washington, D.C., 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

Table 14.25. Example result for Ward 5 1-unit attached

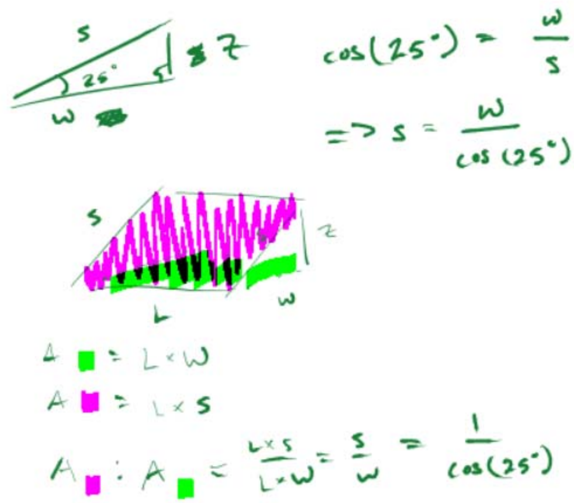
ORIENTATION REFERENCE IN MODEL	TOTAL KW
1	14005
2	2005
3	2005
4	2005
5	2005
6	2005
7	2005
8	2005

b. Commercial
   i. Roof slope
      1. Based on the 2012 Commercial Building Energy Consumption Survey from EIA[443]
      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 D.C.):
               1. 81% low slope
               2. 19% steep slope
            ii. Middle Atlantic (which includes Philadelphia)
               1. 76% low slope
               2. 24% steep slope
            iii. West South Central (which includes El Paso)
               1. 84% low slope
               2. 16% 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 14.26. Commercial building footprint in Washington, D.C., and Ward 5

ANALYSIS REGION CITY	WASHINGTON, D.C.	WARD 5
Commercial building footprint (SF)	99,479,908	18,252,260

      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 D.C., Baltimore, and Philadelphia.
  2. Tilt assumptions are from NREL, 2009 Table C-3

Table 14.27. 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)[444]
  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 14.28. Example maximum commercial PV capacity for Washington, D.C., city-wide

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

Table 14.29. Example maximum commercial PV capacity for Ward 5

ORIENTATION REFERENCE IN MODEL	TILT	AZIMUTH	FLAT (KW)	2-SIDED (KW)	TOTAL KW
1	0	0	79,837	0	79,837
2	25	-90	0	6,667	6,667
5	25	0	0	6,667	6,667
8	25	90	0	6,667	6,667
9	25	180	0	6,667	6,667

c. Multi-family residential
    i. Roof slope
        1. Same fractions as for commercial roofs
    ii. Building footprint

Table 14.30. Multifamily residential building footprint in Washington, D.C., and Ward 5

ANALYSIS REGION CITY	WASHINGTON, D.C.	WARD 5
Multifamily residential building footprint (SF)	13,657,922	1,129,957

    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 14.31. Example maximum multifamily residential PV capacity for Washington, D.C.

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

Table 14.32. Example maximum multifamily residential PV capacity for Ward 5

ORIENTATION REFERENCE IN MODEL	TILT	AZIMUTH	FLAT (KW)	2-SIDED (KW)	TOTAL KW
1	0	0	1,372	0	1,372
2	25	-90	0	109	109
5	25	0	0	109	109
8	25	90	0	109	109
9	25	180	0	109	109

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[445]
   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. D.C.: WASHINGTON D.C. REAGAN AP, VA
      ii. Philadelphia: PHILADELPHIA INTERNATIONAL AP, PA
      iii. El Paso: EL PASO INTERNATIONAL AP [UT], TX
   f. Otherwise, use default PVWatts inputs unless noted above
      i. PV efficiency: 15% (i.e., "Standard" module type)[cxlvi]
      ii. System losses: 14%
      iii. Inverter efficiency: 96%
      iv. D.C. to AC size ratio: 1.1

14.4 Utility rates

We use the most recent (2014 or 2015) annual utility rates from EIA. See Table 14.33 for commercial rates and Table 14.34 for residential rates.

Table 14.33. Commercial utility rates; held constant through analysis (electricity rates are utility-specific—Pepco in D.C., PECO in Philadelphia, and El Paso Electric in El Paso; natural gas rates are state specific)

CITY	WASHINGTON, D.C.		PHILADELPHIA		EL PASO		
Fuel	**Base price**	**Year**	**Base price**	**Year**	**Base price**	**Year**	**Fuel unit**
Electricity[446]	$0.1222	2015	$0.1240	2015	$0.0959	2015	kWh
Natural Gas	$1.19[447]	2015	$0.99[448]	2014	$0.81[449]	2014	therm

Table 14.34. Residential utility rates; held constant through analysis (electricity rates are utility-specific—Pepco in D.C., PECO in Philadelphia, and El Paso Electric in El Paso; natural gas rates are state specific)

CITY	WASHINGTON, D.C.		PHILADELPHIA		EL PASO		
Fuel	**Base price**	**Year**	**Base price**	**Year**	**Base price**	**Year**	**Fuel unit**
Electricity[450]	$0.1278	2015	$0.1439	2015	$0.1149	2015	kWh
Natural Gas	$1.27[451]	2015	$1.15[452]	2015	$1.04[453]	2014	therm

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

15 APPENDIX: ESTIMATING SOLAR PV FINANCIAL INCENTIVES

15.1 Tax credit

There are two federal tax credits available to PV system owners: the residential renewable energy tax credit[454] and the business energy investment tax credit (ITC).[455]

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.[456] Table 15.1 shows the residential solar tax credit schedule used in this analysis.

Table 15.1. 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.[457] 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 15.2 shows the residential solar tax credit schedule used in this analysis.

Table 15.2. 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%

15.2 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.[458] 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).[459] For simplicity, we assume businesses have enough tax appetite to deduct against. Table 15.3 shows the 5-year MACRS schedule used in this analysis.

Table 15.4 shows the bonus depreciation timeline.

Table 15.3. 5-year MACRS schedule[460]

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

Table 15.4. Bonus deprecation timeline[461]

PLACED IN SERVICE DATE	BEFORE 2018	2018	2019	AFTER 2019
Bonus depreciation	50%	40%	30%	0%

15.3 SRECs

We base SREC price assumptions on 5-year annuity contracts from one of the largest SREC aggregators in the country. After 2021, we assume systems receive no SREC value.[cxlvii] Table 15.5 below shows the SREC schedules used in this analysis.

Table 15.5. SREC schedules used in this analysis[462]

YEAR	2017	2018	2019	2020	2021
Value in D.C. ($/kWh)	$0.250	$0.250	$0.250	$0.250	$0.250
Value in Philadelphia ($/kWh)	$0.015	$0.015	$0.015	$0.015	$0.015

15.4 Texas solar and wind energy device franchise tax deduction

Texas allows a company to deduct the cost of a solar PV project from its franchise tax in two ways: (1) total cost can be deduced from the company's taxable capital or (2) 10% of amortized cost of the system can be deducted from the company's income.[463] As before, this report assumes businesses have enough tax appetite to deduct against.

Assume 50-50 split in how deduction used: 50% deduct total cost from taxable capital and 50% deduct 10% of amortized cost from income.

Taxable capital taxed at rate of 0.25% per year, income taxed at a rate of 4.5% per year[464]

Equation 15.1. Total tax benefit based on method (1)

$$Tax\ benefit = System\ cost \times 0.25\%$$

For method (2), must be amortized for at least 60 months in equal monthly amounts or using Federal depreciation.[465] For simplicity, use Federal depreciation as described in Section 15.2.

Equation 15.2. Total tax benefit based on method (2)

$$Tax\ benefit = \sum_{i=0}^{n}\left(10\% \times amortized\ cost_{yr,i}\right) \times 4.5\%$$

[cxlvii] *This is a common assumption among PV developers, investors, etc. who typically assign no value to SRECs beyond year 5 of a PV project.*

16 APPENDIX: ESTIMATING CLIMATE CHANGE IMPACT

16.1 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 CO2 emissions.[466] 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 CO2 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 CO2 emissions than the 2013 update, reflecting small modeling corrections.[467] In this report we use the SCC to capture the benefits of net CO2 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, D.C., Philadelphia, and El Paso. For the District and Philadelphia, we obtained the PJM "Residual Mix" emissions, which approximates the emission rate for electricity in the PJM (which includes D.C. and Philadelphia) from BGE.[468] PJM "Residual Mix" emissions rate is 1,108 lbs CO_2 per MWh for 2014.[469] For El Paso, we obtained emissions information from the City of El Paso. The El Paso emissions rate is 652 lbs CO_2 per MWh for 2015.[470] EPA (2014) provides a CO_2 factor, a methane (CH_4) factor, and a nitrous oxide (N_2O) factor for burning natural gas.[471] 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 16.1).[cxlviii] The result is 5.3 kg CO_2e per therm of natural gas.

Equation 16.1. 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

[cxlviii] 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.471

To determine future electricity emission factors, we use CO_2 emissions rate indices from Lavappa and Kneifel (2015).[472] Lavappa and Kneifel (2015) emissions indices are based on an EPA analysis of Low, 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 16.1 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 16.2). SCC values were obtained from Table A1 of Interagency Working Group on Social Cost of Carbon (IWGSCC) (2015).[473] 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 16.2).

Equation 16.2. 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 16.3. 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 16.1. Projected Carbon Dioxide Emissions Rate Indices for Electricity, by Carbon Policy Scenario[474]

YEAR	NO POLICY	DEFAULT PRICING	LOW PRICING	HIGH PRICING
2015	1	0.91	0.91	0.88
2016	0.99	0.89	0.89	0.85
2017	0.99	0.86	0.86	0.82
2018	0.98	0.83	0.83	0.79
2019	0.98	0.8	0.8	0.76
2020	0.97	0.78	0.77	0.73
2021	0.97	0.76	0.75	0.7
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
2039	0.96	0.39	0.38	0.32
2040	0.96	0.37	0.36	0.29
2041	0.96	0.34	0.33	0.26
2042	0.97	0.32	0.31	0.23
2043	0.97	0.3	0.29	0.19
2044	0.97	0.27	0.26	0.16
2045	0.97	0.25	0.24	0.12

Table 16.2. Annual SCC Values 2010-2060 (2007$/metric ton CO2);[475] 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					

16.2 Global cooling

1) Akbari et al. (2009) and Menon et al. (2010) for the basis for our global cooling calculations[476]
    a. Both modeled the effect of roof and pavement albedo increases on Earth's radiative forcing[cxlix]
    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
            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[cl]
    b. Steep slope albedo change in this analysis: 0.10 → 0.25 = 0.15[cli]
    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[clii]
        ii. Parking: 0.15 → 0.30 = 0.15[cliii]
        iii. Sidewalks: 0.30 → 0.35 = 0.05[cliv]
    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

[cxlix] *Radiative forcing is the difference between the radiant energy received by the Earth (from the Sun) and the energy Earth radiates to space.*

[cl] *Albedo changes in this analysis increase as technology improves in future years.*

[cli] *Albedo changes in this analysis increase as technology improves in future years.*

[clii] *Albedo changes in this analysis increase as technology improves in future years.*

[cliii] *Albedo changes in this analysis increase as technology improves in future years.*

[cliv] *Albedo changes in this analysis increase as technology improves in future years.*

17 APPENDIX: ESTIMATING STORMWATER IMPACT

17.1 Washington, D.C.

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)[clv] determines the stormwater retention requirement based on Equation 17.1.[477] Equation 17.1 can also be used to determine the maximum retention volume that can be certified for SRCs for a given property.

Equation 17.1. 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

17.1.1 Stormwater Fee

In the District, all customers of D.C. Water are charged a "D.C. 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.[478] Similarly, the IAC is used to enable compliance with the federally mandated Clean Rivers Project, part of D.C. Water's Long Term Control Plan, which aims to steeply reduce the number of combined sewer overflows from the District's Combined Sewer System.[479] 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

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[clv] 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. D.C. 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 D.C.'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.

17.1.1.1 Green roofs

Green roof stormwater retention volume is calculated using Equation 17.2.[480]

Equation 17.2. Retention volume for green roofs

$$Sv = \frac{SA \times [(d \times \eta_1) + (DL \times \eta_2)]}{12}$$

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 14.1.1, 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)).[481]

Based on guidance from DOEE, we assume media volume of voids[clvi] and drainage layer volume of voids are both equal to 30 percent.[482] The calculated retention volume for a 10,000 square foot green roof is shown in Table 17.1.

Table 17.1. Stormwater retention volume for lower bound, middle, and upper bound Scenarios

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, D.C.[483] 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, base all discount calculations on the total area of impervious surface.

DOEE's Discount Calculations Spreadsheet forms the basis of our discount estimates.[484] The discounts for a 10,000 square foot green roof estimates are shown in Table 17.2. The CRIAC used for this analysis is

[clvi] *Void volume is empty space in the media or drainage layers that help retain stormwater.*

$20.30 per ERU.[485] The Stormwater Fee used for this analysis is $2.67.[486] We conservatively assume the CRIAC and Stormwater Fee are constant throughout the analysis period.

Table 17.2. Calculated and actual received Stormwater Fee and IAC discounts

CALCULATED STORMWATER FEE DISCOUNT	ACTUAL STORMWATER FEE DISCOUNT RECEIVED[clvii]	CALCULATED CRIAC DISCOUNT	ACTUAL CRIAC DISCOUNT RECEIVE D.C.
78%	55%	6%	4%

17.1.1.2 Urban trees

Newly planted trees receive a retention value of 10 cubic feet (75 gallons).[487] 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).[488] 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 ft^2 (i.e., the circular area of a tree with radius of 10 ft).[clviii]

17.1.2 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 17.1.[489,clix] Based on Equation 17.1, 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.

[clvii] *The maximum Stormwater Fee discount is 55% and the maximum IAC discount is 4%*

[clviii] *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.)*

[clix] *Note: This does not mean a green roof will retain the retention volume from a 1.7-in storm.*

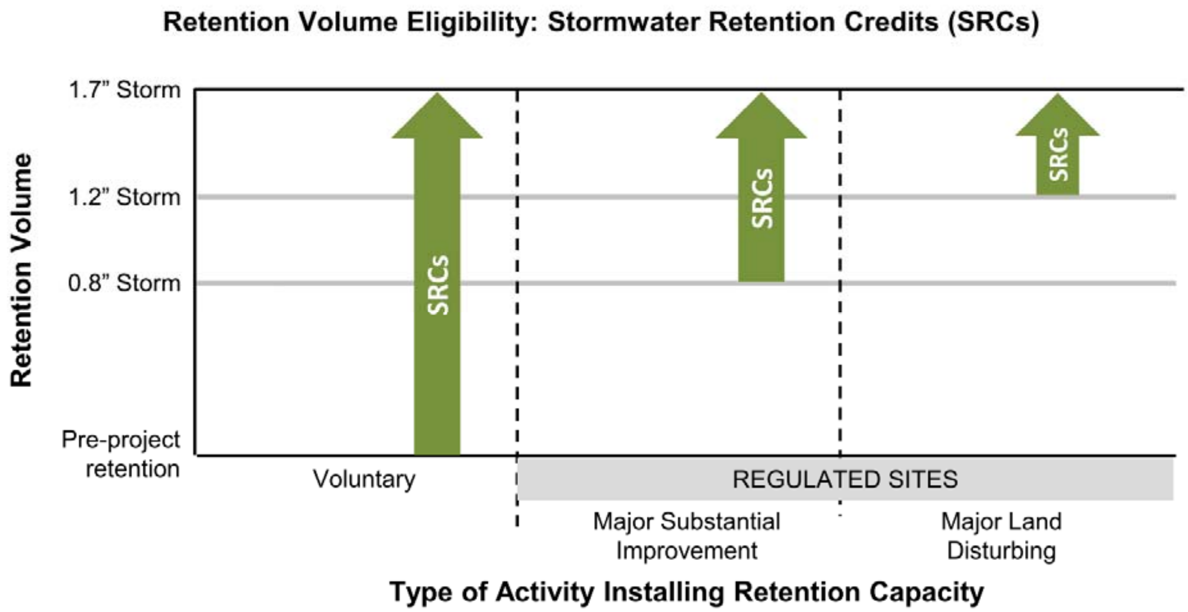

Figure 17.1. Retention volume eligible to earn stormwater retention credits[490]

Based on conversations with DOEE, we assume an SRC price of $1.75 per SRC (a conservative estimate).[491] 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.[492] 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.

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 17.1.1 and 17.1.2 to estimate the stormwater benefits of all trees in this analysis.

17.2 Philadelphia

Like Washington, D.C., and Baltimore, Philadelphia charges property owners a stormwater fee (called the Stormwater Management Service Charge (SWMS)) to help pay for the stormwater burden of impervious surfaces in the city.

8) Two parts to SWMS
    a. Impervious area charge (IAC)
        i. Charged based on impervious area on a property
        ii. Base charge of $4.746 per 500 ft2 of impervious area per month;[493] we hold constant through analysis
    b. Gross area charge (IAC)
        i. Charged based on the total area of a property
        ii. Based charge of $0.59 per 500 ft2 of impervious area per month;[494] we hold constant through analysis

9) Property owners can reduce the SWMS with various credits
    a. Green roofs and trees both provide credits to help reduce SWMS

17.2.1 Green roofs

1) Green roofs get credit for total impervious area managed (IA Managed) and total gross area managed (GA Managed)[495]
    a. Unless other surfaces drain onto the green roof (e.g., adjacent roofs) the green roof area equals IA Managed and GA Managed
        i. For simplicity, we assume green roof area = IA Managed and GA Managed
            1. This is conservative this assumption will result in the lowest SWMS credit all else equal
2) Green roofs receive credit for 80% of IA Managed and GA managed[496]
    a. We calculate SMWS credit from a 10,000 ft2 green roof:
        i. Reduced IAC
            1. Multiply IA Managed (10,000 ft2) by 80%, multiply by the IAC listed above
            2. Multiply the result above by 12 to determine the annual credit
            3. Divide by 10,000 ft2 to determine the credit per ft2
        ii. Reduced GAC
            1. Multiply GA Managed (10,000 ft2) by 80%, multiply by the GAC listed above
            2. Multiply the result above by 12 to determine the annual credit
            3. Divide by 10,000 ft2 to determine the credit per ft2
        iii. Sum the result to get the total credit per ft2 of green roof

17.2.2 Urban trees

1) Urban trees qualify for a 100 ft2 impervious area reduction[497]
    a. This 100 ft2 is the IA Managed and the GA Managed
2) We perform the virtually the same calculations above to calculate SWMS credit provided by urban trees
    a. One difference is divide by assumed urban tree canopy area of 314 ft2 (i.e., the circular area of a tree with radius of 10 ft)[clx]

17.2.3 Additional stormwater benefit

We do not think the SWMS credits provided by Philadelphia fully capture the stormwater benefit of green roofs or urban trees. We think the combined value shown through fee discounts and SRC revenue in Washington, D.C., is approximately right, but perhaps a little aggressive. To more fully capture the stormwater benefits of green roofs and urban trees, we assign 50% of the SRC value for each technology in Washington, D.C., to the respective technology in Philadelphia. We think the combined value of fee discounts and half the SRC value calculated in D.C., is more accurate than just valuing the stormwater benefits of green roofs and urban trees using fee discounts.

[clx] *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.)*

17.3 El Paso

17.3.1 Green roofs

Basis is ref 498

Equation 17.3. Green roof stormwater runoff reduction for El Paso[498]

$$Runoff\ reduction\ (gal) = [annual\ preciptation\ (in) \times green\ roof\ area\ (SF) \times \%\ retained] \times 144\frac{in^2}{SF} \times 0.00433\frac{\text{gal}}{\text{in}^3}$$

- Use 60% retention rate
- Annual precipitation in El Paso = 9.71 inches[499]

Multiply result from

Equation 17.3 by stormwater fee per gallon in El Paso

- Monthly stormwater fee = $3.63 per 2K SF impervious surface[500]
- Convert to per gal using
- Equation 17.3 above and multiply by 12 to get annual → $0.004/gal
    - Use 100% retained and area = 2K SF

17.3.2 Urban trees

Use tree rainfall interception data from ref [501] (see Table 17.3)

Table 17.3. Annual rainfall interception in gallons from 1 tree, 40-yr average, interior west region

TREE	SMALL TREE: GOLDENRAIN TREE	MEDIUM TREE: HONEYLOCUST	LARGE TREE: WHITE ASH
Crown spread (ft)	20	26	29
Canopy area (SF)[clxi]	314	531	661
Avg Annual rainfall interception (gal)	281	573	1245
(gal/SF)[clxii]	0.89	1.08	1.88

- Assume 1/3 of each tree type → gal/SF = 1.29
- Multiply by stormwater value calculated above

[clxi] *Assumes circular crown. This is our calculation.*
[clxii] *Avg annual rainfall interception divided by crown spread. This is our calculation.*

18 APPENDIX: ESTIMATING HEALTH IMPACT

18.1 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 18.1 shows a typical log-linear health impact function.[502,clxiii] Economic valuation functions place a dollar value on estimated health incidence. Equation 18.2 shows a typical economic valuation function.

Equation 18.1. 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 18.2. 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.

18.1.1 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.[clxiv] 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 science.[clxv] Nevertheless, choosing to use EPA's default configuration will introduce some uncertainties

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[clxiii] 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.
[clxiv] We downloaded the ozone and PM2.5 setup on May 15, 2014.
[clxv] One alternative is to substitute DC-specific C-R functions where available.

because the concentration-response functions[clxvi] used in EPA's default setups were developed with national, regional, or city-specific data and characteristics that do not necessarily represent D.C. 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 18.3. We include references to $PM_{2.5}$ in this section (18.1) 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 18.1 shows what we do and do not quantify in this analysis and 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.[503] 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.[clxvii][clxviii] 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))[504]. We follow standard practice for health benefit analysis and do not place a dollar value on individual lives. We 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).[505] We follow EPA recommendations and apply a VSL based on 26 value-of-life studies recommended by the EPA Science Advisory Board.[506] The VSL will increase as personal income increases because the willingness to pay to reduce premature mortality risk increases as personal income increases.[507] See Table 18.1 and Table 18.2 for details on economic valuation of health endpoints in addition to premature mortality.

[clxvi] *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 ( ) of a health impact function is derived from a published concentration-response function.*

[clxvii] *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.*

[clxviii] *Bell et al. (2005) for ozone-related all-cause mortality and Krewski et al. (2009) for PM2.5-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; discussion 115–36.)*

Figure 18.1. What health benefits we do and don't quantify in our analysis[clxix] (Source: EPA (2008))[508]

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.

[clxix] *Note, we do not quantify visibility benefits for $PM_{2.5}$.*

Table 18.1. Ozone- and PM2.5-related health endpoints and studies included

ENDPOINT	POLLUTANT	STUDY	STUDY POPULATION
Premature Mortality			
All cause	Ozone	Bell et al., 2005[509]	All ages
All cause	PM2.5	Krewski et al., 2009[510]	>= 30 years
Chronic Illness			
Nonfatal acute myocardial infarction	PM2.5	Peters et al., 2001[511]	>= 18 years
Hospital Admissions			
All respiratory	Ozone	Burnett et al., 2001[512]	0 - 1 year
		Schwartz, 1995[513]	>= 65 years
		Schwartz, 1995[514]	>= 65 years
	PM2.5	Kloog et al., 2012[515]	>= 65 years
		Zanobetti et al., 2009[516]	>= 65 years
Chronic lung disease	Ozone	Moolgavkar et al., 1997[517]	>= 65 years
	PM2.5	Moolgavkar, 2000[518]	18 - 64 years
Chronic lung disease (less asthma)	Ozone	Schwartz, 1994[519]	>= 65 years
Pneuemonia	Ozone	Moolgavkar et al., 1997[520]	>= 65 years
		Schwartz, 1994[521]	>= 65 years
		Schwartz, 1994[522]	>= 65 years
Asthma	PM2.5	Babin et al., 2007[523]	0 - 17 years
		Sheppard, 2003[524]	0 - 17 years
All cardiovascular (less Myocardial Infarctions)	PM2.5	Bell et al., 2008[525]	>= 65 years
		Moolgavkar, 2000[526]	18 - 64 years
		Peng et al., 2009[527]	>= 65 years
		Peng et al., 2008[528]	>= 65 years
		Zanobetti et al., 2009[529]	>= 65 years
Asthma-related ER Visits	Ozone	Peel et al., 2005[530]	All ages
		Wilson et al., 2005[531]	All ages
		Wilson et al., 2005[532]	All ages
	PM2.5	Glad et al., 2012[533]	All ages
		Mar et al., 2010[534]	All ages
		Slaughter et al., 2005[535]	All ages
Other			
Acute bronchitis	PM2.5	Dockery et al., 1996[536]	8 - 12 years
Upper respiratory symptoms	PM2.5	Pope et al., 1991[537]	9 - 11 years
Lower respiratory symptoms	PM2.5	Schwartz and Neas, 2000[538]	7 - 14 years
Asthma exacerbations, Cough	PM2.5	Mar et al., 2004[539]	6 - 18 years

		Ostro et al., 2001[540]	6 - 18 years
Asthma exacerbations, Shortness of Breath	PM2.5	Mar et al., 2004[541]	6 - 18 years
		Ostro et al., 2001[542]	6 - 18 years
Asthma exacerbations, Wheeze	PM2.5	Ostro et al., 2001[543]	6 - 18 years
Work loss days	PM2.5	Ostro, 1987[544]	18 - 64 years
School loss days	Ozone	Chen et al., 2000[545]	5 - 17 years
		Gilliland et al., 2001[546]	5 - 17 years
Minor Restricted Activity Days (MRADs)	Ozone	Ostro and Rothschild, 1989[547]	18 - 64 years
	PM2.5	Ostro and Rothschild, 1989[548]	18 - 64 years

Table 18.1.2 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[549]	N/A	N/A	N/A	VSL, based on 26 value-of-life studies	None
Hospital Admissions, Respiratory	Burnett et al. 2001[550]	N/A	N/A	N/A	COI: med costs + wage loss	None
Emergency Room Visits, Respiratory	Wilson et al., 2005[551]	None	None	Random or Fixed Effects	COI:Smith et al. (1997);[552] COI: Stanford et al. (1999)[553]	User Defined Weights (0.5 and 0.5)
	Wilson et al., 2005[554]					
	Peel et al., 2005[555]					
School Loss Days	Chen et al., 2000[556]	None	None	Random or Fixed Effects	Use the only School Loss Days valuation function available in BenMAP-CE	None
	Gilliland et al., 2001[557]					
Acute Respiratory Symptoms	Ostro and Rothschild, 1989[558]	N/A	N/A	N/A	WTP: 1 day, CV studies	None
Hospital Admissions, Respiratory	Schwartz, 1994[559]	None	Sum Dependent	Random or Fixed Effects	COI: med costs + wage loss	None
	Schwartz, 1994[560]					
	Moolgavkar et al. 1997[561]	Sum Dependent	Fixed Effects			
	Moolgavkar et al. 1997[562]					
	Schwartz 1994[563]	None				
	Schwartz, 1995[564]	None	None			
	Schwartz, 1995[565]					

Table 18.1.3 PM2.5 pooling and valuation

HEALTH ENDPOINT	STUDY	INCIDENCE POOLING METHOD		VALUATION METHOD	VALUATION POOLING METHOD	
		Level 1	Level 2		Level 1	Level 2
Mortality, All Cause	Krewski et al. 2009[566]	N/A	N/A	VSL, based 26 value-of-life studies	N/A	N/A
Hospital Admissions, Respiratory	Zanobetti et al. 2009[567]	User Defined Weights	None	COI: med costs + wage loss	None	None
	Kloog et al. 2012[568]					
	Babin et al. 2007[569]	Random or Fixed Effects	None	COI: med costs + wage loss	None	None
	Sheppard 2003[570]					
	Moolgavkar 2000[571]	None	None	COI: med costs + wage loss	None	None
Hospital Admissions, Cardiovascular	Peng et al. 2009[572]	User Defined Weights	User Defined Weights	COI: med costs + wage loss	None	None
	Peng et al. 2008[573]					
	Zanobetti et al. 2009[574]	None				
	Bell et al. 2008[575]	None				
	Moolgavkar 2000[576]	None	None	COI: med costs + wage loss	None	None
Acute Respiratory Symptoms	Ostro and Rothschild 1989[577]	N/A	N/A	WTP: 1 day, CV studies	N/A	N/A
Lower Respiratory Symptoms	Schwartz and Neas 2000[578]	N/A	N/A	WTP: 1 day, CV studies	N/A	N/A
Upper Respiratory Symptoms	Pope et al. 1991[579]	N/A	N/A	WTP: 1 day, CV studies	N/A	N/A
Work Loss Days	Ostro 1987[580]	N/A	N/A	Median daily wage, county specific	N/A	N/A
Asthma Exacerbation	Mar et al. 2004[581]	Random or Fixed Effects	User Defined Weights	WTP: bad asthma day, Rowe and Chestnut (1986)[582]	None	None
	Ostro et al. 2001[583]					
	Mar et al. 2004[584]	Random or Fixed Effects				
	Ostro et al. 2001[585]					
	Ostro et al. 2001[586]	None				
Emergency Room Visits, Respiratory	Glad et al. 2012[587]	Random or Fixed Effects	None	COI: Smith et al. (1997);[588] COI: Stanford et al. (1999)[589]	User Defined Weights (0.5 and 0.5)	None
	Mar et al. 2010[590]					
	Slaughter et al. 2005[591]					
Acute Bronchitis	Dockery et al. 1996[592]	N/A	N/A	WTP: 6 day illness, CV studies	N/A	N/A
Acute	Peters[593] 18-24	Sum	None	Not valued	Not	Not valued

Myocardial Infarction (Sum)[clxx]	Peters[594] 25-44	Dependent			valued	
	Peters[595] 45-54					
	Peters[596] 55-64					
	Peters 65-99					
Acute Myocardial Infarction (3%)	Peters[597] 18-24	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[598] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[599]	User Defined Weights (0.5 and 0.5)	Sum Dependent
	Peters[600] 25-44	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[601] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[602]	User Defined Weights (0.5 and 0.5)	
	Peters[603] 45-54	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[604] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[605]	User Defined Weights (0.5 and 0.5)	
	Peters[606] 55-64	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[607] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[608]	User Defined Weights (0.5 and 0.5)	
	Peters[609] 65-99	None	None	COI: 5 yrs med, 5yrs wages, 3% DR, Russell (1998);[610] COI: 5 yrs med, 5yrs wages, 3% DR, Wittels (1990)[611]	User Defined Weights (0.5 and 0.5)	
Acute Myocardial Infarction (7%	Peters[612] 18-24	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[613] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[614]	User Defined Weights (0.5 and 0.5)	Sum Dependent
	Peters[615] 25-44	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[616] COI: 5 yrs med, 5yrs	User Defined Weights (0.5 and 0.5)	

[clxx] 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".

			wages, 7% DR, Wittels (1990)[617]	
Peters[618] 45-54	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[619] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[620]	User Defined Weights (0.5 and 0.5)
Peters[621] 55-64	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[622] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[623]	User Defined Weights (0.5 and 0.5)
Peters[624] 65-99	None	None	COI: 5 yrs med, 5yrs wages, 7% DR, Russell (1998);[625] COI: 5 yrs med, 5yrs wages, 7% DR, Wittels (1990)[626]	User Defined Weights (0.5 and 0.5)

18.1.2 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 the analysis of Washington, D.C., we utilize city- and Ward-specific incidence and prevalence data wherever available. For the analyses of Philadelphia and El Paso, we use the national average incidence and prevalence data included in BenMAP-CE.

The majority of the health data required to run a D.C.-specific health benefit analysis is not freely accessible online and must be requested from the D.C. 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.[clxxi] 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.

18.1.3 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 18.1) is used in health impact functions to calculate changes in various health endpoint incidences.

[clxxi] *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.*

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.[627],[clxxii] 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.[clxxiii] Next, we calculated the three-year mean 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). 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 18.2 shows the baseline air quality concentrations used for this analysis for D.C.

Table 18.2. Baseline ozone

OZONE D8HRMAX (PPB)
Mean Summer Season
51.5

18.2 Ozone reduction

18.2.1 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.[628] 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.[629] Even though there are many studies that *model*

[clxxii] 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.

[clxxiii] 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 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).

the effect of temperature changes on ozone concentration, we use OCPs from Bloomer et al. (2009),[630] who determine OCP based on over two decades of *observational data*.[clxxiv]

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[clxxv] (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. 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.[clxxvi] 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 18.2 reflects these simplifications.

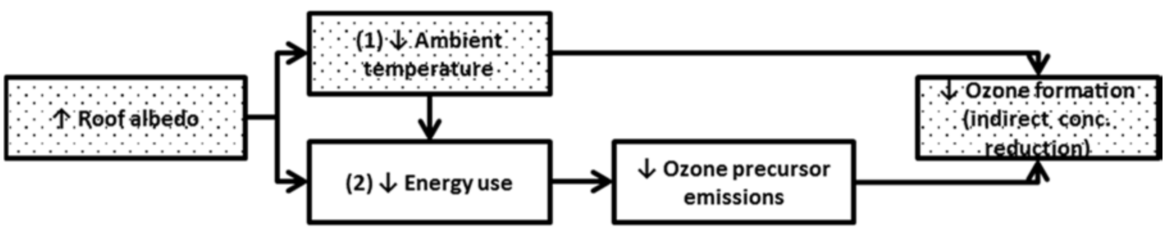

Figure 18.2. Cool roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

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)[631]. Nevertheless, we estimate the impact of ambient cooling on ozone concentrations in Washington, D.C., Philadelphia, and El Paso 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.

[clxxiv] 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.)
[clxxv] Volatile organic compounds (VOCs) and nitrogen oxides (NO_X).
[clxxvi] 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.)

18.2.2 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.

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).[632] 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[clxxvii] 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.[clxxviii] Based on these simplifications, we can our ozone benefits calculations even further. Figure 18.3 reflects these simplifications.

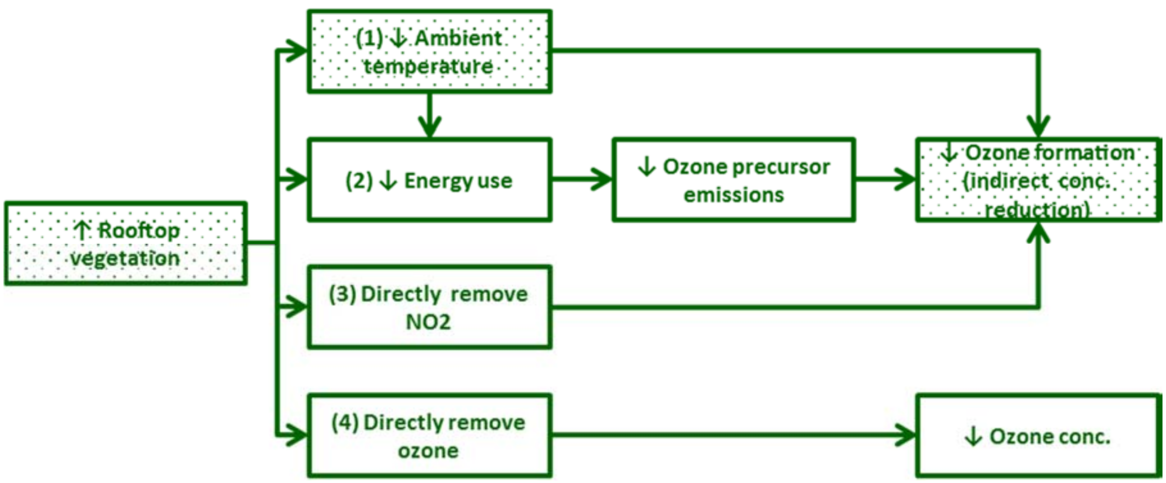

Figure 18.3. Green roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

18.2.2.1 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

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[clxxvii] 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.)

[clxxviii] 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.

States have used i-Tree to estimate the pollution removal benefits of urban forests.[633] In addition, two projects have used UFORE to estimate the pollution removal benefits of green roofs.[634] We utilize the 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, [635] 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.[clxxix] We use Equation 18.3 for scaling pollution removal for different coverage scenarios.

Equation 18.3. 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 [clxxx] 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.[clxxxi] 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.

18.2.3 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 6.4 simplifies out of existence.

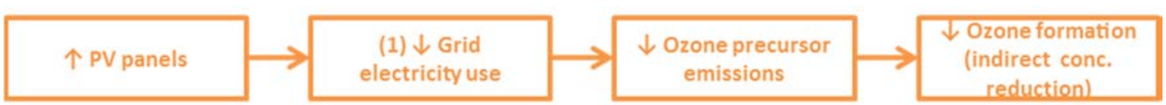

Figure 18.4. Rooftop PV ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

[clxxix] *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.)*

[clxxx] *See the BenMAP section above for more specifics on air quality metrics.*

[clxxxi] *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.)*

18.2.4 Reflective pavements

Using the same rationale as in Sections 18.2.1 and 18.2.2, we simplify our analysis by removing energy-related ozone concentrations reduction pathways. Figure 18.5 reflects these simplifications.

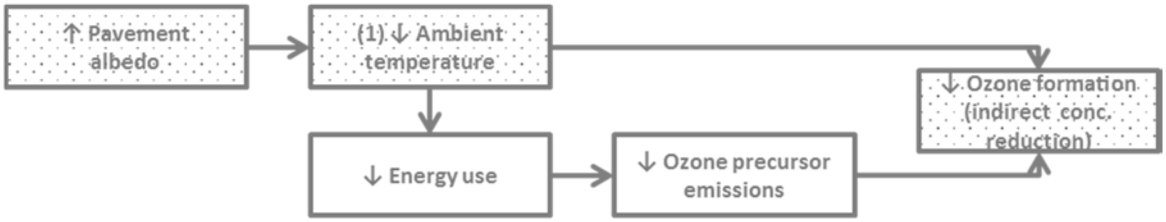

Figure 18.5. Reflective pavement ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

18.2.5 Urban trees

Using the same rationale as in Sections 18.2.1 and 18.2.2, we simplify our analysis by removing energy-related ozone concentrations reduction pathways. However, unlike green roofs, trees provide a significant pollution uptake benefit. We discuss this impact in Section 18.5 below. Figure 18.6 reflects the simplifications for the purposes of our ozone-temperature analysis.

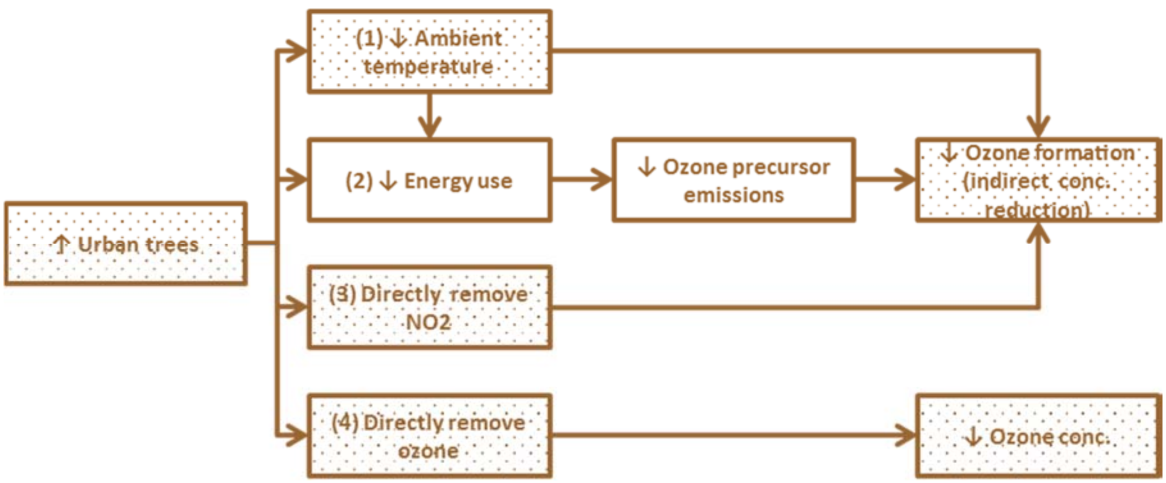

Figure 18.6. Urban tree ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

18.2.6 Ozone reduction calculation process

18.2.6.1 Cool roofs and green roofs

18.2.6.1.1 Washington, D.C.

18.2.6.1.1.1 Determine temperature change

Li et al. (2014)[636] forms the basis for the cool roof and green roof ozone-specific temperature change analysis in Washington, D.C., 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.[clxxxii]

[clxxxii] 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.

We chose Li et al. (2014) for our analysis because it is the most robust analysis of its kind that focuses on the Baltimore-Washington 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)[637] are the only UHI modeling studies that focus on the Washington, D.C., 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 18.7). To utilize this relationship, we plot the data points taken from Figure 18.7 (for data points see Table 18.3 and Table 18.4) and perform a linear regression analysis (Figure 18.8 and Figure 18.9). We perform the linear regression analysis with the y-intercept set to zero for the most realistic fit line.[clxxxiii] 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 18.5).

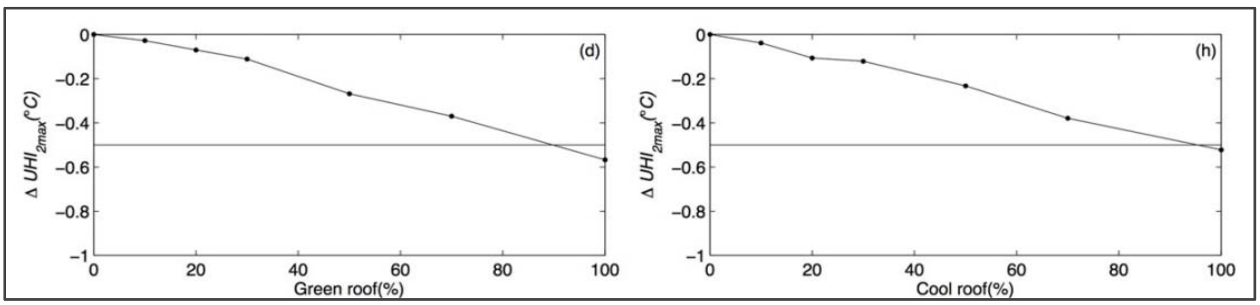

Figure 18.7. Reductions in near-surface urban heat islands from various green roof (right) and cool roof (left) coverage scenarios when the near-surface temperatures reach their maxima[clxxxiv] (Source: Li et al., 2014)

Table 18.3. 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 18.7)

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

clxxxiii 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.
clxxxiv 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.

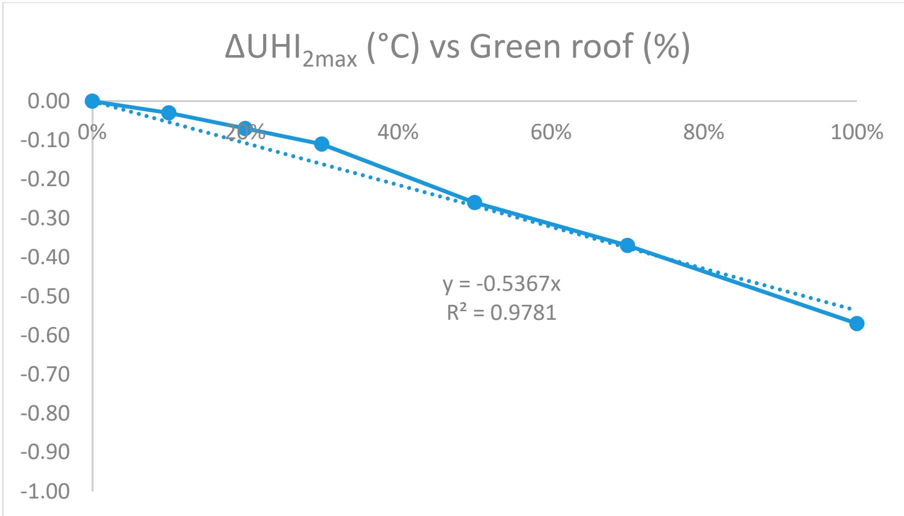

Figure 18.8. Plot of ΔUHI_{2max} (°C) vs Green roof (%) based on data points in Table 18.3

Table 18.4. 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 18.7)

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

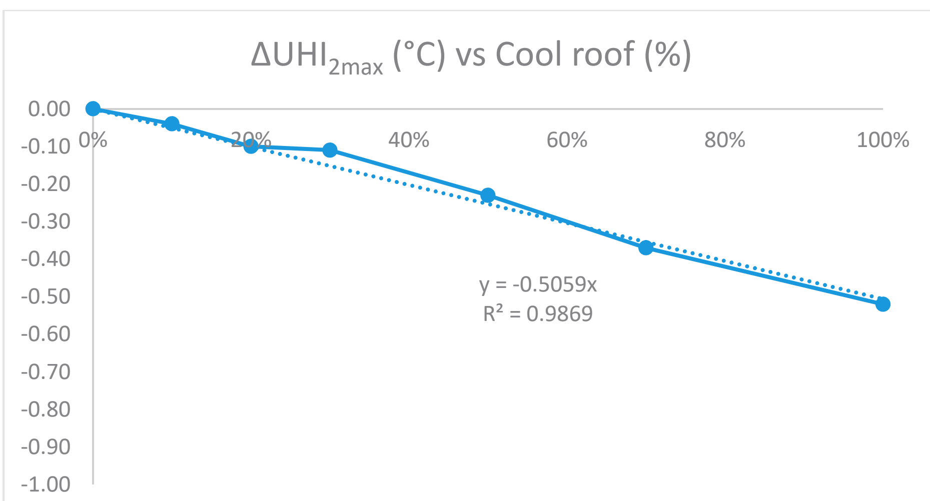

Figure 18.9. Plot of ΔUHI_{2max} (°C) vs Cool roof (%) based on data points in Table 18.4

Table 18.5. ΔUHI2max (°C) per % green roof or cool roof coverage

ROOF TYPE	ΔUHI_{2MAX}/% ROOF TYPE
Green roof	-0.5367
Cool roof	-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 18.6.

For cool roofs, we scale the results based on albedo. Table 18.7 shows the albedo changes used for scaling. We calculate the weighted-average albedo change using

Equation 18.4.[clxxxv] 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 18.10 to determine the cooling impact of cool roof installation.

Table 18.6. Roof properties from Li et al. (2014)

ROOF PROPERTY	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 18.7. Albedo changes for cool roof temperature scaling[clxxxvi]

ALBEDO CHANGES	
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

[clxxxv] *This value is specific to this analysis and will change if the albedo assumptions and roof slope-specific area assumptions change.*

[clxxxvi] *Albedo changes in this analysis increase as technology improves in future years.*

Equation 18.4. 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 18.5. 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 18.6. UHI mitigation potential of green roofs

$$\Delta UHI_{greenroof} = \frac{green\ roof\ area}{roof\ area\ in\ DC} \times \frac{\Delta UHI_{greenroof}}{\%\ greeb\ roofs}$$

We assume that green roofs in this analysis have the same incremental impact as in Li et al. (2014). We use Equation. 18.6 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.[clxxxvii] 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 these 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, D.C., 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, D.C., plans to consider green roofs as a UHI mitigation technology at a large scale, it needs to seriously consider how moisture content is maintained.

18.2.6.1.1.2 Determine ozone concentration change

To estimate the change in ozone concentration when cool roofs or green roofs are installed, we multiply the temperature change calculated using Equation 18.5 or Equation 18.6 by the OCP from Bloomer et al. (2009)[638] (see Equation 18.7). Figure 18.10 shows the regional groupings studied by Bloomer et al. (2009), and Figure 18.11 shows the OCPs for the Mid-Atlantic from Bloomer et al. (2009). We use the post 2002 OCPs in this analysis. (From now on we will use ppb, or "parts per billion", in place of ppbv, "parts per billion by volume".)

[clxxxvii] *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.)*

Equation 18.7. 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

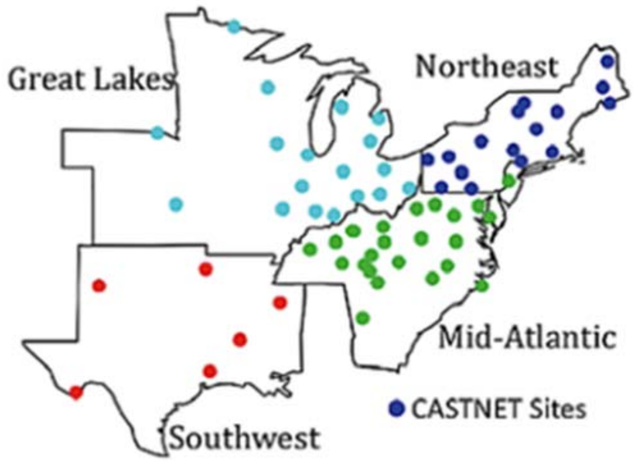

Figure 18.10. Regional groupings in Bloomer et al. (2009).[639]

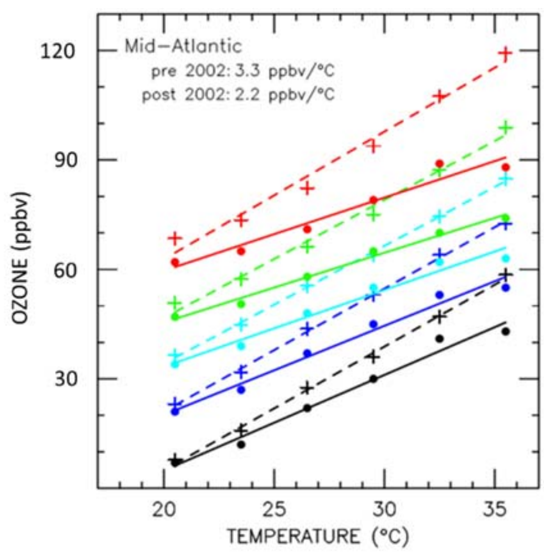

Figure 18.11. Relationship between ozone concentration and temperature in the Mid-Atlantic. Dashed lines and plusses are for the pre 2002 linear fit of ozone as a function of temperature; solid lines and filled circles are for after 2002.[640]

We input the ozone concentration reductions from this analysis into BenMAP (described above) to determine the health incidence impact and value. See Figure 18.12 for a process map of which inputs go where.

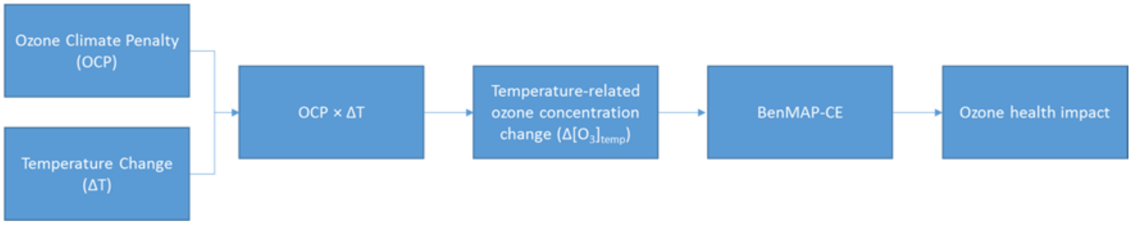

Figure 18.12. Process map for ozone benefits estimation

18.2.6.1.2 Philadelphia

1) Basis is Stone et al. (2014)[641]
    a. S 2014 set out to examine how modifying urban albedo or vegetative cover can offset expected rises in heat-related mortality due to climate change, in the process they estimated temperature reductions
    b. Examine Philly, Atlanta, and Phoenix metropolitan statistical areas (MSA)
    c. Use BenMAP
2) S 2014 looked at effect of changing albedo of all roofs to 0.9
    a. Assume baseline roof albedo of 0.15 → S 2014 measure effect of 0.75 change in albedo
    b. In Philly, we examine effect of 0.15 to 0.65 (change of 0.50) for low slope roofs and the effect of 0.10 to 0.25 (change of 0.15) for steep slope roofs[clxxxviii]
    c. The first scaling factor is factor is 2/3 for low slope roofs and 1/5 for steep slope roofs
3) S 2014 examine an MSA which consists of more people than just city of Philly
    a. Currently, Philly is about 2/3 of population of Philly's MSA
    b. Second scaling factor is 2/3
        i. Use this as way to approximate difference in building footprint
4) Take values from Figure 3 in S 2014 and scale based on above factors (below we finish the analysis for low slope roofs; the process is the same for steep slope roofs)
    a. Value for roofs in S 2014 is temperature reduction of 0.13°C
    b. Scale by scaling factors = 0.058°C

[clxxxviii] *Albedo changes in this analysis increase as technology improves in future years.*

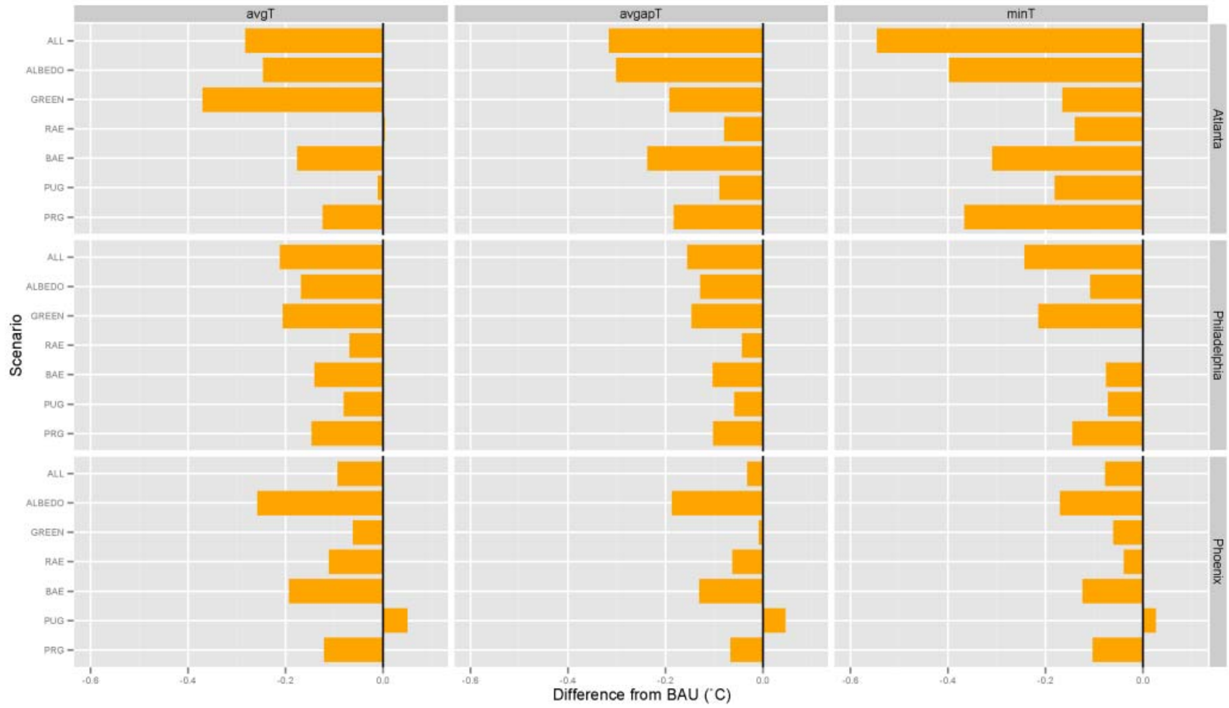

Figure 18.13. Differences in warm season temperature from Business As Usual (BAU); we use the average temperature difference (first column) for the Building Albedo Enhancement (BAE) scenario (Figure 3 from Stone et al. (2014))

5) Divide the above value by the building footprint of Philly to determine the temperature benefit per square foot of roof modified
   a. Building footprint ≈ 700 million ft2[642]
6) Use same OCP as for Washington, D.C.
7) Follow the process in Figure 18.12 to determine the ozone benefit
8) We assume green roofs have the same temperature impact in Philadelphia as low slope cool roofs. This is approximately correct given temperature change discussion on Li et al. (2014) in Section 18.4.

18.2.6.1.3 El Paso

1) Basis is Stone et al. (2014)[643]
   a. Did not find any studies modeling temperature impacts in El Paso
   b. Use Phoenix as proxy for El Paso given similar climates (i.e., desert)
2) Repeat 2) from section above
   a. The first scaling factor is factor is 2/3 for low slope roofs and 1/5 for steep slope roofs
3) S 2014 examine an MSA which consists of more people than just city
   a. Phoenix MSA is approximately 4.2 million people and Phoenix is about 1.5 million; El Paso is population of about 650,000.
   b. (1.5 million / 4.2 million) * (0.65 million / 1.5 million) = 0.155 scale factor
      i. Use as way to approximate difference in building footprint
4) Take values from Figure 3 in S 2014 (Figure 18.13 in this analysis) and scale based on above factors (below we finish the analysis for low slope roofs; the process is the same for steep slope roofs)
   a. Value for roofs in S 2014 in Phoenix is temperature reduction of 0.19°C
   b. Scale by scaling factors → 0.020°C

5) Divide the above value by the building footprint of El Paso to determine the temperature benefit per square foot of roof modified
   a. Building footprint ≈ 600 million ft2
6) Use OCP from Figure 18.14 = 1.4 ppb/deg C
7) Follow the process in Figure 18.12 to determine the ozone benefit
8) We assume green roofs have the ¼ the temperature impact in El Paso as low slope cool roofs due to reduced moisture availability. This concept is discussed by S 2014 in more detail.

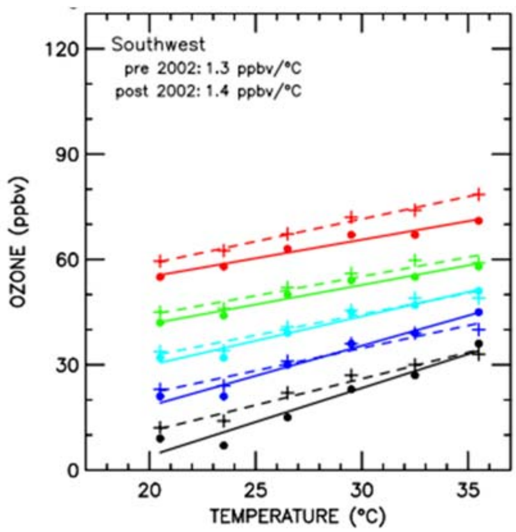

Figure 18.14. Relationship between ozone concentration and temperature in the Southwest. Dashed lines and plusses are for the pre 2002 linear fit of ozone as a function of temperature; solid lines and filled circles are for after 2002.[644]

18.2.6.2 Reflective pavements

18.2.6.2.1 Washington, D.C.

1) Basis for D.C. is Kalkstein et al. (2013);[645]

2) Extract temperature change and city-wide albedo change relationship from K 2013
   a. D.C.: 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
   b. Assume baseline road albedo is 0.15, parking albedo is 0.15, and sidewalk albedo is 0.30
   c. Assumed modified albedo for roads and parking is 0.30 and sidewalks is 0.35[clxxxix]
   d. Albedo change for roads and parking is 0.15 and sidewalks is 0.05
   e. Calculate the change in temperature for each pavement using the equations below

Equation 18.8. Equation used to calculate mortality change from cool roof installation in this analysis

$$\Delta T_{CB} = \Delta T_{KorV} \times \frac{\Delta albedo_{CB}}{\Delta albedo_{KorV}}$$

[clxxxix] *Albedo changes in this analysis increase as technology improves in future years.*

Equation 18.9. Equation used to calculate albedo change from cool roof installation

$$\Delta albedo_{CB} = (albedo_{new} - albedo_{old}) \times \frac{Pavement\ Area}{CityArea}$$

i. D.C.
   1. Road = 14.7% city area[646]
   2. Parking = 7.7% city area[647]
   3. Sidewalk = 5.7% city area[648]

f. Divide the result of Equation 18.9 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 18.12 to determine the ozone benefit

18.2.6.2.2 Philadelphia

1) Basis is Stone et al. (2014)[649]
   a. S 2014 set out to examine how modifying urban albedo or vegetative cover can offset expected rises in heat-related mortality due to climate change, in the process they estimated temperature reductions
   b. Examine Philly, Atlanta, and Phoenix metropolitan statistical areas (MSA)
   c. Use BenMAP
2) S 2014 looked at effect of changing albedo of all pavement to 0.45
   a. Assume baseline pavement albedo of 0.15 → S 2014 measure effect of 0.30 change in albedo
   b. In Philly, we examine effect of 0.15 to 0.30 (change of 0.15) for roads, the effect of 0.15 to 0.30 (change of 0.15) for parking, and the effect of 0.30 to 0.35 (0.05) for sidewalks[cxc]
   c. The first scaling factor is 1/2 for roads and parking and 1/6 for sidewalks
3) S 2014 examine an MSA which consists of more people than just city of Philly
   a. Currently, Philly is about 2/3 of population of Philly's MSA
   b. Second scaling factor is 2/3
4) Take values from Figure 3 in S 2014 and scale based on above factors (below we finish the analysis for roads; the process is the same for parking and sidewalks)
   a. Value for roads in S 2014 is temperature reduction of 0.06°C
   b. Scale by scaling factors = 0.02°C

[cxc] *Albedo changes in this analysis increase as technology improves in future years.*

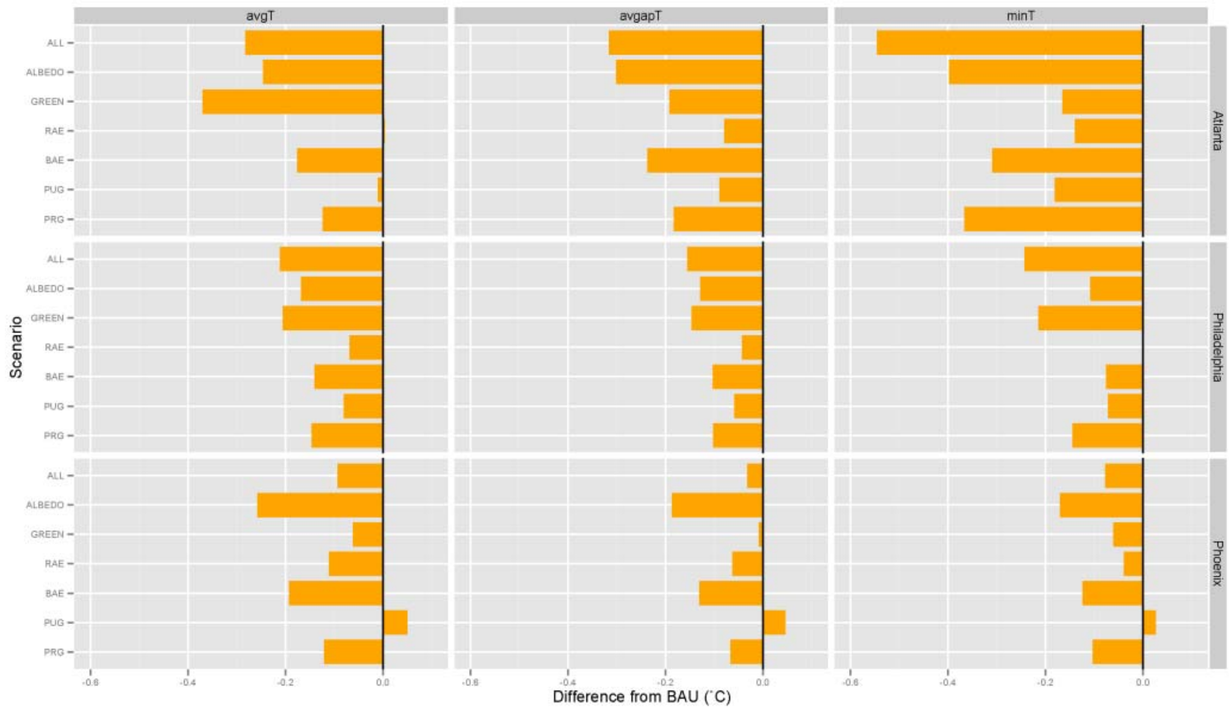

Figure 18.15. Differences in warm season temperature from Business As Usual (BAU); we use the average temperature difference (first column) for the Road Albedo Enhancement (RAE) scenario (Figure 3 from Stone et al. (2014))

5) Divide the above value by the building footprint of Philly to determine the temperature benefit per square foot of pavement modified
    a. Pavement area ≈ 1 billion ft2[650]
6) With this value, we follow the process in Figure 18.12 to determine the ozone benefit

18.2.6.2.3 El Paso

1) Basis is Stone et al. (2014)[651]
    a. Did not find any studies modeling temperature impacts in El Paso
    b. Use Phoenix as proxy for El Paso given similar climates (i.e., desert)
2) Repeat 2) from section above
    a. The first scaling factor is 1/2 for roads and parking and 1/6 for sidewalks
3) S 2014 examine an MSA which consists of more people than just city
    a. Phoenix MSA is approximately 4.2 million people and Phoenix is about 1.5 million; El Paso is population of about 650,000.
    b. (1.5 million / 4.2 million) * (0.65 million / 1.5 million) = 0.155 scale factor
        i. Use as way to approximate difference in pavement area
4) Take values from Figure 3 in S 2014 (Figure 18.13 in this analysis) and scale based on above factors (below we finish the analysis for roads; the process is the same for parking and sidewalks)
    a. Value for roofs in S 2014 in Phoenix is temperature reduction of 0.12°C
    b. Scale by scaling factors → 0.009°C
5) Divide the above value by the building footprint of El Paso to determine the temperature benefit per square foot of roof modified
    a. Building footprint ≈ 960 million ft2
6) Use OCP from Figure 18.14 = 1.4 ppb/deg C
7) Follow the process in Figure 18.12 to determine the ozone benefit

18.2.6.3 *Urban trees*

18.2.6.3.1 D.C. and Philly

1) Basis is Sailor (2003)[652]
   a. Sailor (2003) estimated impact on temperature of albedo increases and vegetation increases
   b. Examined D.C. and Philly, among other cities
   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. D.C.: 0.18°F
   b. Philly: 0.27°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. D.C.: 10% area in Sailor (2003) = 2.3 billion square feet
   b. Philly: 10% area in Sailor (2003) = 2.2 billion square feet
4) With this value, we follow the process in Figure 18.12 to determine the ozone benefit

18.2.6.3.2 El Paso

We use Stone et al. (2014)[653] as the basis of our urban tree temperature calculations for El Paso.

1) We scale the results of S (2014) by 0.155 to account for the difference in population between Phoenix MSA and El Paso
2) S (2014) also analyze more than just trees in their greening scenario (they examine increases in grass and shrub coverage)
   a. We scale their results by an additional 2/3 to account for this
      i. We give more weight to trees because they evapotranspire more than grass and shrubs
3) S (2014) does not specify a specific increase in urban tree canopy
   a. For simplicity we assume tree canopy increases from 0.03% (based on values from i-Tree Landscape) to 50%; a difference of 49.97% or 7.2 billion[cxci] square feet
4) We scale the temperature reduction values from the "GREEN" scenario in Figure 3 of S (2014) (see Figure 18.15 above) using the above factors, and divide by the total tree canopy increase to estimate the temperature impact per square foot for urban trees in El Paso

18.3 PM2.5 reduction

18.3.1 Cool roofs

$PM_{2.5}$ concentration reductions due to cool roof installation are from decreases in energy use (see Figure 18.16). We do not estimate the $PM_{2.5}$ concentration reduction or mass reduction that results from cool 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).[654]

[cxci] *49.97% multiplied by Phoenix land area in i-Tree Landscape (331,486.3 acres)*

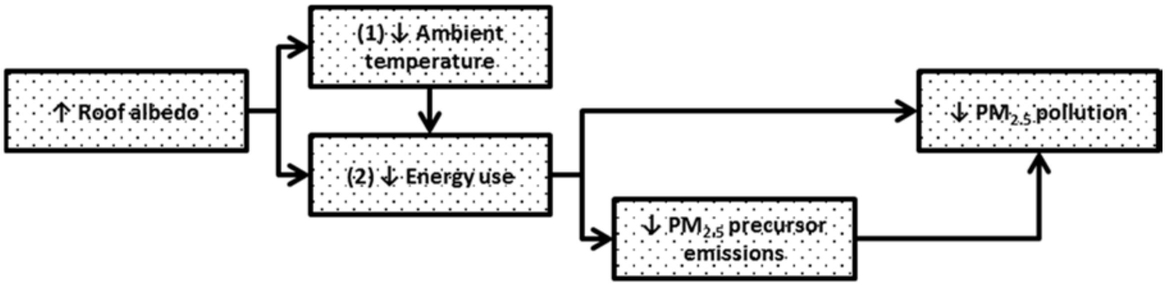

Figure 18.16. Cool roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

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 $PM_{2.5}$.[cxcii] For more details on the calculation process we use, please see Section 18.3.6.

18.3.2 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.[cxciii] Figure 18.17 reflects these simplifications.

[cxcii] *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.)*

[cxciii] *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.)*

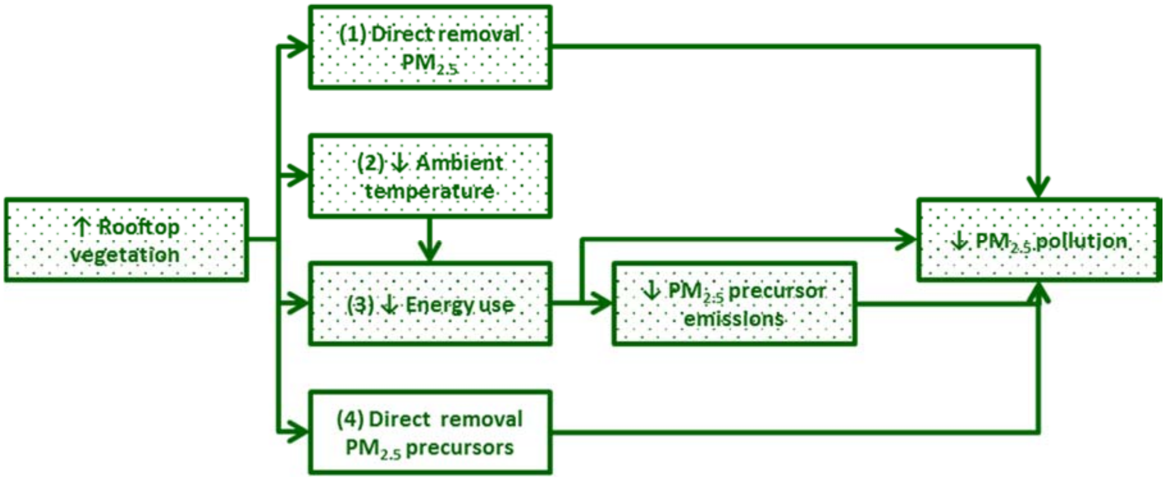

Figure 18.17. Green roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

We estimate the health impact of energy-related $PM_{2.5}$ reductions from green roof (pathways (2) and (3) in Figure 5.6) 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 18.2.2. 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 18.3.6 for the calculation process.

18.3.3 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 18.3.6 for the calculation process.

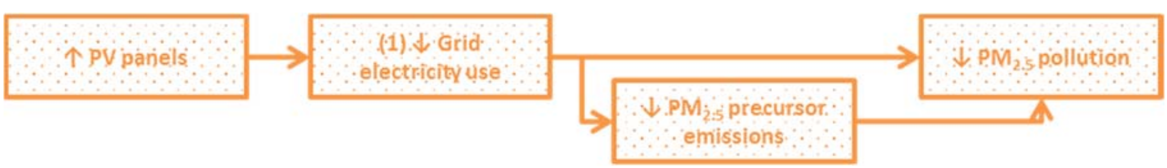

Figure 18.18. Rooftop PV $PM_{2.5}$ concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

18.3.4 Reflective pavements

$PM_{2.5}$ concentration reductions due to reflective pavement installation are from decreases in energy use (see Figure 18.19). 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 18.3.6 for the calculation process.

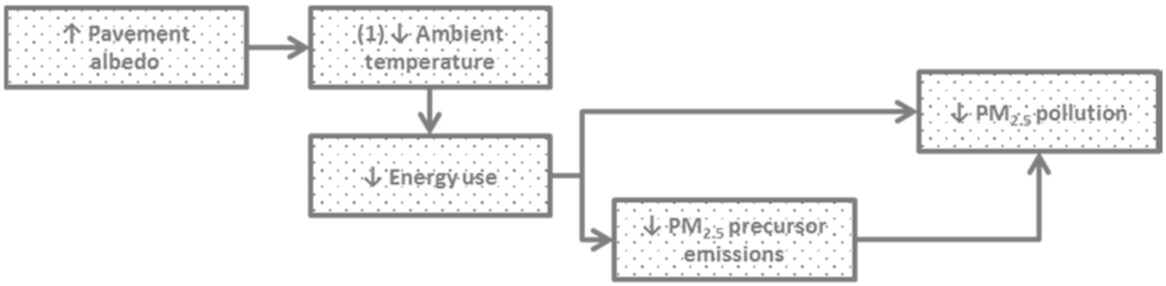

Figure 18.19. Reflective pavement $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

18.3.5 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 18.3.6 for the calculation process and Section 18.5 for discussion of pollution uptake by trees (i.e., pathways (1) and (4) in Figure 18.20).

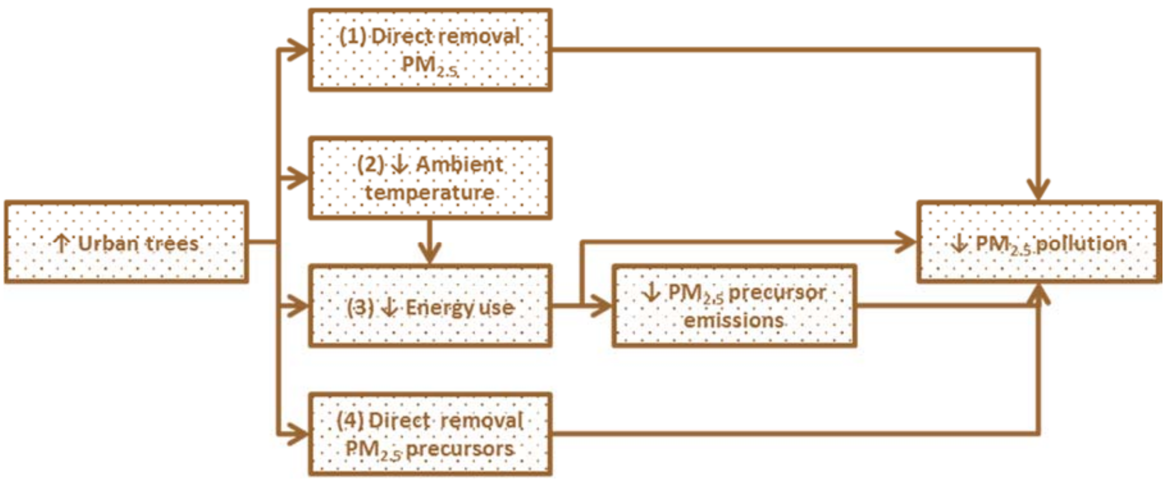

Figure 18.20. Urban tree $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease; shaded boxes indicate pathways included in cost-benefit results)

18.3.6 $PM_{2.5}$ 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 18.10).

See Figure 18.21 for a process map of which inputs go where.

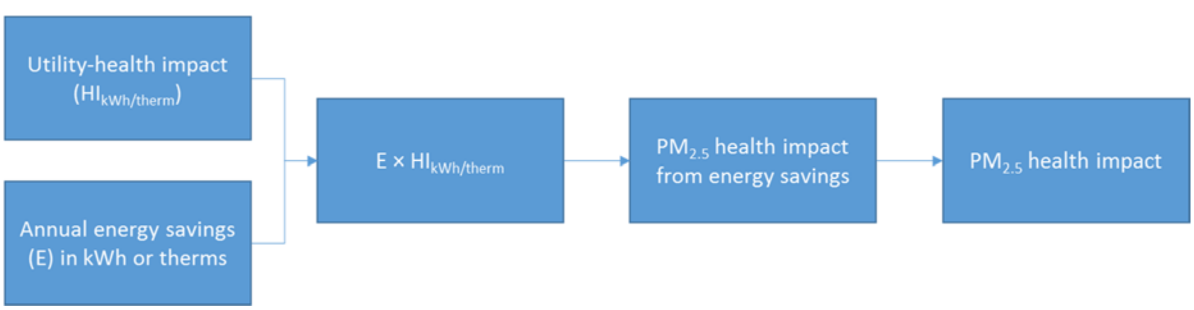

Figure 18.21. Process map for $PM_{2.5}$ benefits estimation

We use 2015 data from Pepco[655] to determine the fuel mix for Washington, D.C., (see Table 18.8) in order to calculate a utility-specific health impact value for energy reductions in Washington, D.C. We asked PECO to provide us with similar fuel mix numbers and were told PECO does not track fuel mix because they are a distribution company, not a generation company. The fuel mix for Pepco is a modified version of the PJM fuel mix to account for slightly different purchasing by each utility,[656] so we use unmodified PJM fuel mix values for $PM_{2.5}$ benefits in Philadelphia.[657]

Table 18.9 shows the fractions of coal, oil, and natural gas in the PECO fuel mix. We use 2015 data from El Paso Electric to determine the fuel mix in El Paso (see Table 18.10).[658] Results for El Paso do not include emissions from the purchased electricity, and so are likely conservative.

We then multiply the fuel mix percentage of each fuel by the low benefit-per-kWh estimates calculated by Machol and Rizk (2013) (Table 18.11).[cxciv] 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.[cxcv] We use Equation 18.10 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 18.10 using the carbon intensity index discussed in more detail in Section 16. 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.

Table 18.8. Pepco fuel mix used for Washington, D.C., $PM_{2.5}$ health benefits calculations

ENERGY SOURCE	PERCENT OF PEPCO FUEL MIX[cxcvi]
Coal	39.4%
Gas	21.0%
Nuclear	34.9%
Oil	0.3%
Unspecified fossil	0.0%
Renewables	4.4%

[cxciv] We use the low estimate of $PM_{2.5}$ benefit per kilowatt hour estimates because our intent is to be conservative.
[cxcv] 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.)
[cxcvi] Numbers may not sum to 100% due to rounding.

Table 18.9. Fuel mix used for Philadelphia $PM_{2.5}$ health benefits calculations

ENERGY SOURCE	PERCENT OF PJM FUEL MIX[cxcvii]
Coal	43.5%
Gas	17.5%
Nuclear	34.7%
Oil	0.3%
Unspecified fossil	0.0%
Renewables	4.0%

Table 18.10. El Paso Electric fuel mix used for El Paso $PM_{2.5}$ health benefits calculations

ENERGY SOURCE	PERCENT OF PJM FUEL MIX[cxcviii]
Coal	6%
Gas	34%
Nuclear	47%
Renewables	>1%
Purchased power	13%

Table 18.11. $PM_{2.5}$ health impact per kWh (Source: Machol and Rizk, 2013)

GENERATION TYPE	LOW ($/KWH)
Coal	$0.19
Oil	$0.08
Natural gas	$0.01

Equation 18.10. 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)

[cxcvii] Numbers may not sum to 100% due to rounding.
[cxcviii] Numbers may not sum to 100% due to rounding.

18.3.6.1 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 18.22) and we discuss which apply to our analysis below.

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 18.22. 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, D.C., it is hard to tell the direction of the impact without doing extensive comparison between national and Washington, D.C.-specific population characteristics.[cxcix]

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 18.3.1).

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),

[cxcix] One reason for this is that different age groups are affected by $PM_{2.5}$ differently.

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.

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).

18.4 Heat-related mortality

18.4.1 Cool roofs and green roofs

18.4.1.1 Washington, D.C.

Kalkstein et al. (2013)[659] forms the basis for our estimation of heat-related mortality in Washington, D.C. There are three parts to our methods for estimating heat-related mortality: (1) estimating the number of heat-related mortalities in Washington, D.C.; (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.

18.4.1.1.1 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)[cc] 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 18.23 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.[cci] 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, D.C., from 2004 through 2013.[660]

[cc] *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."*

[cci] *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 18.23. 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 18.24 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, D.C., 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, D.C., (see Table 18.12).

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 18.24. Mortality responses in different cities when DT and MT+ air masses are present (from Kalkstein et al. (2013)

Table 18.12. Average number of heat-related mortalities associated with DT and MT+ air masses in typical Washington, D.C., warm season

AIR MASS TYPE	DT	MT+	COMBINED
Heat-related mortalities	9	10.71	19.71

18.4.1.1.2 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, D.C., 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, D.C.

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, D.C., is 0.15 and that low slope 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 18.11.[ccii] Once we know the change in average city albedo, we can use Equation 18.12 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, D.C., 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, D.C., (19.71; from Table 18.12); the result is -0.95 heat-related mortalities. We assume green roofs have the same mortality impact as cool roofs.

Kalkstein et al. (2013) consider population at the city-scale. Therefore, we scale the city-wide heat-related mortality impact estimates by the ratio of Ward 5 population to city-wide population in order to better approximate the heat-related mortality impact in Ward 5.

Equation 18.11. 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 18.12. 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)

[ccii] *One can also use a similar equation to estimate the impact of reflective pavements on average city albedo.*

18.4.1.1.3 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).[661] 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.

18.4.1.1.4 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).[662]

18.4.1.2 Philadelphia

1) Basis for heat-related mortality estimation is Stone et al. (2014)[663]
    a. S 2014 set out to examine how modifying urban albedo or vegetative cover can offset expected rises in heat-related mortality due to climate change
    b. Examine Philly, Atlanta, and Phoenix metropolitan statistical areas (MSA)
    c. Use BenMAP
2) S 2014 looked at effect of changing albedo of all roofs to 0.9
    a. Assume baseline roof albedo of 0.15 → S 2014 measure effect of 0.75 change in albedo
    b. In Philly, we examine effect of 0.15 to 0.65 (change of 0.50) for low slope roofs and the effect of 0.10 to 0.25 (change of 0.15) for steep slope roofs[cciii]
    c. The first scaling factor is factor is 2/3 for low slope roofs and 1/5 for steep slope roofs
3) S 2014 examine an MSA which consists of more people than just city of Philly
    a. Currently, Philly is about 2/3 of population of Philly's MSA
    b. Second scaling factor is 2/3
4) Take values from Figure 4 in S 2014 and scale based on above (below calculations are for low slope cool roofs; we use the same process for steep slope cool roofs
    a. Two estimates for Philly in Figure 4: 17 and 20
        i. Take average = 18.5 deaths per year
    b. Scale by scaling factors = 8.22 deaths per year

cciii Albedo changes in this analysis increase as technology improves in future years.

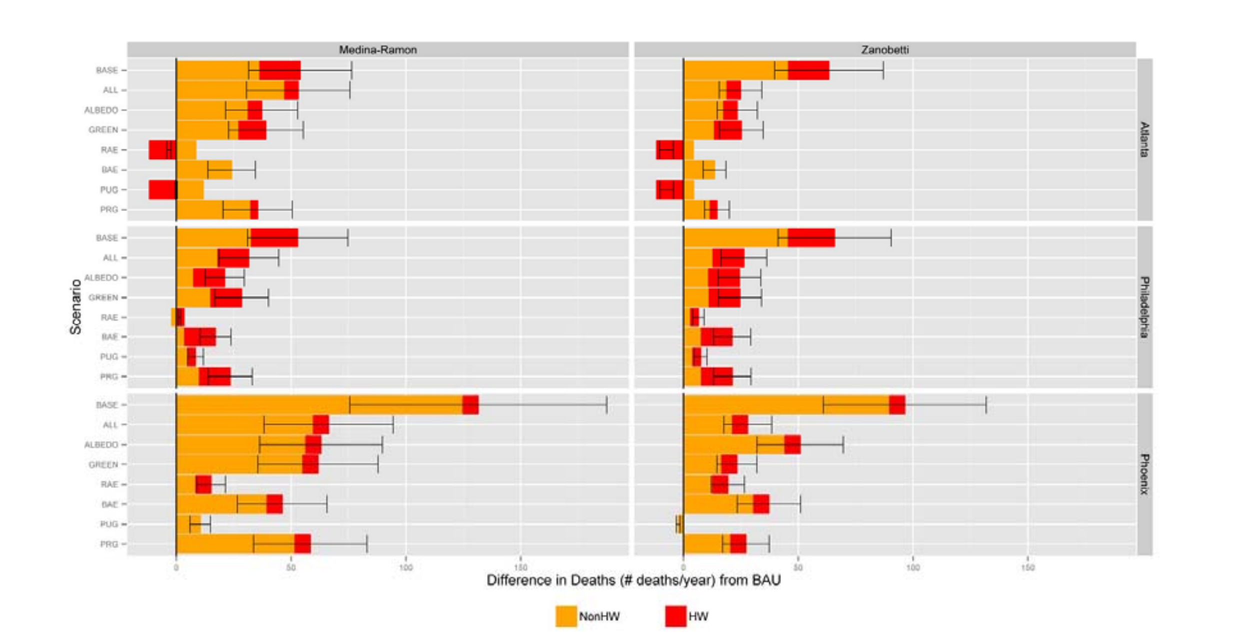

Figure 18.25. Difference in mortality relative to Business As Usual (BAU) by heat management scenario; we use the average mortality difference for the Building Albedo Enhancement (BAE) scenario (Figure 4 from Stone et al. (2014))

5) Value heat-related mortality reduction
    a. Use same VSL from D.C. analysis ($7.4 million)
6) Divide by roof area in Philly
7) As with the Washington, D.C., heat-related mortality analysis for cool roofs and green roofs, we assume green roofs have the same impact as low slope cool roofs
8) Similar to the Washington, D.C., analysis, we scale the city-wide heat-related mortality impact estimates by the ratio of North Philadelphia population to city-wide population in order to better approximate the heat-related mortality impact in North Philadelphia.
9) Potential limitations
    a. Controls for ozone → not limitation as is for Washington, D.C., analysis
    b. Stone et al. (2014) only estimate heat-related mortality related to changes in ambient outdoor temperature, so results don't reflect complete impact of cool or green roof on indoor temperature → results conservative
    c. Accounts for future population growth → not limitation as is for Washington, D.C., analysis
    d. Accounts for extreme heat events and higher average temperatures → not limitation as is for Washington, D.C., analysis

18.4.1.3 El Paso

1) Basis for heat-related mortality estimation is Stone et al. (2014)[664]
    a. Did not find any studies modeling temperature impacts in El Paso
    b. Use Phoenix as proxy for El Paso given similar climates (i.e., desert)
2) Repeat 2) from above
    a. The first scaling factor is 2/3 for low slope roofs and 1/5 for steep slope roofs
3) S 2014 examine an MSA which consists of more people than just city
    a. Phoenix MSA is approximately 4.2 million people and Phoenix is about 1.5 million; El Paso is population of about 650,000.
    b. (1.5 million / 4.2 million) * (0.65 million / 1.5 million) = 0.155 scale factor
        i. Use as way to approximate difference in building footprint

4) Take values from Figure 4 in S 2014 (see Figure 18.25 above) and scale based on above (below calculations are for low slope cool roofs; we use the same process for steep slope cool roofs)
    a. Two estimates for Phoenix in Figure 4: 43 and 38
        i. Take average = 40.5 deaths per year
    b. Scale by scaling factors = 4.2 deaths per year
5) Value heat-related mortality reduction
    a. Use same VSL from D.C. analysis ($7.4 million)
6) Divide by roof area in El Paso
7) As with the El Paso ozone analysis for cool roofs and green roofs, we assume green roofs have ¼ the impact of low slope cool roofs
8) Similar to the Washington, D.C., analysis, we scale the city-wide heat-related mortality impact estimates by the ratio of the El Paso low-income region population to city-wide population in order to better approximate the heat-related mortality impact in the El Paso low-income region.
9) Potential limitations: see above

18.4.2 Reflective pavements

18.4.2.1 Washington, D.C.

We use the same process described in Section 18.4.1 to determine the heat-related mortality impacts of reflective pavements in Washington, D.C. The main differences are the albedo changes for pavements are lower and the area of pavements is generally larger than that of roofs.

18.4.2.2 Philadelphia

To determine the heat-related mortality impact of reflective pavements in Philadelphia we use a combination of methods described in Sections 18.2.6.1.2 (Philadelphia reflective pavement ozone reductions) and 18.4.1.2 (Philadelphia cool and green roof heat-related mortality benefit).

1) Basis is Stone et al. (2014)[665]
    a. S 2014 set out to examine how modifying urban albedo or vegetative cover can offset expected rises in heat-related mortality due to climate change, in the process they estimated temperature reductions
    b. Examine Philly, Atlanta, and Phoenix metropolitan statistical areas (MSA)
    c. Use BenMAP
2) S 2014 looked at effect of changing albedo of all pavement to 0.45
    a. Assume baseline pavement albedo of 0.15 → S 2014 measure effect of 0.30 change in albedo
    b. In Philly, we examine effect of 0.15 to 0.30 (change of 0.15) for roads, the effect of 0.15 to 0.30 (change of 0.15) for parking, and the effect of 0.30 to 0.35 (0.05) for sidewalks[cciv]
    c. The first scaling factor is 1/2 for roads and parking and 1/6 for sidewalks
3) S 2014 examine an MSA which consists of more people than just city of Philly
    a. Currently, Philly is about 2/3 of population of Philly's MSA
    b. Second scaling factor is 2/3
4) Take values from Figure 4 in S 2014 (see Figure 18.25 above) and scale based on above (below calculations are for roads; we use the same process for parking and sidewalks)
    a. Two estimates for Philly in Figure 4: 6.25 and 12.5
        i. Take average = 9.4 deaths per year
    b. Scale by scaling factors = 3.1 deaths per year
5) Value heat-related mortality reduction

[cciv] *Albedo changes in this analysis increase as technology improves in future years.*

a. Use same VSL from D.C. analysis ($7.4 million)
6) Divide by road area in Philly
7) As before, we scale the city-wide heat-related mortality impact estimates by the ratio of North Philadelphia population to city-wide population in order to better approximate the heat-related mortality impact in North Philadelphia.
8) Potential limitations: see similar discussion in Section 18.4.1

18.4.2.3 El Paso

To determine the heat-related mortality impact of reflective pavements in El Paso we use a combination of methods described in El Paso reflective pavement ozone reductions and El Paso cool and green roof heat-related mortality benefit.

1) Basis is Stone et al. (2014)[666]
   a. Did not find any studies modeling temperature impacts in El Paso
   b. Use Phoenix as proxy for El Paso given similar climates (i.e., desert)
2) Repeat set 2) above
   a. The first scaling factor is 1/2 for roads and parking and 1/6 for sidewalks
3) S 2014 examine an MSA which consists of more people than just city
   a. Phoenix MSA is approximately 4.2 million people and Phoenix is about 1.5 million; El Paso is population of about 650,000.
   b. (1.5 million / 4.2 million) * (0.65 million / 1.5 million) = 0.155 scale factor
      i. Use as way to approximate difference in pavement area
4) Take values from Figure 4 in S 2014 (see Figure 18.25 above) and scale based on above (below calculations are for roads; we use the same process for parking and sidewalks)
   a. Two estimates for Philly in Figure 4: 18 and 18
      i. Take average = 16.5 deaths per year
   b. Scale by scaling factors = 0.85 deaths per year
5) Value heat-related mortality reduction
   a. Use same VSL from D.C. and Philly analysis ($7.4 million)
6) Divide by road area in El Paso
7) As before, we scale the city-wide heat-related mortality impact estimates by the ratio of the El Paso low-income region population to city-wide population in order to better approximate the heat-related mortality impact in EL Paso low-income region.
8) Potential limitations: see similar discussion in Section 18.4.1

18.4.3 Urban trees

18.4.3.1 Washington, D.C.

Kalkstein et al. (2013)[667] forms the basis of our urban tree heat-related mortality analysis for Washington, D.C., We use similar methods as described in Section 18.4.1. 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 18.4.1, 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 in Washington, D.C., 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.[ccv] 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). As before, we scale the city-wide heat-related mortality impact estimates by the

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[ccv] *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.*

ratio of Ward 5 population to city-wide population in order to better approximate the heat-related mortality impact in Ward 5.

18.4.3.2 Philadelphia

We use Stone et al. (2014)[668] as the basis of our urban tree heat-related mortality calculations for Philadelphia.

1) We scale the results of S (2014) by 2/3 to account for the difference in population between Philly and the Philly MSA (see Sections 18.2.6.1.2 and 18.4.1.2 for rationale).
2) S (2014) also analyze more than just trees in their greening scenario (they examine increases in grass and shrub coverage)
    a. We scale their results by an additional 2/3 to account for this
        i. We give more weight to trees because they evapotranspire more than grass and shrubs
3) S (2014) does not specify a specific increase in urban tree canopy
    a. For simplicity we assume tree canopy increases from 13.2% (based on values from i-Tree Landscape) to 50%; a difference of 36.8% or 1.4 billion[ccvi,] square feet
4) We scale the average mortality reduction values from the "GREEN" scenario in Figure 4 of S (2014) (see Figure 18.25 above) using the above factors, divide by the total tree canopy increase, and multiply by the VSL to estimate the heat-related mortality impact per square foot for urban trees in Philadelphia

5) As before, we scale the city-wide heat-related mortality impact estimates by the ratio of North Philadelphia population to city-wide population in order to better approximate the heat-related mortality impact in North Philadelphia.

18.4.3.3 El Paso

We use Stone et al. (2014)[669] as the basis of our urban tree heat-related mortality calculations for El Paso.

5) We scale the results of S (2014) by 0.155 to account for the difference in population between Phoenix MSA and El Paso
6) S (2014) also analyze more than just trees in their greening scenario (they examine increases in grass and shrub coverage)
    a. We scale their results by an additional 2/3 to account for this
        i. We give more weight to trees because they evapotranspire more than grass and shrubs
7) S (2014) does not specify a specific increase in urban tree canopy
    a. For simplicity we assume tree canopy increases from 0.03% (based on values from i-Tree Landscape) to 50%; a difference of 49.97% or 7.2 billion[ccvii] square feet
8) We scale the average mortality reduction values from the "GREEN" scenario in Figure 4 of S (2014) (see Figure 18.25 above) using the above factors, divide by the total tree canopy increase, and multiply by the VSL to estimate the heat-related mortality impact per square foot for urban trees in El Paso
9) As before, we scale the city-wide heat-related mortality impact estimates by the ratio of the El Paso low-income region population to city-wide population in order to better approximate the heat-related mortality impact in El Paso low-income region.

[ccvi] *36.8% multiplied by Philadelphia land area (134.1 square miles)*
[ccvii] *49.97% multiplied by Phoenix land area in i-Tree Landscape (331,486.3 acres)*

18.5 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)[670]
        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 $PM_{2.5\text{-}10}$.
2) Sample calculation for Washington, D.C.
    a. Select Washington, D.C., 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

Table 18.13. Pollution uptake value in Washington, D.C.

POLLUTANT	$/YR FOR ENTIRE CANOPY	$/YR/FT2 TREE CANOPY
CO	$17,864	$0.00005
NO2	$56,699	$0.00014
O3	$1,856,026	$0.00469
PM2.5	$4,179,627	$0.01057
SO2	$8,090	$0.00002
PM10	$304,804	$0.00077
SUM	$6,423,110	$0.01624

3) Repeat for Philadelphia and El Paso

Table 18.14. Pollution uptake value in Philadelphia

POLLUTANT	$/YR FOR ENTIRE CANOPY	$/YR/FT2 TREE CANOPY
CO	$6,915	$0.00001
NO2	$134,815	$0.00026
O3	$4,043,938	$0.00794
PM2.5	$7,003,144	$0.01376
SO2	$13,532	$0.00003
PM10	$516,333	$0.00101
SUM	$11,718,677	$0.02302

Table 18.15. Pollution uptake value in El Paso

POLLUTANT	$/YR FOR ENTIRE CANOPY	$/YR/FT2 TREE CANOPY
CO	$638	$0.00001
NO2	$4,346	$0.00004
O3	$58,340	$0.00051
PM2.5	-$53,036	-$0.00046
SO2	$103	$0.00000
PM10	$104,564	$0.00091
SUM	$114,955	$0.00100

4) i-Tree Landscape bases its health impact estimates on county- or city-level population data.[671] Therefore, for low-income regions we scale the county- or city-wide health estimates by the ratio of low-income region population to county population in order to better approximate the pollution uptake impact in low-income regions

19 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.[672] 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.[ccviii] The D.C. Office of Planning (2009) commissioned a green collar job demand analysis for Washington, D.C., that predicted 169,000 green jobs would be created between 2009 and 2018 from existing and proposed District green policies.[673] 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, D.C., by 2020 and 1400 net jobs by 2030.[674,ccix] Expanding the deployment of smart surfaces, particularly green roofs and solar PV, in D.C., Philadelphia, and El Paso would propel the growth of green jobs in these cities.

For the cities in this report 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 cities studied.

19.1 Job Creation by Technology

19.1.1 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.[675] Table 19.1 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.[676] We do not include a baseline value for steep slope roofs because, as discussed below, cool roofs net employment impacts are negligible.

19.1.2 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.

19.1.3 Green Roofs

Green roofs can be installed at a rate of 53 square feet per hour.[677] 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.

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.[678] 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

[ccviii] *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 workers' 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.*

[ccix] *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.*

(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,[679] compared to 20 years for a conventional roof.[680] From an employment perspective, this reduces the net job creation of green roofs since re-roofing is a labor-intensive process. Table 19.1 summarizes green roof labor requirements.

19.1.4 Solar PV

We use NREL's Jobs and Economic Development Impact (JEDI) model to estimate PV employment impact in this report.[681] 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.

Using the pre-2020 solar PV prices, 1 kW of single-family residential solar PV in Pennsylvania requires about 21 hours of project development and on-site labor. This works out to about 10 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 Pennsylvania.

Using the pre-2020 solar PV prices, 1 kW of commercial or multifamily residential solar PV in Pennsylvania requires about 19 hours of project development and on-site labor. This works out to about 9.1 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 Pennsylvania.

Using the post-2020 solar PV prices, 1 kW of single-family residential solar PV in Pennsylvania requires about 16 hours of project development and on-site labor. This works out to about 7.0 jobs per MW of solar PV installed. For commercial or multifamily residential solar PV, 1 kW requires about 12.3 hours of project development and on-site labor. This works out to about 5.9 jobs per MW of solar PV installed. We assume operations and maintenance job creation remains the same for simplicity.

Using the pre-2020 solar PV prices, 1 kW of single-family residential solar PV in Texas requires about 19 hours of project development and on-site labor. This works out to about 9.3 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 Texas.

Using the pre-2020 solar PV prices, 1 kW of commercial or multifamily residential solar PV in Texas requires about 17 hours of project development and on-site labor. This works out to about 8.1 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 Texas.

Using the post-2020 solar PV prices, 1 kW of single-family residential solar PV in Texas requires about 14 hours of project development and on-site labor. This works out to about 6.7 jobs per MW of solar PV installed. For commercial or multifamily residential solar PV, 1 kW requires about 11 hours of project development and on-site labor. This works out to about 5.4 jobs per MW of solar PV installed. We assume operations and maintenance job creation remains the same for simplicity.

Table 19.1 summarizes solar PV labor requirements per square foot of roof area in the District. 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 14.3 (13.9 and 11.4 W per square foot of roof for steep slope and low slope roofs, respectively).

Table 19.1. Square feet of installation per hour of labor in the District.

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)

19.2 Job creation potential by technology

We calculated the job creation potential of each smart surface technology proposed in this report based on interviews with local employers and available literature. [ccx]The methods and assumptions used for each technology are detailed discussed above in Section 19.1.

We only estimate direct job creation, which means that our figures underestimate the total jobs that smart surface installation could create in the District, Philadelphia, and El Paso.[ccxi] For instance, the National

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[ccx] *We would especially like to thank Paul Lanning for his valuable advice. Paul Lanning is the current Managing Director at Lightbox and worked formerly for Bluefin LLC, a national roof management company with operations in the District of Columbia.*
[ccxi] *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.*

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 19.2) include planning, transportation, and construction. We do not include manufacturing because these jobs would likely occur outside of the cities analyzed. 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 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 19.2, we select a 40-year time horizon and assume that all technologies are installed in year one.

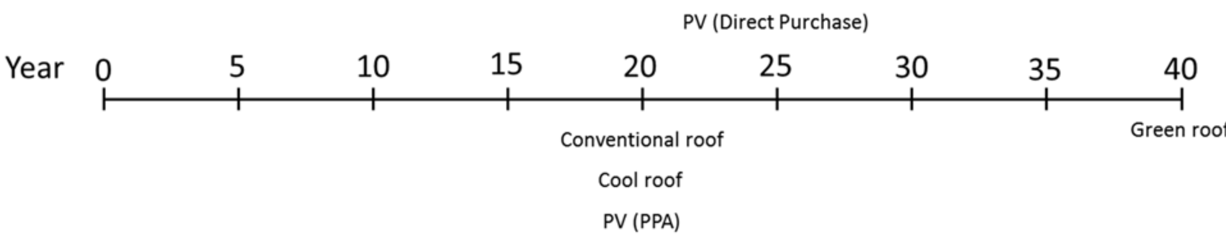

Figure 19.1. Typical lifetime of roof technologies in this analysis

Table 19.2. Labor requirement by technology in the District

TECHNOLOGY	LABOR REQUIREMENT			
	Installation (job-years/ million ft²)		Operation and maintenance (jobs/ million ft²)	
	Total (1 install)	Net[ccxii] (40 years)	Total	Net
Conventional (built-up roof)	1.07	-	-	-
Conventional (modified bitumen)	0.874	(0.389)	-	-
Extensive green roofs	10.3	8.16	1.33	1.33
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

[ccxii] *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.*

19.3 Smart surface job characteristics

The green economy offers jobs across a wide range of skill levels. The D.C. 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.[682] 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.

Installing smart surfaces in D.C., Philadelphia, and El Paso would help provide the unemployed with relatively well-paid work. Expanding smart surface deployment in the cities studied 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.[683] For green roof jobs, 75 percent are taken up by construction, 60 percent of these going to roofers and landscapers.[684] Roofers do not need high school education and earn a median wage of $17.19 per hour in D.C.[685] Smart surface jobs offer individuals without college educations access to living wages.

19.4 Costs and benefits of training

19.4.1 Costs

Jobs training programs typically cost several thousand dollars per student to run. The United Planning Organization's Building Careers Academy in D.C. costs $4000 per participant for a 14-week full-time program,[686] 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.[687] 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.

19.4.2 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[ccxiii] income tax, $3,221 in foregone Federal Insurance Contributions Act (FICA) taxes, $8,530 in foregone federal taxes, and $293 in welfare payments.[688] 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 [ccxi] income taxes, and $44 in welfare payments.[689] We use an average of the values for each age group for benefits calculations. O'Sullivan et al. (2014) also provide numbers for Pennsylvania and Texas.[690] We use these values for estimates in Philadelphia and Texas, respectively, with a minor addition.

[ccxiii] *These can also be thought of as city income taxes.*

Residents in Philadelphia pay federal, state, *and* city income taxes. O'Sullivan et al. (2014) only estimate the lost income from federal and state income taxes. To capture lost city income taxes Philly, we multiply the value of lost state income taxes in PA, respectively, by the ratio of city to state income taxes in each city. In Philadelphia, the city tax rate is 3.98%[691] and the state tax rate is 3.07% (PA has a flat tax).[692]

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 costs, public health expenditures, welfare, and avoided education spending.[693] 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.[694] 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.[695] 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.[696] Thus, workers in their study who were laid off at 40 lost 1-1.5 years of life expectancy, valued at $100,000.[ccxiv] 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.[697]

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.[698] According to the D.C. 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.[699] 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.[ccxv] We expect similar trends in Baltimore and Philadelphia. Were more residents employed in stable jobs with

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[ccxiv] *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.)*

[ccxv] *The District DHS already provides some job training through the TANF and SNAP programs.*

family-supporting wages, jobs the green economy could help create and that training programs could help economically disadvantaged D.C., Philadelphia, an El Paso residents take up fewer of these services would be necessary. Considering these benefits and costs, the case for implementing jobs training programs that successfully place people into employment becomes an easy one to make.

20 APPENDIX: LOW-INCOME REGION SELECTION RATIONALE

20.1 Washington, D.C.: Ward 5

Figure 20.1. Ward map of Washington, D.C., Ward 5 (circled in red) is examined in this analysis (base map from Neighborhood Info D.C.)[700]

We chose Ward 5 because it has a large low-income population and high unemployment rate compared to Washington, D.C., as a whole (see Table 20.1).

Table 20.1. Selected Ward 5 characteristics compared to Washington, D.C.

CHARACTERISTIC	WARD 5	WASHINGTON, D.C.
Population (2014)[701]	80,399	633,736
Income[702]		
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)[703]	10.4	61.05
Building footprint (% region)[704]	14.4%	15.9%
Paved area (roads, parking, sidewalks) (% region)[705]	23.1%	24.1%
Tree canopy (% region)[706]	27.7%	31.2%

20.2 Philadelphia: North Philadelphia

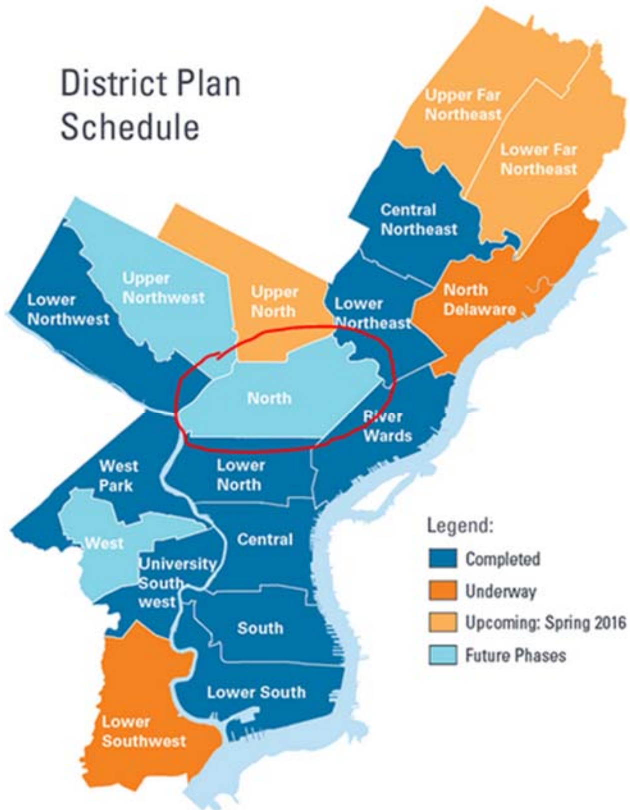

Figure 20.2. Philadelphia planning districts; area circled in red is region selected for analysis (base map from the Philadelphia City Planning Commission)[707]

We chose North Philadelphia for a number of reasons:

1. it has a large low-income population → what we are funded to study
2. based on review of Google Earth satellite images, it does not have as much cool roof coverage as other parts of the city and is not heavily treed → large opportunity for smart surfaces
3. there are multiple neighborhood energy centers operated by ECA → great opportunity for outreach
4. it is served by the combined sewer system → stormwater mitigation important
5. the North Philadelphia District Plan for Philadelphia 2035 has not yet been developed → good timing to support policy and design decisions
6. the North Philadelphia 2035 District approximately aligns with Census tracts → makes data collection and analysis significantly easier; better quality data

Table 20.2. Selected North Philadelphia characteristics compared to Philadelphia

CHARACTERISTIC	NORTH PHILADELPHIA (2035 DISTRICT)	PHILADELPHIA
Population (2014) [708]	142,835	1,546,920
Income[709]		
Median income	$23,115	$37,460
Percent of population below poverty line	45.2%	26.7%
Unemployment rate	24.8%	14.9%
Land use		
Area (square miles)[710]	8.6	134.1
Building footprint (% region)[711]	27.6%	18.7%
Paved area (roads, parking, sidewalks) (% region)[712]	32.9%	26.6%
Tree canopy (% region)[713]	10.1%	20.0%

20.3 El Paso: Region X

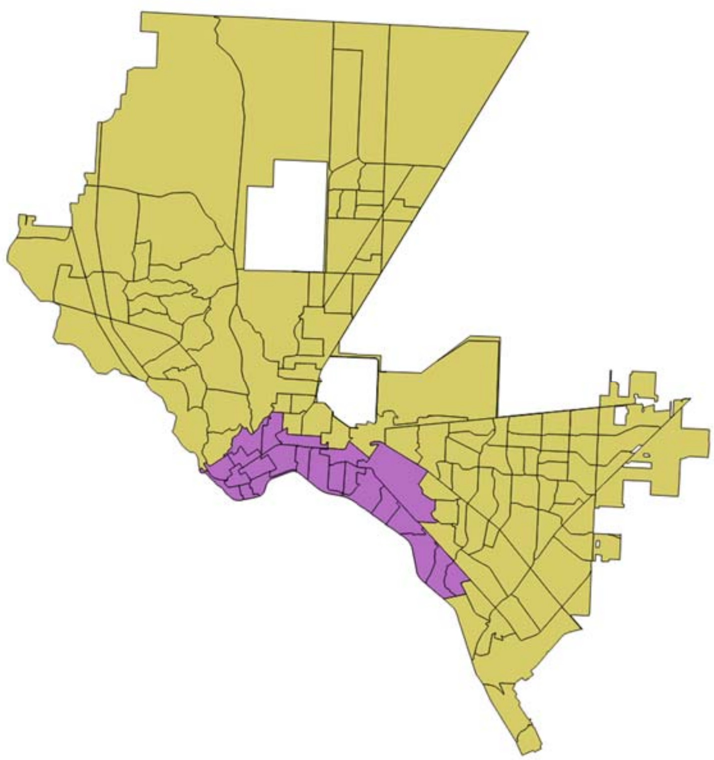

Figure 20.3. El Paso census tracts; purple region is region selected for analysis (base map from Pasa Del Norte Map for Public Access)[714]

Region selection based on discussion with City of El Paso Office of Sustainability and Resilience. Factors considered include: median income, mean income, population, poverty levels, and unemployment.

Table 20.3. Selected Region X El Paso characteristics compared to El Paso

CHARACTERISTIC	EL PASO LOW-INCOME REGION	EL PASO
Population (2014) [715]	76,982	669,771
Income[716]		
Median income	$21,789	$42,037
Percent of population below poverty line	41.5%	21.5%
Unemployment rate	12.7%	8.6%
Land use		
Area (square miles)[717]	19.2	256.3
Building footprint (% region)[718]	14.7%	8.4%
Paved area (roads, parking, sidewalks) (% region)[719, ccxvi]	21.6%	12.3%
Tree canopy (% region)[720]	0.8%	0.8%

[ccxvi] Parking lot data in El Paso is limited, so approximated parking lot area using methods described in the Appendix.

21 APPENDIX: SCENARIO DEVELOPMENT

Surface technology coverage for city-wide and low-income regions by end of analysis period are in Table 21.1.

Table 21.1. Surface coverage in low-income region by end of analysis

SURFACE TECHNOLOGY	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% in D.C. and Philadelphia; 2% in El Paso

21.1 Washington, D.C.

21.1.1 Cool roofs

1) Combine building footprint data[721] and land use data[722] to determine area detached single family, attached single family, multifamily, and "commercial"; conversions below based on D.C. land use codes,[723] personal communication w/ D.C. Government,[724] 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 21.2. Washington, D.C. building class roof areas

BUILDING CLASS	ROOF AREA (FT2)
Detached single-family	52,161,077
Attached single-family	90,924,800
Multifamily	13,657,922
Commercial	99,479,908

Table 21.3. Ward 5 building class roof areas

BUILDIONG CLASS	ROOF AREA (FT2)
Detached single-family	6,772,418
Attached single-family	14,199,448
Multifamily	1,129,957
Commercial	18,252,260

2) Determine roof slope
    a. Single family
        i. Based on slope assumptions used in PV analysis (table replicated below)

Table 21.4. 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 14.3): 81% flat, 19% sloped
c. Commercial
  i. Based on slope assumptions in PV analysis (Section 14.3): 81% flat, 19% sloped

3) Combine steps 1) and 2)

Table 21.5. Washington, D.C. 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

Table 21.6. Ward 5 building type + roof slope areas

BUILDING TYPE + ROOF SLOPE	ROOF AREA (FT2)
Commercial LS	14,784,331
Commercial SS	3,467,929
Residential LS	8,692,231
Residential SS	13,409,592

4) To determine installation rate
  a. Multiply values in
  b. Table 21.6 by corresponding coverage % from Table 21.1 (50% for cool roofs); i.e., we assume 50% of each building type + roof slope is cooled by end of analysis
  c. Divide by 40 to determine annual installation rate

21.1.2 Green roofs

1) To determine installation rate
  a. Green roofs only installed on commercial LS and residential LS
    i. Assume ~2/3 of green roofs on commercial and ~1/3 of green roofs on residential
  b. Divide by 40 to determine annual installation rate

21.1.3 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 District of 1.3 GW,[725] we multiply our maximum capacity estimates by a factor of 1.25. The result is shown in column 2 of Table 21.7.
    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 21.7 by corresponding coverage % from Table 21.1 (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 21.7.
c. We repeat the same process for Ward 5. The result is in Table 21.8.

Table 21.7. Maximum viable and target PV capacity by system type in Washington, D.C.

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

Table 21.8. Maximum viable and target PV capacity by system type in Ward 5

TYPE	MAXIMUM CAPACITY (MW)	TARGET CAPACITY (MW)
Commercial low slope	100	50
Commercial steep slope	33	17
Detached, single family low slope	1.5	0.7
Detached, single family steep slope	13	7
Attached, single family low slope	18	9
Attached, single family steep slope	18	9
Multifamily low slope	1.7	0.9
Multifamily steep slope	0.5	0.3

d. Divide by 40 to determine annual installation rate

21.1.4 Reflective pavements

1) Use pavement area data[726] to different pavement areas
   a. Roads = "Road" + "Intersection" classes in D.C. GIS data
   b. Parking = "Parking Lot" class in D.C. GIS data
   c. Sidewalk = "Sidewalk" in D.C. GIS data

Table 21.9. Washington, D.C. pavement areas

TYPE	AREA (FT2)
Roads	217,636,905
Parking Lot	94,024,811
Sidewalk	99,253,945

Table 21.10. Ward 5 pavement areas

TYPE	AREA (FT2)
Roads	32,012,277
Parking Lot	21,927,511
Sidewalk	12,863,905

2) To determine installation rate
    a. Multiply values in Table 21.10 by corresponding coverage % from Table 21.1 (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

21.1.5 Urban trees

1) To determine planting rate
    a. Add 10% to current tree canopy value in Table 20.1
    b. Divide by 40 to determine annual planting rate

21.2 Philadelphia

21.2.1 Cool roofs

1) Combine building footprint data[727] and land use data[728] to determine area detached single family, attached single family, multifamily, and "commercial"; conversions below based on crosschecking w/ aerial photography
    a. If land use (LU) = low density residential → detached single family building
    b. If LU = medium density residential → attached single family building
    c. If LU = high density residential → multifamily building
    d. If LU = not residential, transportation, water, or vacant → "commercial" building

Table 21.11. Philadelphia building class roof areas

BUILDING CLASS	ROOF AREA (FT2)
Detached single-family	122,499,801
Attached single-family	290,132,277
Multifamily	40,945,599
Commercial	234,160,222

Table 21.12. North Philadelphia building class roof areas

BUILDING CLASS	ROOF AREA (FT2)
Detached single-family	1,640,873
Attached single-family	33,387,689
Multifamily	1,154,476
Commercial	28,157,933

2) Determine roof slope
    a. Single family
        i. Based on slope assumptions used in PV analysis (see
        ii. Table 21.4 of this section)
        iii. Detached: 10% flat, 90% sloped
        iv. Attached: 50% flat, 50% sloped
    b. Multifamily
        i. Based on slope assumptions in PV analysis (Section 14.3): 76% flat, 24% sloped
    c. Commercial
        i. Based on slope assumptions in PV analysis (Section 14.3): 76% flat, 24% sloped
3) Combine steps 1) and 2)

Table 21.13. Philadelphia building type + roof slope areas

BUILDING TYPE + ROOF SLOPE	ROOF AREA (FT2)
Commercial LS	177,961,769
Commercial SS	56,198,453
Residential LS	188,434,774
Residential SS	265,142,903

Table 21.14. North Philadelphia building type + roof slope areas

BUILDING TYPE + ROOF SLOPE	ROOF AREA (FT2)
Commercial LS	21,400,029
Commercial SS	6,757,904
Residential LS	17,735,333
Residential SS	18,447,704

4) To determine installation rate
    a. Multiply values in Table 21.14 by corresponding coverage % from Table 21.1 (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

21.2.2 Green roofs

1) To determine installation rate
    a. Green roofs only installed on commercial LS and residential LS
        i. Assume ~2/3 of green roofs on commercial and ~1/3 of green roofs on residential
    b. Divide by 40 to determine annual installation rate

21.2.3 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 Philadelphia of 4.3 GW,[729] we multiply our maximum capacity estimates by a factor of 1.75. The result is shown in column 2 of Table 21.7.
      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 21.15 by corresponding coverage % from Table 21.1 (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 21.15.
   c. We repeat the same process for North Philadelphia. The result is in
   d. Table 21.16.

Table 21.15. Maximum viable and target PV capacity by system type in Philadelphia

TYPE	MAXIMUM CAPACITY (MW)	TARGET CAPACITY (MW)
Commercial low slope	1,673	836
Commercial steep slope	759	380
Detached, single family low slope	21	11
Detached, single family steep slope	192	96
Attached, single family low slope	765	382
Attached, single family steep slope	765	382
Multifamily low slope	82	41
Multifamily steep slope	35	17

Table 21.16. Maximum viable and target PV capacity by system type in North Philadelphia

TYPE	MAXIMUM CAPACITY (MW)	TARGET CAPACITY (MW)
Commercial low slope	201.2	100.6
Commercial steep slope	91.3	45.6
Detached, single family low slope	1.4	0.7
Detached, single family steep slope	12.7	6.3
Attached, single family low slope	81.2	40.6
Attached, single family steep slope	81.2	40.6
Multifamily low slope	2.3	1.2
Multifamily steep slope	1.0	0.5

   e. Divide by 40 to determine annual installation rate

21.2.4 Reflective pavements

1) Use pavement area data[730] to different pavement areas
   a. Roads = FCODE 1000 or 1200 in Philly GIS data
   b. Parking = FCODE 2200 in Philly GIS data
   c. Sidewalk = FCODE 2210 in Philly GIS data

Table 21.17. Philadelphia pavement area

TYPE	AREA (FT2)
Roads	461,699,293
Parking Lot	339,387,402
Sidewalk	193,113,466

Table 21.18. North Philadelphia pavement area

TYPE	AREA (FT2)
Roads	34,272,854
Parking Lot	24,980,017
Sidewalk	19,518,881

2) To determine installation rate
    a. Multiply values in Table 21.18 by corresponding coverage % from Table 21.1 (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

21.2.5 Urban trees

1) To determine planting rate
    a. Add 10% to current tree canopy value in
    b.
    c. Table 20.2
    d. Divide by 40 to determine annual planting rate

21.3 El Paso

21.3.1 Cool roofs

1) Combine building footprint data[731] and land use data[732] to determine area detached single family, attached single family, multifamily, and "commercial"; conversions below based on zoning descriptions from the City of El Paso and on crosschecking w/ aerial photography
    a. If zoning category (ZC) = light density residential districts or ranch & farm district → detached single family building
    b. If ZC = medium density residential districts,→ attached single family building
    c. If ZC = high density residential districts → multifamily building
    d. If ZC = commercial districts or industrial and manufacturing districts → "commercial" building
    e. If ZC = mixed uses → ½ "commercial," ¼ multifamily, and ¼ single-family attached

Table 21.19. El Paso building class roof areas

BUILDING CLASS	ROOF AREA (FT2)
Detached single-family	402,782,692
Attached single-family	48,242,469
Multifamily	6,358,589
Commercial	144,322,081

Table 21.20. El Paso Region X building class roof areas

BUILDING CLASS	ROOF AREA (FT2)
Detached single-family	30,726,323
Attached single-family	11,793,626
Multifamily	1,626,372
Commercial	34,710,961

2) Determine roof slope
    a. Single family
        i. Based on slope assumptions used in PV analysis (table replicated below)

Table 21.21. 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 14.3): 84% flat, 16% sloped
    c. Commercial
        i. Based on slope assumptions in PV analysis (Section 14.3): 84% flat, 16% sloped
3) Combine steps 1) and 2)

Table 21.22. El Paso building type + roof slope areas

BUILDING TYPE + ROOF SLOPE	ROOF AREA (FT2)
Commercial LS	121,230,548
Commercial SS	23,091,533
Residential LS	69,740,718
Residential SS	387,643,031

Table 21.23. El Paso Region X building type + roof slope areas

BUILDING TYPE + ROOF SLOPE	ROOF AREA (FT2)
Commercial LS	29,157,207
Commercial SS	5,553,754
Residential LS	10,335,598
Residential SS	33,810,723

4) To determine installation rate
   a. Multiply values in
   b. Table 21.6 by corresponding coverage % from Table 21.1 (50% for cool roofs); i.e., we assume 50% of each building type + roof slope is cooled by end of analysis
   c. Divide by 40 to determine annual installation rate

21.3.2 Green roofs

2) To determine installation rate
   a. Green roofs only installed on commercial LS and residential LS
      i. Assume ~2/3 of green roofs on commercial and ~1/3 of green roofs on residential
   b. Divide by 40 to determine annual installation rate

21.3.3 Solar PV

2) To determine installation rate
   a. NREL does not estimate the PV technical potential for El Paso in its recent study, but we assume our methods underestimate the maximum capacity because of future potential increases in PV panel efficiency and increase in canopy (e.g., use of parking canopies and PV overhangs on buildings). We use the same scale factor as for the District for simplicity (1.25). The result is shown in column 2 of Table 21.24.
   b. We multiply the values in column 2 of Table 21.24 by corresponding coverage % from Table 21.1 (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 21.24.
   c. We repeat the same process for the El Paso low-income region. The result is in Table 21.25.

Table 21.24. Maximum viable and target PV capacity by system type in El Paso

TYPE	MAXIMUM CAPACITY (MW)	TARGET CAPACITY (MW)
Commercial low slope	833	416
Commercial steep slope	204	102
Detached, single family low slope	64	32
Detached, single family steep slope	579	289
Attached, single family low slope	14	7
Attached, single family steep slope	14	7
Multifamily low slope	6	3
Multifamily steep slope	2	1

Table 21.25. Maximum viable and target PV capacity by system type in El Paso low-income region

TYPE	MAXIMUM CAPACITY (MW)	TARGET CAPACITY (MW)
Commercial low slope	200.2	100.1
Commercial steep slope	49.0	24.5
Detached, single family low slope	6.1	3.1
Detached, single family steep slope	54.9	27.5
Attached, single family low slope	2.4	1.2
Attached, single family steep slope	2.4	1.2
Multifamily low slope	1.6	0.8
Multifamily steep slope	0.4	0.2

d. Divide by 40 to determine annual installation rate

21.3.4 Reflective pavements

3) Use pavement area data to different pavement areas
    a. Roads = ref [733]
    b. Parking
        i. Parking lot data for El Paso is limited
        ii. Approximated El Paso parking lot area using an average value from the literature (see ref [734])
            1. City
                a. Large area of El Paso is undeveloped, so assume now parking lots in this part of city
                    i. Including this area in calculations would likely lead to an inflated parking lot area, so subtract this area from city and then calculate parking lot area; use 101,889 acres for calc
                        1. Average from ref 734 of 6.4% multiplied by new city area (not including large open space)
                b. When calculated parking lot area is computed as % of city area (include large open space), result is 4%
            2. Low-income region
                a. Use average from ref 734 (6.4%) because low-income region is around downtown El Paso and doesn't have issue of large amounts of open space
    c. Sidewalk = ref [735]

Table 21.26. El Paso pavement areas

TYPE	AREA (FT2)
Roads	492,866,028
Parking Lot	372,808,762
Sidewalk	96,361,894

Table 21.27. El Paso low-income region pavement areas

TYPE	AREA (FT2)
Roads	68,443,376
Parking Lot	34,511,008
Sidewalk	12,905,275

4) To determine installation rate
    a. Multiply values in Table 21.10 by corresponding coverage % from Table 21.1 (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

21.3.5 Urban trees

2) To determine planting rate
    a. Add 2% to current tree canopy value in
    b. Table 20.3
        i. Based on persona communication with El Paso
            1. 1.3% of urbanized area (101,889 acres) is tree cover
            2. Max canopy is 4.4%
        ii. Convert to fraction of entire city
            1. (% X urbanized area) / city area
                a. Current = 0.8%
                b. Max = 2.7%
    c. Divide by 40 to determine annual planting rate

22 APPENDIX: DETAILED RESULTS FOR WASHINGTON, D.C.

22.1 Scenario (NPV)

22.1.1 City-wide impact

Table 22.1 Detailed NPV of city-wide impact in Washington, D.C. (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$33.906M**	**$282.957M**	**$242.487M**	**$499M**	**$43.802M**	**$234.846M**	**$838.495M**
First cost	$24.998M	$194.607M	$163.019M	--	$23.537M	$136.475M	$542.634M
Operations and maintenance	$0	$88.214M	$25.112M	--	--	$77.622M	$190.946M
Additional replacements	$8.909M	--	$54.192M	--	$20.265M	$20.750M	$104.114M
Employment training	$0	$138K	$167K	$499K	--	--	$803M
Benefits	**$281.048M**	**$563.636M**	**$443.693M**	**$450.611M**	**$112.377M**	**$797.038M**	**$2.648,400B**
Energy	$39.987M	$22.103M	$238.953M	$33.202M	$5.014M	$8.352M	$347.608M
Direct energy savings	$30.540M	$19.599M	--	--	--	$3.276M	$53.414M
Indirect (UHI) energy savings	$9.447M	$2.504M	--	--	$5.014M	$5.077M	$22.041M
Electricity value	--	--	$221.329M	$33.202M	--	--	$254.531M
SRECs	--	--	$17.624M	--	--	--	$17.624M
Financial incentives	--	--	$65.604M	--	--	--	$65.604M
Tax Credit	--	--	$14.983M	--	--	--	$14.983M
Depreciation	--	--	$50.622M	--	--	--	$50.622M
Stormwater	--	$478.786M	--	--	--	$694.775M	$1.173,560B
Fee discounts	--	$5.195M	--	--	--	$10.595M	$15.790M
SRC value	--	$473.592M	--	--	--	$684.180M	$1.157.771M
Health	$134.137M	$38.978M	$65.824M	$197.472M	$29.734M	$56.631M	$522.774M
Pollution uptake	--	--	--	--	--	$26.529M	$26.529M
Ozone	$89.385M	$23.720M	--	--	$10.532M	$4.913M	$128.549M
PM2.5	$13.055M	$6.858M	$65.824M	$197.472M	$2.372M	$10.287M	$295.867M
PM2.5 (direct energy savings)	$8.065M	$5.344M	--	--	--	$2.885M	$16.294M
PM2.5 (indirect energy savings)	$4.990M	$1.514M	--	--	$2.372M	$7.403M	$16.278M
PM2.5 (electricity generation)	--	--	$65.824M	$197.472M	--	--	$263.296M
Heat-related mortality	$31.698M	$8.401M	--	--	$16.831M	$14.902M	$71.831M
Climate change	$106.925M	$11.159M	$50.341M	$151.022M	$77.630M	$37.282M	$434.355M
GHG emissions	$218K	$6.308M	$50.341M	$151.022M	$1.519M	$7.645M	$217.051M
GHG emissions (direct energy	-$2.702M	$5.453M	--	--	--	$1.487M	$4.238M

savings)							
GHG emissions (indirect energy savings)	$2.920M	$855M	--	--	$1.519M	$6.158M	$11.452M
GHG emissions (energy generation)	--	--	$50.341M	$151.022M	--	--	$201.362M
Global cooling	$106.707M	$4.852M	--	--	$76.111M	$29.637M	$217.305M
Employment	--	$12.611M	$22.973M	$68.917M	--	--	$104.500M
Employee pay	--	$9.970M	$20.035M	$60.103M	--	--	$90.106M
Welfare payments	--	$32K	$26K	$78K	--	--	$135K
Tax revenue	--	$2.611M	$2.913M	$8.738M	--	--	$14.260M
Federal taxes	--	$2.336M	$2.343M	$7.028M	--	--	$11.705M
State taxes	--	$0	$0	$0	--	--	$0
City taxes	--	$275M	$571M	$1.711M	--	--	$2.555M
NPV	**$247.142M**	**$280.679M**	**$201.206M**	**$450.113M**	**$68.575M**	**$562.193M**	**$1.809,905B**

22.2 NPV per square foot

22.2.1 Cool roofs

Table 22.1. 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**

22.2.2 Green roofs

Table 22.2. 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**

22.2.3 Solar PV

Table 22.3. 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 22.4. 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 22.5. 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 22.6. 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**

22.2.4 Reflective pavements

Table 22.7. 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**

22.2.5 Urban trees

Table 22.8. Costs and benefits per square foot urban tree canopy (albedo and cost held constant)

URBAN TREES	
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**

23 APPENDIX: DETAILED RESULTS FOR PHILADELPHIA

23.1 Scenario (NPV)

Table 23.1. Detailed NPV of city-wide impact in Philadelphia (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$93.527M**	**$698.646M**	**$955.786M**	**$2.156M**	**$118.086M**	**$515.852M**	**$2.384,050B**
First cost	$68.954M	$480.5M	$640.887M	--	$65.720M	$299.776M	$1.555,835B
Operations and maintenance	$0	$217.807M	$102.260M	--	--	$170.500M	$490.566M
Additional replacements	$24.573M	--	$211.922M	--	$52.366M	$45.578M	$334.438M
Employment training	$0	$340M	$719M	$2.156M	--	--	$3.214M
Benefits	**$692.110M**	**$270.707M**	**$1.856,379B**	**$2.089,614B**	**$357.433M**	**$692.420M**	**$5.958,661B**
Energy	$91.878M	$53.741M	$984.150M	$146.931M	$9.440M	$38.727M	$1.324,865B
Direct energy savings	$72.954M	$49.021M	--	--	--	$28.296M	$150.269M
Indirect (UHI) energy savings	$18.925M	$4.720M	--	--	$9.440M	$10.432M	$43.516M
Electricity value	--	--	$979.511M	$146.931M	--	--	$1.126,441B
SRECs	--	--	$4.640M	--	--	--	$4.640M
Financial incentives	--	--	$224.667M	--	--	--	$224.667M
Tax Credit	--	--	$58.412M	--	--	--	$58.412M
Depreciation	--	--	$166.256M	--	--	--	$166.256M
Stormwater	--	$68.140M	--	--	--	$117.264M	$185.403M
Fee discounts	--	$68.140M	--	--	--	$117.264M	$185.403M
SRC value	--	$0	--	--	--	$0	$0
Health	$328.686M	$91.455M	$316.476M	$949.428M	$155.841M	$443.217M	$2.285,100B
Pollution uptake	--	--	--	--	--	$82.732M	$82.732M
Ozone	$24.908M	$6.183M	--	--	$11.706M	$50.719M	$93.514M
PM2.5	$30.237M	$17.332M	$316.476M	$949.428M	$5.196M	$31.716M	$1.350,383B
PM2.5 (direct energy savings)	$18.629M	$13.997M	--	--	--	$13.506M	$46.131M
PM2.5 (indirect energy savings)	$11.608M	$3.336M	--	--	$5.196M	$18.211M	$38.349M
PM2.5 (electricity generation)	--	--	$316.476M	$949.428M	--	--	$1.265,904B
Heat-related mortality	$273.542M	$67.940M	--	--	$138.940M	$278.051M	$758.473M
Climate change	$271.547M	$26.984M	$220.886M	$662.657M	$192.154M	$93.213M	$1.467,438B
GHG emissions	-$10.884M	$15.006M	$220.886M	$662.657M	$1.860M	$28.114M	$917.637M
GHG emissions (direct energy savings)	-$14.865M	$13.869M	--	--	--	$15.445M	$14.448M
GHG emissions (indirect energy	$3.981M	$1.138M	--	--	$1.860M	$12.669M	$19.648M

savings)							
GHG emissions (energy generation)	--	--	$220.886M	$662.657M	--	--	$883.542M
Global cooling	$282.431M	$11.979M	--	--	$190.294M	$65.099M	$549.802M
Employment	--	$30.390M	$110.201M	$330.601M	--	--	$471.190M
Employee pay	--	$24.616M	$96.808M	$290.423M	--	--	$411.845M
Welfare payments	--	$78K	$96K	$288K	--	--	$461M
Tax revenue	--	$5.698M	$13.297M	$39.891M	--	--	$58.885M
Federal taxes	--	$4.658M	$9.212M	$27.635M	--	--	$41.505M
State taxes	--	$466K	$1.785M	$5.354M	--	--	$7.605M
City taxes	--	$574K	$2.301M	$6.902M	--	--	$9.777M
NPV	**$598.584M**	**-$427.938M**	**$900.593M**	**$2.087,459B**	**$239.348M**	**$176.568M**	**$3.574,611B**

Table 23.2. Detailed NPV of city-wide impact in Philadelphia (with ½ SRC value) (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$93.527M**	**$698.646M**	**$955.786M**	**$2.156M**	**$118.086M**	**$515.852M**	**$2.384,050B**
First cost	$68.954M	$480.500M	$640.887M	--	$65.720M	$299.776M	$1.555,835B
Operations and maintenance	$0	$217.807M	$102.260M	--	--	$170.500M	$490.566M
Additional replacements	$24.573M	--	$211.922M	--	$52.366M	$45.578M	$334.438M
Employment training	$0	$340K	$719K	$2.156M	--	--	$3.214M
Benefits	**$692.110M**	**$787.237M**	**$1.856,379B**	**$2.089,614B**	**$357,433B**	**$1.326,577B**	**$7.109,348B**
Energy	$91.878M	$53.741M	$984.150M	$146.931M	$9.440M	$38.727M	$1.324,865B
Direct energy savings	$72.954M	$49.021M	--	--	--	$28.296M	$150.269M
Indirect (UHI) energy savings	$18.925M	$4.720M	--	--	$9.440M	$10.432M	$43.516M
Electricity value	--	--	$979.511M	$146.931M	--	--	$1.126,441B
SRECs	--	--	$4.640M	--	--	--	$4.640M
Financial incentives	--	--	$224.667M	--	--	--	$224.667M
Tax credit	--	--	$58.412M	--	--	--	$58.412M
Depreciation	--	--	$166.256M	--	--	--	$166.256M
Stormwater	--	$584.669M	--	--	--	$751.421M	$1.336,090B
Fee discounts	--	$0	--	--	--	$0	$0
SRC value	--	$584.669M	--	--	--	$751.421M	$1.336,090B
Health	$328.686M	$91.455M	$316.476M	$949.428M	$155.841M	$443.217M	$2.285,100B
Pollution uptake	--	--	--	--	--	$82.732M	$82.732M
Ozone	$24.908M	$6.183M	--	--	$11.706M	$50.719M	$93.514M
PM2.5	$30.237M	$17.332M	$316.476M	$949.428M	$5.196M	$31.716M	$1.350,383B
PM2.5 (direct energy savings)	$18.629M	$13.997M	--	--	--	$13.506M	$46.131M
PM2.5 (indirect energy savings)	$11.608M	$3.336M	--	--	$5.196M	$18.211M	$38.349M
PM2.5 (electricity generation)	--	--	$316.476M	$949.428M	--	--	$1.265,904B
Heat-related mortality	$273.542M	$67.940M	--	--	$138.940M	$278.051M	$758.473M
Climate change	$271.547M	$26.984M	$220.886M	$662.657M	$192.154M	$93.213M	$1.467,438B
GHG emissions	-$10.884M	$15.006M	$220.886M	$662.657M	$1.860M	$28.114M	$917.637M
GHG emissions (direct energy savings)	-$14.865M	$13.869M	--	--	--	$15.445M	$14.448M
GHG emissions (indirect energy savings)	$3.981M	$1.138M	--	--	$1.860M	$12.669M	$19.648M
GHG emissions (energy generation)	--	--	$220.886M	$662.657M	--	--	$883.542M
Global cooling	$282.431M	$11.979M	--	--	$190.294M	$65.099M	$549.802M
Employment	--	$30.390M	$110.201M	$330.601M	--	--	$471.190M
Employee pay	--	$24.616M	$96.808M	$290.423M	--	--	$411.845M

Welfare payments	--	$78K	$96K	$288K	--	--	$461M
Tax revenue	--	$5.698M	$13.297M	$39.891M	--	--	$58.885M
Federal taxes	--	$4.658M	$9.212M	$27.635M	--	--	$41.505M
State taxes	--	$466K	$1.785M	$5.354M	--	--	$7.605M
City taxes	--	$574K	$2.301M	$6.902M	--	--	$9.777M
NPV	**$598.584M**	**$88.591M**	**$900.593M**	**$2.087,459B**	**$239.348M**	**$810.725M**	**$4.725,298B**

23.2 NPV per square foot

23.2.1 Cool roofs

Table 23.3. 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	**$5.47**	**$1.05**	**$3.74**	**$1.04**
Energy	$1.50	$0.08	$0.53	$0.07
Direct energy savings	$1.34	$0.03	$0.36	$0.02
Indirect (UHI) energy savings	$0.17	$0.05	$0.17	$0.05
Health	$3.19	$0.81	$2.82	$0.81
Ozone	$0.22	$0.06	$0.22	$0.06
PM2.5	$0.61	$0.04	$0.24	$0.03
PM2.5 (direct energy savings)	$0.55	$0.02	$0.17	$0.01
PM2.5 (indirect energy savings)	$0.06	$0.02	$0.06	$0.02
Heat-related mortality	$2.36	$0.71	$2.36	$0.71
Climate change	$0.78	$0.16	$0.40	$0.16
GHG emissions	$0.18	-$0.02	-$0.20	-$0.02
GHG emissions (direct energy savings)	$0.17	-$0.02	-$0.21	-$0.02
GHG emissions (indirect energy savings)	$0.01	$0.00	$0.01	$0.00
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	**$5.08**	**$0.19**	**$3.41**	**$0.18**

23.2.2 Green roofs

Table 23.4. 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	**$9.10**	**$8.85**
Energy	$1.95	$1.74
Direct energy savings	$1.78	$1.58
Indirect (UHI) energy savings	$0.17	$0.17
Stormwater	$2.37	$2.37
Fee discounts	$2.37	$2.37
SRC value	$0.00	$0.00
Health	$3.35	$3.14
Ozone	$0.22	$0.22
PM2.5	$0.77	$0.56
PM2.5 (direct energy savings)	$0.71	$0.49
PM2.5 (indirect energy savings)	$0.06	$0.06
Heat-related mortality	$2.36	$2.36
Climate change	$0.48	$0.65
GHG emissions	$0.36	$0.53
GHG emissions (direct energy savings)	$0.35	$0.51
GHG emissions (indirect energy savings)	$0.01	$0.01
Global cooling	$0.12	$0.12
Employment	$0.96	$0.96
Employee pay	$0.77	$0.77
Welfare payments	$0.00	$0.00
Tax revenue	$0.18	$0.18
Federal taxes	$0.15	$0.15
State taxes	$0.01	$0.01
City taxes	$0.02	$0.02
Net total	**-$13.00**	**-$13.24**

Table 23.5. Costs and benefits per square foot of green roof (with ½ SRC value) (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	**$27.06**	**$26.81**
Energy	$1.95	$1.74
Direct energy savings	$1.78	$1.58
Indirect (UHI) energy savings	$0.17	$0.17
Stormwater	$20.33	$20.33
Fee discounts	$0.00	$0.00
SRC value	$20.33	$20.33
Health	$3.35	$3.14
Ozone	$0.22	$0.22
PM2.5	$0.77	$0.56
PM2.5 (direct energy savings)	$0.71	$0.49
PM2.5 (indirect energy savings)	$0.06	$0.06
Heat-related mortality	$2.36	$2.36
Climate change	$0.48	$0.65
GHG emissions	$0.36	$0.53
GHG emissions (direct energy savings)	$0.35	$0.51
GHG emissions (indirect energy savings)	$0.01	$0.01
Global cooling	$0.12	$0.12
Employment	$0.96	$0.96
Employee pay	$0.77	$0.77
Welfare payments	$0.00	$0.00
Tax revenue	$0.18	$0.18
Federal taxes	$0.15	$0.15
State taxes	$0.01	$0.01
City taxes	$0.02	$0.02
Net total	**$4.44**	**$4.20**

23.2.3 Solar PV

Table 23.6. 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	**$59.80**	**$73.26**	**$59.80**	**$73.26**
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	$0.55	$0.55	$0.55	$0.55
Benefits	**$120.17**	**$119.97**	**$128.93**	**$154.36**
Energy value	$57.56	$68.35	$66.59	$79.06
Electricity value	$56.17	$66.70	$65.20	$77.41
SRECs	$1.39	$1.65	$1.39	$1.65
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	$22.38	$1.86	$22.38	$26.57
PM2.5	$22.38	$1.86	$22.38	$26.57
PM2.5 (electricity generation)	$22.38	$1.86	$22.38	$26.57
Climate change	$10.93	$12.98	$10.93	$12.98
GHG emissions	$10.93	$12.98	$10.93	$12.98
GHG emissions (energy generation)	$10.93	$12.98	$10.93	$12.98
Employment	$5.48	$6.73	$5.48	$6.73
Employee pay	$4.82	$5.91	$4.82	$5.91
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.66	$0.81	$0.66	$0.81
Federal taxes	$0.46	$0.56	$0.46	$0.56
State taxes	$0.09	$0.11	$0.09	$0.11
City taxes	$0.11	$0.14	$0.11	$0.14
Net total	**$60.37**	**$46.71**	**$69.14**	**$81.10**

Table 23.7. 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	**$68.63**	**$84.10**	**$68.63**	**$84.10**
First cost	$39.69	$48.71	$39.69	$48.71
Operations and maintenance	$6.61	$8.12	$6.61	$8.12
Additional replacements	$21.97	$26.97	$21.97	$26.97
Employment training	$0.55	$0.55	$0.55	$0.55
Benefits	**$121.91**	**$141.59**	**$121.91**	**$137.49**
Energy value	$66.59	$82.40	$66.59	$79.58
Electricity value	$65.20	$80.68	$65.20	$77.92
SRECs	$1.39	$1.72	$1.39	$1.66
Financial incentives	$11.91	$14.61	$11.91	$14.61
Tax Credit	$11.91	$14.61	$11.91	$14.61
Depreciation	$0.00	$0.00	$0.00	$0.00
Health	$27.47	$27.69	$27.47	$26.75
PM2.5	$27.47	$27.69	$27.47	$26.75
PM2.5 (electricity generation)	$27.47	$27.69	$27.47	$26.75
Climate change	$13.42	$13.53	$13.42	$13.06
GHG emissions	$13.42	$13.53	$13.42	$13.06
GHG emissions (energy generation)	$13.42	$13.53	$13.42	$13.06
Employment	$5.84	$7.17	$5.84	$7.17
Employee pay	$5.13	$6.30	$5.13	$6.30
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.70	$0.86	$0.70	$0.86
Federal taxes	$0.49	$0.60	$0.49	$0.60
State taxes	$0.09	$0.12	$0.09	$0.12
City taxes	$0.12	$0.15	$0.12	$0.15
Net total	**$53.29**	**$57.49**	**$53.29**	**$53.39**

Table 23.8. 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	**$0.55**	**$0.55**	**$0.55**	**$0.55**
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	$0.55	$0.55	$0.55	$0.55
Benefits	**$40.39**	**$48.17**	**$40.83**	**$48.69**
Energy value	$2.81	$3.33	$3.26	$3.87
Electricity value	$2.81	$3.33	$3.26	$3.87
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	$22.38	$26.57	$22.38	$26.57
PM2.5	$22.38	$26.57	$22.38	$26.57
PM2.5 (electricity generation)	$22.38	$26.57	$22.38	$26.57
Climate change	$10.93	$12.98	$10.93	$12.98
GHG emissions	$10.93	$12.98	$10.93	$12.98
GHG emissions (energy generation)	$10.93	$12.98	$10.93	$12.98
Employment	$5.48	$6.73	$5.48	$6.73
Employee pay	$4.82	$5.91	$4.82	$5.91
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.66	$0.81	$0.66	$0.81
Federal taxes	$0.46	$0.56	$0.46	$0.56
State taxes	$0.09	$0.11	$0.09	$0.11
City taxes	$0.11	$0.14	$0.11	$0.14
Net total	**$39.85**	**$47.63**	**$40.28**	**$48.15**

Table 23.9. 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	**$0.55**	**$0.55**	**$0.55**	**$0.55**
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	$0.55	$0.55	$0.55	$0.55
Benefits	**$48.53**	**$50.89**	**$48.53**	**$49.39**
Energy value	$3.26	$4.03	$3.26	$3.90
Electricity value	$3.26	$4.03	$3.26	$3.90
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	$27.47	$27.69	$27.47	$26.75
PM2.5	$27.47	$27.69	$27.47	$26.75
PM2.5 (electricity generation)	$27.47	$27.69	$27.47	$26.75
Climate change	$13.42	$13.53	$13.42	$13.06
GHG emissions	$13.42	$13.53	$13.42	$13.06
GHG emissions (energy generation)	$13.42	$13.53	$13.42	$13.06
Employment	$5.84	$7.17	$5.84	$7.17
Employee pay	$5.13	$6.30	$5.13	$6.30
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.70	$0.86	$0.70	$0.86
Federal taxes	$0.49	$0.60	$0.49	$0.60
State taxes	$0.09	$0.12	$0.09	$0.12
City taxes	$0.12	$0.15	$0.12	$0.15
Net total	**$47.98**	**$50.35**	**$47.98**	**$48.85**

23.2.4 Reflective pavements

Table 23.10. 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	**$0.94**	**$0.94**	**$0.94**	**$0.81**	**$0.81**
Energy	$0.05	$0.05	$0.05	$0.02	$0.02
Indirect (UHI) energy savings	$0.05	$0.05	$0.05	$0.02	$0.02
Health	$0.70	$0.70	$0.70	$0.69	$0.69
Ozone	$0.05	$0.05	$0.05	$0.05	$0.05
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	$0.63	$0.63	$0.63	$0.63	$0.63
Climate change	$0.19	$0.19	$0.19	$0.09	$0.09
GHG emissions	$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
Global cooling	$0.18	$0.18	$0.18	$0.09	$0.09
Net total	**$0.57**	**$0.52**	**-$0.04**	**$0.54**	**$0.27**

23.2.5 Urban trees

Table 23.11. Costs and benefits per square foot urban tree canopy (albedo and cost held constant)

TYPE	WITH DIRECT ENERGY	WITHOUT DIRECT ENERGY
Costs	**$2.91**	**$2.91**
First cost	$1.31	$1.31
Operations and maintenance	$1.10	$1.10
Additional replacements	$0.54	$0.54
Benefits	**$4.71**	**$3.62**
Energy	$0.75	$0.07
Direct energy savings	$0.68	$0.00
Indirect (UHI) energy savings	$0.07	$0.07
Stormwater	$0.75	$0.75
Fee discounts	$0.75	$0.75
SRC value	$0.00	$0.00
Health	$2.89	$2.67
Pollution uptake	$0.53	$0.53
Ozone	$0.33	$0.33
PM2.5	$0.25	$0.03
PM2.5 (direct energy savings)	$0.22	$0.00
PM2.5 (indirect energy savings)	$0.03	$0.03
Heat-related mortality	$1.79	$1.79
Climate change	$0.31	$0.13
GHG emissions	$0.19	$0.01
GHG emissions (direct energy savings)	$0.19	$0.00
GHG emissions (indirect energy savings)	$0.01	$0.01
Global cooling	$0.12	$0.12
Net total	**$1.66**	**$0.60**

Table 23.12. Costs and benefits per square foot urban tree canopy (with ½ SRC value) (albedo and cost held constant)

TYPE	WITH DIRECT ENERGY	WITHOUT DIRECT ENERGY
Costs	**$2.91**	**$2.91**
First cost	$1.31	$1.31
Operations and maintenance	$1.10	$1.10
Additional replacements	$0.54	$0.54
Benefits	**$8.78**	**$7.69**
Energy	$0.75	$0.07
Direct energy savings	$0.68	$0.00
Indirect (UHI) energy savings	$0.07	$0.07
Stormwater	$4.83	$4.83
Fee discounts	$0.00	$0.00
SRC value	$4.83	$4.83
Health	$2.89	$2.67
Pollution uptake	$0.53	$0.53
Ozone	$0.33	$0.33
PM2.5	$0.25	$0.03
PM2.5 (direct energy savings)	$0.22	$0.00
PM2.5 (indirect energy savings)	$0.03	$0.03
Heat-related mortality	$1.79	$1.79
Climate change	$0.31	$0.13
GHG emissions	$0.19	$0.01
GHG emissions (direct energy savings)	$0.19	$0.00
GHG emissions (indirect energy savings)	$0.01	$0.01
Global cooling	$0.12	$0.12
Net total	**$5.61**	**$4.56**

24 APPENDIX: DETAILED RESULTS FOR EL PASO

24.1 Scenario (NPV)

Table 24.1. Detailed NPV of city-wide impact in El Paso (results are additive)

SOLUTION	COOL ROOFS	GREEN ROOFS	PV (DIRECT PURCHASE)	PV (PPA)	REFLECTIVE PAVEMENTS	URBAN TREES	TOTAL
Costs	**$102.751M**	**$605.356M**	**$361.681M**	**$829K**	**$96.197M**	**$450.286M**	**$1.617,98B**
First cost	$75.755M	$416.339M	$240.667M	--	$45.398M	$232.123M	$1.010,280B
Operations and maintenance	$0	$188.723M	$40.826M	--	--	$182.872M	$412.420M
Additional replacements	$26.997M	--	$79.913M	--	$50.799M	$35.292M	$193MM
Employment training	$0	$295K	$277K	$829K	--	--	$1.400M
Benefits	**$443.098M**	**$115.641M**	**$620.417M**	**$436.994M**	**$240.697M**	**$298.134M**	**$2.154,979B**
Energy	$103.093M	$46.127M	$409.793M	$61.472M	$14.095M	$65.312M	$699.889M
Direct energy savings	$80.440M	$39.388M	--	--	--	$50.875M	$170.701M
Indirect (UHI) energy savings	$22.654M	$6.740M	--	--	$14.095M	$14.438M	$57.925M
Electricity value	--	--	$409.793M	$61.472M	--	--	$471.264M
SRECs	--	--	$0	--	--	--	$0
Financial incentives	--	--	$85.450M	--	--	--	$85.450M
Tax Credit	--	--	$21.771M	--	--	--	$21.771M
Depreciation	--	--	$63.511M	--	--	--	$63.511M
Tax Deduction	--	--	$168K	--	--	--	$168K
Stormwater	--	$7.546M	--	--	--	$31.625M	$39.171M
Fee discounts	--	$7.546M	--	--	--	$31.625M	$39.171M
SRC value	--	$0	--	--	--	$0	$0
Health	$120.772M	$14.041M	$25.717M	$77.149M	$54.516M	$51.413M	$343.604M
Pollution uptake	--	--	--	--	--	$6.875M	$6.875M
Ozone	$1.327M	$116K	--	--	$804K	$0	$2.246M
PM2.5	$2.505M	$5.228M	$25.717M	$77.149M	$1.343M	$8.789M	$120.728M
PM2.5 (direct energy savings)	$371K	$4.425M	--	--	--	$4.632M	$9.426M
PM2.5 (indirect energy savings)	$2.135M	$803K	--	--	$1.343M	$4.158M	$8.438M
PM2.5 (electricity generation)	--	--	$25.717M	$77.149M	--	--	$102.865M
Heat-related mortality	$116.940M	$8.698M	--	--	$52.369M	$35.750M	$213.756M
Climate change	$219.234M	$23.101M	$60.356M	$181.068M	$172.087M	$149.786M	$805.629M
GHG emissions	$5.201M	$12.722M	$60.356M	$181.068M	$3.683M	$25.366M	$288.393M
GHG emissions (direct energy savings)	-$122K	$10.849M	--	--	--	$13.684M	$24.410M
GHG emissions (indirect energy savings)	$5.323M	$1.873M	--	--	$3.683M	$11.682M	$22.560M

GHG emissions (energy generation)	--	--	$60.356M	$181.068M	--	--	$241.423M
Global cooling	$214.034M	$10.379M	--	--	$168.405M	$124.421M	$517.237M
Employment	--	$24.828M	$39.103M	$117.308M	--	--	$181.238M
Employee pay	--	$21.329M	$36.158M	$108.474M	--	--	$165.960M
Welfare payments	--	$67K	$46K	$136K	--	--	$249M
Tax revenue	--	$3.433M	$2.900M	$8.698M	--	--	$15.030M
Federal taxes	--	$3.433M	$2.900M	$8.698M	--	--	$15.030M
State taxes	--	$0	$0	$0	--	--	$0
City taxes	--	$0	$0	$0	--	--	$0
NPV	**$340.347M**	**-$489.714M**	**$258.736M**	**$436.166M**	**$144.500M**	**-$152.151M**	**$537.881M**

24.2 NPV per square foot

24.2.1 Cool roofs

Table 24.2. 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	**$4.40**	**$0.79**	**$3.40**	**$0.78**
Energy	$1.98	$0.17	$1.55	$0.17
Direct energy savings	$1.71	$0.09	$1.28	$0.09
Indirect (UHI) energy savings	$0.27	$0.08	$0.27	$0.08
Health	$1.57	$0.43	$1.37	$0.43
Ozone	$0.02	$0.00	$0.02	$0.00
PM2.5	$0.16	$0.01	-$0.04	$0.00
PM2.5 (direct energy savings)	$0.14	$0.00	-$0.06	$0.00
PM2.5 (indirect energy savings)	$0.02	$0.01	$0.02	$0.01
Heat-related mortality	$1.39	$0.42	$1.39	$0.42
Climate change	$0.85	$0.19	$0.48	$0.18
GHG emissions	$0.25	$0.01	-$0.11	$0.00
GHG emissions (direct energy savings)	$0.22	$0.00	-$0.14	-$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	**$4.04**	**-$0.07**	**$3.08**	**-$0.07**

24.2.2 Green roofs

Table 24.3. 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	**$3.86**	**$4.82**
Energy	$1.74	$2.13
Direct energy savings	$1.47	$1.86
Indirect (UHI) energy savings	$0.27	$0.27
Stormwater	$0.30	$0.30
Fee discounts	$0.30	$0.30
SRC value	$0.00	$0.00
Health	$0.52	$0.71
Ozone	$0.00	$0.00
PM2.5	$0.17	$0.36
PM2.5 (direct energy savings)	$0.15	$0.34
PM2.5 (indirect energy savings)	$0.02	$0.02
Heat-related mortality	$0.35	$0.35
Climate change	$0.40	$0.77
GHG emissions	$0.28	$0.65
GHG emissions (direct energy savings)	$0.25	$0.62
GHG emissions (indirect energy savings)	$0.03	$0.03
Global cooling	$0.12	$0.12
Employment	$0.90	$0.90
Employee pay	$0.77	$0.77
Welfare payments	$0.00	$0.00
Tax revenue	$0.12	$0.12
Federal taxes	$0.12	$0.12
State taxes	$0.00	$0.00
City taxes	$0.00	$0.00
Net total	**-$18.08**	**-$17.16**

24.2.3 Solar PV

Table 24.4. 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	**$55.65**	**$68.18**	**$55.65**	**$68.18**
First cost	$31.75	$38.97	$31.75	$38.97
Operations and maintenance	$5.98	$7.34	$5.98	$7.34
Additional replacements	$17.58	$21.57	$17.58	$21.57
Employment training	$0.51	$0.51	$0.51	$0.51
Benefits	**$99.09**	**$112.65**	**$110.27**	**$131.41**
Energy value	$58.04	$68.41	$69.56	$82.00
Electricity value	$58.04	$68.41	$69.56	$82.00
SRECs	$0.00	$0.00	$0.00	$0.00
Financial incentives	$24.63	$30.23	$24.63	$30.23
Tax Credit	$9.52	$11.69	$9.52	$11.69
Depreciation	$15.04	$18.46	$15.04	$18.46
Initial install depreciation	$9.21	$11.30	$9.21	$11.30
Replacement depreciation	$5.84	$7.17	$5.84	$7.17
Tax Deduction	$0.06	$0.07	$0.06	$0.07
Health	$5.23	$0.43	$5.23	$6.17
PM2.5	$5.23	$0.43	$5.23	$6.17
PM2.5 (electricity generation)	$5.23	$0.43	$5.23	$6.17
Climate change	$8.60	$10.13	$8.60	$10.13
GHG emissions	$8.60	$10.13	$8.60	$10.13
GHG emissions (energy generation)	$8.60	$10.13	$8.60	$10.13
Employment	$4.82	$5.92	$4.82	$5.92
Employee pay	$4.46	$5.47	$4.46	$5.47
Welfare payments	$0.00	$0.01	$0.00	$0.01
Tax revenue	$0.36	$0.44	$0.36	$0.44
Federal taxes	$0.36	$0.44	$0.36	$0.44
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.00	$0.00	$0.00	$0.00
Net total	**$43.44**	**$44.47**	**$54.62**	**$63.23**

Table 24.5. 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	**$64.48**	**$79.02**	**$64.48**	**$79.02**
First cost	$37.04	$45.46	$37.04	$45.46
Operations and maintenance	$6.61	$8.12	$6.61	$8.12
Additional replacements	$20.51	$25.17	$20.51	$25.17
Employment training	$0.51	$0.51	$0.51	$0.51
Benefits	**$100.29**	**$118.97**	**$100.29**	**$116.01**
Energy value	$69.56	$85.06	$69.56	$82.51
Electricity value	$69.56	$85.06	$69.56	$82.51
SRECs	$0.00	$0.00	$0.00	$0.00
Financial incentives	$11.11	$13.64	$11.11	$13.64
Tax Credit	$11.11	$13.64	$11.11	$13.64
Depreciation	$0.00	$0.00	$0.00	$0.00
Health	$6.42	$6.40	$6.42	$6.21
PM2.5	$6.42	$6.40	$6.42	$6.21
PM2.5 (electricity generation)	$6.42	$6.40	$6.42	$6.21
Climate change	$10.55	$10.51	$10.55	$10.20
GHG emissions	$10.55	$10.51	$10.55	$10.20
GHG emissions (energy generation)	$10.55	$10.51	$10.55	$10.20
Employment	$5.32	$6.53	$5.32	$6.53
Employee pay	$4.92	$6.04	$4.92	$6.04
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.39	$0.48	$0.39	$0.48
Federal taxes	$0.39	$0.48	$0.39	$0.48
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.00	$0.00	$0.00	$0.00
Net total	**$35.81**	**$39.95**	**$35.81**	**$36.99**

Table 24.6. 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	**$0.51**	**$0.51**	**$0.51**	**$0.51**
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	$0.51	$0.51	$0.51	$0.51
Benefits	**$20.93**	**$24.89**	**$21.49**	**$25.55**
Energy value	$2.90	$3.42	$3.48	$4.10
Electricity value	$2.90	$3.42	$3.48	$4.10
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
Tax deduction	$0.00	$0.00	$0.00	$0.00
Health	$5.23	$6.17	$5.23	$6.17
PM2.5	$5.23	$6.17	$5.23	$6.17
PM2.5 (electricity generation)	$5.23	$6.17	$5.23	$6.17
Climate change	$8.60	$10.13	$8.60	$10.13
GHG emissions	$8.60	$10.13	$8.60	$10.13
GHG emissions (energy generation)	$8.60	$10.13	$8.60	$10.13
Employment	$4.82	$5.92	$4.82	$5.92
Employee pay	$4.46	$5.47	$4.46	$5.47
Welfare payments	$0.00	$0.01	$0.00	$0.01
Tax revenue	$0.36	$0.44	$0.36	$0.44
Federal taxes	$0.36	$0.44	$0.36	$0.44
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.00	$0.00	$0.00	$0.00
Net total	**$20.41**	**$24.38**	**$20.97**	**$25.04**

Table 24.7. 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	**$0.51**	**$0.51**	**$0.51**	**$0.51**
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	$0.51	$0.51	$0.51	$0.51
Benefits	**$25.02**	**$26.89**	**$25.02**	**$26.27**
Energy value	$3.48	$4.25	$3.48	$4.13
Electricity value	$3.48	$4.25	$3.48	$4.13
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	$6.42	$6.40	$6.42	$6.21
PM2.5	$6.42	$6.40	$6.42	$6.21
PM2.5 (electricity generation)	$6.42	$6.40	$6.42	$6.21
Climate change	$10.55	$10.51	$10.55	$10.20
GHG emissions	$10.55	$10.51	$10.55	$10.20
GHG emissions (energy generation)	$10.55	$10.51	$10.55	$10.20
Employment	$5.32	$6.53	$5.32	$6.53
Employee pay	$4.92	$6.04	$4.92	$6.04
Welfare payments	$0.01	$0.01	$0.01	$0.01
Tax revenue	$0.39	$0.48	$0.39	$0.48
Federal taxes	$0.39	$0.48	$0.39	$0.48
State taxes	$0.00	$0.00	$0.00	$0.00
City taxes	$0.00	$0.00	$0.00	$0.00
Net total	**$24.51**	**$26.37**	**$24.51**	**$25.76**

24.2.4 Reflective pavements

Table 24.8. 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
Costs	**$0.34**	**$0.39**	**$0.95**	**$0.24**
First cost	$0.02	$0.02	$0.46	$0.24
Additional replacements	$0.33	$0.38	$0.50	$0.00
Benefits	**$0.58**	**$0.58**	**$0.58**	**$0.34**
Energy	$0.08	$0.08	$0.08	$0.04
Indirect (UHI) energy savings	$0.08	$0.08	$0.08	$0.04
Health	$0.30	$0.30	$0.30	$0.20
Ozone	$0.01	$0.01	$0.01	$0.00
PM2.5	$0.01	$0.01	$0.01	$0.00
PM2.5 (indirect energy savings)	$0.01	$0.01	$0.01	$0.00
Heat-related mortality	$0.29	$0.29	$0.29	$0.20
Climate change	$0.19	$0.19	$0.19	$0.09
GHG emissions	$0.01	$0.01	$0.01	$0.00
GHG emissions (indirect energy savings)	$0.01	$0.01	$0.01	$0.00
Global cooling	$0.18	$0.18	$0.18	$0.09
Net total	**$0.22**	**$0.17**	**-$0.39**	**$0.08**

24.2.4 Urban trees

Table 24.9. Costs and benefits per square foot urban tree canopy (albedo and cost held constant)

URBAN TREES	
Costs	**$1.35**
First cost	$0.53
Operations and maintenance	$0.61
Additional replacements	$0.22
Benefits	**$0.61**
Energy	$0.22
Direct energy savings	$0.17
Indirect (uhi) energy savings	$0.05
Stormwater	$0.11
Fee discounts	$0.11
Src value	$0.00
Health	$0.15
Pollution uptake	$0.02
Ozone	$0.00
Pm2.5	$0.01
Pm2.5 (direct energy savings)	$0.01
Pm2.5 (indirect energy savings)	$0.00
Heat-related mortality	$0.12
Climate change	$0.13
Ghg emissions	$0.01
Ghg emissions (direct energy savings)	$0.01
Ghg emissions (indirect energy savings)	$0.01
Global cooling	$0.12
Net total	**-$0.75**

25 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 and urban trees
HVAC air intake temperature reduction	Net Benefit	Cool roofs, green roofs
Regional cooling	Net Benefit	All
Increase amenity/property value	Net Benefit	Green roofs, solar PV, 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
UHI mitigation	Net Benefit	Solar PV

26 APPENDIX: PHASE 1 RESULTS

26.1 Washington, D.C. (100% low slope)

Table 26.1. Washington, D.C. property costs and benefits per ft² of roof occupied by each technology (NOTE: we assume all rooftop PV and solar hot water is financed through a PPA, so there is no upfront cost)

COMPARISON	COOL compared to conventional	GREEN compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional	CONVENTIONAL w/ shw (ppa) compared to conventional
Costs	**$0.62**	**$22.61**	**$0.00**	**$0.00**
First cost	$0.25	$15.00	N/A	N/A
Stormwater BMP review fee	N/A	$0.02	N/A	N/A
Operations and maintenance	$0.23	$7.59	N/A	N/A
Additional replacements	$0.14	$0.00	N/A	N/A
Benefits	**$4.60**	**$60.89**	**$69.17**	**$124.68**
Energy	$0.53	$2.48	$2.49	$48.73
Direct energy savings	$0.40	$2.35	N/A	N/A
Indirect (UHI) energy savings	$0.13	$0.13	N/A	N/A
Energy generation	N/A	N/A	$2.49	$48.73
Stormwater	N/A	$53.56	N/A	N/A
Fee discounts	N/A	$1.09	N/A	N/A
SRC revenue	N/A	$52.47	N/A	N/A
Health	$4.01	$4.03	$52.10	$27.88
Ozone	$1.99	$1.69	N/A	N/A
PM2.5	$1.41	$1.72	$52.10	$27.88
Heat-related mortality	$0.61	$0.61	N/A	N/A
Climate change	$0.06	$0.83	$14.58	$48.08
Net total	**$3.98**	**$38.28**	**$69.17**	**$124.68**

26.2 Baltimore (11% low slope and 89% steep slope)

Table 26.2. Baltimore property costs and benefits per ft² of roof occupied by each technology (NOTE: we assume all rooftop PV is financed through a PPA, so there is no upfront cost; the cool roof and PV estimates are a weighted-average of the results for low slope and steep slope roofs, while the green roof estimates are only for the low slope roof portion of the property)

COMPARISON	COOL compared to conventional	GREEN compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional
Costs	**$1.31**	**$22.66**	**$0.00**
First cost	$0.70	$15.00	N/A
Stormwater BMP review fee	N/A	$0.07	N/A
Operations and maintenance	$0.23	$7.59	N/A
Additional replacements	$0.39	$0.00	N/A
Benefits	**$1.73**	**$5.34**	**$30.67**
Energy	$0.40	$1.80	$2.19
Direct energy savings	$0.33	$1.15	N/A
Indirect (UHI) energy savings	$0.07	$0.65	N/A
Energy generation	N/A	N/A	$2.19
Stormwater	N/A	$0.80	N/A
Fee discounts	N/A	$0.80	N/A
SRC revenue	N/A	$0.00	N/A
Health	$1.28	$2.54	$22.67
Ozone	$1.06	$1.63	N/A
PM2.5	$0.19	$0.88	$22.67
Heat-related mortality	$0.03	$0.03	N/A
Climate change	$0.05	$0.20	$5.81
Net total	**$0.42**	**-$17.32**	**$30.67**

26.3 Philadelphia (100% steep slope)

Table 26.3. Philadelphia property costs and benefits per ft² of roof occupied by each technology (NOTE: we assume all rooftop PV is financed through a PPA, so there is no upfront cost)

COMPARISON	COOL compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional
Costs	**$1.40**	**$0.00**
First cost	$0.75	N/A
Stormwater BMP review fee	N/A	N/A
Operations and maintenance	$0.23	N/A
Additional replacements	$0.42	N/A
Benefits	**$1.96**	**$5.84**
Energy	$0.26	$0.00
Direct energy savings	$0.21	N/A
Indirect (UHI) energy savings	$0.05	N/A
Energy generation	N/A	$0.00
Stormwater	N/A	N/A
Fee discounts	N/A	N/A
SRC revenue	N/A	N/A
Health	$1.73	$3.07
Ozone	$0.79	N/A
PM2.5	$0.00	$3.07
Heat-related mortality	$0.94	N/A
Climate change	-$0.02	$2.77
Net total	**$0.57**	**$5.84**

26.4 Los Angeles (100% low slope)

Table 26.4. Los Angeles property characteristics

LOCATION	LOS ANGELES, CA
Number of floors	3 to 4
Number of units	39
Number of units on top floor	14
Total occupancy	97[ccxvii]
Roof area (ft^2)	100,000
Non-cool roof substrate material	Currently has a cool roof[ccxviii]
Roof slope	Low slope
Roof insulation (R-value)	R-38
Air conditioner efficiency	14 to 17 SEER
Heating fuel	Electricity
Heating system efficiency	7.7 HSPF
Water heating fuel	Natural gas
Price of electricity ($/kWh)	0.12
Price of natural gas ($/therm)	1.19

Table 26.5. Los Angeles property costs and benefits per ft² of roof occupied by each technology (NOTE: we assume all rooftop PV and solar hot water is financed through a PPA, so there is no upfront cost)

COMPARISON	COOL compared to conventional	GREEN compared to conventional	CONVENTIONAL w/ pv (ppa) compared to conventional	CONVENTIONAL w/ shw (ppa) compared to conventional
Costs	**$0.23**	**$22.68**	**$0.00**	**$0.00**
First cost	$0.00	$15.00	N/A	N/A
Stormwater BMP review fee	N/A	$0.09	N/A	N/A
Operations and maintenance	$0.23	$7.59	N/A	N/A
Additional replacements	$0.00	$0.00	N/A	N/A
Benefits	**$3.32**	**$2.12**	**$59.43**	**$74.47**
Energy	$1.41	$0.56	$2.87	$14.33
Direct energy savings[ccxix]	$1.22	$0.37	N/A	N/A
Indirect (UHI) energy savings	$0.19	$0.19	N/A	N/A
Energy generation	N/A	N/A	$2.87	$14.33
Stormwater	N/A	$0.47	N/A	N/A
Fee discounts	N/A	$0.47	N/A	N/A
SRC revenue	N/A	$0.00	N/A	N/A
Health	$1.63	$0.97	$44.41	$22.07
Ozone	$0.53	$0.53	N/A	N/A
PM2.5ccxix	$1.08	$0.42	$44.41	$22.07
Heat-related mortality	$0.02	$0.02	N/A	N/A
Climate changeccxix	$0.29	$0.11	$12.14	$38.06
Net total	**$3.09**	**-$20.56**	**$59.43**	**$74.47**

27 CITATIONS

[1] *Because this report seeks to rigorously document and quantify a set of technology and policy measures for the first time, we have had to develop some new approaches, methodologies and even a few new terms. This work for the first time looks at technologies from the air, as it were - all city surfaces and how cities manage - or fail to manage – their sun and rain through their choice of surfaces. This report clusters and analyzes for the first time a set of technologies that are applied to the surfaces of cities – roofs, road, parking lots sidewalks etc and describes these collectively with a new term: "smart surfaces" because they cover surfaces and because they are engineered to deliver a range of measurable if sometimes complex benefits and enhancements relative to conventional surfaces. The large majority of these "smart surfaces" for most cities deliver positive net present value. The process we have developed to understand, quantify and compare these "smart surface" choices also demonstrates that these are, overwhelmingly, smarter choices than conventional design.*
It is also clear that the urban heat island reduction strategies such as cool and green roofs and cool pavements if applied city -wide can have large cooling benefits both within the city but also on areas that are downwind in the summers. At the scale of cooling application envisaged – with smart surfaces adopted as baseline standard practice rather than in current limited applications - this downwind cooling impact is cumulative and can be large, potentially doubling peak cooling benefits. This concept is a new one and is potentially very large and so merits a new term - we call it "downwind cooling".

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