Transforming America's Low Income Districts

Reshaping our cities' surfaces to save lives, improve livability, and slow global warming while saving hundreds of millions of dollars

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- Greening Our Built World: Costs, Benefits, and Strategies (Island Press, 2010). Includes widely cited cost-benefit analysis and findings. Extensively excerpted by 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)
- "The Costs and Financial Benefits of Green Buildings." 2003. Written for a dozen California state agencies. Report findings cited as rationale for 2004 California Executive order requiring all future state public construction and retrofits to be green, for New York City legislation requiring all future public construction to be green, for Boston legislation requiring all private and public construction to be LEED certifiable, etc.
- Co-author, "International Greenhouse Gas Trading Programs: Measurement and Accounting" (Energy Policy, 2003)

Keith Glassbrook is Senior Analyst at Capital E. He has extensive experience in environmental analysis and life cycle assessment. Recently, his life cycle assessment and feasibility study of small wind power in Thailand was published in the journal Energy for Sustainable Development. He supported EPA's biogenic 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, DC and securing funding and supporting the launch of a campus-wide bikeshare program at UNC-Chapel Hill. Keith holds a BS in Environmental Science from UNC-CH, where he graduated Phi Beta Kappa with highest distinction. He is the Co-Chair of the Emerging Professionals Committee of the local USGBC chapter.

Executive Summary

How cities manage the sunlight and rain that falls on them has a huge impact on inhabitants' health and quality of life. But city planners generally do not manage or even think about their city's rain and sunshine in any systematic way and as a result mismanage these two great natural gifts. This mismanagement costs cities billions of dollars in unnecessary health-, energy-, and stormwater-related costs and degrades comfort and livability. This is particularly true for low income areas, which are characterized by less greenery and greater unwanted summer absorption of sunlight, resulting in higher temperatures, worse air pollution, and related health costs and discomfort.

With more paved area, less greenery, and more dark surfaces, cities suffer from higher summer temperatures and worse air pollution than surrounding suburban and rural areas. The impacts of higher summer temperatures and air pollution are particularly acute in low income urban areas where residents tend to live in inefficient buildings (sometimes without air conditioning) and disproportionately suffer from respiratory and other health problems (often exacerbated by poor air quality). The publication *Environmental Health Perspectives* notes, 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." Studies find that the urban poor suffer disproportionally from the urban heat island effect because of a higher likelihood of residing in inefficient homes. For example, the greatest incidence of heat-related mortalities in cities occurs on the top floor of apartment buildings and in low-income areas.

Some cities have begun programs supporting adoption of reflective roofs and pavements to cool the urban environment and lower energy bills; green roofs and trees to reduce stormwater runoff and cool the city; and rooftop solar PV to generate electricity and reduce air pollution. But even in these progressive cities, adoption of these technologies is on a pilot and piecemeal basis, reflecting an inability to fully quantify or understand the costs and benefits of these technologies. This report shows these technologies could go a long way towards cost-effectively reducing health and energy costs for low income areas while increasing employment, resilience, and livability.

Until this analysis, there has been no established methodology for quantifying the full costs and benefits for cool roofs, green roofs, solar PV, reflective pavements, and urban trees. And therefore there was no way for cities to evaluate the cost-effectiveness of deploying these technologies. A large and poorly quantified part of the benefits of these technologies relates to health. Health impacts are large and complex, and have generally not been quantified or valued for these roof and surface technologies. This report describes different health impact pathways and methodologies used to estimate these costs and benefits. Because this type of analysis is new, it draws on multiple methods, studies, and models to develop an integrated methodology for quantifying the health impacts.

This kind of full, integrated analysis has not been done before in large part because of its complexity, and because there exists no analytic tool that comes close to quantifying full cost-benefit analysis. The best health valuation model is EPA's BenMAP. We built on this and 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 at ward-level. 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.

SUMMARY OF FINDINGS

This report provides an in-depth analysis of the costs and benefits of applying a set of roofing and surfacing technologies at scale in ward-level low income areas in three cities: Washington, DC, Baltimore, and Philadelphia. The low income areas studied are substantial, representing, on average, about one-tenth of the population of the cities. These low income areas are characterized by far higher poverty rates, lower income, and higher unemployment than the cities they are part of. On average, the low income areas studied have 53% higher percent of population below the poverty line and 64% higher unemployment rates than the cities they are part of. Not coincidently, these low income areas also have 43% lower tree coverage relative to the cities as a whole. Underinvestment in trees and green technologies generally in urban low income areas like these result 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 this 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. As discussed in the report and the report appendix, many additional benefits and some costs were identified but not quantified due to lack of data and/or need to limit study scope. Unquantified benefits exceed unquantified costs, so overall the cost-benefit findings in this report underestimate the cost-effectiveness of these technologies. That is, the net benefits of scale deployment are almost certainly substantially larger than estimated here.

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, DC 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. Furthermore, a city-wide analysis would demonstrate far larger 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 E1. Summary of the net present value (NPV) of costs and benefits for Ward 5 (Washington, DC)

TECHNOLOGY	Cool Roofs	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Urban Trees	TOTAL
COSTS	$5,297,000	$67,970,000	$30,234,000	$14,000	$10,178,000	$47,396,000	$161,087,000
BENEFITS	$47,359,000	$128,469,000	$49,354,000	$45,640,000	$18,199,000	$138,422,000	$427,440,000
NPV	$42,063,000	$60,499,000	$19,120,000	$45,626,000	$8,022,000	$91,027,000	$266,354,000

Table E2. Benefit-to-Cost Ratio summary for each technology in Ward 5 (Washington, DC)

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 E3. 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	$2,858,000	$24,767,000	$16,076,000	$7,000	$6,183,000	$14,136,000	$64,025,000
BENEFITS	$21,475,000	$26,536,000	$26,359,000	$28,912,000	$10,033,000	$25,916,000	$139,228,000
NPV	$18,617,000	$1,770,000	$10,283,000	$28,905,000	$3,850,000	$11,780,000	$75,203,000

Table E4. 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 E5. 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	$8,236,000	$100,076,000	$55,669,000	$25,000	$12,433,000	$14,136,000	$190,573,000
BENEFITS	$70,797,000	$115,154,000	$92,676,000	$95,456,000	$26,789,000	$31,113,000	$431,981,000
NPV	$62,561,000	$15,079,000	$37,007,000	$95,431,000	$14,356,000	$16,977,000	$241,408,000

Table E6. 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 has not been done before, we have worked with and consulted with national and city partners, epidemiologists, technology, stormwater, and energy experts and others to build the data and integrated cost-benefit model. While 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.

Deployment of these technologies at scale in low income areas can address systematic inequity in urban quality of life. Reductions in energy bills matter much more to low income residents than to wealthy city residents. For example, recent research from 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. Similarly, health benefits of the technologies analyzed in this report are larger for low income than for wealthy city residents.

As noted, this analysis does not capture the full set of comfort, health, and livability benefits, and it only includes about one-tenth of each city. City-wide analysis would yield far larger 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.

REPORT GENESIS AND ASPIRATION

This report began almost two years ago when Capital E proposed to do this work for Washington, DC and, separately, for the JPB Foundation. In effect, this work was developed in parallel for both clients, with somewhat different objectives. This process has allowed iterative analysis and feedback that has proven useful.

This report is intended to allow more informed, more cost-effective and more comprehensive building and community policy, design, and investment choices for low income areas as a way to address widespread health and environmental issues, as well as issues of affordability and climate change. In short, this analysis is intended to enable and accelerate informed, cost-effective decisions to make low income areas of our cities healthier, more affordable and more livable.

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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 (often exacerbated by poor air quality). The last decade in the United States has seen the emergence of a set of roof technologies that could go a long way to reducing these environment, health, and energy costs. These technologies include: cool (reflective) roofs to cool the urban environment and lower energy bills; green (vegetated) roofs to reduce stormwater runoff, cool the urban environment, and lower energy bills; and rooftop solar photovoltaics (PV) to generate electricity and reduce air pollution. Urban trees, though commonly seen as a way to beautify cities, are increasingly being recognized for their ability to help manage stormwater, cool the urban environment, reduce pollution, and lower energy bills. And cool (reflective) pavements, a technology still in its infancy, can also be used to cool the urban environment. These technologies are increasingly being 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 CO2 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 the five technologies. In earlier iterations of this work, we estimated the costs and benefits only for individual buildings up to the scale of hundreds of buildings. In reality, there are hundreds of thousands of buildings and hundreds of millions of square feet of pavement in cities the size of Washington, DC ("the District"), Baltimore, and Philadelphia, so it is important for these and other cities to understand the costs and benefits of deploying the three roof technologies and urban trees and reflective pavements at large scale. This gap in knowledge is particularly harmful for low incomes areas because low income areas generally suffer from higher summer temperatures, worse air quality, more severe health problems, and greater energy bills per square foot than more affluent areas. This report is intended to fill this gap and to enable smarter and more cost-effective and comprehensive building and community policy, design, and investment choices as a way to address widespread health and environmental issues, as well as issues of affordability and climate change. In short, this analysis is intended to enable informed, cost-effective city-wide decisions to make cities healthier, more affordable, and more livable and to slow climate change.

Capital E proposed this work to Washington, DC and the JPB Foundation in 2014, and with them developed the relevant scopes of work. The DC Department of General Services (DGS) and the Department of Energy & Environment (DOEE) hired Capital E to undertake this analysis for the five technologies on a city-scale in the District, and JPB hired Capital E to undertake this analysis for the five technologies in low-income regions of three cities (the District, Baltimore, and Philadelphia). This report represents the findings of this work.

1.1 Overview of report structure

This report starts with a brief overview of the Phase 1 report followed by an introduction to the technologies and impacts analyzed and then dives deeper into each individual technology. Following the technology descriptions, this report overviews methods—which are detailed more comprehensively in the Appendix—and then summarizes and discusses the results.[i] The report concludes with key findings and a discussion of next steps. The intent is to provide insights and documentation that enables readers to use data from their building(s) and city conditions to understand, evaluate, and estimate the full costs and benefits of smarter city surface choices, and to then adopt city-wide policies.

All costs and benefits are quantified on a present value, dollars per square foot basis, with explicit assumptions on term and discount rate. This approach results in common, net present value per square foot ($NPV/ft^2) estimates that enable technology and policy choices to be compared to each other and/or be aggregated into neighborhood-wide or city-wide estimates so that cities can, for the first time, make informed decisions about deploying these technologies at scale. This report is designed to allow evaluation of the deployment of integrated options. This report estimates the cumulative impact of these technologies at the low-income ward or ward-like 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 enable and drive city policy design choices nationally and internationally.

Health impacts are large and complex, and have generally not been estimated or valued for these five roof and surface technologies. 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 must draw on multiple methods, studies, and models to develop an integrated methodology for estimating the health impacts. This report also provides a preliminary estimate of the employment impact of the three roof technologies. 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 makes conservative assumptions about how many jobs remain in the city. Because this report is pathbreaking, it estimates some costs and benefits in ways that have not been done before. Assumptions are explicit throughout the text, and in all cases, this report provides references and, where available, links.

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

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[i] The most complex analyses were performed for Washington, DC. The analyses for Baltimore and Philadelphia, while still valid, were performed with less refined data.

2 Overview of Phase 1

The below sections provide an overview of the first phase of this work for JPB, 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: the District, Baltimore, Philadelphia, and Los Angeles.

2.1 Why affordable housing?

The importance of making smart roof choices, decreasing urban heat islands (UHI), and improving air quality is especially significant for low-income populations.[ii] 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."[1] Many roofs in low-income city areas have low solar reflectance (meaning they absorb the large 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.[2] The urban poor suffer disproportionally from the UHIs due to their increased likelihood of residing in inefficient homes and schools.

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.[3] As a consequence, the impact of energy bill reductions is proportionally larger for affordable housing properties.

The greatest incidence of heat-related mortalities in cities occurs on the top floor of apartment buildings and in low-income areas.[4] Additionally, elevated urban temperatures due to UHIs also 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.

2.2 Report outline

In the Phase 1 report developed for JPB (Affordable Housing Smart Roof Report), we describe each of the four roof technologies, focusing on characteristics that affect the costs and benefits of each technology. We then describe how we estimate the costs and benefits of the technologies—including a description of how and why we arrived at each method. Then we turn to estimating the costs and benefits of these technologies. Our intent was to provide a complete description and documentation that enables readers to use data from their building(s) and city conditions to evaluate and estimating the full costs and benefits of these technologies.

[ii] The urban heat island (UHI) effect describes the phenomenon of urban areas being hotter than nearby rural areas. UHIs result from the conversion of natural, pervious land cover to built-up, impervious land cover that is darker and has less vegetation. These changes result in greater absorption of solar radiation and less evapotranspiration, which lead to increased temperatures.

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 common 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 four technologies. Because this kind of analysis has not been done before, in building the cost-benefit analysis methodologies we drew on multiple methods, studies, and models to develop new approaches for estimating the health impacts. We have estimated some costs and benefits that had not been quantified before for roof technologies. We made assumptions explicit throughout the text. And, in all cases, we provide references and, where available, links.

There are a set of additional benefits and impacts that may be significant but that we did not estimate due to insufficient data. Because most of the impacts that are excluded from cost-benefit calculations are benefits, our estimates tend to underestimate the value of cool roofs, green roofs, rooftop PV, or solar hot water. In this sense, the Phase 1 report findings are conservative, that is, they tend to underestimate the net benefits of the four technologies.

2.3 The multi-unit affordable housing properties

In the Phase 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 our Partner Enterprise Community Partners. Table 2.1 includes select information for each property (information on the Los Angeles property can be found in the Appendix). Additional info can be found in the Appendix. Figure 1, Figure 2, and Figure 3 show example views of the District, Baltimore, and Philadelphia properties, respectively.

The properties in this analysis are quite different from each other. For example, the properties in the District and Philadelphia have gas heat, while the property in Baltimore has electric heat. Roof slope also differs across the properties. 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 is all steep slope roofs. These and other differences impact the results of the Phase 1 report. Table 2.2, Table 2.3, and Table 2.4 show cost-benefit results for the District, Baltimore, and Philadelphia properties, respectively. More detailed results and results for the Los Angeles property are in the Appendix.

Table 2.1. Property characteristics

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

Figure 1. Views of the District property tower (left) and townhomes (right)

Figure 2. Views of Baltimore property

Figure 3. Views of Philadelphia property

Washington, DC (100% low slope)

Table 2.2. Washington, DC 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
Stormwater	N/A	$53.56	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**	**$38.28**	**$69.17**	**$124.68**

Baltimore (11% low slope and 89% steep slope)

Table 2.3. 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
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**

Philadelphia (100% steep slope)

Table 2.4. 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
Stormwater	N/A	N/A
Health	$1.73	$3.07
Climate change	-$0.02	$2.77
NET TOTAL	**$0.57**	**$5.84**

2.4 Phase 1 Conclusions

The Phase 1 report developed the first rigorous and fairly 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 cost-effectiveness of green roofs, rooftop PV, and solar hot water in the District is in large part dependent on financial incentives. However, as documented in the Phase 1 report, there are large additional economic benefits to these technologies, especially in the area of public health.

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

The potential for reductions in average daytime and peak summertime temperatures and improvements in air quality and public health indicates that a policy of extending cooling strategies across the roofs of entire low income areas of cities and to other built areas, including roads, pavement and sidewalks, 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. And for low income residents, the cost of paying utility bills in inefficient buildings is a far larger burden than that for the wealthy, so the potential benefits include broad and important fairness and equity benefits. Building on this report to undertake a low income area-wide analysis, broadened to include built surfaces in addition to roofs, would likely demonstrate large, low net cost opportunities to improve health, livability, and environmental footprint of low income residents and neighborhoods while cutting energy bills. This has led us to undertake analyses of the roof technologies, urban trees, and reflective pavements at the low income ward-level in three cities: Washington, DC; Baltimore, and Philadelphia. The balance of this report describes this work and findings.

3 Background

This section provides an overview of the technologies 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 technology specific sections and to 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 a number of 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) and air conditioners[iii] and urban morphology (the dimension and spacing of buildings that tend to trap urban heat).[5]

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. Surface UHIs are most intense during the day and in the summer, though still persist during the night.[6] Surface UHIs in much of the Northeast can be as high as 16°F on a summer day.[7] 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.[8]

There are two types of atmospheric UHIs: canopy layer (or near-surface) and boundary layer.[9] Boundary layer UHIs extend from the tops of trees and buildings to where the urban environment no longer effects the atmosphere. Canopy layer UHIs occur where people live, from the ground surface to the tops of trees and buildings. Canopy layer UHIs are the most common UHI discussed. Subsequently, when this report uses the term UHI, it refers to the canopy layer/near-surface UHI, unless otherwise specified.

A recent analysis by Climate Central studied the summertime UHI in 60 U.S. cities.[10] Using data from 2004 to 2013, it found the average summer daytime UHI in Washington, DC ("the District") is 4.7°F, in Baltimore is 2.7°F, and in Philadelphia is 3.8°F. Climate Central also analyzed the average decadal change in UHI from 1970 through 2013.[iv] Of the three cities analyzed in this report, Baltimore has the fastest increasing UHI at 0.66°F per decade, followed by Philadelphia at 0.53°F per decade, and the District at 0.42°F per decade.

The surface technologies analyzed in this report can help mitigate 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, the technology specific sections, and in the Appendix.

[iii] Heat given off by fuel combustion and air conditioners are often called "anthropogenic" heat.

[iv] 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

Earlier this year (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.[11] 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.[v] The District is ranked 9th, Philadelphia 10th, and Baltimore 12th. 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 and wetter conditions in the future.

3.2.1 The District

Even under low emissions scenarios, the District can expect increases in temperature, precipitation, and sea level rise due to climate change.[12] 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. 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).

In addition to higher temperatures, the District's Climate Projections and Scenario Development report predicts longer and more intense heat waves.[vi] 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. In other words, 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 increase. DOEE predicts the number of days per year with a heat index above 95°F will increase from a baseline of 29 to around 50 by the 2020s and between 70 and 80 by the 2050s. These temperature increases will put a severe strain on the city's infrastructure, including increasing cooling energy use, reducing comfort, and increasing risk of heat-related deaths, demonstrating the need to prioritize urban cooling measures (like those analyzed in this report) in policy making and planning.

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[v] 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.

[vi] Recent modeling studies show that heat waves exacerbate UHIs. (Dan Li and Elie Bou-Zeid, "Synergistic Interactions between Urban Heat Islands and Heat Waves: The Impact in Cities Is Larger than the Sum of Its Parts," *Journal of Applied Meteorology and Climatology* 52, no. 9 (September 2013): 2051–64, doi:10.1175/JAMC-D-13-02.1.)

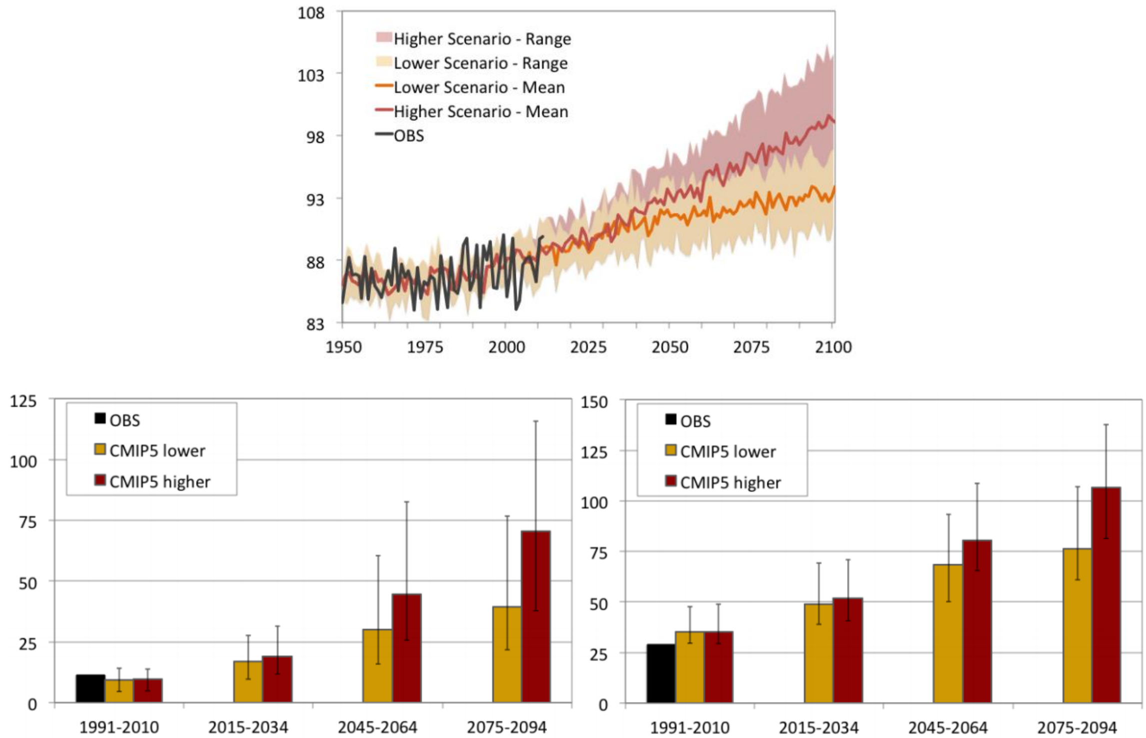

Figure 4. Average summer daytime high temperature in the District (top); number of days per year with maximum temperature above 95°F (bottom left); number of days per year with maximum heat index above 95°F (bottom right) ("OBS" stands for "observed", "CMIP5 lower" and "CMIP5 higher" designate low and high carbon emissions scenarios, respectively; error bars encompass the range of projections from the nine different global climate models used in 13)

DOEE predicts that extreme precipitation events will increase in frequency and intensity and that sea level rise will continue and even accelerate.[14] DOEE predicts the average number of days per year with total precipitation greater than 2 inches in a 24-hour period (currently 1 day per year) will increase to 3.5 days per year by the 2050s. Perhaps more importantly, the depth and frequency of "design" storms, which engineers and designers use to appropriately size stormwater infrastructure, will increase. Coupled with the projected sea level rise (0.6 to 1.9 feet by the 2050s),[15] this will put an enormous burden on the city's stormwater infrastructure, making it vital for the city to fully incorporate green infrastructure, such as green roofs and urban trees that provide additional benefits beyond stormwater runoff reduction, when making policy, planning, and investment decisions.

3.2.2 Baltimore

Baltimore is expected to become warmer and wetter throughout the 21st century. The State of Maryland's climate report predicts about 2°F of average summer warming by 2025 and 3°F to 4°F of average summer warming by 2050 (compared to 1990).[16] The report also predicts longer and more frequent heat waves and more days with higher maximum temperatures, especially in urban areas. Figure 5 below shows that the number of days with maximum temperature at or above 90°F in urban areas will roughly double from 40 days per year in the late 20th century to between 80 and 110 days per year by the late 21st century. MD can expect a similar trend for days with maximum temperatures at or above 100°F, with urban areas in MD experiencing 11 to 31 more days per year with maximum temperatures above 100°F by the end of the 21st century compared to the number of days in the late 20th century. That is between 3.75 and 8.75 times more days above 100°F by the end of the 21st century.

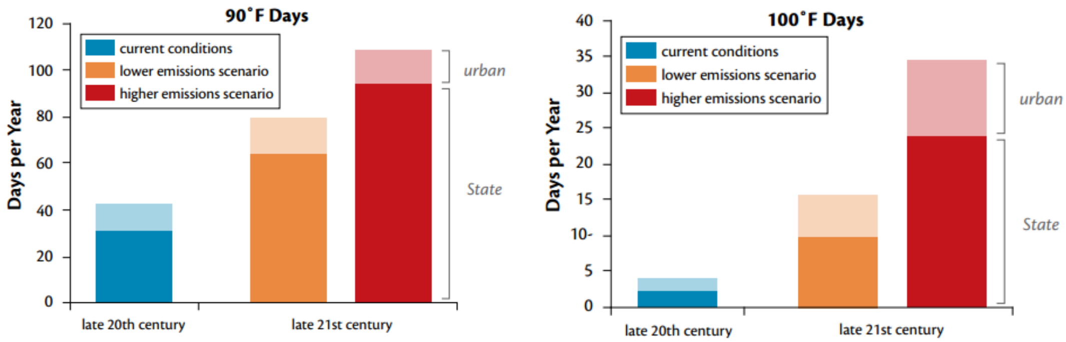

Figure 5. Number of days in Maryland with maximum daily temperatures reaching or exceeding 90°F and 100°F in the late 20th century and projected for the late 21st century under low and high carbon emissions scenarios[17]

Total rainfall amounts are projected to increase as well, with the greatest increase expected in the winter months. Extreme precipitation events are expected to be more intense and more common, increasing risk of flooding. Further compounding the potential for flooding, sea-level rise is also expected to impact coastal and tidal Maryland, including Baltimore.[18] The State of Maryland's most recent sea-level rise report estimates 1.4 feet of sea-level rise by 2050.[19]

These temperature increases will put a severe strain on the city's energy infrastructure, increasing cooling energy use, reducing comfort, and increasing risk of heat-related deaths. Furthermore, the combined impacts of increased precipitation and sea-level rise will increase the burden on the city's aging stormwater infrastructure. The consequences of a hotter and wetter urban environment demonstrate the need to prioritize urban cooling measures and stormwater management measures, like those analyzed in this report, in policy making, planning, and investment.

3.2.3 Philadelphia

As with the District and Baltimore, Philadelphia is expected to get warmer and wetter with climate change (under all projected emissions scenarios). Between 1961 and 2000, the average year-round temperature in Philadelphia was 54.4°F.[20] 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. The greatest warming is expected in the winter months, but summer temperatures will increase as well.

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.[21] 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-cold increase) and between 1 and 4 days per year above 100°F. Not surprisingly, what is defined "very hot" (95th percentile temperatures) and "extremely hot" (99th 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. For example, the maximum number of consecutive days above 90.2°F[vii] will increase from a baseline of 6 days to between 14 and 21 days by mid-century.[22] 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.

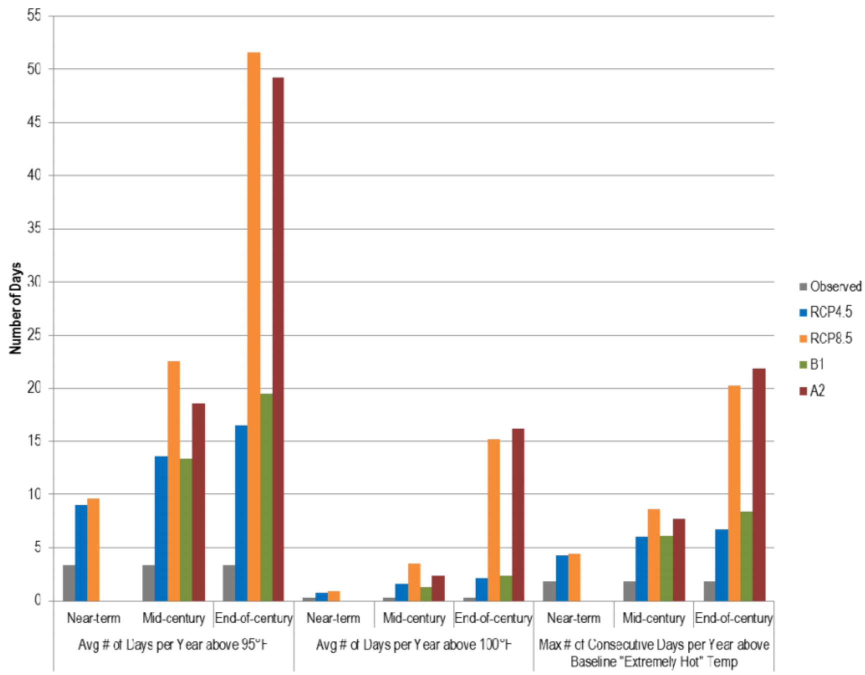

Figure 6. Projected temperatures extremes in Philadelphia (RCP4.5 and B1 are low emissions scenarios and RCP8.5 and A2 are high emissions scenarios)[23]

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.[24] The frequency of extreme precipitation events is expected to increase as well, but the intensity of extreme precipitation events should remain relatively stable. The height of the Delaware River, a tidal river that Philadelphia sits on, 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 between 2000-2004, Philadelphia is predicted to experience between 1 and 4.5 feet (12 and 54 inches) of sea-level rise by the 2080s.[25]

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, such as those analyzed in this report, in policy making, planning, and investment.

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

3.3 Overview of technologies

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

Reflective roofs (commonly referred to as "**cool**" **roofs**) are roofs with a higher solar reflectance than conventional roofs, which are dark and absorb a large majority of solar radiation that falls on them. Because of their higher solar reflectance, cool roofs absorb less solar radiation than conventional, dark roofs. This means that cool roofs do not get as hot, reducing heat transfer to the building below and to the urban environment and resulting 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, importantly, differ in the addition of plants, soil (called "growing media" or "growing medium"), and more robust waterproofing and drainage. Green roofs stay cool through evapotranspiration and shading. They also have higher thermal mass than traditional roofs, meaning green roofs take longer to heat up and cool down. Together this means that buildings with green roofs have lower summer cooling loads and lower winter heating loads. Evapotranspiration also cools the air, resulting in lower ambient air temperatures and air conditioning use, reducing energy costs. The plants and growing medium soak up some of the rain that falls on a green roof, which reduces stormwater runoff volumes and results in 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 7. Cool roof (top left);[26] green roof (top right);[27] solar PV (bottom)[28]

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 8. Reflective pavement on a parking lot[29]

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, respectively. Similar to green roofs, trees also cool the air through evapotranspiration, reducing summer ambient air temperature and cooling load. Also like green roofs, trees and the surrounding soil absorb rain water, which reduces stormwater runoff volumes, delays peak runoff time, and decreases peak runoff volume. For a more in-depth discussion of urban trees, refer to Section 8.

Figure 9. Urban street trees[30]

3.4 Overview of impacts

Four of the technologies this report analyzes are well established: cool roofs, green roofs, rooftop PV, and urban trees. Each technology 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 a 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 technologies 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 technologies, 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 technologies.

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. Akbari et al. (2001) provides an excellent description of these impact categories.[31] 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. Indirect effects result from city-wide changes in climate and are not specific to the buildings that install the technology. City climate-related indirect impacts require widespread deployment of technologies to have a material impact. One example of an indirect benefit is the reduced cooling load for buildings that results from ambient cooling. Another example of an indirect effect is reduced CO2 emissions from power plants that results from energy use reductions directly by the individual buildings and indirectly at the city level.

3.4.2 Energy and greenhouse gases

In the District, Baltimore, and Philadelphia, grid electricity sources are relatively dirty[32] because the power sources include a lot of fossil-fuel-based electricity generation 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 significant. Cool and green roofs directly reduce energy use for space conditioning by reducing heat gain and loss[viii] 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.[33] Rooftop PV also generally offsets grid electricity use during peak demand periods (summer afternoons) 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

[viii] Reduced heat loss only applies to green roofs.

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 Maryland (MD) and Philadelphia (PA), has a renewable portfolio standard that requires that a specific percentage of its energy generation come from renewable sources—the District, MD, and PA also have specific solar targets.[34] In the District, MD, and PA, 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. Ground-level ozone formation generally increases with higher air temperature, so lower summer air temperatures mean lower levels of ground-level ozone and decreased incidence of ozone-related health consequences (e.g., asthma, heart disease, and premature death).[35] Modeling studies demonstrate that ozone concentrations worsen with the higher temperatures caused by climate change.[36] Ozone reductions from ambient cooling due to deployment of these five technologies can help offset climate change-related increases. Green roof vegetation and urban trees can also scrub the air of ozone pollution and ozone precursors.

Ozone basics

Ozone is a secondary pollutant formed when its two primary precursors, volatile organic compounds (VOCs) and nitrogen oxides (NO_x), combine in the presence of sunlight. Ambient ozone concentration depends on a number of factors, including but not limited to temperature, relative humidity, solar radiation, and wind speed.[37] 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.[38]

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.[39] 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.

Numerous studies have examined the health effects of ozone exposure. 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.[40] 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 10).

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 10. The American Lung Association's summary of the EPA's findings on the health impacts of ozone[41] (Note: COPD stands for chronic obstructive pulmonary disease.)

Ozone and temperature

Climate change is expected to result in increased ozone pollution and consequent negative human health effects. For example, Bell et al. (2007) analyzed the effects of climate change on ozone concentrations in 50 U.S. cities and found that climate change can be expected to increase ambient ozone concentrations and thus harm human health.[42] 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.[43,ix] Few studies have examined the relationship between UHI mitigation and ozone concentration, and most focus on California.[44] 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 technologies also contribute to reductions in fine particle pollution from power plants and reductions in related health impacts (e.g., heart disease, asthma, and death).[45] Green roof vegetation and urban trees can also scrub the air of PM2.5 pollution.

$PM_{2.5}$ basics

There are two types of fine particles ($PM_{2.5}$). Primary particles are emitted directly into the atmosphere (most commonly from burning fossil fuels); secondary particles are formed through atmospheric chemical reactions of precursors.[46] Primary $PM_{2.5}$ largely consists of carbonaceous materials (elemental carbon, organic carbon, and crustal materials like soil and ash).[47] Major sources of primary particles

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[ix] These cost increases are in 2008$.

include fires, dust, agricultural processes, stationary fuel combustion (e.g., by electric utilities), motor vehicle operation, and industrial processes (e.g., metal smelters).[48] Secondary particles make up most of the $PM_{2.5}$ pollution in the U.S.[49] 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).[50] 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).[51] In the Northeast, the main components of fine particle pollution are organic carbon and sulfates.[52]

Health impacts of $PM_{2.5}$

Numerous studies examine the health effects of $PM_{2.5}$ exposure. 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 $PM_{2.5}$.[53] 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 11).

> **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 11. The American Lung Association's summary of the EPA's findings on the health impacts of $PM_{2.5}$[54] (Note: COPD stands for chronic obstructive pulmonary disease.)

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.[55] Furthermore, heat waves, which are expected to become more common with climate change, exacerbate urban heat islands (UHI).[56] 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.[57] 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.[58] Extreme heat events are projected to be more frequent, longer lasting, and more severe as the climate warms.[59] 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.[60] Furthermore, UHIs and climate change together are expected to further increase the number of extreme heat events in cities.[61]

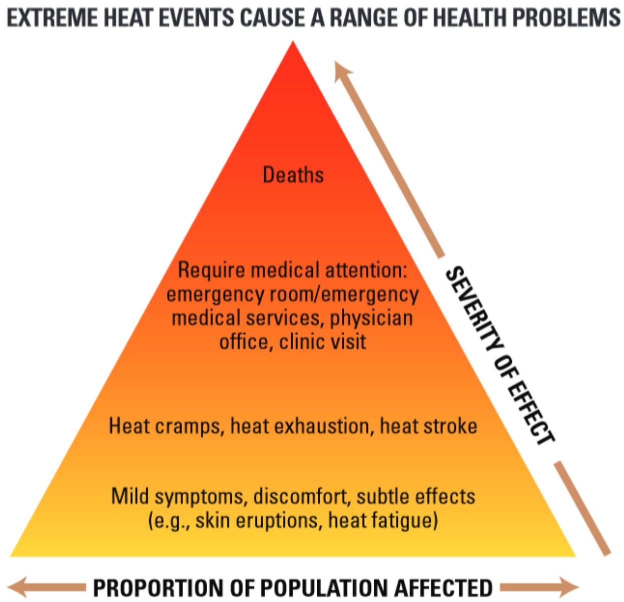

Figure 12. The health problems related to extreme heat[62]

In addition to elevated daytime temperatures due to UHIs, cities take longer to cool off at night and do not cool as much compared to rural areas. This means that urban populations often cannot recover from daytime heat and are thus more vulnerable to elevated temperatures in subsequent days.[63]

There are two ways the technologies analyzed in this study can impact heat-related mortality: by improving outdoor conditions (e.g., decreasing outdoor temperatures) and by improving indoor conditions (e.g., by reducing indoor temperatures). Modeling studies have shown that UHI mitigation technologies can decrease urban heat-related mortalities by improving outdoor conditions.[64] However, this report could not find any studies quantifying the heat-related mortality impact of changes in indoor conditions from the technologies analyzed in this report. 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. Furthermore, the impact of improved indoor conditions may be significant.[65]

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.[x] The DC 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.[66] More recently, a more sober 2014 analysis by the American Council for an Energy Efficient-Economy (ACEEE) estimated that a city-wide commitment to 26% energy use reduction could create 600 net new jobs in the District by 2020 and 1,400 net jobs by 2030.[67] Expanding the deployment of smart surfaces in the District, Baltimore, and Philadelphia would further expand the growth of green jobs.

Labor intensity of green energy tends to be higher than from conventional energy sources. In synthesizing 15 existing studies, Wei et al. (2010) found that all non-fossil fuel energy technologies they studied (including energy efficiency) create more jobs per unit energy than coal and natural gas.[68,xi] Regarding net job creation in cities, another advantage of green energy is that more jobs go to installation, operations, and maintenance compared with conventional power generation. Unlike centralized coal and natural gas plants, renewable sources provide local "distributed" employment.

For the District, Baltimore, and Philadelphia to realize the potentially large employment benefits of an expanded green economy, green jobs should 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.

3.5 Regions of analysis

This report analyzes Ward 5 in Washington, DC, the neighborhood cluster of Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights in Baltimore, and North Philadelphia in Philadelphia. Region selection rationale is explained in the Appendix. The following sections present maps and selected characteristics of each region.

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[x] 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.

[xi] 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.

3.5.1 Washington, DC: Ward 5

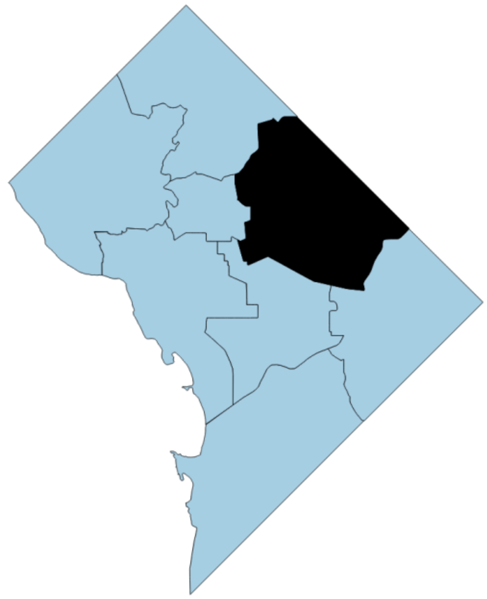

Figure 13. Washington, DC map; Ward 5 is black (base map from DCGIS Open Data,[69] map created with QGIS[70])

Table 3.1. Selected Ward 5 characteristics compared to Washington, DC

Characteristic	Washington, DC	
	Ward 5	City
Population (2010)[71]	74,308	601,723
Income[72]		
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)[73]	10.4	61.05
Building footprint (% region)[74]	14.4%	15.6%
Paved area (roads, parking, sidewalks) (% region)[75]	23.1%	28.2%
Tree canopy (% region)[76]	28.6%	36.0%

3.5.2 Baltimore: Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights

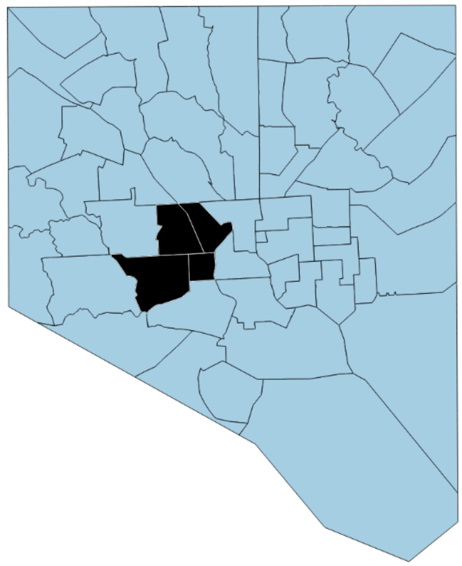

Figure 14. Baltimore map; region of analysis is black (base map from Open Baltimore,[77] map created with QGIS[78])

Table 3.2. Selected Baltimore low income region characteristics compared to Baltimore

Characteristic	Baltimore	
	Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights	City
Population (2010)[79]	48,209	620,961
Income[80]		
Median income	$24,255	$41,819
Percent of population below poverty line	42.4%	24.2%
Unemployment rate	23.9%	13.9%
Land use		
Area (square miles)[81]	3.1	80.9
Building footprint (% region)[82]	25.6%	15.8%
Paved area (roads, parking, sidewalks) (% region)[83]	53.1%	34.5%
Tree canopy (% region)[84]	14.5%	27.4%

3.5.3 Philadelphia: North Philadelphia

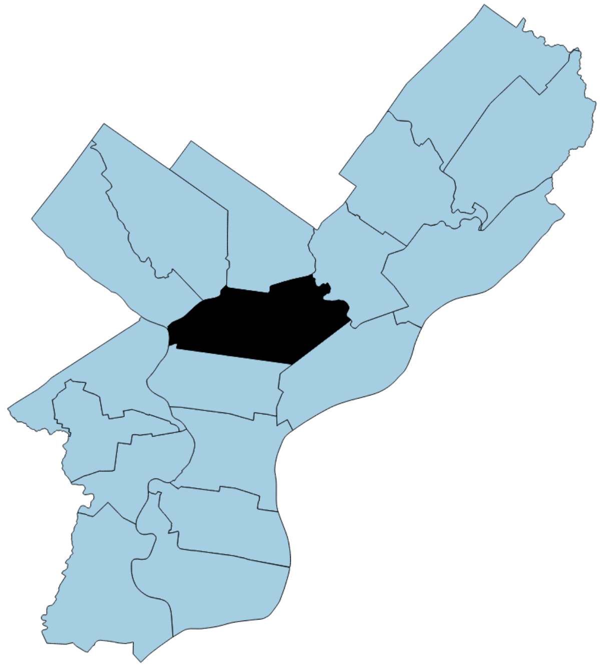

Figure 15. Philadelphia map; North Philadelphia is black (base map from OpenDataPhilly,[85] map created with QGIS[86])

Table 3.3. Selected North Philadelphia characteristics compared to Philadelphia

Characteristic	Philadelphia	
	North Philadelphia (2035 District)	City
Population (2010)[87]	137,849	1,526,006
Income[88]		
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)[89]	8.6	134.1
Building footprint (% region)[90]	27.6%	18.7%
Paved area (roads, parking, sidewalks) (% region)[91]	32.9%	26.6%
Tree canopy (% region)[92]	10.1%	20.0%

4 Cool roofs

The sections below explore 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 increased energy use for heating and glare.

4.1 Cool roof basics

Cool roofs are roofs with a higher solar reflectance[xii] (or albedo) than conventional dark roofs, which have a low solar reflectance. Because of their higher solar reflectance, cool roofs reflect more sunlight and so absorb less solar radiation than conventional, dark roofs. This means that cool roofs do not get as hot, reducing heat transfer to the building below and to the urban environment. Figure 16 below illustrates these concepts.[xiii]

Cool roofs typically reflect the majority of solar radiation that reaches their surface—some 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.

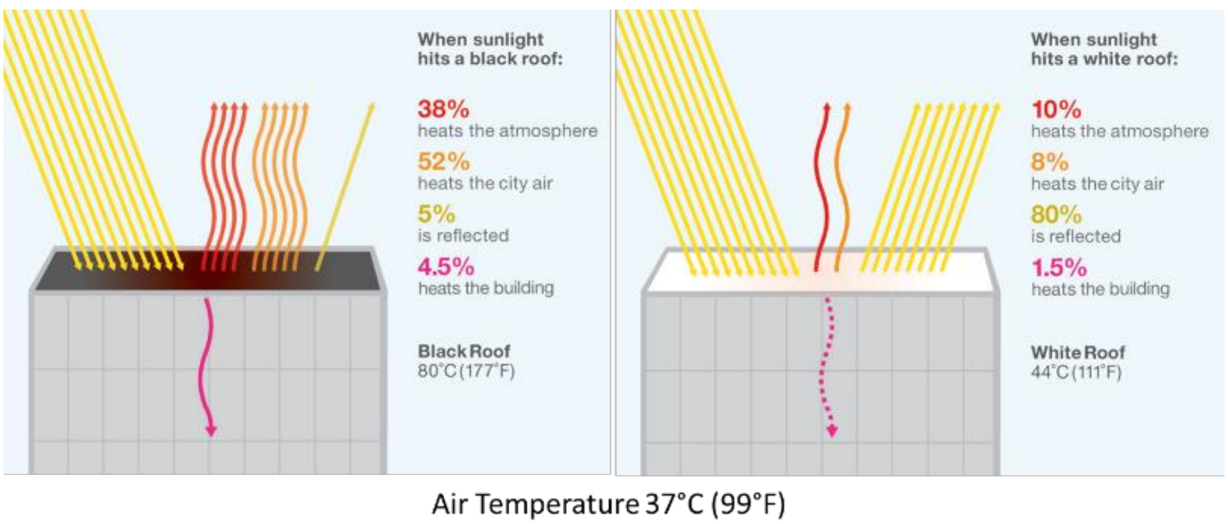

Figure 16. Comparison of a black roof and white roof on a summer afternoon (numbers do not sum due to rounding)[xiv]

[xii] Solar reflectance 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.
[xiii] The solar reflectance of the black roof in Figure 16 is 0.05 and that of the white roof is 0.80.
[xiv] Adapted from Lawrence Berkeley National Laboratory Heat Island Group

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[xv] are common on commercial buildings, multifamily housing, and are also used on row homes. Common types of low slope roofs are built-up roofing, modified bitumen, and membrane roofing. The most common cool roof options for low slope roofs are coatings and membranes.[xvi] Steep slope roofs[xvii] 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 farther behind in development compared to cool low slope roofs.

As cool roofs age, their solar reflectance changes due to weathering and because they accumulate dirt, particulates, and potentially, 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,[93] which is a nonprofit membership organization that maintains credible, independent roof performance ratings and data and provides industry-wide performance testing and rating.

Conventional roofs have solar reflectances ranging from 0.05-0.20, depending on type.[xviii] 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 low slope cool roofs have an aged albedo of 0.65. In 2025 (analysis year 10), this report assumes solar reflectance of newly installed and replaced roofs is 0.70, 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. 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. Currently, most cool steep slope products achieve aged albedos around 0.25.[xix] However, it is currently possible to achieve roof tile aged albedos of 0.35.[94] Given the early developmental stage of steep slope cool roofs, 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

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[xv] No more than 2 inches of vertical rise over 12 inches of horizontal run (U.S. Environmental Protection Agency (EPA), "Cool Roofs," Reducing Urban Heat Islands: Compendium of Strategies, 2008, http://www.epa.gov/sites/production/files/2014-06/documents/coolroofscompendium.pdf.)

[xvi] For more detailed description see: Ibid.; Global Cool Cities Alliance (GCCA) and R20 Regions of Climate Action (R20), "A Practical Guide to Cool Roofs and Cool Pavements," January 2012, http://www.coolrooftoolkit.org/wp-content/pdfs/CoolRoofToolkit_Full.pdf.

[xvii] Greater than 2-inch rise over 12-inch run (U.S. Environmental Protection Agency (EPA), "Cool Roofs.")

[xviii] For example see Global Cool Cities Alliance (GCCA) and R20 Regions of Climate Action (R20), "A Practical Guide to Cool Roofs and Cool Pavements," January 2012, http://www.coolrooftoolkit.org/wp-content/pdfs/CoolRoofToolkit_Full.pdf.

[xix] Based on analysis of Cool Roof Rating Council rated product database (Cool Roof Rating Council, "Rated Products Directory," accessed October 21, 2015, http://coolroofs.org/products/results.)

steep slope cool roofs is 0.40 starting in 2025, reflecting continued innovation of steep slope cool roof materials. Cool steep slope roofs experience a greater albedo increase in 2025 (0.15) compared to cool low slope roofs (0.05) because cool steep slope roof options are currently earlier in development than cool low slope roof options. This report assumes a greater increase in cool steep slope roof albedo in 2025 compared the assumed increase in low slope cool roof albedo in 2025 because steep slope roofs 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-2025**	**Cool roof Post-2025**
Low slope	0.15	0.65	0.70
Steep slope	0.10	0.25	0.40

4.1.2 Installation and maintenance costs

Cool roof installation and maintenance costs presented in this report are based on current literature and on guidance from roofing professionals.[95] Roof replacement, rather than restoration, is the norm when a roof needs repair (e.g., when there is a leak).[96] Low slope cool roofs have been around long enough that they typically are the same or only marginally higher cost than their conventional equivalent.[97] This report assumes a low slope cool roof cost premium of $0.15 per square foot, reflecting the need for a cost premium to drive innovation of increasingly cooler roofs. There is typically a higher cost premium for steep slope cool roofs. Based on Urban and Roth (2010), this report assumes the steep slope cool roof cost premium of $0.55 per square foot.[98] For low slope and steep slope cool roofs, this report assumes a constant cost premium necessary to drive continuous albedo improvements. Table 4.2 summarizes cool roof installation cost premiums.

Although high albedo roofs experience less thermal expansion and contraction than conventional roofs, and so likely have longer lives,[99] this report conservatively assumes cool roofs have the same lifetime as conventional roofs (20 years). This assumption is consistent with assumed values in the literature (e.g., Sproul et al. 2014).[100] 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 insulation and the condition of the existing roof.[xx] 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

[xx] 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.

it is uncommon and usually not cost-effective.[xxi] Table 4.2 summarizes cool roof maintenance cost premiums.

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 Benefits of cool roofs

4.2.1 Direct energy

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 more energy for heating in the winter. The undesirable loss of heat gain in the winter (called the "heating penalty") in the lower 48 states typically does not come close to offsetting cooling energy savings.[xxii] Section 4.3 discusses the heating penalty in more detail.

Cool roofs reduce electricity demand, particularly peak electricity demand, which benefits utilities (because it reduces peak loads) and utility customers (because peak electricity and demand charges can be expensive). Cool roofs may also impact air intake temperature of heating ventilation and air conditioning (HVAC) systems, reducing cooling energy consumption. This report does not include these potentially significant benefits in cost-benefit results due to limitations in data availability. For explanation of these benefits see Section 4.3.

Factors that impact direct energy savings

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

Heat transfer through the roof is diminished by more or better insulation, so buildings with well insulated roofs experience lower heat transfer than buildings with less well insulated roofs. Heat

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[xxi] For example, Sproul et al. (2014) conclude that power washing is not cost-effective. (Julian Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States," *Energy and Buildings* 71 (March 2014): 20–27, doi:10.1016/j.enbuild.2013.11.058.)

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

[xxiii] 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.

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.[102] Therefore, the more floors a building has, the smaller the percentage impact of a cool roof on *total* building energy consumption.

Direct energy savings depend on climate. For example, in a broad modeling study, Levinson and Akbari (2010) found that cooling energy savings generally increase in warmer climates (typically further south), while heating penalties generally increase in cooler climates (typically further north).[103] They 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 one would mean that the savings and penalty exactly offset each other).[xxiv] In the Mid-Atlantic, the load change ratio for office buildings ranged 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, Baltimore, or Philadelphia.[xxv] The load change ratio is typically higher for residential properties for reasons discussed in Footnote xxiii.

4.2.2 Ambient cooling and indirect energy

Because of their increased reflectivity, cool roofs stay cooler than conventional roofs, which reduces heat transfer to the urban environment. At large scale, this can reduce urban air temperatures, helping to mitigate the UHI, or alternatively offsetting part of the warming expected from climate change.

Santamouris (2014) performed a literature review of UHI mitigation studies and found a relationship between urban albedo and air temperature.[104] Santamouris (2014) found that for each 0.1 increase in urban albedo, average urban air temperature decreases by 0.3°C and peak temperature decreases by 0.9°C.[105] The relationship between urban albedo and average air temperature is much better defined than the relationship between urban albedo and peak air temperature.[xxvi]

UHIs are highly location specific, so it is preferred to have a location specific ambient cooling analysis. Fortunately, a few recent studies examined UHI mitigation in the District, Baltimore, and Philadelphia.[106] All studies found albedo increases are effective at reducing UHIs in the three cities. These studies are discussed in more detail in 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 through energy use reductions (this section) and related GHG emissions reductions (Section 4.2.3), improvements in air quality (Sections 4.2.4.1 and 4.2.4.2), and declines in heat-related mortality (Section 4.2.4.3).

[xxiv] A load change ratio less than 1 means that the cooling lead decreased more than the heating load increased, resulting in a net energy savings.

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

[xxvi] Santamouris (2014) notes the R^2 of the regression for urban albedo and average air temperature is high, but notes data for urban albedo and peak air temperature is more scattered. Santamouris (2014) does not report R^2 for the relationship between urban albedo and peak air temperature.

Indirect energy

A city-wide switch from conventional, dark roofs to cool roofs can have a large impact on urban summer air temperature. This air temperature reduction can lead to city-wide net energy savings.[xxvii] The cooling effect is apparent in the cooling season (summer) and the heating season (winter), but it is 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, Akbari and Konopacki (2005) estimate that indirect electricity savings from city-wide installation of cool roofs and shade trees are approximately 17% of total (direct and indirect) electricity savings and indirect gas penalties are approximately 20% of total (direct and indirect) gas penalties.[107,xxviii]

The scale of indirect energy savings/penalties from cool roof installation depends on the building stock in a city. 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 will decrease. Building occupancy patterns also play a role in the scale of the indirect energy impact.[xxix]

4.2.3 Climate change mitigation

Greenhouse gas emissions reductions

It is virtually universally accepted in the scientific community that anthropogenic (human-caused) greenhouse gas (GHG) emissions are the dominant factor driving global climate change.[108] 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.[109] Reducing energy used for space conditioning through cool roof installation reduces building-related GHG emissions.

Global cooling

Cool roofs reflect more sunlight back into space compared to a conventional roof, thereby causing negative radiative forcing[xxx] on the earth and reducing global warming. Studies have found that increasing the albedo of one square foot of roof by 0.25 is equivalent to a onetime GHG offset of between 5.8 and 7.6 kg CO2e.[110] Because the global cooling benefit can be significant, this analysis includes this impact.[xxxi]

The impact of roof albedo changes on Earth's radiative forcing remains an active area of research. One of the key questions to be answered is what impact surface albedo changes have on cloud formation.[111]

[xxvii] Cooling energy savings as well as smaller heating penalties.
[xxviii] Akbari and Konopacki (2005) include electric heating penalties in the electricity savings calculations.
[xxix] 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.
[xxx] Radiative forcing is the difference between the radiant energy received by the Earth (from the Sun) and the energy Earth radiates to space.
[xxxi] One peer-reviewed journal study included the benefit of global cooling in a cost benefit analysis. (Julian Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States," *Energy and Buildings* 71 (March 2014): 20–27, doi:10.1016/j.enbuild.2013.11.058.)

However, clouds are one of the most complex aspects to model so some urban-climate scientists discount the impact of urban albedo changes on cloud formation[xxxii,112] and this is outside the scope of this report.

This report describes the methods used to estimate cool roof climate change mitigation impact in Section 9.5. Figure 17 shows cool roof climate change mitigation pathways.

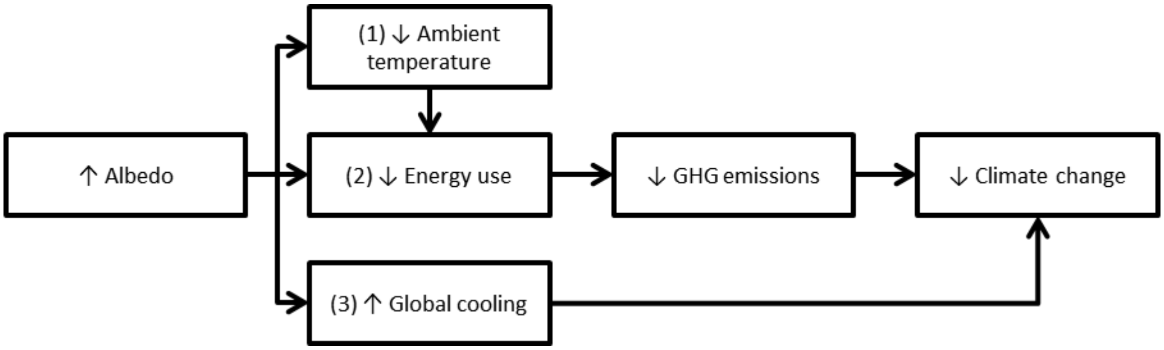

Figure 17. Cool roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

4.2.4 Improved air quality and health

4.2.4.1 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 the background section, the chemical reactions that form ozone are temperature dependent, so decreasing ambient temperature decreases ambient ozone concentration. Decreasing ambient temperature also indirectly reduces summertime building energy use. Cool roofs directly reduce summertime building energy consumption by mechanisms discussed in Section 4.2.1 above. Decreased summertime building energy use leads to decreased ozone precursor emissions. In general, as precursor emissions decline, ozone formation declines as well. Figure 18 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 and pathways in more detail in Section 9.6.1 and in the Appendix.

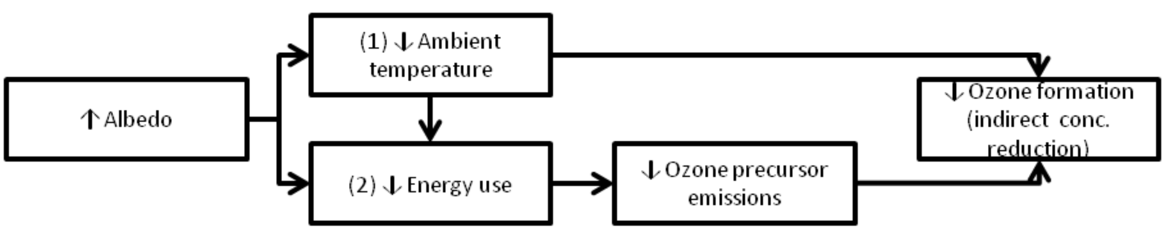

Figure 18. Cool roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

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xxxii And counter by noting that urban areas already increase cloud formation because of particulates they produce.

4.2.4.2 Cool roofs and $PM_{2.5}$

Cool roofs reduce $PM_{2.5}$ pollution indirectly by decreasing building energy use and indirectly by decreasing ambient temperature, which in turn reduces building energy use. Reducing building energy use results in decreased emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors, decreasing primary and secondary $PM_{2.5}$ pollution. Figure 19. shows the $PM_{2.5}$ concentration reduction pathways of cool roofs. This report describes $PM_{2.5}$ impact estimation methods in Section 9.6.2 and in the Appendix.

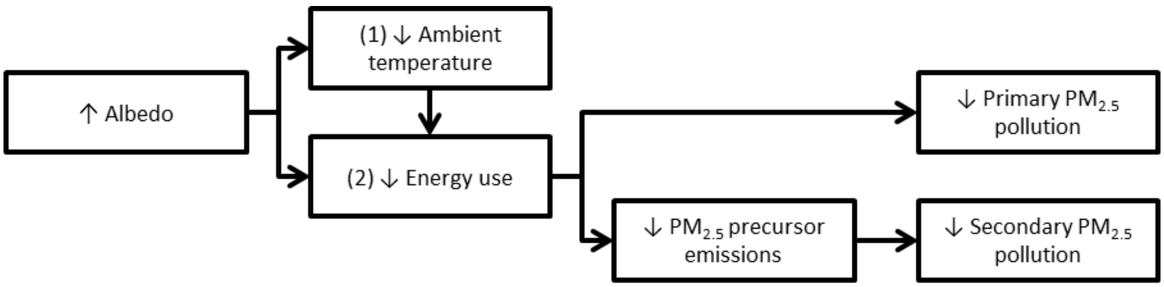

Figure 19. Cool roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

4.2.4.3 Heat-related mortality

Modeling studies have shown that UHI mitigation technologies (e.g., cool roofs and green roofs) can decrease urban heat-related mortalities through changes in ambient air temperature.[113] As noted in Section 3.4.4.3, there are two pathways by which cool roofs can reduce heat-related mortality: by (1) improving outdoor temperature conditions and (2) improving 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 to include in this report. However, as Vanos et al. (2014) notes these could be significant.[114] Because this analysis does not include the heat-related mortality impact of cool roofs from improving indoor conditions, any heat-related mortality benefit estimates are conservative (i.e. underestimate the likely benefits). This report describes heat-related mortality benefit estimation methods in Section 9.6.3 and in the Appendix.

4.2.5 Cool roofs and employment

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

4.2.6 Other benefits of cool roofs

Increased roof life

It is reasonable to assume that cool roofs could last longer than conventional roofs due to reduced thermal expansion and reduced UV radiation absorption.[115] However, in the absence of sufficient data, this report does not include this benefit in cost-benefit estimates.

Reduced HVAC air intake temperature

Another 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 incoming air. This potential benefit is little studied and not well quantified. Wray and Akbari (2007), the only peer-reviewed study this report could find on this topic, estimated a cool roof reduced energy use of a test roof-top air conditioner by between 0.3% and 0.6%.[116]

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 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 are independent of number of floors and could have a significant impact on an entire buildings' energy consumption and, if possible, should be included in future estimates of the energy consumption impact of cool or green roofs, and deserves further research.

Reduced peak electricity demand

Peak roof surface temperatures generally coincide with peak electricity demand, which generally occurs on weekday afternoons during the cooling season (summer).[117] Because cool roofs have lower peak roof surface temperatures, buildings with cool roofs will experience reduced peak electricity demand.[xxxiii] Ambient cooling also contributes to peak electricity demand reductions.[118] Peak electricity demand reductions mean reduced consumption during periods with higher electricity rates (where there are time of use rates) and reduced capacity charges (e.g., for large commercial and industrial buildings), so reduced peak demand can provide significant consumer savings. However, because of limitations in the Green Roof Energy Calculator (GREC)[119] this analysis does not quantify the benefits of peak electricity demand reductions, and energy benefit calculations are conservative as a result.[xxxiv]

Downwind cooling

There is modeling evidence that reducing UHI in cities can reduce UHIs downwind.[120] Zhang et al. (2011) modeled an extreme UHI event in Baltimore in 2007.[121] Their model results showed that hot air from upwind urbanization (i.e., in the District and the areas between the District and Baltimore) contributed to as much as 25% of Baltimore's UHI, or 1.25°C for the event modeled. The authors note the contribution of the District and other urban areas to Baltimore's UHI partially depends on wind direction, so one cannot always assume that reducing the UHI in the District and other urban areas will reduce Baltimore's UHI. Due to the limited number of studies estimating the potential downwind cooling impacts of upwind urban cooling, this report does not include downwind cooling benefits in cost-benefit calculations.

Reduced stormwater runoff temperature

Because roofs absorb more solar radiation than most natural surfaces, they reach much higher temperatures. During a storm event, heat is transferred to rain that falls onto a roof, increasing

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[xxxiii] Based on a sample of nine cool roof studies, EPA (2008a) 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.

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

stormwater runoff temperatures. Stormwater runoff temperatures spike at the beginning of storm events and decrease as rain cools urban surfaces.[122] Increased stormwater runoff temperatures can cause temperature spikes in local waterbodies, though this impact is hard to quantify and value. Cold-water aquatic ecosystems (e.g., cold-water streams home to trout) can be particularly sensitive to heated runoff.[123] Given the large uncertainty and lack of research in this area, this analysis does not include the potential benefit of reduced stormwater runoff temperature in cost-benefit calculations.

Increased PV efficiency

Cool roofs may enhance PV performance. PV panel efficiency degrades slightly with higher panel temperature,[xxxv] so lower near-roof air temperatures on cool roofs may increase PV efficiency. There is currently no convincing work that estimates the impact of cool roofs on PV power output, so this benefit is not included in cost-benefit calculations.

4.3 Potential drawbacks of cool roofs

Increased heating costs

The undesirable loss of heat gain in the winter (called the "heating penalty") typically does not come close to offsetting cooling energy savings[124] 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 (which would affect both cool and conventional dark roofs). Furthermore, peak demand for heating typically occurs after the sun goes down or just as the sun rises—which is when conventional and cool roofs are roughly the same temperature.[xxxvi]

Ambient cooling will also lead to a slight heating penalty, though cooling energy savings more than make up for this penalty. As with the direct heating penalty, the ambient cooling produced by cool roofs in the heating is small because of reduced solar intensity, shorter days, increased cloudiness, and the potential for snow coverage. Both heating (direct and indirect) penalties are included in energy cost savings estimates, climate change mitigation estimates, and $PM_{2.5}$ reduction estimates.

Recent observational and modeling studies from Princeton University show insulation levels are the dominant factor controlling heating needs during the winter for low slope roofs.[xxxvii,125] The studies conclude that white roofs overall are advantageous despite the higher number of heating degree days than cooling degree days in the Northeastern United States.[xxxviii] This work suggests that much of the heating penalty from cool roofs can be minimized by increasing insulations levels.

Downwind warming

Though UHI mitigation leads to downwind cooling, it could also lead to small, atypical pockets of downwind warming. Modeling studies of the District and Baltimore found that urban cooling reduced the sea breeze (which bring cool ocean air inland) because it reduces the land-sea temperature

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[xxxv] All else equal, higher PV efficiency means greater electricity generation.
[xxxvi] 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.
[xxxvii] They found albedo was the dominant factor controlling cooling energy needs during the summer.
[xxxviii] The District, Baltimore, and Philadelphia all have higher numbers of heating degree days than cooling degree days.

differential.[126] The studies found the warming occurs outside the District and Baltimore and is small—e.g., the warmed areas are still cooler than the cities. Because the effect is small, it is not included in cost-benefit calculations in this report. It is also highly location specific, so cooling of many cities, particularly inland cities, will likely not cause downwind warming that is related to a reduced sea breeze.

Glare

Glare from roofs that reflect a large fraction of visible light (e.g., a bright white roofs) might disturb occupants of nearby taller buildings.[127] In situations where this is a concern, cool-colored roofs (discussed in Section 4.1.1) are a good alternative. This should not be a concern for current and near-future steep slope cool roofs as the vast majority are cool-colored[xxxix] already. This is likely a small impact and is also highly location specific, so it is not included in cost-benefit calculations in this analysis.

4.4 Cool roof impact summary

Table 4.3 below summarizes the costs and benefits of green roofs included in the cost-benefit results of this report. There are more benefits than costs excluded from cost-benefit results, and excluded benefits 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

[xxxix] Cool-colored roofs have to have the same color as standard-colored roofs, but have high solar reflectance in the near-infrared band of sunlight, which makes up more than half of sunlight. This is discussed in Section 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, and reduced stormwater runoff. Other benefits include downwind cooling, reduced stormwater runoff temperature, increased amenity and aesthetic value, and increased biodiversity. Potential drawbacks include ambient warming if not well maintained, increased humidity, and downwind warming.

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 (where the plants grow) on top of conventional roofing and water proofing systems.[128] Figure 20 below shows an example of a conventional roofing structure and two green roof structures (one without a drainage system and one with a drainage system).[xl] 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.

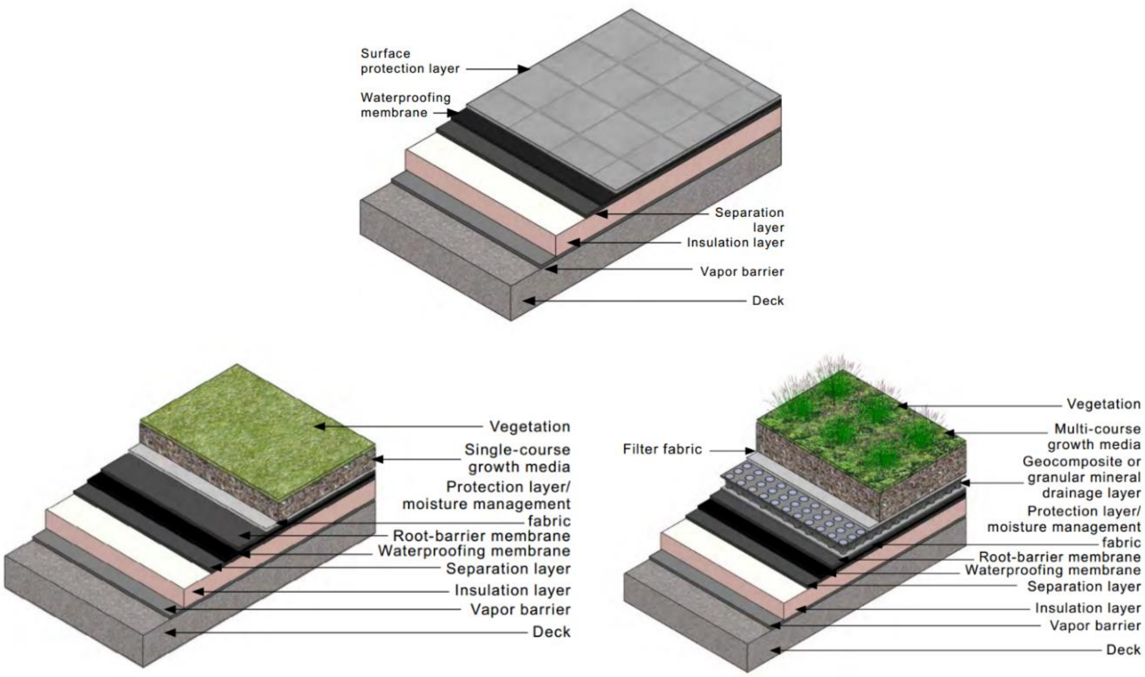

Figure 20. Examples of a conventional roof structure (top), green roof structure without a drainage layer (bottom left), and green roofs structure with a drainage layer (bottom right)[129]

[xl] For more discussion on green roof systems, good resources are: U.S. Environmental Protection Agency (EPA), "Green Roofs," Reducing Urban Heat Islands: Compendium of Strategies, 2008, http://www.epa.gov/sites/production/files/2014-06/documents/greenroofscompendium.pdf. and 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.

There are two general types of green roof systems: (1) built-in place and (2) modular.[130] 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 removed if there are leaks or other issues; however, they are typically more expensive and may negatively impact green roof performance (e.g., because of spacing between trays).[131] There is limited research into the performance differences between the two green roof system types,[132] so this 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 6 inches, able to support a wider variety of and larger plants (like shrubs and sometimes small trees), and often accessible to the public. However, they are heavier and more expensive to install and maintain. Extensive green roofs, on the other hand, typically have soil depths between 3 inches to 6 inches, support herbaceous groundcover plants (sedums are common), and are usually not accessible to the public. Extensive green roofs are lighter and less expensive to install and maintain compared to intensive green roofs.[xli] Extensive green roofs are by far the most common green roof type.[133] Figure 21 below shows examples of an extensive and intensive green roof.

Figure 21. Example of extensive green roof (left) and intensive green roof (right)[134]

[xli] For more discussion on the types of green roofs, good resources are: U.S. Environmental Protection Agency (EPA), "Green Roofs," Reducing Urban Heat Islands: Compendium of Strategies, 2008, http://www.epa.gov/sites/production/files/2014-06/documents/greenroofscompendium.pdf. and 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..

5.1.2 Installation and maintenance costs

We assume all green roofs are of the extensive type, which are the most common type of green roof and have relatively shallow growing media. Additionally, we assume that green roofs have a life of 40 years. This assumption is consistent with other published cost-benefit analyses.[135] Because the cost-benefit analysis runs for 40 years, green roofs are installed once (at the beginning of the analysis) and are not replaced with a new green roof during the analysis period.

Green roof installation and maintenance costs are based on current literature and on guidance from roofing professionals.[136] This report assumes the additional cost of a green roof compared to a conventional roof is $15 per square.[xlii] This report assumes that starting in 2025 the green roof cost premium decreases to $10 per square foot because of a more competitive market and increased market size.

Maintenance for 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.[xliii] 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. However, permanent irrigation can be installed on extensive green roofs if desired.[xliv] It will increase the initial and annual maintenance costs, but can also increase benefits (as discussed in Sections 5.2.1 5.2.2).

This report assumes establishment period maintenance premiums of $0.46 per square foot per year.[137] After the establishment period, the overall maintenance cost will reduce by about 30 percent because less work is required to maintain the roof.[138] Therefore, post-establishment period maintenance costs $0.31 per square foot per year. This report assumes the establishment period lasts three years, so the post-establishment period maintenance take 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.[xlv]

[xlii] Green roof cost per square foot decreases as roof area increases (GSA, 2011). In addition, as the green roof industry matures, the cost per square foot of green roofs should decrease due to economies of scale.

[xliii] GSA (2011) 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. (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.)

[xliv] 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.

[xlv] 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 5.1. 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 Green roof benefits

5.2.1 Direct energy

There are three mechanisms by which green roofs impact direct energy consumption: (1) by increasing roof surface evapotranspiration rates, (2) by shading the roof surface, and (3) by increasing the thermal mass and thermal resistance of the roof.[139] Figure 22 below illustrates the three processes. Combined, these three mechanisms mean that green roofs stay cooler than conventional roofs during the summer—the temperature difference can be as much as 50 °F[xlvi]—leading to cooling energy savings. The thermal mass and thermal resistance provided by green roofs help save on heating energy costs in the winter as well.

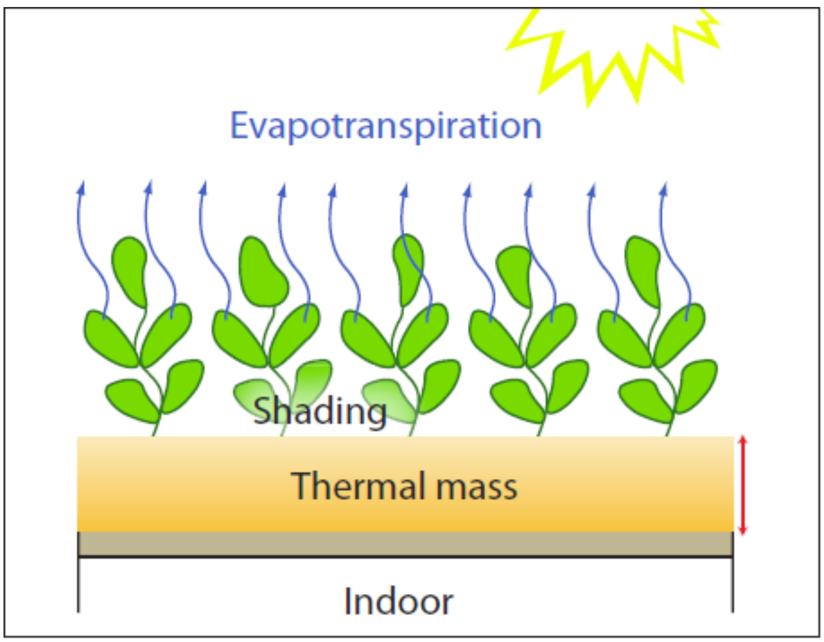

Figure 22. Green roof direct energy benefit features[140]

[xlvi] 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. (U.S. Environmental Protection Agency (EPA), "Green Roofs," Reducing Urban Heat Islands: Compendium of Strategies, 2008, http://www.epa.gov/sites/production/files/2014-06/documents/greenroofscompendium.pdf.

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 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 5.2.7.[xlvii]

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. Water absorbed by green roof vegetation and soil is converted into water vapor using energy from the sun (and to a lesser extent energy in the soil and the surrounding air).[xlviii] 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.

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 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. Sun et al. (2014) studied the impact of green roof irrigation on cooling requirements.[141] They found that, in general, irrigating green roofs increases their evapotranspiration rates—and thus the latent heat transfer away from the roof—increasing the cooling

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

[xlviii] 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. (U.S. Geological Survey (USGS), "Evapotranspiration - The Water Cycle," August 7, 2015, http://water.usgs.gov/edu/watercycleevapotranspiration.html; Julian Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States," *Energy and Buildings* 71 (March 2014): 20–27, doi:10.1016/j.enbuild.2013.11.058.)

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

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 energy available for evapotranspiration (e.g., because solar energy is less available in winter) and plants are less active or are inactive.[l] This reduces the cooling potential of green roofs in this season, so the winter heating penalty caused by evapotranspiration is minimal. The evapotranspiration benefit also increases with air movement because humid air is moved away, making way for drier air, thus increasing evapotranspiration potential.

Shading

Green roof vegetation shades the growing medium (soil), which reduces the solar energy absorbed by the growing medium and results in lower surface temperatures compared to a conventional roof. This lower surface temperature due to shading decreases the amount of heat transferred to the building below and results in lower cooling energy use. The size of the shading impact depends on the type of green roof. Extensive green roof plants provide less shade than intensive green roof plants, and thus less shading benefit.

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

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,[li] green roofs store more heat and take longer to absorb and release heat than conventional roofs. One consequence of this is decreased and delayed heat transfer down through the green roof, slowing heat transfer 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.[lii] This means that less heat is transferred through the roof to the building below, so during the cooling season air conditioning needs are lower than for a similar building with a

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[xlix] 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."
[l] In the northern part of the U.S., evapotranspiration typically begins in April, reaches a peak in June/July, and decreases in October. (R.L. Hanson, "Evapotranspiration and Droughts," in *National Water Summary 1988-89--Hydrologic Events and Floods and Droughts*, U.S. Geological Survey Water-Supply Paper 2375 (Washington, D.C: U.S. Government Printing Office, 1991), 99–104.)
[li] Thermal mass is the ability of a material to absorb and store heat energy.
[lii] Because they heat up slower than conventional roofs, the membrane of a green roof (where the heat transfer between the roof and building occurs) reaches peak temperature after a conventional roofs, reducing peak cooling loads.

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.[142]

Green roofs also provide a small insulation benefit to the building below.[143] The amount of thermal resistance (insulation) provided by green roofs depends on the thickness of the growing medium—a thicker growing medium generally means greater insulating properties—and the moisture content in the growing media—as moisture content increases, insulation value decreases.[144] This is a small benefit, so the effect of soil moisture on the insulating properties of an extensive green roof is minimal and not included in cost-benefit calculations in this report.

Non-green roof factors

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

5.2.2 Ambient cooling and indirect energy

Because of evapotranspiration and shading, green roofs are typically cooler than conventional roofs, reducing heat transfer to the urban air. If green roofs are installed at large scale, this reduces urban air temperatures, helping to mitigate the UHI, or alternatively countering part of the warming expected with climate change.

A recent modeling study sheds light on the general concepts of green roof urban cooling. Sun et al. (2013) found that solar radiation and green roof soil moisture are the main determinants of green roof outdoor thermal performance.[145] As solar radiation increases, the green roof ambient cooling benefit decreases, but is not eliminated. Generally, as soil moisture increases, sensible (what we feel) heat transfer to the urban air decreases—i.e., green roof ambient cooling benefit increases.[liii] Sun et al. (2013) also found that relative humidity does not show a strong impact on green roof ambient cooling benefit.[146]

Compared to the numerous studies examining the impacts of cool roofs, fewer studies have examined the city-wide impact of green roof installation. Two early studies, Liu and Bass (2005), which studied Toronto, and Rosenzweig et al. (2006), which studied New York City, found air temperature reductions from green roof installation.[147] 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,[148] Baltimore,[149] and Philadelphia,[150] all of which generally found that

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[liii] A recent modeling study demonstrates the importance of green roof soil moisture content. Li et al. (2014) 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. (Dan Li, Elie Bou-Zeid, and Michael Oppenheimer, "The Effectiveness of Cool and Green Roofs as Urban Heat Island Mitigation Strategies," *Environmental Research Letters* 9, no. 5 (May 1, 2014): 055002, doi:10.1088/1748-9326/9/5/055002.)

increasing green roof coverage reduces ambient temperatures. Green roof installation may also increase urban humidity, which potentially has negative effects that are discussed in more detail in Section 5.3.

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 5.2.3), improvements in air quality (Sections 5.2.4.1 and 5.2.4.2), and declines in heat-related mortality (Section 5.2.4.3).

Indirect energy

The cooling effect of green roofs is apparent during both the cooling season (summer) and the heating season (winter), but is smaller during the heating season because the sun is at a lower angle in the sky and is above the horizon for fewer hours and evapotranspiration is minimal in the heating season.[liv] As with cool roofs, the scale of net indirect energy savings depends on the building stock in a city, but generally energy savings will dominate.

5.2.3 Climate change mitigation

Reducing energy used for space cooling and heating through green roof installation reduces building-related 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.[151] Unlike for cool roofs, global cooling impact has not been studied specifically for green roofs; however, because global cooling can be a large benefit, this analysis includes this benefit for green roofs as for cool roofs.[lv] 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 do sequester a small amount of carbon,[152] but the amount of carbon sequestered is minimal and much less than the amount reduced by green roofs from energy use reductions and slightly increased reflectivity.[153] For this reason, this report does not include carbon sequestration in green roof cost-benefit analysis results.

Figure 23 shows green roof climate change mitigation pathways.

[liv] 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.

[lv] GSA (2011) and Sproul et al. (2014), two green roof cost-benefit analyses, included this benefit for green roofs in cost-benefit results. (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; Julian Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States," *Energy and Buildings* 71 (March 2014): 20–27, doi:10.1016/j.enbuild.2013.11.058.)

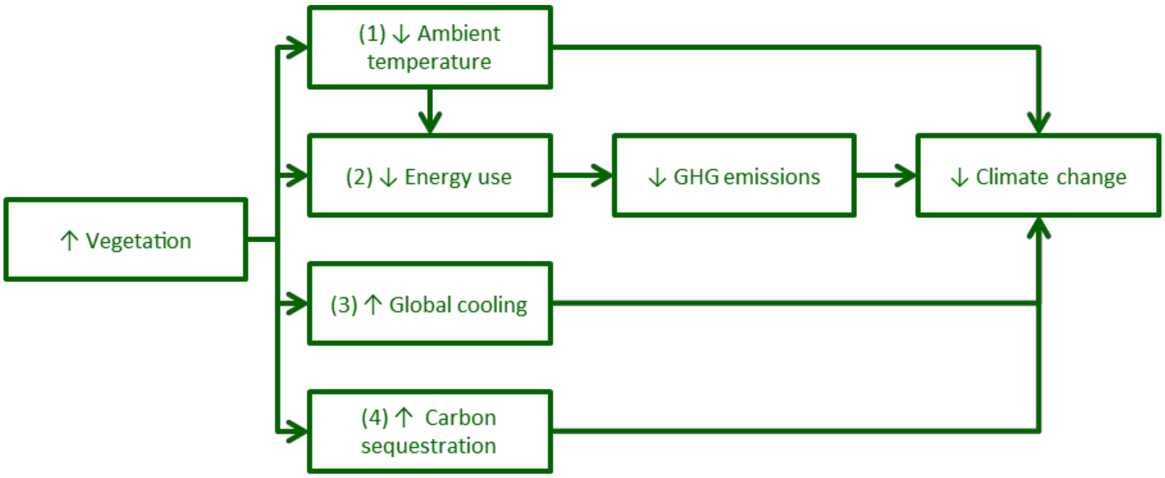

Figure 23. Green roof climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

5.2.4 Air quality and health

5.2.4.1 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 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 periods devoid of precipitation). Figure 24 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 green roofs tends to be small, so this benefit is excluded from cost-benefit calculations as well. This report discusses the methods and pathways in more detail in Section 9.6.1 and in the Appendix.

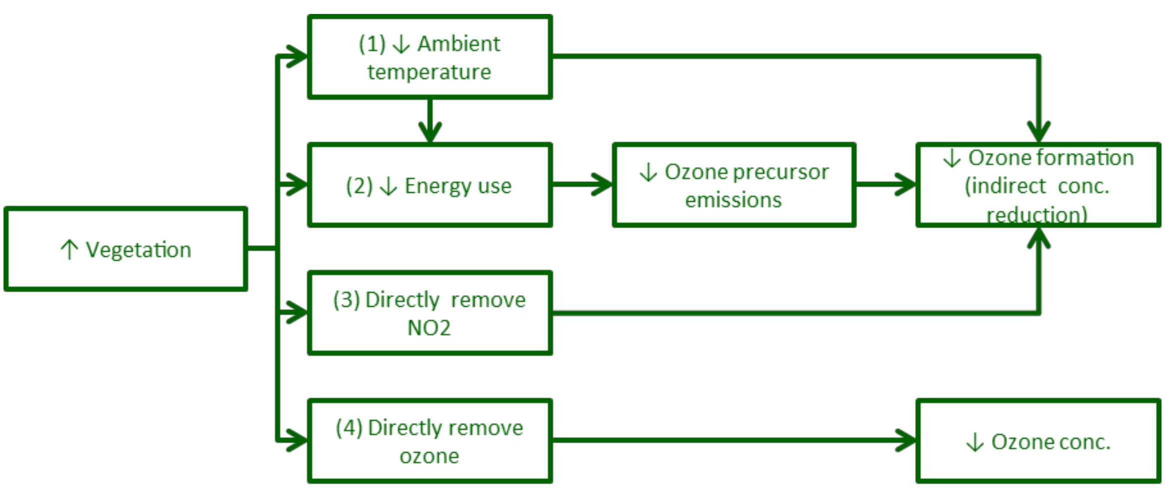

Figure 24. Green roof ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

5.2.4.2 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 25). 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 25). Similar to cool roofs, green roofs reduce $PM_{2.5}$ pollution by decreasing ambient temperature (pathway (2) in Figure 25), and decreasing building energy use (pathway (3) in Figure 25). Figure 25 shows green roof $PM_{2.5}$ concentration reduction pathways. The direct removal of pollutants from the air by green roofs tends to be small, so this benefit is excluded from cost-benefit calculations as well. This report describes $PM_{2.5}$ impact estimation methods in Section 9.6.2 and in the Appendix.

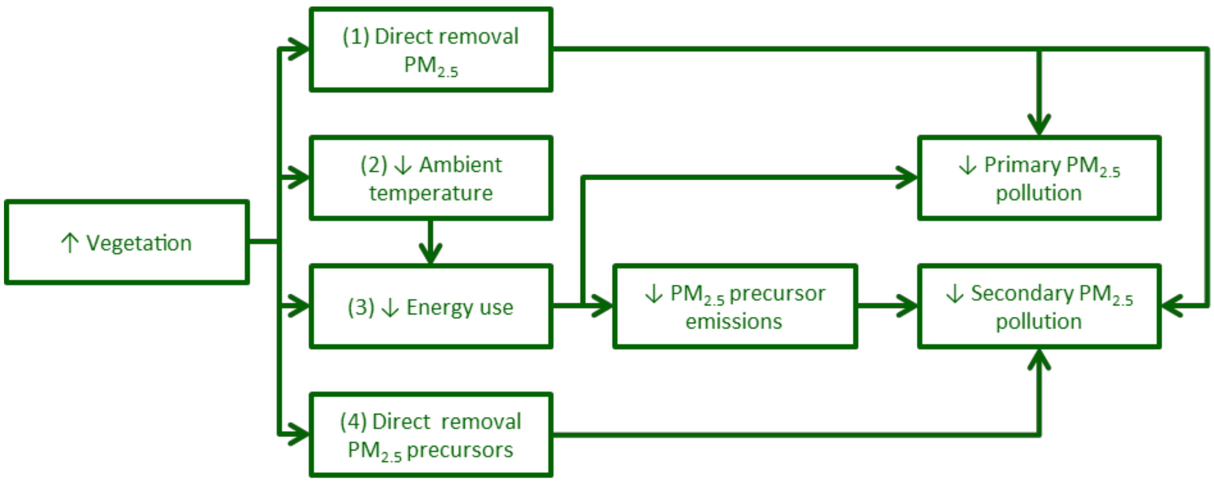

Figure 25. Green roof $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

5.2.4.3 Heat-related mortality

Modeling studies have shown that UHI mitigation technologies (e.g., cool roofs and green roofs) can decrease urban heat-related mortalities through changes in ambient air temperature.[154] As noted in Section 3.4.4.3, there are two pathways by which green roofs can reduce heat-related mortality: by (1) improving outdoor temperature conditions and (2) improving temperature conditions. This report did not find work documenting the potential for green roofs to reduce heat-related mortality by improving indoor conditions, but as Vanos et al. (2014) notes, these reductions could be significant.[155] Because this analysis does not include the heat-related mortality impact of green roofs from improving indoor conditions, any heat-related mortality benefits are conservative (i.e. underestimate the likely benefits of mitigation). This report outlines methods to estimate green roof heat-related mortality impact in Section 9.6.3 and in the Appendix.

5.2.5 Stormwater

Cities like the District, Baltimore, and Philadelphia have high percentages of impervious surface area, resulting in large volumes of stormwater runoff during rain events. 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.[156]

There are three types of stormwater management: treatment, detention, and retention.[157] 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.[lvi] Evapotranspiration and water storage in roof plants provides stormwater retention capacity of green roofs. Water not captured or evaporated from the roof either runs off the roof surface or infiltrates the green roof, where it can be collects or gradually discharges (see Figure 26). Peak runoff rate reduction, delayed peak runoff, and decreased total runoff from green roofs all relieve pressure on aging stormwater infrastructure and reduce water pollution. Figure 27 illustrates these stormwater benefits of green roofs.

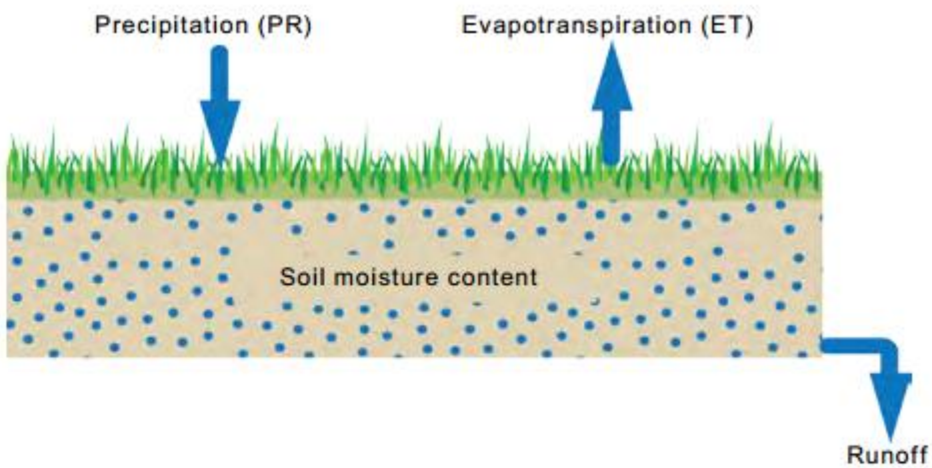

Figure 26. Green roof water budget[158]

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

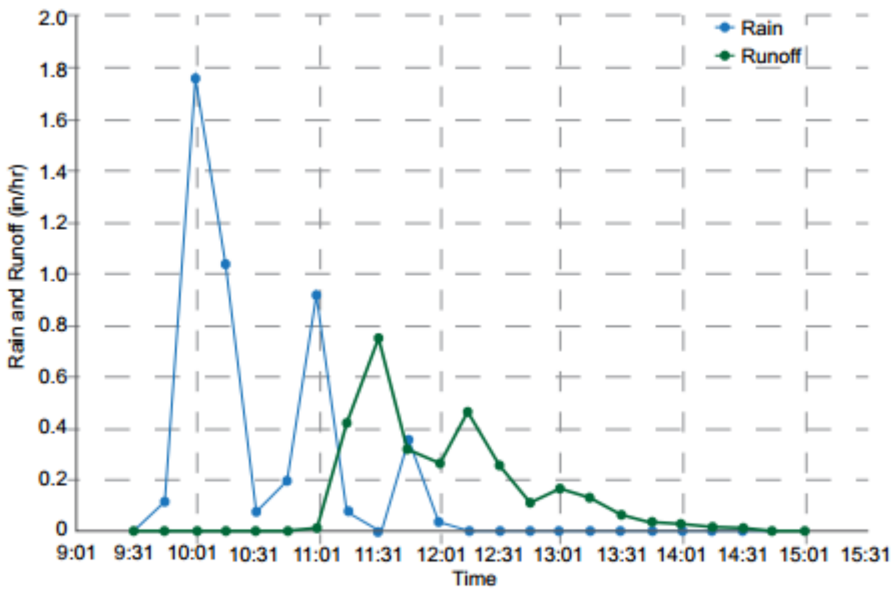

Figure 27. Example timeline of rainfall and green roof runoff[159]

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 will retain the most stormwater during the summer because this is when plants are most active and evapotranspiration (which generally increases as temperature increases) is at its peak.[160] The amount of water a green roof retains depends on the amount of rain that falls, the rate of rainfall, and the length of time since the previous rainfall.[161] 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. Larger green roofs generally reduce peak runoff rates and the time of peak runoff better per unit area than smaller green roofs.[162]

5.2.6 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.[163] 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 estimate includes planning, travel, and on-site construction and is based on an extensive green roof. For extensive roofs, GSA (2011) projects an annual maintenance requirement of 4 person hours per 1,000 square feet per year, assuming three annual site visits.[164] 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. From an employment perspective, 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 technology installation could create.[lvii] All labor intensity estimates for installation in this report include planning, transportation, installation, and maintenance. We ignore manufacturing because these jobs would likely occur outside of the District, Baltimore, and Philadelphia. 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 jobs created go to residents where installations occurs. This assumption is incorrect for cities because many installation jobs go to people living outside cities. Based on discussion with local businesses, as a baseline, this report assumes 25 percent of employment remains in the city. This percent can increase as a result of coordinated city training and employment policies.

5.2.7 Other benefits of green roofs

Reduced HVAC air intake temperature

Like cool roofs, green roofs may impact HVAC air intake temperature. Moseley et al. (2013) compared a green roof to a white roof on a Walmart store in Chicago.[165] They 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 air tempering (i.e., the effect on air intake temperature) 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.[lviii] However, Moseley et al. (2013) did not study the impact of increased humidity on the HVAC systems, which may decrease the projected cooling energy savings as air conditioning units may have to remove more moisture from the air to meet occupant comfort requirements. This potential benefit is little studied and not well quantified, especially compared to conventional roofs, so it is not included in this analysis. Nevertheless, as noted in the cool roof benefits section (Section 4.2.6), this benefit may be significant, particularly for multistory buildings that make up the large majority of buildings in cities, so deserves future research.

Reduced peak electricity demand

Like cool roofs, green roofs typically reduce peak electricity demand. Green roofs result in reduced peak electricity demand and reduced electricity consumption during periods of peak electricity rates (e.g., summer afternoons).[166] As mentioned above, this report does not quantify the benefits of peak

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[lvii] 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.

[lviii] Note that the results of Moseley et al. (2013) 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.

electricity demand and consumption reductions because of limitations in the Green Roof Energy Calculator (GREC).

Downwind cooling

As discussed in the cool roof benefits section (Section 4.2.6), 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 discussed, this analysis does not include this benefit due to limited available research.

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 in this area, this analysis does not include this benefit.

Increased amenity value/real estate value

Amenity value is the extra value a building owner would receive 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.[167] GSA (2011) estimated the "real estate effect" of a green roof (what they define as the "market's value of a green roof") at $13 per square foot of roof per year.[168] However, given the limited research and 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. For green roof installations that include building tenant access and use, this amenity value can be added in, and could have a significant effect on benefits.

Aesthetic value

Green space and vegetation have been shown to reduce stress,[169] lower blood pressure,[170] and decrease crime.[171] These benefits could might to a green roof if it were accessible, but the extensive green roofs analyzed in this study are not typically accessible to building occupants. Green roofs may still provide aesthetic benefits to occupants of neighboring buildings who can see the roof.[172] However, because these studies are not specific to green roofs and, as GSA notes, their "methodology is open to debate,"[173] this analysis does not value aesthetic benefits of green roofs.

Increased biodiversity

Biodiversity refers to the variety of life in an area. Green roofs can increase biodiversity compared to conventional roofs.[174] GSA (2011) 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.[175] 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,[176] so this analysis does not include biodiversity benefits in cost-benefit results.

Increased PV efficiency

Like cool roofs, green roofs may enhance PV performance. However, unlike cool roofs, there is some empirical 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 can measurably increase PV efficiency. A recent study from Carnegie Mellon University, for example, found that when air temperatures were approximately at or above 77 °F, PV panel efficiency for panels over green roofs increased slightly (0.8-1.5%)[lix] compared to PV panels over black roofs.[177] The author notes that in cool climates (e.g., Pittsburgh where the experiment was performed), roof type had little impact on PV performance on a year-round basis. Overall, the author concludes the potential economic benefit of the temperature and power output interaction is minor. Given the small size of this benefit, it is not included cost-benefit calculations.

5.3 Potential drawbacks of green roofs

Increased humidity

While green roofs can decrease city air temperature, they can also increase the moisture content of air, increasing humidity and apparent temperature (essentially how hot it feels).[lx] Higher moisture content in the air can increase cooling energy consumption[lxi] and heat-stress.[lxii] 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,[178] 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. On balance, there may be some small cost to increased humidity from widespread deployment of green roofs, but there is insufficient research to include it in cost-benefit calculations.

Increased heating due to ambient cooling

As noted in the cool roof section (Section 4.3), reduced ambient air temperature in the winter can lead to increased heating costs. This also holds for green roofs. However, there is a smaller ambient cooling impact from green roofs in the heating season because of reduced solar intensity, increased cloudiness, and lower evapotranspiration rates. Furthermore, the direct heating benefit provided by green roof more than makes up for this potential drawback. This cost is included in cost-benefit calculations.

Downwind warming

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

5.4 Green roof impact summary

Table 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 will be conservative (i.e., tend to underestimate the net value of green roofs).

[lix] This is a relative efficiency increase, not an absolute efficiency increase.
[lx] How hot air feels is based on both temperature and moisture content.
[lxi] Because air conditioning systems may have to do more work to deliver air within the set humidity range.
[lxii] Because it is more difficult for humans to cool their bodies in more humid conditions.

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

6 Solar PV

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

6.1 PV basics

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

There are three commonly cited PV sectors: residential, commercial, and utility-scale. Figure 28 illustrates PV systems from each sector. Utility-scale consists of 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 the residential sector, PV on single-family residential properties, and the commercial sector, 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 29). 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 28. Residential PV (top left),[179] commercial PV (top right),[180] and utility-scale PV (bottom)[181]

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

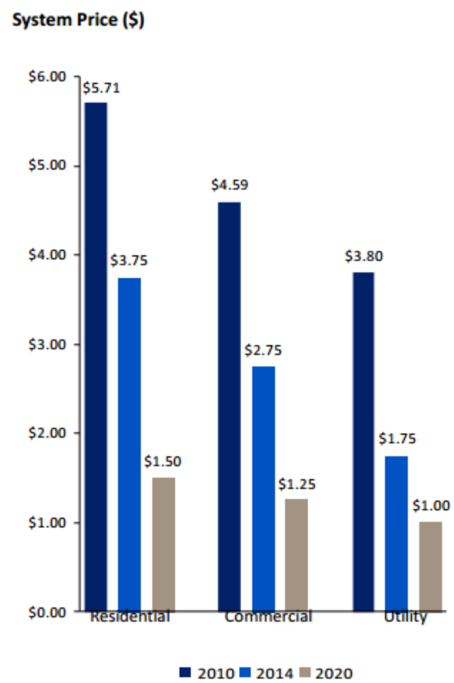

Figure 29. Installed solar PV system price[182]

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.

Direct purchase

Direct purchase is an option for home and building owners with the capital to fund a solar investment and take advantage of solar incentives (e.g., tax credits). Direct purchase has a simple structure: the system owner pays for the PV systems' installation and any maintenance needs[lxiv] and receives all electricity generated by the system and any tax or rebate benefits, but typically responsible for the associated paperwork.

The standard measure for estimating PV system install cost is cost per watt. System install costs have come down dramatically in last decade[183] and are expected to continue to fall in the future. Table 6.1 shows residential and commercial installation and maintenance costs used in this report. This report assumes pre-2020 install costs of $3.50 per watt and $2.90 per watt for residential and commercial systems, respectively. Starting in 2020 and for the remainder of the analysis period, this report assumes install costs of $2.00 per watt and $1.70 per watt for residential and commercial systems, respectively. These cost assumptions are higher than U.S. Department of Energy (DOE) SunShot targets.[lxv,184] This report assumes one cost decline for the entire analysis period for simplicity. This report assumes a system life of 25 years for direct purchase PV systems with an annual system degradation rate of 0.5% per year. This report assumes the PV system has no residual value (or liability) at end of life.

[lxiv] Solar installers often provide maintenance services for a fee.
[lxv] 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

System type	Pre-2020 installation cost[185]	Post-2020 installation cost	Maintenance cost[186]
Residential	$3.50/W	$2.00/W	$0.21/kW-yr
Commercial	$2.90/W	$1.70/W	$0.19/kW-yr

Loan purchase

Loan purchase is similar to direct purchase except that the home or building owner uses a loan to finance some or all of the installation cost. This report does not model loan purchase systems due to the many possible term and rate combinations that would create unnecessary complexity.

Third-party financing

Third-party financing is a popular option for home and building owners interested in rooftop PV who view the up-front cost of rooftop PV as too high, lack capital to fund a solar investment, and/or who cannot take advantage of certain solar incentives (e.g., tax credits). Third-party solar financing involves solar installers or developers 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).[187] Under a solar lease, the electricity user pays a monthly fee for the solar system and gets to use all the electricity the system produces without 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 PV benefits

6.2.1 Energy generation

Rooftop PV saves the energy user by substituting PV-generated electricity for grid-purchased electricity. The District, MD, and PA all have net metering laws recognizing the value of PV electricity generation at the same price as electricity purchased from the utility, so if any electricity produced by the PV system is unused by the home or building, it is sent to the grid and credited towards the buildings next electricity bill. Net metering essentially rolls back the meter so utility customers 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. For direct purchase and loan financed systems, this means that the value of electricity produced by the system is equal to the utility retail electricity rate. 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 all electricity generated by the PV system.[lxvi]

6.2.2 Financial incentives

PV system owners can take advantage of the sometimes large 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 does not recieve these incentives.

Tax credits

There are two federal tax credits available to PV system owners: the residential renewable energy tax credit[188] and the business energy investment tax credit (ITC).[189]

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, 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 10% thereafter.[190]

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, this report assumes all tax credits are used in the year of install. The ITC drops to 26% in 2020, 22% in 2021, and 10% thereafter.[191]

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).[192] 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).[193] For simplicity, this report assumes businesses have enough tax appetite to deduct against. For more details on MACRS, see the Appendix.

Solar renewable energy credits (SRECs)

Solar renewable energy credits (SRECs)[lxvii] are equivalent to one MWh of electricity derived from a solar system. (In MD and the District, solar PV and solar thermal (solar hot water) are eligible to generate SRECs. In Pennsylvania (PA), only solar PV can generate SRECs.)[194] 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 the alternative compliance price (ACP), the solar alternative compliance price (SACP) in PA. 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, whereas in MD they typically trade well below the ACP. In PA, the ACP (or SACP) is determined after the compliance year

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[lxvi] 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.
[lxvii] SRECs are called solar alternative energy credits (SAECs) in PA.

ends and is largely a function of the average market price of SRECs. SRECs in PA are much less valuable than in the District and MD. The District currently has the highest SREC prices in the country. 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 Climate change mitigation

Unlike the two technologies discussed thus far, rooftop PV has one climate change mitigation pathway: reducing building-related GHG emissions by offsetting grid electricity with GHG-free solar electricity. Figure 30 shows the rooftop PV climate change mitigation pathway. This benefit is included in cost benefit calculations. For more on methods, see Section 9.5 and the Appendix.

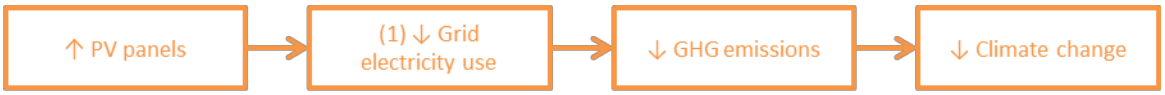

Figure 30. Rooftop PV climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

6.2.4 Air quality and health

6.2.4.1 PV and ozone

Rooftop PV has one ozone reduction pathway. PV panels produce electricity that reduces electricity purchases from the grid. The electricity produced by PV panels does not generate pollution or ozone precursors, whereas electricity from the grid does. Therefore, installing PV panels indirectly reduces ozone concentrations by decreasing electricity-related ozone precursor emissions. Figure 31 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 precursor emissions reductions in cost-benefit analysis calculations.

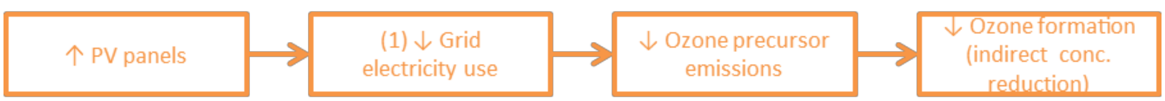

Figure 31. Rooftop PV ozone concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

6.2.4.2 PV and $PM_{2.5}$

Rooftop PV has one PM2.5 reduction pathway. PV panels produce electricity, reducing electricity purchases from the grid. The electricity produced by the PV panels generates no emissions, whereas electricity from the grid causes pollution, including $PM_{2.5}$ and $PM_{2.5}$ precursors. Consequently, installing PV panels reduces $PM_{2.5}$ concentrations by reducing primary $PM_{2.5}$ emissions and $PM_{2.5}$ precursor emissions, respectively. Figure 32 shows the $PM_{2.5}$ reduction pathways of rooftop PV. This report describes $PM_{2.5}$ impact estimation methods in Section 9.6.2 and in the Appendix.

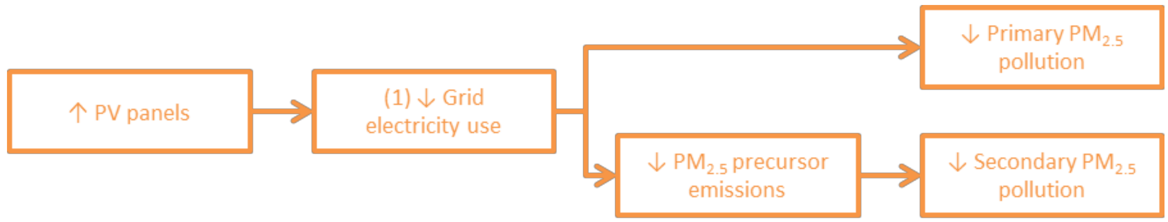

Figure 32. Rooftop PV $PM_{2.5}$ concentration reduction pathway (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

6.2.5 PV and employment

Solar PV panels require 1 person-hour per 25 square foot to install in DC.[195] This works out to approximately 2 jobs-years created per 100,000 square feet of solar PV installed. This estimate is based on results from the Jobs and Economic Development Impact (JEDI) model available through the National Renewable Energy Laboratory (NREL).[196] This estimate is scaled down from those calculated by the model based on solar PV installations in the District.

For operations and maintenance, this report uses results for the District from the JEDI model. The model estimates that 0.2 operations and maintenance jobs are created for each MW of installed capacity in the District. This translates to 0.778 jobs per 1,000,000 square feet of solar panels, based on one MW of capacity for 5.9 acres of PV panel.[197]

Learning curves play a big role in a country or region's given 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.[198] While all new technologies exhibit some learning curve, solar PV has generally shown a faster learning rate than other renewable energy sources.[199] Therefore, the District, Baltimore, and Philadelphia should expect some reduction in its employment factors over time as city contractors become more efficient at installing solar PV.

6.2.6 Other benefits

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 generally outweighs the potential heating penalty. For example, simulations by Dominguez et al. (2011) found that PV on commercial low slope roof in San Diego, CA decreased annual cooling load on the top floor of a building by 38% and had no impact on annual heating load.[200] On a green roof, PV shading can have the added benefit of enhancing vegetation health and allowing for greater vegetation diversity.[201] However, due to the limited amount of research on this benefit, it is not included in the cost-benefit calculations.

UHI mitigation

There is some modeling evidence that large scale deployment of solar PV can reduce urban air temperatures. Sherba et al. (2011) modeled the sensible heat flux from black roofs, white roofs, green roofs, and these three roof types with added PV panels.[202] They 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. Unsurprisingly, putting PV panels on a white or green roof, increases the total sensible heat flux away from these roofs (decreasing their UHI benefit). 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. As Sherba et al. (2011) note, their results cannot be directly translated to changes in temperature,[203] but recent studies did examine the impact of large scale deployment of solar PV on urban temperatures.

Taha (2015) 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.[204] The cooling benefit of PV increased with increasing PV efficiency.[lxviii] 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%, Taha (2015) found regional cooling up to 0.15°C.[lxix]

Reductions in ambient temperature from large scale PV installation could reduce energy use, reduce GHG emissions, and improve air quality and health. 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.

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 almost 4,000 homes sales that included PV, found a sales premium of $4 per watt of installed PV capacity.[205] This equates to a sales premium of about $20,000 for a 5 kW solar PV system. The second and smaller study worked with a team of appraisers to determine the value of solar PV systems in six states. This study found a similar premium to the previous study.[206] The first study notes a sharp decline in sales premium as systems

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

[lxix] Another modeling study, this time of Paris, found a larger temperature benefit from large scale deployment of solar (in this case solar PV and solar thermal). Masson et al. (2014) found a 0.2°C decrease in temperature. However, as the authors note, this likely because Paris does not experience a sea breeze—cities that experience sea breezes tend to have weaker UHIs than cities that do not experience sea breezes, so mitigation technologies in cities with sea breezes will tend to have a smaller temperature impact than in a city without a sea breeze—and because they modeled solar PV and solar thermal—solar thermal is more efficient than solar PV, so per unit of panel area, solar thermal would have a larger UHI mitigation impact. Mason et al. (2014) also modeled the impact of large scale solar deployment on energy use in Paris. They found that the combined effects of shading and urban cooling slightly increased (by 3%) heating energy consumption, however, they note that Paris is heating-dominant and has a low penetration of air conditioning. This means the energy results are likely not applicable in cities like the District, Baltimore, and Philadelphia which have much higher air conditioning use. (Valery Masson et al., "Solar Panels Reduce Both Global Warming and Urban Heat Island," *Frontiers in Environmental Science* 2 (June 4, 2014), doi:10.3389/fenvs.2014.00014.)

age,[207] and the second notes that the effect of system and market characteristics (e.g., system size, available incentives and typical installed prices at time of home sale, and retail electricity rates) on price premium demonstrates a need for a local market-based approach.[208]

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

Avoided transmission and distribution losses

The U.S. Energy Information Administration estimates that transmission and distribution losses in the US average about 6% of the total electricity that is transmitted and distributed.[209] These losses include losses between sources of supply and locations of distribution (transmission losses) and losses in distribution to customers (distribution losses).[210] Rooftop solar PV coverage generally avoids transmission and distribution losses.[211] This report conservatively assumes no benefit from avoided transmission and distribution losses.

6.3 PV impact summary

Table 6.2 below summarizes the costs and benefits of rooftop PV included in the cost-benefit results of this report. There are more benefits than costs excluded from cost-benefit analysis, and excluded benefits likely have a higher value in aggregate than excluded costs, meaning the findings are conservative (i.e., tend to underestimate the net value of solar PV)

Table 6.2. 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 transmission and distribution losses (+)		X

7 Reflective pavements

The sections below explore the basic principles of reflective pavements and their potential impacts. Major benefits include ambient cooling, reduced cooling energy use, reduced greenhouse gas emissions and 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, typically sand or rocks broken into small pieces, provides strength, friction, and resistance to wear.[212] Binder, often asphalt or Portland cement, is like glue; it provides stiffness and prevents pavement from breaking apart under the forces of traffic and weather.[213] Concrete is the composite of aggregate and binder.[214] 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.[215] 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.[216] Asphalt concrete is typically 7 percent asphalt and 93 percent aggregate by weight.[217] Asphalt concrete (commonly called "asphalt") is the most common roadway pavement—about 90% of roads are asphalt concrete.[218] Portland cement concrete consists of Portland cement binder (which is grey or white in color and is derived from calcium and silicon oxides) and aggregate. Portland cement concrete is typically 11 percent Portland cement binder, 33 percent sand, and 56 percent coarse aggregate by weight.[219] 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).[220]

7.1.1 Thermal performance

There are three ways heat transfers from one medium to another: conduction, convection, and radiation. 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).[221] Figure 33 presents a visual representation of heat transfer processes in pavements.

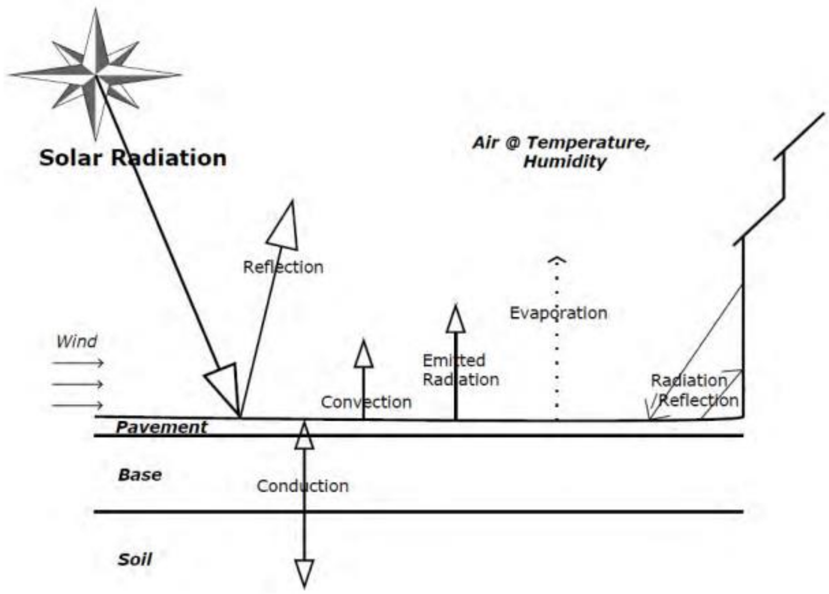

Figure 33. Pavement surface energy balance[222]

The size of the heat transfers described in the previous paragraph are determined by a number of pavement properties: solar reflectance (albedo); thermal emittance;[lxx] thermal conductivity;[lxxi] and specific heat.[lxxii,223] Van Dam et al. (2015) notes 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.[224] As a result, this analysis focuses on pavement albedo changes.

There are several other factors that make analysis of pavements more complicated than that for roofs. Roofs experience relatively consistent environments in that they are not heavily trafficked. Pavements, on the other hand, experience a range of vehicle and pedestrian traffic, leading to wear and increased convection due to traffic movement.[225] Pedestrians, vehicles, and nearby vegetation and structures also shade pavements[226] to a larger degree than experienced by roofs. If pavement is shaded for the majority of the day, it may not make sense to increase its solar reflectance.

7.1.1.1 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 pavements experience are wider ranging than those experienced by roofs. The sections below describe the solar reflectance of

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

[lxxi] 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.

[lxxii] 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.

conventional and reflective pavements drawn from literature and discussion with pavement professionals. There is no standard solar reflectance measure used.

Conventional pavement

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.[227] 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.[228] Albedo will vary to some extent by geography because of different pavement mix design standards.[lxxiii,229] This analysis uses the median of the aged solar reflectances described above in cost-benefit calculations (see Table 7.1).

Brick is an important material for sidewalks, especially in older cities like the District, Baltimore, and Philadelphia. Santamouris (2006) lists red brick as having an albedo between 0.20 and 0.30.[230] For simplicity this report assumes brick sidewalks have an albedo of 0.30, the same as that of concrete.

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

Pavement type	Albedo
Asphalt	0.15
Concrete	0.30
Brick	0.30

Reflective pavements

Reflective pavements work in a similar way to reflective (cool) roofs. They have a higher solar reflectance than conventional pavements meaning 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. Some of the reflected solar energy may also impact nearby buildings (discussed in more detail in Section 7.3).

Increasing albedo of large volumes of asphalt and concrete are difficult and expensive.[231] Based on review of literature and guidance from experts, the most cost-effective way to increase pavement reflectivity is through surface treatments or overlays, essentially adding a thin layer of reflective pavement to the existing pavement surface.[232] The better that application of reflective pavements can fit into existing pavement installation and maintenance practices, the more likely reflective pavements are to be adopted at scale. Thinner pavement layers are also less expensive because they require less material, so cost premiums are minimized.[233] And the top layer of pavement is all that is exposed to the sun, so given the difficulty and expense of pavement albedo increases, changing the albedo of only the exposed material is practical. [234]

Based on discussions with experts,[235] 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. In 2030, this report assumes that due to research, product development, and growing demand, solar

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

reflectance of reflective pavement 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. Sections 7.1.2 and 7.1.3 below discusses installation, maintenance, and cost in more detail.

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

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.[236] 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.[237] 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.[238] 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.[239]

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.[240] Rehabilitation, which typically occurs one or two times during a pavement's lifetime, are major repairs. Examples of rehabilitation techniques for asphalt pavement include patching, surface milling (i.e., removing the top few inches of asphalt), and overlays of a new asphalt (or potentially concrete) surface.[241] 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),[242] diamond grinding, and overlays of a new concrete or asphalt surface.[243]

Maintenance consists of minor repairs and can happen as often as annually or biannually. Maintenance also includes preservation techniques. Surface treatments are the most common type of maintenance or preservation and include techniques like chip seals,[lxxiv] asphalt emulsion sealcoats,[lxxv] slurry seals,[lxxvi]

[lxxiv] For a description of chip seals, see https://en.wikipedia.org/wiki/Chipseal
[lxxv] For a description of emulsion sealcoats, see http://www.pavementinteractive.org/article/emulsified-asphalt/
[lxxvi] For a description of slurry seals, see http://www.pavementinteractive.org/article/slurry-seals/

and bituminous crack sealants.[lxxvii,244] Surface treatments extend pavement life and improve water proofing and skid resistance.[245] The type surface treatment used and its frequency of application depends on the local transportation department and condition of pavement.

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 Cost and timeline

7.1.3.1 Roads

Cost

This report focuses on reflective surface treatments—essentially changing the reflectivity of the topmost pavement layer—because, as noted above, this is currently the most practical way to increase pavement reflectivity.

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 and reconstruction, a new wearing surface (the layer 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, 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, no surface material is removed. Instead a surface treatment is applied to increase the time to next servicing.

In the District, the standard preservation surface treatment is a slurry seal,[lxxviii] with a unit cost of around $4 per square yard ($0.44 per square foot).[246] This analysis assumes a 10% cost premium for a reflective slurry seal, so the unit cost of a reflective slurry seal is about $4.40 per square yard ($0.49 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., $0.40 per square yard ($0.05 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.

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

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

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

reflectivity during these lifecycle phases. However, unlike during the preservation process, during these three processes, the city will pay the full price (i.e., $4.40 per square yard ($0.49 per square foot)) for the reflective slurry seal because it is being added to these processes, not replacing an existing layer as during the preservation process.[lxxix]

For simplicity, this analysis uses these same cost assumptions for the District, Baltimore, and Philadelphia pavements.

Timeline

The condition of the pavement will impact how often a slurry seal is needed. In general, the older or worse the condition 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.[247] 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).[248] This analysis assumes that a slurry seal is needed for pavement condition purposes 10 years after initial construction, reconstruction, or resurfacing.[249]

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

For simplicity, this analysis assumes pavement timelines start in each of two instances: (A) at the beginning of a three-cycle slurry seal application phase and (B) at the beginning of a two-cycle slurry seal application phase.[lxxxi] This analysis assumes the same reflective road timelines in all three cities. Figure 34 shows the pavement timelines and costs associated with reflective road pavements in this analysis.

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

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

[lxxxi] 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.

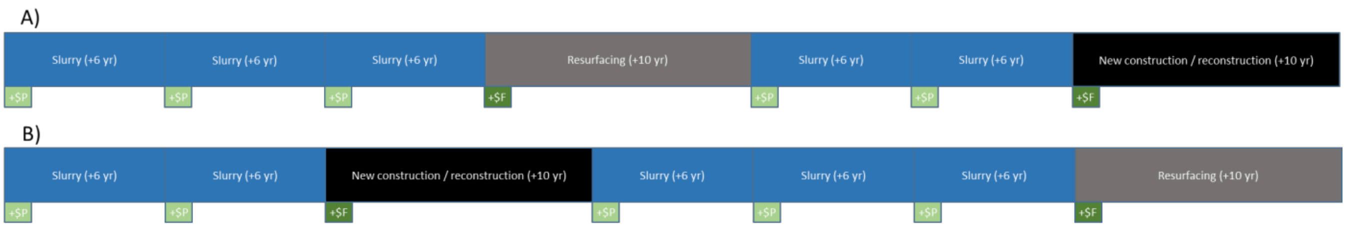

Figure 34. Road maintenance timelines and costs (dark green rectangles with "+$F" indicate the full cost (i.e., $4.40 per square yard) of the reflective slurry seal is paid and light green rectangles with "+$P" indicate only the cost premium (i.e., $40 per square yard) of the reflective slurry seal is paid)

7.1.3.2 Parking lots

Parking lots are typically privately owned, so are not built to the same standard as roads.[250] As a result, this report assumes parking lots do not undergo maintenance or preservation. Therefore, any reflectivity increase for parking lots will come at the full cost. For simplicity, we assume the same costs for reflective surface treatments described in the previous section (7.1.3.1), or $4.40 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 $4.40 per square yard.

Figure 35. Parking lot maintenance timelines and costs (dark green rectangles with "+$F" indicate the full cost (i.e., $4.40 per square yard) of the reflective slurry seal is paid)

7.1.3.3 Sidewalks

Sidewalks typically last for many decades.[251] 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 $44 per square yard ($4.89 per square foot) and $95 per square yard ($10.56 per square foot), respectively.[252] This report assumes reflective sidewalks have a 10% cost premium compared to conventional sidewalks (i.e., $4.44 per square yard for concrete and $9.53 per square yard for brick) that is paid at the beginning of their 40-year lifetime.

Figure 36. Sidewalk maintenance timelines and costs (light green rectangles with "+$P" indicate only the cost premium (i.e., $4.44 per square yard for concrete) of the reflective option is paid)

7.2 Reflective pavement benefits

7.2.1 Ambient cooling and indirect energy

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 4.2.2), 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. Pomerantz et al. (2000) derived an approximate formula for the change in peak air temperature caused by changes in pavement albedo.[253] They estimate that in cities where the formula is valid,[lxxxii] increasing pavement albedo from 0.10 to 0.35[lxxxiii] in the entire city[lxxxiv] will reduce peak air temperatures by 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.[lxxxv] Given the inconsistency of pavement temperature impacts at small-scale, this report focuses on impacts of average urban albedo changes. This report recommends pilot studies at the scale of multiple city blocks with temperatures measured before and after reflective pavement installation to assess reflective pavements effectiveness at cooling the air at small deployment scales.

As noted previously, UHIs are location specific and fortunately, a few recent studies examined UHI mitigation in the District, Baltimore, and Philadelphia.[254] All studies found albedo increases are effective at reducing UHIs in the three cities, though these 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), improvements in air quality (Sections 4.2.4.1 and 4.2.4.2), and declines in heat-related mortality (Section 4.2.4.3).

Indirect energy[lxxxvi]

The cooling effect of reflective pavements is apparent in both the cooling season (summer) and the heating season (winter), but is 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. Akbari et al. (2001) estimated that increasing the albedo of all 1250 km^2 of pavement in Los Angeles by 0.25 would lead to energy savings of $15 million (1998$) per year ($0.01 per square foot of pavement per year).[255,lxxxvii] 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 cities examined in this report.

[lxxxii] 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. Pomerantz et al (2000) cite examples as the Los Angeles Basin, Phoenix, and Dallas.
[lxxxiii] This is approximately equivalent to replacing asphalt pavements with concrete pavements.
[lxxxiv] In the District, roads make up about 15% of the city.
[lxxxv] 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.
[lxxxvi] The effect of reflective pavements on direct energy use is an area of ongoing research so this report does not include it in the main reflective pavements benefit section. The discussion of the direct energy impacts of reflective pavements is in Section 7.2.4.
[lxxxvii] This is equivalent to about $22 million today, or about $0.002 per square foot.

7.2.2 Climate change mitigation

Reflective pavements reduce building space conditioning energy consumption through ambient cooling, reducing GHG emissions at power plants. Like cool roofs, some of the light reflected by reflective pavements is reflected back to space, altering the Earth's radiation balance and countering global warming. As noted in the cool roof section (Section 4.2.3), the global cooling impact of reflective surfaces is an area of ongoing research. However, because this impact can be significant, it is included in cost-benefit calculations.

This report describes the methods used to estimate the climate change mitigation impact of reflective pavements in Section 9.5. Figure 37 shows the climate change mitigation pathways of reflective pavements.

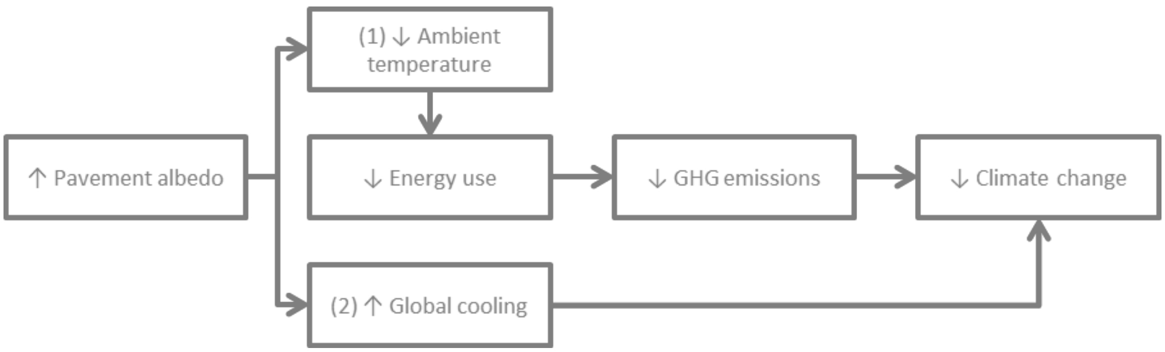

Figure 37. Climate change mitigation pathways of reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease)

7.2.3 Improved air quality and health

7.2.3.1 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 38 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 and pathways involved in the ozone-benefits analysis in more detail in Section 9.6.1 and in the Appendix.

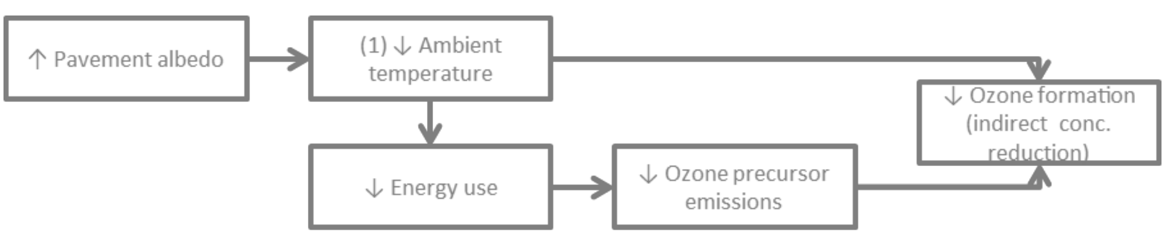

Figure 38. Ozone concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease)

7.2.3.2 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 emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors, decreasing primary and secondary $PM_{2.5}$ pollution. Figure 39 shows the $PM_{2.5}$ concentration reduction pathways of reflective pavements. This report describes $PM_{2.5}$ impact estimation methods in Section 9.6.2 and in the Appendix.

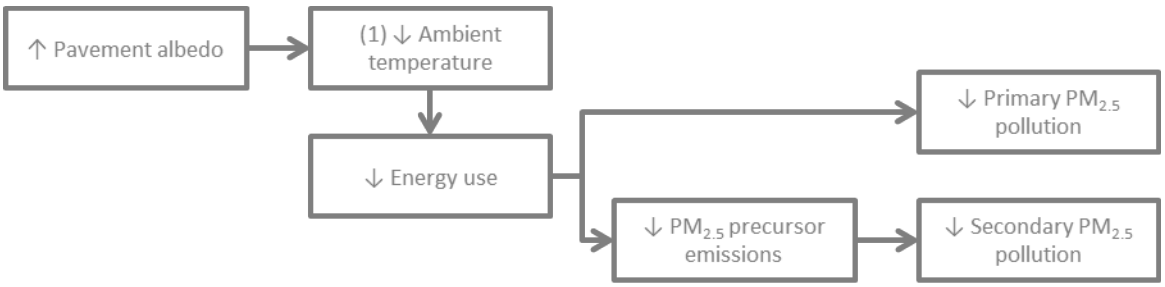

Figure 39. $PM_{2.5}$ concentration reduction pathway for reflective pavements (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease)

7.2.3.3 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 one pathway: improving outdoor temperature conditions. Several modeling studies have found that city-wide adoption of reflective pavements can reduce heat-related mortality.[256] This report describes heat-related mortality benefit estimation methods in Section 9.6.3 and in the Appendix.

7.2.4 Other benefits of reflective pavements

Direct energy

There are two mechanisms by which reflective pavements directly influence building energy consumption: (1) increased heat grain and (2) decreased artificial lighting requirements. Some of the sunlight reflected from reflective pavements is absorbed by surrounding buildings. This increases building heat gain,[257] which in turn increases building cooling energy use in the summer.[258] (The increase in building heat gain also decreases building heating load in the winter, though this effect appears much smaller.)[259] The increased amount of reflected sunlight from reflective pavements can also reduce nearby buildings' artificial lighting needs, which has two direct energy benefits.[260] 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 reduces 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.

Urban geometry is a significant factor in determining the direct energy impact of reflective pavements. The urban canyon's[lxxviii] height-to-width ratio—the height of the buildings that make up the urban canyon walls relative to the width of the street that makes up the urban canyon floor—is one facet of urban geometry that influences the direct energy impact of reflective pavements. Generally, the greater

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[lxxviii] An urban canyon is where a street is lined on both sides by buildings.

the height-to-width ratio, the less pavement albedo impacts nearby building cooling and heating requirements because less sunlight reaches the pavement.[261] The proximity of the reflective pavement to nearby buildings is also relevant in determining the direct energy impact of reflective pavements. The closer pavement is to a building, the greater the "view factor" between the pavement and building—view factor is the proportion of radiation that leaves one surfaces and strikes another.[262] This means a building absorbs more reflected radiation from pavements located closer, so reflective pavements located close buildings increase heat gain more than reflective pavements located farther away.

A building's shell characteristics (e.g., level of insulation, window-to-wall ratio) are relevant in determining the direct energy impact of nearby reflective pavements. Higher levels of insulation mean less direct impact from reflective pavements on a building's cooling or heating requirements.[263] Conversely, higher window-to-wall ratio—the window area relative to the total, or gross, wall area–on the side of the building facing the reflective pavement means more reflected light can enter the building, increasing heat gain, increasing or decreasing space conditioning requirements (depending on the season), and decreasing internal lighting needs,.[264,lxxxix]

Despite the relevance of fully understanding the direct energy benefits of reflective pavements, there are no comprehensive studies that examine the combined impact of increased heat gain and decreased artificial lighting requirements caused by reflective pavements. As a result, this impact is not included in cost-benefit calculations. This impact warrants further research—real-world pilot studies would be particularly useful.

Increased pavement life

Increasing pavement albedo can lead to increased pavement life because the lower temperatures of reflective pavements slow 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).[265] For concrete, lower daytime surface temperature reduces the temperature-related stresses that contribute to cracking.[266] There is limited data 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.

Enhanced nighttime visibility

Increasing pavement reflectivity can enhance nighttime visibility.[267] This can increase driver and pedestrian safety and reduce street lighting needs because reflective pavements better reflective street and vehicle lights.[268] For street lighting, if designers want lighting levels to remain the same, fewer street lights are required with reflective pavements. Figure 40 illustrates the reduced lighting requirements with reflective pavements. There is little, if any, quantitative work studying the impacts of increased nighttime visibility with reflective pavements, so this benefit is excluded from cost-benefit analysis calculations. Furthermore, as cities transition to more efficient LED street lighting, this energy savings benefit will decrease significantly.

[lxxxix] As discussed above, increases in heating energy requirements tend to be smaller than increases in cooling energy requirements because the sun is at a lower angel in the sky and is in the sky for a shorter period of the day during the winter compared to during the summer.

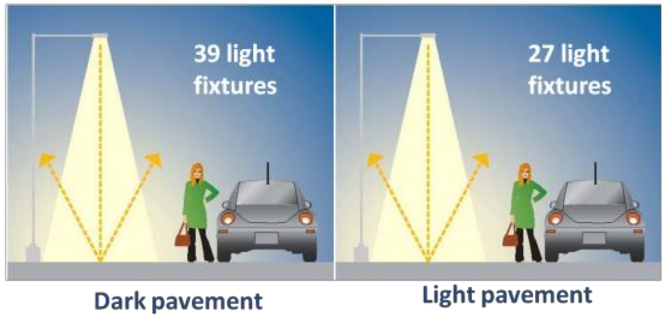

Figure 40. Illustrative example of reduced lighting requirements with reflective pavements[269]

Reduced stormwater runoff temperature

As with cool and green roofs, reflective pavements can reduce stormwater runoff temperatures because they remain cooler than conventional, low albedo pavements. As noted previously, lower stormwater runoff temperatures can help reduce thermal shock to aquatic life in water bodies into which stormwater drains, which is particularly important for cold-water ecosystems. Nevertheless, given the large uncertainty and lack of research in this area, this analysis does not include the potential benefit of reduced stormwater runoff temperature in cost-benefit calculations.

Downwind cooling

As discussed in the cool roof benefits section (Section 4.2.6), hot air from urbanization can heat cities and towns downwind 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.

7.3 Potential drawbacks of reflective pavements

Glare

Reflective pavements may cause glare. Glare is caused by excessive brightness and can be uncomfortable or disabling—glare is also subjective.[270] Brightness is caused by too much visible light entering the eye, so reflective pavements that reflect strongly in the visible spectrum can cause glare. As Akbari et al. (2001) note, 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.[271] 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 41 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 41), about 43% is visible light (green in Figure 41), about 52% is near-infrared light (orange in Figure 41).[272] Lawrence Berkeley National Laboratory, a leader in cool roof and reflective pavement research, notes that it is possible to achieve albedo increases up to 0.40 without affecting a surfaces appearance[273] 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.[xc] 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.[xci]

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 effects of glare from highly reflective pavements deserve further study, particularly in large real-world pilot studies.

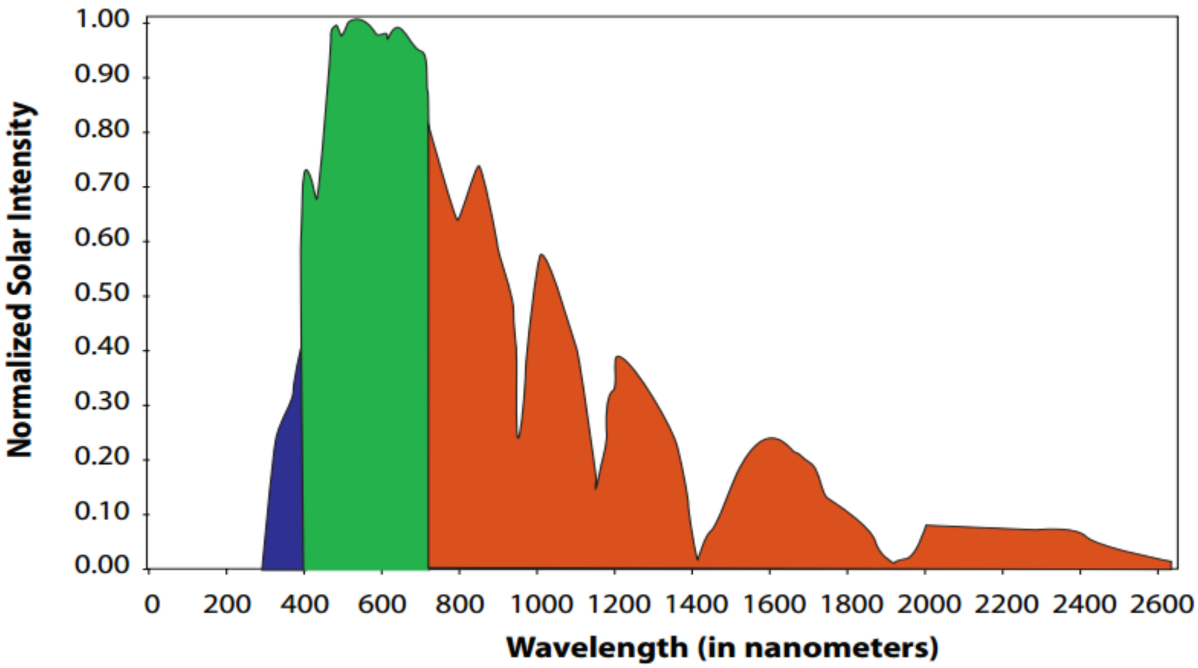

Figure 41. Solar energy versus wavelength reaching Earth's surfaces on a typical clear summer day (blue is ultraviolet wavelengths, green is visible wavelengths, and orange is near-infrared wavelengths)[274]

Reduced thermal comfort

The impact of reflective pavements on thermal comfort is best understood with a brief overview of the factors that impact thermal comfort. Several local microclimate factors commonly used in assessing thermal comfort include: **air temperature** (the temperature of the air surrounding an individual); **mean radiant temperature** (the weighted average of all temperatures from surfaces surrounding an individual; this accounts for the impact of radiation); relative humidity;[xcii] air speed; metabolic rate;[xciii] and clothing insulation.[xciv,275] Air temperature and mean radiant temperature are the most important

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

factors for understanding the thermal comfort impact of reflective pavements (see Figure 42).[xcv] There is currently no clear consensus as to the impact of reflective pavements on outdoor thermal comfort.

One study of high albedo pavement coatings (which had high reflectivity in the near-infrared spectrum) found that the majority of those surveyed felt cooler on the pavement with a high albedo coating than on uncoated pavement.[xcvi] However, these results have limited meaning because the sample size was only six. Two recent modeling studies found reflective pavements decreased pedestrian thermal comfort. The first, Li (2012), simulated a flat, paved area (e.g., a parking lot) and found 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).[276] This increase in mean radiant temperature, however, was not enough to change a pedestrian's thermal sensation[xcvii] (e.g., from "hot" to "very hot").[xcviii] The second study, Erell et al. (2014), simulated various urban canyon[xcix] configurations and found higher albedo surfaces decrease pedestrian thermal comfort.[277] The increased reflected radiation from the higher albedo surfaces counteracted any ambient air temperature reductions.[c,278] Similar to the finding of Li (2012), only in a few circumstances did reflective pavements change the thermal sensation[ci] of pedestrians.

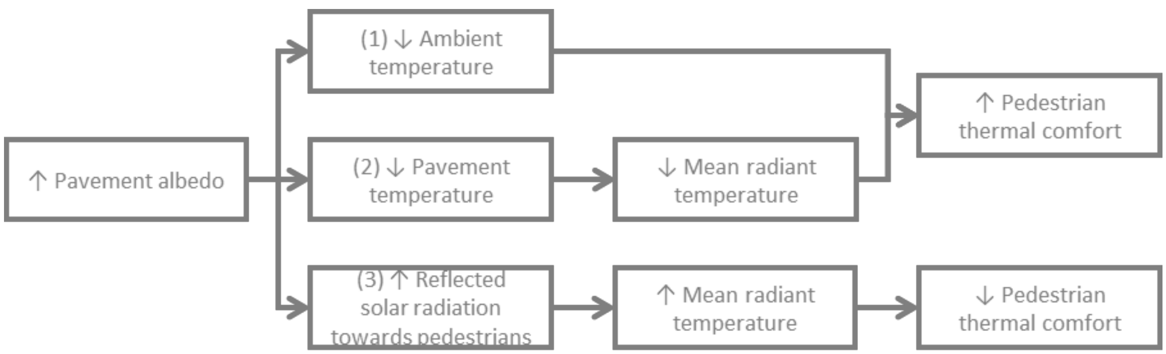

Figure 42. Impact of reflective pavements on summertime pedestrian thermal comfort

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

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[xcv] 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.
[xcvi] M. Iwama et al., "Use of Solar Heat-Blocking Pavement Technology for Mitigation of Urban Heat," in *24th World Road Congress Proceedings: Roads for a Better Life: Mobility, Sustainability and Development* (24th World Road Congress, World Road Association (PIARC): Paris, France, 2011), http://www.miracool.jp/wp-content/uploads/thesis16.pdf; T. Kinouchi et al., "Development of Cool Pavement with Dark Colored High Albedo Coating" (5th Conference on the Urban Environment, American Meteorological Society, 2004), http://ams.confex.com/ams/pdfpapers/79804.pdf
[xcvii] Li (2012) modeled thermal sensation using the Physiological Equivalent Temperature.
[xcviii] It is important to note that Li (2012) did not include air temperature impacts in thermal comfort calculations, though this would have a minor effect if anything.
[xcix] Where the street is lined on both sides by buildings.
[c] 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).
[ci] Erell et al. (2014) modeled thermal sensation using the Index of Thermal Stress.

real-world studies and modeling studies incorporating the ambient cooling impacts of city-wide reflective pavement installation.

Other considerations with increased pavement reflectance

Reflective pavements also mean the potential for increased upward UV light reflectance. As pointed out by Yang et al. (2015), this could be harmful to health[279]—because exposure to UV light can cause sunburn and increases risk of skin cancer. As with glare and visible light, reflectance of UV light can be largely designed out of reflective pavements[280] (at least to the level of conventional pavements). And only about 4% of sunlight is in the UV spectrum (see Figure 41), so this will not have significant impact on goals to achieve high albedo pavements.[281] Given the lack of data on this impact and given its relatively simple solution, this repost does not include the impact of increased upward UV reflectance from reflective pavements in cost-benefit calculations.

There is some concern, as pointed out by Synnefa et al. (2009), that reflective pavements could reduce the visibility of roadway markings (e.g., lane lines, arrows).[282] However, this seems like a design problem that can be easily overcome by selecting the correct color of lane markings to provide the best contrast with the roadway. As a result, any impact reduced visibility of roadways marking could have is not included in cost-benefit calculations.

7.4 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. If cities want to get 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

8 Urban trees

The sections below explore the basic principles of urban trees and their potential impacts. Major benefits include ambient cooling, reduced energy use for cooling and heating, reduced greenhouse gas emissions and global cooling, improved air quality and reduced heat-related mortality, and reduced stormwater runoff. Other benefits include downwind cooling, reduced stormwater runoff temperature, increased property value, aesthetic value, increased biodiversity, and improved thermal comfort. Potential drawbacks include increased humidity, increased emissions of biological volatile organic compounds, increased heating needs due to ambient cooling, and increased pollen production.

8.1 Urban tree basics

8.1.1 Planting and care considerations

As part of tree planting programs, it is important that attention be paid to providing trees with adequate soil volume and choosing species that can survive in the expected conditions. This ensures healthy, long-lived trees that provide benefits at full capacity.

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.[283]

The appropriate soil volume depends on the estimated size of the tree being planted. 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; see Figure 43).[284] Sufficient rooting space ensures better tree health, and minimizes damage to/extends life of paved surfaces.[285] Private land and park space are often best for increasing tree canopy because these areas tend to have most available soil volume.[286] The District Department of Transportation and Casey Trees each provide several design examples to enable adequate soil volume in space-constrained urban areas.[287]

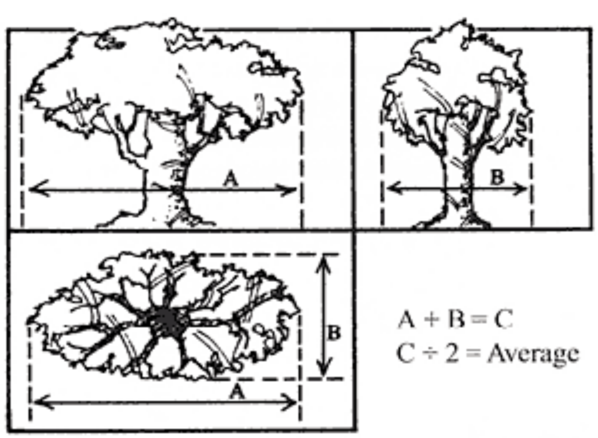

Figure 43. Example of crown spread measurement[288]

Tree selection

Proper tree selection is important for tree health and longevity and to secure the support of residents and local businesses. Factors in tree selection include a tree's water needs, climate tolerance, preferred soil conditions,[cii] preferred light levels, salt tolerance,[ciii] and pollution tolerance.[289] A tree's potential for creating litter (e.g., fruit droppings) is also important to secure the support of residents and local businesses.[civ] Low maintenance 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.).[290]

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. This report assumes middle-of-the-road cost estimates: private trees cost $600 and public trees cost $400.[cv,291] This report uses the average of these estimates for cost calculations (i.e., $500 per tree).

There are also ongoing costs for maintaining trees including pruning, pest and disease control, irrigation, program administration, lawsuits and liability, root damage repair (e.g., to sidewalks), and stump removal.[292] McPherson et al. (2007) estimate trees cost between $8 and $25 per tree per year to maintain, depending on tree size and type (i.e., private or public).[293] Pruning is the costliest maintenance practice. This report assumes a middle-of-the-road estimate of $17 per tree per year for maintenance. Table 8.1 shows planting and maintenance costs used in cost-benefit calculations for this report.

Table 8.1. Tree planting and maintenance costs used in this report

Planting cost (per tree)	$500
Maintenance cost (per tree per year)	$17

Many cities offer free or discounted tree planting. Casey Trees in the District,[294] Tree Baltimore in Baltimore,[295] and Tree Philly in Philadelphia[296] are examples of organizations that offer these programs in the cities examined in this report.

8.2 Urban tree benefits

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 air pollutants through dry deposition, 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 consequences, 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 generated from burning fossil fuels at power plants.

[cii] For example, can it handle the compacted soil common in urban settings?
[ciii] To survive runoff from deiced roads and sidewalks
[civ] 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.
[cv] Both estimates include the cost of the tree and the cost of planting.

Akbari et al. (2001) and EPA (2008) provide excellent descriptions of the benefits of urban trees.[297] Much of the discussion and references cited below draw from these sources.

8.2.1 Direct energy

Urban trees can directly reduce energy of adjacent buildings by shading building surfaces, decreasing the amount of solar radiation absorbed by the building surface. This reduces building surface temperatures[298] and thus the heat transferred into the building, which in turn reduces building cooling energy needs. Huang et al., (1990) estimate that during the summer 10% to 30% of solar energy reaches surfaces under a tree's canopy.[299] In the winter, up to 80% of incident solar energy can reach the surfaces below deciduous tree canopy.

Trees can also serve as windbreaks (i.e., wind shields), reducing the wind speed in the vicinity of buildings.[300] This reduces infiltration of cold air into the shielded building, leading to reduced heating energy use. In summer, the effect of a windbreak can be positive or negative,[301] but potential cooling energy use increases from windbreaks do not typically outweigh savings due to shading.[302]

The extent of the direct energy benefits from urban trees depend on their placement. Direct energy benefits are greatest for trees planted on the west side of a building.[303] The east side and south side are also good options.[304] Tall trees protect from high southern sun in summer (low limbs should be removed to allow for winter sun when sun is lower level in sky) and short trees to the east and west provide shade in the morning when the sun is lower in the sky.[305] Essentially, trees should be close enough to the building to provide shade from western, eastern, and southern sun in warm summer months, but far enough away that they do not block southern winter sun that brings useful heat.[306]

Estimates of direct energy savings vary. One study of a utility tree planting program in Sacramento found cooling energy savings between 7% and 47%.[307] Another study that examined the same utility program found cooling energy savings of 1% per tree and heating energy savings of 2% per tree. [308]A simulation study of trees in various US cities found 20% tree canopy cover over a home yielded between 8% and 18% savings on cooling energy use and between 2% and 8% savings on heating energy use.[309]

8.2.2 Ambient cooling and indirect energy

Evapotranspiration[cvi] and shading from urban trees leads to ambient cooling, reducing cooling energy use.[310] The extent of ambient cooling varies by city. Taha et al. (1996) 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.[311] 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.[312] Sailor (2003) estimated a general relationship between a cities vegetated cover and temperature and found that increasing vegetation by 10% reduced maximum temperature by 0.18°C in the District, by 0.13°C in Baltimore, and by 0.27°C in Philadelphia.[313]

[cvi] Evapotranspiration is described in the green roof section (Section 5.2.1).

Indirect energy

Taha et al. (1996) 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 Washington, DC.[cvii][314]

8.2.3 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,[315]and by global cooling (discussed in Section 4.2.3).

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 electricity that is not used. Rosenfeld et al. (1998) estimated the CO_2 emissions reduction benefits of urban trees in Los Angeles and found that each tree would reduce power plant CO_2 emissions by 18 kg of CO_2 per year,[cviii][316] which is about $0.72 per tree per year, assuming a $40 value of CO2.

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.[317] In 2013 alone, EPA estimates that urban trees in the continental U.S. sequestered 89.5 million metric tons of CO_2e.[318] Some of the carbon stored in a tree is released when it drop leaves or branches,[319] and when a tree dies, most of the CO2 it stored is released to the atmosphere through decomposition, though different disposal techniques can prolong the release.[320,cix] Rosenfeld et al. (1998) found the sequestration benefit to be less than one fourth of the emissions reductions (i.e., less than 4.5 kg of CO2 per year).[321] Given the smallness of the CO_2 sequestration benefit, this report does not include sequestration in cost-benefit calculations.[cx]

Planting urban trees may also lead to global cooling (discussed in Section 5.2.3) because trees have a higher albedo than conventional roofs or pavements they cover—tree albedo ranges from 0.25 to 0.30.[322] Because global cooling can be a large benefit, this analysis includes this benefit for trees as for cool and green roofs and reflective pavements.[cxi] This report uses the low estimate (0.25) of tree albedo. Figure 44 shows urban tree climate change mitigation pathways.

[cvii] 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.

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

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

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

[cxi] GSA (2011) and Sproul et al. (2014), two green roof cost-benefit analyses, included this benefit for green roofs in cost-benefit results. (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; Julian Sproul et al., "Economic Comparison of White, Green, and Black Flat Roofs in the United States," *Energy and Buildings* 71 (March 2014): 20–27, doi:10.1016/j.enbuild.2013.11.058.)

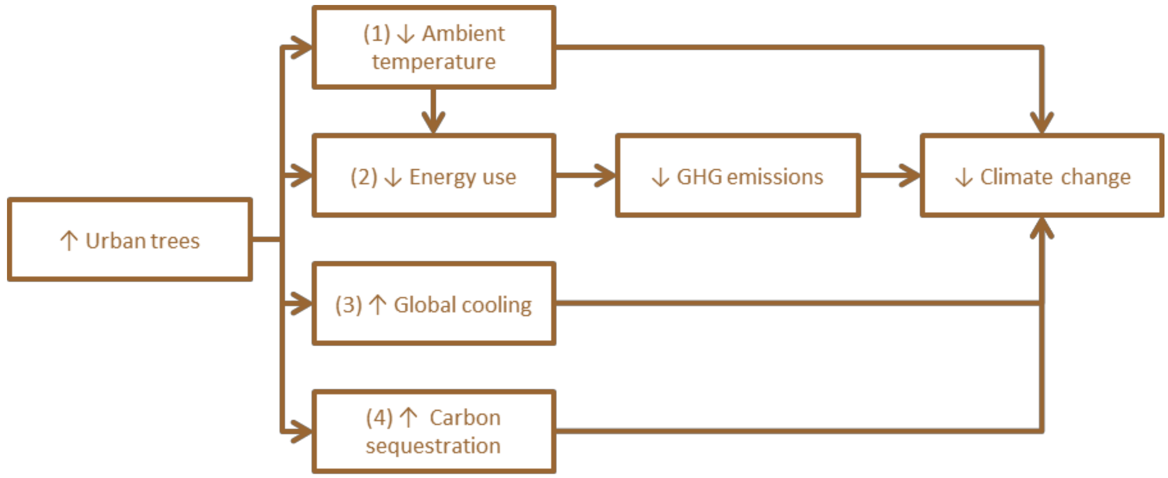

Figure 44. Urban tree climate change mitigation pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

8.2.4 Air quality and health

8.2.4.1 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 45 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 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 Section 8.2.4.3). Methods are discussed in more detail in Section 9.6.1 and in the Appendix.

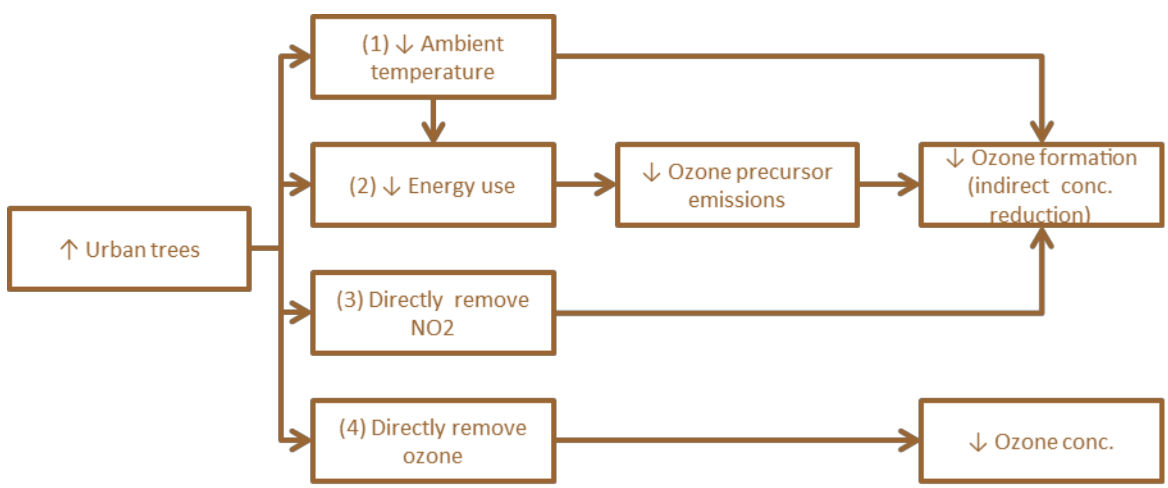

Figure 45. Urban tree ozone concentration reduction pathways (Note: Up arrows (↑) indicate an increase, and down arrows (↓) indicate a decrease)

8.2.4.2 Urban trees and PM2.5

Urban trees reduce $PM_{2.5}$ concentrations in same four ways as green roofs. Urban trees remove $PM_{2.5}$ from the air by dry deposition (pathway (1) in Figure 46). 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 46). Urban trees reduce $PM_{2.5}$ pollution by decreasing ambient temperature (pathway (2) in Figure 46), and decreasing building energy use (pathway (3) in Figure 46Figure 25). Figure 46 shows urban tree $PM_{2.5}$ concentration reduction pathways. In contrast to the green roofs, much work has been done on estimating the value of urban tree pollution uptake. This report includes this benefit for urban trees (see Section 8.2.4.3). This report describes $PM_{2.5}$ impact estimation methods in Section 9.6.2 and in the Appendix.

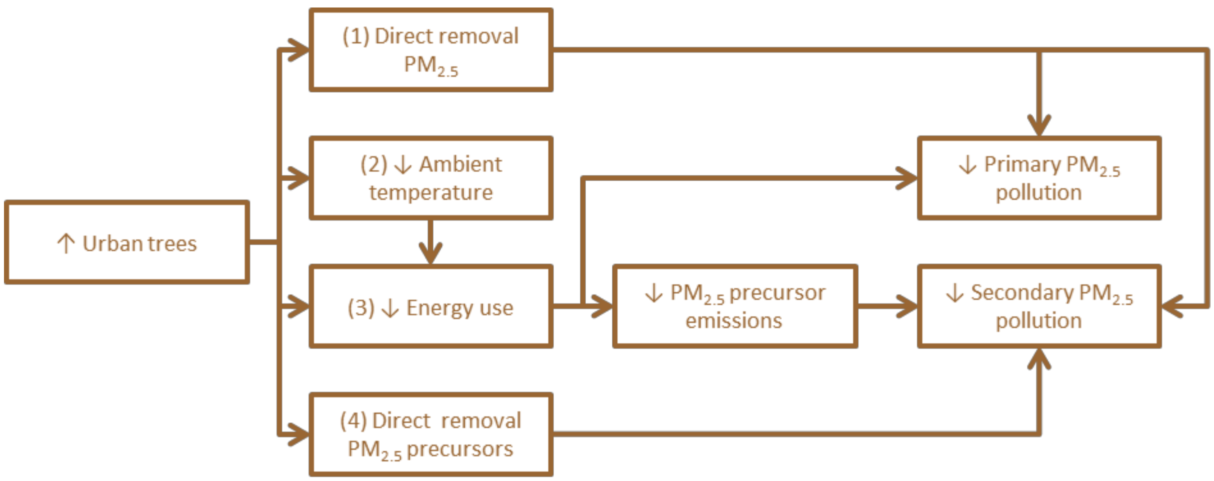

Figure 46. Urban tree $PM_{2.5}$ concentration reduction pathways (Note: Up arrows (↑) indicate an increase and down arrows (↓) indicate a decrease)

8.2.4.3 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.[323] Nowak et al. (2006) estimated that urban trees in the U.S. remove about 711,000 metric tons of pollutants (O_3, PM_{10}, NO_2, SO_2, CO) annually, valued at $3.8 billion.[324] Despite the large value of pollutant removal, actual changes in local ambient air quality are modest and are typically less than 1%.[325] The impact of direct removal of pollutants is included in cost-benefit calculations.

8.2.4.4 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.[326] This report did not find analyses documenting the potential for urban trees to reduce heat-related mortality by improving indoor conditions, but as Vanos et al. (2014) notes, these reductions could be significant.[327] 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 to estimate green roof heat-related mortality impact in Section 9.6.3 and in the Appendix.

8.2.5 Stormwater

Trees, like green roofs, also reduce stormwater runoff volumes and delay time of peak runoff.[328] 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 47 illustrates these and other stormwater runoff reduction pathways. Simulation studies estimate that urban forests reduce city-wide stormwater runoff between 2 and 7 percent.[329]

Interception and soil capture are most effective at reducing stormwater runoff during small rain events, which account for most precipitation events and are responsible for most roadway pollution washoff (e.g., vehicle oils).[330] During large rain events or extended periods of wet weather, an urban tree's capacity for interception and soil absorption will peak and the tree will no longer provide effective stormwater management.[331]

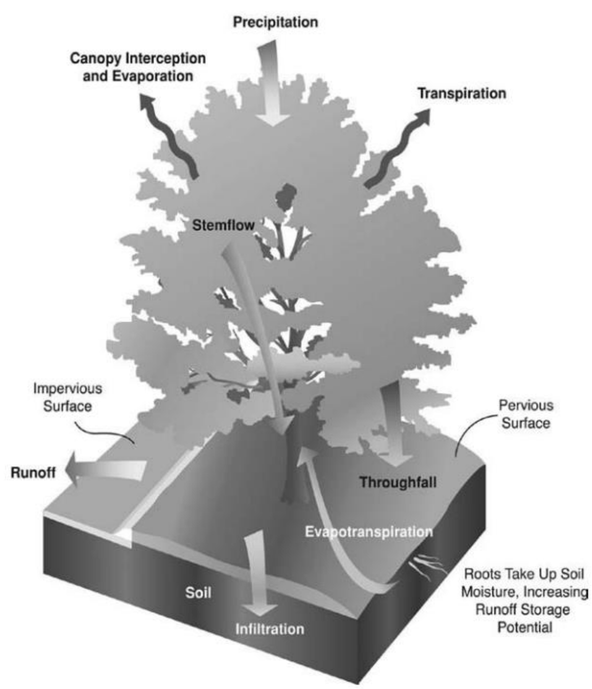

Figure 47. Illustration of tree stormwater runoff reduction pathways[332]

8.2.6 Other benefits of urban trees

Improved thermal comfort

Numerous modeling studies have demonstrated thermal comfort benefits of urban trees across different climates.[333] 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[334]—large scale tree planting is required to provide cities with significant air temperature reductions.

Tree shading reduces mean radiant temperature, enhancing thermal comfort. The size of the thermal comfort impact directly under a tree depends on climate. A simulation study of a hot-dry climate found planting trees in a street canyon reduced physiological equivalent temperature (PET)[cxii] by over 20°C in summer conditions.[335] 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").[336] In a tropical climate (e.g., Brazil), shade from trees can reduce PET by up to 16°C in summer conditions.[337] 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.

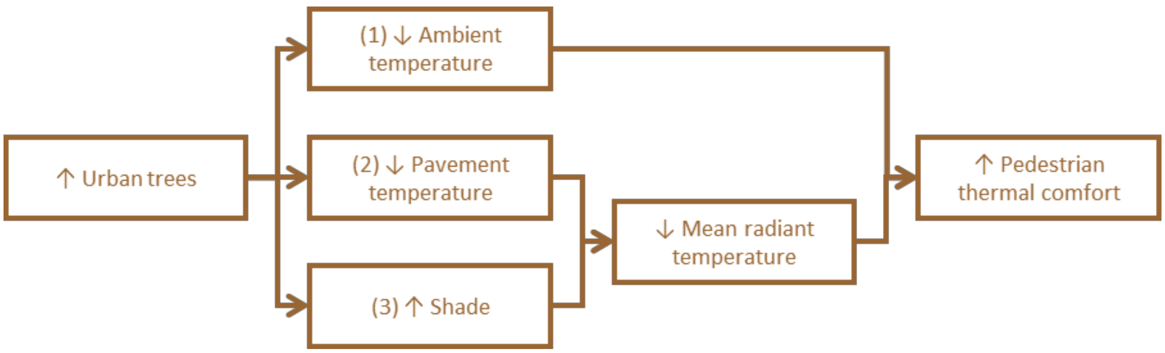

Figure 48. Impact of reflective pavements on summertime pedestrian thermal comfort

Adding additional trees can reduce thermal comfort in winter,[338] as even deciduous trees still block some solar radiation.[339] but in cities with temperate climates (like those analyzed in this report) summer thermal comfort benefits are large.

Given the difficulty in valuing thermal comfort impacts, this report does not include thermal comfort benefits of trees in cost-benefit calculations.

Others

Urban trees can reduce human exposure to direct UV rays, which have adverse impacts on skin and eyes.[340] 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. Studies show that trees can increase residential and commercial property values as well.[341]

Urban trees can enhance quality of life in multiple ways. First, they increase habitat for birds, insects, and other living things.[342] In addition, trees can reduce urban noise,[343] are linked to reduced crime,[344] and provide other psychological and social benefits that help reduce stress and aggressive behavior.[345]

[cxii] 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. (Liang Chen and Edward Ng, "Outdoor Thermal Comfort and Outdoor Activities: A Review of Research in the Past Decade," *Cities* 29, no. 2 (April 2012): 118–25, doi:10.1016/j.cities.2011.08.006.)

As discussed in the cool roof benefits section (Section 4.2.6), 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 could 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 urban surfaces.

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

8.3 Potential drawbacks of urban trees

Increased humidity

Urban trees add water to the air through evapotranspiration, which raises humidity. Increasing humidity can have adverse impact on human health and comfort, and may even increase cooling energy use.[cxiii] However, as EPA (2008) notes, "there is little research on the human health and comfort trade-off between temperature reduction and humidity increases in different climates." This report found no research on the negative or positive impacts of increased humidity from urban trees, so this impact is not included cost-benefit calculations.

Increased biological volatile organic compounds emissions (BVOCs)

Trees can also emit biologic volatile organic compounds (BVOCs), an ozone precursor, that in certain conditions could counteract the ozone reductions that result from reduced ambient air temperature.[cxiv] However, this is a well-known consequence of increasing urban tree canopy so researchers have compiled lists of tree species and the amount of volatile organic compounds they emit.[346] Trees with low ozone-forming potential typically are prioritized for urban tree programs, reducing the potential health costs. This potential health costs is not estimated in this analysis..

Others

Other potential drawbacks include increased winter heating need due to ambient cooling. However, ambient temperature reductions from increased urban canopy will be minimal in the winter because evapotranspiration rates are at their lowest in the winter.

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

[cxiv] 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. (David J. Nowak, "The Effects of Urban Trees on Air Quality" (Syracuse, NY: USDA Forest Service, 2002), http://www.nrs.fs.fed.us/units/urban/local-resources/downloads/Tree_Air_Qual.pdf; U.S. Environmental Protection Agency (EPA), "Trees and Vegetation," Reducing Urban Heat Islands: Compendium of Strategies, 2008, www.epa.gov/sites/production/files/2014-06/documents/treesandvegcompendium.pdf.)

Increasing urban tree canopy can increase pollen production, exacerbating allergies.[347] As with biological volatile organic compounds, this potential drawback can be avoided with proper tree selection.

8.4 Urban tree impact summary

Table 8.2 below summarizes the costs and benefits of urban trees included in the cost-benefit calculations of this report. There are more benefits than costs excluded from cost-benefit calculations, and excluded benefits likely have a higher value in aggregate than excluded costs, so this reports findings will be conservative (i.e., tend to underestimate the net value of urban trees).

Table 8.2. 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

9 Overview of methodology

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

9.1 New additions

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

Table 9.1. Overview of additions to the existing methodology in the literature

Indirect energy	Estimating indirect energy benefit of green roofs
Climate change	Valuing emissions reductions from the technologies studied using the social cost of carbon
	Valuing global cooling impact of the technologies studied using the social cost of carbon
Ozone	Estimating ozone concentration reductions in Washington, DC, Baltimore, and Philadelphia using ozone-temperature relationship
	Estimating ozone concentration reductions due to green roofs
	Valuing health benefits of ozone concentration reductions from the technologies 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 not all jobs generated go to city residents
Combined analysis	Combining new methods above and the existing methods to estimate cost and benefits at region/city scale of all technologies studied
	Scenario development that models gradual implementation of all technologies 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[cxv] 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.[cxvi]

Only trees near buildings provide direct energy benefits. This report uses results i-Tree Eco analyses in Washington, DC and Philadelphia to estimate direct energy impacts of trees. i-Tree Eco only estimates energy benefits for residential buildings. This report uses this assumption and assumes the fraction of

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

trees that provide energy benefits is equivalent to the fraction of residential land use in the region of analysis.

9.3 Energy generation

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

9.4 Ambient cooling and indirect energy

Estimating ambient cooling impacts

Based on a broad literature review, this report uses Li et al. (2014) as the basis for ambient cooling calculations for cool roofs and green roofs in the District and Baltimore.[348] For Philadelphia, this report uses Stone et al. (2014) as the basis for ambient cooling calculations.[349] For reflective pavements in the District and Baltimore, this report uses Kalkstein et al. (2013) and Vanos et al. (2014), respectively, as the basis for ambient cooling calculations.[350] For Philadelphia reflective pavements, this report uses Stone et al. (2014) as the basis for ambient cooling calculations.[351] For urban trees, this report uses Sailor (2003) as the basis for ambient cooling calculations.[352]

Estimating indirect energy impacts

The basis of our indirect energy calculations is from Akbari and Konopacki (2005).[353]

9.5 Climate change

9.5.1 Estimating climate change mitigation impacts of emissions reductions

For emissions intensities in the District, Baltimore, and Philadelphia, this report uses the most recent numbers available from BGE that approximates the emission rate for electricity in the PJM (which includes DC, Baltimore, and Philadelphia).[354]

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.[355] 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.[cxviii] The SCC estimates are built on three widely used climate impact models and each are modelled with discount rates of 2.5%, 3%, and 5%.

9.5.2 Estimating climate change impacts of global cooling

To estimate the CO2-equivalent impact of the global cooling effects of cool roofs and reflective pavements, this report uses Akbari et al. (2009) and Menon et al. (2010).[356] For green roofs and urban

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[cxvii] Solar leases are also common, but as described previously this report includes only PPAs for simplicity.
[cxviii] The SCC was recently reviewed by the U.S. Government Accountability Office (GAO). A report of GAO's finding, published in July, 2014, reaffirmed all SCC methodologies and findings. (U.S. Government Accountability Office (GAO), "Regulatory Impact Analysis: Development of Social Cost of Carbon Estimates," July 2014, http://www.gao.gov/products/GAO-14-663.)

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 technologies.

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.[357,cxix] 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.[cxx]

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).[358] Machol and Rizk (2013) develop a method to determine the $PM_{2.5}$-related health benefits per kWh of electricity. This report utilizes their methodology for $PM_{2.5}$ benefit calculations. Put simply, this report multiplies the energy savings calculated using the methods in Section 9.1 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), Vanos et al. (2014), and Stone et al. (2014) form the basis for the heat-related mortality impact assessment in this report.[359] Kalkstein et al. (2013) is used for the District estimate, Vanos et al. (2014) for Baltimore, and Stone et al. (2014) for Philadelphia. There are several limitations to Kalkstein et al. (2013), Vanos 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).

9.6.4 Estimating pollution uptake by urban trees

For the District, Baltimore, and Philadelphia, this report estimates the health impacts of pollution uptake by urban trees using results from city specific the i-Tree Landscape analyses.

9.7 Stormwater

The District, Baltimore, and Philadelphia have stormwater regulations that require building owners to pay stormwater fees. Income 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

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

installs stormwater management practices. This report estimates stormwater benefits in the District, Baltimore, and Philadelphia using the cities' own stormwater fee discounts.

In 2013, the District introduced stormwater regulations[360] 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 Baltimore and 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, DC is approximately right, though likely high. Baltimore and 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 Baltimore and Philadelphia, this report assigns 50% of the SRC value for each technology in Washington, DC to the respective technology in Baltimore and Philadelphia. The combined value of fee discounts and half the SRC value calculated in Washington, DC is more accurate for estimating stormwater benefits in Baltimore and Philadelphia than only valuing the stormwater benefits of green roofs and urban trees using fee discounts/credits. This is an area for further city-specific research for Baltimore and Philadelphia.

9.8 Employment

See Sections 5.2.6 and 6.2.5 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).[361]

9.9 Summary of key assumptions

9.9.1 Universal

Analysis year 1: 2016

Discount rate: 3% (real)

Dollar year: 2015 (adjusted using the historical consumer price index for all urban consumers)[362]

Table 9.2. Surface coverage in low income region by end of analysis (for a discussion of scenario development, see the Appendix)

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%

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	0.70
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

System type	Pre-2020 installation cost	Post-2020 installation cost	Maintenance cost
Residential	$3.50/W	$2.00/W	$0.21/kW-yr
Commercial	$2.90/W	$1.70/W	$0.19/kW-yr

PPA savings: 5% below utility rates

PPA duration/system life: 20 years

Direct purchase system life: 25 years

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

Annual degradation: 0.5% (compounded annually)

9.9.5 Reflective pavements

Table 9.7. 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: 10%

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 9.8. Tree planting and maintenance costs used in this report

Planting cost (per tree)	$500
Maintenance cost (per tree per year)	$17

Urban tree life: 30 years

10 Scenario Results

This report finds that in general cool roofs, green roofs, rooftop PV, reflective pavements, and urban trees are cost-effective surface technologies in each low income region. Below are scenario summary results tables for each low income region: Section 10.1 shows results for the Ward 5 (Washington, DC) scenario; Section 10.2 shows results for the Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights (Baltimore) scenario; and Section 10.3 shows results for the North Philadelphia (Philadelphia) scenario. All results are presented in 2015 dollars. More detailed tables are in the Appendix.

Given the scope of costs and benefits included in this analysis, the cost-effectiveness of green roofs is highly dependent on the value attributed to stormwater runoff reductions. For example, without SRC value, green roofs are not cost-effective in any scenario. As green roof install costs decline, green roof benefit-to-cost ratio increases. For example, if green roof installation premium begins at $10 per square foot and drops to $8 per square foot (instead of $15 per square foot to $10 per square foot), the benefit-to-cost ratio of green roofs increases by at least 0.25 in each city. Maintenance costs are also important. For example, if maintenance costs decrease by 25%, the benefit-to-cost ratio of green roofs increases by at least 0.10 in each city.

The cost-effectiveness of reflective pavements is highly dependent on the reflective pavement price premium. For example, doubling the premium to 20% reduces the Benefit-to-Cost ratio of reflective pavements by over 0.5 in all scenarios. In addition, using current assumptions, reflective sidewalks have a slightly negative NPV in Washington, DC and Baltimore.

10.1 Washington, DC

Table 10.1. Net present value (NPV) of costs and benefits for Ward 5 scenario

TECHNOLOGY	Cool Roofs	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Urban Trees	TOTAL
COSTS	**$5,297,000**	**$67,970,000**	**$30,234,000**	**$14,000**	**$10,178,000**	**$47,396,000**	**$161,087,000**
First cost	$3,882,000	$47,103,000	$21,938,000	--	$6,066,000	$27,793,000	$106,779,000
Operations and maintenance	$0	$20,835,000	$3,365,000	--	--	$15,078,000	$39,278,000
Additional replacements	$1,415,000	--	$4,928,000	--	$4,112,000	$4,526,000	$14,980,000
Employment training	$0	$33,000	$5,000	$14,000	--	--	$52,000
BENEFITS	**$47,359,000**	**$128,469,000**	**$49,354,000**	**$45,640,000**	**$18,199,000**	**$138,422,000**	**$427,440,000**
Energy	$7,389,000	$5,183,000	$26,876,000	$3,761,000	$832,000	$2,905,000	$46,944,000
Financial incentives	--	--	$8,585,000	--	--	--	$8,585,000
Stormwater	--	$113,081,000	--	--	--	$118,246,000	$231,327,000
Health	$23,080,000	$7,926,000	$7,746,000	$23,352,000	$4,777,000	$10,121,000	$76,999,000
Climate change	$16,891,000	$1,656,000	$5,964,000	$18,007,000	$12,591,000	$7,151,000	$62,258,000
Employment	$0	$624,000	$184,000	$523,000	--	--	$1,330,000
NPV	**$42,063,000**	**$60,499,000**	**$19,120,000**	**$45,626,000**	**$8,022,000**	**$91,027,000**	**$266,354,000**

Table 10.2. Benefit-to-Cost Ratio summary for each technology in the Ward 5 scenario

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

10.2 Baltimore

Table 10.3. Net present value (NPV) of costs and benefits for Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights scenario

TECHNOLOGY	Cool Roofs	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Urban Trees	TOTAL
COSTS	**$2,858,000**	**$24,767,000**	**$16,076,000**	**$7,000**	**$6,183,000**	**$14,136,000**	**$64,025,000**
First cost	$2,095,000	$17,164,000	$11,695,000	--	$3,379,000	$8,289,000	$42,619,000
Operations and maintenance	$0	$7,592,000	$1,759,000	--	--	$4,497,000	$13,847,000
Additional replacements	$764,000	--	$2,622,000	--	$2,805,000	$1,350,000	$7,539,000
Employment training	$0	$12,000	$3,000	$7,000	--	--	$22,000
BENEFITS	**$21,475,000**	**$26,536,000**	**$26,359,000**	**$28,912,000**	**$10,033,000**	**$25,916,000**	**$139,228,000**
Energy	$3,366,000	$1,940,000	$14,230,000	$2,091,000	$590,000	$1,853,000	$24,066,000
Financial incentives	--	--	$3,232,000	--	--	--	$3,232,000
Stormwater	--	$20,984,000	--	--	--	$17,903,000	$38,886,000
Health	$9,646,000	$2,468,000	$5,174,000	$15,598,000	$1,164,000	$3,487,000	$37,534,000
Climate change	$8,465,000	$935,000	$3,636,000	$10,978,000	$8,280,000	$2,675,000	$34,966,000
Employment	$0	$212,000	$88,000	$246,000	--	--	$545,000
NPV	**$18,617,000**	**$1,770,000**	**$10,283,000**	**$28,905,000**	**$3,850,000**	**$11,780,000**	**$75,203,000**

Table 10.4. Benefit-to-Cost Ratio summary for each technology in the Poppleton/The Terraces/Hollins Market, Sandtown-Winchester/Harlem Park, Southwest Baltimore, Upton/Druid Heights scenario

TECHNOLOGY	Cool Roofs	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Urban Trees
Benefit-to-Cost Ratio	7.52	1.07	1.64	Very high	1.62	1.83

10.3 Philadelphia

Table 10.5. Net present value (NPV) of costs and benefits for North Philadelphia scenario

TECHNOLOGY	Cool Roofs	Green Roofs	PV (Direct Purchase)	PV (PPA)	Reflective Pavements	Urban Trees	TOTAL
COSTS	**$8,236,000**	**$100,076,000**	**$55,669,000**	**$25,000**	**$12,433,000**	**$14,136,000**	**$190,573,000**
First cost	$6,036,000	$69,352,000	$40,434,000	--	$7,919,000	$8,289,000	$132,029,000
Operations and maintenance	$0	$30,676,000	$6,153,000	--	--	$4,497,000	$41,325,000
Additional replacements	$2,201,000	--	$9,075,000	--	$4,515,000	$1,350,000	$17,139,000
Employment training	$0	$49,000	$9,000	$25,000	--	--	$82,000
BENEFITS	**$70,797,000**	**$115,154,000**	**$92,676,000**	**$95,456,000**	**$26,789,000**	**$31,113,000**	**$431,981,000**
Energy	$11,041,000	$7,636,000	$49,519,000	$7,436,000	$787,000	$883,000	$77,298,000
Financial incentives	--	--	$13,947,000	--	--	--	$13,947,000
Stormwater	--	$91,941,000	--	--	--	$17,903,000	$109,844,000
Health	$33,970,000	$12,221,000	$16,973,000	$51,169,000	$11,529,000	$10,229,000	$136,090,000
Climate change	$25,787,000	$2,544,000	$11,927,000	$36,010,000	$14,473,000	$2,100,000	$92,838,000
Employment	$0	$814,000	$312,000	$842,000	--	--	$1,967,000
NPV	**$62,561,000**	**$15,079,000**	**$37,007,000**	**$95,431,000**	**$14,356,000**	**$16,977,000**	**$241,408,000**

Table 10.6. Benefit-to-Cost Ratio summary for each technology in the North Philadelphia scenario

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

11 Conclusion

This report provides an in-depth analysis of the costs and benefits of applying a set of roofing and surfacing technologies at scale in ward-level low income areas in three cities: Washington, DC, Baltimore, and Philadelphia. The low income areas studied are substantial, representing, on average, about one-tenth of the population of the cities. These low income areas are characterized by far higher poverty rates, lower income, and higher unemployment than the cities they are part of. On average, the low income areas studied have 53% higher percent of population below the poverty line and 64% higher unemployment rates than the cities they are part of. Not coincidently, these low income areas also have 43% lower tree coverage relative to the cities as a whole. Underinvestment in trees and green technologies generally in urban low income areas like these result in higher summer temperatures, worse air quality, more severe health problems, and higher energy bills per square foot than more affluent areas.

Some cities have begun programs supporting adoption of reflective roofs and pavements to cool the urban environment and lower energy bills; green roofs and trees to reduce stormwater runoff and cool the city; and rooftop solar PV to generate electricity and reduce air pollution. But even in these progressive cities, adoption of these technologies is on a pilot and piecemeal basis, reflecting an inability to fully quantify or understand the costs and benefits of these technologies. This report shows these technologies could go a long way towards cost-effectively reducing health and energy costs for low income areas while increasing employment, resilience, and livability.

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, DC 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. Furthermore, a city-wide analysis would demonstrate far larger 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.

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 has not been done before, we have worked with and consulted with national and city partners, epidemiologists, technology, stormwater, and energy experts and others to build the data and integrated cost-benefit model. While 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. Deployment of these technologies at scale in low income areas can address systematic inequity in urban quality of life. Reductions in energy bills matter much more to low income residents than to wealthy city residents. Similarly, health benefits of the technologies analyzed in this report are larger for low income than for wealthy city residents.

Until this analysis, there has been no established methodology for quantifying the full costs and benefits for cool roofs, green roofs, solar PV, reflective pavements, and urban trees. And therefore there was no way for cities to evaluate the cost-effectiveness of deploying these technologies. A large and poorly quantified part of the benefits of these technologies relates to health. Health impacts are large and complex, and have generally not been quantified or valued for these roof and surface technologies. This report describes different health impact pathways and methodologies used to estimate these costs and benefits. Because this type of analysis is new, it draws on multiple methods, studies, and models to develop an integrated methodology for quantifying the health impacts.

This kind of full, integrated analysis has not been done before in large part because of its complexity, and because there exists no analytic tool that comes close to quantifying full cost-benefit analysis. The best health valuation model is EPA's BenMAP. We built on this and had to solve a large set of benefit estimation challenges, such as estimating the indirect energy benefit of green roofs; developing simple, yet robust temperature-based methods to estimate city ozone concentration reductions; valuing health benefits of PM2.5 emissions reductions due to installing cool roofs, green roofs, reflective pavements, and urban trees; valuing heat-related mortality reductions due to cool roofs, green roofs, reflective pavements, and urban trees; and combining new methods and existing methods to estimate costs and benefits at ward-level. This has involved a great deal of synthesis of existing studies and necessarily making informed choices.

As discussed in the report and the report appendix, many additional benefits and some costs were identified but not quantified due to lack of data and/or need to limit study scope. Unquantified benefits exceed unquantified costs, so overall the cost-benefit findings in this report underestimate the cost-effectiveness of these technologies. That is, the net benefits of scale deployment are almost certainly substantially larger than estimated here.

Furthermore, this analysis does not capture the full set of comfort, health, and livability benefits, and it only includes about one-tenth of each city. City-wide analysis would yield far larger 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.

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