Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits

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Green (vegetated) roofs have gained global acceptance as a technology that has the potential to help mitigate the multifaceted, complex environmental problems of urban centers. While policies that encourage green roofs exist at the local and regional level, installation costs remain at a premium and deter investment in this technology. The objective of this paper is to quantitatively integrate the range of stormwater, energy, and air pollution benefits of green roofs into an economic model that captures both the building-specific and city scale implementation. Currently, green roofs are mainly valued based on increasing the roof longevity and their ability to reduce stormwater runoff, with occasional consideration of reducing building energy consumption. Proper valuation of these benefits can reduce the present value of a green roof if investors look beyond the upfront capital costs. In this paper a net present value (NPV) analysis comparing a conventional roof system to a green roof system demonstrates that at the end of the

green roof's lifetime the NPV for the green roof is less than the NPV for the conventional roof. Increasing evidence suggests that green roofs may play a significant role in urban air quality improvement. For example, public health benefits per metric ton of NOx reduction are estimated to range from $1683 to $6383. These benefits were included in this study, and results indicate that this translates to an annual benefit of $895 to $3392 for a 2,000 square meter vegetated roof. Improved air quality leads to a mean NPV for the green roof that is 25% to 29% less than the mean conventional roof NPV. This study also assessed large-scale roof greening within the Detroit and Chicago metropolitan areas. Greening ten percent of metropolitan roofs would result in 1.53E4 to 1.85E4 Mg of NOx reduction (from direct and indirect uptake) reducing annual public health costs between $25.8 million to $97.7 million in Detroit and between $31 million to $118 million in Chicago. Through innovative policies, the inclusion of air pollution mitigation and the reduction of municipal stormwater infrastructure costs in economic valuation of environmental benefits of green roofs can reduce the cost gap that currently hinders US investment in green roof technology.

Introduction

Continual growth and horizontal expansion of cities and surrounding areas in the United States of America (USA) increase stress on private and public utilities. The annual rate of urbanization in the USA is expected to be 1.19 percent between 2000 and 2030 exceeding the global urbanization rate of 1.8 percent and annual population growth estimates of 1 percent (1). Growth creates a demand for energy, water and sewer services, and transportation. To meet the increased energy demand, more than 150 new coal-fired power plants are proposed in the USA alone (2). Converting green space into neighborhoods, shopping malls, and other developments increases stress to storm sewer systems. For example, forty-two percent of projected sewer infrastructure costs between 2001 and 2030 in Southeast Michigan is attributable to new sewer construction (3). New road infrastructure leads to increased vehicle emissions, and along with parking lots and rooftops, roads contribute to elevated urban surface temperatures by reducing a city's albedo. Increased urban temperatures, in combination with emissions from the electric utility industry, impact local and regional air quality (4). As growth is inevitable, a multi-faceted and scalable solution is needed to temper the environmental impacts of growing cities. Increasingly, developers, architects, and city planners recognize that green (vegetated) roofs may be part of the solution. Composed of a drainage layer, a solid matrix "soil" layer, and vegetation (5), green roofs increase the insular capabilities of roofs and restore the water balance between evapotranspiration and runoff (6).

There are two main parameters that influence the solar radiation reaching the roof deck, leaf foliage and soil media. The more extensive the foliage development of a particular plant, the more the heat flux through the roof decreases (7, 8, 9) and the greater decrease in surface temperatures (10). Thick soil layers insulate during summer months while thin layers result in little cooling benefit (9). The observed reduction in heat flow tends to be greater in the summer months (70-90%) than in the winter (10-30%) (11). Secondary parameters include relative humidity and wind speed. A dry environment and to a lesser extent wind speed increase the rate of evapotranspiration aiding the absorbance of solar radiation by plants (8, 9).

Green roofs can reduce the demand on sewer systems by retaining as much as fifty to seventy percent of annual rainfall precipitation depending on regional climate (12, 13). Rainfall retention is also affected by slope and substrate depth: in general, the flatter the roof, the greater the retention and peak flow reduction (13, 14). Effects due to substrate depth are less transparent. While increased thickness provides increased storage capacity, moisture is also retained for a longer period of time limiting the effectiveness of retention for subsequent storm events.

Stormwater modeling has shown the potential benefits for large-scale roof-greening projects. For Washington, DC, greening 2 million square meters of rooftops could store over 1.6 million cubic meters annually (1.7% of citywide runoff); the volume captured would reduce the total number of combined sewer overflows (CSOs) by fifteen percent (15).

Green roofs exhibit the capacity to reduce pollution in urban environments. As elevated temperatures increase the production of ground level ozone (16), the reduction of the heat island effect through large-scale greening of roofs may indirectly reduce ozone and smog generation (17). The cooling of urban areas further reduces vertical thermal air movements affecting the movement of particulate matter (18). It was estimated that greening six percent of Toronto would reduce the urban heat island effect by 1 to 2 degrees Celsius preventing 0.62 MT (Mega tons) of greenhouse gases indirectly from urban heat island reduction (19).

A few studies have modeled the removal of air pollutants by green roofs. For example, Peck (2003) estimated that current roof greening (covers over 6.5 million square meters) results in a 5-10% reduction in NO_X and SO_2 concentrations in the air, and 30 tons of particulate matter (19). The potential benefit of green roofs to remove NO_2, $S0_2$, CO, PM10, and ozone has been studied using the Urban Forest Effects (UFORE) computer model (15, 20). The model was developed to quantify the benefits provided by urban forests given local hourly pollution concentrations, meteorological data, and plant-specific air pollution removal rates. Assuming a 50:50 mix of evergreen shrubs and grasses, the estimated annual removal of all pollutants by green roofs (per ha.) ranged from 71.95 kg (Toronto) to 83.27 kg (Washington, DC) (20, 15).

Although green roofs have been shown to mitigate stormwater runoff volume and to reduce the heating and cooling loads of buildings, the challenge facing widespread integration of green roofs include the premium cost over conventional roofs, and widely diverging municipal management practices for stormwater and air pollution control. For example, in the USA, the financial burden of managing stormwater is rarely applied to property owners according to area and intensity of impervious area. While some cities have succeeded in encouraging the technology through a command-and-control approach (e.g. Tokyo, Japan; Berlin, Germany), the internal rate of return on the investment (or investment recuperation timeframe) is highly dependent on local conditions (21). Reducing the uncertainty in the quantification of economic benefits of green roofs is a necessary first step to develop policies aimed at stimulating widespread acceptance of the technology in the United States.

The objective of this paper is to quantitatively integrate probabilistic ranges of stormwater, energy, and air pollution benefits in an economic model capturing both the building-specific and city-wide scale. A secondary goal is to assess the impact and opportunities of market-based air credit valuation as a policy tool for green roof diffusion.

Materials and Methods

To address the need for a cost-benefit analysis, a two-fold approach was developed. The first step describes a cost-benefit analysis that can be applied to a range of green roof projects through a probabilistic evaluation procedure. This analysis provides information relevant to building owners, developers, or designers regarding the costs and benefits of green roof technology.

Results were scaled using both environmental and health benefits for a city. This section summarizes the steps for the cost-benefit analysis at the building and city scale.

Building Scale Analysis

The environmental benefits (stormwater reduction, energy savings, and air quality) of roof greening were quantified to assess environmental impact at the building scale, targeting mixed-use office buildings. Several parameters were evaluated: conventional and green roof installation costs, stormwater fees and fee reductions for green roofs, energy costs due to the heat flux through a roof and the potential savings by installing a green roof, and the additional economic valuation of the public health benefits due to air pollution mitigation.

Installation Costs for Conventional and Green Roofs To determine how the environmental benefits reduce the installation cost gap between green and conventional roofs, the magnitude of the gap was first determined. Cost and size data were obtained for seventy-five campus roofs from the University of Michigan in Ann Arbor, Michigan. From the sample, the mean cost of a conventional flat roof was determined to be \$167 per m^2 (standard deviation: \$28 per m^2). The mean campus roof is 1870 m^2 and the mean building floor area is 9730 m^2.

The distribution of green roof installation costs was determined from available green roof case data (22, 23). As the price of green roofs can vary according to design and function (e.g. intensive green roof can serve as a garden), the cases used in the data analysis were limited to extensive roofs with a depth between 5 and 15 centimeters. The collected data represented the additional cost of the green roof components. The distributions of the conventional roof and green roof were summed to obtain the total cost of installation for a new green roof with a new conventional roof. The mean difference between the cost of the green roof and the conventional roof is defined as the cost gap. The internal rate of return was then determined for each environmental benefit.

Stormwater Fees and Reductions Stormwater volume reduction by green roofs benefit municipalities; however, not all local water authorities pass the economic savings on to the owner of the green roof. Traditionally, the budget for stormwater management is provided through property taxes or potable water use fees. In recent years, municipalities have been moving toward stormwater fees based upon total impervious surface on a property, creating an opportunity to "credit" green roofs for stormwater reduction. For this study, data were collected from eleven municipalities with established stormwater management fees (Table 1, SI). It was assumed that the reduction in stormwater fees due to a green roof is normally-distributed at fifty percent of the stormwater fee for the building footprint. Impacts to stormwater infrastructure are only assessed at scale.

Energy Savings Determination and Valuation This study focuses on energy savings to mixed-use administrative/laboratory buildings at the University of Michigan campus in Ann Arbor, Michigan. Total expenditures for energy (natural gas and electricity) consumption (mean $225,000), total energy consumption (mean 4050 MWh), and energy consumption by fuel source (mean 2370 MWh from electricity and 1670 MWh from natural gas) were obtained for 130 university buildings for fiscal year 2003. National commercial building energy consumption statistics provided additional data (e.g. average commercial conductance, system load factors) (24). To determine the roof's contribution to the HVAC energy requirement, the heat flux through the roof was determined according to the following 1-dimensional heat flux equation:

$$\dot{Q} = h \cdot A \cdot \Delta T \qquad \text{(Equation 1)}$$

where Q is the heat flux through the roof (W), A is the area of the roof (m^2), ΔT is the temperature difference between the building interior and the ambient temperatures (K), and h is the heat transfer coefficient ($W/m^2/K$).

$$h = \frac{k}{\Delta x} = \frac{1}{R} \qquad \text{(Equation 2)}$$

h is a function of the thermal conductivity of a material, k, and the material thickness, Δx. The inverse of h is the R-value, which represents a material's resistance to heat flow. The larger the R, the less heat flux Q. In the construction industry, R-value (ft^2*°F*h/Btu) is commonly used to compare the effectiveness of insulation in building materials. An average R-value of 11.34 ft^2*°F*h/Btu (conductance of 0.50 $W/m^2/K$) was assumed for the conventional roof according to national commercial building data (24).

Energy costs due to the heat flux were determined assuming natural gas for heating and electricity for cooling. With available energy expenditures per university building, prices were assumed to be $0.08/kWh for electricity and $0.02/kWh of natural gas. Energy savings through the use of a green roof were based on an assumption of an R-value of 1.2 ft^2*°F*h/Btu (conductance of 4.7 $W/m^2/K$) per centimeter depth for a 10.2-cm soil media. The total combined R-value for a conventional roof with a green roof is 23.4 ft^2*°F*h/Btu (total conductance of 0.24 $W/m^2/K$).

The requisite energy consumption by the HVAC system to compensate for the loss through the roof was then determined. Annual totals for heat loss and cooling loss were multiplied by a system factor as suggested by Huang and Franconi (24).

Air Quality Improvement and Valuation Impact on air quality was limited to the mitigation of nitrogen oxide (NOx). Nitrogen oxide emission allowances are currently traded in the US aiding the exploration of a market-based economic valuation. To quantify nitrogen oxide uptake by plants (per unit area), data from Morikawa, et al. (1998) were used (25). That study evaluated the NO_X uptake potential of 217 plant taxa under controlled conditions in a greenhouse environment. Although sedums, the traditional vegetated roof plants of choice, were not evaluated, the study included a member of the same family, *Crassulaceae*. Published results were in terms of mg N g^{-1} dry weight per 8 hours of daylight exposure. The following assumptions were made to obtain the uptake capacity per unit area (kg_{NO2} m^{-2} y^{-1}): (i) Ninety percent of plant mass is water; (ii) Leaf thickness is 2 mm; (iii) Leaf area index (LAI) is 5 (m^2 leaf area per m^2 surface area); (iv) Average hours of daylight per day (twelve). Calculations were performed to capture the potential impact of all 217-plant taxa on NO_X uptake. The distribution of uptake potentials (Figure 1, SI) is assumed to be lognormal with a mean of 0.27 ± 0.44 kg_{NO2} m^{-2} y^{-1}. An implicit assumption was that the uptake capacity is constant on a year-to-year basis.

Once the annual uptake of NO_X was determined, the result was translated to health benefits in dollars per year. These calculations were based upon two estimation methods developed by the US Environmental Protection Agency (EPA) as part of a regulatory impact analysis of NO_X reductions in 1998 (26, 27). The conclusion of the analysis for the Eastern US, was that fewer premature deaths and fewer cases of chronic bronchitis translated into an economic benefit between \$1680 and \$6380 per Mg adjusted to 2006 dollars (27). The two estimates were based upon the results of several atmospheric models that provided estimates for secondary ozone, nitrogen deposition, and particulate formation (27). The range of economic benefit accounts for uncertainty in atmospheric acid sulfate concentration, which affects ammonium nitrate particulate formation (27). For the purposes of this study, the estimates are referred to as the *low estimate* (\$1680 per Mg) and the *high estimate* (\$6380 per Mg).

Economic Analysis and Sensitivity Analysis Once the costs and benefits were determined on a per unit area basis, the results were integrated into an economic model to determine the length of time required for a return on investment in a 2,000 m^2 green roof using a net present value (NPV) analysis (Table 2, SI). An interest rate of six percent and inflation rate of three percent were used.

It was assumed that the conventional roof would be replaced after twenty years (28). Maintenance costs have not been included in this analysis. Until plants are established (1-3 years), maintenance costs may be greater for a green roof. After establishment, expenses should be equal to or less than a conventional roof (18). A sensitivity analysis evaluated model sensitivity to economic parameters, climate factors, and variability in air pollution uptake.

City Scale Analysis

To assess the scalability of benefits, a city-wide greening evaluation was conducted and applied to two US cities (Chicago, Illinois and Detroit, Michigan) As total roof area data are unavailable for most cities, values were estimated through the extrapolation of roof area estimates for Sacramento, California. (29). In that study authors used high-resolution orthophotos to link roof area to land use zones (residential, commercial, industrial). For the purpose of this study, the percentage roof area per land use zone in Sacramento was extrapolated to the Chicago and Detroit metropolitan areas. Chicago metropolitan land use data were aggregated from data sets provided by the Northeastern Illinois Planning Commission (1995) (30). For the Detroit metropolitan area, the individual county datasets were merged prior to accessing land use data for the region (31). For this analysis, areas were ignored if they fell outside of residential, commercial, or industrial land use zones or were primarily composed of undeveloped or minimally developed land (Figures 2 and 3, SI). For the Detroit metropolitan area,of 886,000 ha, it was estimated that roofs cover 54,200 ha. In the Chicago metropolitan areas (948,000 ha), 65,400 ha are estimated to be roofs. Environmental benefits for the metropolitan areas were then evaluated according to the procedures previously discussed.

Results and Discussion

The following summarizes the NPV analysis. The implications of the benefits on city environmental policy are also discussed.

Stormwater Benefits

The mean stormwater fee was found to be $0.17/m^2 (standard deviation: $0.12/m^2) (32-41). Potential fee reductions for green roofs resulted in a mean stormwater fee of $0.08/m^2 (standard deviation: $0.06/m^2). For the 2,000 m^2 roof, conventional roof fees would be $340 while the green roof scenario would have fees of $160 per year.

A few municipalities offer fee reductions to green roof projects (assuming reduced impervious area and adequate storm capture) to pass the value of the public benefit of stormwater reduction to the building owner (e.g. Minneapolis, Minnesota) (37). Additional benefits may be captured by evaluating retention at the city scale. Deutsch et al (2005) estimated that greening ten percent of green roof ready buildings in Washington, DC (approximately 70 ha) would reduce infrastructure costs to the city's long-term control plan (LTCP) (estimated capital cost of 1.9 billion dollars) by 10 million dollars assuming the roofs would retain 450,000 cubic meters of the 97 million cubic meters of stormwater that are managed annually (15). For the Detroit metropolitan area, assuming a retention rate of 65% of annual precipitation (0.84m for Detroit), greening ten percent of rooftops (5420 ha) would retain more than 29 million cubic meters of water (Table 3, SI). Considering that the estimated costs of the LTCP are $3.5 billion (42), this translates to a reduction of $ 114 million, suggesting substantial opportunity to invest in above-ground roof infrastructure.

Energy Assessment

The heat flux was based on a 2,000 m^2 roof located in Ann Arbor, Michigan. The annual energy consumption was 129 MWh for the conventional roof (116 MWh for heating and 13 MWh for cooling), and 62 MWh for the green roof (56 MWh for heating and 6 MWh for cooling). Uncertainty for this calculation is not included in the NPV analysis as the link between frequency of precipitation and green roof soil media conductance has not been investigated in the literature. Based on energy costs for 2003 and adjusted to 2006 dollars (2003 energy expenditure data was available from the university and energy prices for 2004 and 2005 were unusually high), this translates in $3,240 and $1,580 per year for the conventional and green roof, respectively.

To verify the appropriateness of the assumptions used in the analysis, calculated energy costs through the conventional roof were compared to actual expended total natural gas and electric energy costs for university buildings. Assuming that 35% of total building energy consumption is due to heating, ventilation, and air conditioning (HVAC) system use (43), 90% of all buildings (75 total) were within the expected costs attributed to HVAC use. The eight buildings with higher energy expenditures had roof area-to-floor-space ratios much greater than one (R/F area >> 1). The ratio can be explained by the inclusion of roof areas outside the interior building floor area (e.g. exterior walkways, loading docks), including these areas in the heat flux calculations would overestimate contribution to the HVAC consumption.

Sensitivity analysis included geographical location of the building. Based on the assumptions for conventional and green roof conductance, the percent difference in heat flux between the conventional roof and the green roof remains constant. However, the geographic location of the roof does change the total energy loss through the roof. Similar sized theoretical roofs were evaluated for Atlanta, Georgia and Portland, Oregon (two cities pursuing green roofs). Although the total energy consumed in both of these cities was less than the total energy consumed in Ann Arbor, the total cost for energy loss through a roof in Atlanta was greater due to increased electricity consumption for cooling (total cooling energy was 34 MWh for the conventional roof and 16 MWh for the green roof) (44). For Portland, a more moderate climate resulted in less energy use for heating and cooling, yielding lower annual energy expenditures (44). From this evaluation, annual energy expenditures for a 2,000 m^2 conventional roof range from $2,000 to $4,000 while the expenditures for a green roof of the same size range from $1,000 to $2,000.

Air Pollution Mitigation

The benefit assessment included both direct and indirect methods of uptake. The uptake capacity per area for the 217 plant taxa evaluated by Morikawa et al. (1998) had a mean of 0.27 $kg_{NO2}/m^2/y$ (variance: 0.17 $kg^2_{NO2}/m^4/y^2$)(25). For a building with a roof area of 2000 square meters, this results in an uptake of 530 Mg_{NO2}/y (variance: 700 Mg^2_{NO2}/y^2). The public health benefits for greening a 2000 m^2 roof were determined to be \$890 (variance: 2.0E6 $\$^2$) for the low benefit estimate and \$3390 (variance: 2.8E7 $\$^2$) for the high benefit estimate.

The potential health benefits at the city scale from uptake of NO_X were determined and translated into economic terms according to the two EPA estimates. Greening ten percent of Chicago roofs (6540 ha) would uptake 17,400 Mg_{NO2}/y resulting in city-wide benefits of \$29.2 million to \$111 million annually. For Detroit, greening ten percent (5420 ha) would uptake 14,400 Mg_{NO2}/y, resulting in benefits of \$24.2 million to \$91.9 million annually.

These values were compared to two previous studies that relied on the Urban Forest Effects Deposition (UFORE-D) Model to evaluate air pollution mitigation scenarios in Toronto, Ontario and Washington, DC (20, 15). For Toronto, uptake values were found to be 0.0015 kg $NO_2/m^2/y$ (20), with Washington, DC similar at 0.0011 kg $NO_2/m^2/y$ (15). Using the UFORE-D model, the uptake is two orders of magnitude smaller than the mean uptake value (0.27 $kg_{NO2}/m^2/y$) based on experimental plant studies (25). While the DC study did not include an economic analysis, the Toronto study translated the economic benefits of all pollutant reductions (model evaluated CO, O_3, SO_2, and PM_{10} in addition to NO_2) for the City of Toronto to be \$1.97 million annually (\$0.04 per square meter). The UFORE-D model assigns an economic value for NO_2 mitigation of \$6752 per metric ton removed, based on median externality values for the US and is consistent with the estimated benefit provided by the EPA.

There are several factors that could explain the difference in plant uptake rates (green house vs. UFORE model). The UFORE-D model limited the uptake, which was determined from calculations of atmospheric pollutant flux, boundary resistance, and a hybrid of big-leaf and multilayer canopy model (45), to a mix of two types of plants. The minimum uptake rate for this study is the same order of magnitude (Figure 1, SI) as the value determined by the UFORE-D model (0.002 $kg_{NO2}/m^2/y$). The UFORE-D model is based upon hourly weather conditions and assumes that uptake occurs only via dry deposition of pollutants onto vegetation (45). While this assumption is valid when NO_2 is considered, fast reaction rates in the troposphere yield compounds that are more water soluble (e.g. HNO_3) (46). Periods of precipitation were assumed to result in no pollutant uptake; the reported values of NO_2 uptake using the UFORE-D model would be expected to be less than the values used in the current study.

Large-scale roof greening also indirectly benefits public health by reducing energy consumption. Green roofs can reduce peak energy demand resulting in fewer atmospheric emissions from power plants that run additional generators at peak times. Based upon emissions data for coal-fired utilities and natural gas combustion, estimates for avoided emissions for greening ten percent of Chicago are 2.21 million Mg_{NO2}/y and for Detroit are 1.83 million Mg_{NO2}/y (Table 4, SI) (47). Combining both direct (plant uptake) and indirect (fossil fuel reduction) methods of emission mitigation, greening ten percent of area roofs in Detroit would decrease public health costs by \$3.1 billion to \$11.8 billion per year, and in Chicago public health benefits would be \$3.8 billion to \$14.2 billion per year.

Net Present Value Analysis

The results were integrated into an economic model to determine the length of time required for a return on investment (ROI) in a green roof. Figure 1 shows the results of the analysis over the lifetime of the green roof system, and evaluates the green roof under a low air pollution benefit and a high air pollution benefit. The green roof is more expensive than the conventional roof at installation ($464,000 versus $335,000). Over the 40-year lifetime of the roof, the NPV of the green roof system is between 25% (low air pollution benefit estimate) and 29% (high air pollution benefit estimate) less than the NPV for a conventional system ($602,000).

Under the low estimate for health benefit valuation, the greatest potential economic contribution is due to energy savings. Annual benefits for the green roof system in this scenario are $2740 (2006$) per year. Energy savings account for nearly $1670 or 61% of the benefits. In this scenario, benefits due to mitigation of nitrogen oxides account for 33% of the annual benefits. Stormwater fee savings only account for 7% of the annual benefits.

When a high estimate for valuation of public health benefits is used, air pollution mitigation becomes the dominant benefit economically. With total annual benefits of $5240, 65% of the benefits ($3390) are attributable to air pollution mitigation. Energy savings remain the same but account for only 32% of the total annual benefit. The stormwater benefit is further reduced to only three percent of the total. While the monetary value of the health benefits is uncertain, in both the high and low estimates, public health benefits contribute significantly to the total annual benefit of green roofs.

While currently green roof adoption is driven by stormwater benefits and energy savings (48), benefits due to direct air pollution uptake and energy savings control the ROI. Additional savings due to reduced onsite stormwater infrastructure are not included at the building scale as infrastructure savings at individual building sites could only be realized for new building construction or significant renovation projects. Similarly, while system loads to HVAC were taken into account to determine the total reduction in energy, infrastructure savings (from size reduction) were not included. This analysis focused on the opportunity for green roofs on existing buildings that could support an extensive vegetated roof with minimal impact on the building and roof. All other parameters remaining constant, varying degree days to evaluate other climate regions (the southeastern states or the western states) changed the total energy consumed resulting in the $2000 range for both the conventional and the green roof.

For large-scale urban greening projects, it should be noted that not all of these roofs may be conducive to green roof implementation due to restrictive architectural features (e.g. roof slope, HVAC system placement, structural limitations of building). The analysis contained here limits roof greening to twenty percent of existing roofs, similar to the analysis for Washington, DC by Deutsch et al. (15). For scaled stormwater benefits, the economic savings are over the long-term after greening projects began most likely occurring during normal maintenance and replacement of existing stormwater infrastructure.

Policy Implications

The mean green roof cost is 25 to 29 percent less over 40 years, with the investment breaking even after twenty years. Incorporation of air pollution benefits the greatest potential social cost factor into the economic analysis. Further work is required to incorporate HVAC size reductions, stormwater infrastructure size reductions, and multiple air pollutant reductions. Results from this analysis revealed that the benefit of improved air quality should not be ignored by policymakers as proper valuation of the benefit can greatly influence the NPV.

Proper valuation of environmental benefits requires changes to current policies that affect green roofs. Currently, the analysis performed here incorporated mean stormwater fees at $ 0.17 per m^2 of land, yet projected long-term control plans are at $3.36 per m^2 of land. Inclusion of these costs will impact the benefit analysis. Policies that make stormwater infrastructure expenses more transparent to the citizenry through stormwater fees or a market-based tradable permit scheme for contribution to impaired local waterways are two strategies that have potential to rectify the price discrepancy. Translating the air pollution mitigation ability of green roofs into an economic benefit to the technology would further reduce the NPV by 9%. This could be achieved through direct incentives reducing the upfront cost of a green roof or through the incorporation of green roofs into existing regional air pollution emission allowance markets. Further research into these policy alternatives will aid the design and development of strategies to translate the societal environmental and health benefits of green roofs to the building owners that ultimately construct green roofs.

To quantify the benefit of reducing NO_X emissions for building owners, green roofs could be integrated into the existing air emission allowance markets. If green roofs are considered an abatement technology, then incorporating sinks into a cap-and-trade program could allow the pollution taken up by a green roof to be traded on the open emissions allowance market. Such a program does not currently exist, in part due to the constraints placed on the demonstrations that a new technology fits abatement criteria. On-going research through professional organizations such as Green Roofs for Healthy Cities have emphasized the need for quantitative measurements of the green roof benefits (stormwater, energy, air) as a priority for influencing regional and national policy in this realm.

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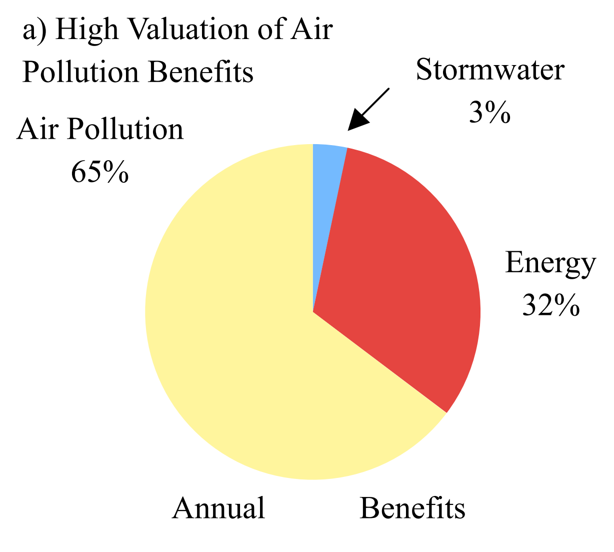
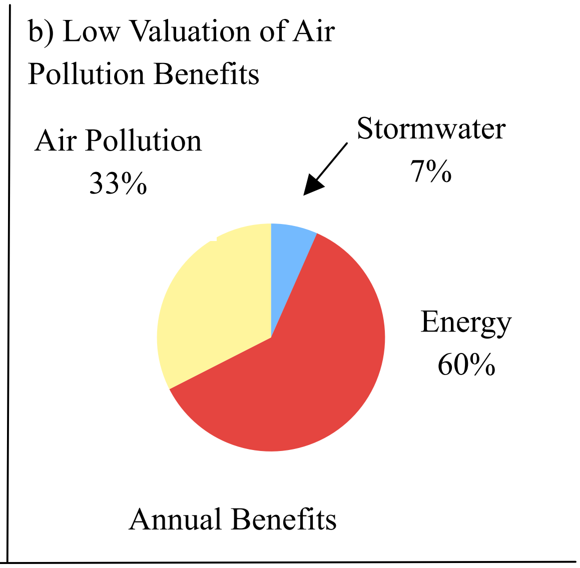
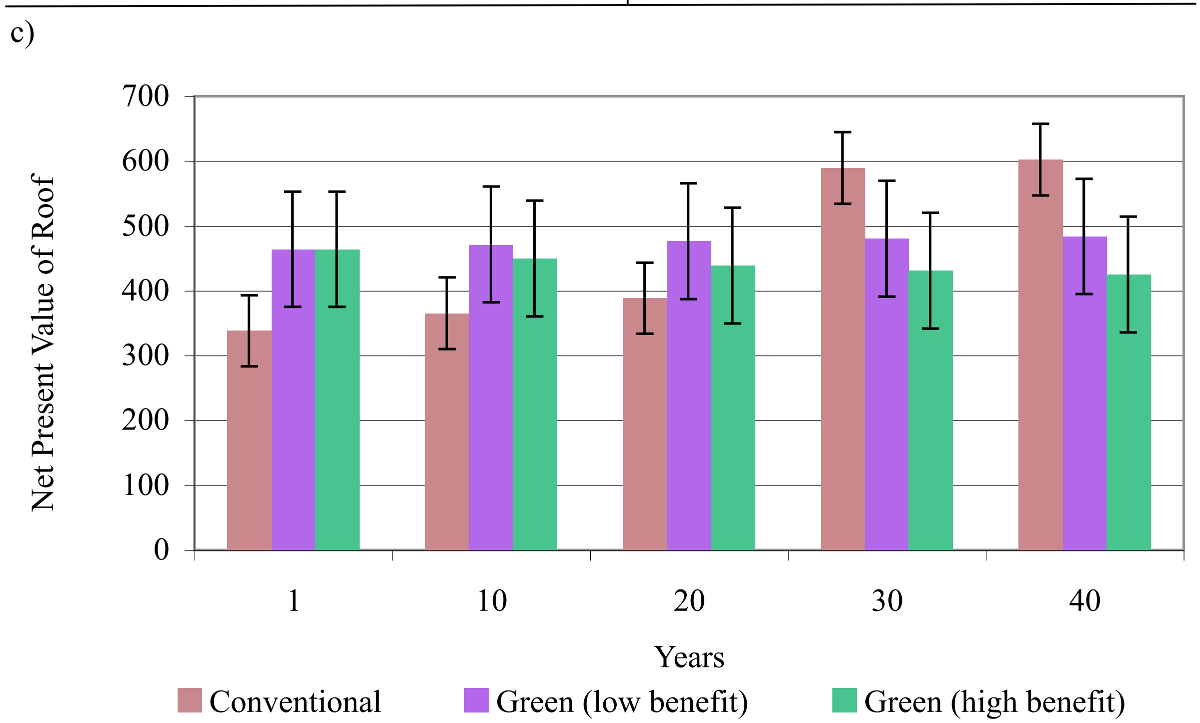
SUPPORTING INFORMATION. Technical attributes for economic analysis.



a) High Valuation of Air Pollution Benefits
Stormwater 3%
Air Pollution 65%
Energy 32%
Annual Benefits



b) Low Valuation of Air Pollution Benefits
Air Pollution 33%
Stormwater 7%
Energy 60%
Annual Benefits



c)
700
600
500
400
300
200
100
0
Net Present Value of Roof
1
10
20
30
40
Years
Conventional
Green (low benefit)
Green (high benefit)

Figure 1. Net present value (NPV) analysis of the conventional roof and the green roof under two public health valuation scenarios. Annual benefits for the green roof are broken into economic value realized from stormwater reduction, energy savings, and air pollution reduction under (a) the high valuation and (b) the low valuation of the contribution of NO2 reduction to public health. The benefits are incorporated into over the 40-year lifetime of the roof (c). At the end of year 20, the conventional roof is replaced; at this point the mean NPV of the green roof is less than the mean NPV of the conventional roof.

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