



Green Roof Planning Study

For the City of Boston

28 October 2009

Prepared by

ARROWSTREET

212 Elm Street, Somerville, MA 02144, 617.623.5555

Table of Contents

Acknowledgments.....	5
Executive Summary	7
Sustainable Roof Types.....	12
Benefits of Green Roofs	14
Benefits of Cool Roofs.....	18
Vegetated Roof System Components.....	19
Modular Vegetated Roofs	21
Cool Roofs.....	21
Photovoltaic Roofs.....	23
Recommended Green Roofing System	24
Preliminary Construction Costs.....	25
Design Considerations	26
Climate and Geographical Location.....	26
Roof Construction and Structural Capacities	26
Wind Loads / Uplift.....	28
Roof Drainage	28
Irrigation	29
Plant Selection	30
Planting Medium	33
Vegetation-Free Zones.....	34
Fire Prevention	34
Access and Accident Prevention.....	35
Testing	35
Code Compliance.....	35
Maintenance Plan.....	36
Measuring Criteria.....	37
Warranties / Guarantees	39
LEED Certification	40
Life Cycle Cost Analysis.....	41
LCC Factors	42
Summary and Conclusions.....	43

Selection Criteria and Database 47

Appendix I – Existing Boston Area Green Roof Installations 50

Appendix II – Roof Membrane Systems 53

Appendix III – Prototype Specifications 55

Appendix IV – Prototypical Construction Details 57

Appendix V – Life Cycle Cost Analyses 59

Appendix VI – Selection Criteria Worksheet 61

Appendix VII – City of Boston Sustainable Roof Database..... 63

Appendix VIII – References 65

Appendix IX – Glossary 67

Acknowledgments

This Study was funded with a grant from FY09 Municipal Technical Assistance Grant from Massachusetts Department of Environmental Protection.

Commonwealth of Massachusetts

Deval Patrick, Governor

Department of Environmental Protection

Brooke Nash

Branch Chief, Recycling Program

City of Boston

Thomas M. Menino, Mayor

Property and Construction Management Department

Michael J. Galvin

Chief of Public Property

Joseph I. Mulligan III

Deputy Director

Charles E. Worcester

Assistant Director

Carlene Laurent Rosati

Director of Alterations and Repairs

Maureen Anderson

Senior Project Manager

Hector Munguia

Senior Design Review

Cathy Murphy

Clerk

The Environmental Department

D. Bryan Glascock

Director

Carl Spector

Director, Air Pollution Control

Office of Budget Management

Laurie Pessah

Deputy Director of Capital Planning

Project Team

Arrowstreet

James Batchelor, FAIA, LEED AP

Laurence S. Spang, AIA, LEED AP

Tina T. Soo Hoo, AIA

Architects and Planners

Principal in Charge

Project Manager

Project Planner

CBA Landscape Architects

Clara Batchelor

Landscape Architects

Landscape Architect

Kalin Associates

Mark Kalin, AIA

Specifications Consultants

Specifier

D.M. Berg Associates

Ali Borojerdi

Davis Langdon

Seamus Fennessey

Structural Engineers

Structural Engineer

Cost Estimating Consultant

Cost Estimator

Executive Summary

In support of the Executive Order of Mayor Menino Relative to Climate Action in Boston, the City of Boston through the Property and Construction Management Department (PCMD) and the Environment Department have commissioned this Green Roof Planning Study to identify design standards, costs and benefits of a sustainable roof design and retrofit program for the City of Boston's municipal buildings.

The purpose of this study has been to analyze the feasibility for green roof retrofits for the City of Boston's municipal buildings. The Study has investigated green roof design and construction; developed guidelines for green roof retrofits, including prototype details and specifications; prepared cost estimate and Life Cycle Analysis for green roofs; developed selection criteria for determining which buildings may be suitable candidates for green roof retrofit; developed a database of information about existing municipal buildings; and, applied the selection criteria to the database to develop a short list of buildings that may be the best candidates for future green roof retrofit.

This Final Report documents the Study and provides recommendations for the next steps in the City's evaluation of potential green roof retrofit.

This Study was funded with a grant from FY09 Municipal Technical Assistance Grant from Massachusetts Department of Environmental Protection.

Introduction

Several types of sustainable roofs that have been investigated as part of this Study, including the following:

1. Vegetated (Green) roofs consisting of plants and soils on top of various protection membranes. Green roofs are typically classified as:
 - a. Extensive Green Roofs generally have a thin 4" to 6" thick growing medium (soil) layer and are typically planted with drought tolerant plants such as sedum and other succulents. The growing medium is typically a specialized formula containing a mix of natural and artificial ingredients such as lava, gravel, vermiculite and perlite or recycled material such as crushed brick or concrete. Plants and growing media are usually designed not to need permanent irrigation, although start-up irrigation is usually required for the first 12 to 18 months.
 - b. Simple Intensive Green Roofs generally have 8" to 12" of growing medium and are capable of supporting larger and more diverse plant types. Depending on the plants and growing media, permanent irrigation may be required.
 - c. Intensive Green Roofs generally have more than 12" deep growing medium and can support a variety of plants and trees. Intensive Roofs are frequently used for roof decks and other habitable spaces and generally require permanent irrigation.

2. For those roofs which may not be capable of supporting vegetation, a Cool (white) roof membrane should be considered to help reflect the sunlight and reduce heat gain through the roof.
3. Recent developments in roofing technology have led to Integrated Photovoltaic (PV) arrays on roof membranes. Although more commonly seen in Europe, Integrated PV roofs are starting to be installed in the U.S.
4. This Study also has looked briefly at Rooftop Agriculture as a potential source of additional benefits from a vegetated roof. Typically roof-top agriculture would require a minimum of 12" growing medium, so it may be difficult to accomplish in existing buildings without significant structural reinforcing.

To assist the City understand the costs and benefits of green roofs, this Planning Study has included the following tasks:

- Summarized available research and identified industry standards for green roof construction.
- Reviewed existing green roof installations and researched short and long term maintenance issues.
- Developed Design Guidelines for Green Roof installations, including prototypical construction details and specifications for Chapter 149 public bid construction.
- Identified typical costs and developed Life Cycle Analyses to better understand the cost benefits of green roofs.
- Developed a Selection Protocol for understanding which municipal buildings may be good targets for green roof retrofit.
- Developed a Database of building information for municipal buildings.
- Applied the selection protocol to the list of municipal buildings in the database to develop a shortlist of candidates for further study for a potential green roof retrofit.
- Developed evaluation criteria to measure the impact of green roof installations.

Findings

Through the course of this study, the following direct benefits have been identified from sustainable roofs:

- Green roofs can result in a substantial heat gain reduction from the roof, resulting in less heat build-up in the interior spaces and energy savings for the building (particularly cooling loads).
- Green roofs can lead to substantial reduction in stormwater run-off, particularly during summer months.¹ Substantial benefits in stormwater quality from vegetated roofs

¹ Note: due to typical sewer system utility rate structures, there is not usually a direct financial benefit from reduction in stormwater since rates are not usually set by stormwater outflow.

have also been documented, including reduction in particulate matter and associated chemicals in run-off.

- Green roofs help to protect the waterproofing membrane from damage from ultraviolet light and temperature fluctuations due to heat gain, helping to prolong the life span of the roof system.
- Cool (White) roofs can also result in a significant reduction in heat gain from the roof.

Other more indirect benefits include overall reduction in urban heat island effect, restoration of natural habitat and increased bio-diversity, potential noise reduction for interior spaces, and potential use and visual enjoyment by building occupants.

These benefits come with a cost: the initial costs for retrofitting a building for a green roof can be substantial. The green roof assembly system, including protection membranes, growing medium and plants can cost between \$12 to \$15 per square foot, or approximately twice the cost of a typical roof membrane system.

In addition, an extensive green roof with 4” to 6” soil depth can increase the structural load on the roof by 20 to 35 pounds per square foot (PSF) or approximately 30% to 50% of the roof’s carrying capacity. Given this additional load, it is likely that most buildings will require some type of structural reinforcing to support a green roof. Concrete framed buildings are more likely to be able to support a green roof; wood framed buildings less likely. Additional secondary modifications may also be required to install the structural reinforcing, such as removal and replacement of interior finishes or relocation of existing MEP/FP systems.

This Study has prepared Life Cycle Cost analyses comparing a typical modified bitumen roof with a cool (white) roof and green roof to understand the cost benefits. These LCC analyses suggest that the payback for the additional capital costs of a green roof is long term, varying between 40 to 60 years depending on the cost of the installation and the potential for energy savings in the building. However, further more detailed investigations are necessary before more definitive payback periods can be established for the following reasons:

1. The cost for structural reinforcing required to support a green roof will vary significantly from building to building. A structural analysis of each existing building will need to be performed to more accurately assess the scope of work and associated costs necessary to support the additional load of a green roof.
2. The potential energy savings of a green roof will also vary between existing buildings. An energy model of each building should be developed to more fully understand potential energy savings to determine the potential payback.

Despite these limitations, there is significant potential for green roofs to contribute to the overall sustainable improvements of the City’s building stock. For those buildings which may not be cost effective to provide a green roof, a Cool (white) roof can provide many of the same heat reduction benefits of a green roof.

This Study has developed a Selection Protocol and database of existing municipal building information to assist the City’s planning for future green roof installations. The Selection

Protocol is a point system intended to rate an existing building's potential for green roof retrofit. Working with information provided by PCMD, the Study has developed a database of building information and applied the point system to the database to establish a shortlist of potential candidates for further study.

Conclusions

The work completed as part of this Study has advanced the City's understanding of green roofs. The Study has investigated existing green roof installations and industry standards, developed green roof construction guidelines, and evaluated potential cost benefits. This Study has identified the following conclusions:

1. Green roofs can provide direct, tangible benefits consistent with the Mayor's Executive Order Relative to Climate Action in Boston. These benefits include building energy savings, reduction in stormwater run-off quantity, improvements in run-off quality, improved roof membrane life span, and noise abatement for interior spaces. Indirect benefits include reduction in urban heat island effect, increased bio-diversity, and potential benefits for building users and occupants.
2. Green roofs are part of an emerging sustainable emphasis of the construction industry and the number of green roof manufacturers and installers is increasing rapidly. Through discussions with PCMD's technical staff, the Study has identified recommended guidelines for construction details and specifications for future green roof installations.
3. The potential costs for green roofs is substantial, particularly for structural reinforcing that is likely to be required for existing buildings. The payback period for these capital costs is long term, probably in the 40 to 60 year time frame.

Next Steps

This Study has developed a short list of existing buildings which may be candidates for green roof retrofit. More detailed studies of these buildings should be performed to evaluate whether a green roof is feasible and what the costs and benefits are likely to be. The additional studies should include the following steps:

1. Evaluation of the existing roof for green roof installation, including:
 - a. Evaluation of the existing roof condition and projected lifespan, including identification of potential remedial work that may be required to the roof deck, roof edge, flashings, etc.
 - b. Identification of available planting area(s) and areas to remain plant-free zones around roof top equipment and transition areas.
 - c. Evaluation of access for construction and maintenance.
 - d. Availability of water for temporary or permanent irrigation, including evaluation of water pressure and capacity. If not readily available, identification of supplemental work required to provide water service to the roof.

2. Preliminary/Conceptual design of green roof, including recommended roof membrane system, depth of soil and planting types. Identification of additional, supplemental work that may be required, such as roof access improvements, irrigation requirements, and secondary modifications like interior renovations to allow structural reinforcing.
3. Evaluation of existing structural systems and identification of structural reinforcing that may be required for green roof retrofit. This should be performed in accordance with Chapter 34 requirements of the Massachusetts Building Code.
4. Development of an energy model for the building to understand potential energy savings associated with the green roof. Additional energy improvements being considered, such as increased roof insulation or downsizing of mechanical equipment, should be included in the energy model to determine the overall benefit(s) of the project.
5. Development of a preliminary cost estimate for the work. The cost estimate should include direct work, such as the green roof membrane system, plantings and growing medium, as well as secondary improvements that may be required, including structural reinforcing, interior renovations, roof access improvements, irrigation installation, etc.
6. Development of a Life Cycle Analysis to understand cost benefits for the green roof, including potential payback period, if any.

To further the City's goal to evaluate green roofs as an on-going part of the City's capital improvement program, we recommend that the City establish a pilot program to evaluate and construct a few prototypical green roofs on a few existing buildings as a test for a broader retrofit program. This would allow the City to evaluate green roofs and 'road test' the construction before implementing it on more buildings.

In addition to these next steps, the City should monitor new green roofs constructed at the Roosevelt K-8 School in Hyde Park, planned for the new Area B2 Police Station in Roxbury, and installed at the City Hall terrace.

Sustainable Roof Types

There are two primary types of sustainable roofs in common practice: green (vegetated) roofs and cool (white) roofs. While this study has primarily focused on green roofs, it has also investigated cool roofs as an alternative to green roofs. The following is a brief summary of sustainable roof types.

Extensive Greening

Soil is generally 4” to 6” deep. Involves cultivation of vegetation in forms which create a ‘virtual nature’ landscape and requires hardly any external input for either maintenance or propagation. The plants which are used will be particularly well suited to coping with the full range of conditions which they are likely to encounter at the locations in which they will be planted, and they will be capable of self-propagation. Local flora should be considered.²

Extensive green roofs are usually planned to require irrigation only during the first one to two year start-up period. Irrigation varies because of plant selection, micro climates and age of plantings.

Simple Intensive Greening

Soil is generally 8” to 12” deep. As a rule, simple intensive greening involves the use of grass, shrubs and bushes as ground cover, but the range of options available to the user and the architect is not as wide as that intensive greening has to offer. The plants which are used make few demands on the layering superstructure and need little watering and feeding, which reduces the amount of attention required. Depending on the range of plants, regular irrigation may be required beyond the start-up period. A simple intensive greening site is typically less costly to construct than is an intensive greening site.³

Intensive Greening

Soil is greater than 12” deep. The term ‘intensive greening’ covers the planting of shrubs and bushes, as well as grassed areas, even an occasional tree. These may be laid out either on the same level, at different heights or in individual plantings spread about the site. The wide range of options available for designs and uses means that sites can be fitted out in such a manner as to create an amenity comparable to park facilities at ground level. The plants which are used make heavy demands on the layered superstructure. Regular attention is needed to maintain sites of this type in good order, in particular regular watering and feeding is required.⁴ Intensive green roofs are most typically used in plaza applications.

² German FLL Guidelines for the Planning, Execution and Upkeep of Green-roof sites 2002

³ German FLL 2002

⁴ German FLL 2002

	Extensive	Simple-Intensive	Intensive
Maintenance	Low	Periodic	High
Irrigation	No (except start-up irrigation)	Periodic	Regular
Plant Communities	Moss-Sedum-Herbs and Grasses Low growing plants; Hardy, self-sufficient and self-propagating	Grass-Herbs and Shrubs	Lawn or Perennials, Shrubs and Trees; More varied, larger species, and specialty species
Plant Heights	2" to 12"	12" to 24"	12" to 36"+
Growing Media Depth	1.5" to 8", 4" to 6" typical	4" to 20"	4" to 79"+
Costs	Less	Medium	More
Use	Ecological protection layer, Usually non-accessible	Designed Green Roof	Park-like Garden Designed for access (typically)
Stormwater Reduction	Low	Medium	High
Roof Slopes	Slopes up to 30 degrees		Only used on low slopes or terraced roofs
General Weights (saturated)	13 to 30 psf	25 to 40 psf	35 to 100+ psf

Figure 1: Green Roof Characteristics

Cool Roofs

A cool roof is a light colored roof to reflect and emit the sun's heat back to the sky instead of transferring it to the building below. The two basic characteristics that determine the 'coolness' of a roof are solar reflectance (SR) and thermal emittance (TE). Both properties are rated on a scale from 0 to 1, where 1 is the most reflective or emissive.⁵ Solar Reflectance Index (SRI) is a value that incorporates both solar reflectance and emittance in a single value to represent a material's temperature in the sun. SRI quantifies how hot a surface would get relative to standard black and standard white surfaces. It is calculated using equations based on ASTM E 1980. It is expressed as a fraction (0.0 to 1.0) or percentage (0% to 100%).⁶

Integrated Photovoltaic Arrays

Roof membranes with integrated Photovoltaic (PV) arrays have been developed in Europe and are beginning to be marketed in the United States. A layer of thin film photovoltaic cells is adhered to a PVC roof during installation. An integral wiring network is installed in the roof insulation to connect the PV arrays with the building electrical system. The system is intended for large scale installation – over 30,000 SF. At this time, the only manufacturer to offer an integrated PV array system in the Boston area is Sarnafil, so it would need to be specified as a propriety product.

⁵ Cool Roof Rating Council

⁶ EPA Heat Island Effects

Benefits of Green Roofs

The benefits of Green Roofs can be substantial, including the following:

Direct Benefits

- Increase thermal efficiency, particular in warm months; energy savings

Green roofs have been demonstrated to improve energy efficiency by reducing the heat gain through the roof, primarily by blocking sunlight from heating the roof surface and also by evapotranspiration – the cooling affect produced by water vapor production from the vegetation.

Energy efficiency improvements are more pronounced in the summer cooling months than in the winter heating season since the layer of soil does not supply much additional roof insulation. See Figure 2 below.

Since one of the primary benefits of a green roof is the reduction in the cooling load of a building, a non-air conditioned building would not financially benefit as much from a green roof as an air conditioned building. However, a green roof would likely reduce the heat gain onto the building, making it more comfortable for its occupants. This is overall true for one or two-story buildings where the roof is a higher percentage of the building envelope.

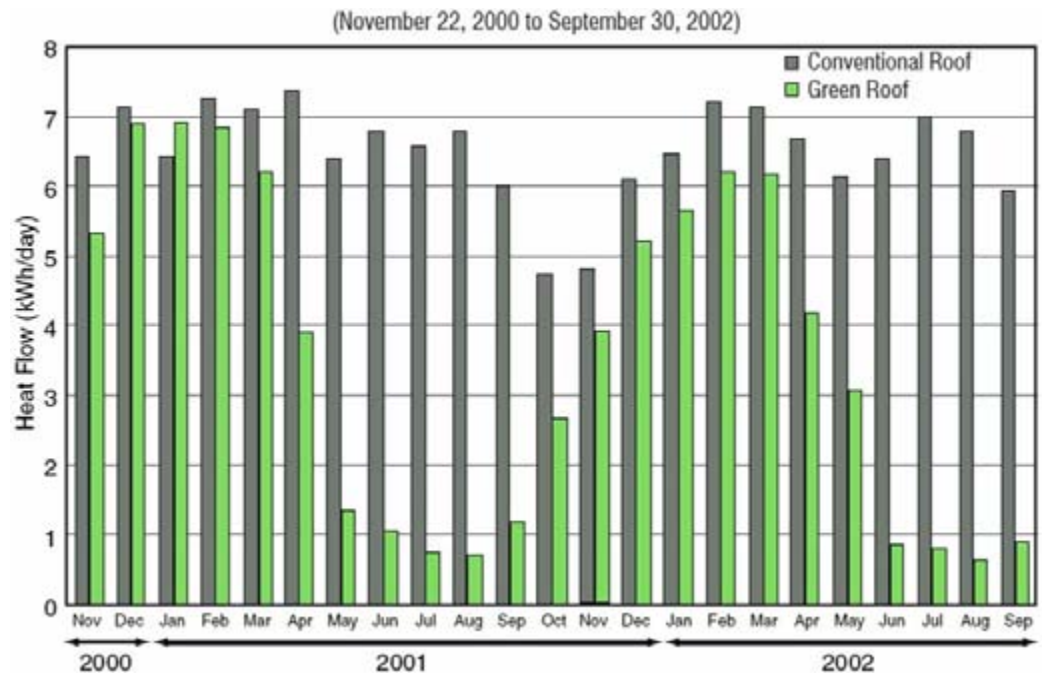


Figure 2: Average Daily Heat Flow through Green Roof and Conventional Roof Systems⁷

⁷ Source: National Research Council of Canada 2003.

Studies differ on the extent of energy savings from green roofs. The 2003 study by Liu and Baskaran for the National Research Council Canada showed a 75% savings of cooling energy demand. The Study was based on an 800 SF test installation that “can represent a low slope industrial roof with a high roof-to-wall ratio.” Alternatively, a study by the University of Pennsylvania Center for Green Roofs Research showed a reduction of approximately 10%.⁸

Based on the varying conclusions, this Study recommends that an energy model be developed for roofs being considered for green roof installation to determine the potential energy savings. For the purposes of the Life Cycle Analysis undertaken as part of this Study, we have used a figure of 15% energy savings as a medium value for energy savings. The 15% reduction is based on a Life Cycle Cost analysis produced for Columbia University.⁹

- Reduction in Stormwater runoff and improved Stormwater quality

Green roofs have been demonstrated to reduce stormwater runoff from roofs by absorbing rainwater. According to a study performed by Penn State Center for Green Roof Research, a green roof can result in a 64% reduction of stormwater runoff from an ordinary roof membrane.

The extent of stormwater runoff varies depending on the time of year. During winter months, the green roof is more likely to be saturated and/or frozen, so stormwater retention is relatively less than the summer months when the plants and soil are more likely to absorb larger amounts of water. See Figure 3. Also, the amount of water retention will decrease over an extended storm period as the soil becomes saturated.

⁸ Dr. Robert Berghage, 2004

⁹ Kenneth Acks, Cost-Benefit Group, LLC, *A Framework for Cost-Benefit Analysis of Green Roofs: Initial Estimate*, 2007.

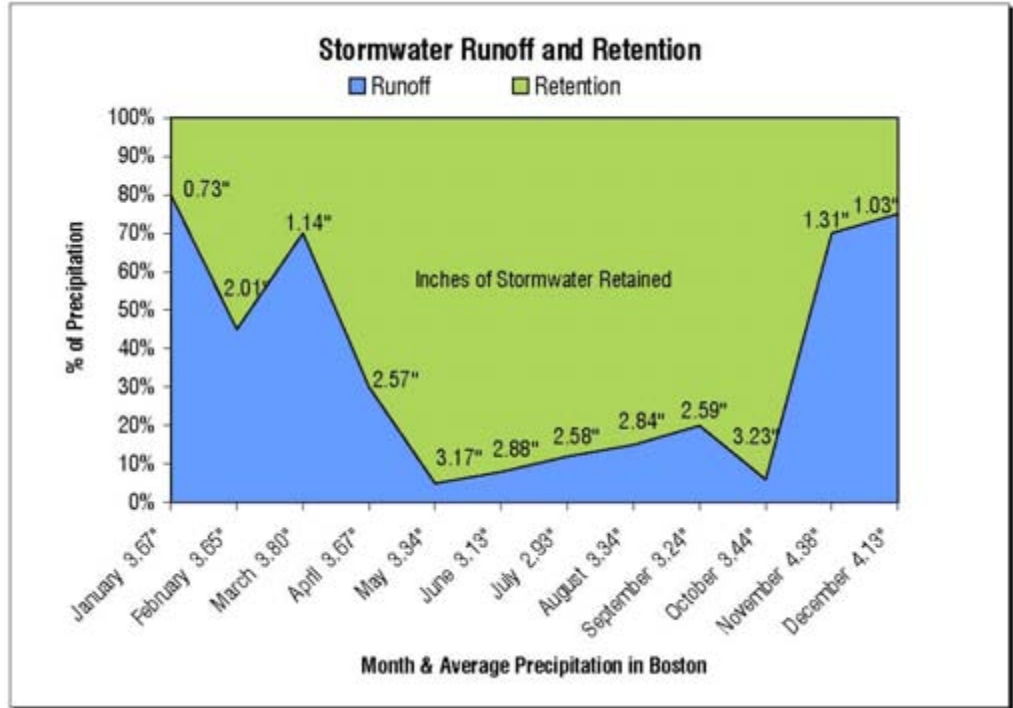


Figure 3: Stormwater Runoff and Retention¹⁰

Green roofs can also result in benefits to the quality of stormwater runoff by reducing particulate matter and filtering chemicals from the water. According to a 2005 study, green roofs can remove up to 95 percent of the cadmium, copper and lead from stormwater runoff and can reduce 80 to 95 percent of suspended solids and hydrocarbons.¹¹

Despite the benefits, typically there is no economic gain from stormwater reduction since most jurisdictions do not charge separately for stormwater run-off. In Boston, for instance, rates are typically applied based on water usage – sanitary and stormwater sewer is typically not metered. So savings of stormwater may not be an economic benefit to the City.

The benefit of stormwater run-off reduction will need to be balanced by the Groundwater Conservancy Overlay District in the Boston Zoning Code, which requires infiltration of rainwater into the ground to help recharge the underlying groundwater level. According to the Zoning Code, a proposed project must promote infiltration of rainwater into the ground by capturing a volume of rainfall on the lot equivalent to not less than 1.0 inches across an impervious surface area of the lot. The Overlay District covers a large portion of the Back Bay and South End neighborhoods (see Figure 4).

¹⁰ Source: PennState Center for Green Roof Research, Rock Springs, PA, 2005; Gaisma.com Solar and Surface Meteorology.

¹¹ 2005 Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto as noted in the Environmental Protection Agency (EPA) *Reducing Urban Heat Islands: Compendium of Strategies Green Roofs (Draft)*

Use of green roofs in these areas should be undertaken in consultation with the BRA and BWSC to ensure compliance with the intent of the Groundwater Conservancy Overlay District.

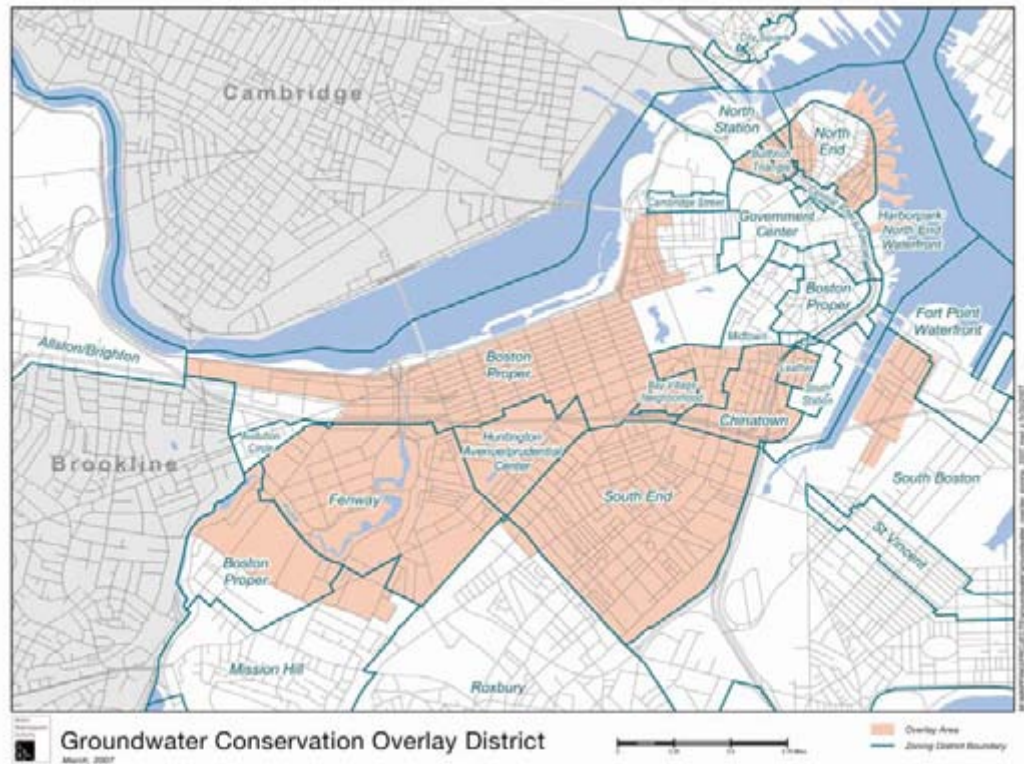


Figure 4: Groundwater Conservation Overlay District Map

- Reduces interior noise levels, specially in urban areas and near airports

A green roof can contribute to sound attenuation, particularly from overhead noise sources such as airplanes.

According to a 2008 study, green roofs can provide a sound transmission loss of 5 dB to 13dB for low and mid-range frequencies (50Hz to 2000 Hz) and a 2 dB to 8 dB in the higher frequency range.¹²

The study further notes that sound transmission loss from a green roof may be valuable in buildings where the ceilings are eliminated due to other sustainable considerations such as improved daylighting.

The extent of sound attenuation is dependant on the depth and type of soil, waterproofing membrane system, and roof construction type.

- Extends roof life; protects roof membrane

The green roof system protects the waterproofing membrane from damaging ultraviolet light and temperature swings, resulting in a longer life span for the roof

¹² Connelly and Hodgson. *Sound Transmission Loss of Extensive Green Roofs*. 2008 Greening Rooftops for Sustainable Communities Conference.

membrane system. According to the Athena Institute, the projected life span of a green roof system can average 39 years or approximately twice the average lifespan of a conventional roof membrane system of 15 to 20 years.¹³

Indirect Benefits

Additional Indirect benefits have been attributed to green roofs, including the following

- Green roofs can help reduce the overall temperature of an urban neighborhood (the “heat island“ effect) by decreasing the heat being trapped and released by roofs.
- Depending on the types of plants and soils, a green roof can provide natural habitat for animals, insects and plants and can help increase the biodiversity of an urban area.
- Green roofs can help reduce dust and air pollution levels
- To the extent that a green roof is visible, it can provide potential aesthetic and visual benefits to building occupants and/or neighbors
- A habitable green roof such as a roof terrace or garden has the potential to provide additional usable space for the building or create additional urban open space for a neighborhood.
- A green roof can provide potential educational opportunities either directly such as a school or community center, or indirectly through public awareness education.
- An increasingly interesting benefit of green roofs is the potential for agricultural benefits. Although more demanding in terms of depth of soil and irrigation requirements, a future benefit of green roofs may be a food source.

Benefits of Cool Roofs

If it is not feasible to install a green roof due to structural or cost limitations, it may still be beneficial to install a Cool (White) roof which can improve the building thermal efficiency by reflecting sunlight off the roof surface, resulting in lower roof temperatures and less heat gain through the roof. A cool roof has the advantage of being installed like a conventional dark roof, so would not typically require additional structural reinforcing or other building modifications. There is usually a slight cost premium for cool roofs and unlike a green roof, a cool roof does not contribute to stormwater management, acoustical isolation, or longer life span for the roof membrane.

In northern climates, white roofs can create a “heating penalty” by reflecting sunlight during the winter which would otherwise help to warm the roof and heat the building (or slow the loss of heat through the roof). The extent of the heating penalty will vary based on the roof exposure, insulation, and winter daylight/sunshine conditions. The use of the building will also impact whether the heating penalty would otherwise benefit the building’s energy usage. For example, a high occupancy office building can typically generate substantial heat from the

¹³ *Maintenance, Repair and Replacement Effects for Building Envelope Materials* (2002) prepared by Morrison Hershfield Ltd. for the Athena Institute

occupants, lights, and equipment, so the heat gain from the roof may be less useable than for a building with less intense occupation, such as a school or residence.

Despite the heating penalty, it is likely that a white or light colored roof will provide an overall energy benefit for a building. Based on a preliminary study using the U.S. Department of Energy's Cool Roof Calculator, the heating penalty in Boston can be as much as 30% of the overall energy savings of a Cool Roof. (See Appendix V for further information.)

Vegetated Roof System Components¹⁵

Although different manufacturers have different roof systems, the following is a general list of components that go into a vegetated roof system.

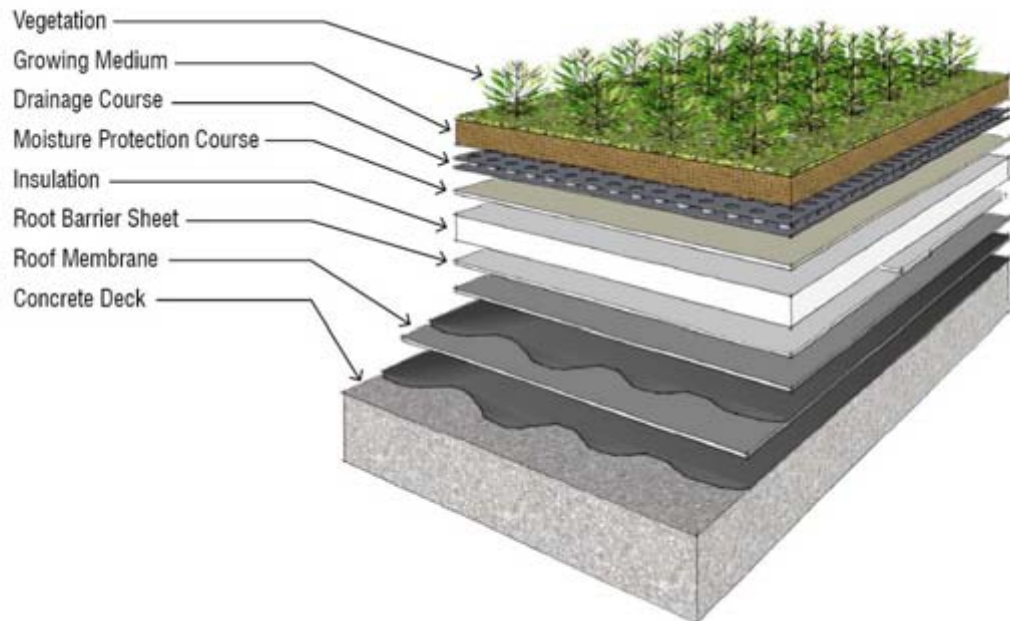


Figure 5: Green Roof System with modified bitumen waterproofing

Roof Substrate: Concrete recommended. Steel deck is generally adequate. Wood decking may be acceptable if sufficient load and deflection capacity are available.

Roof Membrane: National Roof Contractors Association (NRCA) recommends waterproofing systems be fully adhered to the substrate and be able to provide hydrostatic resistance based on the expected amount of water drainage and retention.

Protection Course: Protects roof membrane from damage after installation of the waterproofing / roofing membrane.

¹⁵ NRCA 2007, FLL 2002, Construction Specifier 'Living with a Green Roof' 2009

Root Barrier: A material that prevents plant roots from damaging the waterproofing membrane.

Separation Layer: Installed if necessary to keep chemically incompatible materials apart.

Anti-bonding Layer: Prevents unwanted bonding between different materials and/or reduces shear stress levels between any pair of courses.

Drainage Layer: Provides a location for moisture to move laterally through the green roof system; also relieves hydrostatic pressure from material's surface and the associated weight of water.

Water Reservoir Layer: Retains or stores moisture for overburden growth.

Water Retention Layer: Retains or stores moisture for plant growth.

Water-resistance Insulation: Extruded Polystyrene Foam Insulation, R-value of 5.0 per inch thickness, specify R-value to meet Massachusetts building and energy codes.

Filter Fabric: Tightly woven fabric used to restrict the flow of fine soil particles and other contaminants while allowing water to pass freely through, thereby protecting the drainage systems from clogging.

Growing Media: An engineered soil-based medium, specially formulated to provide a proper growing environment for the specific plants.

Vegetation: Selected according to climate and geographical location; plants may include moss, sedums, small to large shrubs, coppices, grass, and small to large trees.

Erosion Mat: Mat / blanket to control erosion while plants are established, often made from natural materials like jute or core; biodegradable as plants establish themselves, and provide an important layer of mulch to retain moisture and suppress weeds in the process.

Wind Net: Net to control wind uplift of the growing medium and plants depending on the design wind loads calculated for the building.

Modular Vegetated Roofs

A modular vegetated roof is composed of a series of pre-planted modules typically made of recycled plastics that can be placed directly on a roof or other structure with sufficient structural capacity. A protection board / course is typically placed over the existing or new roofing membrane prior to placement of the modular trays. The modular trays are designed to be a complete self-contained system and are typically pre-planted. The benefits of modular systems are easy and quick installation. The modulars are typically light weight which allows them to be moved for repair and set back into place. The vegetation in the modulars are typically pre-planted and pre-grown to give the immediate benefits of an established vegetated roof.

Cool Roofs

Cool roofs are typically made from white or light colored roofing membranes. The roof membranes are made of highly reflective and emissive materials that reflect sunlight and typically remain approximately 50° to 60° F (28-33° C) cooler than traditional dark roof materials during peak summer weather.¹⁶

How Light Colored Roofs Save Energy:

- Reflect solar radiation: Reduces heat gain through the roof to reduce air-conditioning use, which is a direct effect
- Alter the surface energy balance: Reduces outdoor temperature, which is an indirect effect¹⁷

To meet LEED Criteria, the roof must have a Solar Reflective Index of 78 or higher. The following are types of Cool Roofs:

Cool Roof Coatings are surface treatments that are best applied on low-sloped roofs in good condition. They have the consistency of thick paint and contain additives that improve their adhesion, durability, suppression of algae and fungal growth, and ability to self-wash, or shed dirt under normal rainfall.

Single-Ply Membranes come in a pre-fabricated sheet that is applied in a single layer to a low-sloped roof. The materials are generally adhered (recommended) or mechanically fastened in place over the entire roof surface, with the seams sealed by taping, gluing, or heat-welding. A number of manufacturers formulate these products.

Asphalt Shingles, Metal Roofing, Tiles, and Shakes are commonly used for steep-sloped roofs.

¹⁶ Heat Island Group

¹⁷ U.S. EPA "Reducing Urban Heat Islands: Compendium of Strategies Green Roofs"

²⁰ EcoStructure magazine Jan/Feb 2009

Protected Roof Membranes such as extruded polystyrene insulations used on Inverted Roof Membrane Assembly (IRMA) type roofs have reflective coatings for cool roofs

Architectural Pavers such as pre-cast concrete pavers and stone pavers are available as cool roof products that provide solar reflectance and emittance values.

There have been some recent reports of concerns with Light Colored Roofs. These include:

- Potential glare in adjoining spaces
- Potential heat gain in adjoining building materials due to reflected radiant energy
- Some reports of condensation and ice under white roof²⁰

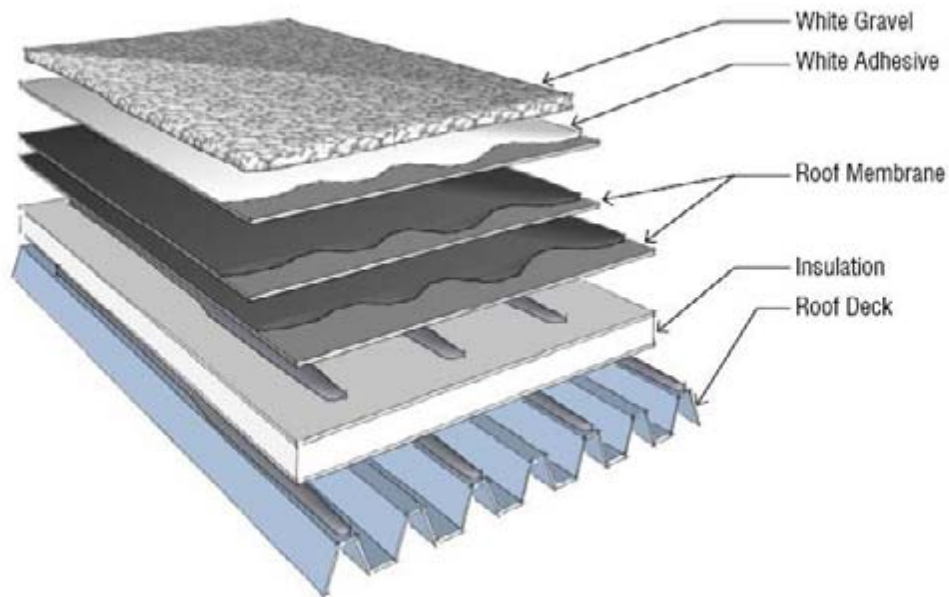


Figure 6: Cool Roof System with White Gravel

²⁰ EcoStructure magazine Jan/Feb 2009

Photovoltaic Roofs

BiPV (Building Integrated Photovoltaic) refers to systems and concepts in which photovoltaic, as well as having the function of producing electricity, also takes on the role of building element.

Thin-film lightweight Photovoltaic (PV) fused to single ply roofing membrane provides a flexible durable solar roofing panel for low sloped roofs. Currently there is only one source for PV array roofing membrane, Sarnafil.

- No exposed wiring and cable clutter
- Solar roofing panel is hot-air welded to roof membrane
- 10' x 20' panels, each provides 744 watts
- Lightweight – 12 ounces per square foot
- 20-year warranty
- Generally viable for large installations 30,000 SF or larger
- Approx. \$30-35 per SF / \$8.00 per watt

Thin-film PV has better performance characteristics than Crystalline PV at actual operating temperatures, under lower light intensities, and even when damaged.

Characteristics	Thin-film PV	Crystalline PV
Flexibility	Very flexible	Rigid
Performance-Temperature	-4% @ 140o F (60o C)	-15% @ 140o F (60o C)
Performance- Low Light	20% more Watt hours/day	20% less Watt hours/day
Performance- Shaded	Slight reduction (4% - 5%)	Loss of at least 30%
Performance- Damage	Slight reduction	Degrades to zero
Durability / Breakability	Flexible/unbreakable	Rigid/breakable glass

Figure 7: Characteristics of Thin-film PV and Crystalline PV

Recommended Green Roofing System

This study reviewed a number of roofing systems for the City's roofing standards, including modified bitumen (Tremco and others), hot fluid applied rubberized membrane (Hydrotech and Cetco), PVC membrane (Sarnafil), Thermoplastic Polyolefin ('TPO' – Carlisle and Firestone among others) and EPDM membrane (also Carlisle and Firestone). See Appendix II for detailed review of alternate roofing membrane systems.

All systems have their own strengths and weaknesses. Discussions with PCMD focused on the need for a high quality system that provides a good long-term waterproofing membrane. In particular is concern about the longevity of the system and ease of repair, particularly with limited maintenance budgets and the potential for damage due to natural causes or vandalism. Based on these discussions and review of alternate systems, this Study recommends use of modified bitumen roofing for most vegetated or cool roof applications.

However, it should be noted that one system is not the perfect answer for all building applications. For particular applications, alternate roofing systems may be more advantageous. For example, if a portion of an existing roof is being upgraded, it will make sense to use a roof membrane to match the existing system. For this reason, we recommend that the particular roofing system be chosen as part of the design analysis for each particular building.

Preliminary Construction Costs²¹

Typical Re-roofing Costs \$12 to \$15 / SF New insulation, re-use existing flashing
(Modified bitumen roof) \$18 to \$20 / SF With new flashing

White Roof Premium \$1 to \$2 / SF Additional cost for TPO Roof

Extensive Green Roof Premium
(does not include structural reinforcing and roofing)
\$12 to \$15 / SF Green Roof System (includes installation)
\$16 to \$26 / SF Modular (4" ht.) Green Roof System
(includes installation)

Roof Membrane Costs \$6.50 / SF EPDM Membrane
\$7.50 / SF TPO Membrane
\$8.50 to \$9 / SF PVC Membrane
\$16 to \$18 / SF Modified Bitumen

Note: Does not include general contractor mark-up, overhead, profit, general conditions, and bonds.

Cost Estimate Example

For the purposes of the Life Cycle Analysis prepared as part of this Study, a prototypical 10,000 square foot (SF) building was evaluated. The anticipated cost breakdown of the green roof installation is as follows:

Demolition	\$1 to \$2 per SF	\$10,000 to \$20,000
Typical Roof Installation	\$18 to \$20 per SF	\$180,000 to \$200,000
Green Roof (Premium)	\$12 to \$15 per SF	\$120,000 to \$150,000
	Total	\$310,000 to \$370,000

For the purposes of the Life Cycle Analysis presented later in this report, an initial capital cost of \$350,000 for the green roof has been assumed.

²¹ Cost figures provided by Davis Langdon (February 2009)

Design Considerations

The following items should be taken into account when considering sustainable roofs for either new or existing buildings.

Climate and Geographical Location

Variable	J	F	M	A	M	J	J	A	S	O	N	D
Insolation, kWh/m ² /day	1.74	2.62	3.58	4.58	5.45	5.80	5.88	5.29	4.14	2.93	1.87	1.53
Clearness, 0 - 1	0.46	0.50	0.49	0.49	0.50	0.50	0.53	0.53	0.51	0.49	0.44	0.45
Temperature, °F	28.58	30.33	36.46	45.16	54.86	64.42	69.66	69.35	63.50	53.53	44.01	34.27
Wind speed, mph	17.27	17.45	16.93	15.14	13.71	13.27	11.61	11.54	12.15	14.20	16.69	17.69
Precipitation, in	3.67	3.65	3.80	3.67	3.34	3.13	2.93	3.34	3.24	3.44	4.38	4.13
Wet days, d	10.9	9.8	11.4	11.0	11.3	10.8	9.0	9.9	8.5	8.6	11.0	12.0

Figure 8: Solar Energy and Surface Meteorology for the City of Boston²²

The annual precipitation in Boston is approximately 42.7”.

Although typical roofs are exposed to full sun, some may be partially shaded by building elements:

North and East facing roofs are most desirable:

- Reduces evaporation and direct solar exposure, which helps support vegetation
- Reduces need for irrigation

South and West facing roofs are least desirable:

- Have the most solar exposure
- May require greater soil depth and irrigation, unless shaded by other structures
- For white roofs, be aware of the potential impact of reflected sunlight and heat build-up on adjacent spaces, exterior walls, etc.

Roof Construction and Structural Capacities

Whether the design of a green roof is for new construction or retrofit of an existing building, a structural engineer shall make an evaluation of the building structural capacity to determine the required loading capacity. The loads of a green roof can vary greatly depending on the depth of the growing media and types of vegetation specified. The following issues should be considered:

²² Gaisma.com

- The roof must be structurally capable of supporting the load of the green roof based on a complete design plan (including the weight of the plants, wet/saturated growing media, all other vegetated roof layers, and waterproofing layers).
- The building seismic / lateral loading capacity should be reviewed to verify the impact of the additional roof load on the overall building structure.
- Point loading of materials during installation, maintenance personnel, and equipment should be confirmed.
- The roof is free of structural defects. Any defects should be corrected prior to installation of new roofing system and green roof.

In addition to the dead load of the vegetated roof, if the space is to be occupied the building code requires a live load of 100 lbs. per square foot to be included.

Structural Carrying Capacity:

As noted above, the additional load created by a green roof will vary greatly depending on the thickness of the growing medium, types of plants, and waterproofing system. For an extensive green roof of approximately 4 to 6 inches thick, the additional load can be range from 15 to 35 pounds per square foot (PSF). Figure 9 below lists typical loading requirements for different structural systems – concrete, metal deck and wood – and includes both dead load (the weight of the structure itself) and code required live load for snow loading (not including snow drift factors) As outlined below, the additional load from a green roof can result in an increase of 15 to 40% for concrete structures and 25 to 60% for metal deck and wood framed structures.

In addition, if a green roof is occupied, a Code required 100 PSF live load factor needs to be included.

	Concrete Deck	Metal Deck	Wood Deck
Dead Load	50 - 60 psf	20 - 30 psf	20 - 30 psf
Snow Load	32 psf	32 psf	32 psf
Total Load	82 - 92 psf	52 - 62 psf	52 - 62 psf
Extensive Green Roof Weight (saturated, soil ht. 1 - 4.75")	± 12 - 38 psf	± 12 - 38 psf	± 12 - 38 psf
Total Load w/ Green Roof	94 - 130 psf	64 - 100 psf	64 - 100 psf
Increased Load %	15 - 41%	23 - 61%	23 - 61%
Live Load Considerations			
Live Load (occupied use)	100 psf		

Figure 9: Table of Loading Requirements for Green Roofs²³

²³ Massachusetts State Building Code and DM Berg Consultants

Unless there is significant additional capacity in the existing structural framing system, it is likely that most existing buildings will require additional reinforcing to support the green roof. This is likely to include supplemental beams to reduce the span of an existing roof deck and may also require additional beam or column reinforcing to support the supplemental beams. The structural engineer will also need to verify that the existing foundation system is sufficient to support the additional column loads. Reinforcing of concrete framed or wide flange steel structures will likely be easier to accomplish than reinforcing of steel joist or wood framed structures.

Note that if additional structural reinforcing is required, there is likely to be additional secondary work required, such as removal and replacement of interior finishes, fireproofing and modifications or relocations of existing MEP/FP systems.

Wind Loads / Uplift

Wind loads on the roof can vary depending on the building location, exposures, and wind speeds determined for the area. Exposures are defined as a measure of terrain roughness: i.e. centers of large cities; suburban areas, city outskirts; and open level terrain with scattered buildings, open water or shorelines.

Refer to the **Massachusetts State Building Code 780 CMR**, Chapter 16 Structural Design, 1609 Wind Loads, Design wind loads shall be determined from ASCE 7, Section 6.

Recommendations to Prevent Wind Uplift:

Vegetation-free zones should be located at perimeters (min. 24" width) and corners to prevent wind uplifts. Modular systems can be tied together for greater loads against wind uplift. Erosion Mats may need to be installed to prevent soil erosion from wind and rain. Factory Mutual recommends using concrete pavers for green roofs on buildings over 150 feet (46 m) high. See page 31 for additional information on Vegetation-free zones.

Roof Drainage

Roofs should be sloped and drained to meet code and avoid standing water. When designing a green roof, slopes, drain locations and quantities should be generally similar to a conventional roof. A green roof generally will capture and retain rainwater as illustrated on the following page, Figure 10.

Percentage of Annual Water Retention on Green Roofs				
Type of Green Roof	Soil Depth (inches)	Plants / Vegetation	Water Retention Annual Avg. in %	Annual Coefficient of Discharge
Extensive	0.8 - 1.5	Moss / Sedum	40	0.60
	> 1.5 - 2.3	Sedum / Moss	45	0.55
	> 2.3 - 4	Sedum / Moss / Herbaceous	50	0.50
	> 4 - 6	Sedum / Herbaceous / Grass	55	0.45
	> 6 - 7.8	Grass / Herbaceous	60	0.40
Intensive	6 - 7.8	Lawn / Shrubs / Coppices	60	0.40
	9.8 - 20	Lawn / Shrubs / Coppices	70	0.30
	> 20	Lawn / Shrubs / Coppices / Trees	>90	0.10

Figure 10: Percentage of Annual Water Retention on Green Roofs²⁴

Maintenance is critical for green roof drainage systems. The vegetation and growing media should be kept away from drains with gravel or concrete pavers. Drainage inspection boxes should be used to allow inspection of the drains. The roof drains require periodic inspection and must be readily accessible.

Irrigation

Depending on the requirements of the planting design, the green roof will likely require temporary or permanent irrigation. Extensive green roofs with drought tolerant plants (sedums and succulents, for example) typically do not require permanent irrigation but will require temporary irrigation for a period of 12 to 18 months. Semi-intensive or Intensive green roofs will likely require permanent irrigation to support more diverse plantings. Rooftop agriculture will typically require permanent irrigation since vegetables are not typically drought tolerant.

Irrigation systems should be designed as part of the green roof planning. For temporary irrigation, it may be sufficient to provide hose bibs at key locations around the roof to allow maintenance workers to water the plants on a regular basis – potentially as often as weekly during dry periods. Care should be taken to provide paving, ballast or roof protection pads immediately surrounding the hose bibs to avoid damage to the roof membrane from maintenance activities. Consideration should also be given to allowing sufficient space between planted areas for hose movement.

²⁴ German FLL 2002

Permanent irrigation systems would be similar to conventional lawn systems, with adequate distribution of sprinkler heads and control valve system to avoid over watering. Drip or trickle irrigation systems are typically preferable to avoid overspray from windy conditions or tall buildings and to minimize evaporation. If possible, it is recommended to use of a cistern to store collected rainwater for later use. Permanent sprinkler systems will need to be drained in the winter time to avoid freezing.

Frequency of irrigation should be controlled to avoid over watering. Since extensive green roof plants are typically drought tolerant, control meters should be calibrated to irrigate only during very dry periods.

For both temporary and permanent irrigation systems, sufficient roof slope and drainage should be provided to avoid ponding or other drainage problems that could contribute to potential roof leaks.

Plant Selection

Appropriate plant selection is important part of Green Roof design. Vegetation should be chosen first and foremost for its ability to thrive in the local climate, withstand the harsh conditions of a roof and mimic the surrounding landscape's structure, function and diversity. The building's shade and shadow conditions, wind speeds, adjacencies to exhaust vents and HVAC equipment should also be considered when selecting and placing plants on the roofs.

Common procedures for planting green roofs are:

- Seeding (Not a common practice for green roofs in the U.S.)
- Individual Plants
 - Cuttings
 - Plugs
 - Containers
- Pre-Vegetated Mats (rolls or sheets of pre-grown plants)
- Modular Trays (self-contained modular trays with drainage, filter, growing media and plants)

The plant lists below are organized by minimum depth of planting medium required.²⁵ All are Zone five or below and are generally available within the nursery trade. In addition, no plants identified as invasive by the New England Wildflower Society have been included. The recommended plants grow best in the sun, and their drought tolerance is high (H), moderately high (M-H), and moderate (M).

The maximum depth of planting medium that is listed is six to eight inches. For the purposes of the Guidelines, the list focuses on plants that require less than eight inches of planting medium. Additional plants can be used in deeper soil depths. All items to comply with FLL and ASTM standards.

²⁵ Green Roof Plants by Edmund C. and Lucie L. Snodgrass, Planting Green Roofs and Living Walls by Nigel Dunnett and Noel Kingsbury, Garden Roof Planning Guide, Hydrotech

Plant Medium Depth: 1.6 to 2.4 inches Drought Tolerance

Acinos alpinus	H
Allium (bulbs)	H
Carex caryophylla	M-H
Chiastophyllum oppositifolium	H
Herniaria alpinus	H
Petrorhagia saxifrage	H
Rosularia seboides alba	H
Saxifraga paniculata	H
Sedum acre	H
S. album	H
S. cauticola	H
S. cyaneum	H
S. dasplyllum	H
S. hispanicum	H
S. lydium	H
S. nevii	H
S. reflexum	H
S. sediforme	H
S. sexangulare	H
S. spathulifolium	H
S. spurum	H
Semparvivum arachnoideum	H

Plant Medium Depth: 2.4 to 4.8 inches Drought Tolerance

Alyssum montanum	H
Armeria juniperifolia	M-H
A. maritime	M-H
A. pseudoarmeria	M-H

Plant Medium Depth: 2.4 to 4.8 inches Drought Tolerance

Cerastium tomentosum	H
Corydalis cheilanthifolia	M-H
Dianthus deltoides	M-H
D. Gratianopolitanus	M-H
D. pulmarius	M-H
Festuca cinerea	H
F. ovina	H
Potentilla agentea	M-H
P. neumanniana	M-H
Primula veris	M-H
Saponaria ocymoides	M-H
Sisyrinchium augustifolium	H
Teucrium chamaedrys	M-H
Thymus praecox	H
Verbascum chaixii	H
V. phoeniceum	H

Plant Medium Depth: 4-6 inches Drought Tolerance

Achillea millefolium	M
Alyssum saxatile	M
Anaphalis margaritacea	M

A. triplinervis	M
Artemisia schmidtiana	H
Calamintha grandiflora	H
Campanula portenschlagiana	M
C rotundifolia	M
Centranthus ruber	H
Edraianthus graminifolius	H
E. tenuifolius	H
Erigeron glaucus	M-H
Eryngium planum	H
Euphorbia amygdaloides	H
Festuca amethystina	H
Filipendula vulgaris	H
Geranium sanguineum	M-H
Gypsophila paniculata	M-H
G. repens	M-H
Hedera helix	M
Jasione montana	H
Korleria glauca	H
Limonium latifolia	H
Linaria purpurea	H
Linum perenne	M
Lychnis coronaria	M-H

Plant Medium Depth: 4-6 inches

Drought Tolerance

Malva moschata	M
Nepeta 'Walker's Low'	M-H
Oenothera fruticosa	H
Opuntia humifusa	H
Origanum humifusa	M-H
Phlox subulata	H
Pulsatilla vulgaris	H
Scabiosa columbaria	M-H
Sedum spectabile	H
S. telephium	H
Veronica prostrate	M

Plant Medium Depth 6-8+ inches (includes low shrubs)

Buddleia davidii	M-H
Cottoneaster adpressus	M
C. horizontalis	M
Cytisus (low growing varieties)	H
Hemerocallis species	H
Iberis sempervirens	H
Juniperus communis	H
J. horizontalis	H
J. procumbens	H
Lavandula angustifolia 'Munstead'	H
Perovskia atriplicifolia	M
Pinus mugo pumilio	M
Potentilla fruticosa	H
Prunus pumilla depressa	M

Rudbeckia fulgid	H
R. Hirta	H
Salix purpurea	M
Salvia officinalis	M-H
Santolina chamaecyparissus	H
Spirea japonica	M

Planting Medium

Planting medium characteristics for extensive green roofs need to be:

- Highly efficient at absorbing and retaining water,
- Well draining,
- Must be able to absorb and supply nutrients,
- Lightweight,
- Granular with 60 to 70% air space,
- Low in organics (75 to 90% inorganic).

Planting medium for green roofs needs to be manufactured. Topsoil is generally not appropriate for extensive roofs because it does not have the characteristics listed above. Components for the manufactured medium can include the following:

- Components can include:
 - Natural Minerals
 - Sand (limited amounts)
 - Lava
 - Gravel
- Artificial Minerals
 - Perlite
 - Vermiculite
 - Expanded clay granules
 - Expanded shale
- Recycles or waste materials
 - Crushed clay brick or tiles, brick rubble
 - Crushed concrete
 - Subsoil

The composition of the planting medium may vary based on its depth and the plant palette. Media will also vary depending upon if the plants are to be permanently irrigated or not.

Green roof system's manufacturer must approve growth medium for green roofs. Standard growth mediums must consist of both organic and inorganic components formulated to culture micro-organisms beneficial to plant performance while maintaining growth medium structure and stability. Growth medium components must meet green roof's manufacturer's requirements for sustainability standards. All items to comply with FLL and ASTM standards.

Vegetation-Free Zones

Vegetation-free zones are important for wind uplift control, and also for areas of roof transitions, such as seams, gaps, expansion joints, roof penetrations, roof drains, curbs, parapets, around HVAC equipment and other rooftop equipment. Vegetation-free zones should also be used to create walkway paths to rooftop equipment and other maintenance areas.²⁶ Vegetation-free zones should be planned around areas that may be subject to chemical contamination from window washing or HVAC equipment.

Vegetation free zones can be finished with pavers, gravel or roof membrane depending on the location, expected use and foot traffic, and adjacent roof conditions. At walkways or other high traffic areas, pavers, gravel or walkway pads should be used to avoid wear and tear on the roof membrane. At roof drains, HVAC equipment, and other similar locations, it may be advisable to provide gravel for water flow and membrane protection. At roof edges, the plantings can be held back with a transition strip and the exposed membrane make the transition.

Fire Prevention

FLL guidelines for fire protection suggest that a green roof cover of succulent plant species, which has high water content and only a few grasses should be used to maximize fire protection. In general, it was found that green roofs have better fire resistance values than conventional roofs.²⁷

UL has determined that the Garden Roof Assembly “surfacing would have no deleterious effects upon the fire resistant properties of the system”.²⁸

According to NRCA “a fire-resistance rated membrane is generally considered acceptable for use.”²⁹

The integration of “fire breaks” at regular intervals across the roof, at the roof perimeter, and around all roof penetrations is recommended. These breaks would be made of a non-combustible material such as gravel or concrete pavers (24” wide), and located at every 130 feet in all directions.³⁰

²⁶ “Maintaining Green Roofs” The Construction Specifier January 2009

²⁷ Green Roofs Tree of Knowledge,

²⁸ American Hydrotech

²⁹ Green Roofs Tree of Knowledge,

³⁰ “Design Guidelines for Green Roofs” by S. Peck and M. Kuhn, Canada Mortgage & Housing Corporation

Access and Accident Prevention

The Occupational Safety and Health Administration's (OSHA) Construction Fall Protection Guidelines notes that most of the same hazards associated with the installation of conventional roofing materials are present with the installation of green roofs. Landscape contractors installing green roofs must comply with OSHA's construction standards.

Green roofs will require periodic maintenance, particularly during the initial start-up phase when regular irrigation and weeding will be required. Ease of access to the roof must be considered and appropriate OSHA and other industry standards for access and fall protection need to be provided. The installation of fall protection devices / systems, i.e. anchors, guard rails, safety nets, etc., may be required.

If the green roof is occupied space, i.e. available for building users or the general public to use and enjoy, the code requirements for roof deck protection will need to be provided. This will include additional live load of 100 PSF, guardrails and two means of egress depending on the size and proposed use. If the roof deck is generally unoccupied, then standard fall protection measures for maintenance workers will need to be provided.

Testing

Following installation of the waterproofing membrane, the following tests should be conducted prior to installation of the overburden:

Flood test completed membrane assembly with 2" minimum water for 24 hours. Visually inspect underside of roof for leaks.

Electronic Leak Detection

Connect a low voltage pulse generator to roof membrane and supporting structure. Using a potentiometer with probes, identify locations where leak or breach in roof membrane allows electrical current to pass between membrane and structure. Identified leaks must be fixed and retested prior to installation of overburden.

Code Compliance

Massachusetts State Building Code 780 CMR (7th Edition)

Chapter 34 Existing Structures of the Building Code will require a structural engineer to make an evaluation of the existing building to determine the adequacy of all structural systems that are affected by the green roof.

At a minimum, the Code will require a Level 1 assessment (3408.6). The evaluation will need to include review of relevant available documentation about the building design and

construction, a field investigation of the existing conditions, and a structural analysis. When deemed necessary by the structural engineer, the evaluation will also need to include detailed field surveys, testing, and laboratory analysis. Depending on the extent of the structural reinforcing that may be necessary, the work may be required to meet Level 2 through Level 5 requirements (3408.4.3 – 3408.4.6).

If the green roof is proposed to be inhabited, such as a roof deck or terrace, appropriate code compliant handrails and means of egress from the space must be provided.

Massachusetts Architectural Access Board (AAB) Rules and Regulations 521 CMR

To the extent that a green roof becomes a public space, the roof will need to comply with AAB requirements for accessibility. This may include elevator access to roof level, accessible thresholds and door hardware, and other requirements that are similar for the rest of the building.

Zoning

Green roofs may trigger zoning compliance requirements, particularly if the space is occupied as a roof deck. In addition, the requirements of the Groundwater Conservancy Overlay District should be reviewed for compliance.

Boston Zoning Ordinance

Groundwater Conservancy Overlay District

Boston Water and Sewer Commission (BWSC)

Combined Sewer Systems

Combined Sewer Overflow

Maintenance Plan

The design of the green roof should facilitate the future maintenance requirements. Plant free zones should be provided around roof drains, mechanical equipment, roof transitions, and other sensitive areas. Inspection boxes should be provided at roof drains.

Requirements for documentation of the roof design and construction should be included in the project close-out requirements of the construction documents. As-built drawings, warranties, contact lists, manufacturer's information and other project documentation should be specified in the documents and collected at the end of the project. Warranty information should be accessibly stored for reference throughout the life of the roof.

A Maintenance Plan for the roof should be developed as part of the project design and should be tailored to the specific plant mix, growing media, and roof membrane system specified for the building. Measures which should be included in the Maintenance Plan include the following:

Start-up Period: (Approximately 1 year)

- Regular irrigation of plants until well established. The irrigation requirements should be established as part of the green roof design and incorporated into the Contractor's warranty period.
- Provide mulch until plants have filled in.
- Fertilize plants as appropriate to the species and recommended by FLL standards
- Remove any debris, trash, branches, or leaves
- Inspect after major storms for leaking, ponding water, or other signs of poor drainage.

Regular Maintenance

- Inspect drains to make sure they are clear on a regular basis (approx. monthly) and after major storm events.
- Inspect the health and coverage of the vegetation. Check for evidence of drought, disease or pest damage. Remove and replace as needed (approx. quarterly)
- Regular weeding, (a few times per year to monthly)
- Where plants are replaced or have not filled in, provide mulch seasonally to control weeds (bi-annually)
- Inspect the waterproof membrane for deterioration at the perimeter of the building, roof transition areas, inspection boxes, seams and other locations (annually)
- Pest control (when problems are detected)
- Fertilize (when problems are detected)
- Remove debris and trash (a few time per year to monthly)
- Document maintenance activities to both verify execution and to benchmark against anticipated maintenance requirements.

Plants should be fertilized in accordance with the growing media manufacturer's recommendations and FLL guidelines for the plant species. Per FLL recommendations, nutrients should be administered by means of coated slow-release fertilizer capsules at rates between 5g to 8g N/m². Herbicides should not be used for weed control.

Cool Roof Maintenance

Cool roofing surfaces should be washed on a regular basis to remove surface contaminants such as dust and dirt that will reduce the reflectivity of the membrane. According to a study performed by the Oak Ridge National Laboratory, a typical white roof with an initial solar reflectance exceeding 0.8 can deteriorate to a solar reflectance of less than 0.55 (a reduction of almost 30%) after only 3 years.³²

Measuring Criteria

As noted previously, the direct benefits from green roofs are energy efficiency, stormwater run-off reduction, interior noise reduction, and prolonged roof lifespan. Following installation of a green roof, the following criteria can be measured for effectiveness.

³² See www.ORNL.gov/SCI/roofs+walls/facts/solarraditioncontrol.htm for further information.

- If not already present, energy monitoring devices can be installed in the building to track energy usage both before and after the green roof installation. Optimally, the energy monitoring devices would be installed a minimum of one year in advance of the proposed green roof installation to document the baseline condition. Following installation, the energy usage of the building should be monitored for a minimum period of one year and preferably for a longer period.

If it is not feasible to install energy monitoring devices, the change in energy usage of the building can be roughly approximated by comparing utility bills from before and after the green roof installation.

If the green roof is installed with other related energy improvements, such as increased roof insulation, it may be difficult to isolate the energy savings associated with the green roof. If performance data is available, it may be possible to estimate the potential benefits from the green roof through an energy modeling analysis.

- Stormwater reduction can be measured by the installation of a weather station to measure precipitation and flow monitoring meters in the roof leaders or downspouts to measure runoff. This would allow the amount of rainfall to be correlated with the stormwater run-off.

Optimally, a weather station and flow monitoring meters would be installed a year prior to the green roof installation to measure the baseline condition. After the green roof has been installed, a similar monitoring period should be completed to evaluate improvements in stormwater retention.

In addition, it would be useful to test stormwater runoff for quality as well as quantity. This can be accomplished by testing water gathered from the weather station with the stormwater runoff in the roof leaders or downspouts. Testing should be done for various chemicals, including TSS solids, heavy metals, nitrous, phosphates and other materials.³³

³³ See for example “Monitoring of a New Green Roof for Water Quality and Quantity” (Glass and Johnson, 2008)

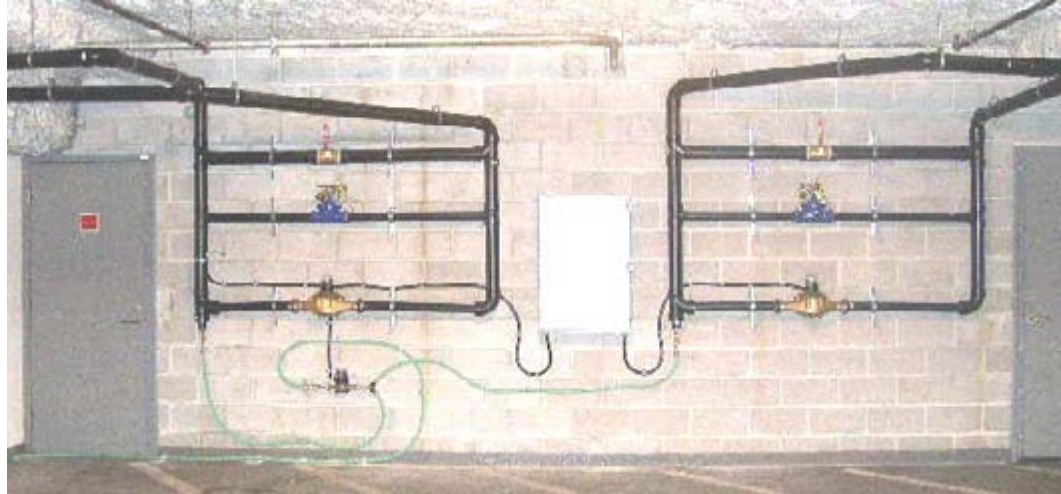


Figure 11: Stormwater runoff monitoring system, Vancouver Public Library³⁴

- Ambient noise levels can be monitored before and after installation. Assuming conditions are generally constant, a noise monitoring meter can be set up within the space for a period of time ranging from 48 hours to a week, depending on the source of exterior noise. Following the installation of the green roof, the noise monitoring meter should be set up for the similar period of time to compare readings.
- Measuring the lifespan improvements of the green roof will require longer term monitoring. If part of the building does not have a green roof, it should be possible to compare the life span of each roof section. Alternatively, maintenance records for a similar, non-green roof could be compared to the green roof maintenance requirements.

Warranties / Guarantees

Warranties for Green Roofs may vary greatly depending on how it was sourced and constructed. Many manufacturers will provide warranties in 5 year increments, and typically up to 20 years. A single-source provider is typically preferred where a single warranty, as opposed to many separate warranties, is provided to the building owner. The single source warranty will typically warrant the performance of the waterproofing system and vegetated cover. Most manufacturers will require a flood test or a test for water-tightness (i.e. electronic leak detection system) in order to warrant the waterproofing system. If a leak(s) occurs, typically the single source warranty will include removal and replacement of the overburden (growing medium and vegetation) to find and fix the leak(s).

³⁴ Vancouver Public Library Green Roof Monitoring Project (Johnston, McCreary, Nelms, 2004)

LEED Certification

Green roofs can contribute towards the LEED Certification of new or existing buildings. Based on the new LEED 2009, a green roof may assist with the following LEED points.

SS credit 5.1	Protect or Restore Habitat	1 point
SS credit 5.2	Maximize Open Space	1 point
SS credit 6.1	Stormwater Design, Quantity Control	1 point
SS credit 6.2	Stormwater Design, Quality Control	1 point
SS credit 7.2	Heat Island Effect, Roof	1 point
WE credit 1.1 and 1.2	Water Efficient Landscaping	1 to 4 points
EA Prereq 2	Minimum Energy Performance	Required
EA credit 1	Optimize Energy Performance	up to 19 points
MR credits 3.1 and 3.2	Materials Reuse	1 to 2 points
MR credit 4.1	Recycled Content	1 point
MR credits 5.1 and 5.2	Regional Materials	1 to 2 points
MR credit 6	Rapidly Renewable Materials [plants]	1 point
ID credit 1	Innovation In Design	1 to 5 points

Life Cycle Cost Analysis

To evaluate the long-term benefits of green roofs, this Study prepared a Life Cycle Cost (LCC) Analysis of the potential costs and benefits for several prototypical roof installations. This LCC Analysis uses the GreenSave Calculator developed by the Green Roofs for Healthy Cities, a not-for-profit industry association working to promote green roof installations.³⁵ The GreenSave Calculator takes into account typical life cycle costing factors, such as initial capital costs, annualized maintenance costs, projected roof system lifespan, replacement costs, and projected energy savings. These factors are then calculated to provide a Net Present Value³⁶ and potential payback period for different roof installations.

The LCC Analysis has been developed for three alternate roof scenarios: a typical modified bitumen roof based on the City's current roofing standard, a cool (white) roof, and an extensive green roof. The Analysis is based on a prototypical roof footprint of 10,000 SF. The study period has been projected for 60 years to allow the benefit of the longer projected lifespan of a green roof to be incorporated. Additional factors included in the Analysis are listed in further detail below.

The LCC Analysis was run using three building models. Since the primary benefit from a vegetated roof occurs during the cooling season when the vegetated roof provides significant reduction of heat gain into the building, the LCC analysis was developed to test the condition when there is no energy savings (such as a non-air conditioned building) and some energy savings (air conditioned building).

In both cases, it was assumed that there are no structural reinforcing costs. In the third model, a rough estimate of structural reinforcing costs was added to the analysis.

1. The first model is a non-air conditioned building, such as a school, where the potential energy savings from a cool or green roof is negligible. This model tests whether the additional life span of a green roof can provide a cost benefit over the study period.
2. The second model incorporates potential energy savings from a vegetated roof. The extent of real energy savings should be calculated from an energy model of each building, however for the purposes of this analysis the expected energy savings have been estimated to be 10% savings for a cool roof and 15% savings for a vegetated roof.
3. The third model incorporates potential roof reinforcing costs into the Life Cycle Analysis. Although this will vary depending on the existing building, for the purposes of this analysis additional reinforcing has been estimated at an equivalent of 7 pounds of steel per square foot of building area at a cost of approximately \$3 to \$4 per pound of steel. For the 10,000 SF prototype analysis, this results in an additional cost of

³⁵ GreenSave Calculator: www.Greenroofs.org

³⁶ According to Wikipedia, Net Present Value is defined as the total present value (PV) of a time series of cash flows.

\$210,000 to \$280,000. Note that secondary improvements, such as interior finish renovations that may be required to install the structural reinforcing, are not included.

Several additional factors have not been included in the LCC Analysis, including the following:

- Potential savings from stormwater retention has not been included since current utility rate structures do not provide a direct payback from stormwater savings.
- Indirect benefits such as increased worker productivity and biodiversity also have not been included in this Analysis since there is not firm data to support the savings from these potential indirect benefits.

LCC Factors

The following data were used for the Life Cycle Cost Analysis.

Data Input	Value	Source
First cost, conventional roof	\$20 / SF	1
First cost, green roof components	\$15 / SF	1
O&M budget, conventional roof	\$0.20 / SF – year	2
O&M budget, green roof	\$0.35 / SF – year	2
Heating savings, green roof	0 therms / SF – year	4
Cooling savings, green roof	0 kWh / SF – year	4
Initial electricity rates	\$0 / kWh	3
Initial natural gas rates	\$0 / therm	3
Changes in stormwater costs, green roof	0 % / SF	9
Energy price real escalation rate	3 % / year	8
Conventional roof price real escalation rate	3 % / year	5
Conventional roof life	20 years	6
Green roof life	40 years	6
Life cycle period	60 years	6
Discount rate	5.0 % / year	7

Figure 12: Life Cycle Cost Factors

Source Key:

1. Davis Landon
2. 1% of first cost, data from GreenSave Calculator

3. Not applicable
4. Assumptions for no savings
5. Cost of the conventional roof was assumed to escalate at the same rate as fossil fuels. Energy Information Administration, U.S. Data Projections
6. Several sources indicate that green roofs last from two to three times longer than conventional roofs
7. Based on average discount rate.
8. Energy Information Administration, U.S. Data Projections
9. BWSC does not currently have any grants or incentives for reducing stormwater runoff

Summary and Conclusions

The LCC Analysis was performed for both negligible energy savings (non-air conditioned buildings) and some anticipated energy savings (air conditioned buildings). A summary of each LCC is provided in Figures 9, 10 and 11 below. See Appendix V for detailed report of the LCC Analysis.

Model 1: No Energy Savings

With no projected energy savings, a green roof is approximately 15% more expensive over 20 years. The initially higher capital cost is somewhat offset by the longer projected life cycle of the green roof membrane system. Over the full 60 year study period, the green roof is approximately 8.6% more expensive than a conventional roof, based on the Net Present Value (NPV).

Without projected energy savings, a cool roof is more expensive than a conventional roof both in the 20 year period and the full 60 year period. The cool roof is also more expensive than the green roof due to the more frequent replacement costs.

	Conventional Roof	White PVC Roof	Extensive Green Roof
Installed Capital Costs	\$180,000	\$220,000	\$350,000
Roof Replacement Interval³⁷	19 Years	15 Years	39 Years
NPV (20 years)	(\$500,000)	(\$586,000)	(\$572,000)
NPV (40 years)	(\$727,000)	(\$855,000)	(\$850,000)
NPV (60 years)	(\$884,000)	(\$1,047,000)	(\$960,000)
Payback Period	NA	Exceeds Study Period	Exceeds Study Period

Figure 13: LCC Analysis – No Energy Savings (Non-Air Conditioned Building)

³⁷ Roof replacement intervals from Maintenance, Repair and Replacement Effects for Building Envelope Materials (2002) prepared by Morrison Hershfield Ltd. for the Athena Institute.

Model 2: 10% and 15% Projected Energy Savings

For the purposes of this analysis, the projected energy savings were estimated at 10% for a white PVC roof and 15% for a green roof. As previously noted, this is likely to vary depending on building type and should be verified with an energy model of the building.

With the projected energy savings, a green roof is more expensive than a conventional roof after 20 years (approximately 9%). Over the full 60 year study period, the green roof is only slightly more expensive than a conventional roof (approximately 2.25%), based on the Net Present Value (NPV).

A cool roof with a projected 10% energy savings is more expensive than a conventional and green roof in both the 20 year period and the full 60 year period.

	Conventional Roof 0% Energy Savings	White PVC Roof 10% Energy Savings	Extensive Green Roof 15% Energy Savings
Installed Capital Costs	\$180,000	\$220,000	\$350,000
Roof Replacement Interval	19 Years	15 Years	39 Years
NPV (20 years)	(\$500,000)	(\$570,000)	(\$547,000)
NPV (40 years)	(\$727,000)	(\$826,000)	(\$807,000)
NPV (60 years)	(\$884,000)	(\$1,010,000)	(\$904,000)
Payback Period	NA	Exceeds Study Period	Exceeds Study Period

Figure 14: LCC Analysis – Energy Savings (Air Conditioned Building)

Model 3: Structural Reinforcing Costs

The third LCC model incorporates potential structural reinforcing costs into the initial capital cost of a green roof. For the purposes of this analysis, an estimated \$250,000 (\$25/SF) for structural reinforcing has been included, although as previously noted this is likely to vary depending on building type and should be verified with a more detailed structural analysis. In this model, the energy savings is kept at 10% for the white roof and 15% for the green roof.

With the \$250,000 additional capital cost for structural reinforcing, the green roof becomes more expensive than a conventional roof in the short term and the long-term. Over the 20 year period, the NPV of a green roof is approximately 60% more than a conventional roof and over the full 60 year study period, the roof is 30% more.

	Conventional Roof 0% Energy Savings	White PVC Roof 10% Energy Savings	Extensive Green Roof 15% Energy Savings
Installed Capital Costs	\$180,000	\$220,000	\$350,000
Structural Reinforcing	NA	NA	\$250,000
Roof Replacement Interval	19 Years	15 Years	39 Years
NPV (20 years)	(\$500,000)	(\$570,000)	(\$797,000)
NPV (40 years)	(\$727,000)	(\$826,000)	(\$1,057,000)
NPV (60 years)	(\$884,000)	(\$1,010,000)	(\$1,154,000)
Payback Period	NA	Exceeds Study Period	Exceeds Study Period

Figure 15: LCC Analysis – Structural Reinforcing

LCC Results

The Life Cycle Cost Analysis results show that even with favorable conditions (15% energy savings, no structural reinforcement costs) the Net Present Value (NPV) of the green roof exceeds the NPV of the Conventional Roof by approximately 9%. Over the longer 60 year analysis period, however, the green roof is only 2.5% more expensive than the conventional roof. As previously noted these figures should be confirmed for specific buildings to verify both the structural reinforcing costs and potential energy savings.

Potential options that could help improve the payback period for green roofs include:

- Grant funding could be used to help offset some of the additional capital costs for the green roof.
- The stormwater reduction provided by green roofs could be a source of additional savings, either through reduction or rebates of sewer costs. Currently, the Boston Water and Sewer Commission (BWSC) does not separate sewer use and water use for billing.
- Downsizing of HVAC equipment requirements due to smaller heating and cooling loads, assuming that the HVAC equipment is replaced at the same time as the green roof is installed.

This page intentionally left blank.

Selection Criteria and Database

To help PCMD determine which buildings may be good candidates for green roof retrofits, this Study has developed two tools to collect and sort information about the numerous buildings that the City owns and operates.

Working with PCMD, the Study has developed a database of building information such as the year built, building and roof areas, type and age of existing roof system(s), planned capital improvement projects, building structural framing system, roof access and other information. The database is a working tool that will allow PCMD to track and sort various information about the existing building inventory, including the potential for green roof retrofit. Please see Appendix VII for printouts of the City of Boston Sustainable Roof Database.

The Study also developed a selection criteria protocol to help sort the information about the existing buildings into a framework for deciding which buildings may be good candidates for green roofs. Included in Appendix VI is the Sustainable Roof Planning Worksheet which was developed to help PCMD collect and sort building information from user agencies.

The Worksheet categorizes information into four steps to help evaluate the potential for green roofs: 1) General Building Information, 2) Building Suitability, 3) Quantifiable Benefits, and 4) Building Feasibility Study. Buildings are evaluated according to a weighted scoring system: higher scores mean a building is more likely a good candidate for a green roof.

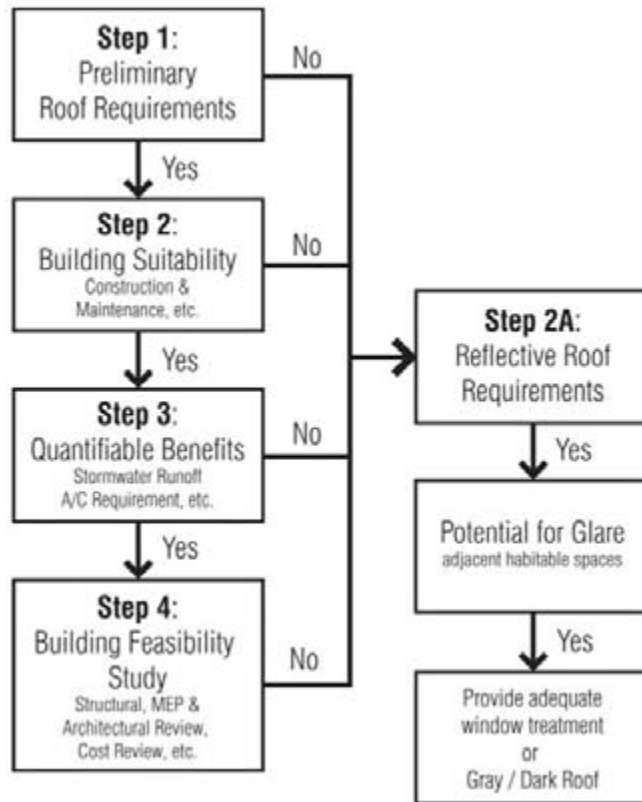


Figure 16: Selection Criteria flow chart

The Step 1 considerations include general information such as roof slope, potential for roof uplift due to taller building or high wind conditions, and roof size. A “yes or “no” response to any of the criteria determines whether a building is a good candidate for further evaluation. For example, a roof that is smaller than 2,000 SF is less likely to be a good green roof candidate since a larger portion of the roof is likely to be unavailable for plantings due to mechanical equipment and roof edge conditions. If a building does not meet the Step 1 criteria, then it is likely a good candidate for a reflective roof, and should proceed to Step 2A – Building Suitability for Reflective Roofs.

1. The Step 2 criteria evaluate the existing roof in more detail and establish a point score to evaluate the green roof potential of the building. The Step 2 criteria include the condition of the roof, building structural system, existing roof system and roof access. Points are awarded for each criteria and the buildings which score the highest are good candidates for further evaluation.
2. The Step 3 criteria evaluate the potential benefits of a green roof on the building, including consideration of the benefits of stormwater reduction, energy savings (air conditioned), and roof orientation. Buildings which rate higher in the Step 3 evaluation have a better opportunity to provide tangible benefits from a green roof installation.
3. The Step 4 criteria is a more detailed feasibility study which would be performed to investigate the structure, MEP/FP systems, architectural analysis, design benefits, occupant benefits, liability assessment, costs and life cycle benefits for a proposed green roof. The Step 4 evaluation is beyond the scope of this Study.

This Study has applied the Step 1 through Step 3 criteria to the City of Boston Sustainable Roof Database (Appendix VII) to develop a shortlist of candidates for further evaluation, included below.

Figure17 below is the shortlist of the nine buildings which scored the highest on the Selection Protocol point scoring system as the best candidates for green roof consideration.

Building			Selection Criteria: Step 1, Step 2 and 3							
Roof No.	OBM No.	Building Name	Flat Roof	Concrete / Metal Roof Deck	Roof is 15 years or more	Roof ht. under 15 floors	Roof is in urban area	Roof is greater than 2,000 SF	Min. 50% of roof is available	Total Point Score
23	22761	Area A-1 Station	Yes	Yes	Yes	Yes	Yes	Yes	Yes	42
20	22766	North End Library	Yes	Yes	Yes	Yes	Yes	Yes	Yes	36
17	22766	West End Library	Yes	Yes	Yes	Yes	Yes	Yes	Yes	36
11	22604	Engine 14	Yes	Yes	Yes	Yes	Yes	Yes	Yes	36
25	22368	Area C-11 Station	Yes	Yes	Yes	Yes	Yes	Yes	Yes	32
18	22766	Adams Street Library	Yes	Yes	Yes	Yes	Yes	Yes	Yes	32
8	22894	Thomas Johnson Community Center	Yes	Yes	Yes	Yes	Yes	Yes	Yes	32
7	22894	Gallivan Community Center	Yes	Yes	Yes	Yes	Yes	Yes	Yes	28
6	22894	Archdale Community Center	Yes	Yes	Yes	Yes	Yes	Yes	Yes	24

Figure17: Vegetated Roof Candidates – Shortlist

Green Roof Planning Study – Final Report

Applying the cost figures outlined previously, the anticipated green roofing costs for the nine short-listed buildings are included in Figure 18 below.

Building			Preliminary Construction Cost*			
Roof No.	OBM No.	Building Name	Total Roof Area (SF)	Mod-Bit Roof \$20 / SF	Green Roof Premium \$15 / SF	Total Cost** \$ 35 / SF
23	22761	Area A-1 Station	6,860.00	\$137,200.00	\$102,900.00	\$240,100.00
20	22766	North End Library	8,370.00	\$167,400.00	\$125,550.00	\$292,950.00
17	22766	West End Library	6,495.00	\$129,900.00	\$97,425.00	\$227,325.00
11	22604	Engine 14	7,982.00	\$159,640.00	\$119,730.00	\$279,370.00
25	22368	Area C-11 Station	10,235.00	\$204,700.00	\$153,525.00	\$358,225.00
18	22766	Adams Street Library	7,189.00	\$143,780.00	\$107,835.00	\$251,615.00
8	22894	Thomas Johnson Community Center	10,971.00	\$219,420.00	\$164,565.00	\$383,985.00
7	22894	Gallivan Community Center	10,971.00	\$219,420.00	\$164,565.00	\$383,985.00
6	22894	Archdale Community Center	10,943.00	\$218,860.00	\$164,145.00	\$383,005.00

Figure 18: Vegetated Roof Candidates – Cost Budget

* Preliminary Construction Costs (February 2009). Cost does not include general contractor mark-up. Cost does not include any structural modifications or other adjustments to the existing building.

** Cost based on total roof area and actual area for a vegetated roof may be less.