# Green Roofs, Energy, and Climate:

## A Summary and Review of the Energy and Climate Benefits of Green Roofs

GREEN ROOFS FOR HEALTHY CITIES

GREEN INFRASTRUCTURE FOUNDATION

# About

## About Green Roofs for Healthy Cities

Green Roofs for Healthy Cities is a non-profit 501(c)(6) professional industry association working to grow the green roof and wall industry throughout North America since 1999. GRHC's activities including the publishing of the Living Architecture Monitor Magazine, and online training through the Living Architecture Academy.

## About the Green Infrastructure Foundation

The Green Infrastructure Foundation (GIF) is the charitable, 501(c)(3) arm of Green Roofs for Healthy Cities. GIF partners with communities to shape healthy, resilient, and sustainable places using living green infrastructure.

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Cover Photo courtesy Jorg Bruening, Green Roof Technology.

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# Executive Summary

## ES.1. Introduction

Buildings account for around 40 percent of energy use in developed countries, partially because poor building envelope design is compensated for using energy-intensive heating, ventilation, and air conditioning (HVAC) systems. The average age of commercial buildings in the United States is 52 years old - many were constructed in eras of extremely permissive building codes and low energy costs. This presents an opportunity for retrofits that can significantly improve energy performance, reduce costs and greenhouse gas emissions.

Redesigning our built environment to bring in green infrastructure in a way that provides a range of ecosystem services is also a promising pathway to more resilient communities. Green roofs (as well as green walls) have been used for hundreds of years for their insulative properties, and provide numerous benefits, described below:

Building-scale benefits include:

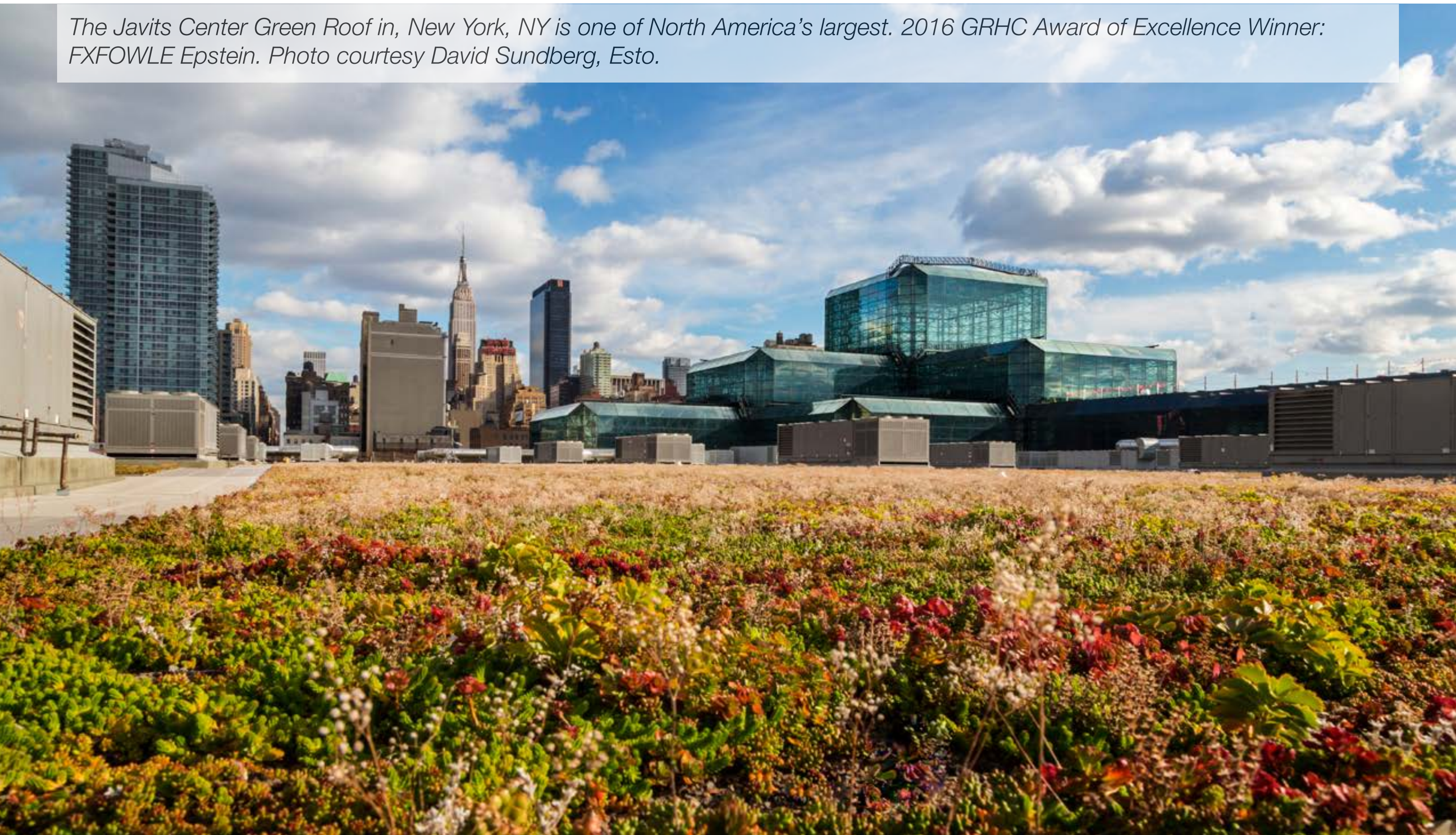
- Moderation of heat transfer through the building envelope, reducing heating and cooling energy use
- Improving the performance of HVAC systems through integration
- Improving the efficiency of solar PV and creating opportunities for other renewable energy technologies

Larger-scale (city-scale and global-scale) energy and climate benefits include:

- Reducing the urban heat island (UHI) effect
- Carbon sequestration and avoided GHG emissions
- Secondary and tertiary benefits, including reducing the energy required to process stormwater, and reducing energy inputs for material manufacture by extending the lifespan of building materials

## ES.2. Moderation of Heat Transfer Through the Building Envelope

Thermal moderation of a building envelope is one of the most important benefits of living architecture. Green roofs cannot be compared directly to insulation or be assigned an R-Value, because the thermal performance of living architecture is far more complicated, and green roofs use many different methods of heat transfer and dispersal to moderate heat transfer through a building envelope:



*The Javits Center Green Roof in, New York, NY is one of North America's largest. 2016 GRHC Award of Excellence Winner: FXFOWLE Epstein. Photo courtesy David Sundberg, Esto.*

## ES.2.1. Green Roof Factors

- **Evapotranspiration** (latent heat loss): Transpiration occurs when water is moved from the growing medium through a plant and then released as water vapor through stomata in its leaves. Water also evaporates directly from the growing medium. The phase change, or evaporation, from liquid to vapor causes latent heat to be released, lowering the surrounding temperature. Our bodies use essentially the same method of cooling when we sweat.
- **Convection** (sensible heat loss): Convection refers to the transfer of heat from one element to another by the movement of a fluid. In this case, foliage transfers heat to the surrounding atmosphere by the movement of wind, due to its larger surface area compared to a conventional building surface. Many plants wilt or go dormant during the winter, reducing their surface area and by extension, convective heat losses.
- **Reflectivity** (albedo): Green roofs tend to have a higher albedo (or reflectivity) than conventional roofs, making them absorb less solar radiation. Some plants, like sedums, become more reflective under heat stress. Many plants also shrivel in the winter, reducing their surface area and decreasing albedo. This allows for more heat to be absorbed when desirable.
- **Thermal mass**: All the layers of a green roof or wall system contribute to increased thermal mass compared to a traditional roof or wall. The increased mass allows for the absorbance of heat during the day and the slow release of heat at night. Increased water content contributes significantly to thermal mass, and many succulent plants like sedums store water, increasing this effect.
- **Solar shading**: Foliage in living architecture shades building surfaces from direct exposure to solar radiation, reducing heat gain. As foliage absorbs heat, it uses mechanisms described above to dissipate heat much more effectively than a building surface.

Every component of a green roof plays an important role in its thermal behavior: the canopy shades the surface of the growing medium from solar radiation. Plants absorb most solar radiation, using it for their biological functions (evapotranspiration, photosynthesis, etc.). Evaporation from the foliage decreases leaf surface temperature and cools the air in contact with the foliage. The layer of air between the canopy and growing media is significantly cooler than the ambient air temperature on a sunny day due to the shading and evapotranspirative effects of the foliage. This air also forms an insulating layer and acts as a convective buffer, minimizing heat gain. The layer of growing medium has a high thermal mass and acts as a heat sink, especially when moisture levels are high.

Living walls and green façades also thermally moderate a building envelope in a way similar to green roofs, generally using the same methods of heat transfer and dispersal. The roof to envelope ratio is an important factor when considering the effectiveness of a green roof or green wall at moderating a building envelope. A green roof will have a significantly larger effect on a large, low-rise building than it will on a high rise with a small floor plate. Conversely, living walls and green façades will have less of an effect on a low-rise building with a large floor plate.

## ES.2.2. Non-Green Roof Factors

Factors relating to building, site, weather, and climate can also affect the potential energy benefits of green roofs and other forms of living architecture:

- Roof insulation has a large impact on the thermal effects of green roofs - older and poorly insulated buildings tend to feature significantly more heat flux through the building envelope. This offers the opportunity to use green roofs to moderate this heat flux and provide greater benefits on older buildings.
- Weather and climate are also important factors. Research has shown that green roofs can reduce the summer peak temperature under the roof membrane in a wide range of climates, ranging from temperate to tropical. At the same time, research also demonstrates the ability of green roofs to reduce heat loss through the roof in cold winter climates. Given the importance of weather and climate to the performance of living architecture, more research is needed regarding performance in different climates. Table 2.2.2 describes possible strategies for green roofs to optimize energy performance by designing for desired benefits, based on common climate zones in North America.

# ES.3. Integration into Building Energy Systems

An emerging benefit of living architecture comes through the potential to integrate living architecture into building heating, ventilation and cooling (HVAC) systems, and to design living architecture to optimize their performance.

*The HVAC-integrated living wall at Weiser Hall at the University of Michigan in Ann Arbor, MI. 2018 GRHC Award Winner: Diamond Schmitt Architects*

An emerging benefit of living architecture comes through the potential to integrate living architecture into building HVAC systems, and to design living architecture to optimize their performance. The shading of outdoor HVAC units by vegetation can lower their operating temperature and make them operate more efficiently. Denser and more productive vegetation can be located closer to HVAC air intakes to lower the ambient temperature of intake air. Since cooler air requires less energy to condition it for indoor use, this reduces the energy required for air conditioning.

Advances in indoor green wall technology have also made it possible to integrate green walls into HVAC systems to improve indoor air quality; these are sometimes called biowalls. Indoor air is contaminated by processes within buildings and must be periodically exchanged for 'fresh' outdoor air. Biofiltration can be utilized to help remove contaminants like carbon monoxide and volatile organic compounds. Air is drawn through the root zone of plants that support microbial communities that break down airborne contaminants, while leaves also help remove these contaminants. When these indoor living walls are integrated into building HVAC systems, there is the potential to reduce the frequency of air changes, reducing heating and air conditioning costs, while maintaining a high air quality indoor environment.

# ES.4. Renewable Energy Integration

Using green roofs in combination with solar photovoltaic (PV) arrays brings the benefits of green roofs (energy savings, stormwater management, biodiversity improvement) together with the benefits of solar PV panels (on-site energy generation, carbon-free energy generation, reduction of grid-sourced energy use) and synergies between both systems. These synergies have the potential to be wide ranging, and include:

- Increased efficiency of solar PV panels due to reduced ambient temperature from evapotranspiration
- On-site generation of renewable energy
- Better use of space that captures the benefits of both technologies
- Increased revenue/savings (from generated energy) can offset the additional costs of a green roof
- Solar PV panels protect the plants and growing media from direct exposure to sunlight and wind, reducing drying and excessive evapotranspiration, which enhances plant growth and creates microhabitats that encourages species variety
- The thermal capacity of plants helps protect solar PV panels from winter cold
- Racking and support systems for solar PV panels can be designed so that the green roof layers act as ballast, thereby saving the need for roof penetrations or concrete pavers
- Increased membrane life due to the protection of green roofs mean solar PV panels must be moved for re-roofing less often

While research is still in its infancy, other potential integrations have been explored:

- Using vertical axis wind turbines at edges and corners of green roofs could take advantage of turbulent wind without regard to orientation, while also reducing wind uplift forces and allowing for a more moderate rooftop microclimate.
- There are also possibilities to grow plants for biomass on or within building envelopes, as seen in the BIQ House in Hamburg, which uses an innovative bioreactor facade with algae growing within. The algae can be harvested and turned into biogas, which generates electricity.
- Similarly, the residual biomass of green roof or wall plants can be harvested to generate energy. If biomass production is a goal, plants that produce more biomass than typical green roof plants can be selected if water, nutrients, and structural loading capacity are available.

*The green roof on the Van Dusen Botanical Garden Visitor Centre contributes to the buildings Living Building Challenge Certification. 2017 GRHC Award Winner: Connect Landscape Architecture. Photo courtesy Brett Ryan Studios.*

# ES.5. Urban Heat Island Reduction

Urbanization has replaced large areas of natural landscape with artificial structures and surfaces, altering near-surface climate and causing air temperatures to rise. This phenomenon, referred to as the UHI effect, occurs because building materials commonly used in urban areas, such as concrete and asphalt, have significantly different thermal and surface radiative properties than natural landscapes. Reduced evapotranspiration because of less vegetation, combined with waste heat from buildings, cars, and industrial activities, can also contribute to the UHI effect.

There are several negative effects caused by UHI, including:

- Increased energy consumption due to elevated temperatures and increased air conditioning demand. Additionally, increased summer peak loads cause problems for power utilities, requiring expensive and often dirty peak power plants that only operate a few days a year.
- Increased air pollution – Elevated temperatures caused by the UHI effect promote chemical reactions where volatile organic compounds, nitrous oxides and other industrial pollutants mix to form ground level ozone.
- Health impacts - Air pollution has a host of negative health impacts, including respiratory problems like asthma, as well as cardiac irritability. Greater instances of extreme heat also mean increased levels of heat stress and other heat-related illnesses.
- Ecosystem impacts – Increased heat and air pollution can damage vegetation by affecting photosynthesis and fruit/seed production. Extreme heat can also stress plants and animals and reduce their ability to survive and thrive in the urban environment.
- Economic impacts - In addition to increased costs of energy, healthcare, water and transportation, more extreme heat negatively affects tourism and related activities.
- Increased water use – More water is needed to support stressed vegetation. Increased energy generation due to increased demand also requires more water to operate more power plants.

Green roofs, along with green walls, trees, and other greenery, are an important tool in an overall strategy to reduce UHI. The UHI effect is caused by an alteration of land from natural to artificial surfaces; green roofs help to reverse that phenomenon by returning vegetated surfaces to the urban environment, especially in constrained areas with limited at-grade space for trees or other vegetated surfaces.

# ES.6. Carbon Sequestration and Avoided Emissions

Carbon sequestration is the process of capture and long-term storage of atmospheric carbon dioxide. The process of photosynthesis captures carbon dioxide from the atmosphere and stores it in plant biomass. Some of this carbon is transferred to the growing media via plant litter and exudates. Green roofs and walls can take advantage of photosynthesis to capture and sequester carbon from the atmosphere, in both plants and growing media.

Additionally, by reducing energy both directly (by reducing heating and cooling energy required by moderating heat flux through a building envelope) and indirectly (by reducing the UHI), green roofs can reduce emissions associated with each.

# ES.7. Conclusion

Green roofs (and other forms of living architecture like green façades and living walls) offer significant potential to provide energy and climate benefits to both building owners and the community. With knowledge of the factors that contribute to increased performance, designers and other green roof professionals can help building owners and investors reduce energy consumption and improve the output of rooftop solar PV panels. At the same time, a holistic approach to encouraging and incentivizing green roofs can provide community-scale benefits like a reduction in the UHI effect, and even global-scale benefits like carbon sequestration and avoided emissions.

Understanding the mechanisms through which green roofs moderate heat flux through a building envelope, as well as the design, building, and climatic variables that influence performance are essential to unlocking and maximizing their energy and climate benefits.

# Green Roofs, Climate, and Energy: A Summary and Review of the Energy and Climate Benefits of Green Roofs

## 1. Introduction

### Buildings and Energy

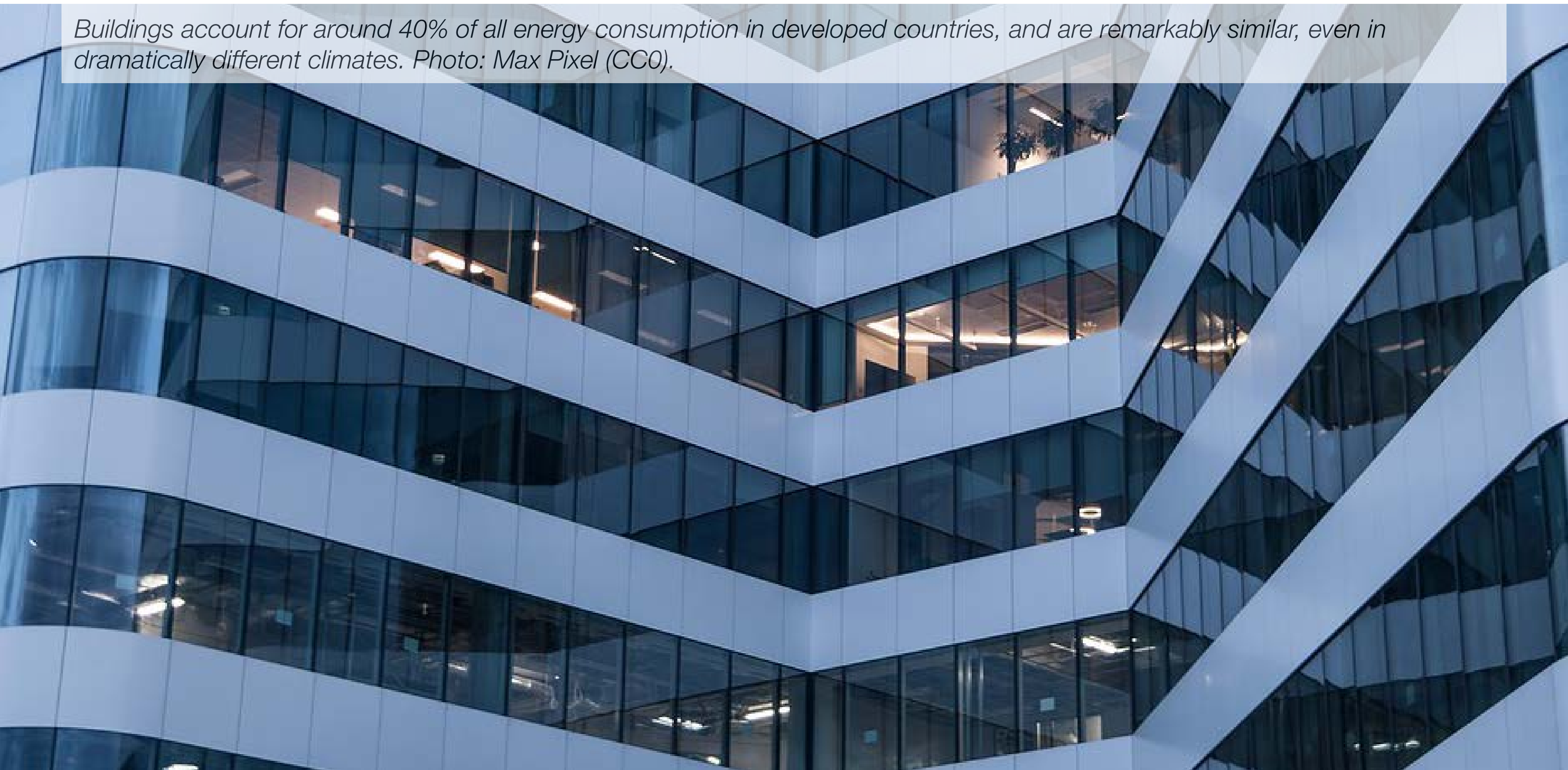
The buildings sector is the single largest global user of energy, accounting for around 40% of energy use in developed countries (US Energy Information Commission, 2021; European Commission, 2015). The homogenization of building design means that buildings are often designed without regard to local context, climate, or available local water, energy, and material resources. Rather, the drivers of new building design continue to be minimal initial cost and the ability to be rapidly constructed. Poor building design is compensated for by using increasingly energy-intensive heating, ventilation, and air conditioning (HVAC) systems. These HVAC systems allow us to maintain a uniform indoor environment and discourage climate-adapted design, regardless of the location of the building. Despite the dramatic differences in climate between Phoenix and Boston, for example, the average new building in each city is remarkably similar.

While energy conservation or generation is a concern in new construction, the situation is even more troubling in older buildings. The average age of commercial buildings in the US is over 52 years (SMR Research, 2020), and 80% of its housing stock is over 15 years old (Institute for Market Transformation, 2012). Similarly, 35% of all buildings in the European Union are over 50 years old (European Commission, 2015). Many of these older buildings were constructed in eras of extremely permissive building codes. It may not be feasible or desirable to replace many of these poorly designed buildings for several years, even though energy and maintenance costs build up. This presents an opportunity for retrofits that can significantly improve energy performance.

### Green Roofs and Energy

Rapid climate change and its potentially devastating cascading effects has increased the urgency in which we need to decarbonize our infrastructure and use energy more efficiently. Our growing understanding of the services already provided by our ecosystems can help us achieve this goal. Redesigning our built environments to conform to ecosystem attributes holds the key to a more sustainable future (Allen, 2013).

Green roofs have been used for hundreds or even thousands of years for their many benefits. While the hanging gardens of Babylon – one of the original Seven Wonders of the World - were mostly prized for their aesthetic



*Buildings account for around 40% of all energy consumption in developed countries, and are remarkably similar, even in dramatically different climates. Photo: Max Pixel (CC0).*

*Green roofs have been used for hundreds of years for their insulative properties - like these sod roofs in the Faroe Islands. Photo: Dave Marcus (CC BY-NC-SA 2.0).ection*

appeal, sod roofs have been used in Scandinavia since the middle ages for their insulative properties. Similarly, vines have been planted in urban areas throughout history, not only as a source of food, but also for their shade.

Green roofs and walls have come a long way since those early designs, and today is part of a complex field that requires knowledge of architecture, biology, landscape architecture, building science, and mechanical and electrical engineering. Using an integrated design process is essential to designing green roofs for performance and optimal benefit.

Green roofs have many potential building-scale energy benefits that largely fall into three categories:

- Moderation of heat transfer through the building envelope, reducing heating and cooling energy use
- Improving the performance of building HVAC systems through integration
- Improving the efficiency of solar PV and creating opportunities for other renewable energy technologies

Additionally, there are several larger-scale (city-scale and global-scale) energy and climate benefits:

- Reducing the urban heat island effect (UHI)
- Carbon sequestration and avoided GHG emissions
- Secondary and tertiary benefits, including reducing the energy required to process stormwater, and reducing energy inputs for material manufacture by extending the lifespan of building materials

The following sections explain the benefits and as summarize the research into each.

# 2. Moderation of Heat Transfer Through the Building Envelope

The energy balance of a green roof or wall is similar to that of a traditional roof or wall: it is dominated by incoming solar radiation, and balanced by sensible (convective) and latent (evaporative) heat flux from growing media and plant surfaces, along with conduction of heat into plants and the growing media.

Thermal moderation of a building envelope is one of the most important benefits of green roofs. In fact, engineers, architects, investors, and building owners often ask a simple question when considering a green roof to conserve energy: “What is the R-Value?”. This question is impossible to answer, because the thermal performance of a green roof is far more complicated than merely a layer of insulation, and green roofs use many different methods of heat transfer and dispersal to moderate heat transfer through a building envelope (Figure 2a):

- Evapotranspiration (latent heat loss)
- Convection (sensible heat loss):
- Reflectivity (albedo)
- Thermal mass
- Solar shading

Each is explored in greater detail in sections 2.1.1 - 2.1.5.

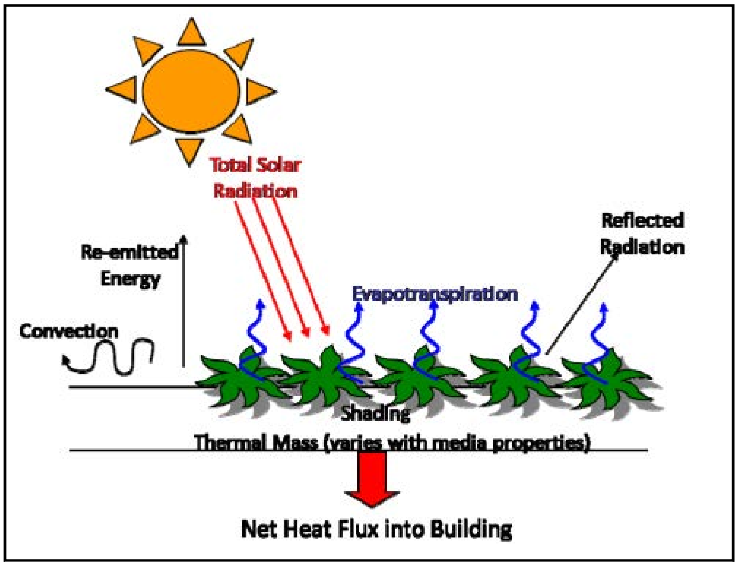



*Figure 2a: An energy balance model for a green roof, showing the different methods of heat transfer and dispersal used to moderate heat flux through a building envelope. Image: Clark et al. (2010).*

### Research Highlights:

- Feng et al. (2010) presented an energy balance model of green roofs, and found that the vast majority of heat gain (99.1%) associated with a green roof was through solar radiation. When growing medium moisture levels are high, evapotranspiration plays a large role in heat dissipation (58.4%), while convection from the canopy to the atmosphere was also an important factor (30.9%). Only 0.6% of heat is transferred to the room below. The authors suggest that when growing medium moisture levels are lower, convection plays a more important role in the dissipation of heat, but more heat is transferred to the building. They argue that the climate-appropriate use of irrigation is an effective way to optimize green roof energy performance.
- Feng and Hewage (2014) modeled the energy benefits of green roofs and walls for a LEED certified building in Kelowna, British Columbia. They found that covering the roof and walls of the building would reduce 3.2% and 7.3% of the annual cooling energy required respectively, but had no impact on heating energy.
- A study by Liu and Minor (2005) in Toronto tested two lightweight green roof systems, as well as a bare reference roof (steel deck with thermal insulation and modified bitumen waterproofing above). They found that the heat gain through the green roofs was reduced by 70-90% in the summer and the heat loss was reduced by 10-30% in the winter, compared to the reference roof. These numbers varied because of the different growing medium depths, and the different insulation used for each green roof. Additionally, peak temperatures were delayed by around 5 hours to past the peak cooling periods of the late afternoon, and only a small proportion of the roof heat was transferred to the room below.
- Tam et al. (2016) found that in Hong Kong, green roofs can reduce interior temperatures by 3.4 ˚C (6.1 ˚F), and that growing media depths and plant types are particularly significant to thermal performance. Deeper growing media may have a higher efficiency in moisture retention and lead to higher evaporation efficiency from the plants that leads to a higher thermal performance.
- Simmons et al. (2008) studied six different types of green roofs, in addition to reference black and white (reflective) roofs in the subtropical climate of Austin, TX. They found that compared to the reference roofs, all green roofs had significantly reduced temperatures on and below the surface. Additionally, peak temperature was delayed by 1-3 hours. The reduced temperature below roof membranes had an effect on internal temperatures, making them up to 18 ˚C (32 ˚F) cooler than spaces under the black roof, even with the presence of roof insulation. Although white roofs also reduced internal temperatures, the effect was much smaller (5˚ C/9˚ F).

# 2.1. Green Roof Processes

Every component of a green roof plays an important role in its thermal behavior: the canopy shades the surface of the growing media from solar radiation. The level of shading depends heavily on the vegetation type and foliage density (expressed in leaf area index, [LAI] defined as the one-sided leaf area per ground surface area). While this shading can be achieved by shading devices like screens or pergolas, the shading devices would absorb or reflect solar energy, deflecting energy to the surrounding environment or increasing thermal transmittance due to its increased temperature.

Conversely, plants absorb most solar radiation but use it for their biological functions (evapotranspiration, photosynthesis, etc.). Biologically motivated, forced evaporation from the foliage decreases leaf surface temperature and cools the air in contact with the foliage. As long as there is enough moisture in the growing medium, the intensity of evapotranspiration is directly proportional to the heat stress. This means that this biological cooling mechanism is adapted to ambient heat stress and is maximized during times of high solar intensity, when the need for cooling in buildings is also highest (Wark, 2011).

The layer of air between the canopy and growing media is significantly cooler than the ambient air temperature on a sunny day due to the shading and evapotranspirative effects of the foliage. This air also forms an insulating layer and acts as a convective buffer, minimizing heat gain. The layer of growing medium has a high thermal mass and acts as a heat sink, especially when moisture levels are high. It absorbs heat during the day, holds it and releases it slowly at night, minimizing transfer to the building below (Wark, 2011).

The roof to envelope ratio is an important factor when considering the effectiveness of a green roof at moderating a building envelope. A green roof will have a significantly larger effect on a large, low-rise building than it will on a high rise with a small floor plate. Conversely, living walls and green façades will have less of an effect on a low-rise building with a large floor plate.

Living walls and green façades can also thermally moderate a building envelope in a way similar to green roofs. While there are many different types of green wall technologies that work differently, green walls and façades can generally use the same methods of heat transfer and dispersal as green roofs and can be effective energy conservation tools. The effects of living walls and green façades are explored further in section 2.3.

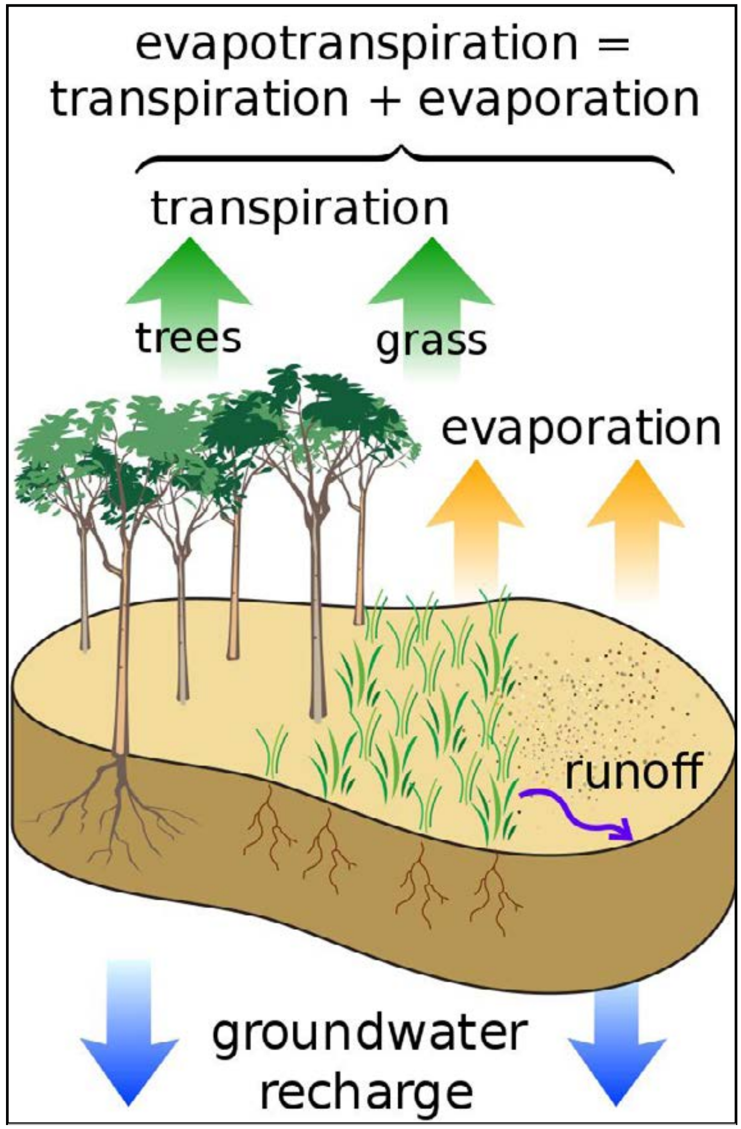



*Figure 2.1.1a Evapotranspiration is a combination between transpiration - water moved from the growing medium through the plant and then released as water vapor; and evaporation - the phase change between liquid and vapor. Image: M. W. Toews (CC BY 4.0).*

## 2.1.1. Evapotranspiration (latent heat loss)

Transpiration occurs when water is moved from the growing medium through a plant and then released as water vapor through stomata in its leaves. Water also evaporates directly from the growing medium. The phase change, or evaporation, from liquid to vapor causes latent heat to be released, lowering the surrounding temperature. Our bodies use essentially the same method of cooling when we sweat (Wark, 2011).

**Research Highlights:**

- Cascone et al. (2019) found that the main factors affecting the evapotranspiration process were volumetric water content, stomatal resistance, LAI, solar radiation, wind velocity, relative humidity, growing media thickness, and substrate composition. The authors noted that while many studies have compared roofs with and without vegetation and different plant species, very few compared the effect of substrate on evapotranspiration.
- A model developed for a single family home in La Rochelle, France, found that increases in LAI decreased summer indoor air temperatures and cooling demand, but increased winter cooling demand, mainly due to transpiration and solar shading. However, increasing LAI offers diminishing returns, especially at higher levels of LAI. It is also important to note that these findings are in the temperate climate of La Rochelle,

France, where winter temperatures rarely fall below freezing. These findings could be different in colder climates where transpiration is negligible in winter, and roofs may be snow-covered.

- Kumar and Kaushik (2005) developed a model that found canopy temperatures were reduced approximately 70%, and heat flux was reduced approximately 50% when LAI was increased from 0.5 to 3.5. They determined that this was largely due to the additional evapotranspiration and insulation provided by denser foliage.
- Lazzarin et al. (2005) modelled the role of evapotranspiration on a hospital green roof in northeastern Italy. They modelled wet and dry green roofs, and found that the dry roof was able to reduce the incoming heat flux by 60% compared to the bare reference roof. The wet roof was even more effective, losing twice as much heat through evapotranspiration than the dry roof. This suggests that wet green roofs can not only prevent heat flux through the building but also act as passive coolers, drawing heat from out of the building.
- While the literature on plant selection for optimized evapotranspiration is limited, Oberndorfer et al. (2007) make some inferences based on literature they studied. They argue that green roof energy models determine that most summer cooling benefits are associated with evapotranspiration, and in order to optimize this function, selecting plants with large surface areas or high leaf conductivity is a sound strategy. They go on to argue that performance is influenced by two main properties: the ability to recover from environmental fluctuation and disturbance and the optimal use of resources. They suggest using more resilient plants to increase the duration of plant functions, and designing for high plant diversity to optimize resource use and more constant plant coverage.

## 2.1.2. Convection (sensible heat loss)

Convection refers to the transfer of heat from one element to another by the movement of a fluid. In this case, foliage transfers heat to the surrounding atmosphere by the movement of wind, due to its larger surface area compared to a conventional building surface. Many plants wilt or go dormant during the winter, reducing their surface area and by extension, convective heat losses (Wark, 2011).

**Research Highlights:**

- Ayata et al. (2011) developed a model to measure the convection or sensible heat flux of green roofs. They argue that because green roof surfaces have many parameters, they cannot be compared to regular surfaces used in existing energy models. The researchers argue that surface roughness, as measured by vegetation coverage and LAI, is an important factor in sensible heat flux. They go on to state that sensible heat flux is inversely proportional to growing medium moisture – as evapotranspiration decreases in dry periods, convective heat transfer becomes a more important part of the roof energy balance.
- Theodosiou (2003) found that convective heat loss is a factor in green roof performance, and is influenced by wind speed. He argues that higher wind speed not only increases convective heat loss, but also facilitates the removal of vapor near the green roof surface, encouraging higher rates of evapotranspiration.

## 2.1.3. Reflectivity (albedo)

Green roofs tend to have a higher albedo (or reflectivity) than conventional roofs, making them absorb less solar radiation. Some plants, like sedums, become more reflective under heat stress. Many plants also shrivel in the winter, reducing their surface area and decreasing albedo. This allows for more heat to be absorbed when desirable (Wark, 2011).

**Research Highlights:**

- Gaffin et al. (2005) aimed to model the 'equivalent albedo' of a green roof – the albedo (or level of reflec-

*Many plants shrivel in the winter, reducing their surface area and decreasing albedo, as seen here in Chicago's Millennium Park Green Roof. 2005 GRHC Award Winner: Terry Guen Design Associates.*

tivity) required by a non-green roof to reproduce the surface temperatures found on a green roof, taking into account both reflectivity and latent cooling potential. They found that the equivalent of a green roof is 0.7- 0.85, comparable to the brightest possible white roofs and significantly more than the average black roof. Additionally, they found that the albedo of white roofs declines by about 0.15 a year because of weathering and dirt accumulation.

- Wark (2011) argues that succulent plants like sedums have a naturally adapted variable albedo. During hotter periods with lower water availability, they are waxy and more reflective, exhibiting a higher albedo. During the winter, their leaves become smaller and less shiny, and emit less heat due to their reduced surface area.

*Succulent plants like sedums get waxy and more reflective during periods of heat stress, while becoming smaller and less shiny in the winter. Photo: Michel Langeveld (CC BY 4.0).*

- While white roofs may perform better when newly installed, the albedo of white roofs declines by about 0.15 a year because of weathering and dirt accumulation. Power washing of white roofs can remedy this, but is expensive, and many operators of buildings with large white roofs (like Walmart) do not power wash white roofs. Moseley et al. (2013) estimated that the maintenance costs of a white roof are more than twice that of an extensive, drought-tolerant green roof, even when power washing is not considered. This is largely because the green roof layers protect the membrane, reducing leaks and drain clogging, and more than doubling membrane lifespan.

## 2.1.4. Thermal mass

All the layers of a green roof or wall system contribute to increased thermal mass compared to a traditional roof or wall. The increased mass allows for the absorbance of heat during the day and the slow release of heat at night. Increased water content contributes significantly to thermal mass, and many succulent plants like sedums store water, increasing this effect (Wark, 2011).

### Research Highlights:

- Experiments by Liu and Minor (2005) on two green roofs in Toronto found that growing media depth improved thermal performance. Despite low vegetation coverage, the green roofs studied lowered heat flow in both the summer and winter. Greater growing medium depth was associated with better performance in summer. The roof with the shallower growing medium performed better in winter, but the researchers theorize that this is because of the extra insulation provided by different components in the construction of that green roof.
- Del Barrio (1998) modelled the summer cooling potential of green roofs in Athens, Greece, finding that growing medium depth, density, and moisture content were important factors in thermal performance. Greater depth and less dense growing media reduced heat flux. Less dense and coarser growing media is a poorer heat conductor, and additional air pockets in the growing media contribute to its insulating properties. Conversely, higher moisture content was found to lead to increased heat flux.

## 2.1.5. Solar shading

Foliage in living architecture shades building surfaces from direct exposure to solar radiation, reducing heat gain. As foliage absorbs heat, it uses mechanisms described above to dissipate heat much more effectively than a building surface (Wark, 2011).

### Research Highlights:

- Sailor et al (2011) compared energy performance in four US cities (New York, Phoenix, Houston, and Portland) and showed that the energy performance of green roofs was particularly improved by the increase in planting density in every city. Jaffal et al. (2012) reached the same conclusion, determining that vegetation coverage has a significant influence on the absorption of solar radiation by the foliage and thus on the solar shading effect.

- Fioretti et al. (2010) measured solar radiation on the surface of a green roof, as well as below the foliage, finding that the shading effects of plants are apparent and the growing media is exposed to significantly less radiation when shaded by plants. It can be assumed that the level of shading is influenced by plant factors like LAI, fractional vegetation coverage, and plant height. During periods where absorbing solar energy is desirable (the heating season), using plants that go dormant or shed foliage may be more appropriate.
- Clay et al. (2012) studied the effects of green roofs in the semi-arid Mediterranean climate of Adelaide, Australia. They discovered that the addition of a mesh walkway 150 mm over the surface of a green roof bed reduced daily temperature variations 1.9 times compared to the equivalent uncovered green roof bed. They theorize that this is due to the effects of shading, while also allowing enough sunlight and air to allow for healthy plant growth.

## 2.2. Non-Green Roof Factors

### 2.2.1. Effect of Insulation

Roof insulation has a large impact on the thermal effects of green roofs - older and poorly insulated buildings tend to feature significantly more heat flux through the building envelope. This offers the opportunity to use green roofs to moderate this heat flux and provide greater benefits.

Jaffal et al. (2012) modeled a single family home in La Rochelle, France, and found that a green roof reduced the mean and maximum indoor air temperatures by 6.5 ˚C (11.7 ˚F) and 9.3 ˚C (16.7 ˚F) on an uninsulated roof in a temperate climate, but by less than 1 ˚C (1.8 ˚F) on a roof with 30 cm of insulation. This reduced building energy reduction by 50% for the uninsulated roof, but only 3% for the insulated roof.

Similarly, Niachou et al. (2001) found that while a non-insulated building in a Mediterranean climate could reduce energy consumption by 37% with the addition of a green roof, a well-insulated building would see a reduction of less than 2%. These findings suggest that older, poorly insulated buildings are ideal candidates for green roof retrofits to reduce energy use. While adding additional insulation would undoubtedly be cheaper, green roofs act as passive coolers and would perform better than simple insulation, especially if irrigated (in addition to providing numerous other benefits additional insulation would not).

A variable insulation green roof model proposed by La Roche and Berardi (2014)(See Figure 2.2.1a) could be the solution to optimizing green roof and insulation use in both summer and winter. The system uses a plenum between the green roof and the building below and a sensor-operated fan that couples (or decouples) the green roof from the room below.

The plenum is ventilated only when the fan is operational, creating a variable insulation system that couples the roof with the building when its cooling potential is highest. Additionally an air change fan can be used to discharge green roof thermal mass when outdoor air is cooler. Both the plenum fan and the air change fan can be turned off when cooling is undesirable, so that the plenum is used as insulation.

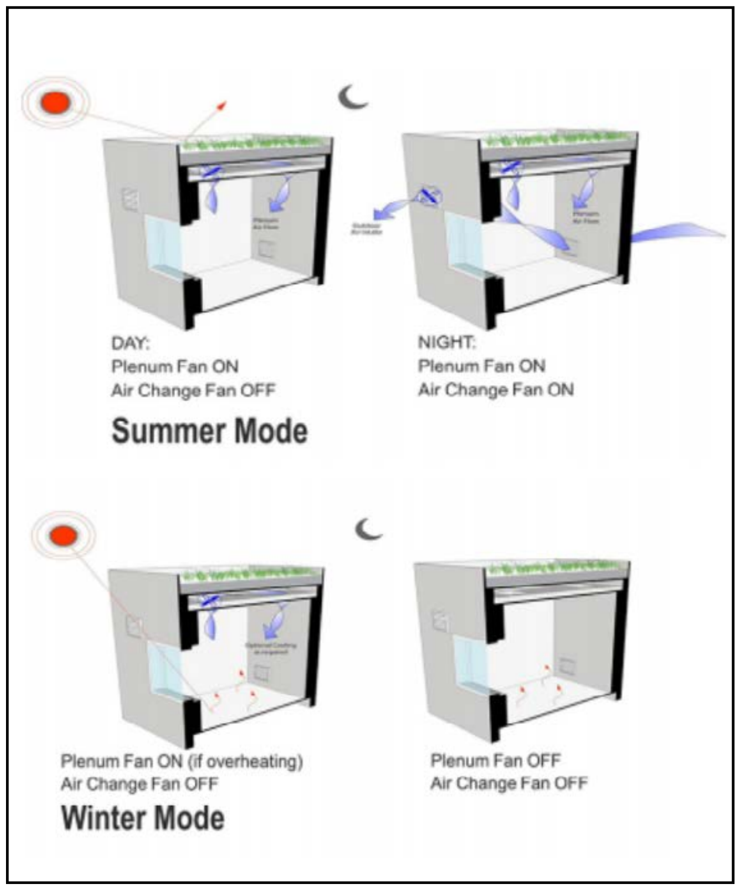



*Figure 2.2.1a: A variable insulation green roof. Image: La Roche and Berardi, 2014.*

## 2.2.2 Climate and Weather

Summer temperatures on concrete roof slabs have been found to be significantly reduced under a green roof versus under a conventional roof – up to 30 ˚C or more. This holds true in the temperate, warm summer climate of La Rochelle, France (Jaffal et al. 2012); the hot and humid summer of Osaka, Japan (Onmura et al., 2001); the hot tropical summers of Taiwan (Lin et al., 2011) and Singapore (Wong et al., 2003); and the hot Mediterranean summer of Marche, Italy (Fioretti et al., 2010). Conversely, in the cold and snowy climate of Tartu, Estonia, the temperature under a green roof was 30 ˚C (54 ˚F) warmer than that of a conventional steel sheet roof (Teemusk and Mander, 2010).

Alexandri and Jones (2008) determined that green roofs and living walls have beneficial impacts in 'urban canyons' – the area between buildings in a dense urban environment. Based on a model developed by researchers, the microclimatic effects and reduced UHI of greening roofs and walls could lead to reductions in energy used for cooling buildings by 32-100%, depending on the climate.

Theodosiou (2003) found that foliage height, foliage density (expressed in LAI), and growing medium thickness were all directly correlated to the ability of a green roof to cool a building. Interestingly, they argued that in the hot-summer Mediterranean climate of Greece, using no insulation was the most effective design choice. This allows for a stronger thermal connection to the building and maximizes the cooling potential of green roofs during hot weather. They also found that green roofs are more effective at cooling when relative humidity is lower, and wind speeds are higher. This is because lower humidity and higher winds facilitate vapor removal from foliage and lead to higher evapotranspiration. Theodosiou did find that heating costs do increase marginally in the winter, but this is unlikely to be an issue in a colder climate where insulation is necessary and winter evapotranspiration levels are very low or non-existent.

Song et al. (2013) outlined an innovative approach that could reduce energy costs while also dramatically improving stormwater management performance and increasing biodiversity: using constructed wetland ecosystems on green roofs. Their study of an experimental wetland green roof demonstrated that wetland plants have high evapotranspiration rates, working to cool the building in hot summer months. At the same time, the layer of water has a high thermal mass, which moderates temperature fluctuations. Wetland macrophytes are drought-resistant, flood resistant, low-maintenance and accumulate high biomass, acting as a carbon sink. By planting for full coverage to reduce evapotranspiration off the water surface, the wetland ecosystem would actually require less irrigation than a terrestrial, grass-based green roof (Song et al., 2013). While a wetland green roof would require more water than a green roof planted with sedums or other drought-tolerant plants, this approach may be worth exploring when structural capacity is available, when greywater reuse is planned, or in areas of high precipitation.

*A wetland integrated green roof. Image: Zehnsdorf et al. (2019)*

Similarly, Zehnsdorf et al. (2019) conducted a review of wetland green roof literature, and found that wetland green roofs could be a vital water management tool, especially in constrained urban areas, given sufficient water. They identified the potential of wetland green roofs to treat wastewater, while retaining nearly all stormwater, and providing important energy and biodiversity benefits in the process.

Given the importance of weather and climate to the performance of living architecture, more research is needed regarding performance in different climates. Detailed design strategies to optimize energy performance in arid climates should be explored further, as well as the potential to integrate water management and energy performance by capturing and reusing water. The energy performance of green roofs in cold climates where plants are dormant and/or green roofs are covered by snow should also be explored further.

The following table describes possible strategies for green roofs to optimize energy performance by designing for desired benefits, based on common climate zones in North America. For example, a green roof in a cooling-season dominated climate would be designed for maximum cooling potential, while one in a climate where both heating and cooling are prevalent would balance summer cooling with winter insulation.

Table 2.2.2 – Summary of green roof energy design strategies for typical climates in North America

| **Type of Climate** | **Example** | **Heating** | **Cooling** | **Precipitation** | **Design Strategies** |
|---|---|---|---|---|---|
| Dfa (Humid Continental); Cfb (Temperate Maritime) | Toronto; Chicago; Seattle | Moderate - High | Low - Moderate | Moderate, year round | • Use plants that go dormant or shed foliage to maximize winter solar gain<br>• Maximize summer evapotranspiration by using an optimum plant mix and a high leaf area index<br>• Maximize water availability by using deeper growing media, a water storage layer or providing irrigation (preferably using captured rainfall, greywater, or other non-potable water sources) |
| Csb (Mediterranean); Bwh (Hot Desert) | Los Angeles; Phoenix | Low | High - very high | Low/very low, mostly in winter | • Design for maximum evapotranspiration by using an optimal plant mix and increasing leaf area index<br>• Irrigate only using captured rainfall, greywater, or other non-potable water sources (essential in water stressed regions)<br>• Use hardy, drought-tolerant plants<br>• Use plants with a high albedo<br>• Maximize thermal mass to minimize diurnal temperature swings<br>• Use shading structures or solar panels to increase shade and reduce heat stress on plants |
| Cfa (Sub-tropical); Am (Tropical) | Washington,DC, Houston; Miami | Very low - low | High - very high | High, year round/mostly in summer | • Design for maximum evapotranspiration by using an optimal plant mix and increasing leaf area index<br>• Use plants with a high albedo<br>• Orient green roof toward wind to maximize convective cooling<br>• Consider using a wetland ecosystem if structurally possible |

# 2.3. Green Walls - Facades and Living Walls

While many of the findings of green roof research could be applied to green façades and living walls, the energy effects of green façades and living walls have also been studied. It is important to note that due to the diversity of living wall and green façade designs, generalizations are sometimes made. However, hydroponic and growing medium-based living walls may not perform the same way, just as direct (building attached) and indirect (using a supporting structure) green façades may not perform the same way.

Living walls generally use many of the same methods of heat transfer and dispersal as green roofs – shading, evapotranspiration, increased albedo, convective cooling and potentially increased thermal mass – depending on the system. Depending on their design, green façades also use two other methods – providing a thermally insulating air cavity, depending on the distance of the façade to the wall; and convective shielding (reduced wind speed on the wall), which is particularly important at reducing heat loss in winter (Hunter et al., 2014).

Plant selection for green façades can be based on orientation; for example, planting deciduous vines on western, southern, and eastern exposures (in the northern hemisphere) will maximize summer shading while allowing sunlight and heat gain in the winter. Using evergreen plants on northern exposures will trap an insulating layer of air against the building envelope, acting as a buffer against winter winds – a major contributor to convective heat loss in colder climates. For naturally ventilated buildings, using living walls or green façades will reduce the temperature of air intake and act as a passive cooling device (Allen, 2013).

### Research Highlights:

- Kontoleon and Eumorfopoulou (2010) modeled the effects of plant-covered walls, finding that they would lead to superior interior thermal comfort, especially when walls are not insulated. They suggest using green façades or living walls to compensate for poorly oriented walls. They argued that plant coverage was the key variable, and east or west-facing walls were the most effective at reducing cooling requirements. Cheng et al. (2010) also argued for the importance of plant coverage, and found growing medium moisture to be another important determinant of cooling effectiveness.
- In their analysis of eight different types of living wall (all growing medium-based) and one green façade system (supported by a mesh system) in Singapore, Wong et al. (2010) found they hold significant promise in cooling buildings. They also suggested that lower ambient temperatures would reduce the temperature of air conditioning intakes, also translating into reduced cooling costs. While they found that the living walls performed better due to the insulation and moisture retention offered by the substrate, the green façade also significantly reduced wall surface temperature. They suggest further research to analyze factors like physical structure, materials, plant species, etc. to determine which are most important in performance.
- Tests conducted by Bass and Baskaran (2001) in Toronto, found that a garden set up against a sun-exposed, southwest facing slanted metal wall (essentially a very rudimentary living wall) reduced the wall surface temperature by up to 29 ˚C (52 ˚F). They suggest designing living walls unique to each context in order to optimize energy goals. For example, designing a south facing living wall as an awning (Figure 2.3a), angled to take advantage of the different azimuths of the sun in summer and winter, which would offer shade from summer sun while still allowing indirect light, while allowing winter light and heat gain.

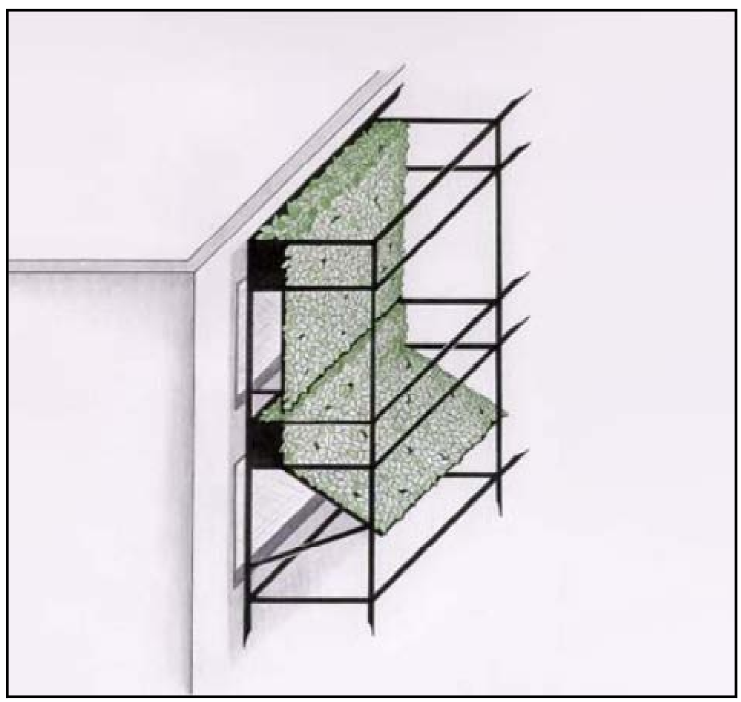


*Figure 2.3a: A green wall window awning. (Bass and Baskaran, 2001)*

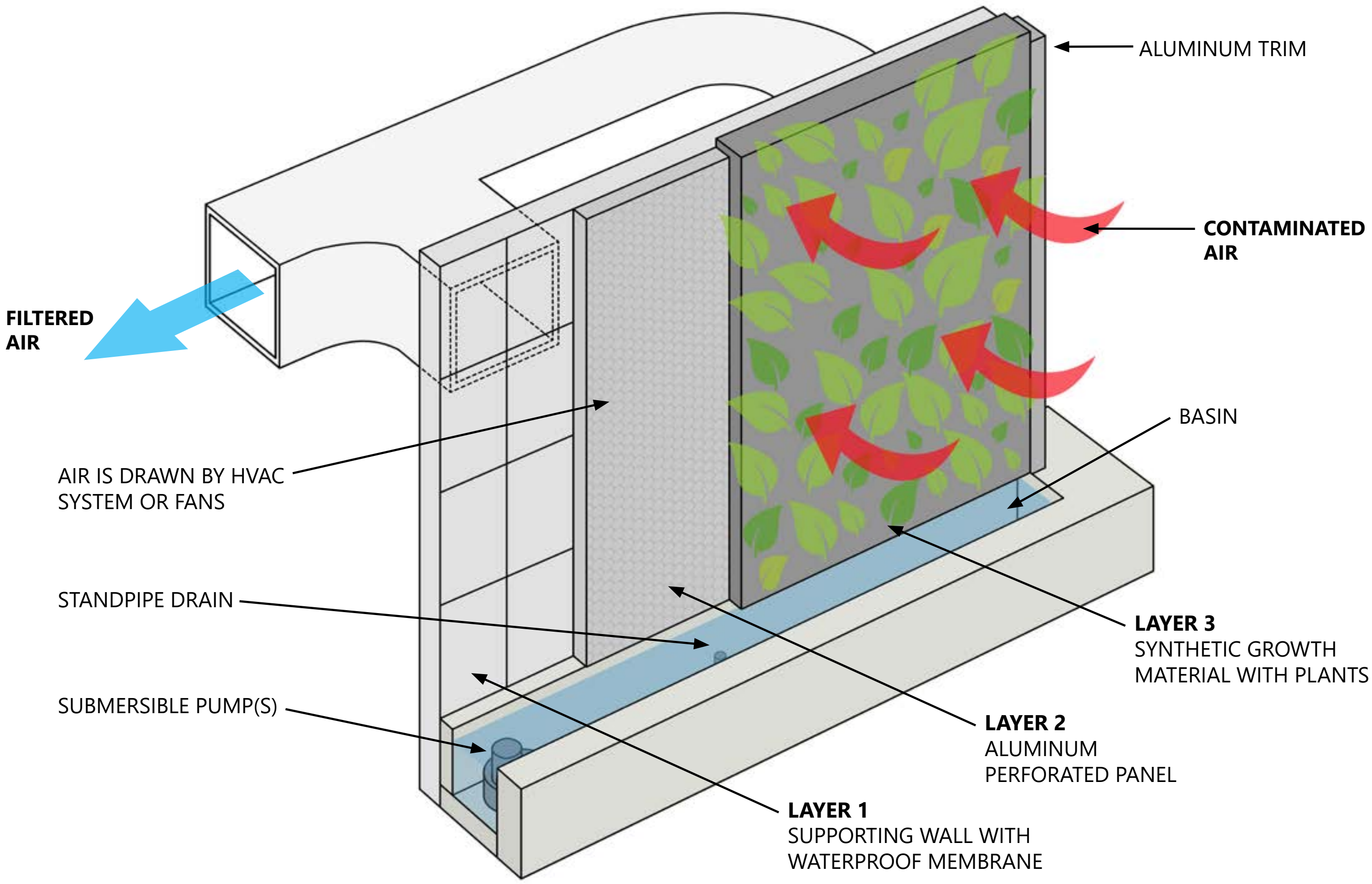
- Experiments by Tilley and Price (2010) compared experimental buildings covered in green façades with identical unvegetated buildings. They found that the façades reduced internal temperatures by 1 ˚C (1.8 ˚F) when they covered the south wall, and 2 ˚C (3.6 ˚F) when they covered the west wall. While the west-facing façade reduced heat flux more, and for a longer period of time, the south-facing façade reduced heat load by 70%, compared to 50% for the west façade. Because the west-facing façade reduces temperatures later in the day, there are implications based on the intended use of the building. Office buildings that are occupied during the day might benefit more from a south-facing green façade, while a residential building would probably benefit more from the west-facing green façade.
- Carlos (2015) studied green façades in the winter in Portugal and found that they have significant energy saving potential. His modeling found that evergreen façades oriented away from solar radiation (north, west, and east) act as an insulation layer in the winter, augmenting the thermal resistance of the wall. Using denser foliage also helps to create a layer of air between the plants and the building, buffering convective heat losses from winds. Carlos did find that green façades on southern exposures reduce heat gain in the winter, increasing heating costs – he therefore suggests using deciduous plants on southern exposures. This will reduce undesirable heat gain in the summer, but allow for light and heat penetration in the winter.
- Sandifer and Givoni (2002) studied a wide variety of green façades - vines growing on south and west facing walls in the hot-summer Mediterranean climate of Los Angeles, CA. They determined that vines grown against a building or on an adjacent pergola could reduce surface temperatures to slightly below ambient temperatures, reduce west-wall heat gain in the summer, shade glazed openings and provide a more comfortable exterior space next to buildings.
- Hunter et al. (2014) argue that while green façades hold significant potential, there are limiting factors that make them suitable under only certain conditions. They argue that extreme solar radiation patterns (intense sunlight and periods of dark shade), high wind speeds, low humidity and increased ambient temperatures are harsh conditions that only certain plants can survive. The authors suggest further research using standardized approaches to help understand and quantify the performance of green façades in different climates and using different building aspects. Many of their conclusions can be applied to living walls, as literature in the field is still nascent and quantifying energy performance is still inconsistent.

An additional level of complexity associated with measuring living wall performance is the diversity of technologies. Growing medium-based and hydroponic living walls are very different, but the performance differences between both types of systems are still relatively unknown.

## 3. Integration into Building Energy Systems

An emerging, but promising, benefit of green roofs and walls comes through the potential to integrate them into building HVAC systems, and to design them to optimize their performance. The shading of outdoor HVAC units by vegetation can lower their operating temperature and make them operate more efficiently. Denser and more

*The green roof on New York's Javits Center reduces the temperature of the air entering rooftop HVAC units, thereby reducing cooling energy required. 2016 GRHC Award of Excellence Winner: FXFOWLE Epstein. Photo courtesy David Sundberg, Esto.*




*The HVAC-integrated living wall at the East Building Addition of the Adlai E. Stevenson High School in Lincolnshire, IL cleans the air, allowing for fewer outdoor air exchanges while maintaining high indoor air quality. Living Architecture Performance Tool Platinum Project: Wight and Company, Omni Ecosystems, and Nedlaw Living Walls.*

productive vegetation can be located closer to rooftop or building-adjacent HVAC air intakes to lower the ambient temperature of intake air. Since cooler air requires less energy to condition it for indoor use, this reduces the energy required for air conditioning (Mankiewicz and Simon, 2007).

Advances in indoor green wall technology have made it possible to integrate green walls into HVAC systems to improve indoor air quality; these are sometimes called biowalls. Indoor air is contaminated by processes within buildings (respiration by people, exhaust from equipment, and volatile organic compounds from building materials) and must be periodically exchanged for 'fresh' outdoor air. Biofiltration can be utilized to help remove some of these airborne contaminants – large wet surfaces are used that allow biofilms to form. These biofilms accumulate contaminants, which are then broken down by bacteria. These biological processes can be supported by plants and integrated into indoor living walls, where roots support microbial communities and leaves help remove contaminants. When these indoor living walls are integrated into building HVAC systems, there is the potential to reduce the frequency of air changes, reducing heating and air conditioning costs, while maintaining a high-quality indoor environment (Allen, 2013).

## Research Highlights:

- Air conditioners work by taking in outside air, using a refrigeration cycle to absorb and remove heat from this air, and then discharging this heat back outside. Therefore, the input air temperature is an important factor in air conditioning efficiency. Reducing ambient air temperatures around air conditioner intakes and units can improve air conditioner efficiency (Mankiewicz and Simon, 2007). This could take the form of using green roofs or walls to increase evapotranspiration and albedo, or using vegetated structures to shade air intakes and air conditioner units. The moderation of heat transfer through the building envelope by living architecture can affect design decisions around building HVAC systems. By reducing heating and cooling loads, living architecture could allow for a reduction in the size of HVAC systems. This can significantly reduce capital and life cycle costs of these systems (Webb, 2010).

- In their study of an experimental roof on a Walmart store in Chicago (part green roof, part white roof), Moseley et al. (2013)(See Figure 3a) found that summer air at rooftop HVAC units (0.9 m / 3 ft above the roof surface) was significantly cooler on the green roof side (Figure 5). Similarly, winter air was mostly warmer on the green roof side, suggesting both heating and cooling savings. The researchers did find a similar, but less pronounced effect on air handling units (AHUs) located 1.5 m / 5 ft' above the roof surface, so they suggest locating air intakes as close to the green roof surface as possible to maximize the moderating effects of the plant layer on ambient temperature. This finding has implications for the potential of energy savings in tall buildings. While rooftop heat flux does not have as much of an impact on energy performance, these buildings often have HVAC equipment located on roofs.

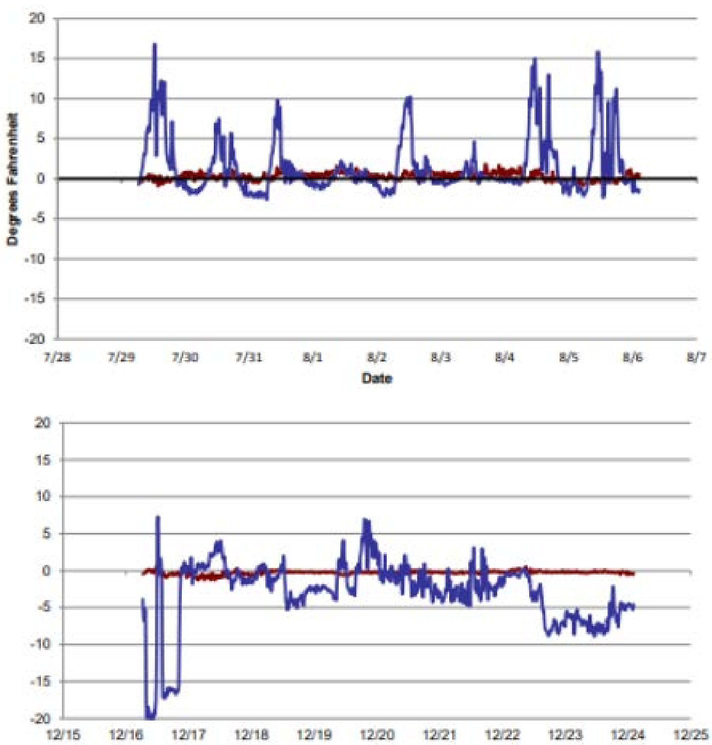



*Figure 2.3a: Summer (top) and winter (bottom) rooftop (blue) and AHU (red) air temperature difference (˚F) between intakes above white and green roofs. Positive value (on y axis) means air was cooler on the green roof side (Moseley et al., 2013).*

# 4. Renewable Energy Integration

Using green roofs in combination with solar PV arrays brings the benefits of green roofs (energy savings, stormwater management, biodiversity improvement) together with the benefits of solar PV panels (on-site energy generation, carbon-free energy generation, reduction of grid-sourced energy use) and synergies between both systems. These synergies have the potential to be wide ranging, and include (Lamnatou and Chemisana, 2015; Peck and van der Linde, 2010):

- Increased efficiency of solar PV panels due to reduced ambient temperature
- Increased incident sunlight reflected to solar PV panels due to increased roof albedo
- On-site generation of renewable energy, which can also be used to power irrigation equipment for the green roof
- Better use of space that captures the benefits of both technologies
- Increased revenue/savings (from generated energy) can offset the additional costs of a green roof
- Solar PV panels protect the plants and growing media from direct exposure to sunlight and wind, reducing drying and excessive evapotranspiration, which enhances plant growth and creates microhabitats that encourages species variety
- The thermal capacity of plants helps protect solar PV panels from winter cold
- Racking and support systems for solar PV panels can be designed so that the green roof layers act as ballast, thereby saving the need for roof penetrations or concrete pavers
- Increased membrane life due to the protection of green roofs mean solar PV panels must be moved for re-roofing less often

While research is still in its infancy, the potential benefits of integrating other living architecture with other forms of renewable energy are promising. Wind turbines have the potential to be integrated with living architecture. Building height and form often contribute to increased, but unpredictable and turbulent wind (Allen, 2013). While conventional wind turbines cannot harness this wind, innovations in vertical axis wind turbines allow

Many researchers have found synergies between rooftop solar PV panels and green roofs; while many think they compete for roof space, they are complementary technologies. Photo: ZinCo.

them to harness turbulent wind without regard to orientation (Eriksson, 2008). Placing turbines on the edges of green roofs could take advantage of the windiest locations, while also reducing wind uplift forces and allowing for a more moderate rooftop microclimate.

There are also possibilities to grow plants for biomass on or within building envelopes. The BIQ House in Hamburg (Figure 4a) uses an innovative bioreactor façade: Microalgae (plants that are barely bigger than bacteria) grow within this façade. Nutrients are supplied, and the algae uses sunlight to photosynthesize and grow. The algae can be harvested and turned into biogas, which generates electricity. Similarly, the residual biomass of green roof or wall plants can be harvested to generate energy. If biomass production is a goal, plants that produce more biomass than typical green roof plants can be selected if water, nutrients, and structural loading capacity are available (Arup, 2013).

Figure 4a: The BIQ House in Hamburg, Germany, features an innovative bioreactor façade. Photo: Arup

## Research Highlights:

- Solar PV panels are less efficient as ambient temperatures rise. High rooftop temperatures increase the conductivity of a crystalline silicon panel's semiconductor, which in turn inhibits charge separation and lowers the voltage of the solar cell (Peck and van der Linde, 2010). Solar PV panels are 0.4-0.5% less efficient per 1 ˚C (1.8 ˚F) increase in ambient temperature, above 25 ˚C (77 ˚F) (Chemisana and Lamnatou, 2014; Lazzarin et al., 2005).
- Jahanfar et al. (2020) created an evapotranspiration model for solar PV-integrated green roofs, finding that shading and wind-shielding from solar PV panels directly block solar radiation onto the underlying plants, reducing evapotranspiration rates and by extension, water use. Additionally, the panels shield the plants from wind, further reducing evapotranspiration. At the same time, reduced solar PV temperatures increase efficiency and life span of the panels. Within

these synergies, there is a need to better understand the effect of solar PV shadows on green roof evapotranspiration rates, in order to increase the ecological efficiency of green roof systems.

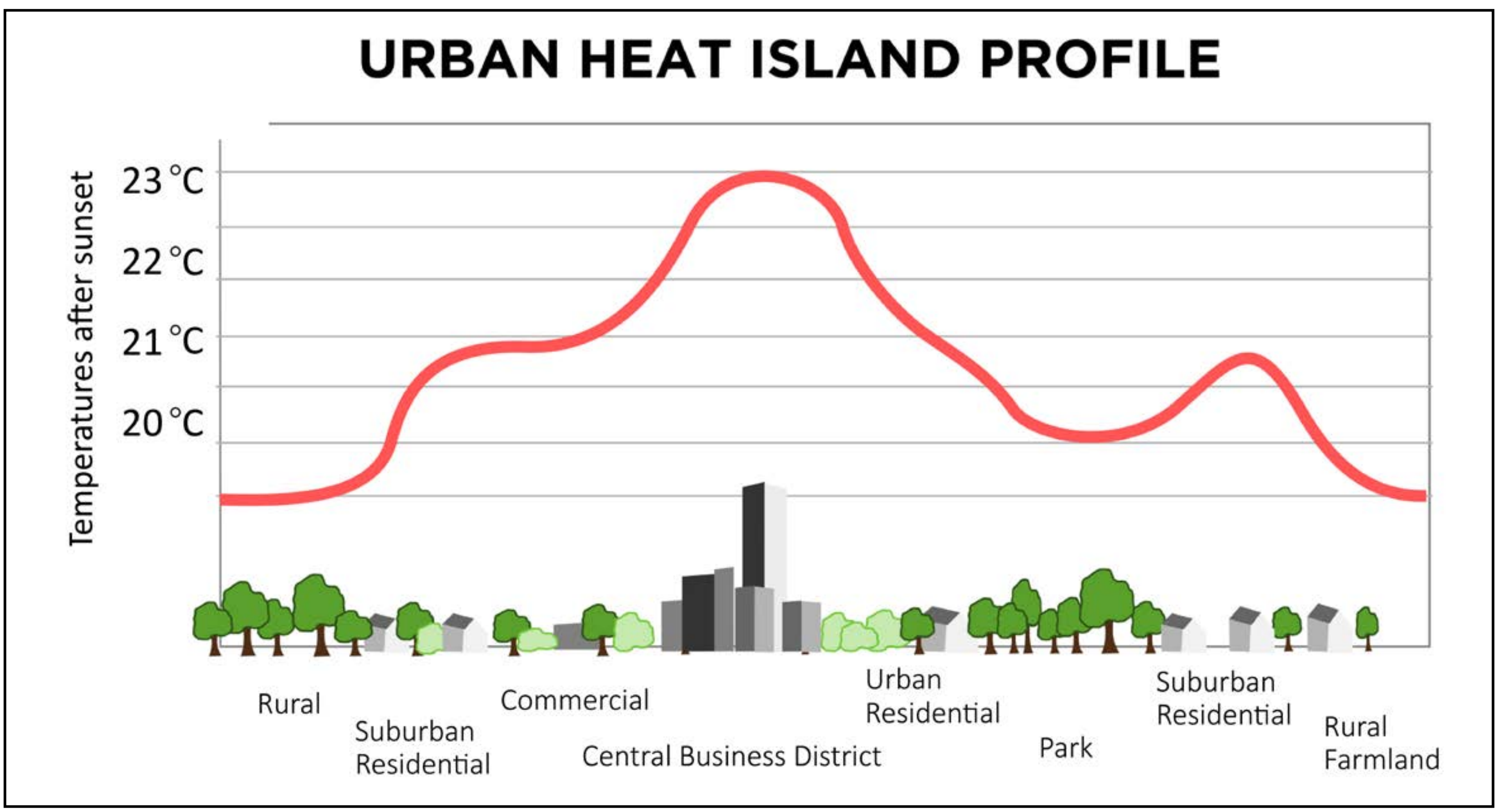
- Bousselot et al. (2017) studied plant growth and coverage in Denver, Colorado, comparing exposed locations with locations protected by solar PV panels. They found that average summer temperatures in the protected locations were lower, with higher performing plants and greater coverage. The authors hypothesized that shading from solar PV panels may produce effects that resemble natural ecotones, tending towards greater plant coverage and biomass, and therefore greater green roof resilience.
- A study by Hui and Chan (2011), modelled performance of a rooftop PV array along with that of an integrated green roof-PV array on a low-rise commercial building in Hong Kong, and found that the green roof PV array generated 8.7% more electricity than the PV array alone. They carried this into an experiment on a sunny summer day from 11 am to 2 pm, and found that the green roof-PV array generated 4.3% more electricity than the PV array alone.
- A test by Chemisana and Lamnatou (2014) in Lleida, Spain, found that solar PV panels mounted on a bed of *Sedum clavatum* increased the maximum power output of the solar PV panels by 3.33%, compared to a gravel mounted solar PV installation.

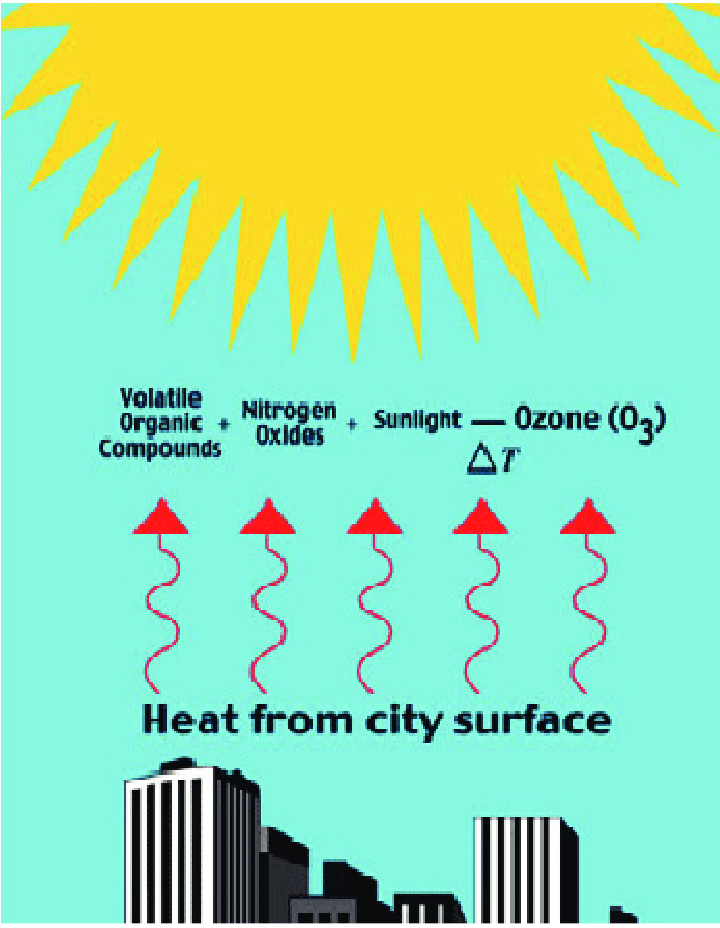
# 5. Urban Heat Island Reduction

Urbanization has replaced large areas of natural landscape with artificial structures and surfaces, altering near-surface climate and causing air temperatures to rise. This phenomenon, referred to as the urban heat island (UHI) effect, occurs because building materials commonly used in urban areas, such as concrete and asphalt, have significantly different thermal and surface radiative properties than natural landscapes. Materials such as waterproofing, asphalt, and concrete absorb energy from the sun and convert it to sensible heat (Peck and Richie, 2009; Wong, 2005). Reduced evapotranspiration because of less vegetation, combined with waste heat from buildings, cars, and industrial activities, can contribute to the UHI effect. On some days, the temperatures in dense urban areas can be as much as 12 ˚C (22 ˚F) higher than in surrounding rural areas (Oke, 1987).

There are several negative effects caused by the UHI effect, including:

- Increased energy consumption – a 1 ˚C increase in summer air temperature increase has been correlated





*The UHI effect contributes to the formation of ground level ozone, a significant hazard to human and vegetation health. Image: Sun Yaguang (CC BY-NC-ND 3.0)*

with a 4% increase in peak demand load for air conditioning (Bass et al, 2003). Air conditioner use also creates waste heat that further increases urban air temperatures. Additionally, increased summer peak loads cause problems for power utilities, requiring the construction and upkeep of expensive peak power plants that only operate a few days a year.

- Increased air pollution – Elevated temperatures caused by the UHI effect promote chemical reactions where volatile organic compounds, nitrous oxides, and other industrial pollutants mix to form ground level ozone. These conditions dramatically degrade air quality and also damage vegetation (Peck and Richie, 2009).
- Health impacts - Air pollution has a host of negative health impacts, including respiratory problems like asthma, as well as cardiac irritability. Greater instances of extreme heat also mean increased levels of heat stress and other heat-related illnesses. In the United States, more than 1,300 people die on average every year due to extreme heat (Sarofim et al., 2016).
- Ecosystem impacts – Increased heat and air pollution can damage vegetation by affecting photosynthesis and fruit/seed production. Extreme heat can also stress plants and animals and reduce their ability to survive and thrive in the urban environment (Peck and Richie, 2009).
- Economic impacts - In addition to increased costs of energy, healthcare, water, and transportation, more extreme heat negatively affects tourism and related activities as many residents leave urban areas to avoid excessive heat (Peck and Richie, 2009).
- Increased water use – More water is needed to support stressed vegetation. Increased energy generation due to increased demand also requires more water to operate more power plants (Peck and Richie, 2009).

Green roofs, along with green walls, trees, and other greenery, are clearly an important tool in an overall strategy to reduce UHI. The UHI effect is caused by an alteration of land from natural to artificial surfaces; green roofs help to reverse that phenomenon by returning vegetated surfaces to the urban environment, especially in constrained areas with limited at-grade space for trees or other vegetated surfaces. Forward thinking planners envision cities in which stormwater and greywater are captured and retained to help reduce the UHI effect.

## Research Highlights

- In 1998, the UHI Pilot Project conducted by the EPA used flyovers to measure surface temperatures and identify hotspots in five cities. They found that rooftops were the hottest spots, with temperatures of up to 71 ˚C (160 ˚F). Conversely, the coolest areas were water bodies or vegetated areas, with temperatures of 24-35 ˚C (75-95 ˚F). Because most roofs are dark (i.e. have a low albedo), they reflect very little solar energy, and therefore heat rapidly. Cool roofs (also known as white or reflective roofs) help to reduce the UHI effect because they have a higher albedo, absorbing significantly less of the sun's energy (Peck and Richie, 2009).
- While green roofs generally have a higher albedo than conventional dark roofs (but not cool roofs), they also use other methods of heat transfer and dispersal to mitigate UHI that cool roofs do not (evapotranspiration, increased convection, solar shading, increased thermal mass). (Bass et al, 2003; Scherba et al, 2011; Wark, 2011).
- A 2006 report prepared for the New York State Energy

Research and Development Authority by the Columbia Center for Climate Systems Research explored opportunities to reduce New York City's UHI. The study utilized a regional climate model in combination with observed meteorological satellite and GIS data to determine the impact of urban forestry, green roof, and light-colored surfaces on UHI. During the summer months, the daily minimum surface and near-surface air temperature in the city was 4 ˚C (7 ˚F) warmer than that in the surrounding rural and suburban areas. The results indicated that vegetation rather than surface albedo alone or other features of the urban physical geography, such as road density, was crucial in determining the urban heat potential (See Figure 5a). The report concluded that a combined strategy of implementing green roofs and maximizing the amount of vegetation in New York by planting trees along streets and in open areas offers more potential cooling than any one strategy (Rosenzweig et al., 2006).

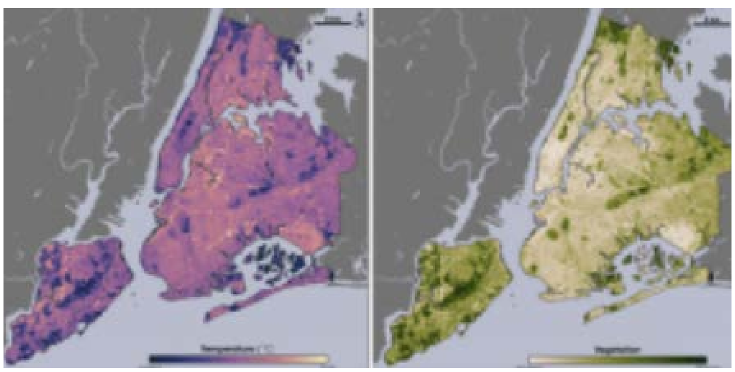


*Figure 5a: Surface temperature (left) and vegetation density (right) are strongly related, and Rosenzweig et al. found that green roofs and other vegetation offers high potential to cool the city. Image: NASA*

- Similarly, a study by Bass et al. (2003) used a regional simulation model using 50% green roof coverage distributed evenly throughout Toronto. The authors found that the impact was significant – reducing temperatures by as much as 2 ˚C (3.6 ˚F) in some areas. Scherba et al (2011), modeled roofs in six U.S. cities; they compared black, white, and green roofs with and without solar PV panels. They found that white roofs performed slightly better at reducing heat flux into the urban environment, and both white and green roofs vastly outperformed black roofs. However, the authors only studied sensible heat flux, and did not take latent heat flux (evaporation), which is an important mechanism for green roof cooling, into account. In fact, Sailor (1994) concluded that low latent heat flux due to lack of vegetation in urban areas is the single most significant contributing factor to the UHI phenomenon.
- Cities like New York, Toronto, Chicago and Washington, DC have made urban greening, including the use of green roofs, a central part of aggressive efforts to combat UHI. New York has a property tax abatement program as well as a green infrastructure grant program; Toronto has a green roof requirement on all new large commercial, institutional, or residential buildings as well as an incentive program for existing buildings; Chicago uses density bonuses and an expedited building permit system; Washington DC has an incentive program, green area ratio, and stormwater credit trading system (Green Roofs for Healthy Cities, 2019).
- Stuttgart, Germany, has taken a slightly different, forward thinking approach. The city is located in a valley characterized by low wind speeds and weak air circulation, leading to significant urban microclimatic effects, including UHI. Besides encouraging green roofs and walls, the city has created linear green spaces as ventilation passages and induction corridors to support air exchange. These corridors are selected based on detailed study of urban climatology and help promote the transport of cool, fresh air from the hillsides surrounding the city (Hebbert and Webb, 2011). While it may be unfeasible to create natural corridors in already developed cities, there are lessons to be learned from Stuttgart. Cities could designate green corridors along prevailing winds, where encouraging and incentivizing the use of living architecture could have impacts on the urban climate and microclimate. Creating a series of connected living architecture projects can have the added benefit of encouraging urban biodiversity and creating habitat corridors (Rosenzweig, 2003).
- It is difficult to separate the influence of green roofs on the UHI effect from their influence on building energy conservation, because they are strongly linked. Additionally, green roofs use the same mechanisms of heat transfer and dispersal to reduce both UHI and energy use. However, studies have attempted to examine the connection. A modeling study by Alexandri and Jones (2008) found that using green roofs and green façades to green 'urban canyons' in dense urban areas lowers ambient air temperatures, reduces UHI and reduces the energy required for air conditioning in the summer.

- A study by Akbari et al. (2001) found that implementing strategies to reverse the UHI effect in major U.S. cities could reduce air conditioning energy use by about 20%, with the resulting savings estimated to be $10 billion per year1. Similarly, an unpublished Environment Canada study focused on Toronto found that the energy demand associated with 1 °C (1.8 °F) temperature increase in the summer is equivalent to 3.8% of total demand (Liu, 2006). Cooling the entire city is an energy demand management strategy that has yet to be widely implemented, but holds significant promise.

# 6. Carbon Sequestration And Avoided Emissions

Carbon sequestration is the process of capture and long-term storage of atmospheric carbon dioxide. The process of photosynthesis captures carbon dioxide from the atmosphere and stores it in plant biomass. Some of this carbon is transferred to the growing media via plant litter and exudates (Getter et al., 2009). Green roofs and walls can take advantage of photosynthesis to capture and sequester carbon from the atmosphere, in both plants and growing media.

Additionally, by reducing energy both directly (by reducing heating and cooling energy required by moderating heat flux through a building envelope) and indirectly (by reducing the UHI). Researchers have attempted to quantify these, especially the former. Designers can calculate the avoided emissions associated with a green roof if they have access to a building energy model (for new projects) or utility records (for existing green roofs), as well as the emissions intensity of their grid.

### Research Highlights

- Getter et al. (2009) found that extensive green roofs have the potential to sequester a small, but still significant amount of carbon; the entire system of sedum-based roof studied (above and below-ground plant biomass as well as growing medium organic matter) sequestered an average of 375 g C/m2 (1.2 oz/ft2).
- Kuronuma et. al (2018) attempted to calculate the carbon payback of modular extensive green roofs. They found CO2 emissions related to production and maintenance to be 25.2 kg/m2 and 0.33/kg/m2/year, respectively. They also found that the annual CO2 sequestration of three irrigated grass species to be about 2.5/kg/m2/year, while the avoided emissions from reduced building energy consumption added up to another 1.703-1.889/kg/m2/year. This led to a carbon payback period of between 5.8 and 15.9 years, indicating that the modular extensive green roofs studied contributed to carbon reduction over their lifespans. Using green roof materials that are less carbon intensive, plants that sequester more carbon, and/or approaches that maximize building energy use could reduce this payback period.
- Luo et al. (2015), who studied test plots in Chengdu, China, explored an innovative approach. They found that a 1:1 mix of sewage sludge and growing media sequestered significantly more carbon than growing media alone. The researchers theorize that this may be due to the increased organic content and water retention provided by the mixed sewage sludge soil. This study suggests that using sewage sludge as a growing medium addition can improve carbon sequestration on green roofs, as well as reducing growing media costs, and providing an efficient way to utilize sewage sludge. However, it is important to approach this strategy with care, since it may lead to nutrient leaching and other adverse impacts to stormwater runoff quality that have not been studied.
- While it is possible to sequester carbon in living architecture, it is important to consider the life-cycle impacts of living architecture components (growing media, membranes, support systems, etc.). The manufacture of these components incurs a 'carbon debt', and sequestration in plants and growing media may take several years to offset this debt (Getter et al., 2009).
- Because green roof plants are generally selected for their hardiness and resource efficiency, selecting plants that produce larger amounts of biomass when resources are available can maximize carbon sequestration. Whittinghill et al. (2014) suggest using a deeper growing medium and more complex plant communities to maximize the carbon sequestration potential of green roofs.
- Living architecture's potential for carbon sequestration is still a largely unexplored area of research, and further exploration should be conducted. Pyrolysis - or the process of heating biomass (like plant waste) to high temperatures in oxygen-starved environments creates biochar, a carbon-rich soil amendment. Cao et al. (2013) found that biochar amendments not

only increase the carbon content of green roof growing media, but also increases water holding capacity without increasing substrate weight loading, as well as increases plant available water. They found that the use of biochar also reduced growing media weight and improved plant available water; potentially expanding plant selection in dry climates and improving their stormwater retention capabilities.

# 7. Secondary And Tertiary Energy Benefits

There are several secondary and tertiary energy benefits associated with living architecture that are out of the scope of this paper, but should be noted:

- The treatment of stormwater and wastewater is an energy intensive process; using living architecture as part of a low-impact approach to managing stormwater reduces this energy requirement (Mittal and Gaffigan, 2011). Similarly, using living architecture to help treat and reuse greywater reduces the energy used to treat wastewater off-site.
- Living architecture offers building materials additional protection from the elements (UV rays, wind, excessive moisture, thermal flux). Many of these building materials are hydrocarbon-based (asphalt, bitumen, PVC, TPO, etc), or contain significant amounts of embodied energy (concrete, steel). Living architecture can replace these materials or increase their lifespan, reducing the life cycle energy costs associated with them (Wark, 2011).

# 8. Conclusion

Green roofs (and other forms of living architecture like green façades and living walls) offer significant potential to provide energy and climate benefits to both building owners and the community. With knowledge of the factors that contribute to increased performance, designers, and other green roof professionals can help building owners and investors reduce energy consumption and improve the output of rooftop solar PV panels. At the same time, a holistic approach to encouraging and incentivizing green roofs can provide community-scale benefits like a reduction in the UHI effect, and even global-scale benefits like carbon sequestration and avoided emissions.

Understanding the mechanisms through which green roofs moderate heat flux through a building envelope, as well as the design, building, and climatic variables that influence performance are essential to unlocking and maximizing their energy and climate benefits.

*The green roof on the Bridgepoint Active Healthcare building in Toronto, ON reduces energy consumption, while also providing space for therapy and education. 2016 Award Winner: Diamond Schmitt Architects.*

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