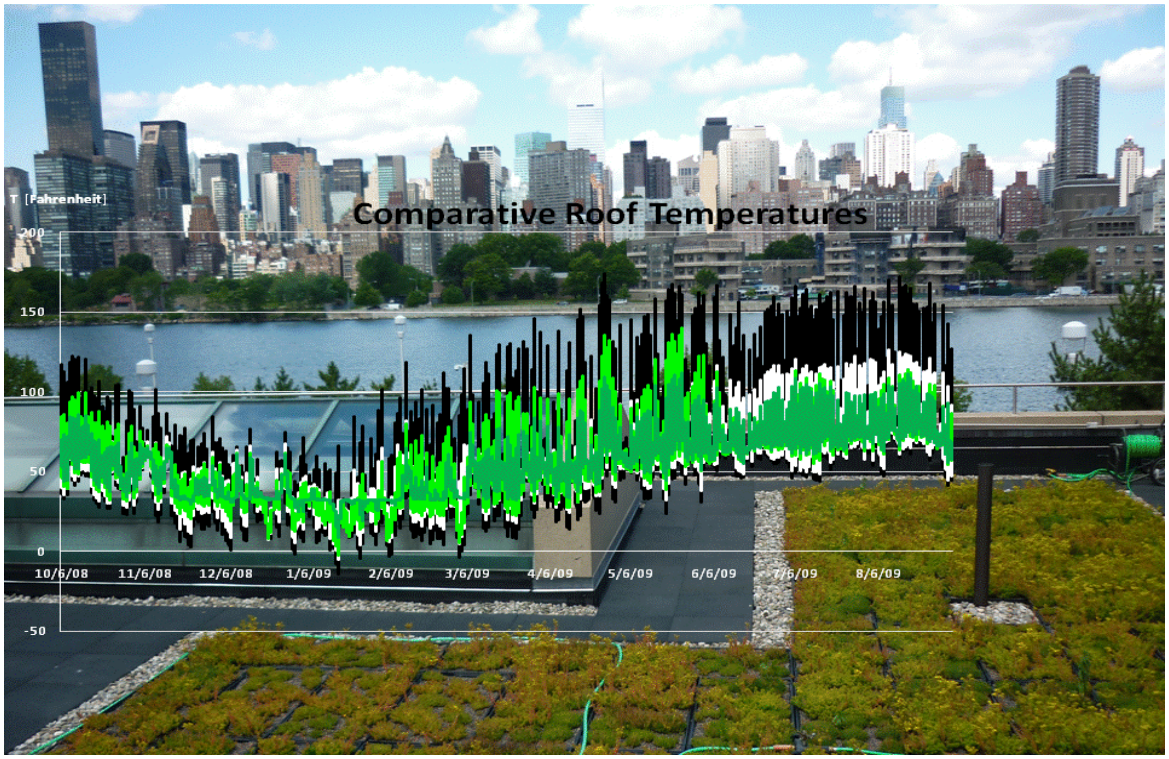
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

A Temperature and Seasonal Energy Analysis of Green, White, and Black Roofs



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SUMMARY OF KEY FINDINGS

There is growing public awareness of the role that low-reflectance (e.g., dark), impervious surfaces play in generating excess urban heat and stormwater runoff, and attention is turning to alternative systems that mitigate these effects and provide other benefits. We have analyzed temperature data collected from three different roof surface treatments at the Con Edison "Learning Center" (TLC) in Long Island City (LIC), Queens, New York. The three test roofs include (1) a green roof (4-inch depth modular sedum system),[1] (2) a nearly black Ethylene-Propylene-Diene-Monomer (EPDM) membrane, and (3) a high-reflectance white EPDM membrane. From the first year of temperature data we report the following key findings.

- The Con Edison LIC area is showing a relatively strong urban heat island signal that correlates with low vegetation abundance in the area.
- The black roof daily temperature extremes are extraordinary in all seasons. However *average* seasonal black roof temperatures are still within 10.8°F (6°C) of either the green or white roofs.
- White roof membrane temperature peaks are on average 30°F (17°C) cooler than black in summer. Green roof membrane temperature peaks are on average 60°F (33°C) cooler than black in summer. **These peak reductions support claims for prolonged roof service life on white and green roofs.**
- With respect to direct atmospheric heating and urban heat island mitigation, the new white and green roofs are performing comparably. The data suggest that the young green roof is also improving its temperature control relative to the white surface.
- **The white roof surface is not showing any "winter heat penalty" relative to the black roof.**
- **The average winter heat loss rate on the green roof (-4.16 W/m^2) was 34% lower than under the black roof (-6.5 W/m^2). The summer heat gain rate on the green roof (+0.41 W/m^2) was 84% lower than under the black roof (+2.57 W/m^2).**
- **These building energy heat flow reductions refer only to the vertical heat flow through the roof insulation layers and not to any other building heat flows or energy requirements.**
- Although the percentage heat flow reductions on the green roof are significant, the realized energy savings are still modest. We estimate that the 1,000 m^2 (10,764 sq ft) green roof on the Con Ed building is saving roughly $400/yr in heating costs and $250/yr in cooling costs. If this area had been a white roof instead, we estimate that cooling savings would have been $200/yr.
- **Energy savings are low because the annual energy costs of the "worst case" black roof itself are low owing to a combination of factors: (1) Despite extreme temperature highs and lows on black roofs, the *average* seasonal temperatures are more moderate; (2) the roof is underlaid with thermally effective insulation board; and (3) fossil fuel energy costs are low, and cooling and heating efficiencies are improving.**

[1] Weston Solutions, GreenGrid System: http://www.greengridroofs.com/greenroofs.htm

- **We estimate an equivalent R-value for the green and white roofs of ≅100 and ≅50, respectively, during the warm months and ≅7 and ≅0, respectively, during the cold months.**
- **The TLC roofs are brand new. We expect there will be significant changes in the green and white roof temperature performance as the biomass fills in and the white roof darkens and loses reflectivity. A second year of analysis is recommended to confirm the first year's findings and also to give a sense of the aging changes.**
- **There are other benefits and environmental services performed by green roofs that have no counterparts from impervious roofs. These include: water runoff control, water quality improvements, direct air quality improvements, urban biodiversity, noise reduction, and building amenity value, including to urban residences overlooking the green roofs. With respect to heat island mitigation, green roofs do work—they maintain surface temperatures as low, or lower than, white roofs.**
- **White roofs, however, have a unique role to play in increasing urban albedo[2]. They can be viewed as a noncontroversial form of "geo-engineering." Considering the potential land area worldwide of human dwellings with roofs, maximizing high-albedo roofing as well as green roofing should become an urgent priority.**

Introduction

It has long been recognized that New York City has a vast roofscape that serves little productive use other than providing waterproof building façades. A cursory *New York Times* archive search shows that since at least 1940, the newspaper has regularly reported new trends that suggest New Yorkers are beginning to turn these neglected spaces into something virtuous and useful.[3] Still, 70 years on, the urban rooftop environment remains largely unchanged. New York City has more than 30 square miles (77.7 km^2) (more than 22 times the area of Central Park) of roof space that qualifies for the most part as "tar beaches."

But now—although history may repeat itself—it really does look like this impasse in intelligent urban design use is going to change. One example is the mayor's new white roofing program that will begin in earnest this year.[4] Another example is the undeniable interest in green roofs that seems to be growing exponentially.[5]

If a widespread transformation does take place, the spur will arguably have been the specter of global climate change and the ongoing growth in worldwide urban population. These trends mean that we can no longer treat cities as places devoid or removed from nature and insulated from the environment. This new perspective has raised concern for the physical properties of traditional roofs that have been obvious all along—not only are they

[2] Albedo is the fraction of incoming sunlight reflected by a surface.

[3] "Country Life on City Roofs," *New York Times*, August 18, 1940; "Tides of Change Alter the Look of the Tar Beach," *New York Times*, August 15, 1973; "Rooftop Crops," *New York Times*, May 18, 1980.

[4] "Bloomberg Hypes Energy-Efficient Rooftop Painting," *New York Post*, Sept. 24, 2009, http://www.nypost.com/p/news/local/bloomberg_hypes_energy_efficient_w4c1QCjsR3n0qctCJQaFHL.

[5] See for example: Green Roofs for Healthy Cities, www.greenroofs.org.

unproductive, they are environmentally harmful. As extremely efficient collection surfaces for sunlight and for rainfall, they are a leading contributor to both the urban heat island (UHI) and combined sewage overflow (CSO) problems that plague urban areas worldwide.

The Con Edison "Learning Center" Roof Project

The Con Edison TLC roofing project comes, therefore, at a propitious time for New York City. As the discussion over how best to transform the urban roofscape progresses, at least two fundamental environmental alternatives to the standard roof have emerged: (1) high-reflectance (i.e., white) roofs and (2) green, living roofs of plants. The TLC roof has all three treatments: black, white, and green. Moreover, the roof has been instrumented to collect temperature, heat flow, moisture, rainfall, and other key metrics, and thus offers a unique opportunity to compare and contrast the various treatments.

There are many environmental claims being made for all types of roofing systems, generating a number of potential "urban legends." The overriding goal of this project is to sort through the various claims using rigorous data and analysis to either support or refute the various statements. This is the only way to inform policy and cost-benefit analysis for such urban environmental initiatives.

In this report we analyze the basic temperature and heat flow data that are being collected on all three rooftop surfaces: (1) black, (2) white, and (3) green. A follow-on report will deal with the water retention performance.

Instrumentation

The rooftop monitoring equipment was selected and installed under the supervision of the Principal Investigator (PI) in September to early October 2008. All sensors are operational and are recording data as planned. The data are being securely logged on a computer that is located inside the access room to the roof. The PI periodically visits the roof to download the data for analysis at Columbia University. **Figures 1–3** show the roofs and sensor deployment.

Figure 1: Photograph of the green roof modular system after one year showing above-grade monitoring stands

The modular green roof system shown in **Figure 1** is from GreenGrid.[6] In the picture, there are two sensor stands holding above-grade monitoring equipment. The stand on the left holds an "allwave" radiometer that measures the net flux of radiant energy (net shortwave plus net longwave) absorbed by the roof. These data are fundamental to the energy balance of the roof. The stand on the right is holding standard weather station sensors, including ambient air temperature, relative humidity, and wind speed and direction sensors.

[6] greengridroofs.com/greenroofs.htm.

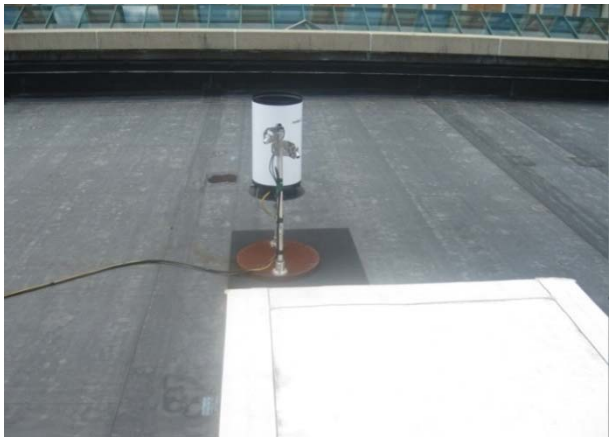

Figure 2: Photograph of control roof sensors

Figure 2 shows the control roof surfaces and equipment. The white "bucket"-shaped device is the rain gauge. The two small "cigar"-shaped devices (visible against the rain gauge background) pointing toward the white and black roofs are infrared radiometers that measure surface temperatures. The white and black control roofs are made of EPDM. This is a rubber membrane that has good resistance to ultraviolet radiation, hail, and extreme cyclic temperature breakdown. The white membrane has an initial clean rated reflectance of around 80%, meaning 80% of incident sunlight is reflected from the surface, lowering daytime temperatures correspondingly.

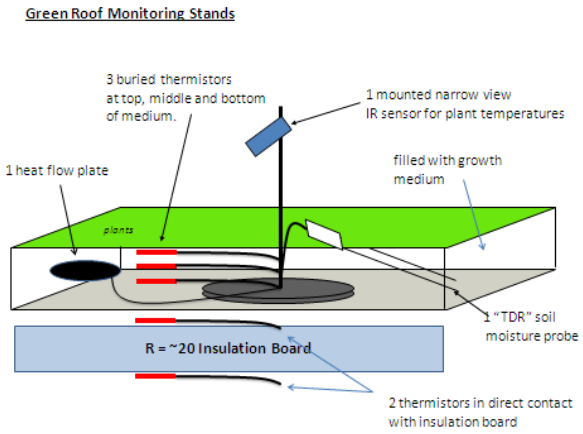

Figure 3: Green roof monitoring equipment above and below grade

Figure 3 depicts the below-grade instrumentation on the TLC green roof that is not visible in **Figure 1**. Two sets of this instrumentation have been installed—one set in the northern (sunny) area of the green roof and a second replication in the southern (partially shaded) section of the green roof. In each case, two thermistors were strategically placed above and below the insulation board (R≅20) and offer a precise estimate of the temperature gradients and thus heat flows through the board and into or out of the building envelope.

Surface Energy Balance and Roof Heat Flows

The placement of thermistors above and below the insulation board (**Figure 3**) supplies direct data for quantifying seasonal building energy savings, as it avoids the complex processes of energy flow within the green roof layers and gets directly to the temperature gradient driving heat into and out of the building. The temperature and moisture data being collected within the green roof layer will, however, be important for understanding the water retention and evapo-transpiration processes within the green roof layers.

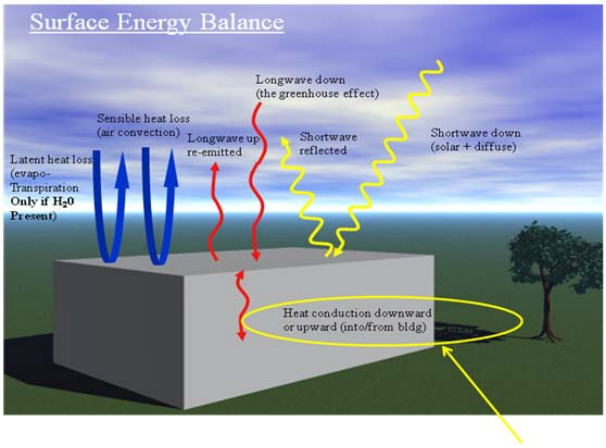

Figure 4: General surface energy balance for a rooftop

Figure 4 shows the general surface energy balance valid for a rooftop, or for any other surface object. The seven fluxes illustrated are basic radiation, mass, and heat flow

processes occurring everywhere at Earth's surface.[7] The heat conduction vector depicted and circled corresponds to the "energy savings" that may accrue from a particular roof surface treatment such as green or white roofs, which act to reduce this heat flow. A central finding of this report is our estimate for this heat flow for both the winter and summer seasons under the three different roof surfaces: green, white, and black.

There are other ways in which rooftop temperatures will affect building energy consumption, such as through rooftop air intake systems, which are quite common in New York and also present on the Con Edison roof. The present monitoring equipment does not yet have sensors that allow quantification of this effect.

Discussion of Key Findings

Long Island City Urban Heat Island Strength

The weather station on the TLC roof (**Figure 1**) has allowed us to compare the "urban heat island" intensity in LIC with other comparable weather stations we have around the NYC metropolitan region. A graph of the hourly average temperatures of these four stations is shown in **Figure 5**. Among the four such stations we have installed currently in our network, the TLC/LIC station is showing the second strongest nocturnal heat island strength. In general, heat island strength is most clearly revealed by nocturnal temperatures.[8]

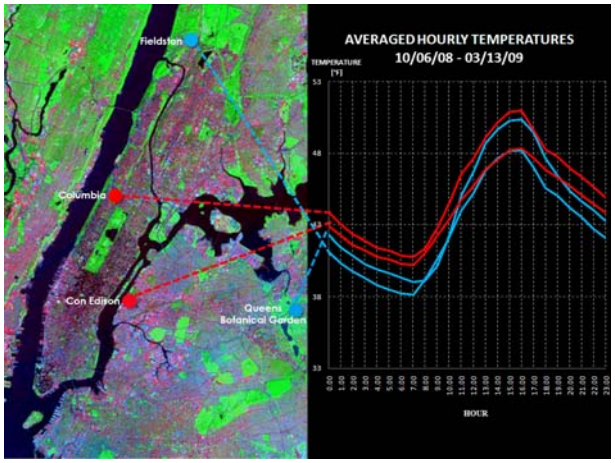

Figure 5: NYC vegetation map and average hourly temperature data at green roof weather stations

The map on the left side of **Figure 5** shows local vegetation abundance in green. It was generated by Dr. Chris Small of Columbia University using various sources of remote sensing data.[9] The correlation between the relative temperatures at these four sites and vegetation abundance is striking—the two cooler sites are occurring in areas of the city with abundant green space and vegetation. Fieldston is located in Riverdale, near the large Van Cortlandt Park area. Queens Botanical Garden is similarly proximal to a large green space and park areas. In contrast, the TLC and Columbia sites have low vegetation abundance. Thus the Con Edison TLC data, in conjunction with our other station data, suggest that urban vegetation can significantly offset the urban heat island, with attendant benefits on energy consumption. There are, however, other cofactors that may be correlating with the vegetation and playing a role in the relative cooling, such as less dense urban building areas and less vehicular traffic.

[7] T. Oke, *Boundary Layer Climates*, 2nd ed. (New York: Routledge Press, 1986).

[8] S. R. Gaffin et al., "Variations in New York City's Urban Heat Island Strength over Time and Space," *Theoretical and Applied Climatology* 94 (2008): 1–11.

[9] C. Small (2009), Vegetation Mapping, http://www.ldeo.columbia.edu/~small/NYCveg.html.. Map reprinted here with permission of C. Small.

We are currently performing the same calculations for the summer season and will also be using other vegetation abundance indices to correlate with the temperature data.

Comparative Black-White-Green Membrane Temperatures

Figure 6 shows the comparative "membrane" temperatures for the three respective roof treatments. Membrane temperature refers to the contact temperature of the waterproof membrane in each case. For the white and black roofs, this is simply the surface temperature of the EPDM membrane exposed to the atmosphere. For the green roof, this is the temperature below the tray system containing the medium and plants.

Many interesting features are worth noting from this graph. The peak noontime membrane temperature reductions on the white and green roofs compared to the black roof are dramatic. The black membrane reached a peak temperature of 176°F (80°C). During the summer season, the peak white membrane temperature was on average 30°F (17°C) cooler than the black. The peak green membrane temperature was on average 60°F (33°C) cooler than the black.

A surprising finding is how cold the black and white membrane temperatures became at night—well below ambient atmospheric air temperatures. This must be owing to a combination of efficient longwave radiative and convective cooling on these smooth exposed surfaces. Longwave radiative cooling is depicted by the upward red line in **Figure 4,** and convective cooling is depicted by the blue circular arrow directly to the left of it. There is generally no standing water on the control roofs, so latent heat cooling does not occur on them, while it does on the green roof. During the winter, the black membrane approached temperatures below -4°F (-20°C). The green membrane, by contrast, since it is not as directly exposed to the atmosphere, maintained a "comfortable" temperature above freezing during the winter.

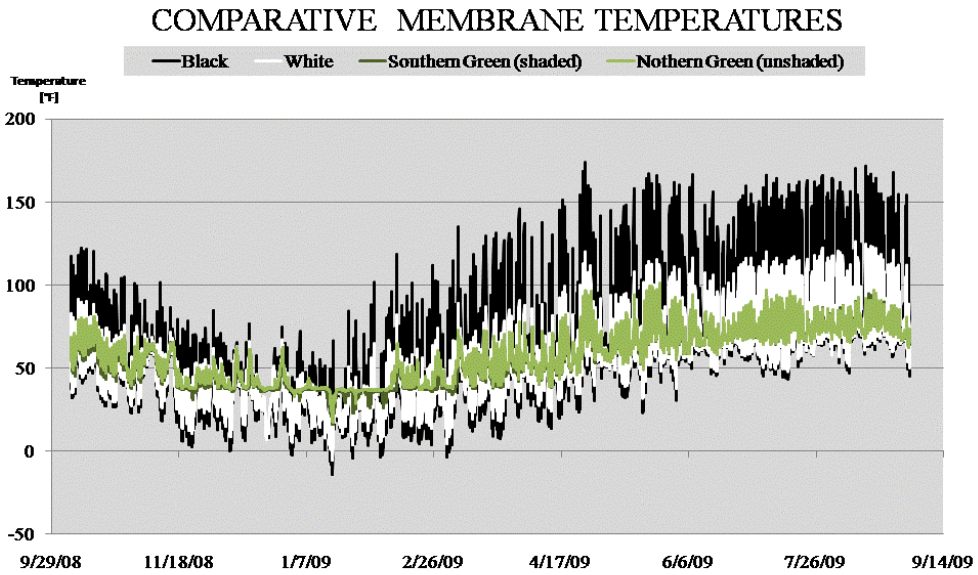

Figure 6 Comparative membrane temperatures for black, white and green roofs

These temperature cycle amplitude differences have clear implications for membrane durability. The black membrane is undergoing enormous temperature swings, owing to both the extreme peak temperatures and extreme low nighttime temperatures. These cycles imply membrane expansions and contractions that are a major cause of rooftop deterioration over time. The white membrane has a reduced amplitude that will likely lead to membrane service life improvement over time. However, the green membrane clearly has the smallest amplitude cycle by far, and this supports the contention that green roofs will outlast other roof systems, perhaps by a factor of 2 to 3 or more.

Rooftop Urban Heat Island Mitigation: Green versus White Roofs

Urban heat island mitigation refers to the ability to reduce extreme air temperature heat sources in cities.[10] Dark rooftops are clearly one of the most ubiquitous such heat sources in urban areas worldwide. Two fundamental strategies exist to counter such heat: (1) raise the solar reflectivity of the surface (usually in the visible spectrum, but increasing reflectivity in other spectral regions, such as near-infrared, may be equally effective); and (2) create latent heat loss on the roof by making moisture available, most effectively with green roofs.

The reflectivity of any surface is more commonly called "albedo" in climate science. Dark roofs typically have a low albedo, such as 5%, meaning 95% of incident solar radiation is absorbed by the roof and transformed into heat energy. White roofs usually have rated albedos in the 75%–80% range, meaning only 20%–25% of incident solar radiation is absorbed. According to the white roof sample manufacturer, the Carlisle White EPDM Membrane has an initial albedo of >80%. We are currently in the process of testing this albedo using an outdoor albedometer at Columbia University.

With respect to UHI mitigation, an important question is how do green roof surface temperatures (i.e., the plant leaf surface temperatures) compare to white roof surface temperatures? A graph of the comparative surface temperatures of the green versus white roofs on the Con Edison TLC roof is shown in **Figure 7**.

The white roof data in **Figure 7** are identical to those in **Figure 6**, while the green roof data in **Figure 7** are different from those in **Figure 6**. In this case, it is the sedum plant leaf temperatures that are being shown, because this is the temperature directly exposed to the atmosphere.

[10] C. Rosenzweig et al., "Mitigating New York City's Heat Island: Integrating Stakeholder Perspectives and Scientific Evaluation," *Bulletin of the American Meteorological Society* 90 (9) (2009): 1297–1312.

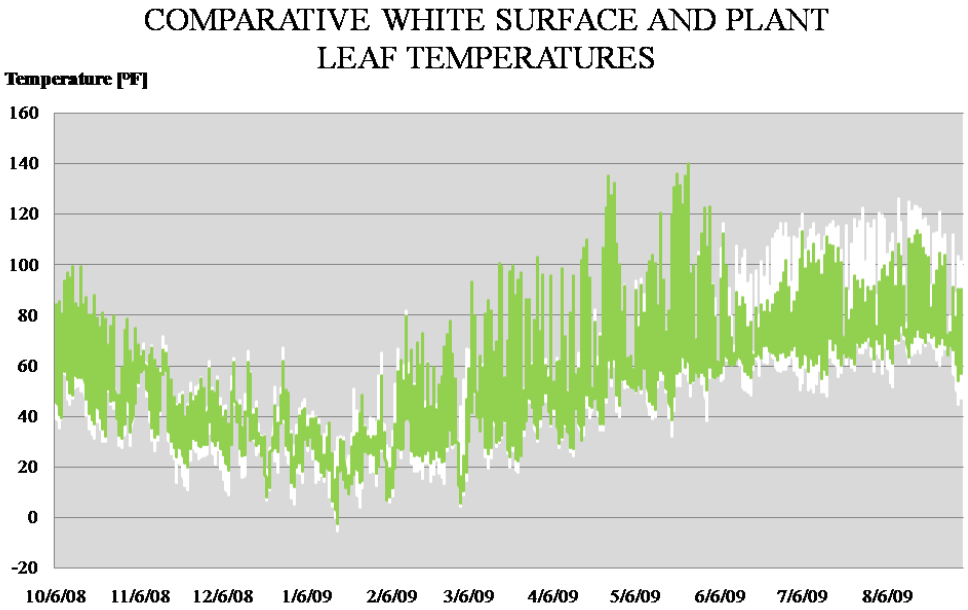

Figure 7: Comparative white and sedum plant leaf temperatures

It is important to note that the white and green roofs are achieving temperature reductions largely through two fundamentally different strategies: white roofs are reflecting most of the sunlight, whereas green roofs—although more reflective than black—are transforming the absorbed sunlight into water vapor through evapo-transpiration, also called "latent heat loss." Green roofs do have a significantly higher albedo than black roofs. We have measured them as having an approximately 20% albedo.[11] But this accounts for a smaller fraction of the cooling as compared to latent heat loss, which is an extremely powerful mechanism of heat loss in living systems, including the human body.

An interesting finding is that the white and green roof surface temperatures are fairly close. In other words, green roofs are cooling at least as effectively as the most reflective white roof commercially available. This comparative performance was theoretically predicted by the PI in an earlier analysis.[12] During wet periods, such as the unusually wet spell of June 2009 (**Figure 7**), the green roofs are significantly cooler than the white roofs.

Over time, white roofs will lose reflectivity due to darkening and weathering, especially in sooty urban environments. This loss in reflectivity will increase temperatures. An important research challenge is to determine the rate and extent of such albedo declines without maintenance.

[11] S. R. Gaffin, R., Khanbilvardi, and C. Rosenzweig, "Development of a Green Roof Environmental Monitoring and Meteorological Network in New York City," *Sensors* 9 (2009): 2647–2660; doi:10.3390/s90402647.

[12] S. R. Gaffin, C. Rosenzweig, L., Parshall, D. Beattie, R. Berghage, G., O'Keeffe, and D., Braman, "Energy Balance Modeling Applied to a Comparison of Green and White Roof Cooling Efficiency," in *Proceedings of the 3rd Annual Greening Rooftops for Sustainable Cities Conference*, Washington, D.C., May 4–6, 2005.

Average Seasonal Heat Fluxes for Black, White, and Green Roofs

A key goal of this study is to assess the relative energy benefits of replacing a dark roof, which is a typical membrane, with either a white or green roof. While there may be different approaches to this assessment, we believe the most direct is afforded by the thermistor placement above and below the insulation board, shown in **Figure 3**. Regardless of how the heat energy is being transferred through the various green roof layers, ultimately it is the heat that transfers through the insulation board that enters or leaves the building envelope. Modeling heat flow through a green roof medium is a complex process.[13] By having temperatures above and below the board, we can obviate the need for such complex heat transfer.[14]

We have used the membrane temperature data shown in **Figure 6** along with the below-insulation-board thermistor data under the green roof to model heat flow under the three roof treatments. For the green roof, this is a straightforward process: the temperature difference between the upper and lower thermistors is simply divided by the R-value of the insulation board, which is ≅20. For the white and black roofs, we use the hourly membrane temperatures shown in **Figure 6** and use two models for the lower temperature: (1) the below-insulation-board temperature under the green roof and (2) a fixed lower temperature of 70°F (≅21°C).

These models for the white and black roofs are necessary because we did not have an opportunity to place additional thermistors below the insulation board on those roofs. Nevertheless, we feel that the two models for the lower temperature are probably overestimating the seasonal heat flows under the black and white roofs because the temperatures under the green roof are lower in the summer and higher in the winter. Thus using those temperatures for the black and white roofs should overestimate the temperature gradients in each season. As will be seen next, such an overestimate will not change our conclusion about relatively modest heat flows in all cases.

With these caveats, **Table 1** shows our estimates for the average winter (Dec.–Feb., 2009) heat losses per unit area, in units of Watts/meter^2 (W/m^2), for the three roof types. For the black and white roofs, the two lower boundary temperature models are shown as separate line items ("lower green temp model" and "fixed lower temp model").

The green roof has the lowest heat loss rate and the black roof has the highest heat loss rate for both bottom temperature models. The overall percentage decline from black to green is roughly 37%.

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[13] D. J. Sailor, "A Green Roof Model for Building Energy Simulations," *Energy and Buildings* 40 (2008): 1466–1478.

[14] Modeling actual green roof heat flow is useful, however, for assessing the latent heat (evapo-transpiration) losses and thus the water balance on the roof. This is why the green roof embedded sensors (heat flux plate, soil moisture, etc.) were included in the monitoring installation (**Figure 3**).

WINTER (DJF) AVERAGE HEAT LOSS UNDER TLC ROOF TREATMENTS	Avg Heat Flux Loss (W/m^2)
Northern Green (unshaded)	-4.16
Southern Green (shaded)	-5.21
White Roof ("lower green temp model")	-5.73
Black Roof ("lower green temp model")	-5.90
White Roof ("fixed lower temp model")	-6.34
Black Roof ("fixed lower temp model")	-6.56

37% reduction in heat loss

Table 1: Winter (Dec.–Feb., 2009) average heat fluxes across R-20 insulation board

Absence of Winter Heat Penalty on White EPDM Membrane

Interestingly, and contrary to expectations, the white roof in winter has about the same loss rate (or even slightly less) than the black roof. This is not expected given the fact that white roofs of similar composition should be cooler than black roofs during the day and, one would assume, the same at night, and therefore cooler overall during the winter. This effect is sometimes referred to as a potential "winter heat penalty" for white roofs. As seen from **Table 1**, we do not find any winter heat penalty for the Con Edison white roof membrane. We traced this paradoxical result to unexpected higher nocturnal temperatures on the white membrane than on the neighboring black membrane during the winter. This can be seen in the data shown in **Figure 6**. It is surprising given the fact that the two membranes are side by side (**Figure 2**) and thus exposed to identical atmospheric conditions.

There are two possible explanations. The first is that there is an intrinsic thermal property difference between the black and white membranes that is manifest at night. This would most likely be an "emissivity" difference. The emissivity coefficient measures how efficiently a body emits thermal radiation at a given temperature (the upward red arrow in **Figure 4**). A perfect emitter has an emissivity of 1. Most organic-based materials have a high emissivity in the 0.9–1.0 range (see note 7). Metals, by contrast, are poor emitters and have low emissivities in the 0.2 range, which makes them good cookware materials. If the white roof has a lower emissivity than the black roof, then at night, with no sunlight and identical atmospheric exposure, the white roof should be warmer than the black membrane. However, the manufacturer has reported the white membrane as having a high thermal emittance of 0.91 using American Society for Testing and Materials (ASTM) protocols.[15]

On September 2, 2009, the PI took an informal emissivity reading at 1:15 p.m. using a combined handheld radiometer and contact temperature probe for both the white and black membranes. We found an emissivity of 0.45–0.5

[15] Carlisle Syntec Incorporated, *Technical Data Bulletin for Sure-White™ Fleeceback® EPDM Membrane,* October 2008.

for the white membrane and an emissivity of 0.94 for the black membrane. This could explain the different temperatures. If correct, then one would want to ascertain what it is about the manufacturing process or pigments that might have led to such an emissivity difference.[16] However, we have found in our fieldwork that such handheld readings are very difficult to make in outdoor settings, and they are very sensitive to small wind and sunlight variations. Given that the manufacturer reports their data from an ASTM protocol, our informal readings should be considered tentative.

The second possibility is that the two membranes were applied differently. The Con Edison project manager has informed us that the white membrane was applied on top of the black membrane, thus it effectively has an additional membrane layer. This, too, could create a thermal difference leading to extra warmth on the white surface. To test this possibility we are recommending that an additional layer be added to the black membrane so they have identical thicknesses, and we will re-examine the data during winter 2010.

Table 2 shows the average summer heat gains for the three roofs. Here again, the green roof has the best thermal performance and the lowest heat gain. Black, as expected, has the highest heat gain, and the white membrane is intermediate. The green roof has reduced the summer heat flow to close to zero, and this represents an 84% reduction as compared to the black roof. It is possible that the improved thermal performance of the green roof in the summer (**Table 2**) compared to the winter (**Table 1**) may be owing to the significant growth of the plants in summer 2009. As noted, during the previous winter, the plants were hardly established and the biomass was very low. This suggests that a second year of data will be helpful.

Seasonal Energy Costs for 1,000 m^2 Black, White, and Green Roofs

We have converted the seasonal heat losses and gains in **Tables 1** and **2** into seasonal energy costs, assuming a 1,000 m^2 roof area, which is roughly the area of the TLC green roof. **Table 3** shows the winter heating costs using standard natural gas and heating oil fuel efficiency and price assumptions.[17] **Table 4** shows the summer cooling costs using standard air-conditioning efficiency and electricity price assumptions.[18]

The easiest way to summarize these tables and their implications is to focus first on the black roof. For the black roof, the combined winter and summer energy costs are less than $1,300 per year or <$1000 (w) + <$300 (s). For a 1,000 m^2 (10,764 sq ft) roof area, this translates into an annual energy cost of less than $1.30/$m^2$, or less than $0.13/sq ft. This is a small annual energy cost. This result is due to a combination of factors: (1) the roof is underlaid with thermally effective R-20 insulation board which, despite extreme temperature peaks and lows, leads to relatively small *average* seasonal heat flows through the roof (less than 7 W/m^2);

[16] It is interesting to consider the possibility that a lower emissivity for the white roof might be desirable if it helps avoid a significant winter heat penalty.

[17] We assumed natural gas and heating oil furnace efficiencies (AFUE) of 65% and 89%, respectively. The energy and cost estimates can be easily adjusted for different efficiencies simply by multiplying the natural gas and oil columns by the ratio: 65 or 89/new efficiency. We assumed natural gas and heating oil prices of 0.2306 kW·h/¢ and 0.1819 kW·h/¢, respectively.

[18] We assumed a cooling efficiency ratio (SEER) of 13 BTU/W·h and electricity price of 0.0556 kW·h/cent.

and (2) the low costs of fossil fuel energy plus improving cooling and heating efficiencies.

SUMMER (JJA) AVERAGE HEAT GAIN UNDER TLC ROOF TREATMENTS	Avg Heat Flux Gain (W/m^2)
Northern Green (unshaded)	+0.41
Southern Green (shaded)	+0.18
White Roof ("lower green temp model")	+0.70
Black Roof ("lower green temp model")	+2.13
White Roof ("fixed lower temp model")	+1.14
Black Roof ("fixed lower temp model")	+2.57

84% reduction in heat gain

Table 2: Summer (Jun.–-Aug., 2009) average heat fluxes across R-20 insulation board

WINTER (DJF) HEAT ENERGY ANALYSIS Heating Energy & Costs for 1000 m^2 Roof	Avg Heat Flux Loss (W/m^2)	Natural Gas (kW·h)	Energy Cost	Heating Oil (kW·h)	Energy Cost
Northern Green (unshaded)	-4.16	13838.45	$600.11	10106.73	$555.62
Southern Green (shaded)	-5.21	17316.53	$750.93	12646.90	$695.27
White Roof ("lower green temp model")	-5.73	19042.85	$825.80	13907.70	$764.58
Black Roof ("lower green temp model")	-5.90	19611.51	$850.50	14323.01	$787.41
White Roof ("fixed lower temp model")	-6.34	21233.31	$920.79	15507.50	$852.53
Black Roof ("fixed lower temp model"	-6.56	21801.97	$945.45	15922.79	$875.34

Heat savings: $330-$350/yr

Table 3: Estimated winter heating costs for 1,000 m^2 black, white, and green roofs

SUMMER (JJA) COOLING ENERGY ANALYSIS Cooling Energy & Costs for 1000 m^2 Roof	Avg Heat Flux Loss (W/m^2)	Cooling Energy ($kW \cdot h$)	Energy Cost
Northern Green (unshaded)	+0.41	234.57	$42.19
Southern Green (shaded)	+0.18	104.55	$18.80
White Roof ("lower green temp model")	+0.70	402.55	$72.40
Black Roof ("lower green temp model")	+2.13	1232.87	$221.74
White Roof ("fixed lower temp model")	+1.14	657.84	$118.32
Black Roof ("fixed lower temp model")	+2.57	1488.16	$267.66

Cooling savings: $225/yr

Table 4: Estimated summer cooling costs for 1,000 m^2 black, white, and green roofs

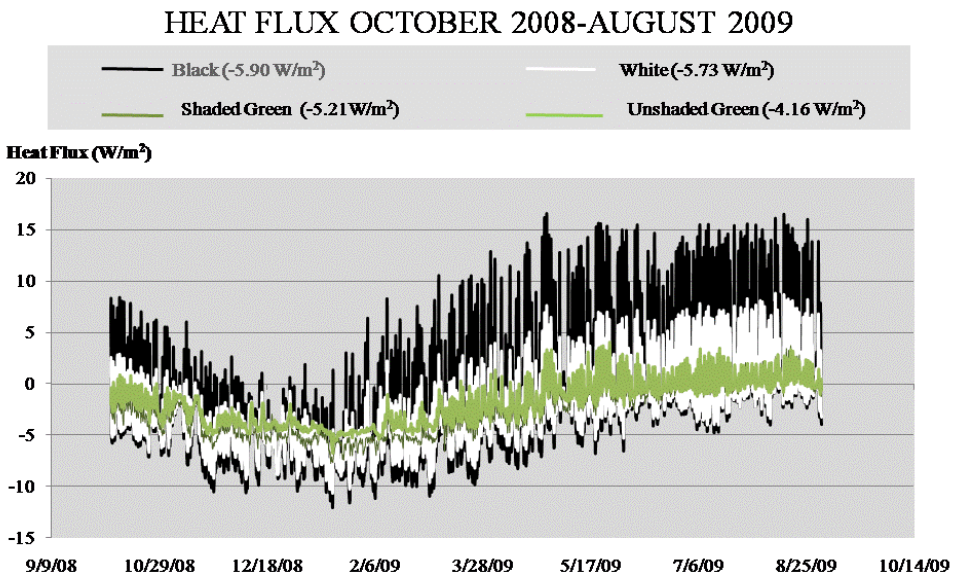

Figure 8: Hourly and annual average heat fluxes across the R-20 insulation layer for the three roof surfaces

Despite the extreme temperature fluctuations on black roofs, mean heat flows are much lower than peak heat flows. To illustrate the last point, **Figure 8** shows the hourly heat flows for each of the roofs. For the black roof, although the daily peak heat losses and gains are quite large, they are short-lived, and the mean seasonal heat flows are much more modest and not drastically different from the white and green surfaces (annual averages are shown in the legends above the hourly data).

ALL HEAT LOSS MONTHS Heating Energy & Costs for 1000 m^2 Roof	Avg Heat Flux Loss (W/m^2)	Natural Gas (kW·h)	Energy Cost	Heating Oil (kW·h)	Energy Cost
Northern Green (unshaded)	-3.05	23860.33	$1034.71	17426.08	$958.00
Southern Green (shaded)	-4.03	31567.76	$1368.94	23055.10	$1267.46
White Roof ("lower green temp model")	-3.76	29425.23	$1276.03	21490.34	$1181.44
Black Roof ("lower green temp model")	-3.85	30172.7	$1308.44	22036.24	$1211.45
White Roof ("fixed lower temp model")	-4.67	36591.01	$1586.77	26723.77	$1469.15
Black Roof ("fixed lower temp model")	-4.45	34854.75	$1511.48	25455.72	$1399.43

Table 5: Estimated annual heating costs for 1,000 m^2 black, white, and green roofs

ALL HEAT GAIN MONTHS Cooling Energy & Costs for 1000 m^2 Roof	Avg Heat Flux Loss (W/m^2)	Cooling Energy (kW·h)	Energy Cost
Northern Green (unshaded)	+0.27	234.57	$38.08
Southern Green (shaded)	-0.07	104.55	$9.31
White Roof ("lower green temp model")	+0.37	402.55	$51.08
Black Roof ("lower green temp model")	+1.79	1232.87	$249.27
White Roof ("fixed lower temp model")	+0.69	657.84	$96.12
Black Roof ("fixed lower temp model")	+2.11	1488.16	$294.31

Table 6: Estimated annual cooling costs for 1,000 m^2 black, white, and green roofs

R-EQUIVALENT INSULATION VALUE	Heat Loss Months (10/2008–4/2009)		Heat Gain Months (5/2009–8/2009)	
	Green Roof	White Roof	Green Roof	White Roof
Lower Green Model	5.03	0.48	105.51	73.81
Fixed Lower Model	8.77	-0.90	128.01	39.22

Table 7: R-equivalent insulation value of the green or white roofs for the heating and cooling months

The low energy cost for the black roof means there is a relatively small direct energy benefit from switching to a green or white roof. **Tables 5** and **6** aggregate *all* heat gain and heat loss months, not just the DJF winter and JJA summer months. Considering a full year of heating and cooling (**Tables 5** and **6**), we estimate that the 1,000 m^2 (10,764 sq ft) green roof on the Con Edison building is saving approximately $400/yr in heating costs and $250/yr in cooling costs. If this area had been a white roof instead, we estimate that there would have been no heating difference, and cooling savings would have been $200/yr.

A study of green roof heat flows using a building simulation model was performed recently by Sailor[19] and was for a building of comparable dimensions and insulation as the Con Edison green roof. The heat flows reported from the simulations are comparable to the ones we directly estimate from field data.

Equivalent R-Value of Green Roofs and White Roofs

The heat flow data also allow us to estimate an interesting new metric for green or white roofs. We call this the "equivalent" R-value of the green or white roofs surface treatments. This value essentially estimates how much *additional* insulation would have to be added to the current black roof to reduce the heat flows to the same levels as the green or white roofs.

We calculate this using the following heat flow equation:

$$\frac{\Delta T_{black}}{(3.35 + R_{equivalent})} = \phi_{green\,/\,white}$$

where 3.35 is the R-value of the current black roof insulation in K·m²/W, and ΔT_{black} is the temperature gradient of the black roof. $\phi_{green/white}$ is the average heat flux through the northern, unshaded green roof or the white roof. Solving for $R_{equivalent}$:

$$R_{equivalent} = \frac{\Delta T_{black}}{\phi_{green\,/\,white}} - 3.35$$

Finally, we convert back to h·ft²·°F/Btu from K·m²/W using the conversion 1 K·m²/W=5.678263 h·ft²·°F/Btu. **Table 7** shows the results using the two lower boundary models for the data.

For the colder months, the green roof is providing roughly an additional R-value of 5–9. The white roof is providing no additional thermal insulation because its average temperatures are comparable to the black roof. (Had there been a winter heat penalty, we would have found a negative R-equivalent.)

For the warmer months, the green roof is providing a great deal of additional insulation on the order of R>100. The very high summer numbers reflect the extremely low average heat flux through the green roof (0.4 W/m^2), close to zero heat flow. For the white roof, the equivalent warm month R-value is 40–75. Roughly speaking, therefore, the green roof is providing insulation equivalent to R-100 and the white roof is providing insulation equivalent to R-50 during the warm months of the year.

[19] Sailor, "A Green Roof Model."

Concluding Remarks

The key findings list in the Summary includes all the conclusions made in the body of the report, so it is not necessary to relist them here. Rather, we will comment on areas of the research that we think will benefit from a second year of analysis and how the results may change.

The fact that the roofs are so new should be borne in mind. For the first year, the green roof was delivered as small plugs and had a low biomass. A green roof is not really considered established until the second year. The plants and biomass filled in considerably by the summer of 2009, and further vegetation growth is to be expected over the next few years. By contrast, the white roof starts out with the highest albedo it will ever have, and this is well-known to degrade over time as soot and weathering processes begin to darken the surface. How each of these roof systems age is an important research question, as the performance could vary considerably over time. Generally, we expect the green roof performance to improve over time, while the white roof temperature benefits degrade. A second year of analysis will begin to give a sense of the rates of these changes.

The absence of any winter heat penalty on the white membrane is an interesting finding and relevant to urban research in more temperate and polar climates, where winter heat loss is the dominant building energy concern. It will be important to diagnose the source of the nocturnal white roof warmth relative to the black roof. It may be an artifact of the additional layering, or it could be an unrecognized thermal property of the white EPDM membrane, such as emissivity. The PI's informal field testing showing a low emissivity should probably be considered an artifact until it is corroborated, because the field test we undertook is very difficult. A second black membrane was applied on October 29, 2009, so that now both the monitored black and white membranes have identical layering. If the relative nocturnal warmth on the white roof persists this winter, then the case for an emissivity difference will be stronger and can be assessed.

A second year will also help to confirm the modest energy savings through direct vertical roof heat flow across the insulation board; however, we think this a relatively robust finding. Even if the green roof thermal performance improves as expected, the fact that the energy costs associated with the black roof are low means that any savings from switching from dark to green roofs will have to be low as well. But there is another potential energy impact from roofs when the HVAC system has air intake from the rooftop, as is the case at Con Edison. It may be possible and relatively easy to install thermistors above green roof and control roof air intake vents to see if a significant air temperature difference occurs.

Of course, energy and temperature reduction are not the only rationales for green roofs. They perform many other valuable environmental services including water runoff control, water quality improvements, direct air quality improvements, maximum membrane protection and roof service life, urban biodiversity, noise reduction, and building amenity value, including value to urban residences overlooking the green roofs. With respect to heat island mitigation, green roofs do

work—they maintain the surface temperature as low, or lower than, white roofs. Urban heat island mitigation is another public benefit that will accrue to urban residents with widespread adoption.

The stormwater runoff quantity and quality control of green roofs may be their most important attribute of all, as the combined sewage overflow problem is quite severe already and will get worse with climate change.[20]. The next phase of the research will focus on quantifying these water retention benefits from the Con Edison green roofs.

A final comment is in order about the unquestionable importance of white roofs for increasing urban albedo. Any land surface modification that increases albedo can be viewed as a noncontroversial form of geo-engineering. By, in principle, returning sunlight back to space, such surfaces will become extremely important in the future, as efforts to adapt to climate change intensify. Clean white roofs, with an albedo of 70% or more, clearly have this geo-engineering property whereas green roofs, with an albedo of ≅20% are limited in this respect. Considering the potential land area worldwide of human dwellings with roof surfaces, such white roof geo-engineering on a planetary scale needs to be encouraged as much as possible. A pioneering study on this issue was published by Akbari et al.[21] In addition, it would be worthwhile to encourage green roof research that increases green roof albedo through a combination of growth medium and plant selections.

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[20]C. Duhigg, "As Sewers Fill, Waste Poisons Waterways," *New York Times*, November 22, 2009. Available on: http://www.nytimes.com/2009/11/23/us/23sewer.html?_r=1 [01/15/2009].

[21] H. Akbari, S. Menon, and A. Rosenfeld, "Global Cooling: Increasing Worldwide Urban Albedos to Offset CO_2. *Climatic Change* 94 (2009): 275–286; DOI: 10.1007/s10584-008-9515-9.

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http://ccsr.columbia.edu/cig/greenroofs

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