Green Roof Heat Transfer and Thermal Performance Analysis

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May 12, 2011

Acknowledgments

The authors thank their research advisors Professor Dave Dzombak of Carnegie Mellon and Mr. John Buck of Civil and Environmental Consultants. They also thank Ms. Darla Cravotta, special projects manager for Allegheny County, for enabling access to the Allegheny County green roof and the monitoring data being collected for it; and to Mr. Ron Ripper, manager of the CEE Hauck Environmental Engineering Laboratories at Carnegie Mellon, Mr. Chaz McNulty of Cuddy Roofing, and Mr. Eric French of Eisler Landscapes for their assistance with various aspects of the project.

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Abstract

Green roofs have been hypothesized to reduce heat gain and loss in buildings. This project aims to quantify the effect on heat transfer of the green roofs on Hamerschlag Hall at Carnegie Mellon and on the Allegheny County Office Building. Conductive heat transfer was quantified using data from temperature sensors embedded in roof layers and information about the thermal properties of those layers. By comparing conductive heat transfer through conventional layers in the green roof and a control roof at each location, the effect that the green roof media has on the thermal performance of the roof system was evaluated. The Hamerschlag Hall green roof was found to lose 26% less heat than the control roof in heating months. The Allegheny County Office Building green roof was found to lose 8.2% less heat than the control roof in heating months and gain 75% less heat than the control roof in cooling months.

1 Introduction

Green roofs are roofs that are partially or completely covered with vegetation and a growing medium. Green roofs can provide public benefits for the city/community, and private benefits for the building owner. Some public benefits include:

- Improved Storm Water Management – The plants and soil can retain storm water. In urban areas this assists in decreasing combined sewer overflows.
- Reduced “urban heat island” effect – A green roof reduces the level of absorbed heat in dense concrete areas.
- Extended life of the roof – Protects the roof from weather, reducing maintenance costs.

- Reduced heating and cooling costs – Provides extra roof insulation. And reduction in the building's overall heating and cooling costs.
- Aesthetics – Makes the building attractive from aerial view, and provides building users a green space.
- Improved air quality – Plants can absorb carbon dioxide and other pollutants.
- Space for local food production

The purpose of our research was (1) to characterize the green roofs installed on Hamerschlag Hall at Carnegie Mellon University and the Allegheny County Office Building in downtown Pittsburgh, and (2) to investigate the effects on roof heat transfer provided by the green roofs

The end goal of green roof characterization was to create manuals (Becker and Wang, 2011; Wang and Becker, 2011) that would allow future student researchers to understand the green roofs and their thermal monitoring systems. The manuals provide a physical description of each roof, an explanation of how thermal data are collected on the roofs, and how to interpret the data.

The specific thermal benefit that this research focused on was the reduction of conductive heat transfer. We worked to determine the R-value of green roof "soil," to calculate an overall R-value for the roof and to evaluate the legitimacy of using an R-value to quantify energy savings for the roof. By analyzing heat flow through the layers of the roof below the soil which are well characterized with respect to an R-value, we examined some of the benefits that the green roof provides.

By comparing heat flow between the conventional roof layers in the green roofs and control roofs we were able to quantify the reduction in heat loss or gain that the green roof provides. This information may be used with a building energy model to quantify the energy savings that the green roof allows for.

2 Background Information on Thermal Performance of Green Roofs

The thermal properties of a green roof are different from a conventional roof due to the presence of the soil, plants, and water. To understand the overall thermal system of a green roof, each of the following modes of heat transfer and storage must be considered (Wark, 2010).

Conduction – This is when heat transfers through a solid material from high temperature areas to low temperature areas. The rate of heat transfer through a specific material is governed by its thermal conductivity (k). The higher the thermal conductivity, the greater the heat transfers. The role that insulation plays in a roof is to slow down conductive heat transfer, since insulation materials have low thermal conductivities. Generally, materials with a higher thermal mass have higher thermal conductivities, and thus, having a layer of soil and vegetation on a roof can affect the overall thermal conductivity of a roof.

Convection – This is when heat is transferred due to a flowing gas or liquid. The presence of moving water through the soil and drainage layers in a green roof will affect the overall temperature of the roof. The effect of wind blowing across the roof will also be a factor

Radiation – This is the electro-magnetic heat transfer from warmer surfaces to cooler surfaces. The roof is exposed to solar radiation, which it then absorbs or reflects. The roof will also emit long-wave radiation heat back to the atmosphere (Wark 2010).

Evaporation and evapotranspiration – It takes heat to change water from liquid to gas, so the evaporation of stored rainwater water from the soil will help to cool the soil. Also, the plants on the roof will uptake water through their roots, and transpire the water through their leaves into the atmosphere. That also helps to keep the roof cool.

Thermal Mass – Materials with a high thermal mass have the ability to store heat. The soil and water both have the ability to store heat, and can contribute to stabilizing the temperature of the roof.

Figure 1 shows a representation of these modes of heat transfer through green roof layers (Wark, 2010).

2.1 Soil Heat Transfer

2.1.1 General theory of heat transfer through soil

Soil is a porous material that is made up of solid particles, water, and air. The way that heat travels through a soil depends on many different variables, including:

- Particle size
- Water content
- Bulk density
- Mineral composition
- Soil temperature

From previous research (Nakshabandi, 1964) on the effects of the aforementioned variables on soil thermal conductivity, the following conclusions have been reached: (1) Heat travels much better through water than through air, and much better through minerals than water. (2) When water content is zero, heat is more likely to transfer across particles through points of contact. As the water content of the soil increases, thermal conductivity will quickly increase because the water helps to bridge gaps between particles, and increase the contact surface area. (3) After reaching a certain water content, thermal conductivity will increase at a slower rate, because the additional water will not contribute any more to facilitating heat transfer through the solids. (4) Heat will not transfer linearly through a thickness of soil; it will travel through the path of least resistance (highest thermal conductivity). (5) Thermal conductivity measurements are unique for a specific composition of soil and geographic location.

2.1.2 Green Roof Soil

Since the composition of green roof soil is significantly different from naturally occurring soil, it was important to find thermal property measurements that were specific to green roof soil. We obtained our thermal conductivity data from the research done by Sailor (2007).

According to Sailor, "Ecoroof soils typically consist of three components: a lightweight inorganic aggregate, compost, and sand." (P.1247) The lightweight aggregate is highly porous, which keeps the green roof from being too heavy, but also allows a greater storage of water. Expanded shale is a popular choice for aggregate in the eastern U.S. The organic component, peat or compost, also aids in water storage. Ultimately, the green roof soil is engineered to be lightweight, allow fast drainage, but also high water storage. The water drains quickly through the soil, but is retained in the small pores between the smaller particles.

2.1.3 Thermal Resistance of Soil

The thermal resistance of soil that was used in our heat flux analysis was obtained from Sailor's research. Sailor tested several combinations of soil composition and moisture content. The composition that best matched the soil on the roofs we studied was the following: Sample No. DH08; Composition: 75% Shale (by volume), 10% Compost, 15% Sand; Moisture Capacity: 0.24 g/g. Table 1 shows the four different moistures (% saturated), for which the soil sample was tested at, and the corresponding thermal conductivities.

Table 1. Source: Sailor (2007). Thermal property data for sample DH08 at multiple moisture levels.

Moisture (% sat)	k (W/(mK))
0	0.18
17	0.26
33	0.30
82	0.41

Thus, according to Table 1, soil sample DH08 had a thermal conductivity of 0.18 W/mk when there was no moisture.

3 Hamerschlag Hall and ACOB Green Roofs

3.1 Allegheny County Office Building

One of the two roofs that we analyzed was the Allegheny County Office Building's green roof, in downtown Pittsburgh. The western half of this 8000 square feet roof was retrofitted with a green roof in June 2010. The eastern half remains a conventional modified bitumen roof.

The green roof utilizes both extensive and intensive green roof technology. Extensive soil depths range from 2 to 4 inches, and the primary vegetation planted on extensive soil is sedum sod. Intensive soil depths range from 6 to 10 inches, and there are a variety of plants on intensive soil. The existing roof underneath the green roof layers is the same as the control roof.

There are 41 thermocouple sensors on the roof, collecting data from within the soil, above and below the true ceiling, and in the air. The sensors collect and report data every 5 minutes, which are compiled and stored on www.hobolink.com. More information on the ACOB green roof can be found in the manual (Wang and Becker, 2011).

3.2 Hamerschlag Hall

The other roof that we analyzed was the Hamerschlag Hall green roof at Carnegie Mellon University. This is a 150 ft by 30 ft green roof which was built on top of a conventional modified bitumen flat roof. The soil depth varies from 4 to 8 inches, but remains constant at 4 inches in the monitoring areas. The control roof was a conventional modified bitumen flat roof on Porter Hall, an adjacent building. The conventional roof layers are identical in the control roof and the green roof.

Thermocouple sensors are above and below every layer that has a non-negligible R-value. These sensors collect temperature data every minute. More information on the temperature sensors and features of the HH green roof can be found in the manual (Becker and Wang, 2011).

4 Methods for Analyzing Thermal Performance

4.1 Objective

The goal of this project was to understand how much heat is entering or leaving the green roof compared to the control roof. Almost all of the heat transfer through the conventional modified bitumen flat roof (conventional roof) layers is conductive. For these layers, a calculated conductive heat flux will be very near the total heat flux. A more complex model which also considers convective and radiant heat transfer would be needed to understand the total flux for the soil layer of the roof. For this reason, the soil layer was not considered in this analysis.

The conventional roof layers on each roof, including the concrete deck and insulation, were compared to understand the benefits of the green roof layers. If the soil layer allows for less heat to escape the roof in the winter and/or less heat to enter the roof in the summer, this will be reflected in the conductive heat transfer in the conventional roof layers below.

4.2 Time Periods

Because the temperature data are collected every minute, we needed to select a time period over which to calculate the flux and total energy lost or gained. Initially we plotted average daily flux values over a year. This provided too much detail and made it difficult to see trends in the data. Plotting the average monthly flux values made it easy to see trends but oversimplified some of the data. For this reason, we plotted weekly average flux values to understand how the heat transfers through the roof over time.

For the total amount of heat escaping or entering the roof, we selected a period of one month. We chose one month because energy is billed monthly. Although this heat energy loss or gain from the roof is not equivalent to the changes in energy consumption, viewing energy differences on a monthly basis will be relevant to a building owner.

4.3 Heat Flux

Heat flux is a measurement of the rate of heat transfer through a material per unit area. A low heat flux means that less heat is moving across a certain layer. Heat flux varies with temperature, material, and depth of material. The variables we used to calculate heat flux are shown in Table 2.

Table 2: Variables used to calculate heat flux

Variable	SI Units	Description
q	W/m^2	Heat flux
R	m^2K/W	Thermal resistance for conduction
ΔT	K	Temperature gradient over a roof layer
L	m	Depth of roof layer
k	W/mK	Thermal conductivity

Heat flux is calculated using Equation 1 (Incropera et al, 2007):

$$\boldsymbol{q = \Delta T/R} \qquad (1)$$

The R-value, or thermal resistance, of a material is an indicator of the insulating properties of a material. To calculate the R-value, we first researched the thermal conductivity of the roof materials. The thermal conductivity value used for insulation was specified by the manufacturer. The value used for concrete was found to be 1.40 W/mK (ASHRAE, 1967). The gravel drainage layer was estimated as sand. The thermal conductivity value for dry sand is 0.27 W/mK (ASHRAE, 1967). The thermal conductivity for soil was only used on the ACOB roof analysis, since the uppermost sensor used on the green roof analysis, 2BN, was sitting in 1.5 inches of soil above the surface of the ceiling. For the ACOB analysis, the soil was considered to be fairly saturated at the bottom of the soil layer, where the soil analysis was done. Thus, a thermal conductivity value of 0.41 W/mK was used (corresponding to 82% moisture from Table 1). For the Hamerschlag hall roof, no soil was used in the analysis, because all of the sensors used were located within the ceiling, not within the soil. The thermal conductivity, layer depth, and thermal resistance values for the materials in the Hamerschlag Hall and Porter Hall roofs are shown in Table 3 and the values for the materials in the ACOB roof are shown in Table 4.

Table 3: Layer depth, thermal conductivity, and thermal resistance values used for each layer of Hamerschlag Hall green roof and Porter Hall control roof.

Layer	***L* (m)**	***k* (W/mK)**	***R* (m^2K/W)**
Gravel drainage layer (estimated as sand)	0.06	0.27	0.24
Polyisocyanurate Insulation	0.05	0.02	2.13
Concrete Deck	0.20	1.40	0.14
Total for Conventional Roof Layers	0.25	0.11	2.27

Table 4: Layer depth, thermal conductivity, and thermal resistance values used for each layer of ACOB roof.

Layer	*L* (m)	*k* (W/mK)	*R* (m^2K/W)
Soil	0.04	0.41	0.09
Lightweight Concrete	0.05	0.42	0.12
Cork	0.06	0.04	1.48
Concrete Deck	0.10	1.7	0.06
Total for Conventional Roof Layers	0.22	0.13	1.66

By dividing the temperature gradient over a layer by the calculated R-value from the same layer we were able to calculate heat flux values for every interval that data were collected (every minute at Hamerschlag Hall and every five minutes at ACOB). These heat flux values were then averaged to get average weekly and monthly heat flux. The average weekly heat flux values were plotted directly to see the differences in heat transfer in different layers and different roofs. The average monthly heat flux values for the conventional layers in the green roofs and control roofs were used to calculate heat loss and gain per unit area.

4.4 Heat Loss or Gain

By calculating the heat flux, we were able to see the way that heat travels through each layer of the roof over time. This is useful for understanding the contribution of individual layers, and to see if the green roof performs better than the control roof. However, the heat flux values alone do not communicate the overall thermal performance of the green roof compared to the control roof. To quantify the amount of heat that the green roof prevents the building from losing in cold weather and from gaining in warm weather, the flux values have to be converted to heat energy lost or gained.

To simplify comparison between roofs, we calculated energy loss and gain per square meter (J/m^2) of roof. Heat flux measures a rate of heat transfer per unit area, so to convert to a quantity of heat transferred, the heat flux must be multiplied by the chosen time period. In this case, the time period was one month. This conversion is shown in Equation 2:

$$\boldsymbol{Energy\ loss\ or\ gain/m^2} = \boldsymbol{q_m} \times \boldsymbol{t_m} \tag{2}$$

where q_m is the average heat flux over one month (W/m^2), and t_m is the number of seconds in one month. This result was expressed in MJ to reduce confusion between heat energy loss and changes in energy consumption.

4.5 Data Used

To compute the weekly average flux and estimate the quantity of energy gained or lost from the roof in a month, daily average flux values were first computed. The daily average values were computed from temperature data from the sensors in the roofs. Average weekly temperature gradient values were used for analysis.

4.5.1 Hamerschlag Hall

Temperature data have been collected from the Hamerschlag Hall and Porter Hall roofs since 2007. To use the most recent data, but also to have some perspective on how situations might change year to year, data from 2009 and 2010 were used. There is one monitoring area on the control roof and two monitoring areas on the green roof (Becker and Wang, 2011). Data from the control roof and the "G2" area of the green roof were used for this analysis. Data from sensors below the concrete deck (T1), between the concrete deck and insulation (T2), and above the insulation/on the control roof surface (T3) were used at both of these locations. Data from sensors above (T5) and below (T4) the gravel drainage layer at G2 were also used to compare the flux through the gravel to the flux through the conventional roof layers. Sensor locations are shown in the cross sectional diagram of Figure 2 in Becker and Wang (2011).

Due to equipment malfunctions and lack of monitoring personnel during various periods, continuous data for each year are not available. In 2009, data were missing for part of April and were missing from July 9 to October 8. Additionally, we decided not to use some of the data from March because sensors were not working properly. In 2010, the sensors were not working for some days in February and March so some of those data were not used. Data were missing from May 6 to August 25, and some were missing for part of September and part of December. The average weekly temperature gradient values that were used for 2009 are shown in Table 5, and the data used for 2010 are shown in Table 6.

Table 5: Weekly average temperature gradient values used for analysis for Hamerschlag Hall green roof and Porter Hall control roof in 2009

2009	ΔT (°C)						
	Green				Control		
Week	Gravel[1]	Insulation[2]	Concrete[3]	Conv. Layers[4]	Insulation[2]	Concrete[3]	Total[4]
1-Jan	0.68	12.34	5.42	18.15	17.1	6.16	23.26
8-Jan	0.76	13.41	4.73	18.54	18.41	6.26	24.67
15-Jan	1.1	14.31	4.53	19.25	17.39	9.37	26.76
22-Jan	1.04	14.93	4.7	20.06	18.24	8.07	26.31
29-Jan	0.8	15.24	3.82	19.48	18.53	6.28	24.81
5-Feb	0.59	14.14	3.93	18.47	14	6.12	20.12
12-Feb	0.75	12.41	3.63	16.39	16.56	5.74	22.31
19-Feb	0.85	13.88	3.4	17.66	19.92	7.03	26.95
26-Feb	0.88	12.58	3.38	16.31	15.83	6.2	22.03
5-Mar	0.8	14.92	3.49	7.82	6.68	4.52	11.2
12-Mar	0.62	9.58	2.72	12.24	8.59	3.75	12.34
19-Mar	1.15	8.65	3.54	12.46	10.49	2.99	13.48
26-Mar	0.56	8.7	3.2	12.16	9.1	2.42	11.52
2-Apr	0.56	8.78	2.08	11.1	5.68	2.11	7.79
9-Apr	0.78	8.68	3.96	12.92	8.77	2.9	11.67
16-Apr	0.73	6.6	1.5	8.28	6.53	1.92	8.45
23-Apr	0.69	5.08	0.84	6.05	5.64	1.82	7.46
30-Apr	0.79	4.41	-0.64	3.85	4.76	1.72	6.48

[1] Calculated using data from T5-T4

[2] T3-T2

[3] T2-T1

[4] T3-T1

2009	ΔT (°C)						
	Green				Control		
Week	Gravel 1	Insulation 2	Concrete 3	Conv. Layers 4	Insulation 2	Concrete 3	Total 4
7-May	0.84	4.55	-0.62	4.02	2.1	1.18	3.28
14-May	1.1	3.26	0.06	3.39	-1.04	0.41	-0.63
21-May	0.93	1.69	-0.36	1.36	-3.9	-1.07	-4.96
28-May	1.01	1.69	-0.65	1.07	-1.78	-0.41	-2.19
4-Jun	0.76	1.88	-0.38	1.53	-3.36	-0.56	-3.92
11-Jun	0.83	1.13	-0.66	0.48	-2.68	-0.78	-3.46
18-Jun	0.5	2.87	-0.54	2.38	-5.26	-0.9	-6.16
25-Jun	0.88	0.28	-0.89	-0.61	-3.4	-1.04	-4.44
2-Jul	0.74	1.36	-1.04	0.33	-3.5	-0.42	-3.93
9-Jul	0.26	7.32	0.61	8.1	5.9	-0.11	5.79
16-Jul							
23-Jul							
30-Jul							
6-Aug							
13-Aug							
20-Aug							
27-Aug							
3-Sep							
10-Sep							
17-Sep							
24-Sep							
1-Oct							
8-Oct	0.54	7.53	1.85	9.58	6.67	4.6	11.27
15-Oct	0.47	10.18	2.81	13.27	9.48	6.26	15.75
22-Oct	0.51	7.41	1.8	9.41	7.07	4.69	11.77
29-Oct	0.53	8.31	1.53	10.06	9.71	5.33	15.04
5-Nov	0.33	9.24	1.91	11.4	11.31	3.55	14.86
12-Nov	0.52	8.33	1.97	10.53	10.3	3.5	13.81
19-Nov	0.29	8.3	2.83	11.38	11.94	3.07	15.01
26-Nov	0.3	9.86	4.47	14.65	14.9	4.13	19.03
3-Dec	0.59	12.65	3.81	16.83	19.22	6.81	26.03
10-Dec	0.22	12.71	5.17	18.27	17.29	6.69	23.98
17-Dec	0.2	12.27	4.88	17.53	16.37	6.72	23.09
24-Dec	0.25	12.13	5.35	17.87	17.76	6.72	24.47

Table 6: Weekly average temperature gradient values used for analysis for Hamerschlag Hall green roof and Porter Hall control roof in 2010

2010	ΔT (°C)						
	Green				Control		
Week	Gravel[1]	Insulation[2]	Concrete[3]	Conv. Layers[4]	Insulation[2]	Concrete[3]	Total[4]
1-Jan	0.35	13.37	5.39	19.17	17.38	7.37	24.75
8-Jan	-0.05	13.13	4.95	18.47	17.31	7.74	25.05
15-Jan	0.29	13.14	4.91	18.45	15.64	5.99	21.63
22-Jan	0.37	12.65	4.39	17.41	15.3	5.22	20.52
29-Jan	0.26	14.14	4.9	19.46	18.88	8.49	27.38
5-Feb	0.18	14.11	4.46	18.97	16.53	6.37	22.9
12-Feb	0.16	11.1	4.67	16.21	16.91	5.81	22.72
19-Feb	0.71	15.2	4.15	19.85	16.89	6.01	22.9
26-Feb	0.41	14.08	3.8	19.41	16.47	6.56	23.03
5-Mar	0.55	10.48	4.87	15.77	13.59	5.62	19.21
12-Mar	0.49	9.43	3.31	13.02	8.05	3.3	11.35
19-Mar	0.71	8.2	1.59	10	6.65	2.57	9.22
26-Mar	0.61	9.16	2.89	12.31	7.51	3.23	10.73
2-Apr	0.79	5.29	-0.88	4.51	1.03	0.7	1.72
9-Apr	1.03	5.99	0.31	6.44	5.81	2.62	8.43
16-Apr	0.79	5.87	0.77	6.78	5.63	2.49	8.12
23-Apr	0.91	6.06	-1.06	5.11	4.92	2.12	7.04
30-Apr	0.78	4.32	-1.86	2.51	-0.28	0.49	0.21
7-May							
14-May							
21-May							
28-May							
4-Jun							
11-Jun							
18-Jun							
25-Jun							
2-Jul							
9-Jul							
16-Jul							
23-Jul							
30-Jul							
6-Aug							
13-Aug							

2010	ΔT (°C)						
	Green				Control		
Week	Gravel[1]	Insulation[2]	Concrete[3]	Conv. Layers[4]	Insulation[2]	Concrete[3]	Total[4]
20-Aug	0.53	2.05	-2.69	-0.66	-5.83	-0.34	-6.17
27-Aug	1.43	0.8	-2.62	-1.85	-4.64	-1.04	-6.94
3-Sep	1.29	1.94	-3.55	-1.65	0.81	0.36	0.91
10-Sep	1.22	2.94	-3.07	-0.13	1.85	0.72	2.44
17-Sep	0.73	3.22	-3.04	0.19	-0.6	0.79	1.69
24-Sep							
1-Oct	0.51	4.73	-2.33	2.62	8.47	2.86	11.21
8-Oct	0.56	5.42	-1.49	4.02	6.57	2.22	8.79
15-Oct	0.43	6.7	-1.45	5.36	10.06	3.43	13.5
22-Oct	0.45	7.71	-1.43	6.41	8.21	3.13	11.34
29-Oct	0.45	8.67	-0.67	8.17	14.13	4.77	18.9
5-Nov	0.14	9.77	-0.38	9.6	13.34	4.73	18.07
12-Nov	0.17	9.81	-0.91	9.1	13.65	4.68	18.33
19-Nov	0.56	10.78	-0.68	10.33	12.32	4.34	16.66
26-Nov	0.3	11.64	1.71	13.65	16.62	6.46	23.08
3-Dec	0.17	12.62	3.5	16.47	18.97	8.27	27.24
10-Dec							
17-Dec							
24-Dec							

4.5.2 Allegheny County Office Building

The green roof was newly installed in June of 2010, and data from June 2010 to April 2011 were analyzed. Two locations on the roof were selected for analysis. One is on the control roof and one is on the green roof side.

The control roof sensing location has two sensors that are used in the analysis – one on top of the roof surface (2AN), and one below the true ceiling (2ACN). The control roof sensor is located on the north side of the roof (see Wang and Becker, 2011). This location was selected because conditions are most similar to the green roof sensing location.

The green roof sensor is located at the north side of the roof, and the two sensors significant to the analysis are the one below the ceiling (2BCN) and the one near bottom of the soil layer (2BN, 2.5”bgs). The soil at that location is four inches thick, and the sensor is 2.5” below ground surface.

The average weekly temperature gradient values that were used for analysis for 2010 data are shown in Table 7, and for 2011 data are shown in Table 8.

Table 7: Weekly average temperature gradient values used for analysis for Allegheny County Office Building in 2010

	ΔT (°C)	
Week	**Green[5]**	**North[6]**
23-Jun	-3.29	-7.22
30-Jun	-2.13	-10.31
7-Jul	-2.50	-7.90
14-Jul	-2.21	-6.74
21-Jul	-3.16	-9.45
28-Jul	-3.72	-6.85
4-Aug	-2.77	-6.78
11-Aug	-0.59	-7.59
18-Aug	1.31	-1.53
25-Aug	0.58	-6.55
1-Sep	2.88	-1.47
8-Sep	6.40	2.31
15-Sep	7.65	3.58
22-Sep	5.72	3.93
29-Sep	13.55	16.72
6-Oct	13.30	9.40
13-Oct	15.41	17.84
20-Oct	15.80	13.51
27-Oct	20.77	21.58
3-Nov	25.82	26.96
10-Nov	24.89	24.57
17-Nov	24.37	25.14
24-Nov	29.41	30.72
1-Dec	33.44	39.27
8-Dec	36.89	38.71
15-Dec	37.42	43.14
22-Dec	38.78	38.33
29-Dec	34.80	34.16

[5] Calculated using data from 2BN-2BCN

[6] 2AN-2ACN

Table 8: Weekly average temperature gradient values used for analysis for Allegheny County Office Building in 2011

	ΔT (°C)	
Week	**Green**	**North**
5-Jan	38.39	42.85
12-Jan	37.55	38.06
19-Jan	36.86	38.86
26-Jan	37.10	38.07
2-Feb	35.08	35.62
9-Feb	37.35	35.21
16-Feb	29.15	27.07
23-Feb	30.45	30.17
2-Mar	30.82	29.86
9-Mar	27.18	0.00
16-Mar	32.63	0.00
23-Mar	0.00	0.00
30-Mar	21.34	15.52
6-Apr	10.50	11.82

5 Data Analysis

5.1 Hamerschlag Hall

5.1.1 Heat Flux Findings

A plot of the heat flux through the gravel drainage, insulation, and concrete layers as well as the total flux over the concrete and insulation layers (conventional layers) for the Hamerschlag Hall green roof in 2009 is shown in Figure 2. In this plot, positive heat flux indicates heat is transporting out of the roof.

It can be seen from the plot that the insulation layer governs the way that heat travels through the conventional roof layer. It can also be seen that the absolute value of the flux through the concrete deck was higher than through the other layers. This is in part because the R-value of concrete is lower than that of the other layers (Table 3). The high R-value of the insulation also contributes to the higher flux through the concrete. The insulation prevents heat from escaping the roof, so heat may be travelling through the concrete horizontally and escaping through the wall. This plot also shows the general flux trends over the year. As expected, heat leaves the roof during the heating months (October through March) and enters the roof during the cooling months (May through August).

The plot for the heat flux through the same layers in 2010 (Figure 3) shows similar patterns. The flux through the concrete reached much lower levels in September 2010 than were seen at any point in 2009. No data were available to compare for September 2009 to determine if flux this low in the concrete is typical for that time of year.

Flux values for the Porter Hall control roof were also calculated for the insulation and concrete layers, as well as the combined conventional roof layers. A comparison of the flux values for the conventional layers between the roofs in 2009 is shown in Figure 4.

It can be seen that the heat flux in the control roof was higher in heating months and lower in the cooling months than in the green roof. This indicates that the green roof is reducing heat loss in the heating months and reducing heat gain in the cooling months. Figure 5 shows the same values for 2010. The same trends can be seen in 2010, again indicating that the green roof is improving the thermal performance of the roof.

The flux values show that the thermal performance of the green roof is better than the control roof in terms of reduced conductive heat transport. Converting the flux values to heat loss and gain values will allow us to understand the improvement in performance quantitatively.

5.1.2 Heat Loss and Gain Findings

Using the daily average flux values, monthly average flux values were computed. These values were then converted into monthly average heat loss or gain values per square meter. In Figure 6 the heat loss and gain values for 2009 are shown. Again it can be seen that the control roof lost more heat in the heating months and gained more heat in the cooling months than the green roof. It is interesting to note that for June and July, the control roof gained heat, but the green roof allowed the roof to lose heat even when the outside temperature was usually higher than the temperature inside the building.

The data for 2010, shown in Figure 7, exhibits similar trends. A notable difference is the behavior of the roofs in April. In 2009 the control roof released more heat than the green roof, but in 2010 the green roof released more heat than the control roof. This could occur if it was warmer on average in April, 2010 than in April, 2009. According to the National Weather Service records, the average temperature in Pittsburgh over the dates of interest in April, 2009 was 11.6°C, and was 13.8°C over the dates of interest in April, 2010.

The behavior of the roof will likely change year to year for April because it is a transitional month from heating to cooling. We expect similarly unpredictable behavior for September because it is a transitional month from cooling to heating. For this reason, analysis of heating months did not include April and analysis of cooling months did not include September.

In order to summarize how much the green roof layers improved the performance of the roof, the percentage difference in heat loss from the green roof and the control roof was compared during the heating months of 2009 and 2010. A similar calculation was not performed for the cooling months because data were not available for a full cooling season for either year.

The percentage difference was calculated using Equation 3:

$$\%\ \textbf{Difference in heat loss} = \frac{\textbf{Heat Loss in Control} - \textbf{Heat Loss in Green}}{\textbf{Heat Loss in Control}} \times \mathbf{100}\% \quad (3)$$

The values from the results of these calculations are shown in Table 9. On average, the control roof lost 26% more heat in the heating months than the green roof in 2009 and 2010.

Table 9: Percent difference in heat loss between conventional layers in Hamerschlag Hall green roof and Porter Hall control roof over heating months in 2009 and 2010

Month	**2009**	**2010**
January	30%	22%
February	27%	25%
March	17%	9%
October	38%	13%
November	32%	40%
December	30%	34%
Average	29%	24%
Average over 2009 and 2010		**26%**

These values cannot be directly related to energy savings, but could be combined with a building energy model to calculate actual energy savings. The values may be useful for estimating energy savings in the room directly below the roof, but cannot be translated to the entire building.

5.2 Allegheny County Office Building

5.2.1 Heat Flux Findings

Heat flux measurements using the temperature gradient between the upper and lower sensing locations allow for comparison of heat flow through the conventional layers of each roof.

A plot of the average weekly flux from June to April for the green roof and sensing location in the control roof is shown in Figure 8. The data from the control roof indicate that the green roof absorbed less heat in the summer and lost less heat in the winter than the control roof, similar to the data from the Hamerschlag Hall roof. It is difficult to compare green roof and control roof results due to the differences in the amount of sun and wind to which the sensing locations are exposed.

5.2.2 Heat Loss and Gain Findings

Similar to the analysis performed on the Hamerschlag Hall and Porter Hall data, the heat flux values from ACOB were converted to heat lost or gained by the roof per month. These values are plotted in Figure 9. From this plot the reductions in heat gain and loss from the green roof compared to the data from the control roof seem to be low. When compared to the data from Hamerschlag Hall and Porter Hall however, the reductions seen in the cooling months at ACOB were actually much higher, but in the heating months the reductions were not as high as what was seen at Hamerschlag Hall.

The percent difference in heat loss and gain that the ACOB green roof provides were calculated using Equation 3. The values are shown in Table 10.

Table 10: Percent difference in heat gain in cooling months and heat loss in heating months between conventional layers in ACOB green roof and control roof, June 2010 through March 2011

Month	**% Reduction**
June	66.9%
July	69.9%
August	89.1%
Cooling months average	**75.3%**
November	8.1%
December	13.7%
January	10.4%
February	1.9%
March	7.0%
Heating Months Average	**8.2%**

The cooling season was considered to be May through August as used in analyzing Hamerschlag Hall roof data, although data were only available June through August. The heating season was considered to be October through March, consistent with the heating season definition used for the Hamerschlag Hall data. Reductions in heat gain during cooling months from the green roof are significant, about 75%. In the heating months the green roof allowed for reductions in heat loss, but they were fairly low, around 8%.

From these results it appears that the ACOB green roof is more effective at reducing cooling loads than it is at reducing heating loads.

6 Summary and Conclusions

The goal of this research was to quantify the thermal performance improvements from a green roof. Because the equipment used in this analysis only allowed us to measure conductive heat transfer, we only analyzed conductive heat flux through the conventional roof layers of the green roofs and control roofs at Hamerschlag Hall and ACOB. Most of the heat transfer through these layers is conductive. Other forms of heat transfer play a larger role in the green roof layers, so flux through those layers was not considered in the analysis. By comparing heat flux through the same conventional layers in each roof, we were still able to evaluate the thermal performance.

Analysis of the 2009-2010 data from the Hamerschlag Hall green roof and the Porter Hall control roof indicate that the green roof improved the thermal performance of the roof by reducing heat gain in cooling months and reducing heat loss in heating months. In the heating months of 2009 and 2010, it was found that on average, 26% less heat was lost from the green roof than was lost from the control roof. This indicates a reduction in the heating load of the room directly below the roof, but may not necessarily indicate major reductions for the entire building.

The 2010-2011 data from the green roof and control roof at ACOB also showed that the green roof improved the thermal performance of the roof. At an average of 8.2%, the reductions in heat loss in heating months were not as high as those seen at Hamerschlag Hall. However, the 75% reduction in heat gain in cooling months was larger than observed for the Hamerschlag Hall roof. This indicates that the thermal performance of the ACOB green roof is better in the summer than in the winter compared to the control roof.

The results of our analysis of the Hamerschlag Hall and ACOB green roofs indicate that the green roof layers have improved thermal performance of the roof with respect to reduced conductive heat gain and loss. Further analysis must be done on these roofs so that the benefits of the green roof can be more fully evaluated. This should include analysis of the other modes of heat transfer that occur in the green roof soil medium, such as evaporative heat transfer. Additionally, building energy modeling is needed to convert heat loss and gain values to energy savings, so that heat loss and gain values determined in this study can be used to estimate energy savings.

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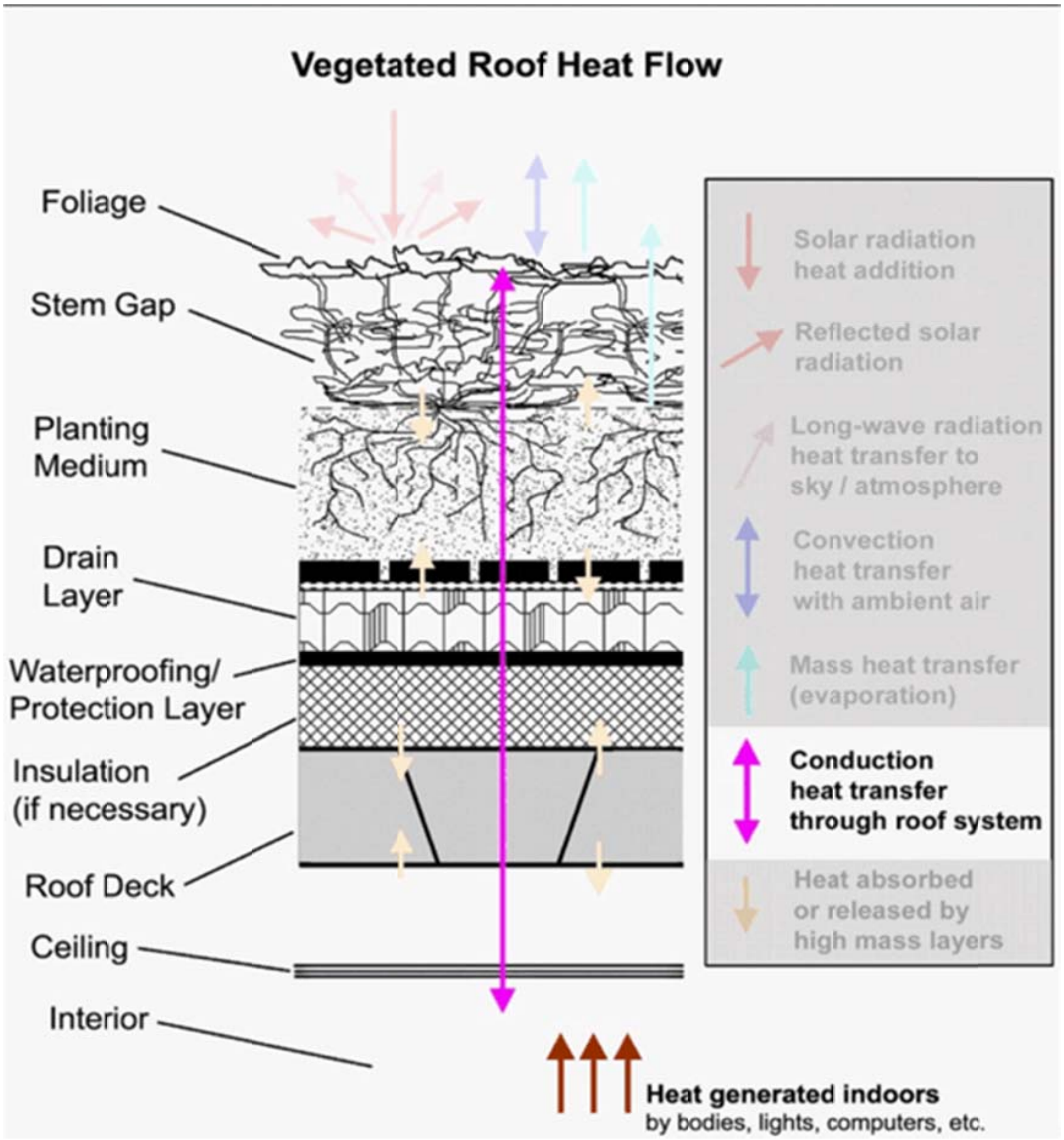

Figure 1: Modes of Heat Transfer Through Generic Green Roof. Source: Wark (2010)

Figure 2: Average weekly heat flux through Hamerschlag Hall green roof layers in 2009

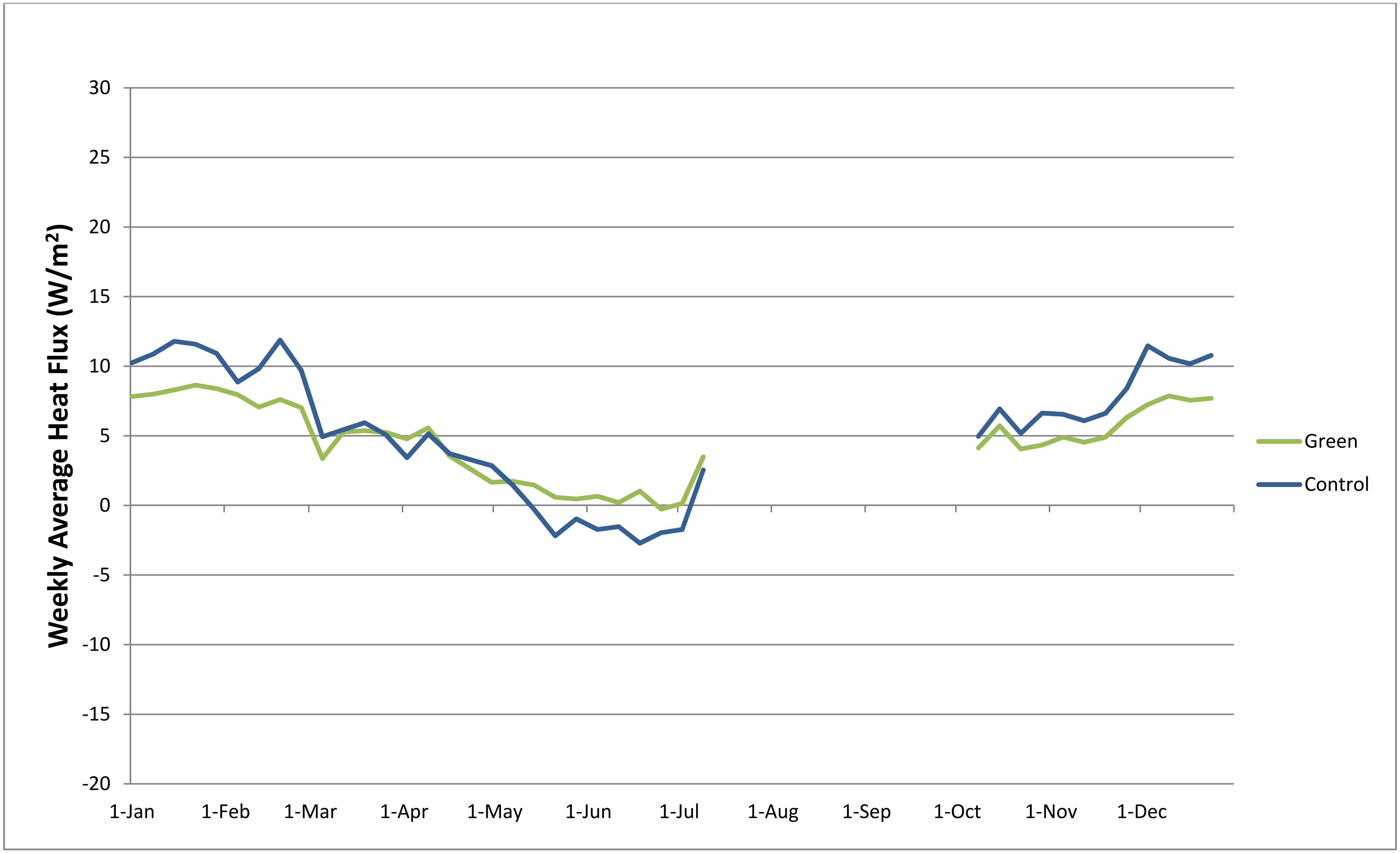

Figure 3: Average weekly heat flux through conventional roof layers in Hamerschlag Hall green roof and Porter Hall control roof in 2009

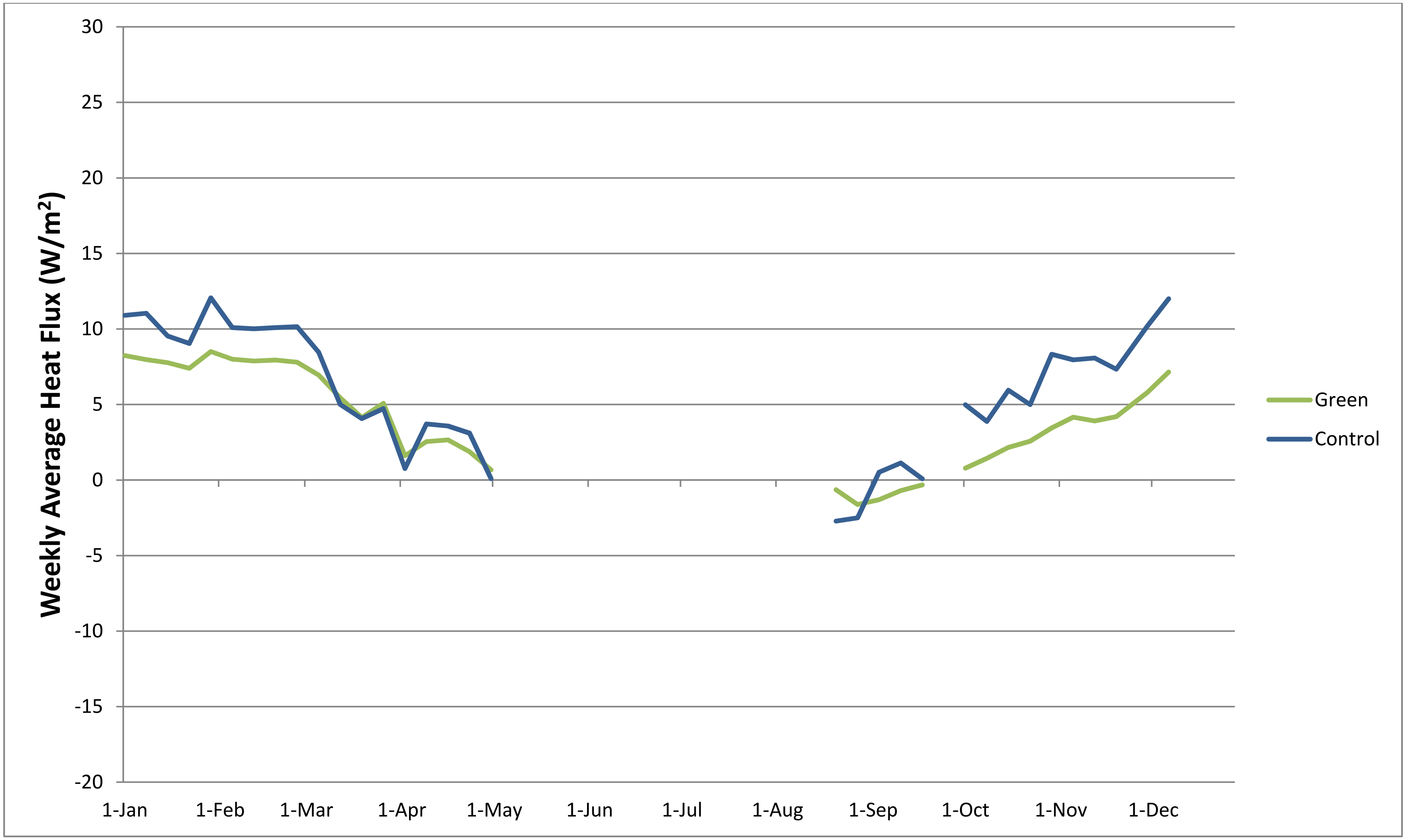

Figure 4: Average weekly heat flux through conventional roof layers in Hamerschlag Hall green roof and Porter Hall control roof in 2010

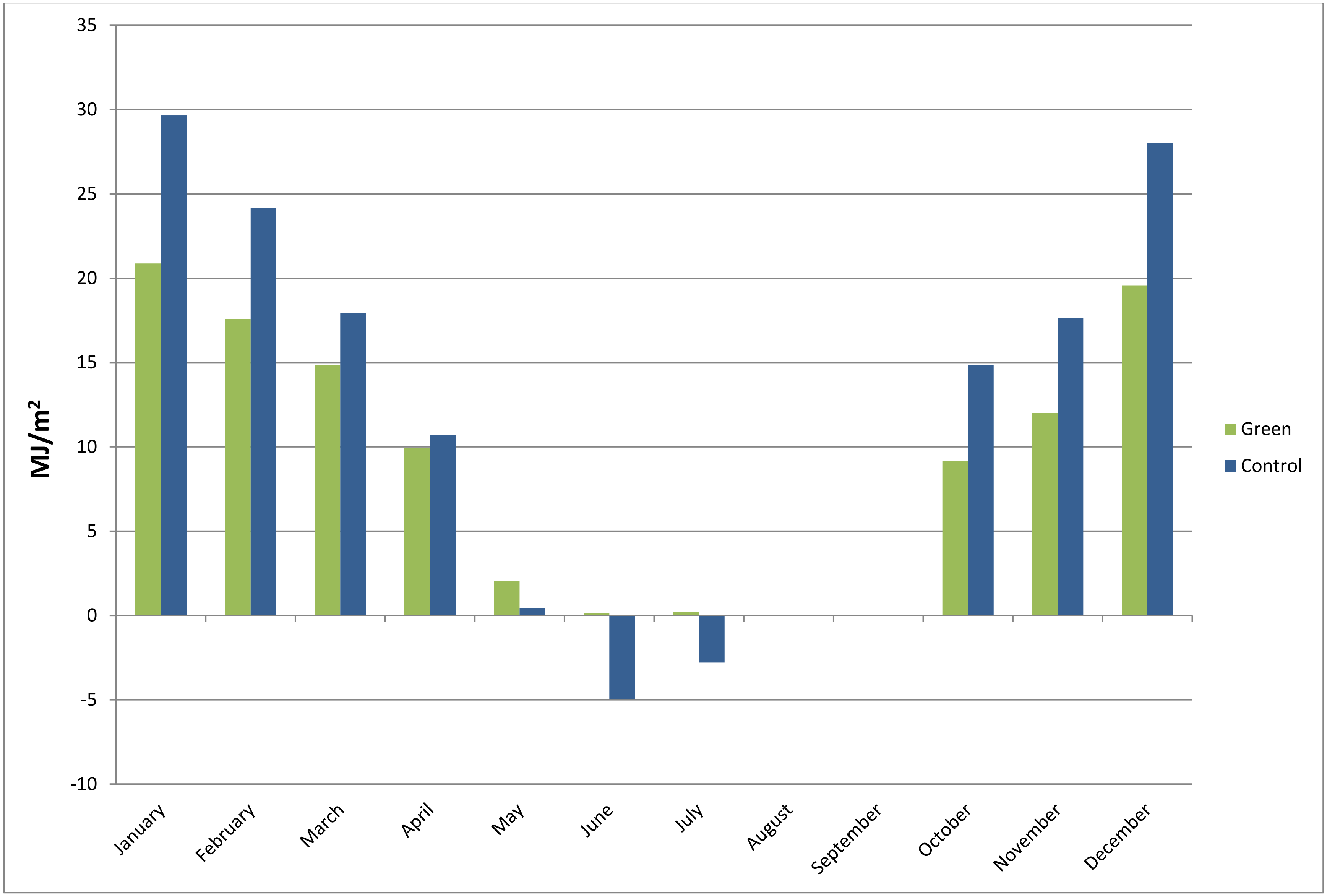

Figure 5: Heat loss or gain per month for Hamerschlag Hall green roof and Porter Hall control roof in 2009

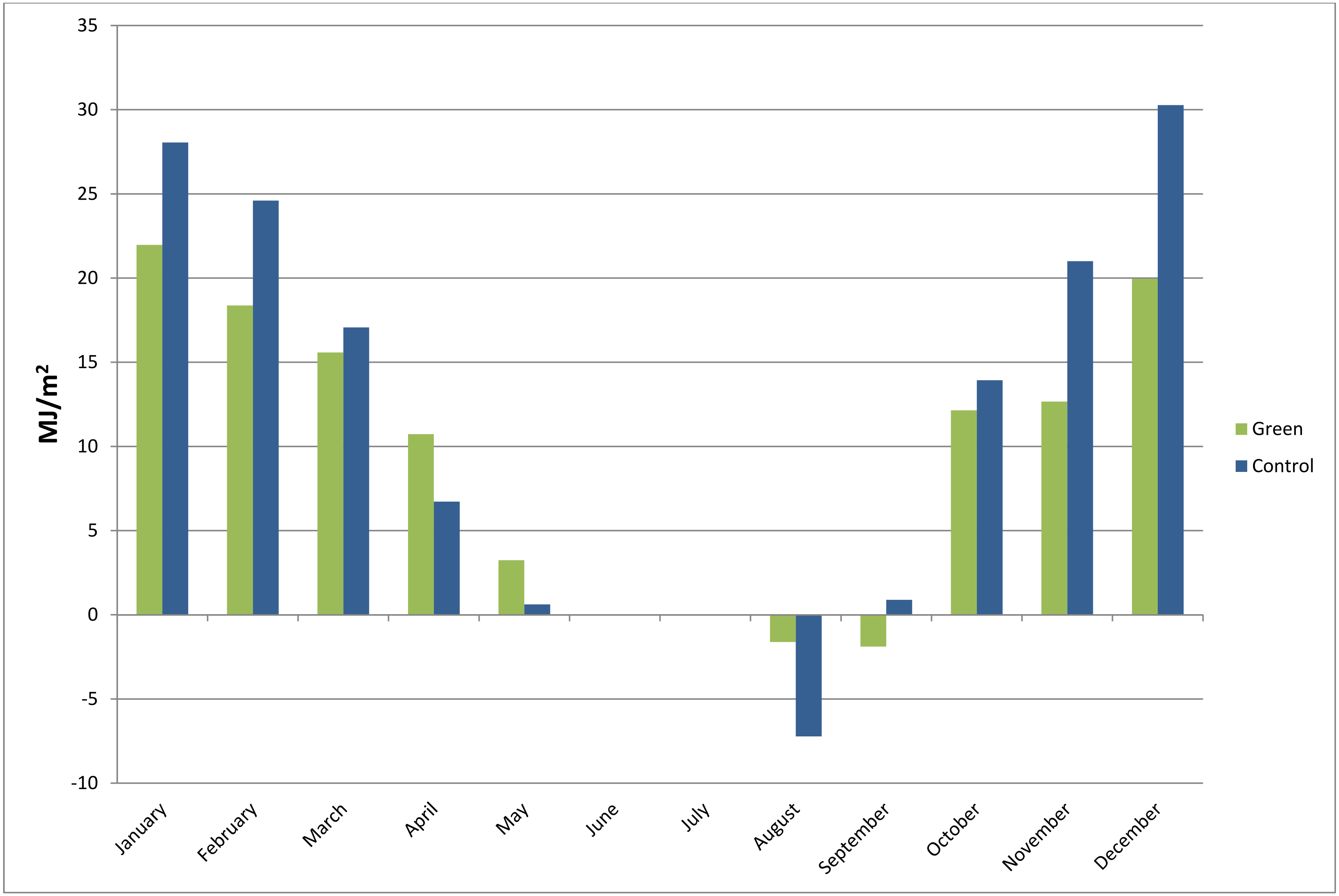

Figure 6: Heat loss or gain per month for Hamerschlag Hall green roof and Porter Hall control roof in 2010

Figure 7: Average weekly heat flux through conventional roof layers in green roof and control roof at ACOB, June 2010 through April 2011

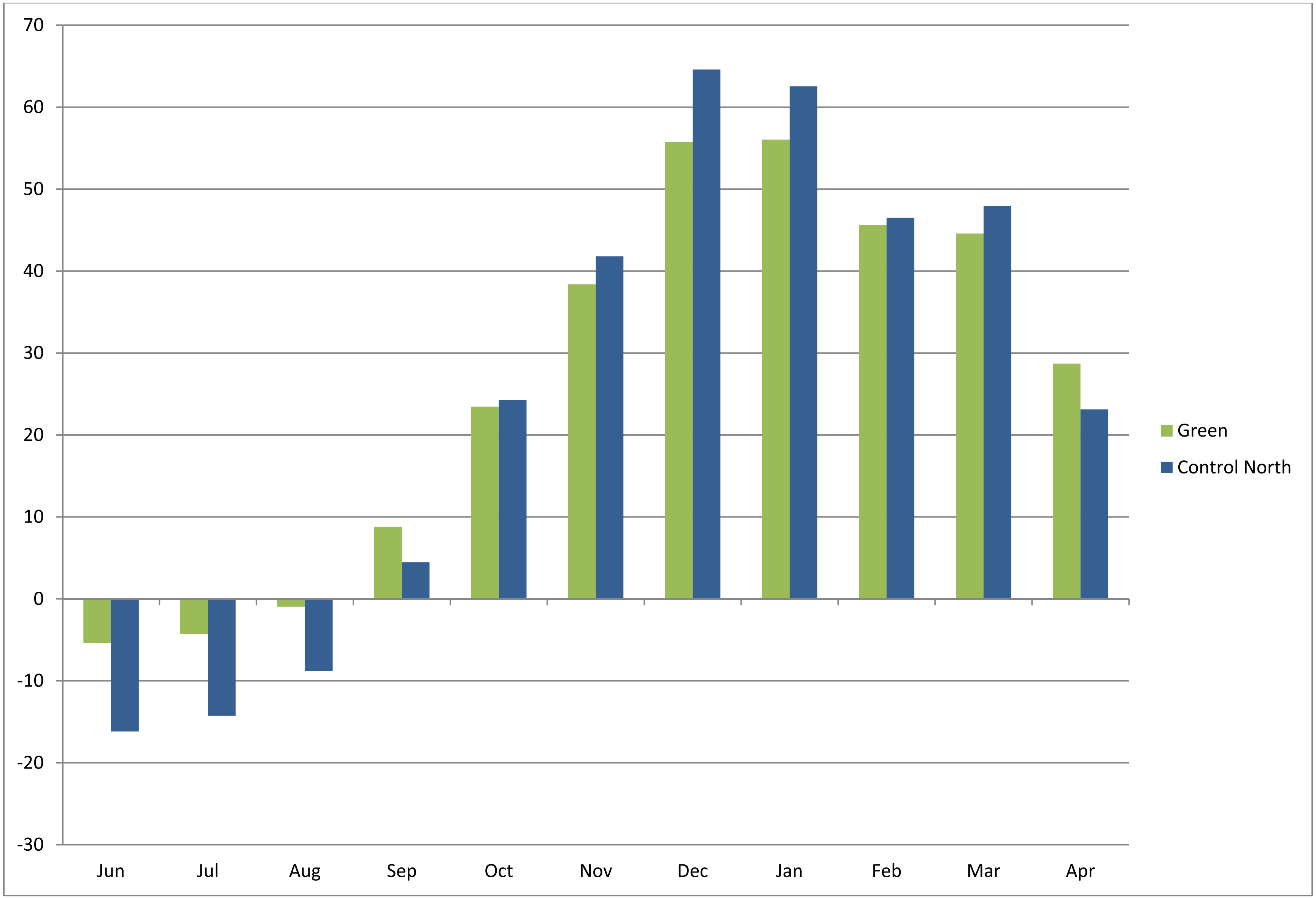

Figure 8: Heat loss or gain per month for ACOB green roof and control roof, June 2010 through April 2011