An environmental cost-benefit analysis of alternative green roofing strategies

Reshmina William^a, Allison Goodwell^a, Meredith Richardson^a, Phong V. V. Le^a, Praveen Kumar^{a,b,*}, Ashlynn S. Stillwell^a,

^a*Department of Civil and Environmental Engineering, University of Illinois, Urbana, IL 61801, USA*

^b*Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61801, USA*

Abstract

Green roofs and cool roofs are alternative roofing strategies that mitigate urban heat island effects and improve building energy performance. Green roofs consist of soil and vegetation layers that provide runoff reduction, thermal insulation, and potential natural habitat, but can require regular maintenance. Cool roofs involve a reflective layer that reflects more sunlight than traditional roofing materials, but require additional insulation during winter months. This study evaluates several roofing strategies in terms of energy performance, urban heat island mitigation, water consumption, and economic cost. We use MLCan, a multi-layer canopy model, to simulate irrigated and non-irrigated green roof cases with shallow and deep soil depths during the spring and early summer of 2012, a drought period in central Illinois. Due to the dry conditions studied, periodic irrigation is implemented in the model to evaluate its effect on evapotranspiration. Traditional and cool roof scenarios are also simulated by altering surface albedo and omitting vegetation and soil layers. We find that both green roofs and cool roofs significantly reduce surface temperature compared to the traditional roof simulation. Cool roof temperatures always remain below air temperature and, similar to traditional roofs, require low maintenance. Green roofs remain close to air temperature and also provide thermal insulation, runoff reduction, and carbon uptake, but might require irrigation during dry periods. Due to the longer lifetime of a green roof compared to cool and traditional roofs, we find that green roofs realize the highest long term cost

*Corresponding author

Email address: kumar1@illinois.edu (Praveen Kumar)

savings under simulated conditions. However, using longer-life traditional roof materials (which have a higher upfront cost) can help decrease this price differential, making cool roofs the most affordable option due to the higher maintenance costs associated with green roofs.

Keywords: Green roofs, cool roofs, energy costs, ecohydrology

1. Introduction

The emergence of highly urbanized landscapes has led to a plethora of environmental problems such as increased storm runoff, degraded water and air quality, high building energy use, and the urban heat island (UHI) effect. Green building standards incentivize passive technologies that reduce the energy and environmental footprint of structures [1] and mitigate many of these problems. One simple strategy to improve building energy efficiency is to increase roof thermal insulation. Cool roofs and green roofs are alternative methods that also promote the natural reduction of air temperatures during the summer months. Cool roofs involve a highly reflective layer [2] to reflect incoming radiation and absorb less heat than a conventional roof, while a green roof is a rooftop with a planting medium and partial to complete vegetation coverage [3]. There are various trade-offs involved in the implementation of either alternative roofing strategy in terms of building energy efficiency, UHI effect reduction, cost, and other environmental concerns such as water consumption and runoff reduction. Particularly for green roofs, performance is highly dependent on seasonal climate variability and vegetation composition [4, 5], and must be assessed on a regional basis. We introduce a detailed modeling approach to compare performance and trade-offs between green roofs, cool roofs, and traditional roofs during a dry spring and summer season in central Illinois.

Cool roofs have similar installation and maintenance costs as traditional roofs, and effectively reduce rooftop temperatures in hot climates. However, they can increase energy costs in colder climates due to their decreased heat absorption capacity [2], and must be combined with added insulation to keep buildings warm during the winter [6]. Green roofs have multiple benefits, making them an attractive solution for many issues facing urban areas. Similarly to cool roofs, green roofs can significantly reduce the UHI effect [4, 6–9] due to increased reflectivity. In addition to reducing ambient air temperatures in hot climates, the soil and vegetation layers of green roofs provide natural insulation that mitigates short-term fluctuations in air temperature [8]. This natural insulation leads to reduced building cooling

33 requirements during the summer and reduced heating during the winter [9].
34 Finally, rooftop vegetation can increase biodiversity [10], improve air quality
35 through leaf carbon uptake, and reduce stormwater runoff [11]. Plant species
36 are typically chosen to be drought resistant and have shallow taproots [12],
37 and include sedums, other succulents and local native species [13, 14]. A
38 potential disadvantage of green roofs is the moisture requirement for plant
39 species during dry periods. Water availability dictates soil moisture and
40 vegetation health, which both impact the cooling or insulating properties
41 of the rooftop [5–7, 11]. Depending on plant species, soil depth, and wa-
42 ter retentive properties, a green roof might require added maintenance and
43 irrigation during drought periods.

44 Recent studies include analysis of green or cool roof thermal properties
45 [6, 7, 15–17], hydrologic characteristics [11, 18], or the impact of moisture
46 conditions on thermal properties [5]. In most studies, the vegetation canopy
47 layer is assumed to be vertically homogeneous [19], and certain aspects are
48 set as constants or are not considered, such as soil moisture [19], precipita-
49 tion intensity [15], or vegetation characteristics [18].

50 In this study, we take a detailed modeling approach to evaluate green roof
51 and cool roof performance compared to traditional roofs in terms of temper-
52 ature, water consumption, and economic cost. We use MLCan, a multi-layer
53 canopy model, which resolves the water and energy balance through coupled
54 soil and vegetation layers [20, 21]. We simulate intensive (deep soil layer) and
55 extensive (shallow soil layer) green roof cases over a 72-day drought period
56 over the spring and summer of 2012 in central Illinois, U.S.A. In terms of
57 water consumption, we consider a dry study period as a worst-case scenario
58 in terms of vegetation water stress and potentially high irrigation require-
59 ments. We simulate the effect of added irrigation on vegetation behavior,
60 evaluating the benefit of irrigation as part of regular maintenance [5]. To
61 model roof impacts on ambient and interior temperature, we also simulate
62 traditional and cool roof cases using MLCan and compare green roofs, cool
63 roofs, and traditional roofs in terms of surface temperatures and heat fluxes.
64 The results of the temperature analysis show the effect of the surface reflec-
65 tivity and insulating layers on both building energy requirements and the
66 UHI effect. The results of the modeling analysis are integrated to perform a
67 cost comparison of types of roofs in terms of installation, maintenance, and
68 energy costs.

69 2. Materials and Methods

70 2.1. Study Site and Forcing Data

71 We study the Business Instructional Facility (BIF) green roof at the Uni-
72 versity of Illinois at Urbana-Champaign which was installed in 2008 to satisfy
73 requirements for LEED (Leadership in Energy and Environmental Design)
74 platinum status. The roof is comprised of four monolithic vegetated beds
75 that cover a total of 372 m². Each of the beds contains nine species of se-
76 dums, herbaceous plants and native grasses. The planting medium depth is
77 20 cm, and the roof is classified as intensive. However, the monolithic struc-
78 ture and lower maintenance needed for this roof means that it is further
79 classified as “simple intensive”. The planting medium is engineered high-
80 porosity LiteTop media with a water retention panel underneath. Sensors
81 on the green roof measure air temperature (T_{air}), relative humidity (RH),
82 wind speed (U), and incoming radiation (R_g) at a 2.2 m height, in addition
83 to rainfall (PPT) and volumetric moisture content (θ), all at 1-minute in-
84 tervals. An additional conventional roof is located adjacent to and 4.3 m
85 above the green roof. This conventional roof partially shades the green roof
86 until about 10:00 a.m., causing lower than expected observed R_g and T_a in
87 the early morning. Further details of the placement and calibration of the
88 sensors can be found in [22].

89 We averaged the 1-minute data from the BIF green roof to 30-minute
90 intervals for simulations. We selected the dates of March 29 to June 11,
91 2012 (Julian Days of Year (DOY) 88-160) based on data availability and
92 as an example of a particularly dry period. Several gaps in wind speed
93 during the period were filled using bias-corrected hourly data from the Na-
94 tional Oceanic and Atmospheric Administration (NOAA) at Champaign,
95 Illinois [23]. Hourly atmospheric pressure (P_a) data were obtained from
96 North American Land Data Assimilation System (NLDAS) [24] forcing data
97 for a grid point in central Illinois and interpolated to half-hourly for input
98 forcing data.

99 We also referred to the BIF green roof setup for information on the
100 vegetation types typically planted on an Illinois green roof as well as soil
101 characteristics. For green roof simulations, we chose the plant *Koeleria*
102 *macarantha* (prairie junegrass). This native grass species is used in many
103 green infrastructure applications, including green roofs [12], and is one of
104 the native grasses used on the BIF green roof. It is highly resistant to heat,
105 cold, and drought, and has an average leaf area index (LAI) of 3.6 [25] and
106 an approximately vertical leaf distribution. In general, a higher LAI leads to
107 more latent heat flux and consequently more cooling of the roof. We chose

an intermediate value to decrease water demand and be representative of the spring and early summer seasons.

2.2. Ecohydrological modeling of green roofs

Green roof simulations are performed using the vertically-resolved canopy-root-soil model, MLCan [20, 21]. The model incorporates explicit coupling between leaf-level ecophysiological processes (photosynthesis and stomatal conductance), physical processes (energy balance and boundary layer conductance), and below-ground states (soil water content and soil temperature) to capture interactions between soil, vegetation, and climate. MLCan incorporates both C3 and C4 photosynthetic pathways and resolves the vertical radiation, thermal, and environmental regimes within the canopy and soil-root systems. The model has been validated for both C3 and C4 vegetation [20, 26] and evaluated for its ability to capture acclimatory responses of vegetation to elevated CO₂ [26, 27].

In the above-ground system, MLCan resolves the short- and long-wave radiation regimes throughout the vertical canopy space. Radiation attenuation is in large part determined by the vertical distribution of foliage characterized by the leaf area density (LAD). MLCan provides predictions of photosynthetic CO₂ assimilation and respiratory losses, as well as latent (LE) and sensible heat (H) fluxes for each canopy layer. This prediction is done through consideration of the energy balance for both sunlit and shaded leaf fractions. Water storage on foliage as a function of dew or rainfall interception is likewise considered.

In the below-ground system, soil moisture and soil heat are resolved throughout the vertical soil domain. While throughfall, soil evaporation, and plant transpiration provide the surface flux boundary conditions and sinks/sources for the soil moisture model, ground heat flux into the soil obtained from the surface energy balance sets the flux boundary conditions for the soil heat model. Variation of soil temperature at the surface and bottom of the soil profile over the course of the day is used to evaluate the efficacy of green roof strategies. For the soil moisture model, in addition to plant water uptake, hydraulic redistribution [28] is included to simulate the passive transport of moisture throughout the root and soil column following water potential gradients. In our simulations, thin soil layer discretization (~ 1 cm) is used to accurately capture the distribution of temperature and moisture in shallow soil depth simulations. In addition, the efflux of CO₂ from the soil surface is determined using a simple model to account for the known temperature dependence of soil respiration in the net carbon balance [29].

2.3. Roofing Scenarios

Extensive and intensive green roof conditions (20 cm and 50 cm of planting media, respectively) were compared with traditional roofs and cool roofs (Figure 1). To simulate non-vegetated roof conditions, the MLCAn model and forcings were adjusted to reflect extremely low ($\theta = 0.01$) soil moisture, no vegetation ($LAI = 0$), and no precipitation. This approximation assumes that there is no ponding on the roof, and that any evaporation of moisture would have a negligible effect of cooling of the roof surface. The soil reflectivity (albedo) was set to 0.95 to simulate a white (cool) roof, and 0.05 to simulate a black (traditional) roof. For comparison, the soil reflectivity of the green roof is set to 0.2. However, the main drivers of reflectivity and energy balance partitioning for the green roofs are the moisture and vegetation conditions, which do not exist in the traditional and cool roof cases.

Figure 1: The four roofing strategies simulated using MLCAn are (a) a traditional (black) roof, (b), a cool (white) roof, (c), an extensive green roof with 0.2 m soil layer, and (d) an intensive green roof with 0.5 m soil layer.

Most green roofs include both a high-porosity, high-conductivity planting medium to increase infiltration and a water retention panel underneath this layer to improve the unit's overall water storage properties. For the extensive and intensive cases, 20 and 50 soil layers were simulated, respectively. In the simulation, the top soil layer has a hydraulic conductivity of $12\text{e-}3$ m/s and has a slight exponential increase for deeper layers due to compaction and a free-flow bottom boundary. Due to lack of soil moisture data at multiple layers of the study green roof, we assume that this conductivity and boundary layer condition balance the effects of the porous planting medium, water retention panel, and roof drainage. To assess the need for irrigation during the study period, we simulated both extensive and intensive green roof cases with and without artificial irrigation. On days preceded by

48 hours of dry conditions (no precipitation), 1 mm of precipitation was added between 6:00 a.m. and 6:30 a.m. (Figure 5a,b). This condition was met for 40 of the 73 simulated days, so that the total irrigation depth is 40 mm during the study period. Table 1 provides a summary of the different scenarios compared for this study.

Table 1: Summary of scenario properties

Roof type	LAI [m ² /m ²]	Soil reflectivity	Soil depth [m]	Description
T-1	0	0.05	0.01	Traditional (Black), no PPT, no irrigation
T-2	0	0.95	0.01	Cool (White), no PPT, no irrigation
T-3	3.6	0.2	0.2	Green extensive roof, PPT only
T-4	3.6	0.2	0.2	Green extensive roof, PPT and irrigation
T-5	3.6	0.2	0.5	Green intensive roof, PPT only
T-6	3.6	0.2	0.5	Green intensive roof, PPT and irrigation

2.4. Roofing alternatives cost analysis

To model the impact of multiple changes such as wall insulation, leakage and roofing on a building’s interior climate, researchers often use complex software to model the impact of circulation and the heating, ventilation and air conditioning (HVAC) system on building temperatures [30]. However, in this study we solely focus on the detailed energy analysis of the rooftop obtained from this model. The modeling analysis provides bottom-of-soil (or, in the case of the traditional and cool roofs, rooftop) temperatures, and we estimate the amount of heat leaving or entering the building using a simple conductance model. The conductance model states that the heat flux into the building is determined by the thermal resistance (R-value) of the concrete and the insulation material, and the temperature difference between the bottom of the soil (or rooftop) and the desired internal building temperature. Based on this heat model, we estimate energy cost for building operation based on current pricing data and installation costs. This study assumes that the main factors that impact building temperatures are the type of roof and the depth of roof insulation, and that other factors such as energy leakage remain constant. The conductance model works to model the heat transfer into the top floor of the building. In other words, the study estimates the incremental change in the energy required to heat or cool the building due to different types of roofing without considering the complexities of modeling the building’s internal HVAC system.

It is recommended that building temperatures be kept between 21 °C and 23 °C for occupants’ health and comfort [31]. The lower bound of

201 this temperature range was selected as the desired building internal tem-
 202 perature. Most steel structure buildings have a corrugated metal roof deck
 203 surrounding a layer of insulation and covered with waterproofing. Green
 204 roofs have additional loadings associated with the dead weight of the soil
 205 layer and vegetation and the transient loads of any water stored in the soil
 206 [32]. Consequently, roof decks supporting green roofs often contain 7.6 cm
 207 of unreinforced medium strength concrete in addition to extra bracing be-
 208 neath the deck. This depth of unreinforced concrete typically has an R-value
 209 (thermal resistivity) of $0.0461 \text{ }^{\circ}\text{C m}^2/\text{W}$ [33]. In comparison, a typical 2.54
 210 cm (1 in) thick roof insulation unit has an R-value of $0.31 \text{ }^{\circ}\text{C m}^2/\text{W}$ (6.0
 211 $^{\circ}\text{F ft}^2/\text{W}$); a typical 5.08 cm (2 in) unit has an R-value of $0.62 \text{ }^{\circ}\text{C m}^2/\text{W}$
 212 ($12.1 \text{ }^{\circ}\text{F ft}^2/\text{W}$) [34]. Energy cost analyses were conducted for both the 2.5
 213 cm and the 5 cm insulation on the green roof, cool roof and traditional
 214 roof to allow for comparison. R-values are additive for materials in series,
 215 allowing us to calculate the transmittance of heat from the bottom of the
 216 soil through both the concrete and insulation. This additivity allows us to
 217 consider the insulative properties of the composite design of the roof. A
 218 conductance model based on a simple 1-D heat flux equation can be used
 219 to solve for the power required to heat or cool the building, as shown in
 220 Equation 1. Other studies have shown that when only building roof charac-
 221 teristics are in consideration, this simplified approach gives an appropriate
 222 estimate of the building heat flux from the roof [35].

$$Q = \frac{1}{R_c + R_i} \times A \times \Delta T \quad (1)$$

223 in which Q is the power required to heat or cool the building in each half-hour
 224 timestep in watts; A is the area of the roof (371.61 m^2 for the study site);
 225 ΔT is the difference in temperature ($^{\circ}\text{C}$) between the bottom-of-soil temper-
 226 ature (T_b) and the desired indoor temperature of $21 \text{ }^{\circ}\text{C}$; and R_c and R_i are
 227 R-values representing the thermal resistivity of the concrete and the insula-
 228 tion, respectively. As previously mentioned, for this analysis, $R_c = 0.0461$
 229 $^{\circ}\text{C m}^2/\text{W}$, $R_i(2.5 \text{ cm}) = 0.31 \text{ }^{\circ}\text{C m}^2/\text{W}$, and $R_i(5.1 \text{ cm}) = 0.62 \text{ }^{\circ}\text{C m}^2/\text{W}$.
 230 For the green roof, $\Delta T = T_b - 21$; note that for the cool and traditional roofs,
 231 $T_b = T_{surf}$. To convert from watts (W) to kilowatt-hours (kWh) for each
 232 30-minute timestep, the power (Q) was multiplied by a factor of 5×10^{-4} .

233 Real-time pricing data produced by U.S. energy company Ameren were
 234 used to generate hourly electricity prices for the time period of the MLCan
 235 simulations [36]. Because data were not publicly available for the 2012
 236 time period, 2014 data were used as a reasonable representation of trends.
 237 Heating for the study area is typically provided by the Abbott Power Plant

(a combined heat and power facility supporting the university campus), which predominantly uses natural gas to generate steam, but uses some coal during the winter [36]. Natural gas monthly pricing averages for March-June 2014 were obtained from the US Energy Information Administration (EIA) [37]. Based on typical values, we estimated the heating efficiency for the building HVAC system to be 75% and the cooling coefficient of performance (COP) to be 2.2 [30].

Green roof installation costs vary significantly, depending on the roofing structure, types of plants, and existing drainage. Installation costs start at \$215/m² for extensive green roofs [38][J. Bruce, personal communication, May 12th 2016] and \$323/m² for intensive green roofs [38][J. Bruce, personal communication, May 12th 2016], with an annual maintenance cost of \$8/m² [39]. However, maintenance costs might be higher depending on the vegetation types and other green roof properties, such as the type of planting media and rooftop drainage systems used [39]. Green roofs have a typical design life of 30-50 years, due to the protection that the vegetation and soil provide from physical and UV damage [38, 40–42]. For this study, we assumed an average green roof life-span of 40 years.

A typical (traditional) three-ply asphalt built-up roofing system costs \$129/m² and has a design life of 10 years [42] [J. Bruce, personal communication, May 12th 2016]. We anticipate that a typical cool roof installation using reflective paint will not cost significantly more than installing a traditional roof and will also have a similar design life. However, we conducted a sensitivity analysis to investigate the impact of installing a traditional/cool roof with a slightly higher up-front cost but a higher design life. A modified, more expensive, roofing system has a cost of \$151/m² and a design life of 20 years [42] [J. Bruce, personal communication, May 12th 2016]. Maintenance costs for both traditional and cool roofs are usually estimated at around 2% of the installation cost annually to ensure that the roof lasts for its full design life [43]. These prices, along with the calculated building energy costs, are used to determine an annualized cost associated with each of the roofing types considered over a 39-year period, assuming an average 3.5% annual interest rate [44]. A similar analysis was conducted using a 7% interest rate, with similar conclusions.

3. Results and Discussion

3.1. Roof Temperature

During the spring and early summer study period, the average peak air temperature T_{air} is about 23 °C (Figure 2), with average night-time

276 temperatures of 14 °C. T_{air} reaches a day-time peak of 35 °C near the end
 277 of the study period (Figure 3b) and a night-time minimum of 0 °C early in
 278 the study period (Figure 3a). The green roof soil surface temperature is very
 279 similar for all cases; the extensive green roof with irrigation case is presented
 280 as an example (Figure 2). The variation of soil surface temperature T_{surf}
 281 closely follows T_{air} , with $T_{surf} > T_{air}$ during the day and $T_{surf} < T_{air}$ at
 282 night. The cool (white) roof temperature remains on average about 4 °C
 283 below T_{air} regardless of time of day. In contrast, the traditional roof T_{surf}
 284 is nearly equal to T_{air} at night, but is on average 25 °C higher than T_{air}
 285 during the time of peak solar radiation (Figure 2).

Figure 2: The average diurnal surface temperature for different roofing strategies compared to air temperature shows extreme heating of traditional roof surface compared to alternative roof types. The extensive green roof (GE-Bottom) bottom layer temperature indicates the insulating effect of the soil layers.

286 Particularly at the beginning of the study period in late March, the cool
 287 roof T_{surf} is several degrees below T_{air} (Figure 3c). On rainy or cloudy days
 288 during this several day period, the traditional roof T_{surf} is only slightly
 289 higher than T_{air} . On other days, the traditional roof T_{surf} is up to 40
 290 °C warmer than T_{air} (Figure 3c,d). When considered over large surface
 291 areas, this temperature difference demonstrates the drastic effect that a
 292 non-reflective surface can have on the urban heat island effect.

293 We also consider the implications of roofing types in terms of building
 294 energy use. For the green roof cases, the bottom layer soil temperature
 295 dictates the necessary amount of building energy used for heating or cooling,
 296 notwithstanding any other layer of insulation. The soil depth dictates the
 297 damping and lagging of the diurnal T_{air} signal. For the intensive (0.5 m soil

Figure 3: Air temperatures during (a) coolest 5-day period (DOY 100-105) and (b) warmest 5-day period (DOY 145-150) illustrate the range of temperature conditions for green roof simulations. The difference between air and surface temperatures ($\Delta T = T_{surf} - T_{air}$) for the different roof types during the coolest period (c) and the warmest period (d) show heating of the traditional roof surface, cooling of the cool roof surface, and maintenance of green roof temperature close to air temperature. The difference between roof bottom temperature and desired interior temperature of 21 °C ($\Delta T = T_b - 21$) for the coolest (e) period shows that traditional roofs require cooling during the day and heating at night, and cool roofs always require heating. During the warmest period (f), the traditional roof is always warmer than desired indoor temperature.

depth) green roof simulation, the diurnal temperature signal is extremely small at the bottom layer (Figure 3e,f). In general, the intensive green roof is a better moderator of indoor temperatures and energy consumption than the extensive roof due to the greater soil depth. However, a trade-off is the necessary structural support for the increased volume of soil in addition to the higher installation costs. The main difference between green roof cases in terms of temperature is due to the extensive and intensive soil depths, but the addition of irrigation caused slight decreases in soil temperature as well.

306 This decrease is due to an increase in evaporative cooling, or LE , from the
 307 additional moisture, so that less heat is absorbed by the soil and transferred
 308 to the building. Compared to traditional and cool roofs, all green roof cases
 309 maintain soil bottom temperatures closer to T_{air} . During the coolest several
 310 day period of the study, cool roof temperatures are up to 20 °C below the
 311 desired interior building temperature of 21 °C (Figure 3e), indicating the
 312 need for additional heating or added insulation. Day-time traditional roof
 313 T_{surf} is significantly higher than the building temperature even during cool
 314 periods near the beginning of the study. During warm periods, traditional
 315 roof T_{surf} is 50 °C above the desired interior temperature (Figure 3f).

316 In general, we see that the cool roof and green roofs behave similarly in
 317 terms of mitigating the UHI effect, maintaining T_{surf} equivalent to or lower
 318 than T_{air} . Cool roofs most actively decrease the UHI effect, but surface tem-
 319 peratures are very low during cool periods, necessitating additional building
 320 heating, as described in Equation 1 [35]. A future avenue for roofing ma-
 321 terials is the implementation of directionally reflective materials [45] that
 322 can absorb more heat when the sun angle is low to avoid excessive cooling.
 323 In contrast to cool and traditional roofs, green roof soil layers inherently
 324 provide an insulating layer, causing green roofs to be more efficient in terms
 325 of building heating and cooling. Both types of green roofs (intensive and
 326 extensive) are similar in terms of surface temperature but vary in terms of
 327 soil bottom temperatures due to the soil depths (Figure 3e,f).

328 3.2. Green Roof Ecohydrology

329 For the irrigated green roof cases, an increase in average diurnal LE is
 330 observed starting at 6:00 a.m., the hour of irrigation addition on days pre-
 331 ceded by dry periods (Figure 4a). The added water maintains the increased
 332 LE through most of the day. This effect corresponds to reduced energy par-
 333 titioning to H (Figure 4,b). We see that irrigation serves to increase carbon
 334 uptake (An), indicating that the vegetation is functioning more optimally
 335 due to the added moisture (Figure 4c). Due to the previously mentioned
 336 shading effect until 10:00 a.m. on the green roof, we see low LE , H , and
 337 An in the early morning. The addition of irrigation does not appear to sig-
 338 nificantly impact surface or soil temperatures, but it is an important factor
 339 to consider in terms of the potential maintenance and water use required to
 340 ensure vegetation health during dry periods. For both irrigated and non-
 341 irrigated cases, H is positive during the day, indicating that the surface is
 342 warming the atmosphere.

343 In addition to damping diurnal temperature variation and reducing the
 344 urban heat island effect, green roofs provide the benefit of reduced surface

Figure 4: A comparison between non-irrigated and irrigated green roof simulation shows increased vegetation activity in irrigated cases through (a) increased diurnal latent heat flux LE , (b) decreased sensible heat flux H , and (c) increased photosynthetic rate during the afternoon hours.

runoff due to storage in the planting media and subsequent evaporation and transpiration. However, in non-irrigated cases, near surface soil moisture is extremely low during several days of the study, particularly for the extensive

Figure 5: MLCAN simulations were performed (a) without irrigation and (b) with 1 mm of irrigation during dry periods for both extensive and intensive green roof cases. (c) Extensive (20 cm depth) green roof soil moisture (θ) is extremely low during dry periods without irrigation, and irrigation greatly increased soil moisture (d). Intensive (50 cm depth) green roof soil moisture is higher throughout study period (e), and increased slightly with irrigation (f).

Figure 6: Cumulative precipitation (PPT) and evapotranspiration (ET) for irrigated and non-irrigated extensive green roof cases show increased ET due to irrigation. The same increase in ET was observed for the intensive roof simulation.

green roof case (Figure 5c). For both green roof types, the addition of irrigation during dry periods increases soil moisture (Figure 5) and results in higher evapotranspiration (ET) than the non-irrigated case (Figure 6). Higher ET and An for irrigated cases indicate improved vegetation health due to the irrigation. In terms of runoff reduction, we see that precipitation is retained in the soil layer to be evaporated from the soil or transpired by the canopy. In certain climatic regions, precipitation might be adequate for green roofs to thrive for most of the year, but the need for irrigation might constitute an added cost during dry periods. In certain regions, the additional cost of water should thus be included in the cost-benefit analysis.

3.3. Roof Cost Analysis

Table 2 shows the average daily heating and cooling costs associated with each of the roof types investigated with 2.5 cm thick roof insulation. Typically, the highest cooling costs are incurred on the traditional and cool roofs starting from late morning through mid-afternoon, peaking at around 3:00 p.m. Conversely, the highest cooling costs for the green roofs typically are lagged by around five hours, and peak at around 8:00 p.m. (Figure 7). All five of the alternative roofs show significant cost savings compared to the traditional roof, and the cool roof results in the least savings. The cool roof decreases the roof temperature significantly, eliminating cooling costs but increasing heating cost to maintain the desired interior temperature. Although the price of natural gas is an order of magnitude lower than the price of electricity, heating costs ultimately make the cool roof less cost-effective in terms of energy consumption than the green roof technologies. The highest energy cost savings are associated with the intensive (0.5 m) green roof. Irrigation does not make a large difference in cost savings, assuming that the cost of water is negligible compared to energy costs in Central Illinois. However, water consumption can be a significant limitation to green roof implementation in dry areas with high water costs. The most important factor in energy costs is the roof insulation, and we see that overall energy costs are almost halved by doubling the thickness of the roof insulation (Table 2).

In the case of the low-cost asphalt roofing, over the course of a 39-year timespan the intensive green roof has the highest annual cost, while the extensive green roof has the one of the lowest (Table 3). This discrepancy is due to the difference between the initial installation costs for the two types of green roofs. The cool roof shows significant savings in maintenance and energy costs compared to the green roofs. However, the recurring cost of replacing the cool roof every 10 years drives up the costs in the long-term. On the other hand, if the green roof scenarios are compared against the more

Table 2: Average monthly energy cost savings for different roof types

Roof type	Heating Costs [\$]		Cooling Costs [\$]		Total Costs [\$]		ΔTC [\$]†	
	2.5 cm	5.0 cm	2.5 cm	5.0 cm	2.5 cm	5.0 cm	2.5 cm	5.0 cm
T-1	12.6	6.2	120.9	60.0	133.5	66.2	—	—
T-2	23.0	11.4	9.3	4.6	32.3	16.0	-101.2	-50.2
T-3	11.6	6.1	9.7	5.2	21.3	11.3	-112.2	-54.9
T-4	11.5	6.1	10.1	5.4	21.7	11.5	-111.8	-54.7
T-5	10.9	5.8	4.9	2.6	15.7	8.3	-117.8	-57.9
T-6	10.7	5.7	5.1	2.7	15.9	8.4	-117.6	-57.8

†Difference in total cost from T-1

Figure 7: A plot of the diurnal average combined heating and cooling costs for traditional, cool, and green roof scenarios show costs that vary with time of day. The bottom inset highlights the higher cost for cool roofs (the pink dashed line) during the night. The top inset highlights the difference between the cool and green roof in the late afternoon.

expensive 20-year lifespan cool and traditional roofs, we see that the long-lifespan cool roof is in fact the most cost effective alternative. This result is due to the higher maintenance costs of the green roofs – almost three times higher than the cool roof. Although the cost of the cool roof installation is higher, the green roof turns out to be more expensive overall. Comparing the annual costs between the roofs with 2.5 cm versus 5 cm insulation, we see that the added insulation has the greatest impact on the traditional roof, decreasing the annual cost by nearly \$700.

395 4. Conclusions

396 Alternative roofing strategies are an attractive means of both mitigating
397 environmental impacts and reducing costs. Table 4 summarizes key aspects
398 of the comparison of traditional and alternative roofing techniques. On
399 average, the traditional roof is 7 °C higher than T_{air} and 3 °C higher than
400 the desired interior temperature. Later in the summer these temperature
401 differences are expected to be even higher. Cool roofs have the largest
402 impact in terms of reducing roof temperatures and mitigating the urban
403 heat island effect. As shown in Table 4, cool roof average temperatures
404 are far below both T_{air} and interior temperature and would be expected to
405 be closer to interior temperatures as the summer progresses. However, the
406 required building heating when the air temperatures are cooler leads to high
407 overall energy costs compared to green roofs for the time period of study.
408 The green roof temperatures are very close to T_{air} and similar to the cool
409 roof in terms of interior temperatures. The green roof soil layers provide an
410 extra insulating layer that dampens diurnal variations in temperature. This
411 additional temperature consistency leads to lower daily averaged cooling and
412 heating costs. All alternative roofing strategies have lower average costs
413 than the traditional roof, indicating the economic feasibility of any of these
414 techniques.

415 The temperature reduction and damping of the diurnal temperature sig-
416 nal are particularly important in late spring/early summer when nighttime
417 temperatures are still fairly low but daytime temperatures require some sort
418 of cooling. The balance between heating and cooling is a significant annual
419 cost, and it is advantageous to minimize the switching between heating and
420 cooling. While natural gas prices are not currently increasing, it is never-
421 theless important for future economic sustainability to ensure that heating
422 costs are not unnecessarily high.

423 In terms of other aspects of green roofs, the simulated green roof cases
424 show the complete elimination of stormwater runoff from the rooftop. Note,
425 however, that green roofs do not always eliminate stormwater runoff for all
426 storms, but rather delay and attenuate peak runoff. Since the study period
427 is under a drought condition, we see improved green roof vegetation health
428 and performance with the addition of irrigation. For the 372 m² roof under
429 consideration, 0.2 m³ of daily added water causes an average increase of 0.07
430 m³ of evapotranspiration and 0.06 kg of carbon uptake per day. The addi-
431 tion of irrigation also helps to decrease rooftop temperatures, but this effect
432 is relatively small compared to the differences between roof techniques. Fi-
433 nally, we show in Table 4 that the carbon uptake of the green roof ecosystem

Table 3: Breakdown of net present value (NPV) and annual costs for different roofs with 2.5 cm and 5 cm insulation

Roof type	Monthly Energy Cost [\$]		Annual Maint. Cost [\$]		Installation Cost [\$]		Total NPV [\$]		Annual Cost [\$]	
	2.5 cm	5.0 cm	2.5 cm	5.0 cm	2.5 cm	5.0 cm	2.5 cm	5.0 cm	2.5 cm	5.0 cm
T-1	33,000	16,400	20,300	20,300	123,300	123,300	176,500	159,900	8,300	7,600
T-1L ^a	33,000	16,400	23,600	23,600	84,100	84,100	140,800	124,100	6,600	5,800
T-2	8,000	4,000	20,200	20,300	123,300	123,300	151,500	144,000	7,100	6,900
T-2L ^b	8,000	4,000	23,600	23,600	84,100	84,100	115,800	144,000	5,400	5,200
T-3	5,300	2,800	61,200	61,200	80,000	80,000	146,400	183,200	6,900	6,700
T-4	5,400	2,800	61,200	61,200	80,000	80,000	146,500	183,300	6,900	6,700
T-5	3,900	2,000	61,200	61,200	120,000	120,000	185,100	183,200	8,700	8,600
T-6	3,900	2,100	61,200	61,200	120,000	120,000	185,100	183,300	8,700	8,600

^a Longterm traditional black roof

^b Longterm cool white roof

Table 4: Average Daily Statistics for 372 m² roof

Roof Type	Water			Carbon	Temperature [†]		Cost
	Runoff [m ³ /d]	Irrigation [m ³ /d]	ET [m ³ /d]	Uptake [kg C/d]	$\bar{T}_{surf} - \bar{T}_{air}$ [°C]	$\bar{T}_b - 21$ [°C]	Daily Total [\$]
T-1	0.68	0.00	–	–	6.95	3.25	0.141
T-2	0.68	0.00	–	–	-3.29	-7.00	0.016
T-3	0.00	0.00	0.73	0.87	0.02	-3.70	0.009
T-4	0.00	0.20	0.80	0.93	-0.02	-3.74	0.008
T-5	0.00	0.00	0.73	0.88	0.04	-3.74	0.002
T-6	0.00	0.20	0.80	0.94	-0.02	-3.80	0.002

[†] T_{surf} : Surface temperature

T_{air} : air temperature

T_b : temperature at bottom layer

is another significant environmental benefit, as rooftops might be one of the few opportunities for vegetated space in urban areas with high CO₂ concentrations. Although the carbon uptake reported in this study represents an intermediate storage rather than long term sequestration, it has been found that green roofs can have significant sequestration benefits similar to native ground vegetation [46]. This study does not account for carbon losses due to plant die off during the winter and subsequent mineralization of litter or carbon loss due to drainage.

In general, roof insulation is important, regardless of which roofing type is selected. Roof insulation helps to dramatically reduce the energy consumption for heating or cooling the building. For example, doubling the thickness of a conventional commercial insulation essentially halves the cost of energy. A cool roof with the proper insulation might achieve similar heating and cooling costs to a green roof. However, the repeated roof replacement required for a standard cool roof in the long-term makes it less cost-effective than the extensive green roof. Upgrading the type of roof to one with a higher upfront cost increases the life time of the roof, and makes the upgraded cool roof the most cost-effective option, due to the high maintenance costs associated with the green roof. It should be noted, however, that our cost analysis does not monetize the other major benefits or detractors of green roofs such as runoff reduction, improved air quality, and additional water consumption via irrigation. Overall, both cool and green roofs provide significant economic and environmental benefits within urban environments. However, the choice of which roof type is most appropriate is highly location-specific and should be carefully considered, in order to maximize benefits while keeping costs low.

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