Development and features of the Green Roof Energy Calculator (GREC)

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Sailor, D., Bass, B., 2014. Development and features of the Green Roof Energy Calculator. Journal of Living Architecture. 1(3): 36-58. [http://greenroofs.org/resources/JOLA2014Volume1\(Issue3\)SailorBass](http://greenroofs.org/resources/JOLA2014Volume1(Issue3)SailorBass)

Abstract

A data base-driven web tool has been developed from detailed energy modeling simulations to enable green roof practitioners to explore the energy, water, and urban climate implications of design decisions. Provided with basic characteristics of a green roof project, the Green Roof Energy Calculator performs a multi-layered interpolation within a database of 8000 simulations to estimate whole building energy use, storm water runoff, and sensible and latent heat exchange with the urban atmosphere. Output from each user query produces information for the specified green roof system, but also includes information for alternatives of both white and dark membrane roofs.

Keywords: Sustainable Roofing, Energy Budget, Building Energy Simulation, Cool Roofs

Introduction

A green roof is a roof covered by growing media (soil) and a vegetation layer. The growing media is usually a light weight mix of aggregate such as pumice and sand with a low content of organic matter (Sailor and Hagos, 2011; Graceson et al., 2013). There are many varieties of vegetation used on green roofs, but among the most common are variants of sedums (Dvorak and Volder, 2010). While green roofs have been in use for centuries, there recently has been a surge in interest in installing green roofs in both retrofit and new construction applications.

Green roofs provide many potential benefits. One of the most important benefits of green roof systems is that they can reduce the peak of storm water runoff as well as the magnitude (Czemieli Berndtsson, 2010). A growing body of literature indicates that the annual reduction in storm water runoff resulting from installing a green roof can be more than 50% (e.g., Carson et al., 2013; Jianjun et al., 2011). Of course, such benefits depend on the depth of the growing media, seasonal soil moisture status, precipitation patterns, and the design of the drainage layer for the green roof.

Other potential benefits of green roofs include provision of habitat (e.g., Lundholm, 2006), benefits to the urban atmospheric environment by reducing the magnitude of urban heat island (e.g., Susca et al., 2011), and building energy savings.

It is the building energy savings prospect which motivates the present study. Specifically, any roof treatment has the potential to alter heat flow through the roof, thus affecting heating and cooling demand for the building. It should be noted that this potential energy savings is primarily felt on the top floor of a building, and thus total energy savings depends on the surface area of the roof, being largely independent of building height. Furthermore, the cost of any roof

treatment (e.g. installing a white membrane roof or a green roof) is also primarily a function of the surface area of the roof, not the height of the building. Thus, any evaluation of the energy savings of such roof treatments should be considered in absolute terms (e.g., kWh) or on the basis of a per unit area of roof installation (e.g., kWh/m²). Thinking of such savings in terms of a percentage of whole building energy consumption saved would be inappropriate and misleading.

While the potential energy savings of green roofs is widely touted as an important benefit, with few exceptions it has not been studied in much detail. While “cool” (highly reflective) roofs have long been recognized for their energy savings potential (Akbari et al., 1999; DeSouto and Pickett, 2005), recent studies are also showing comparable effects for green roofs (Bass, 2010; Saiz et al., 2006; Sailor, 2008). In fact, these studies have found that green roofs can have similar summertime energy benefits, but also may introduce significant wintertime heating savings not found with “cool” roof alternatives. A number of observational studies have found similar benefits (Kumar and Kaushik, 2005; Lazzarin et al., 2005; Sonne, 2006) and have also pointed to the potential green roof benefits associated with significantly increased roof life. Of course, green roofs also present some additional maintenance challenges not found with conventional roofing (e.g., irrigation, weed control, nutrient supply).

There is a growing need for comprehensive design tools that developers and architects can use to evaluate the potential benefits of green roofs and assist in the design process. Such tools not only must have a sound scientific foundation, but they must also be suitable for use by the non-specialist. This is important because many design decisions regarding installation of green roofs are made by individuals (architects, building owners, etc.) who have limited skills with respect to conducting or interpreting results from building energy simulation software.

Recent advancements introduced by co-authors of this manuscript have implemented green roofs in sophisticated building energy simulation software packages (EnergyPlus and ESP-r). These efforts represent a step forward in addressing the needs for green roof design tools. Their fundamental limitation, however, is that they are not readily used by key decision makers due to the steep learning curve required to use these whole-building energy simulation packages. To address this gap between simulation modeling and implementation, a green roof energy savings calculator has been developed for use by building developers, architects, urban planners, and others to assess the building energy use, storm water runoff, and urban heat island implications of various green roof design decisions such as growing media depth, plant type/coverage, and irrigation.

Whole Building Energy Modeling Overview

The US Department of Energy’s EnergyPlus software is a widely accepted simulation engine for modeling annual building energy consumption. Released in April 2001, EnergyPlus replaced its predecessors, BLAST (Building Loads Analysis System Thermodynamics) and DOE-2, which had some technical and structural limitations. Specifically, BLAST and DOE-2 simulated

building load response separately from Heating, Ventilation, and Air Conditioning (HVAC) system operation. As such, they were unable to account properly for feedback of HVAC calculations into the overall energy balance analysis, which led to inaccurate space temperature estimates (Crawley et al. 2004). EnergyPlus, in contrast, uses simultaneous simulation, allowing HVAC calculations to be represented in each time step of building load calculation (DOE 2007). The Environmental Services Performance research (ESP-r) model is another general-purpose, transient building simulation tool developed at the University of Strathclyde in Glasgow, Scotland. Both energy models simulate the heat, air, moisture, and electrical power flows of a building under the control of a plant system, to evaluate the thermal and acoustic performance of buildings. These models use a finite element approach in which a set of conservation equations for energy and mass are integrated as a function of time in response to climate, occupant/equipment schedules and control variables. The models treat each thermal zone (room/hallway) as a well-mixed region, ignoring any thermal stratification. They also treat each floor of a building as adiabatic (e.g. no heat conduction between floors of a building). The outputs available from these whole-building energy models are the energy consumption as well as the indoor ambient temperature and relative humidity. Typical simulations employ time steps of less than 20 minutes and require several minutes of run time on a typical workstation computer to simulate a full year.

The input data required by these models to simulate the energy performance of the building include the definition of building geometry, mechanical equipment, load and occupancy schedules, and outdoor environmental conditions. The building is divided into zones that can be as broad as a room or as small as a segment within a wall, allowing for a precise definition of a building if required for the problem at hand.

All building energy simulations require local weather observations as input. The weather files used are usually based on Typical Meteorological Year (TMY) data. For each city these TMY files represent a sort of average climate for the local airport weather station. Specifically, the TMY creation process extracts a 30-year record of hourly observations from the weather station (Wilcox and Marion, 2008). For each month of the year it then calculates relevant statistics and identifies the year from the data record with the most representative conditions for that month. Data from 12 distinct months in the record are then stitched together with a smoothing algorithm.

Green Roof Modules for use in Building Energy Models

The Green Roof Energy Calculator builds on two prior independent modeling efforts that each sought to create a detailed representation of the green roof energy and water balances for use in whole-building simulation software commonly used by engineers in designing and sizing equipment for buildings. These green roof modules were implemented in EnergyPlus and ESP-r building energy simulation programs and are described briefly in the following sections.

Green Roof Module in EnergyPlus

During the period 2004-2007 Portland State University developed a physically-based energy balance simulation module for representing green roofs in whole building energy simulation software. This module was integrated with EnergyPlus and in April 2007 became part of the standard release of EnergyPlus (Sailor, 2008). A similar module based on this initial development has since been introduced into the TRNSYS (TRaNsient Systems Simulation) building energy simulation software (Jaffal et al., 2012). These models of a green roof incorporate a vegetation canopy and soil transport model that represents the following green roof physics:

- long and short wave radiation exchange within the canopy (multiple reflections, shading)
- effect of canopy on sensible heat exchange among the ambient air, leaf, and soil surfaces
- thermal and moisture transport in the growing media with moisture inputs from precipitation (and irrigation if desired)
- evaporation from the soil surface and transpiration from the vegetation canopy

This canopy model is fully coupled with the underlying EnergyPlus building energy simulation code that accounts for internal and environmental loads on the building, mechanical/HVAC equipment schedules/efficiencies, and models any building system for each of the 8760 hours in a "typical" year. Further details and application specifics are provided in the Methods section of this paper.

The green roof module as implemented in the EnergyPlus program represents all aspects of heat transfer and moisture transport in a vegetated canopy – long and short wave radiation exchange, convection, evapotranspiration, and conduction (and storage) in the growing media. It also accounts for precipitation and irrigation. **Figure 1** depicts the energy balance represented by this model. The model has been validated using surface temperature data from green roofs on buildings in Florida (University of Central Florida), Pennsylvania (Penn State University test buildings), and a combination of surface temperature and soil moisture data from several test roofs on the Portland State University campus in Oregon (Moody, 2012; Sailor, 2008).

Figure 1. The energy balance for a green roof, including latent heat flux (L), sensible heat flux (H), and shortwave radiation (I_s). Conduction into the soil and the complex exchange of longwave (LW) radiation within the canopy are also shown. From (Sailor, 2008).

This module has been part of the standard release of EnergyPlus since April 2007. The model formulation is based on the Army Corps of Engineers' Fast All-season Soil Strength (FASST) vegetation models (Frankenstein and Koenig, 2004a), drawing heavily from two models used extensively in the atmospheric modeling community—the Biosphere Atmosphere Transfer Scheme (Dickinson et al., 1993) and the Simple Biosphere model (Sellers et al., 1986). The module simultaneously solves for soil surface and foliage temperature each time step. The two heat flux equations shown below – one for the soil surface, the other for the vegetation canopy – are solved simultaneously:

$$F_f = \sigma_f \left[I_s^\downarrow (1 - \alpha_f) + \epsilon_f I_{ir}^\downarrow - \epsilon_f \sigma T_f^4 \right] + \frac{\sigma_f \epsilon_g \epsilon_f \sigma}{\epsilon_1} (T_g^4 - T_f^4) + H_f + L_f \quad (3)$$

$$F_g = (1 - \sigma_f) \left[I_s^\downarrow (1 - \alpha_g) + \epsilon_g I_{ir}^\downarrow - \epsilon_g T_g^4 \right] - \frac{\sigma_f \epsilon_g \epsilon_f \sigma}{\epsilon_1} (T_g^4 - T_f^4) + H_g + L_g + K * \frac{\partial T_g}{\partial z} \quad (4)$$

The details of the parameterizations for each of the terms in these equations are too involved to be presented here, but can be found in the original FASST documentation (Frankenstein and Koenig, 2004a, b). The full model description as implemented in EnergyPlus can be found in the EnergyPlus Engineering Reference document and within the corresponding journal article (Sailor, 2008).

Green Roof Module in ESP-r

During roughly the same period as the above development of a green roof module for EnergyPlus, researchers at the Environment Canada and University of Toronto were developing an empirically-based method of estimating impacts of green roofs on energy consumption in buildings. Their work was focused on the building energy simulation program ESP-r. Two versions of the green roof model were implemented in ESP-r. The first version (Saiz et al., 2006) parameterizes each layer of the roof according to the thickness, volume, density, specific heat, thermal conductivity, absorptivity, and emissivity. To input the green roof in the model, the vegetation layer is modelled by an equivalent thin plate with values for the optical properties (absorption, emissivity, reflectivity and transmittance) obtained from the literature. Evapotranspiration and photosynthesis are accounted for by an equivalent absorption that is calculated by subtracting the energy consumed by the plant from the net absorption. The second version of the ESP-r green roof model uses a simpler energy balance formulation (Gaffin et al., 2005; Gaffin et al., 2006) and experimental results obtained from test buildings (DeNardo et al., 2003). The latent heat transfer is simulated with a proportionality factor multiplied by the convective heat transfer from the rooftop surface to the surrounding air. This factor of proportionality, the dimensionless Bowen ratio (β), is the ratio of the sensible heat flux (H) to the latent heat flux (L). Thus the latent heat flux from a green roof may be expressed as:

$$L = \frac{H}{\beta} \quad (1)$$

For a control roof, the Bowen ratio is assumed to be infinitely large (no latent flux). The convection heat transfer term is calculated as a function of the wind speed and temperature differences between the surface and air.

$$H = \begin{cases} \gamma_1 \cdot u^{0.8} (T_{surf} - T_{air}) & \text{for } u > 1.75 \\ \gamma_2 \cdot (T_{surf} - T_{air}) & \text{for } u \leq 1.75 \end{cases} \quad (2)$$

where velocities (u) are in ms^{-1} , temperatures (T) are in degrees C, and the convection coefficients (γ) have units of $\text{W m}^{-1} \text{K}$.

As implemented in ESP-r this green roof module assumes convective heat-transfer from the green roof is similar to a conventional roof. Any changes in heat-transfer from the green roof are, instead, caused by the latent heat transfer. The Bowen ratio can be altered to reflect the variation that is experienced on an extensive green roof (Gaffin et al., 2006). The growing medium is modelled as a homogeneous layer of solid material with thermal properties that vary as a function of the moisture content. In the ESP-r green roof models the direct thermal resistance provided by the vegetation layer is ignored because the values for the conductivity of the vegetation layer vary from $0.06 \text{ W/m}^2\text{°C}$ to $0.2 \text{ W/m}^2\text{°C}$ (Niachou et al., 2001). This variation results from the different inner structure of each plant and the continuous seasonal changes in the plant's physiology.

GREC Development Methods

Each of the green roof energy modeling approaches described above require the end-user to have substantial expertise in energy modeling. In 2008 the two teams partnered with Green Roofs for Healthy Cities and developed a proposal to create a much simplified on-line tool for use by non-energy modeling experts. The goal was to create a tool that enabled architects, developers, and others to obtain quick estimates of how green roof design decisions might impact building energy use. The result of this effort—the Green Roof Energy Calculator (GREC)—has been available on-line since 2011 and is currently in its 2nd version.

The ESP-r green roof model is relatively quick to implement, but because the roof model is empirically based, it has significant limitations for application in the development of a more general tool. Specifically, its parameterization relies on measurements of roof surface data, soil moisture and other variables from specific green roofs in order to drive its estimates of HVAC energy use for the corresponding buildings. The parameters are fixed and cannot be altered during an experiment to cope with fluctuations in plant growth and moisture. Therefore, in the development of the GREC, the EnergyPlus-based green roof model was used to generate all of the required simulations. The ESP-r model was then used to simulate a subset of green roof test cases for comparison with the database output. This comparison provided for a separate gauge of the uncertainty in the model output.

The initial purpose of the EnergyPlus green roof module was to enable the estimation of the effect that green roof designs would have on building HVAC loads. A byproduct of the physical basis of this model, however, allows it to be used also to estimate sensible and latent fluxes from the roof and the net annual runoff of water from a green roof system. These features have not been explicitly validated, but are directly tied to the accuracy of the underlying energy balance parameterizations in the model. It should be noted, however, that storm water runoff is sensitive to growing media composition and compaction characteristics as well as the details of the drainage layer—all of which are static in this model.

Building Archetypes

The Department of Energy (DOE), in conjunction with three of its national laboratories, has developed and made available commercial building benchmark models for building professionals to use when analyzing whole-building energy performance across the commercial building stock. The commercial benchmarks are available for DOE's EnergyPlus simulation software as input

files (idf format). The models provide a consistent baseline of comparison and improve the value of computer-generated energy simulations. These commercial benchmarks include sixteen building types covering various office, retail, housing, and other building categories. Two of these building types were thought to be particularly relevant for evaluation of green roofs, and were thus selected for use in this calculator: the medium office building and the midrise apartment. The medium office building was a three story building with a floor area of 4982 m² (roof surface area of 1661 m²). The apartment building consisted of four stories with a total floor area of 3122 m² (roof surface area of 780 m²). As noted above the effects of the green roof on the energy use of the building will scale with roof surface area, not with the height of the building. Thus, it is reasonable to apply model output from these two archetypes to similar buildings of various heights.

Input files for each benchmark building are available for each of sixteen distinct North American climate zones. Furthermore, there is a suite of benchmark building files available for different vintage buildings. For this calculator simulations were conducted for both "NEW" and "OLD" buildings. The "NEW" buildings correspond to building characteristics as specified in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 90.1-2004. The "OLD" category of buildings generally represents building characteristics typical of 1980s vintage construction. Two vintages of buildings were modeled to investigate the effects associated with changes in glazing, internal loads, and the level of roof insulation that has increased substantially over the years. Older buildings with less roof insulation would be expected to demonstrate a stronger coupling between the roof energy balance and the interior space of the building. Hence, one would expect a green roof on an older building to result in a more substantial effect on the building's HVAC energy use.

City Selection

For the Green Roof Energy Calculator, 100 North American cities (95 US and 5 Canadian) were chosen for analysis. The US cities were selected based primarily on metropolitan population (> 500,000), but also for geographic representation (e.g. the inclusion of Fairbanks, AK, Cheyenne, WY, etc). Input files were created for each city by modifying the benchmark file for that city's climate zone with city specific information, including: site information, utility rate schedules (current as of 2009), and annual precipitation profiles.

Roof Options

For each of the building input files for each city (office and apartment) eleven files were created to capture the effects of roof type. For the first file, the outer roof layer of the benchmark building was given a reflectivity (albedo) of 0.15; this is the "dark" roof. For the second file, the

reflectivity of the roof membrane was changed to 0.65; this is the “white roof.” A matrix of green roofs was then created for each building by changing the outer roofing layer to a green roof, and then varying key green roof design parameters. The leaf area index (LAI) is a particularly important parameter that varies with the type of vegetation used. LAI is a measure of the canopy density and thus plays an important role in transpiration and radiative shading. As a simple example, vegetation that on average has two leaves above any area of the ground surface would have an LAI of 2.0. Accurate measurement of LAI requires removing vegetation from a sample area, measuring the top surface area of vegetation and then calculating the ratio of vegetation surface area to ground surface area sampled. Typical values of LAI range from 1.0 for grasses to greater than 10 for bushes and trees. Depending upon the planting a sedum-based green roof would typically have an LAI between 2 and 4. The soil depth is another important green roof design parameter. Deeper soils will retain more moisture and provide more resistance to heat flow into the building. While there are many other parameters affecting green roof performance, LAI and soil depth are useful for making estimates of the overall performance of typical green roof designs. Three levels of LAI (0.5, 2.0, and 5.0) and three levels of growing media depth (5, 15, and 30 cm) were simulated. Table 1 presents a summary of all building/roof conditions simulated for the development of GREC.

Table 1. Summary of simulation conditions modeled for GREC

Variable	Values simulated
Building type	Apartment, Mid-size office
Building vintage	Old (pre 1980), New (~2004)
Membrane roofs	White (albedo=0.65), Dark (albedo=0.15)
Green Roof LAI	0.5, 2.0, 5.0
Green roof soil depth	5, 15, 30 cm

The growing media characteristics for all green roof simulations were set as follows: thermal conductivity 0.35 W/mK; density 1100 kg/m³; specific heat 1200 J/kgK; saturation volumetric moisture 0.3; residual volumetric moisture 0.01; initial volumetric moisture 0.1.

Precipitation and Irrigation

The US Department of Energy has published a set of representative precipitation schedules for all of the US cities modeled in this project. These profiles were generated using a similar approach to that used in generating TMY files. EnergyPlus precipitation schedules are not available for Canadian cities, however. Instead, precipitation schedules for geographically similar US cities were used, adjusted so that the total annual rainfall equaled that of the Canadian city. Specifically, the precipitation profile for the corresponding US city was multiplied by a

scaling factor (ratio of annual Canadian city precipitation to that of the nearest major US city). Table 2 lists the schedule factors that were used. While such an approach introduces uncertainty with respect to the timing of precipitation in Canadian cities, this uncertainty is believed to be small given the relative proximity and geographic similarity of the paired cities. Furthermore, use of typical climate conditions (based on 30 years of historical data) introduces uncertainties that are equally important. Since the development of the GREC, however, there have been improvements in how weather is handled in EnergyPlus such that current versions of the software incorporate precipitation statistics for all cities using TMY3 weather files. Future versions of the GREC will incorporate these updates.

The ESP-r green roof model did not require precipitation as soil moisture is a fixed parameter. However, a comparison of output from both models did not reveal major or consistent discrepancies in building energy performance.

Table 2. Mapping of precipitation schedules to Canadian cities from US counterparts. Data are from NOAA (www.nws.noaa.gov) and Environment Canada (www.climate.weatheroffice.gc.ca).

Canadian City	Annual precipitation for Canadian city (m)	Corresponding US city	Annual precipitation for the corresponding US city (m)	Scaling factor
Calgary	0.41	Spokane, WA	0.42	0.98
Montreal	0.98	Burlington, VT	0.88	1.11
Ottawa	0.94	Massena, NY	0.91	1.03
Toronto	0.83	Buffalo, NY	0.98	0.85
Vancouver	1.59	Seattle, WA	0.94	1.69

It should be noted that in practice there is a great deal of variability in how irrigation is applied. This includes variations in the period of year irrigated, time of day, irrigation rate, type of irrigation, and whether the irrigation controller has information regarding modeled or measured soil moisture and/or recent precipitation events. While the green roof module in EnergyPlus allows for a variable schedule of any frequency and amount desired, or an optional “smart” schedule that uses soil moisture information to limit application of irrigation water, a simplified approach was used for the GREC simulations. The cases including irrigation ran the “simple” irrigation schedule from EnergyPlus with irrigation occurring from June through September on two mornings each week for an hour before sunrise (total of 2.54 cm per week).

Green Roof Model Accuracy

The green roof model used in GREC as implemented in EnergyPlus has been validated previously against field measurements in Florida, Oregon, and Pennsylvania, while the green roof model in ESP-r was validated against field measurements in Pennsylvania, Illinois and Madrid. For example, the comparison of EnergyPlus model output to observations for a vegetated green roof in Pennsylvania (Sailor, 2008) showed that the average bias of soil surface temperatures was 2.9°C with an RMSE of 4.1°C. More recent validation experiments for a green roof in Portland Oregon reproduced soil surface temperatures with seasonal average temperature errors of 0.3 to 1.2°C and seasonal RMSE values of 2.4 to 3.5°C (Moody and Sailor, 2013).

While validation of software-generated surface temperature estimates is relatively straightforward, it is more difficult to validate energy model estimates of whole building energy use. This is due to the large number of uncontrolled variables contributing to whole-building energy use, and variability in occupancy and occupant behavior, in particular. Nevertheless, it is instructive to compare the model output predictions from the EnergyPlus model and the version employed in ESP-r. While these are fundamentally different simulation approaches, the comparison of their output provides a sense of the likely order of magnitude of the uncertainty in either model. Toward this end, simulation output from the two approaches were compared for six cities across a range of climates. For each city, a new construction office building was simulated with an irrigated 5,000 m² green roof having a soil depth of 10 cm and an LAI of 2.0. Each model's predicted energy use for gas and electricity was then compared to energy use output resulting when the same software was used to model a dark (reflectivity of 0.15) roof. The results of this comparison are given in Table 3. While there is substantial variability in predicted green roof energy savings for these two modeling approaches, the differences are typically less than +/- 20%, and no consistent bias was detected. The two approaches were also very similar in simulating white roof summer performance.

Table 3. Inter-comparison of EnergyPlus (E+) and ESP-r modeling approaches for estimating annual building energy savings associated with replacing a 0.15 reflectivity membrane roof with a vegetated roof having LAI of 2.0 and soil depth of 10 cm.

City	Gas (kWh)		Electricity (kWh)		Difference in predicted total savings	
	E+	ESP-r	E+	ESP-r	(kWh)	(%)
Atlanta, GA	182	-320	6291	7574	781	11
Chicago, IL	1393	1379	6179	4982	-1211	-17
Denver, CO	518	427	9069	7552	-1608	-18
Detroit, MI	1402	1440	5045	5265	258	4

Houston, TX	78	-33	5284	7142	1747	28
Memphis, TN	223	-220	5739	7283	1101	17

Interpolation and Scaling Algorithms

In all, a total of 8000 simulations were conducted for this calculator using EnergyPlus running on two windows-based workstations. Given the large number of model runs, the input/output data were generated/extracted using Java scripts. Simulations were conducted for 100 cities, 2 building vintages, 2 building categories (office & residential), and 20 roof types. Two of the roof types corresponded to dark and white (control) membrane roofs. There were also 9 distinct green roofs modeled, and each green roof was modeled both with and without irrigation.

In order to simplify the interpolation and scaling of results, all model output from the original 8000 simulations was stored on a per-unit roof area basis. This output includes electricity use for air conditioning (E''), natural gas use for heating (NG''), sensible and latent heat flux from the roof surface (Q_H'' and Q_L''), and runoff (R''). For each city, each of these dependent variables has discrete values for each possible value of the following independent variables: building type (BT), leaf area index (LAI), soil depth (D), irrigation flag (I), membrane color (C). So, for example, the electricity use data are stored in the multidimensional array: E'' (BT,LAI,D,I,C).

The Green Roof Energy Calculator then linearly interpolates the simulation output to determine predicted performance based on the user input values for building type, location, green roof LAI, soil depth and area. For example, if the user has requested performance information for a green roof with LAI of 3 and a soil depth of 12 cm the data base lookup tool will first interpolate between the per unit area output for LAI of 2.0 and 5.0 to obtain data for an LAI of 3.0 for both a soil depth of 10 cm and 15 cm. It then linearly interpolates between these intermediate values to obtain estimates for a soil depth of 12 cm.

The user has also supplied information regarding what fraction of the roof is covered by green roof and also what the composition of the non-green roof is (either white or black). The interpolation scheme then does a simple area-weighted average of the model output for the interpolated values of the green roof output parameters and those from the corresponding non-green roof. For example, a typical roof might only be 85% covered by vegetation with the remainder being white membrane walking paths. In such a case, all model output would be weighted accordingly.

Once the proper interpolations have been performed for the green roof design parameters, and the weighting has been applied to account for any non-green roof area, the GREC multiplies all

of the per-unit-area output by the given roof surface area (RA). For example $E(BT, LAI, D, I, C) = RA * E''(BT, LAI, D, I, C)$.

Green Roof Energy Calculator (GREC) On-Line Software

The Green Roof Energy Calculator (GREC) was developed as an on-line calculator that includes a PHP-based graphical user interface (GUI) as a front end for an SQL data base containing simulation results from the EnergyPlus green roof module for 8000 test cases. As usability was one of the top priorities for GREC the interface was developed to allow the user to completely specify the building and roof construction with as few inputs as possible.

The Green Roof Energy Calculator (GREC) consists of two basic screens—the input screen and the output screen. As illustrated in Figure 2, the input screen requests the following information:

- Choice of units (both conventional US and SI are available)
- State and City (using drop-down menus)
- Surface area of the roof
- Building type (old or new, office or apartment)
- Growing media depth (limited to $5 \text{ cm} < D < 30 \text{ cm}$)
- Leaf Area Index (limited to $0.5 < LAI < 5$)
- Irrigation flag (yes or no)
- Percent of roof covered by green roof
- Type of roofing for non-green roof area (black or white)
- Utility rates (use built-in rate schedules or specify simple constant costs for electricity and natural gas)

Upon filling in the above information the user presses a “Calculate” button. If any fields are out of range or empty an error message is returned until all errors are corrected. All of the necessary interpolations for LAI and soil depth are then made and the outputs are weighted and scaled as discussed above. The output screen (see Figure 3) is then displayed. This screen first presents a summary of the building model input description. It then provides summary output for energy use, sensible and latent heat emissions, and water balance. The energy use data are presented as green roof energy savings relative first to a dark membrane control roof and then to a white membrane. These results are presented for electricity savings (kWh), natural gas savings (GJ) and total energy cost savings (USD) based on 2009 rate data. Negative values are possible and simply imply that the corresponding conventional membrane roof uses less energy or has an energy cost savings relative to the green roof design being tested. Because rate schedules can be complex, varying with time of day or season, it is possible for a net energy savings to be accompanied by a net energy dollar cost, and vice-versa.

Figure 2. Main data entry screen for the Green Roof Energy Calculator (GREC).

Green Roof Energy Calculator (v. 2.0)

This calculator was developed through a collaboration involving researchers and staff at Portland State University, University of Toronto, and Green Roofs for Healthy Cities. The effort was funded by the US Green Building Council with additional financial and in-kind support from University of Toronto, Portland State University, GRHC, and Environment Canada.

The green roof energy calculator allows you to compare the annual energy performance of a building with a vegetative **green roof** to the same building with either a **dark roof** or a **white roof**. At the present time simulations are available for new construction (ASHRAE 90.1-2004) and old construction (pre-ASHRAE 90.1-2004) office and residential buildings driven by typical precipitation and weather data. Representation of an irrigation schedule is optional. [Read more about how the Calculator works.](#)

Estimate Annual Green Roof Performance

Would you prefer to use US Customary or SI units? ☐ US Units ☒ SI Units

Building Information

What State/Province is your building located in? Colorado

What city is your building located in? Denver

What is the total area of your **roof**? 2000 m² (roof area)

Which **Type** is your building? New Residence Bldg.

Green Roof Information

What is your **Growing Media** Depth? (1 to 30) 10 cm

What is your **Leaf Area Index**? (0.5 to 5) 2

Is your green roof irrigated? No

What percentage of your roof does the Green Roof cover? (1 to 100%) 100 %

If your green roof covers less than 100% of your roof area, what type of roof covers the rest? Dark (0.15 albedo)

Utility Rate Information

This calculator uses utility rates for each city that were valid in May 2010. Would you like to enter your own utility rates instead? ☐ Yes ☒ No

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Figure 3. Output screen from an example run of the Green Roof Energy Calculator (GREC).

Example Output

To illustrate the range of simulation output results that might be expected a matrix of simulations is presented below for three representative cities, Portland Oregon, Chicago Illinois, and Denver Colorado. Due to the large possible number of combinations of parameters a full-factorial summary of model output would include at least 64 combinations for each city. So, only a subset

it presented to illustrate the model behavior. It should be further emphasized that the simulations presented are exemplars and are not intended to represent the full range of possible green roof implementations or management strategies. The selection of Portland output is used to illustrate the role of LAI and soil depth. Chicago is used to illustrate the role of irrigation and building vintage. The Denver simulation outputs illustrate the role of building type and fractional coverage of the green roof. In all cases, the energy consumption savings for the green roof are relative to a building with a conventional dark (reflectivity of 0.15) membrane roof.

The simulations summarized in Table 4 are for Portland simulations with the following fixed parameters for the green roof—old office building with an irrigated green roof that covers 100% of a 2000 m² roof surface. Since the green roof is irrigated it is less able to retain precipitation. The green roof model implemented in EnergyPlus is capable of reporting the total volume of water that leaves the roof as runoff. It also has, as input, hourly data on precipitation and can therefore produce estimates of retained precipitation. Of particular interest is the fraction of incoming precipitation that does not leave the roof as storm water runoff (e.g., evapotranspiration/ precipitation). The fraction of retained precipitation is consistently less than 50% for Portland. Retention of precipitation nearly doubles for cases where the roof is not irrigated (not shown here). Retention is increased by roughly 50% when the soil depth is increased from 5 to 15 cm. The effect of soil depth on annual energy use can be significant. Increasing soil depth from 5 to 15 cm results in a substantial increase in electricity (cooling energy) savings, particularly for the case of a relatively sparse vegetation canopy (LAI of 1). An inspection of the energy savings with larger LAI suggests that as the canopy thickness increases, the role of soil depth for air conditioning loads becomes relatively unimportant. This result was confirmed with ESP-r by varying the parameters that control evapotranspiration, assuming a higher rate of evapotranspiration with a lush canopy.

In contrast, however, increasing soil depth appears to uniformly reduce energy use for heating, regardless of the LAI. It should be noted that in the case of the lush canopy with a thin soil the annual natural gas (heating energy) use is higher than for a building with a black membrane roof. This result is due to the fact that the benefits of added thermal insulation resulting from the thin soil layer are not sufficient enough to overcome the undesirable shading of solar heat by the lush canopy. As illustrated in this table, the soil depth has very little effect on the sensible heat flux to the outdoor environment and only a modest effect on latent heat exchange—with latent heat exchange increasing with both soil depth and LAI.

Table 4. Summary GREC output for varying LAI for an old office building in Portland Oregon with an irrigated green roof that covers 100% of the surface of a 2000 m² roof. Energy savings are based on comparison with a conventional dark (0.15 reflectivity) membrane roof.

LAI	Depth (cm)	Annual electricity savings (kWh)	Annual natural gas savings (kWh)	Summer average sensible heat (W/m ²)	Summer average latent heat (W/m ²)	Fraction of precipitation retained (annual)
1	5	6972	1284	41.7	60.9	22%
5	5	11444	-529	30.5	64.5	30%
1	15	10108	1870	41.7	65.1	36%
5	15	13291	461	29.7	67.3	43%

Table 5 presents summary model output for Chicago simulations. This set of simulations is intended to illustrate the important role that irrigation plays in affecting building energy performance and storm water retention. This set of simulations also contrasts performance from older and newer vintage buildings that differ in terms of internal gains, construction characteristics, and most notably, roof insulation levels.

Annual electricity savings associated with irrigation in the Chicago simulations is relatively modest. For older construction, the incremental benefit of irrigating a green roof is an additional annual electricity savings of 484 kWh. For newer construction the incremental benefit of irrigation was even smaller, at 303 kWh. In contrast, the effect of adding a green roof on annual natural gas (heating energy) use savings is twice as large for the older buildings as compared with the newer buildings . Furthermore, this natural gas savings effect is relatively independent of irrigation (which is applied only in summer). The results for heating energy savings are intuitive as the newer buildings have substantially more insulation, reducing the relative importance of the soil insulation value.

In contrast to the results for Portland, however, the fraction of precipitation retained is much higher, being 59% for irrigated roofs and up to 90% for roofs that are not irrigated.

The results summarized in Table 6 illustrate the role of building type and extent of green roof surface cover. Note that the high fraction of annual rainfall retained by the green roof in Denver is due to the relatively light and infrequent precipitation events that lead to a total annual precipitation of only 360 mm, as compared with 830 and 810 mm for the cities of Portland and Chicago, respectively.

Table 5. Summary GREC outputs for old and new office buildings in Chicago Illinois with green roof that covers 100% of the surface of a 2000 m² roof. The green roof has a fixed LAI of 2.0 and soil depth of 10 cm. Energy savings are based on comparison with a conventional dark (0.15 reflectivity) membrane roof.

Building vintage	Irrigation?	Annual electricity savings (kWh)	Annual natural gas savings (kWh)	Summer average sensible heat (W/m ²)	Summer average latent heat (W/m ²)	Fraction of precipitation retained (annual)
Old	yes	6639	4589	27.6	106.8	59%
Old	no	6155	4602	33.3	69.4	90%
New	yes	7399	1668	27.6	106.8	59%
New	no	7096	1669	33.4	69.4	90%

Table 6. Summary GREC outputs for older vintage 3 story office and 4 story apartment buildings in Denver Colorado with non-irrigated green roof that covers a portion of an otherwise dark membrane roof. The roof surface area is 2000 m². The green roof has a fixed LAI of 2.0 and soil depth of 10 cm. Energy savings are based on comparison with a conventional dark (0.15 reflectivity) membrane roof.

Building type	Green roof coverage	Annual electricity savings (kWh)	Annual natural gas savings (kWh)	Summer average sensible heat (W/m ²)	Summer average latent heat (W/m ²)	Fraction of precipitation retained (annual)
Office	100%	12466	6171	41.8	32.3	99%
Office	50%	6233	3085	36.2	16.2	50%
Apts.	100%	6209	29926	41.8	32.3	99%
Apts.	50%	3105	14963	36.1	16.2	50%

Discussion and Observations

The Green Roof Energy Calculator (GREC) has been developed based on thousands of individual building simulations with a state-of-the-science green roof module that is part of one of the leading building energy simulation software packages. The underlying building model is physically based and has been validated against multiple field studies. The simulations for GREC

explore the roles of three key green roof parameters (soil depth, vegetation density via LAI, and use of irrigation). The simulations also include two building vintages, primarily to explore the role of roof insulation, and two building types (office and residential), primarily to explore the role of differences in building operations and HVAC schedules.

Outputs from GREC demonstrate possible storm water retention differences resulting from differences in location, climate and use of irrigation. For example, the modeled green roof in Chicago, which experiences more than 30% of its annual precipitation in three summer months (with a peak monthly precipitation in June), had its storm water retention decrease from 90% when not irrigated to 59% when irrigated. This output could be expected as Chicago receives more than 30% of its annual precipitation during the summer.

Another key model finding is that increasing vegetation density (LAI) can provide an electricity savings associated with air conditioning, but increases natural gas for heating due to undesired shading and evaporative cooling effects in colder months. Increasing growing media depth, on the other hand, was beneficial for both cooling and heating energy consumption.

Also, while not commonly investigated in the literature, the building type (residential vs. office) can play an important role in determining the energy benefits of a green roof. Annual air conditioning electricity savings of installing a green roof were largest for office buildings, while annual heating energy savings were largest for residential buildings. This result is intuitive if one considers the relative timing of peak cooling and heating loads in relation to occupancy for office vs. residential buildings.

The story is more complicated with respect to insulation levels. For Chicago, the green roof had more of an air conditioning (electricity) benefit for newer construction than for older construction. While this result is counterintuitive it may be due in part to improvements in end-use energy efficiency and windows such that for newer buildings the roof plays a more important role in determining total cooling load than it does for older buildings that might be more dominated by internal gains and poor window performance. This is clearly an area where further investigation is merited. The impact of a green roof on heating loads was more intuitive. Namely, installing a green roof on an older (less insulated) building provided more natural gas savings than installing a green roof on a newer building.

The goal of the GREC is to provide a broad user market (e.g. planners, architects, developers, building owners) with an easy-to-use web-based tool for gathering quantitative estimates of the effect of green roof design parameters on a number of important outcomes—annual and seasonal HVAC energy use; storm water retention; and benefits to the urban thermal environment. As illustrated here, the tool is easily applied by a user with only very rudimentary understanding of green roof systems and no specific knowledge of building energy modeling. Furthermore, the results are readily interpreted and presented in an unbiased manner that enables easy comparison with alternative roofing solutions.

At the same time, however, it is important to recognize the limitations of the GREC. First, while the underlying green roof energy model available within Energyplus offers the user significant control over building and roof construction and operation details, the packaging of this capability into a user-friendly web tool requires simplification in many areas. Some of the key simplifications are as follows. GREC does not allow simulation of different types of vegetation or growing media which may affect storm water runoff and the surface energy balance in ways that are not captured simply by varying LAI and growing media depth. Furthermore, GREC does not allow the user to explore variations in irrigation schedules. Rather, it is simply assumed that the roof is either irrigated using a standard schedule in summer or not irrigated. Finally, the GREC presents results for only two specific buildings—a 4-story apartment building and a 3-story office building. Nevertheless, as the roof energy balance and water balance are essentially independent of building height and the GREC presents output in terms of absolute changes in building energy consumption, the users of GREC can readily apply model outputs from these archetype buildings to similar buildings of differing heights.

As noted in the presentation of sample GREC output, the performance of a green roof system depends very much on geographic location (local climate), building type and age, growing media depth, lushness of vegetation, and whether or not the roof is irrigated. As the literature is replete with results that are limited to specific applications (e.g., a specific design on a particular type of building in one climate using one irrigation management strategy), it is difficult to find generalizable results that can be applied in practice. Thus, the introduction of the GREC offers individuals interested in optimizing the sustainability performance of their green roofing systems a useful resource that can readily be tailored to most specific applications of interest. The model has been available since September, 2011 at greenbuilding.pdx.edu/grcalc.html.

Acknowledgements

This work was supported in part by the US Green Building Council. The authors also wish to acknowledge significant contributions to this research by students (Max Gibson, Tzazna Miranda Leal, Jordan Richie, Jeremy Tucker, and Igor Yeremin) and colleagues Mr. Steven Peck and Dr. Graig Spolek. The authors would also like to thank three anonymous reviewers for very detailed comments that have greatly improved this manuscript.

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