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Development and application of a building energy performance metric for green roof systems

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ABSTRACT

This study develops a thermal performance metric for vegetated roof systems. The Dynamic Benefit of Green Roofs (DBGR) is the ratio of Heating, Ventilation and Air-Conditioning (HVAC) energy use for a building with a conventional roof to that of a building with a green roof. If the green roof results in lower energy use than a conventional roof with the same level of thermal resistance the value of DBGR is greater than unity.

Data from a field study in Portland Oregon were used to validate the green roof model incorporated within a whole-building energy simulation program. This model was then used to estimate the DBGR for a new construction office building in four climates: Portland, Oregon; Chicago, Illinois; Atlanta, Georgia; and Houston, Texas. Results suggest that a green roof in Atlanta and Houston would provide net annual HVAC energy savings compared with a traditional roof. The Chicago case, with severe winter and mild spring/summer/fall, resulted in a smaller energy savings. The DBGR for Portland was less than unity, suggesting a net energy consumption penalty associated with the green roof. This was due, in part, to the undesirable evaporative cooling in the shoulder seasons which led to increased building heating loads.

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1. Introduction

There is a growing interest in sustainable building practices. With this has come a rise in popularity and construction of green (vegetated) roofs [1,2]. Green roof systems can play multiple roles in helping a building achieve sustainability goals. When properly designed, constructed, and maintained, a green roof system has the potential to extend roof longevity an estimated 20–30 years[3], provide storm water mitigation of between 25 and 75%[4–6], reduce the urban heat island (UHI) by up to 1.5 °C[7,8,9,10], improve urban bio-diversity[11] and potentially lower building energy consumption through surface temperature and heat flux reduction[12–14].

Thermal performance benefits of green roof systems have been documented in many studies [12,15–20]. A standardized design method for incorporating green roof thermal performance into building energy load calculations, however, has not been developed and poses a great challenge when considering the many design criteria and parameters involved.

Current practice in design of a green roof primarily considers storm water and esthetics but does not consider the plant and soil layer contribution to the thermal performance of the building. The question for green roof systems becomes: how does a designer estimate the time-varying system performance attributes so that a green roof can be effectively used as part of a building load calculation/credit when following a performance-based path for building energy code compliance? This manuscript addresses this question by developing and applying a quantitative approach for evaluating the dynamic thermal performance of green roof systems.

2. Green roof energy balance

Plant, soil, insulation, and support layers are the four key elements affecting the thermal performance of a green roof. These layers combine to create a unique composite material that acts as a thermal mass with evaporative cooling and time-varying thermal properties. Treating such a complex system as a simple insulative layer with an enhanced "*R*-value" is fundamentally wrong as it does not capture the transient thermal storage and evaporative cooling that take place on a green roof. Therefore, recently developed physically-based models of the energy balance of green roof systems (e.g., [13]) represent an important advance in the analysis of green roofs.

2.1. Plant layer

The relevant parameters for thermal performance of the green roof plant layer are stomatal resistance, radiation absorptivity, fractional vegetation cover, and leaf area index (LAI). Transpiration is

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the method by which a plant moves water and minerals from its roots to its leaves for photosynthesis. Plant transpiration occurs through stomata which are adjustable pores in the leaf surface that allow exchange of the gases and water vapor necessary for plant photosynthesis. More pertinent to plant thermal performance, stomata regulate the amount of water that changes phase from liquid to vapor, thus affecting the surface energy balance at leaf surface. Leaf-level absorptivity of solar radiation is important to the photosynthesis process. Plants can directly absorb nearly 40% of solar energy incident upon their leaves [21]. The high level of radiation absorptivity by green roof plants thus contributes greatly to the overall thermal performance of a green roof. Fraction vegetation cover is simply the fraction of the roof surface covered by vegetation. Leaf Area Index (LAI) is the one-sided projected area of leaf surfaces occupying the horizontal projected area of the vegetation [22]. LAI is the primary factor in determining the fraction of energy intercepted by the plant canopy and used by the plant for photosynthesis. The LAI of a canopy varies with plant species and changes over time. In forests the maximum LAI typically varies from 6 (deciduous trees) to 8 (coniferous forest plantations). In agricultural fields LAI varies from 2 to 4 for annual crops with a mean LAI for grassland of 2.5 [23]. Values of LAI for green roof systems are not commonly available in the literature, but our measurements for Sedum systems have resulted in LAI estimates in the range of 1 to 4.

2.2. Soil layer

Within the building industry *R*-value is used to describe a material's ability to resist the flow of energy (heat flux) as a function of a driving potential (temperature difference) across the thickness of the material. The underlying definition of *R*-value requires steady-state conditions, which are reasonably approximated by insulation materials with little thermal mass. In such cases:

$$R = \frac{\Delta T}{q''}, \tag{1}$$

where ΔT is the temperature difference across the material and *q*" is the steady state heat flux through the material. Units of *R*-value are $[\mathrm{m^2\,K\,W^{-1}}]$.

Like conventional building materials a green roof soil can be evaluated for its thermal conductivity (k), density (ρ), and specific heat capacity (C_p) While the relatively high thermal mass (ρC_p) of soil leads to transient conduction throughout a typical diurnal cycle, the steady state *R*-value can be determined in the laboratory by fixing a temperature differential across a given thickness of soil and measuring heat flux after the system has reached a steady state. This steady-state *R*-value is useful as a reference, but does not capture the dynamic aspects of the energy balance on a green roof. Thermal performance of green roof soil is further complicated by the fact that, unlike a typical building material, green roof soil retains significant moisture which helps to mitigate storm events and maintain the health of plants. Thermal properties of the soil vary significantly with the volumetric moisture content (M) [24–26]. Thus, the thermal performance of a green roof is tightly coupled with the time-varying moisture content within the soil layer.

3. Massive systems performance metrics

In 2001 the Oak Ridge National Laboratory (ORNL) proposed a measure of thermal effectiveness for thermally massive building envelope systems. The Dynamic Benefit for Massive System (DBMS) metric is defined as a material or assembly's ability to thermally perform above its steady state *R*-value due to material configuration and climate interactions. According to ORNL, "DBMS has no physical meaning; it is a modeled relative measure of thermal performance as compared to a modeled standard construction" [27]. The DBMS of a thermally massive material is the dimensionless ratio between a hypothetical equivalent thermal mass *R*-value ($R_{\mathrm{T,mass}}$) and the actual measured steady state *R*-value (R_{ss}) of the construction:

$$\mathrm{DBMS} = \frac{R_{\mathrm{T,mass}}}{R_{\mathrm{SS}}} \tag{2}$$

The equivalent *R*-value $R_{\mathrm{T,mass}}$ is the *R*-value that a conventional (non-massive) system would need to have to result in the same annual heating, ventilation, and air conditioning (HVAC) energy use. A DBMS value greater/less than 1 indicates a thermal mass assembly has better/worse relative thermal performance than a corresponding assembly with the same steady state *R*-value. A DBMS value of unity indicates that the thermal mass of the system has no net effect on annual energy consumption for the building.

In the present study we adapt this concept for use in modeling the performance of a vegetated green roof. Here, the required dynamic performance metric must account for not only thermal storage in the massive construction element (soil) with time-varying thermal properties, but also long and short wave radiation shielding of the vegetation and the evaporative cooling of the soil-vegetation system. We also wish the metric to be a relative measure of energy use rather than a ratio of steady state and "effective" *R*-values. We therefore define the Dynamic Benefit of Green Roofs (DBGR) as follows:

$$\mathrm{DBGR} = \frac{E_{\mathrm{HVAC,SS}}}{E_{\mathrm{HVAC,GR}}} \tag{3}$$

where $E_{\mathrm{HVAC,SS}}$ is the annual HVAC energy use for a conventional membrane roof with an *R*-value equal to the measured steady-state *R*-value of the green roof construction, and $E_{\mathrm{HVAC,GR}}$ is the annual HVAC energy use for the green roof system. As with DBMS, a value of DBGR greater than unity indicates that the green roof system is performing better than a corresponding membrane roof with the same steady-state *R*-value. The DBGR formulation is qualitatively similar to DBMS, but greatly simplifies the calculation procedure as a total of only two simulations are needed to calculate DBGR. In contrast, DBMS requires an iterative approach involving multiple simulations in an attempt to find an effective *R*-value that results in equivalent annual HVAC energy use for the conventional and massive systems. Nevertheless, both metrics are application-specific with values that will depend on the roof design characteristics, the baseline roof used for comparison, the building design/operation, and the local climate.

4. Green roof energy modeling

Evaluation of the DBGR for a green roof system requires whole-building energy simulation that can adequately account for the complexities of the green roof energy balance. In this study we used the EnergyPlus whole building energy simulation software from the U.S. Department of Energy [28,29]. EnergyPlus is designed to assist engineers and architects in sizing HVAC equipment, evaluating building retrofit options, performing life cycle cost analysis and optimizing building energy performance. EnergyPlus contains a green roof simulation module that takes into account: long wave (LW) and short wave (SW) radiation exchange within the plant canopy; plant canopy effects on convective heat transfer; evapotranspiration (latent heat) from the soil and plants; and heat conduction (sensible heat) and storage in the soil layer [13].

The green roof module in EnergyPlus requires specification of vegetation and soil parameters including soil thermal properties, soil thickness, vegetation coverage (fractional vegetation cover and LAI), and vegetation stomatal resistance. This information is combined with building design and management data and a local

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