A PARAMETRIC STUDY OF THE THERMAL PERFORMANCE OF GREEN ROOFS THROUGH ENERGY MODELING

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ABSTRACT

In recent years, there has been great interest in the potential of green roofs as an alternative roofing option to reduce the energy consumed by individual buildings as well as mitigate large scale urban environmental problems such as the urban heat island effect. There is a widespread recognition and a growing literature of measured data that suggest green roofs can reduce building energy consumption. This paper investigates the potential of green roofs in reducing the building energy loads and focuses on how the different variables of a green roof assembly affect the thermal performance of a building.

A green roof assembly is modeled as part of the roof construction of a prototypical office building located in California Climate Zone 8, using Design Builder- a 3D graphical design modeling and energy use simulation program that uses the EnergyPlus simulation engine. The thermal performance of several green roof assemblies is then evaluated for that climate zone, looking at whole building energy use. The parametric study involves altering one parameter of the green roof for each simulation run in order to understand its effect on building's energy loads. These parameters include different insulation thicknesses, leaf area indices (LAI) and growing medium or soil depth. The energy use intensities resulting from the use of these green roof assemblies are compared with each other and to a cool roof base case to determine the energy load reductions, if any. The simulation results are then organized and finally presented as a decision support tool that would facilitate the adoption of green roof technologies and make it possible to account for green roof benefits in energy codes and related energy efficiency standards such as LEED.

1. INTRODUCTION

Urban development has replaced much of the vegetated landscapes with built structures and surfaces, leading to the Urban Heat Island effect. Green roofs have become important to green building practices, as a response to mitigating the negative impacts of Urban Heat Island. These roofs, also known as eco-roofs, living roofs or vegetated roofs, are partially or completely covered with vegetation and a growing medium, planted over a water-proofing membrane. They may also include additional layers such as root barrier and drainage and irrigation systems. Green roofs differ from the conventional roofs because they act as a heat sink- an active energy device, literally collecting, processing, and releasing energy according to its immediate need. Its thermal resistance (R-value) is not constant and keeps changing depending on the moisture content of the growing medium. The water evaporation from the vegetation as well as thermal mass and thermal resistance of the green roof contribute to reduce indoor and outdoor temperatures in the building and urban area depending on the type of vegetation, depth and type of growing medium and local climate. This in turn helps to reduce the cooling load of a building, resulting in reduced air cooling requirements and therefore reduced energy consumption and associated output of atmospheric carbon. This paper investigates the quantitative benefits of building energy load reductions, caused by different parameters of a green roof assembly.

2. ENERGY MODELING OF GREEN ROOFS

A lot of research has been done in investigating the effects of green roof construction and the likely magnitude of energy savings associated with this roofing type. However, most of these studies were based on time consuming field experiments and real building monitored data collected over the years. With the help of a quantitative and physically-based building energy simulation tool that represents the effects of green roof constructions, the process of assessing green roof benefits becomes much quicker and it also allows an individual (the architect, developer or client) to make an informed decision regarding the assembly choice.

A physically based model of the energy balance of a vegetated rooftop has been developed by Dr. David J. Sailor, a Professor of Mechanical and Materials Engineering and Director, Green Building Research Laboratory at Portland State University. His model has been integrated into the EnergyPlus building energy simulation program. This green roof module allows the energy modeler to explore green roof design options including growing media thermal properties and depth, and vegetation characteristics such as plant type, height and leaf area index. The model has been tested successfully using observations from a monitored green roof in Florida. It uses the following two simultaneous equations for the energy balance calculations-

Energy Budget in the foliage layer:

$$F_f = \sigma_f \left[I_s^{\downarrow} \left(1 - \alpha_f\right) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \sigma T_f^4 \right] + \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} \left(T_g^4 - T_f^4 \right) + H_f + L_f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Energy Budget in the soil layer:

$$F_g = \left(1 - \sigma_f\right) \left[I_s^{\downarrow} \left(1 - \alpha_g\right) + \varepsilon_g I_{ir}^{\downarrow} - \varepsilon_g T_g^4 \right] - \frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1} \left(T_g^4 - T_f^4 \right) + H_g + L_g + K^* \frac{\partial T_g}{\partial z} \ldots\ldots (2)$$

The details of the parameterizations for each of the terms in the above equations are too involved to be described within the page limits of this paper. The description of the full model can be found in Sailor's paper-'A green roof model for building energy simulation programs' (Sailor 2008). This study is carried out using Sailor's model.

3. CLIMATE DATA

For the purpose of this research, the prototypical office building is located in Los Angeles which falls under California Climate Zone 8. This zone is characterized by hot dry conditions; both heating and cooling are required in order to achieve thermal comfort, as can be seen from Fig. 1 and 2 (Source: Pacific Gas and Electric Company).

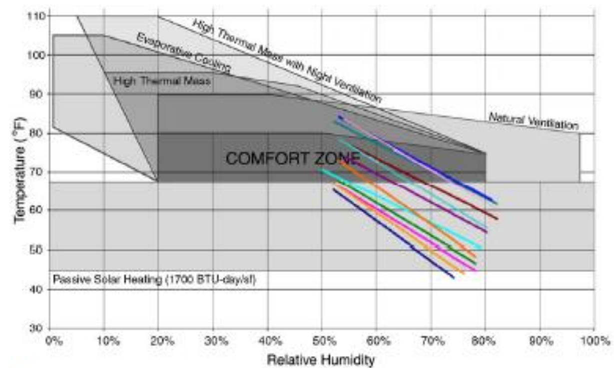

Fig. 1: Bioclimatic chart of California Climate Zone 8.

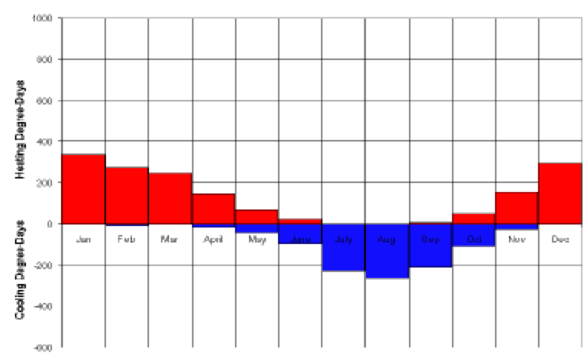

Fig. 2: Cooling and heating degree days for California Climate Zone 8 (Base 65F)

4. THE BUILDING ENERGY MODEL (BEM)

4.1. Building the Prototype Model

The parametric study is carried out on a prototypical small sized office building that is modeled using the Design

Builder energy modeling program. The simulation engine EnergyPlus, which is well integrated within the program, runs all the necessary calculations related to the building energy model (BEM) and reports the results within the Design Builder interface.

The single story prototype is constructed as a code compliant building, referencing to Commercial Buildings Energy Consumption Survey (2003 CBECS), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Standard 90.1-2004) and ASHRAE Ventilation Standard 62.1-2004 (ANSI/ASHRAE 2004) for building envelope information, operating schedule recommendations and ventilation requirements. References to the U.S. Department of Energy (DOE) Commercial Reference Building Models, developed by Pacific Northwest National Laboratory (PNNL) have also been made, while developing the model.

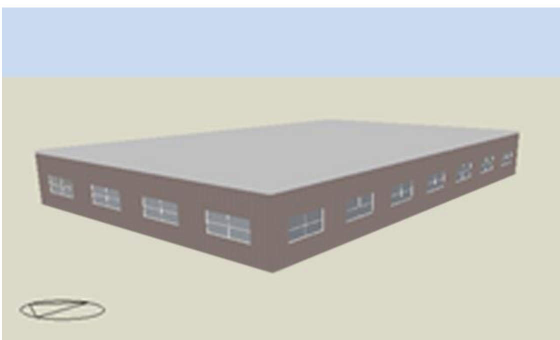

Fig. 3: Prototypical office building modeled in Design Builder

The building is 10,000 sq. ft. (125ft x 80 ft.) and single storied. The floor is divided into five thermal zones- one core and four perimeter zones- to provide a reasonable representation of a typical HVAC operation (see Fig. 4).

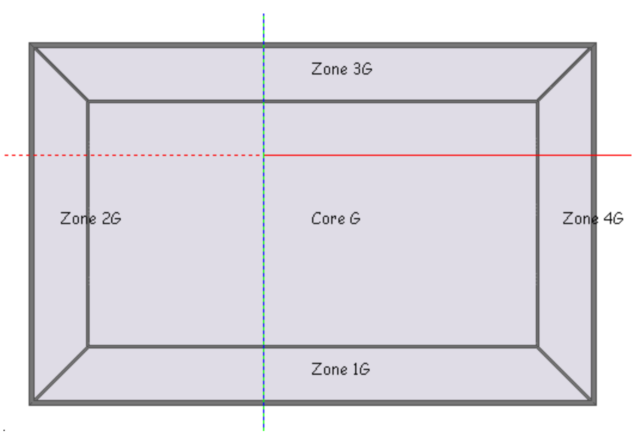

Fig. 4: HVAC zoning diagram (typical floor)

The basic BEM inputs that have not been discussed earlier are illustrated in Table 1.

TABLE 1: BASIC BEM INPUT CATEGORIES

CATEGORY	INPUT	DATA SOURCE
Orientation	East-west (longer axis)	
Area per floor	10,000 sq. ft.	
Floor to floor height	13 ft. (9 ft. flr to ceiling + 4 ft. plenum)	
Glazing fraction	0.33	2003 CBECS
Shading	Interior blinds	
Exterior walls	Steel frame wall with insulation	ASHRAE 90.1
Roof	Cool roof- metal deck (basecase)	ASHRAE 90.1
	Green roof – metal deck (variable)	
Floors	Slab on grade floors, unheated+carpet	ASHRAE 90.1
Windows	Single pane, 0.25 SHGC	ASHRAE 90.1
HVAC	VAV with terminal reheat Heating: Natural gas Cooling: Electricity	2003 CBECS
SHW	Fuel type: Natural gas	
Lighting (LPD)	1 w/ft2	ASHRAE 90.1
Occupancy	0.005 people/ft2	ASHRAE 90.1

The base case model is developed with a cool roof, which is the code requirement for any new construction in California currently. The green roof model differs from the base case only in the construction of the roof assembly.

4.2. Green Roof Model Description

In the Design Builder modeling environment, the green roof is present as 'Ecoroof' material that forms the outer layer of the roof assembly (metal deck). Certain parameters pertaining to the vegetation layer or growing medium are present that help to define the green roof type, like as shown in Fig. 5.

Apart from the vegetation layer, the green roof comprises a growing medium (soil) of certain depth, a root barrier membrane, a drainage layer, insulation (may or may not be present) and a waterproofing membrane. The structural roof is a metal deck, same as in the base case of a cool roof. A cross-section through the entire green roof assembly as modeled is illustrated in Fig. 6.

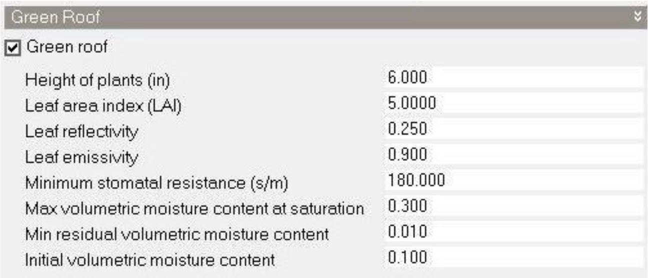

Fig. 5: Green roof parameters related to vegetation (Ecoroof layer)

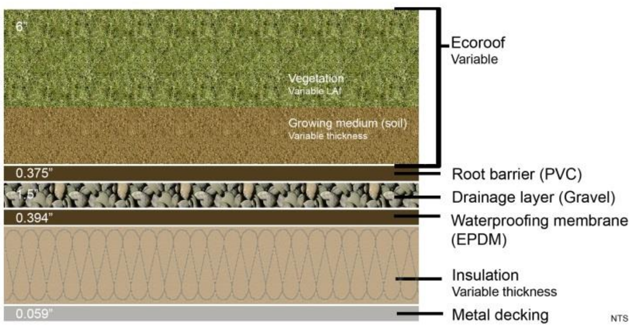

Fig. 6: Different layers of the green roof assembly as modeled in Design Builder

Each layer of the green roof deals with heat flow differently. The depth of the topsoil and type of plant chosen would vary the insulation values owing to different U-values. Both the plants and substrates increase the R-value resulting in energy cost savings. Also, the moisture content in the soil affects the heat flow through it. The modeled roof is irrigated. The green roof irrigation is set to a smart schedule which means that the roof is irrigated according to the maximum irrigation rate (feet per hour) input, and overrides the irrigation schedule to be turned off when the soil is 30% or more saturated with water, so as to avoid over watering of the roof.

This scope of this paper is limited to the thermal performance and heat transfer study of three of the above mentioned layers, although there are several other parameters that affect the thermal performance of the green roof assembly. The three parameters that are chosen for this study are-

- Insulation thickness
- Vegetation type (in terms of Leaf Area Index-LAI)
- Growing medium or soil depth

Each of these parameters has subset variables that are discussed later in the paper.

4.3. Limitations of the Green Roof Model

It is important to note here that Sailor's model has only been tested with the ConductionTransferFunction (CTF) solution algorithm, and any other solution algorithm choice would give an error during the simulation. Also, there are limitations on the data input, for this algorithm to work. The input data ranges have been clearly defined in the EnergyPlus documentation, The Encyclopedic Reference to EnergyPlus Input and Output.

5. PARAMETERS AND THEIR SUBSETS

5.1. Parameter One: Insulation Thickness (N)

Green roofs, due to the presence of vegetation and soil layers, act as a thermal mass themselves. The green roof may or may not have additional insulation depending on the design of the assembly. The insulation parameter in this study considers polystyrene insulation of varying thicknesses. This insulation is placed under the waterproofing membrane and just above the structural roof of the building. The four different variables to be investigated in this study include:

- 0" thick insulation- Without insulation (N0)
- 2" thick insulation (N2)
- 4" thick insulation (N4)
- 8" thick insulation (N8)

5.2. Parameter Two: Vegetation type (L)

Green roofs can comprise of different vegetation depending on climate, geographic location and desired aesthetics. Different plant types have different leaf area indices (LAI), which is broadly defined as the amount of leaf area in a vegetation canopy per unit land area (Scurlock et al. 2001). LAI is a critical parameter that is known to affect the heat fluxes between atmosphere and vegetation. In the context of green roofs, it affects thermal performance of the roof assembly, primarily on account of the amount of solar shading it provides to the roof surface. The vegetation type parameter in this study includes the following two variables:

- LAI= 1.0 (L1)
- LAI= 5.0 (L5)

5.3. Parameter Three: Growing medium or soil depth (S)

The growing medium or soil depth of a green roof assembly is generally dictated by the plant type. However, for the purpose of testing the soil depth parameter, the vegetation type (LAI=5 or LAI=1) is assumed to be able thrive at the different thicknesses of growing media being tested. The following three variables are investigated:

- 3” thick soil (S3)
- 6” thick soil (S6)
- 12” thick soil (S12)

6. SIMULATION RESULTS AND DATA ANALYSIS

The annual energy simulations are carried out for the baseline cool roof model and green roof model and the energy use intensity (EUI) of the building is observed as a performance metric, in addition to a few others like peak heating and cooling loads, heat balance through the roof etc. With each subsequent simulation one variable of each parameter of the green roof assembly is altered and the effect on the above mentioned metrics is noted.

If the thermal performance of the green roof assemblies is seen from the perspective of a single parameter, it is observed that by increasing insulation, the overall energy performance of the building does not significantly improve. The green roof assemblies perform better without any insulation and the difference between the EUI of assemblies with the lowest and the highest EUI is 1.07 kBtu/sq.ft. As can be seen from Fig. 7 that shows the effect of increasing insulation against simulated EUI for the different assemblies, the EUI changes steeply when insulation is increased from 0” to 2” and then it steadily decreases with increasing insulation with the exception of one assembly (L1S3).

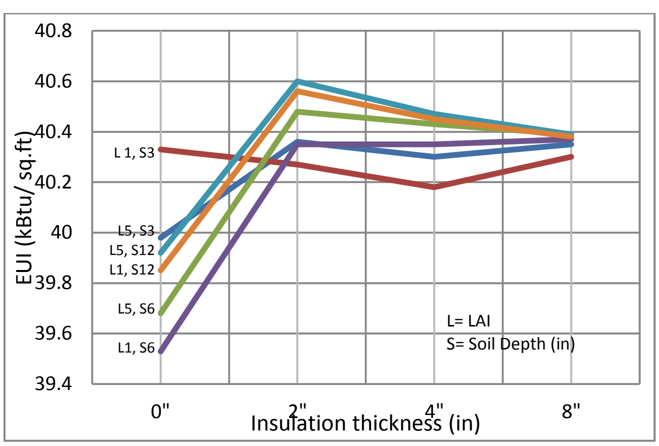

Fig. 7: Effect of green roof insulation on EUI

Also, the differences in EUI between assemblies are more prominent when insulation is absent and gets minimized with increasing insulation thickness.

Theoretically, greater LAI means more shading on the roof, which in turn means reduced solar heat gains through the roof. Fig. 8 shows the effect of increasing LAI against simulated EUI, where the general trend is observed as increase in LAI causes increase in EUI. One of the assemblies (S3N0), however, has a negative correlation and also shows maximum impact of changing LAI on EUI.

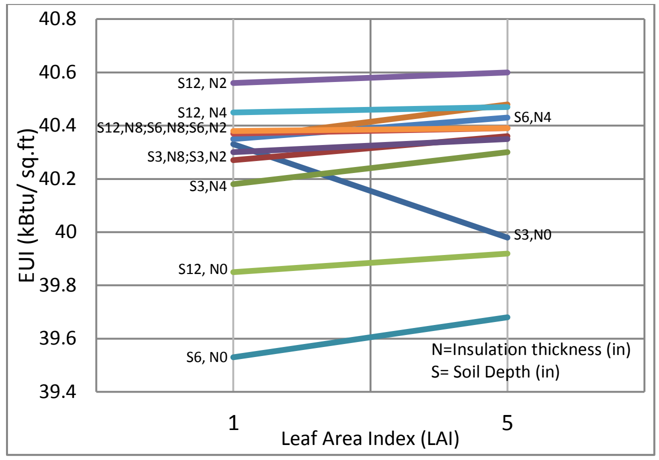

Fig 8: Effect of green roof LAI on EUI

Like in the case of insulation, the best performing assemblies (with respect to lowest EUI) are the ones that are uninsulated and have a LAI of 1. Also, as the insulation increases, the effect of LAI gets minimized. The average increase in EUI for changing the LAI of the assembly from 1 to 5 is 0.04 kBtu/sq.ft.

The soil depth parameter shows a similar trend as LAI with respect to EUI (Fig. 9).

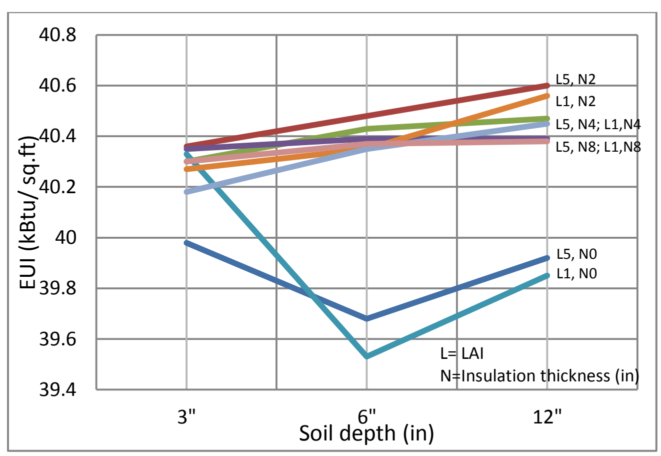

Fig. 9: Effect of green roof soil depth on EUI

As can be seen from the figure, the uninsulated assemblies differ from the general trend which is increase in EUI with increasing soil depth. That said, the effect of increasing soil depth is not that significant on the EUI of the building for this particular climate. While there is some change observed in the uninsulated green roof assemblies, the effect becomes insignificant in green roof assemblies with higher insulation thickness. The average reduction in EUI for changing the soil depth from 3” to 12” of an uninsulated green roof is 0.27 kBtu/sq.ft. Again, this observation is specific to the dry soil that was used in the model (thermal conductivity 2.4 Btu in/ hr. ft^2 F, Density 68.7 lb/ft^3, Specific heat 0.29 Btu/lb-F). For wet soil, the results will be slightly different, since the conductivity of the soil is different.

The heat balance of the roof assembly for the whole year as well as for certain days is also studied as a part of this research. Fig. 10 shows the heat balance through the roof over the period of a year, for different green roof assemblies. The assemblies with LAI=5 are denoted with dashed lines while those with LAI=1 are in continuous lines. The thick blue line denotes the heat balance through the cool roof basecase.

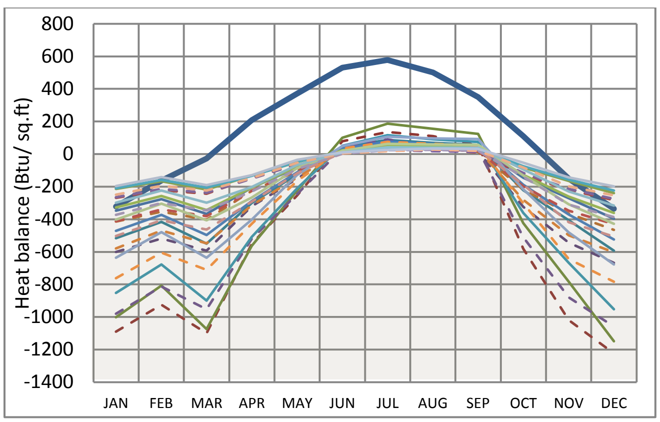

Fig. 10: Heat Balance through roof (annual)

From the above figure it can be observed that green roof assemblies mostly suffer from heat loss over the year rather than heat gain. For the cool roof base case, it is the reverse. Also, the assemblies have greater variance between themselves in terms of heat loss in winter months, whereas less variance in summer months. In addition, assemblies with greater insulation show lesser fluctuation, in terms of heat flux.

A micro scale study (one day hourly simulation) using the uninsulated green roof assembly with 6” thick soil and LAI=1 is carried out to understand the heat gain-loss through the roof over a day’s cycle. Fig. 11 illustrates the heat balance through the roof on the peak heating and cooling day and compares it to the cool roof. This figure also highlights the thermal lag (of around 3 hours) that is caused by the green roof assembly, which is more prominent during the cooling season.

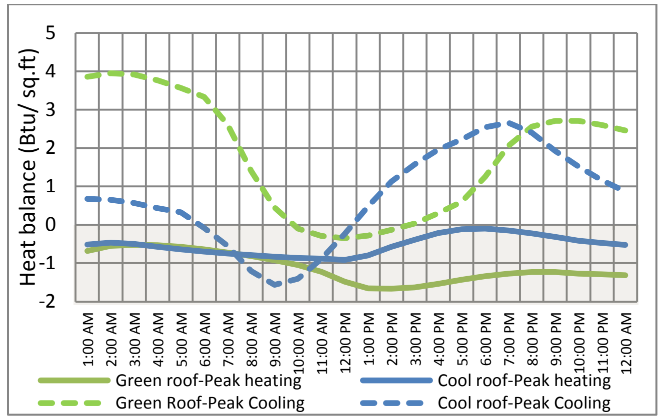

Fig. 11: Heat balance through roof on peak heating and cooling days

From the annual whole building energy simulation results, it is seen that there is heat gain of 1652 Btu/ sq.ft through the cool roof assembly, per year. In case of the uninsulated green roof assembly with 6” thick soil and LAI=1, there is a heat loss of 5763 Btu/ sq.ft. Although both, the peak heating and cooling load is reduced by around 11% over the cool roof base case, the annual cooling load reduction is double that of annual heating load reduction. This indicates that green roofs are more effective in reducing the cooling loads of a building than heating loads for this climate type. The annual cooling load of the building can be reduced by as much as 20%.

For the cool roof base case, the EUI is 41.76 kBtu/ sq.ft. and this acts as a benchmark EUI against which the EUI of all green roof assembly variants are measured. Table 2 shows the matrix of variables and the corresponding simulated percentage EUI reductions (over base case) of the different green roof assemblies.

TABLE 2: MATRIX SHOWING PERCENTAGE REDUCTIONS IN EUI OF DIFFERENT GREEN ROOF ASSEMBLIES WHEN COMPARED TO A COOL ROOF

Soil depth	Insulation thickness				Vegetation type (LAI)
	0”	2"	4"	6"	
Soil= 3"	4.26%	3.35%	3.50%	3.38%	LAI=5
	3.42%	3.57%	3.78%	3.50%	LAI=1
Soil=6"	4.98%	3.07%	3.18%	3.28%	LAI=5
	5.34%	3.38%	3.38%	3.33%	LAI=1
Soil=12"	4.41%	**2.78%**	3.09%	3.28%	LAI=5
	4.57%	2.87%	3.14%	3.30%	LAI=1

This table basically sums up all the parametric effects that are discussed in earlier sections of this paper. From the matrix it can be seen that the most effective green roof assembly for this particular climate type, is the one with no insulation, 6" thick soil and LAI=1 whereas the least favorable one would be the assembly with 2" thick insulation, 12" soil depth and LAI=5. The bar chart in Fig.12 simplifies the above matrix, indicating that uninsulated green roofs are more favorable irrespective of the other parameters. The average percentage reduction of EUI over basecase for uninsulated assemblies is around 4.5% while for the rest of the variants it is around 3.3%.

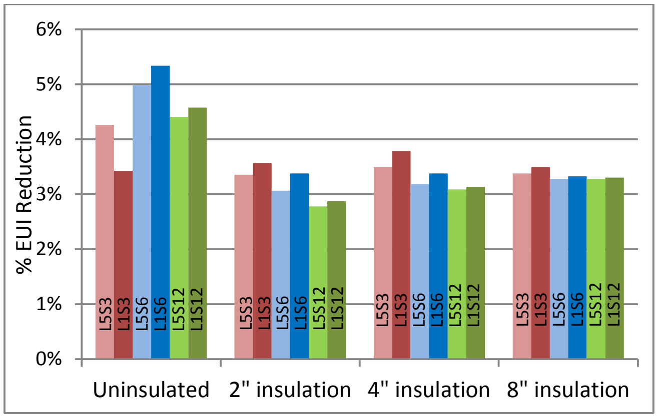

Fig. 12: Bar chart showing percentage reduction of EUI over basecase

7. CONCLUSION AND RECOMMENDATION

The parametric study of the green roof assemblies shows that they have a positive thermal impact on the building and have the potential to reduce the energy use intensity of the same, in comparison to a cool roof. The simulated data output from Design Builder helps to drawn the following conclusions-

- Green roofs can reduce the EUI of a single storied office building located in California Climate zone 8 by up to 5.3%. This suggests that although green roofs contribute to energy savings, this may not be the best energy efficiency measure (EEM) in this kind of climate for reducing a building's energy consumption, particularly because the effect of green roofs will diminish with increasing number of floors.

- The thermal performance of green roof assemblies is affected by various parameters to varying degrees. While insulation thickness and soil depth have a greater impact on the heat flow through the roof, the LAI has less of an impact. Uninsulated green roofs have the lowest EUI for this climate zone, and insulation thickness is the parameter that has the greatest impact on the EUI.

- The assemblies that are most effective in reducing the cooling loads (peak or annual) are the uninsulated ones with soil depth=6" or 12", while those most effective in reducing the heating loads are the ones with highest insulation thickness of 8". For this particular climate zone, annual cooling load may be reduced by 20.1% (Assembly type- uninsulated, soil depth= 3", LAI=5) and annual heating load may be reduced by 10.4% (Assembly type- insulation= 8", soil depth= 12", LAI=1) over cool roof basecase.

There are several other parameters of the green roof that may be tested to determine the corresponding impacts on the thermal performance of the same, although only three such parameters are covered within the scope of this paper. Also, the energy savings may be different for different climates. These areas can be covered under future work.

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