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Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs

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A R T I C L E I N F O

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A B S T R A C T

Heating and cooling of residential and commercial buildings account for approximately 40 percent of world's total energy consumption [1]. This considerable amount of energy consumption have made scientist to search for every possible way to reduce it. Among the most effective approaches is the use of green roof for buildings. Although the positive effects of using such roofs are well proven, the amount of energy reduction which can be achieved by this method is another issue that this paper is trying to investigate. In this study, three different climates of Iran are chosen for the analysis. The results demonstrate that using green roof in Very Hot Dry (Bandar Abbas), Warm Dry (Isfahan), and Mixed Dry (Tabriz) climates causes energy consumption to decrease by approximately 8.5, 9.2 and 6.6 percent, respectively. Considering the reduction of energy consumption as the only desirable benefit of green roof, the payback period would be 25–57 years (depending on the climate).

1. Introduction

The ever-increasing human population of the world requires more construction and more energy supply. Furthermore, considering the fact that the resources of fossil fuels, which are considered to be primary sources of energy production in the world, are in limited supply; men have started to look for other new efficient methods of reducing energy demand, especially in the area of buildings energy consumption. One of these innovative methods is use of green roof.

Green roof is defined as the use of vegetation covering on the roof of a building.

Using green roof has many advantages such as decreasing Urban Heat Island Effects [2–6], improving stormwater management [7–9], better usage of space [10], decreasing the amount of dust particles in the air [11,12], decreasing noise pollution [13], providing natural habitat for animals and birds [14–16], and decreasing costs of repair and renovation [17–19]. However, the main advantages of green roof are decreasing a building energy consumption by increasing insulation thickness of the roof, providing a natural shade against direct rays of the sun, thus decreasing temperature of inner and outer surfaces of the roof as well as decreasing inside temperature of the building, and therefore optimizing rate of energy consumption in the building [8,10,20–22].

Although using green roof is equally advantageous in all parts of the world, Europe and North America are the regions where green roofs are more advantageous [17,19].

As a general classification, green roofs are classified as Intensive and Extensive types. Extensive green roofs have thinner layer and less vegetation density (soil thickness is generally less than 15 cm) compared to intensive green roofs (soil thickness is generally more than 15 cm) [8,17,22–25].

Regarding the selection of green roof type for the building, it must be noted that extensive green roofs are better option to use in the buildings with roofs which cannot tolerate unusual (unexpected) loads [17]. Also, use of vegetation with high capacity for maintaining water is more desirable in these types of buildings. Ease of installation and plantation are also important [10]. Also, choosing the best type of vegetation and proper layers of soil depends on many variables including climate [26].

Positive effect of green roof on building inside temperature and consequently on the rate of energy consumption depends on many factors including Leaf Area Index (LAI) and soil layer depth; which are studied in the present paper. Furthermore, this article which studies three different climates in Iran, investigates the effect of the number of building floors on green roof benefit. Eventually, economic analysis and return on investment issues regarding the application of green roofs are investigated.

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Nomenclature

C_e^g	bulk transfer coefficient regarding the latent heat
C_h^g	bulk transfer coefficient regarding the sensible heat
Cp_a	air specific heat at constant pressure (J kg^{-1} K^{-1})
C	bulk transfer coefficient
C_{energy}	energy rate (US$ kWh^{-1})
e_0	windless sensible heat correction factor (2.0 Wm^{-2})
E_p	total initial costs
F	sum of energy terms (Wm^{-2})
H	sensible heat transferred (Wm^{-2})
i	interest rate
I_s	shortwave radiation (Wm^{-2})
$I_s^{\downarrow}$	incoming solar radiation (Wm^{-2})
I_{ir}	long wave radiation (Wm^{-2})
$I_{ir}^{\downarrow}$	incoming infrared radiation (Wm^{-2})
L	latent heat (Wm^{-2})
l	latent heat of evaporation (J kg^{-1})
LAI	leaf area index
N	hours of system operation in a year
p	payback period
q	mixing ratio of air
q''_{sg}	Conductive heat transfer in soil
q_{af}	ratio of air mixture adjacent to vegetation surface
$q_{f,sat}$	ratio of saturation mixture at leaf temperature
r''	foliage surface wetness factor
T_{af}	temperature of air surrounding the leaf (Kelvin)
T_r	temperature at the top level of the roof slab (Kelvin)
W_{af}	wind velocity between air and leaf (in ms^{-1})
$\dot{W}_{net}$	performed work in kW
$q_{f,sat}$	ratio of saturation mixture at leaf temperature
r''	foliage surface wetness factor
T_{af}	temperature of air surrounding the leaf (Kelvin)

Greek symbols

σ	Stefan-Boltzmann coefficient (5.699×10^{-8} Wm^{-2} K^{-4})
ε	emissivity factor
ρ_{af}	density of air surrounding the leaf (kg m^{-3})
α	shortwave albedo

Subscripts

n	Time step
f	foliage
g	ground

2. Modeling

2.1. Energy modeling

Modeling of green roof and analysis of building energy consumption can be carried out using the simplest and most common method – which is choosing the proper heat transfer coefficients and performing energy balance [20,27,28]– however, other more accurate methods, which consider more details, also exist [2,23,29–33]. The following items are among the details that must be considered for more accurate analysis [23]:

- Short and long wave radiation into canopy and soil
- Conductive heat transfer in soil
- Convective heat transfer between the foliage and the air and between the air and soil in the canopy
- Heat transfer by evapotranspiration in the foliage

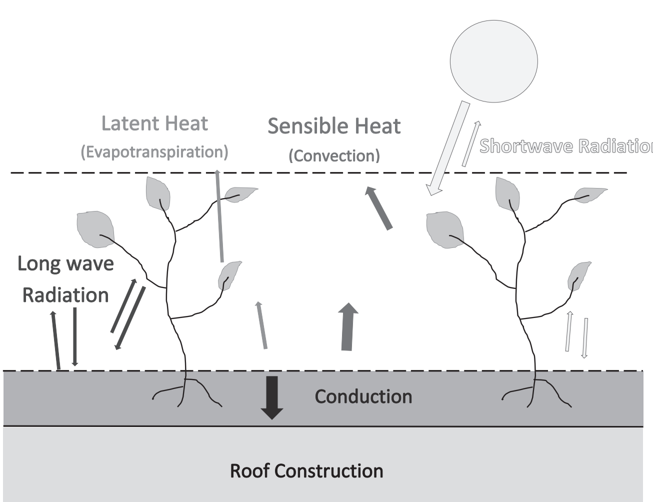

Fig. 1. Thermal balance for a green roof.

The best and most comprehensive method is the method used by Sailor [23], it is based on the calculations introduced by Frankenstein and Koenig (FASST method) [32]. This method is also the computational basis for commercial software EnergyPlus [34]. EnergyPlus is computational software for energy analysis and thermal load simulation in a building. This software, which has a non-user-friendly environment, uses an independent computational engine to run the thermal simulation. Therefore, DesignBuilder used in this study also functions on the same computational basis as EnergyPlus, but with a more user-friendly environment. A brief description of the method is presented here. Variables and symbols used in the formulas, all were given in nomenclature and their description was avoided within text.

According to the following figure, thermal balance for canopy is as follows:

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

where $[I_s(1-\alpha_f)+\varepsilon_f I_{ir}-\varepsilon_f\sigma T_f^4]$, $\frac{\sigma_f\varepsilon_f\varepsilon_g\sigma}{\varepsilon_1}(T_g^4-T_f^4)$, H_f and L_f are shortwave solar radiation absorption by foliage, long wave radiation exchange between the sky and foliage, convective heat transfer between the air and foliage as sensible heat flux, and evapotranspiration in foliage surface as latent heat flux, respectively.

ε_1 can be written as:

$$\varepsilon_1=\varepsilon_f+\varepsilon_g+\varepsilon_f\varepsilon_g \quad (2)$$

Sensible heat flux (convective heat) (H_f) is calculated by using the equation introduced by Deardoff [35]:

$$H_f=\left(e_0+1.1LAI\rho_{af}Cp_aC_fW_{af}\right)\left(T_{af}-T_f\right) \quad (3)$$

Latent heat flux between vegetation and the air adjacent to the vegetation surface (surface perspiration) is obtained from the following relation: