Applied Energy 104 (2013) 845–859

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning?

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HIGHLIGHTS

- Scarce literature investigates the technical–economical feasibility of green roofs.
- This paper provides a wide analysis of their energy/economical performances.
- The amount of required irrigation is a key node in order to achieve benefits.
- In cold climates, green-roofs allow good performances, both in summer and winter.
- In warm climates, green roofs are not advantageous for well-insulated buildings.

ARTICLE INFO

Article history:
Received 2 May 2012
Received in revised form 6 September 2012
Accepted 28 November 2012
Available online 3 January 2013

Keywords:
Green roofs
Cool roofs
European climates
Energy performances
Technical feasibility

ABSTRACT

Several studies show the potential benefits achievable by recurring to roof vegetation. Really, little literature investigates the economic feasibility of such solution. The paper verifies utility of green roofs, under environmental and energy point of views, by considering all the aspects that influence their performances. With reference to several climates, intensity of rainfalls, needs of irrigation and kind of building use, a large parametric analysis evaluates the technical and economical feasibility of green roofs applied to a modern office building, considering various vegetations and different external coatings. The scarce amount of rainfall – and thus the irrigation cost – can nullify the savings in energy demand for air-conditioning. Moreover, even if green roofs show satisfactory performance if monthly rainfalls do not imply significant additional watering – the economic investigation shows scarce convenience for well-insulated buildings, above all if the higher initial cost of a green roof, compared to traditional roofing coating, is computed. Finally, cool roofs, by means of high-reflective and high-emissive coatings, are suitable solutions in warm climates, strongly improving the summer performances, with low extra costs for installation and maintenance.

1. Introduction

Green roofs are complex technological systems, adopting vegetation as integral part of the building shell. A proper design implies energy and environmental benefits, with reference to: microclimate inside the building; reduction of urban heat islands, improving of outdoor air quality, supporting for the wastewater disposal system. Leaving out aspects that are not strictly "energy-related", green roofs are aimed to reduce roof temperature and thus the summer solar gains, without worsening the winter energy performance.

About the cooling needs, recent European directives [1,2] strongly promote the energy savings for the summer air-conditioning.

Differences between green roofs and green walls should be pointed out. Green walls have more or less spontaneous growing of vines on the vertical facades, by improving lightly the building summer performances, as regard the summer cooling load. However, this phenomenon is related to the decreasing of the solar radiation on the vertical wall structure, because of the high reflectance of the vine's foliages. In winter conditions, usually green

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http://dx.doi.org/10.1016/j.apenergy.2012.11.068

Nomenclature

U_{VALUE}	thermal transmittance of a building component ($W\,m^{-2}\,K^{-1}$)
EP	yearly primary energy requests for unitary floor space ($kWh\,m^{-2}\,y^{-1}$)
λ	material thermal conductivity ($W\,m^{-1}\,K^{-1}$)
Y_{IE}	periodic thermal transmittance ($W\,m^{-2}\,K^{-1}$)
S	time lag effect (h)
f_a	decrement factor (−)
SEER	seasonal energy efficiency ratio of the cooling system ($Wh_{TH}\,Wh_{EL}^{-1}$)
CDD	cooling degree–days (baseline 18 °C) (°Cd)
$\eta_{OVERALL}$	seasonal energy efficiency ratio of the heating system (−)
η_{EL}	thermoelectric conversion efficiency of the specific country (−)
$C_{e,g}$	bulk transfer coefficient for latent heat near the ground (−)
C_f	bulk transfer coefficient for turbulent heat in the foliage (−)
C_{hg}	bulk transfer coefficient for sensible heat near the ground (−)
$C_{p\text{-}air}$	specific heat of air (1005.6 J/kg K) ($J\,kg^{-1}\,K^{-1}$)
LAI	leaf area index ($m^2\,m^{-2}$)
F_f	sum of energy terms at the atmosphere/foliage interface ($W\,m^{-2}$)
F_g	sum of energy terms at the ground surface ($W\,m^{-2}$)
H_f	sensible heat at the atmosphere/foliage interface ($W\,m^{-2}$)
H_g	sensible heat at the foliage/ground interface ($W\,m^{-2}$)
$I_s^{\downarrow}$	total incoming solar radiation ($W\,m^{-2}$)
$I_{ir}^{\downarrow}$	total incoming infrared radiation ($W\,m^{-2}$)
l_f	latent heat of vaporization at the foliage temperature ($J\,kg^{-1}$)
l_g	latent heat of vaporization at the ground temperature ($J\,kg^{-1}$)
q_{af}	mixing ratio of the air at the foliage interface (−)
$q_{f,sat}$	saturated foliage mixing ratio (−)
r''	surface wetness factor (−)
T_{af}	air temperature in the foliage (K)
RH_{af}	relative humidity of the air in the foliage (%)
T_f	temperature of the foliage (K)
T_g	temperature of the ground surface (K)
w_{af}	wind speed in the foliage ($m\,s^{-1}$)
z	height or depth (m)
α_f	solar absorptance of the foliage (−)
α_g	solar absorptance of the ground (−)
ε_f	infrared emissivity of the foliage (−)
ε_g	infrared emissivity of the ground (−)
ρ_{af}	density of the air at the foliage temperature ($kg\,m^{-3}$)
ρ_{ag}	density of the air at the ground temperature ($kg\,m^{-3}$)
σ	constant of Stefan–Boltzman ($W\,m^{-2}\,K^{-4}$)
σ_f	fractional vegetation coverage (−)
SRI	solar reflectance index (−)
SPB	economic index 1: simple pay-back (year)
DBP	economic index 2: discounted pay-back (cumulating the cash-flows) (year)
NPV	economic index 3: net present value (€)
IP	economic index 4: index of profit (referred to a retrofit action = NPV/Cost) (−)

Subscripts

a	air
af	air within the foliage
g	ground
h	sensible heat flow term
e	latent heat flow term
Thermal	thermal energy
Primary	the energy value before any conversion
Electric	electric energy

walls loose the vegetable coating, delineating a thermal neutrality of this technology. If there is a continuous vegetation (i.e., 12 months), the only winter benefit would be the reduction of the heat transfer by convection, being the presence of cavities, determined by the morphology of climbing plants, suitable to reduce the action of wind. Definitively, as regards the green-walls, the quantification of eventual energy benefits is quite difficult and weak. Really, new effective technologies are recently tested, as, for instance double-skin green facade and perimetric flowerpots, as evidenced by Perez et al. [3].

On the other hand, green roofs offer clear benefits, allowing technical/economical evaluations of installation opportunity, criteria for design optimization, estimation of costs and energy savings.

The following list summarizes the physical phenomena that occur during the green roof operation:

- exploitation of the inertial mass as a heat storage;
- vital processes of vegetations that absorb thermal energy, through photosynthesis;
- evapotranspiration phenomena: soil and vegetative layers induce evaporative cooling on the roof.

A green roof can have "multi-layer" or "single-layer" configurations. Multi-layer technologies have three different functions placed "in series" (from top to bottom): (1) vegetative substrate, (2) filter layer and (3) drainage layer. "Single-layer" green roof, instead, has the vegetation – inclusive of plants and crop – directly placed on the waterproofing and antiroot membranes. Multi-layer solutions, although requiring higher initial costs, imply higher energy performances. Single-layer solutions are used only in north European climates, especially in suburban regions (e.g., Ireland, Scotland, Fær Øer Islands). Anyway, these do not present characteristics inherent to the targets of this paper.

Multi-layer green roofs are usually classified in: (a) intensive green, (b) extensive green. Intensive green roofs are real hanging gardens, that require significant costs in terms of installation and maintenance. The substrates are complex and also the mechanical stress (e.g., weight, solicitation, etc.) on the building structure must be carefully evaluated. Generally, thickness, mass and nature of the vegetative layers do not allow the installation on existing buildings. On the other hand, extensive green roofs require lower initial costs, and low thickness, weight, operating costs and maintenance requirements.

Green roofs have an ancient history. The first documented examples are surely the Babylon's hanging gardens (around 590 B.C.), mentioned in the History of Herodotus (fifth century B.C.) as one of the seven Wonders of Ancient World and described by Filon of Byzantium in the second century B.C.

More than twelve centuries after the gardens of Semiramis, green roofs and, more generally, green houses were used by Vikings. This northern Europe population used, between the eighth and the eleventh century A.C., green roofs as an energy solution, in order to protect the building envelope against thermal dispersions, wind and rains. Still today, the Fær Øer Islands, situated between Norway and Iceland, show many examples of dwellings equipped with old-style green roofs.