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Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs

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ABSTRACT

The intensification of the Urban Heat Island effect (UHI) is a problem that involves several fields, and new adequate solutions are required to mitigate its amplitude. The construction sector is strictly related with this phenomenon; in particular, roofs are the envelope components subject to the highest solar irradiance, hence any mitigation strategy should start from them and involve their appropriate design process.

For this purpose, cool materials, i.e. materials which are able to reflect a large amount of solar radiation and avoid overheating of building surfaces have been deeply analyzed in the last years both at building and urban scales, showing their benefits especially in hot climates. However, green roofs also represent a possible way to cope with UHI, even if their design is not straightforward and requires taking into account many variables, strictly related with the local climatic conditions.

In this context, the present paper proposes a comparison between cool roofs and green roofs for several Italian cities that are representative of different climatic conditions. In search of the most effective solution, the answers may be different depending on the perspective that leads the comparison, i.e. the need to reduce the energy consumption in buildings or the desire to minimize the contribution of the UHI effect.

1. Introduction

The urban sprawl, to which global warming is strictly related, has caused a series of environmental hazards that are well-known but difficult to tackle: the Urban Heat Island effect (UHI) is one of them. According to this phenomenon, urban areas experience higher outdoor air temperatures than those measured in rural areas, due to the heat released by human activities, the lack of greenery, the scarcity of air circulation in urban canyons and the great amount of solar radiation absorbed by urban surfaces [1]. The Urban Heat Island effect was first observed in London in the 19th century, as a consequence of the industrial revolution, but in the last decades it has gained increasing attention especially in those countries that experience high solar irradiance in the summer [2].

Indeed, urban surfaces usually present high solar absorptance, low permeability and other thermal properties very favorable to increase urban air temperature. Rizwan et al. [3] carried out an interesting review of previous studies focused on the generation and the mitigation of the UHI phenomenon, finding three possible ways to tackle the problem: reducing anthropogenic heat release, adopting appropriate cooling strategies (e.g., humidification and shading by means of PV modules) and improving roofs' designs.

In particular, it is proven that the roof surface plays a very important role. Indeed, roofs represent about 20–25% of urban surfaces and 60–70% of the building envelope on average in Italy, depending on the building typology. Moreover, the solar radiation impinging on the roofs can easily raise their outer surface temperature up to 50–60 °C, that is to say, 10–15 °C higher than in the surrounding green areas [4].

In this context, many studies have been carried out in order to develop new finishing materials for urban surfaces. As concerns the roofs, the most promising passive strategies seem to be the use of highly-reflective coatings (cool roof) and the placement of a vegetation cover on top of the roof surface (green roof).

The use of highly reflective cool paints for roofs and road pavements has been investigated in a pioneering way by Akbari in various works [5–7], showing the potential energy and money savings in space cooling achieved by using materials with medium–high solar reflectance and high thermal emittance. Considering the sensible heat fluxes measured in the framework of an experimental campaign carried out by the Kobe University, Takebayashi and Moriyama [8] compared the thermal performance

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Nomenclature

Variables

A	Roof surface [m^2]
C_h^g	Sensible heat flux bulk transfer coefficient [–]
$C_{p,a}$	Specific heat of air at constant pressure [$J \cdot kg \cdot K^{-1}$]
COP	Coefficient of Performance [–]
EER	Energy Efficiency Ratio [–]
F	Net heat flux [$W\,m^{-2}$]
g	Solar factor [–]
H	Sensible heat flux [$W\,m^{-2}$]
h_c	Convective coefficient [$W\,m^{-2}\,K^{-1}$]
h_p	Height of plants [m]
I_{ir}	Total incoming long wave radiation [$W\,m^{-2}$]
I_s	Total incoming short wave radiation [$W\,m^{-2}$]
k	Dry soil thermal conductivity [$W\,m^{-1}\,K^{-1}$]
L	Latent heat flux [$W\,m^{-2}$]
m_{sr}	Minimum stomatal resistance [$s\,m^{-1}$]
PER	Primary Energy Ratio [–]
Q	Thermal energy needs [$MWh\,y^{-1}$]
r	Solar reflectance [–]
T	Temperature [K]
U	Thermal transmittance [$W\,m^{-2}\,K^{-1}$]
w	Wind speed [$m\,s^{-1}$]

Greek letters

ε	Thermal emissivity [–]
ε_1	View factor [–]
η	Efficiency [–]
ρ	Density of air [$kg\,m^{-3}$]
σ	Stefan-Boltzmann constant [$W\,m^{-2}\,K^{-4}$]
σ_f	Fractional vegetation coverage [–]

Subscripts

af	Air-foliage
c	Convective
f	Foliage layer
g	Ground layer
I	Indoor air
o	Outdoor air
s	Summer
so	Outer surface
w	Winter

of different roof finishing layers: traditional concrete tiles, green roofs (both bare soil and with lawn) and highly reflective paints (gray and white colored). They found out that, for the specific climatic conditions of Kobe, green roofs present the lowest incoming sensible heat flux (2 $W\,m^{-2}$ on average during two typical summer days), followed by the highly reflective white (20 $W\,m^{-2}$) and gray (97 $W\,m^{-2}$) paints and by concrete tiles (72 $W\,m^{-2}$).

On the other hand, Scherba et al. [9] modeled and validated through experimental measurements the heat fluxes released by different roof solutions (dark membrane, cool roof and green roof), together with the shading effect of PV modules installed on them, and found out that both green and cool roofs are able to cut the peak flux by about 70%.

Moreover, Santamouris et al. [10] investigated the effectiveness of various materials (highly reflective and highly emissive light colored materials, cool materials, phase change materials and dynamic cool materials) in reducing their surface temperature when hit by solar radiation, finding that cool materials are the commercially available solution most appropriate both under the energy and the economic point of view. On the other hand, coatings with dynamic optical characteristics are very promising but need further investigation about their aging and degradation.

Through this brief summary, it is clear how the use of cool and green materials are among the most effective technical solutions to reduce the roof outer surface temperature, thus mitigating the UHI phenomenon. As an example, their application allowed to reduce the peak air temperature in an urban park of Athens by about 1–2 °C [11], and also to strongly reduce the cooling energy needs of a building in Italy [12].

However, these studies only consider the roof behaviour in summer. If one takes into account also the winter period, these solutions may imply a reduction in the solar heat gains through the roof, hence an increase in the building energy needs for space heating.

To clarify this issue, the present paper shows the results of annual dynamic simulations for a sample office building in three Italian cities with different climatic conditions. The simulations will compare the energy performance (heat fluxes and primary energy needs) and the external roof temperatures for five different scenarios: the existing roof, green roof without irrigation (dry), green roof with an appropriate irrigation schedule and cool roofs with two different values of solar reflectance (r = 0.65 and r = 0.80).

The aim is to demonstrate that the choice between green and cool roofs has to be made with extreme attention, in relation to the peculiar climatic constraints, namely solar irradiation and precipitation. Moreover, depending on the perspective that drives the comparison – UHI mitigation or energy savings for air conditioning – the choice between the two solutions may be different.

2. Modeling green and cool roofs

2.1. Green roofs: equations and key parameters

Modeling green roofs involves the study of mass and heat transfer through the different layers, as well as elements of plant physiology. Several models are available in the literature: the simplest models only consider the reduction of roof thermal transmittance based on in-situ measurements [13], while other studies analyze more in detail the complex phenomena due to foliage shading and evapotranspiration [14].

Amongst these models, the one developed by Del Barrio [15] divides a green roof in three different layers: the canopy, the soil and the support. By imposing the horizontal homogeneity of the roof slab, heat and mass fluxes are assumed to be mainly vertical, so one-dimensional equations can be adopted to describe the thermal behavior of each layer. This model has been validated through a sensitivity analysis for a concrete roof slab of 10 cm in Athens, and represents the main reference for other one-dimensional models, such as those developed by Kumar and Kaushik [16] or by Lazzarin et al. [17]. On the other hand, two-dimensional models are much less common: an example in the literature is given by Alexandri and Jones [18], aimed to evaluate the thermal effect of green roofs and green walls.

Anyway, nowadays the one-dimensional EcoRoof model developed by Sailor [19] is maybe the most used one, and thanks to its high reliability it has been implemented in the software tool EnergyPlus. Based on the previous work of Frankenstein and Koenig [20], who developed the FASST (Fast All-Season Soil Strength) model, Sailor calculates two different heat fluxes for the green roof, respectively at the foliage surface F_f (see Eq. (1)) and at the ground surface F_g (see Eq. (2)):

$$F_f = \underbrace{\sigma_f[I_s(1-r_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4]}_{\text{radiant\_sky}} + \underbrace{\frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1}(T_g^4 - T_f^4)}_{\text{radiant\_ground}} + \underbrace{H_f}_{\text{sensible}} + \underbrace{L_f}_{\text{latent}} \quad (1)$$