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A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs

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ABSTRACT

The reduction of energy demand for space cooling, as well as the mitigation of the Urban Heat Island effect (UHI), require adequate solutions at building and urban scale. In particular, the roofs of buildings have been identified as a possible field of intervention that could contribute to provide significant energy savings and environmental benefits. In this context, cool and green roofs are two very interesting solutions, which may allow obtaining both the reduction of the energy consumption and the improvement of the comfort sensation in the outdoor and indoor environment.

This paper presents a numerical comparative analysis of the energy and environmental performance of three typologies of roof, namely a standard roof (SR), a cool roof (CR) and a green roof (GR). This analysis, developed through dynamic energy simulations under temperate climate, highlights the different thermal behavior for the investigated roof scenarios, also as a function of the level of thermal insulation. Moreover, with the aim to obtain a classification between SR, CR and GR in Mediterranean climate, a scoring system is presented, which considers the whole performance of the investigated roof scenarios under a broad perspective.

As a result, it is found that green and cool roofs provide higher energy savings and environmental benefits than highly insulated standard roofs. In particular, scarcely insulated green roofs showed the best performance in relation to the UHI mitigation under the climatic conditions typical of the Mediterranean area.

1. Introduction

Innovative energy solutions and passive techniques for improving the energy performance of buildings have become a strategic environmental and economic issue. Indeed, the envelope of many existing buildings is inadequate to reduce heat losses in winter, or to contrast the solar heat gains in summer [1]. In particular, the behavior of the roof surface highly affects the peak load and the energy cooling demand in conditioned buildings, as well as the indoor thermal comfort in non-conditioned buildings [2,3]. Moreover, in summer the solar radiation that hits a roof causes the increase of the outer surface temperature by several degrees above the outdoor air temperature [4,5].

On a city scale, this effect contributes to the increase in the urban air temperature, i.e. the well-known phenomenon called *Urban Heat Island effect* (UHI) [6]. This is defined as the air temperature rise in densely built environments with respect to the countryside surroundings, and its main cause is the modification of the land surface in the urban area, where the vegetation is replaced by paved roads and building surfaces. The heat island effect is found to be the net result of several competing physical processes. In general, reduced evaporation in the city center and the thermal properties of building and paving materials are the dominant parameters. Furthermore, buildings, sidewalks and car parks prevent the heat coming from the ground from being dissipated into the cold night sky. Hence, the air temperatures in UHI remain high even during nighttime, thus increasing the needs for air conditioning and the emission of air pollutants and greenhouse gases from fossil-fuel power plants. An excessive energy demand during nighttime can stress the electrical grid on hot summer afternoons, making it more susceptible to brown-outs and black-outs. Warmer air also accelerates the formation of smog from airborne pollutants like nitrogen oxides and volatile organic compounds. Therefore, it can be stated that the UHI negatively affects the urban community and the environment.

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Now, building materials are usually characterized by high solar absorptivity, high impermeability and favorable thermal properties for energy storage and heat release, which makes the areas around buildings warmer. Hence, the modification of these thermal properties can be a successful strategy to mitigate the UHI phenomenon [7,8].

Nevertheless, one of the most adopted strategy to reduce the heating and cooling loads of buildings is the increase of the thermal insulation of the envelope components, including the roofs [9–11]. However, even if high thermal insulation is suitable to reduce the energy needs in winter, it may produce overheating in summer, and could may adverse effects on the indoor thermal comfort [5,12]. Indeed, it is well-know that over-insulation of the building envelope risks to reduce the effectiveness of passive strategies traditionally employed to reduce solar heat gains in summer [13,14].

Furthermore, even though the Directive on the Energy Performance of Buildings (EPBD 2002/91/CE) imposes the adoption of suitable techniques to reduce the cooling load in Southern European countries, just few qualitative provisions have been set in each country. Amongst these, cool and green roofs have been recently applied as passive strategies for reducing the cooling needs of buildings [3,15], to mitigate the UHI effects [16,17] and for air pollution removal [7,18].

Several studies have already been conducted to investigate the energy performance of cool roofs [19–21] and green roofs [22–24] as well as the consequent reduction of the outdoor surface peak temperature. In this context, the aim of this work is to propose a broader perspective to approach a thorough energy and environmental analysis of different roof typologies, i.e. standard roof (SR), cool roof (CR) and green roof (GR), subject to different thermal insulation thickness. Globally, ten scenarios are investigated, i.e. SR with four different thickness of thermal insulation, CR with three different thickness of thermal insulation and GR with three different thickness of thermal insulation. These configurations have been chosen so as to present a wide overview, depending also on the thickness of the thermal insulation.

Dynamic thermal simulations were carried out on a sample building to evaluate the performance of each roof scenario in terms of energy needs, thermal behavior and indoor thermal comfort. A multi-criteria comparison between the investigated roof solutions was performed, by assigning a score to different parameters that characterize the energy and environmental performance of each roof scenario. In particular, these parameters are the energy needs for heating (Q_H) and cooling (Q_C), the surface outdoor temperature (T_{so}), an index to measure internal discomfort (*ITD*) and the thermal stress, measured through the maximum difference between the surface outdoor and indoor temperature (ΔT_{s_max}). This approach allowed to draw interesting conclusions about the performance of green and cool roofs in Mediterranean climate.

2. Material and methods

2.1. Green roof

A green roof consists in a vegetation cover on top of a roof surface. Two types of green roofs are generally identified: extensive green roofs, whose soil thickness is below 15 cm, and intensive green roofs, with a soil thickness above 20 cm [25]. Because of their low additional loads, extensive green roofs do not require any additional strengthening, so they are suitable for building retrofitting [26]. The typical layers of an extensive green roof, from the inner to the outer side, are: load-bearing slabs (roof deck), vapor barrier, insulation layer, roofing membrane, root barrier, drainage layer with/without aeration and storage water, filter layer, growing substrate/porous soil and vegetation layer [23,27].

Several studies have highlighted the favorable environmental and energy performance of green roofs, showing how they introduce a reduction of both the heating and the cooling loads, an improvement of thermal comfort and of the urban air quality. Moreover, it is possible to observe a reduction of noise transmission, a mitigation of the Urban Heat Island effect and the extension of roof life [14,27–32].

Indeed, a green roof absorbs a high percentage of solar radiation for performing the biological functions of the vegetation, thereby only a low heat flux is transferred to the indoor space [33]. The effects of shading and evapotranspiration, as well as the thermal mass of a green roof, help to stabilize internal temperatures, delay the outdoor surface temperature peak and keep the internal conditions within the comfort range [22,23,27,34–36].

2.1.1. Energy balance for the green roof

The energy balance of a green roof is governed by radiant and convective heat exchange, evapotranspiration from soil and plants, evaporation/condensation of water vapor, as well as heat conduction and storage in the soil layer. Generally, a green roof is subdivided into three main layers for modeling its energy balance: structural support, soil and canopy (leaf cover) [37,38].

The soil component contains a solid phase (mineral and organic material), a liquid phase (water) and a gaseous phase (air and water vapour). The canopy is composed by the leaves and the air within the leaf cover. The height of the plants and the leaf area index (*LAI*), which is the total one-sided area of leaf tissue per unit ground surface area ($m^2 \cdot m^{-2}$), are two of the fundamental characteristics of the canopy. Other characteristic parameters are the emissivity, the reflectivity, the absorptance and the transmissivity of the leaves, and the minimum stomatal resistance, which governs the flow of water vapor through the stomates.

The evaporation from the ground surface and the evapotranspiration from the vegetation layer strongly depend on the moisture content of the soil layer, which is variable between 0.15 ($m^3\ m^{-3}$) and 0.50 ($m^3\ m^{-3}$) when the soil is in saturation conditions.

The analysis developed in this article has been based on the "Fast All Season Soil Strength" (FASST) model developed by Frankenstein and Koenig, which is available in the EnergyPlus program [39–41].

The radiant heat fluxes include the solar radiation absorbed by the leaves, the long-wave radiation exchanged between the leaves and the sky, between the leaves and the soil surface and between the leaves themselves (Fig. 1). This computational model involves the soil surface temperature (T_g) and the foliage temperature (T_f). Therefore, two energy balance equations need to be simultaneously solved at each time step for calculating the heat flux at the soil (F_g) and foliage (F_f) level. The heat balance through foliage and soil is respectively given by Eq. (1) and Eq. (2):

$$F_g = \left(1-\sigma_f\right)\cdot\left[I_s^{\downarrow}\left(1-r_g\right)+\varepsilon_g I_{IR}^{\downarrow}-\sigma\varepsilon_g\cdot T_g^4\right] - \frac{\sigma_f\cdot\varepsilon_f\cdot\varepsilon_g\cdot\sigma}{\left(\varepsilon_g+\varepsilon_f-\varepsilon_f\cdot\varepsilon_g\right)}\cdot\left(T_g^4-T_f^4\right)+H_g+L_g+\lambda_g\frac{dT_g}{dz} \quad (1)$$

$$F_f = \sigma_f\cdot\left[I_s^{\downarrow}\left(1-r_f\right)+\varepsilon_f I_{IR}^{\downarrow}-\sigma\varepsilon_f\cdot T_f^4\right] + \frac{\sigma_f\cdot\varepsilon_f\cdot\varepsilon_g\cdot\sigma}{\left(\varepsilon_g+\varepsilon_f-\varepsilon_f\cdot\varepsilon_g\right)}\cdot\left(T_g^4-T_f^4\right)+H_f+L_f \quad (2)$$