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Green and cool roofs' urban heat island mitigation potential in European climates for office buildings under free floating conditions

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Abstract

Heat island which is the most documented phenomenon of climatic change is related to the increase of urban temperatures compared to the suburban. Among the various urban heat island mitigation techniques, green and cool roofs are the most promising since they simultaneously contribute to buildings' energy efficiency. The aim of the present paper is to study the mitigation potential of green and cool roofs by performing a comparative analysis under diverse boundary conditions defining their climatic, optical, thermal and hydrological conditions. The impact of cool roof's thermal mass, insulation level and solar reflectance as well as the effect of green roofs' irrigation rate and vegetation are examined. The parametric study is based on detailed simulation techniques coupled with a comparative presentation of the released integrated sensible heat for both technologies versus a conventional roof under various climatic conditions.

Keywords: Green roofs; Cool roofs; Urban heat island; Mitigation potential; Sensible heat

1. Introduction

The heat island effect concerns higher temperatures in central urban areas as compared to suburban areas, and is considered as the most documented phenomenon of climatic change (Santamouris, 2001). Important research has been carried out to understand this phenomenon and also document its magnitude in various parts of the planet (Mihalakakou et al., 1998; Mirzaei and Haghighat, 2010; Mohsin and Gough, 2012; Santamouris, 2007). Existing data shows that the intensity of the phenomenon may be very important and may reach values close to 10 K (Giannopoulou et al., 2011; Gobakis et al., 2011; Livada et al., 2002; Mihalakakou et al., 2004, 2002; Santamouris et al., 1999). The increase of urban temperatures in association to the important climate change influences the quality of life of urban citizens (Cartalis et al., 2001; Livada et al., 2007). In particular, there is a considerable increase in the energy consumption for cooling buildings (Asimakopoulos et al., 2012; Hassid et al., 2000; Kolokotroni et al., 2012; Santamouris, 2012; Santamouris et al., 2001) while high temperatures intensify pollution problems and increase ozone concentration (Sarrat et al., 2006; Stathopoulou et al., 2008). In parallel, the outdoor thermal comfort conditions are deteriorated (Pantavou et al., 2011), the ecological footprint of cities is increasing (Santamouris et al., 2007a), while the thermal stress is more intense for low income population (Sakka et al., 2012).

To counterbalance the aforementioned conditions various mitigation techniques have been developed. Some of the more important mitigation techniques deal with the increase of the albedo of buildings and urban structures (Rosenfeld et al., 1995; Santamouris et al., 2011, 2008),

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the use of additional green spaces in cities (Zoulia et al., 2009), the installation of green gardens on the roof of buildings (Niachou et al., 2001; Santamouris et al., 2007b) as well as the use of cool sinks for heat dissipation, such as the ground and water (Jacovides et al., 1996; Mihalakakou et al., 1994).

In particular, the increase of urban albedo may decrease substantially carbon dioxide emissions in the atmosphere. Recent studies have shown that a long-term global cooling effect of 3×10^{-15} K corresponds to each 1 m^2 of a surface with an albedo increase of 0.01 and this is equivalent to a CO_2 emission reduction of about 7 kg (Akbari et al., 2012). Increase of the albedo in the built environment can be achieved by using high reflectance surfaces in roofs, pavements and other urban surfaces. Natural materials as well as high reflectance white paints have been proposed and used with important results in buildings,(Doulos et al., 2004; Synnefa et al., 2006). Recent studies and applications have shown that the use of cool roofs is associated to important reductions of the cooling load of the corresponding buildings (Kolokotsa et al., 2011; Synnefa and Santamouris, 2012; Synnefa et al., 2012). In parallel, colored materials based on the use of infrared reflective pigments present a much higher reflectivity than conventional colored paints (Akbari and Levinson, 2008; Kolokotsa et al., 2012; Synnefa et al., 2007). Further research on the field of cool coatings has permitted to develop advanced reflective materials, such as thermochromic paints, PCM doped coatings and reflective asphaltic materials that contribute towards better performing buildings and urban structures (Karlessi et al., 2011, 2009; Synnefa et al., 2011).

Green roofs are fully or partially covered with vegetation and a growing medium over a waterproofing membrane. Two types of green roofs are available: Intensive roofs, which are heavy constructions and can support small trees and shrubs, and extensive roofs, which are covered by a thin layer of vegetation. There are several advantages associated to green roofs like decreased energy consumption, better air quality, noise reduction, increased durability of the roof materials, etc. (Mentens et al., 2006; Sfakianaki et al., 2009; Theodosiou, 2009).

Important energy benefits are associated to the use of green roofs. Energy reductions depend on the design of the green roofs, the local climatic conditions and the characteristics of the building (Castleton et al., 2010; Takakura et al., 2000). A discussion on the main parameters defining the performance of the green roofs is given in (Santamouris, 2012).

The total surface of roofs in the urban world is estimated close to 3.8×10^{11} m^2, while roofs constitute over 20% of the total urban surfaces (Akbari et al., 2009, 2003; Zinzi and Agnoli, 2011). Thus roofs provide an excellent medium for the application of mitigation techniques as the construction cost is much lower than that of the available free ground area, while at the same time they offer additional benefits, such as the reduction of the energy consumption of the corresponding buildings.

Cool and green roofs are excellent mitigation technologies applied on the roof surface of buildings. The overall energy performance of the two examined mitigation techniques depends mainly on the climatic conditions and the constructional characteristics. A classification of the comparative performance of both roof mitigation techniques based on existing experimental and theoretical data is provided in (Santamouris, 2012).

The present paper aims to investigate the comparative performance of cool roofs and green roofs under diverse boundary conditions defining their climatic, optical, thermal and hydrological condition. Parametric studies have been performed using detailed simulation techniques for both technologies and conclusions are extracted and discussed.

2. The mitigation potential of reflective and green roofs: factors affecting their performance

The mitigation potential of reflective and green roofs depends on a number of parameters as summarized in (Santamouris, 2012). Four categories of performance parameters have been identified as described below:

(a) Climatic parameters like solar radiation, ambient temperature and humidity, wind speed and precipitation. Solar radiation determines the thermal balance of the roofs and defines at large their temperature. Ambient temperature regulates the amount of sensible heat released to the atmosphere as convective heat flux is a function of the temperature difference between the roof and the air. Wind speed determines the heat transfer coefficient between the roof and the atmosphere while relative humidity and precipitation define the moisture balance in green roofs.
(b) Optical parameters like solar reflectivity and emissivity for reflective roofs and the absorptivity of the plants for the green roofs.
(c) Thermal parameters, such as the thermal capacity of the roofs and the overall heat transfer coefficient, *U*-value, between the roof and the building.
(d) Hydrological parameters that define the latent heat budget in green roofs.

A direct or indirect comparison of the energy performance and the heat island mitigation of reflective and green roofs is performed by many theoretical and experimental studies (Chen et al., 2009; Gaffin et al., 2005; Hodo-Abalo et al., 2012; Ray and Glicksman, 2010; Sailor et al., 2012; Saiz et al., 2006; Scherba et al., 2011; Simmons et al., 2008; Susca et al., 2011; Takebayashi and Moriyama, 2007; Zinzi and Agnoli, 2011). Both technologies contribute to decrease the energy consumption of buildings, however, their performance and the corresponding energy benefits depend strongly