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Experimental and numerical analysis of the energy performance of a large scale intensive green roof system installed on an office building in Athens

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ABSTRACT

The aim of this study is to investigate the thermal behaviour and the energy efficiency of an intensive green roof system composed of indigenous aromatic plants with low irrigation needs, installed in the 10,000 m^2 roof of a fully insulated, low energy office building in Athens, Greece. It consists of almost 16,000 Mediterranean plants of at least 14 different kinds and a running track of a stabilized ceramic floor. The urban heat island mitigation potential of the green roof as well as its energy contribution is investigated using experimental and theoretical methodologies. The surface temperature of the green roof is found to be up to 15 K lower than that of a conventional roof. Plants having a low absorptivity to solar radiation together with a dense foliage are found to present a much lower surface temperature and a higher mitigation potential. The surface temperature of the plants is found to be highly influenced by the ambient air temperature. Using simulation techniques it is calculated that such a type of green roofs can decrease the average indoor temperature of a non air conditioned building up to 0.7 K, while it may decrease substantially its annual cooling and heating needs.

1. Introduction

Urban warming is a major threat to urban populations. Increase of the ambient temperature in cities is due to the combined effect of the heat island phenomenon and the global climate change. Urban heat island is the more documented phenomenon of climate change and deals with the increase of the urban temperature compared to the temperature of the surrounding rural areas. Urban warming has a very important impact on the quality of life of urban dwellers. It increases considerably the energy consumption spent for cooling purposes [1], it rises the peak electricity demand [2], while it deteriorates the environmental quality, and causes discomfort and increased health problems in cities [3].

To counterbalance the serious impact of urban warming, important mitigation strategies have been proposed, developed and implemented in real scale projects [4]. Urban mitigation technologies aim to decrease the strength of heat sources and enhance the potential of heat sinks in the cities. Among the more efficient of the mitigation technologies are: (a) those aiming to expand the green spaces in cities through the use of green roofs or additional park and green areas [5], (b) technologies increasing the albedo of the cities through the use of cool materials presenting a high reflectivity in the solar spectrum together with a high emissivity factor [6,7], (c) strategies to decrease the anthropogenic heat released in cities and (d) technologies employing the use of low temperature sinks to dissipate the excess urban heat [8].

Urban green involving parks, green roofs, trees in the streets and open spaces contribute extensively to mitigate urban warming as it provides solar protection and cooling of the ambient air through evapotranspiration processes. Vegetative roofs are partially or completely covered by plants over an engineered planting substrate on specialized build up of polymer materials. They are differentiated by the type of plants they may support. Extensive type green roofs are covered by low vegetation while intensive green roofs may support growing of shrubs and small trees. Important benefits are associated with the use of green roofs. Because of the solar and heat protection they provide, contribute to lower the energy consumption of buildings, while through latent heat processes, decreases the surface temperature of the roofs and reduce the release of sensible heat to the atmosphere. In parallel, green roofs help with the storm water runoff management, provide better air quality, reduce noise, prevent erosion and increase the durability of the roof materials [9]. Disadvantages associated with planted roofs are the additional load that the building has to support

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actually mitigated with the installation of lightweight specialized build up systems- and the relatively high investment cost.

The energy and mitigation performance of the vegetative roofs is governed by several climatic, optical, thermal and structural parameters. In particular, air temperature, solar radiation, ambient humidity, precipitation and wind speed are the main climatic parameters influencing the performance of green roofs. In parallel, thermal, optical and hydrological parameters like the thermal capacitance and *U* value of the roof, the absorptivity of the green roof as a system, and the frequency of watering of plants determine the efficiency of the green roofs. Finally, the total one sided area of photosynthetic tissue per unit of ground surface area, LAI (Leaf Area Index), is a crucial parameter defining the latent heat losses of the roof [10].

The reduction of the energy consumption of buildings with green roofs has been evaluated through numerous experimental and theoretical studies [11–18]. The exact energy contribution of the green roof systems depends on the parameters defined previously and also the specific characteristics of the building. However, the performance of a green roof is mainly determined by the magnitude of the released latent heat. Previous studies have shown that latent heat from a green roof varies between 100 and 600 W/m^2 as a function of the specific characteristics of the green roof and the building and the water content in the roof [4]. Given that the humidity levels in the atmosphere determine the evaporation potential of green roofs its thermal performance is higher in dry climates.

The heat island mitigation potential of green roofs is investigated through a limited number of experimental and theoretical studies [19–25]. Simulations of the mitigation potential of vegetative roofs for Crete, Greece and London, UK, are reported in [21]. It is found that the average sensible heat released by a conventional roof is 157 W/m^2 in Crete and 87 W/m^2 in London. This is reduced to 104,70,33, and 21 W/m^2 for a non irrigated green roof with LAI'S of 0, 5, 1, 2 and 3 respectively in Crete, while the corresponding values for London are 56, 37, 17 and 10 W/m^2. The annual released sensible heat by a green roof with LAI = 2 is found to be 73 kWh/m^2 in Crete and 20 kWh/m^2 in London. The corresponding figures for a conventional were found equal to 176 kWh/m^2 and 119 kWh/m^2. Several theoretical studies have used mesoscale models to evaluate the possible decrease of the ambient temperature because of the extensive use of green roofs in buildings. Studies are available for New York, Chicago, USA, Tokyo, Japan and Hong Kong. Simulations shown that in Chicago the ambient temperature between 19:00 and 23:00 may be reduced to about 2–3 K [22]. While in New York the calculated decrease of the ambient temperature during August and at 12:00 LST was between 0.3 and 0.55 K [23]. On the contrary, the mitigation potential of green roofs in Tokyo and Hong is found to be negligible [24,25].

This paper aims to present a detailed thermal investigation of a prototype large scale green roof installed in an office building in Athens, Greece. The green roof system covers an area of 10,000 m^2, and hosts 16,000 indigenous aromatic plants of 14 different species presenting reduced irrigation needs. To our knowledge, it is the largest green roof experiment in the area of Southern Europe. In parallel, it is the first application of indigenous aromatic Mediterranean plants in a large scale green roof, according to the up to date technological solutions.

2. Description of the building and the green roof system

The green roof system, consisted of specialized polymer materials and engineered substrate, is installed in an office building located in the sparsely built industrial zone of Peania, an east suburb of the area of Athens. It is a three-storey building with three basements, equipped with a green roof system (G.R.S.). It has a surface of almost 10,000 m^2 per floor and 60,000 m^2 in total while the elevation of each floor is equal to 3.60 m. The main axis of the building is northwest–southeast oriented and all external surfaces are exposed to solar radiation as it stands by itself and there is no shading from neighbouring buildings. The aspect ratio, which is the ratio of the building's height over its width, is equal to 0.07, while the ratio of the surface covered by windows over the surface covered by wall is equal to 0.53. It is fully insulated: the exterior walls consist of heavyweight reinforced concrete and insulation of extruded polystyrene, the floors are made of heavyweight reinforced concrete, a particle board and a linoleum coating, while the ceilings of a metal false ceiling and mineral wool. The whole façade is also covered by metal shades which have the ability to move. The building is accredited a Gold LEED certification (Fig. 1).

The intensive type green roof system builds up installed on the 10,000 m^2 roof of the building and it consists of specialized polymer materials and engineered planting substrates with almost 16,000 indigenous aromatic plants of at least 14 different kinds. The plants present low irrigation needs and are fully adapted to the specific climatic characteristics of the Mediterranean zone. A panoramic view of the green roof is given in Fig. 2 while a picture of the various plants in the roof is given in Fig. 3. The rest of the area is covered by a running track of 2000 m^2 made by stabilizing ceramic floor. It is an ecological, bioclimatic and water permeable material which consists of ground tiles, mosaic, quartz, sand and pumice. The different layers of the G.R.S. build up (from outside to inside) are presented in Table 1 and the species and the characteristics of the different plants in Table 2. The green roof is irrigated through a drip irrigation system, that allows water to drip to the roots of the plants. Such a system consumes the minimum necessary water and is appropriate for the dry Mediterranean climate.

3. Details of the experimental program

The main aims of the experimental investigation of the specific building were the following three:

(a) To identify the energy contribution of the green roof system on the energy balance of the building.
(b) To investigate the possible heat island mitigation potential of the green roof during the summer period.
(c) To study the specific UHI mitigation potential of the 14 different plants used in the green roof system.

Experiments have been carried out during the summer period, between 30/05/2013 and 30/07/2013 and consist of the following measurements:

- Outdoor and indoor temperature and relative humidity: calibrated miniature type data loggers were used. The accuracy of the used temperature sensors is close to ±0.2 K. The outdoor sensors were placed inside meteorological cages to be protected from the solar and ambient heat. Measurements were taken every 5 min during the whole period. Indoor temperature was measured in a representative office room in the upper floor of the building. The outdoor temperature and humidity sensors were placed in a protected and fully shaded and ventilated part of the roof. All used sensors were calibrated using high precision reference equipment. In parallel, indoor temperature data were available for all the main zones of the building through the BMS system. During the experimental period the average ambient temperature was 26.4 °C while the maximum was 40.4 °C and the minimum: 15.5 °C.
- The indoor roof surface temperature in the upper floor, located just behind the green roof. Measurements were performed every