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 AND STATE OF THE ART

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). Existing data shows that the intensity of the phenomenon may be very important and may reach values close to 10K. The increase of urban temperatures in association to the important climate change influences the quality of life of urban citizens. In particular, there is a considerable increase in the energy consumption for cooling buildings, while high temperatures intensify pollution problems and increase ozone concentration. In parallel, the outdoor thermal comfort conditions are deteriorated, the ecological footprint of cities is increasing, 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, the use of additional green spaces in cities, (Zoulia, Santamouris, and Dimoudi 2009), the installation of green gardens on the roof of buildings, as well as the use of cool sinks for heat dissipation, such as the ground and water. 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, Damon Matthews, and Seto 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,(Synnefa, Santamouris, and Livada 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, Saliari, and Santamouris 2012; Synnefa and Santamouris 2012). 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 and noise reduction, increased durability of the roof materials, etc. (Mentens, Raes, and Hermy 2006; Sfakianaki et al. 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, Kitade, and Goto 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, Menon, and Rosenfeld 2009; Akbari, Rose, and Taha 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:

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.

Optical parameters like solar reflectivity and emissivity for reflective roofs and the absorptivity of the plants for the green roofs

Thermal parameters, such as the thermal capacity of the roofs and the overall heat transfer coefficient, U-value, between the roof and the building.

Hydrological parameters that define the latent heat budget in green roofs.

3 THE METHODOLOGY

The urban heat mitigation technologies associated with roofs, are: a) the cool (or reflective) roofs, and b) green roofs (or living) roofs. Both technologies can lower the surface temperatures of roofs and thus decrease the corresponding heat flux released to the atmosphere. The methodology followed in order to calculate, analyze and compare the mitigation potential of both technologies under different boundary conditions, is described below: A building model was developed using Energy Plus, which is a well-known computational package software for transient building simulation with conventional roof construction characteristics. Comparison of simulated against experimental results has shown that the model is very accurate to estimate the performance of cool and green roofs. A parametric study was performed concerning the sensible and latent heat flux released to the atmosphere for roofs under different building construction characteristics and climatic conditions. The parametric study included the following:

For the cool roofs, the impact of the albedo, the U-value of the roof and its thermal capacitance has been determined for different climatic conditions in Europe. In particular, the following sensitivity analyses have been performed: (i)Analysis of the sensible heat flux released for different solar reflectance versus the building's thermal mass. (ii)Analysis of the sensible heat flux released for different solar reflectance versus the building's insulation. (iii) Analysis of the sensible heat flux versus the climatic conditions.

For green roofs, the impact of plant characteristics and irrigation rate has been calculated for the same climatic conditions as above. In particular, the following comparisons have been performed: (i) Analysis of the sensible heat flux released versus the characteristics of the plants. (ii)Analysis of the sensible heat flux released versus irrigation rate.

Based on the sensitivity results a detailed comparison of both technologies is performed and presented below.

3.1 The building model

An office building model is developed using Energy Plus v7.1 as it offers the capability to evaluate the sensible heat flux from the roofs while latent heat flux is also calculated using the "ecoroof" module for the simulation of green roofs. The building is designed using Google Sketchup plugin for Energy Plus (Table 1).The specific characteristics of the building are tabulated in Table 1. The building was simulated as free floating without any use of heating, ventilation air conditioning system and thermostatic control during the whole day and night.

Table 1 Reference building characteristics

General Information	
Building type	Office (two storey)
Surface area	~800 m^2
Orientation	N-S
Building envelope	
Walls	brick, insulation, concrete, plasterboard total U: 0.429W/m^{2}K, Surface area 560 m^2
Roof	200 mm concrete, 25 mm insulation, acoustic tile ceiling of total U= 0.581 W/m^{2}K, Surface area 400 m^2
Windows	Double glazing windows with: U= 2.720 W/m^{2}K, Surface area 46 m^2 (8% of the wall area)
Floor	One layer (concrete) floor with U= 4.142 W/m^{2}K
Shading	Shading the south openings of the building

3.2 The mitigation potential of cool roofs

The first step in the analysis of the mitigation potential for cool roofs was to calculate the sensible heat flux released for different optical and thermal properties of cool roofs under hot and moderate climatic conditions and in particular for various representative climatic zones. This is performed using the model described in section 3.1 for the climatic conditions of the Southern and Mid Latitude Europe. The flux of the sensible heat computed for the whole summer period, (June-August), and for roof albedos equal to 0.9, 0.8, 0.7, 0.6 and 0.3 and for the city of Chania, is depicted in Figure 1.

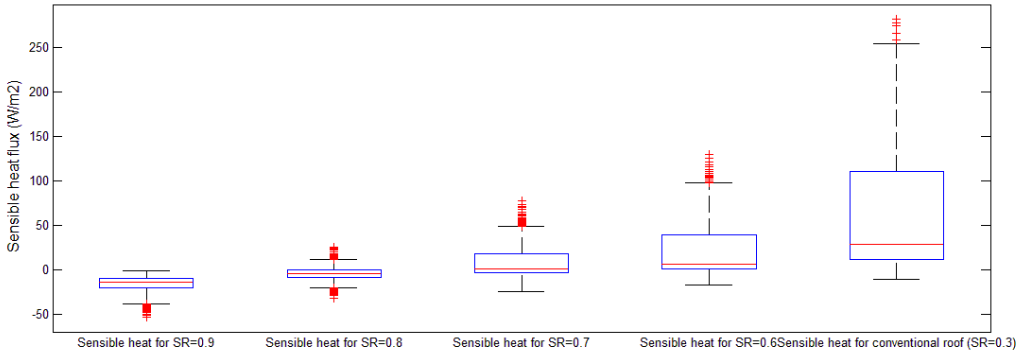

Figure 1. Comparison of heat island mitigation potential in Chania Greece, for a typical construction, between cool and conventional roof

As shown for highly reflective roofs the median sensible heat flux is negative while the maximum value is of the order of a few W/m^2. For reflectivity close to 0.8 and 0.7 the median value of the sensible heat flux is close to zero while the maximum value varies between 15 – 50 W/m^2. On the contrary, conventional roofs present a median sensible heat flux close to 30 W/m^2, and a maximum flux value around 270 W/m^2. Moreover, from the same figure it can be seen that the range of sensible heat flux values is larger for the conventional roofs compared to the cool roofs for the cooling season (summer period). This proves that the use of cool materials minimizes the roofs' heat stress.

3.2.1 Cool Roofs versus thermal mass characteristics

The combined effect of the roof's solar reflectance and thermal mass to the overall heat gain is very important but its impact sometimes is neglected or ignored. In the present section five different roof thermal mass configurations are examined through the corresponding thickness and materials, i.e. very heavyweight concrete, medium weight concrete, lightweight concrete very lightweight concrete and wooden construction roof. These configurations combined with the solar reflectance were used to calculate the sensible heat flux using Energy Plus 7.1 building model described before. Figure 2 depicts the output of the calculations in the climatic conditions of Southern Europe for SR=0.9 in different thermal mass conditions. From the specific figure it can be concluded that : a) During the night, the heat island mitigation potential for all levels of thermal mass is quite similar with a difference in the order of 2 W/m^2, b) During peak hours i.e. 11:00-17:00, the impact of the thermal mass is quite important. Heavyweight roofs present much higher mitigation potential than the lightweight roofs. The relative difference between the two cases for a roof with albedo equal to 0.9 in southern Europe is close to 13 W/m^2. The same pattern but with smaller variations for the heavyweight construction can be noticed for the other European climates. For example the daytime benefit of heavyweight roofs of very high albedo in London is close to 7 W/m^2

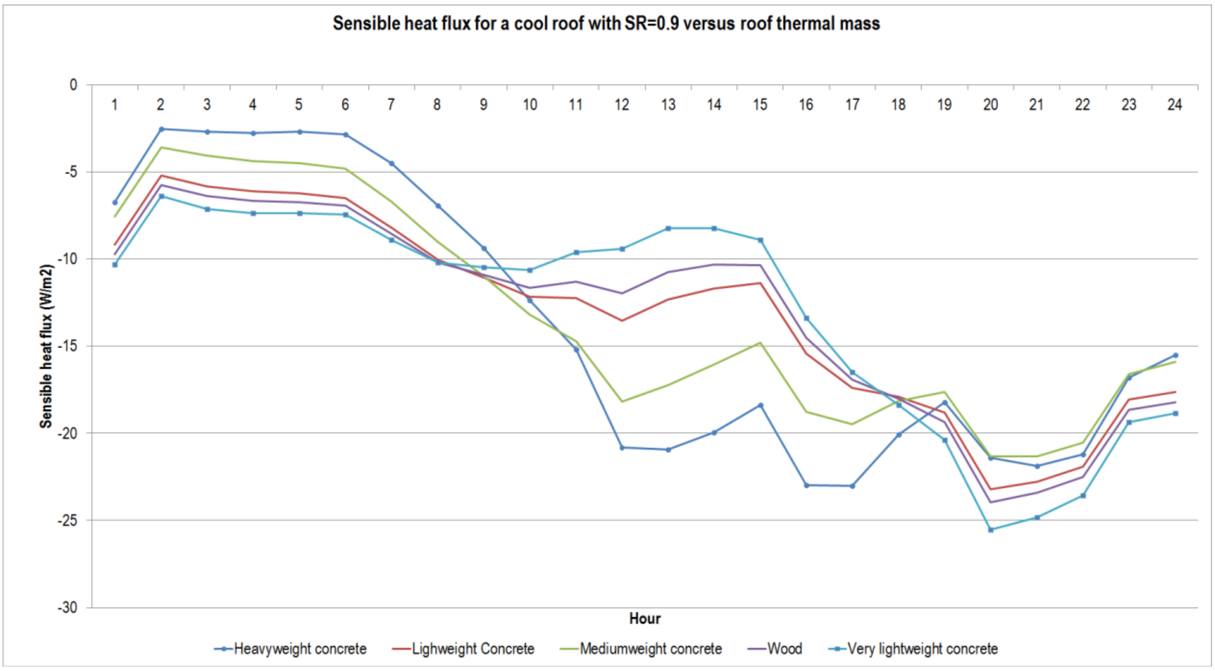

Figure 2. The sensible heat flux versus thermal mass for a cool roof with SR=0.9 and for the Southern Europe (Crete)

The day-night fluctuation of calculated sensible heat flux released by heavyweight roofs is much higher for the climatic conditions of southern Europe, while it reduces for northern climates. As shown, heavyweight roofs offer an integrated reduction of the sensible heat during the whole summer period of around 70 kWh/m^2 if compared to the lightweight constructions. Therefore the lower the albedo, the higher the benefit that heavyweight roofs offer. In particular, the sensible heat reduction for roofs with albedo equal to 0.8, 0.7, 0.6 and 0.3 are 210 kWh/m^2, 286 kWh/m^2 and 490 kWh/m^2 respectively. This is easily explained by the fact that the sensible heat flux from the roofs is inversely proportional to their albedo.

3.2.2 Cool Roofs versus thermal insulation

The present section studies the mitigation potential of the cool roofs versus the insulation level of the construction. The insulation type considered is polystyrene with thermal conductivity 0.3 W/mK while the layers used by the simulation ranged from 25mm to 150 mm with various solar reflectance characteristics. The simulation results (depicted in Figure 3) for Crete climatic conditions show that the insulation level does not influence considerably the sensible heat flux released by the roofs. The same occurs under the London climatic conditions. For albedo values of 0.9 the increase of the insulation level from 25 mm to 75 mm in Crete and London decreased the integrated summer sensible heat released by 1-2 kWh/m^2. In parallel, it decreases the peak summer indoor temperature by 0.1K in Crete and increases it by 2.2K in London. Such an increase of the temperature in London is due to the low surface temperatures at the exterior part of the roof, (almost 13-14 °C). Lower insulation levels increases the flow of heat from the interior to the exterior of the building's roof and contributes to the decrease indoor temperatures. On the contrary, in Crete, indoor and exterior roofs surface temperatures are quite similar and the flow of heat is negligible.

For lower albedo values the impact of the insulation continues to be non-important for all the thermal mass conditions. In almost all cases the increase of the insulation levels decreases the integrated summer sensible heat released. It is characteristic that in Crete and for albedo values close to 0.3 the increase of the insulation levels contribute to increase slightly the integrated summer sensible heat released. Given that for such albedo values, the maximum daily surface temperature of the roof is close to 65 °C, higher insulation levels limits the flow of heat to the interior of the building and thus contribute to slightly higher surface temperatures, and increased integrated summer sensible heat, but also to lower indoor temperatures. In this case, summer indoor maximum temperatures for 75mm insulation are to about 0.7 °C lower than for 25mm insulation.

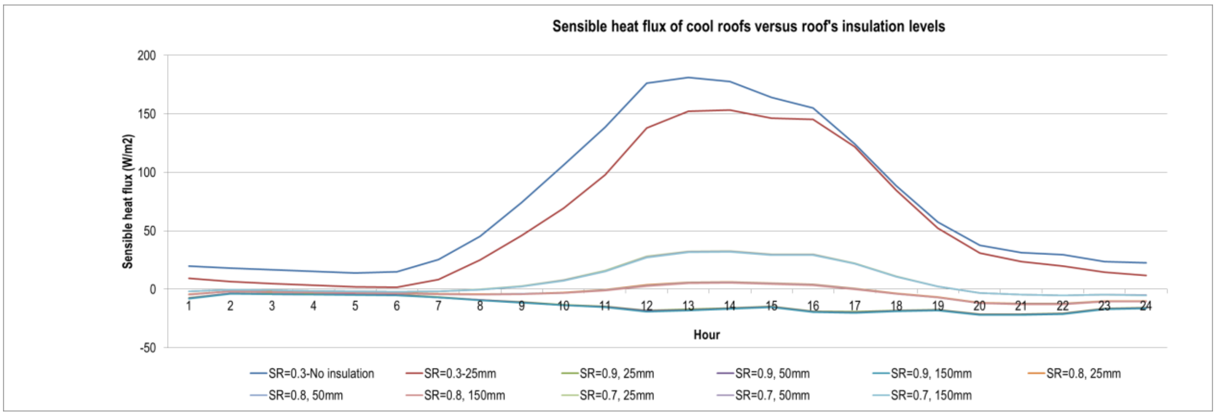

Figure 3: Sensible heat flux released from cool roofs with various insulation levels for a typical summer day

The phenomenon is more intense for less massive roofs. For northern climates, the daily surface temperature of the roof is much lower and the heat flux between the roof and the building is reduced. For example in London, the maximum daily surface temperature for albedo equal to 0.3 is close to 38°C, and the possible increase or decrease of the insulation level does not contribute to any significant variation of the integrated summer sensible flux. However, the maximum summer indoor temperature is found to increase to about 0.4K for higher insulation levels. This is explained as during the night period, the exterior surface temperature of the roof is much lower that the corresponding indoor temperature. Thus, the heat transferred from inside to the outside part of the roof during the night period is much higher for low insulation levels and the corresponding indoor temperature is also lower. Night cooling of the building contributes to lower daily indoor temperatures in low insulated buildings until the early afternoon period.

3.3 The mitigation potential of green roofs

The technology of green roofs, has gained ground during the last decades, as it reduces the energy consumption of buildings while improving the microclimate of the wider urban space where the building is situated.

The most important energy advantage of green roofs is their contribution to the insulation of the buildings, which usually results in energy savings both for heating and cooling. Apart from their impact on building energy consumption, planted roofs contribute to the mitigation of heat islands. They increase the total water-permeable city surface, helping water to be retained in the soil and allowing larger quantities to be available for evapotranspiration. At the same time, planted roofs present much higher albedo values than dark urban roof surfaces, thus reflecting off greater proportion of the incident solar radiation and not transforming it into heat (Getter et al, 2006).

3.3.1 Sensible Heat of Green Roofs as a function of LAI and Irrigation Rate

LAI represents the amount of leaf material in an ecosystem and is geometrically defined as the total one-sided area of photosynthetic tissue per unit ground surface area. Therefore the highest the LAI the denser the vegetation used in the green roof. A typical value of LAI for green roofs is LAI=1.

Sensitivity analysis has been performed for LAI values 0.05, 0.5, 1, 2 and 3 to cover all the range of possible vegetation. The maximum daily sensible heat released for a conventional roof in Crete is 157 W/m^2, while the corresponding values for LAI values 0.5,1,2,and 3 are

104 W/m^2, 70 W/m^2, 33 W/m^2 and 21 W/m^2 respectively. Values decrease by about 20-25 % for the case of an irrigated green roof. The specific values of the maximum daily sensible heat during the summer period in Crete for various LAI and irrigation rates are given in Table 3. As shown, the increase of the irrigation rate from zero to 0.1 reduces the sensible load in Crete by 20-25 %, while the increase of the irrigation rate from 0.1 to 0.3 has almost a negligible effect. As it concerns indoor ambient temperatures in Crete, green roofs with LAI=3 present almost 3°C lower maximum summer indoor temperatures than roofs with LAI=1. The sensible heat flux released by the same green roof (i.e. extensive green roof type with LAI=1 and with no irrigation rate) is calculated under different climatic conditions. The peak sensible heat released under different climatic conditions varies considerably ranging from 50-70W/m2 but it always remains lower than the conventional constructions.

Table 2. Maximum daily sensible heat released during the summer period in Crete for various LAI and irrigation rates, (W/m2).

LAI	**IRRIGATION=0**	**IRRIGATION=0.1**	**IRRIGATION=0.3**
0.05	157	113	113
0.5	104	79	78
1	71	54	54
2	34	25	25
3	21	15	15

In London, for LAI values close to zero, (0.05), the maximum daily sensible heat released is close to 87 W/m2, for irrigated and non-irrigated green roofs. The corresponding values for LAI equal to 0.5,1,2, and 3 are 56 W/m^2, 37 W/m^2, 17 W/m^2, and 10 W/m^2. Almost similar values are obtained for irrigated roofs.

In parallel, the sensible energy released during the whole summer period by a non-irrigated green roof in Crete is close to 176 kWh/m^2 while it is reduced to 124 kWh/m^2, 88 kWh/m^2, 73 kWh/m^2 and -8 kWh/m^2 for LAI values of 0.5,1, 2, and 3 respectively. The corresponding values for London are substantial lower and in particular: 119 kWh/m^2, 86 kWh/m^2, 62 kWh/m^2, 20 176 kWh/m^2, and 12 kWh/m^2, for LAI values of 0.05, 0.5,1,2 and 3 respectively.

4 RESULTS AND DISCUSSION

The maximum daily sensible heat flux for various cool and green roof configurations is given in a comparative way for the climate of Crete in Figure 4, in (W/m^2) and for London in Figure 5. As shown the main parameters that define the performance of cool and green roofs are the albedo and LAI value respectively. The thermal mass as well as the insulation level of cool roofs and the irrigation rate in green roofs play an important role on the sensible heat released but are less significant.

For the climatic conditions of Crete, cool roofs with an albedo of 0.9 present the best performance and the maximum daily sensible heat released is negative for the specific climatic conditions. Negative values are also obtained for green roofs with a LAI value of 3 and for irrigated and non-irrigated roofs. All other configurations present a positive maximum daily sensible heat released. When the albedo of cool roofs decreases to 0.8 the corresponding mitigation potential is very similar to that of a green roof with a LAI of 2. In this case the maximum sensible heat released is between 5 to 10 W/m^2. The better performance is achieved by very well insulated cool roofs, while well irrigated green roofs present a higher mitigation potential than non-irrigated roofs. Cool Roofs presenting an albedo of 0.7 and 0.6 release less sensible heat during the day than green roofs with a LAI of 1. When the albedo is 0.7 the released sensible heat is less than 50 W/m^2, while for albedos close to 0.6 the corresponding heat is around 60-70 W/m^2. In comparison, green roofs with LAI values equal to 1, release almost 70-80 W/m^2. When LAI decreases to 0.5 the sensible heat released is higher than 100

W/m^2 and may reach values close to 130 W/m^2. However, when the albedo decreases to 0.3 the corresponding maximum sensible heat released is higher than 150 W/m^2.

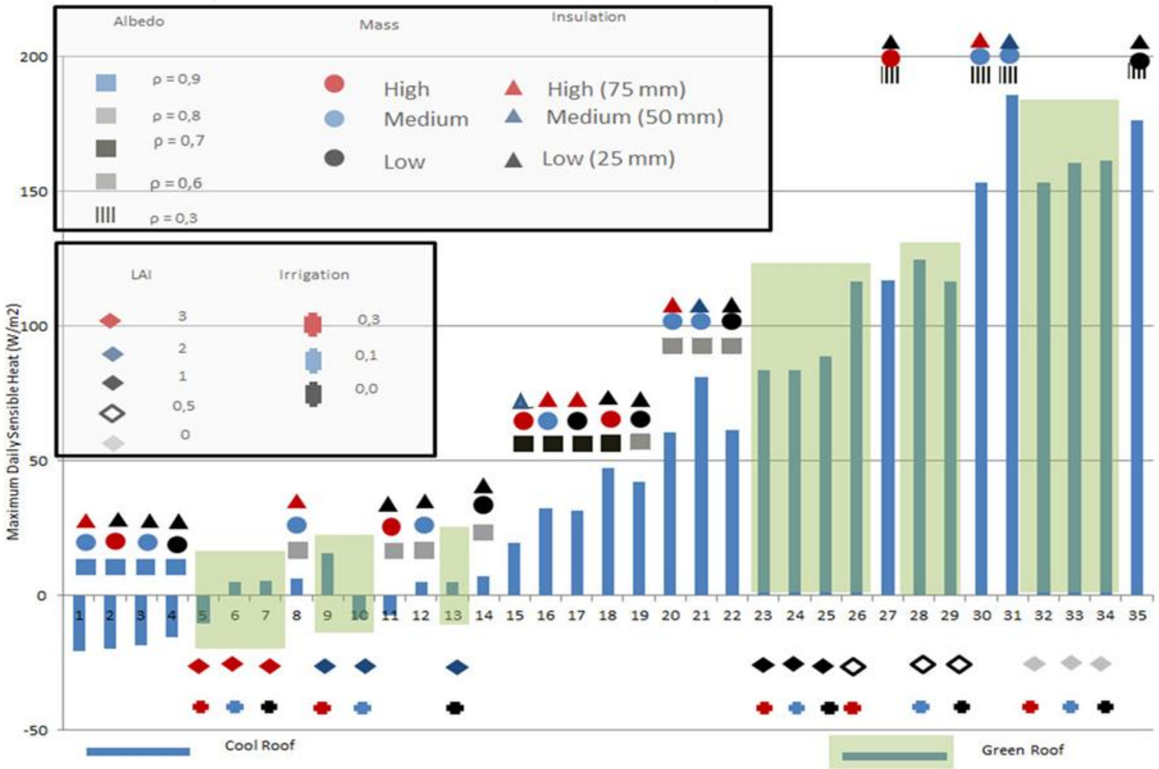

Figure 4. The maximum daily sensible heat flux extracted by cool and green roof configurations for a typical summer day in Southern Europe, (W/m^2)

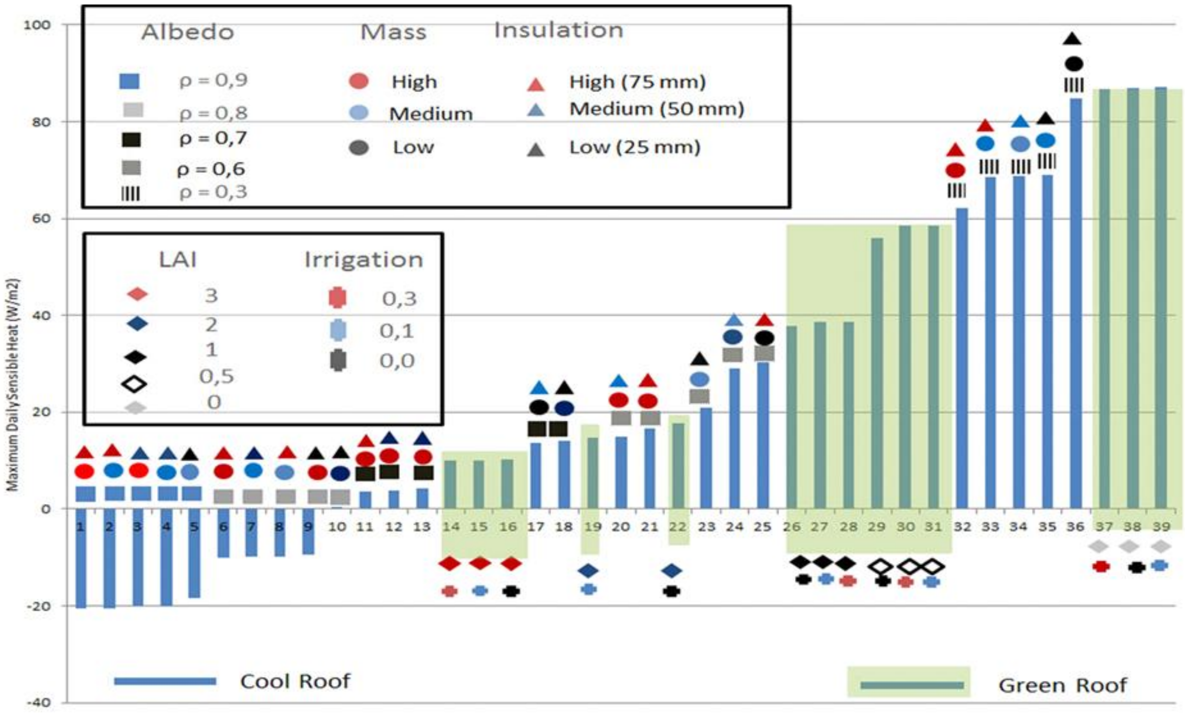

Figure 5 The maximum daily sensible heat flux extracted by cool and green roof configurations for a typical summer day in London, (W/m^2)

For Northern Europe and in particular London, cool roofs with albedos 0.9 and 0.8 present a negative daily maximum sensible heat released during the summer period and contribute highly to mitigate urban heat island. In particular, the released sensible heat is -20 W/m^2 and -10 W/m^2 for albedos of 0.9 and 0,8 respectively. Green roofs with a LAI value of 1, have also a very low daily maximum sensible heat that is close to 10 W/m^2, while for LAI values of 2 the corresponding sensible heat is below 20 W/m^2.Similar values are also obtained for cool roofs with an albedo of 0,7. When the albedo decreases to 0.6, the corresponding sensible heat increases to about 30 W/m^2. Green roofs with LAI = 1 and LAI=0.5 have a sensible load just below 40 W/m^2 and 60 W/m^2 respectively. Finally, the sensible heat released by a roof with an albedo of 0.3 releases on average about 70 W/m^2.

5 CONCLUSIONS

In this paper a comparative analysis of the green and cool roofs' urban heat island mitigation potential is performed under different climatic conditions.

By examining the overall analysis it is evident that both cool and green roofs can contribute considerably to the improvement of the urban environment while simultaneously decrease the energy demand. Since the observed high ambient temperatures intensify the energy problem of cities, deteriorate comfort conditions, put in danger the vulnerable population and amplify the pollution problems, all available solutions should be examined in order to improve the urban thermal microclimate.

As a result a careful design taking into account the specific performance of green and cool roofs but also other factors like the ageing of cool materials, the green roofs' irrigation needs as well as the climatic diversities should be taken into account to maximize the mitigation perspective.

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