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Cool and green roofs. An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region

M. Zinzi*, S. Agnoli

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development Technical Unit for the Energy Efficiency, Via Anguillarese, 301, 00123 S. Maria di Galeria, Rome, Italy

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A B S T R A C T

The increase of peak and energy demand during the cooling season is becoming a crucial issue, as well as the intensification of the urban heat island effect. This trend is observed at several latitudes, including areas where overheating was unknown at building and urban levels. This phenomenon involves different issues: reduction of greenhouse gases, quality and comfort in outdoor and indoor environment, security of energy supply, public health. The building sector is directly involved in this change and adequate solutions can provide great benefit at energy and environmental levels. Roofs in particular are envelope components for which advanced solutions can provide significant energy savings in cooled buildings or improve indoor thermal conditions in not cooled buildings. Cool materials keep the roof cool under the sun by reflecting the incident solar radiation away from the building and radiating the heat away at night. Roofs covered with vegetation take benefits of the additional thermal insulation provided by the soil and of the evapo-transpiration to keep the roof cool under the sun. These two technologies are different in: structural requirements, initial and lifetime maintenance costs, impact on the overall energy performance of buildings. This paper presents a numerical comparative analysis between these solutions, taking into account the several parameters that affect the final energy performances. By means of dynamic simulations, the paper depicts how cool and green roofs can improve the energy performance of residential buildings in different localities at Mediterranean latitudes.

1. Introduction

The effects of global warming and climate changes are of relevant concern for environment and human activities in the Mediterranean area. The average air temperature rise of 2 °C represents a critical limit beyond which dangerous climate changes should occur by 2030 [1]. More than 90 million people live in the twenty most populated Mediterranean metropolitan areas; according to the actual trend other 70 million of people are expected to move to leave the countryside towards the urban area by 2025 [2]. The global warming and the urban sprawl causes a number of environmental hazards, the urban heat island (UHI) is one of these.

This phenomenon is defined as the air temperature rise in densely built environments respect to the countryside surroundings. The main cause is the modification of the land surface in the urban area, where the vegetation is replaced by extensively built surfaces (typically paved roads and buildings surfaces), characterised by high solar absorption, high impermeability and favourable thermal properties for energy storage and heat release, as well as several anthropogenic. The UHI was first monitored in London back to the 19th century [3]; many studies were performed during the past decades [4–10], showing the quantitative effects of the phenomenon and the correlation with the previously enounced causes. Daily mean UHI typically ranges between 2 and 5 °C, while UHI intensities (defined as maximum difference between urban and background rural temperatures) up to 12 °C were registered under particular conditions. This UHI impacts important issues such as: the quality of life; the public health, especially for the most vulnerable population; the environmental hazards.

Roof surfaces of the building accounts for the 20–25% of the total urban surfaces, hence they can successfully used to reduce the air and surface temperature of urban area [11]. Cool and green roof, widely described in the next paragraph, are used to mitigate the UHI and the impact was proved by several studies [12–15]. These techniques can also have significant benefits on the energy performance of buildings, providing passive cooling to the built environment. This topic is of special interest because of the rapid increase of the

* Corresponding author. Tel.: +39 06 3048 6256/4188; fax: +39 06 3048 3930.
E-mail address: michele.zinzi@enea.it (M. Zinzi).

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energy consumption and peak demand for cooling in Europe and in the Mediterranean basin [16].

This study aims at analysing and comparing how these UHI mitigation techniques can also improve the energy performance of cooled buildings and the thermal comfort of not-cooled buildings at Mediterranean latitudes. Special attention is paid to residential buildings, where accurate design concepts and technologies can strongly reduce the use and the installation of cooling systems without affecting the occupants comfort expectations and help achieving international environment targets.

2. Building applications of cool and green roofs

Cool roofs are characterised by materials having: high solar reflectance (SR) and high thermal emittance (TE). The former expresses the ability of the materials of reflecting most of the incident solar radiation during daytime, keeping their surfaces cooler respect to conventional construction materials. The high thermal emittance allows the materials to radiate away the heat stored in the structure, mainly during night time. This thermal behaviour allows the roof to reduce the heat transfer to the built environment. Roofs characterised by low emittance values tend to not dissipate the stored heat at night and can be considered cool only if they have a very high solar reflectance. White mortars and plaster were widely used in ancient massive Mediterranean dwellings, in order to create a more comfortable built environment during the hot season. The coastal villages of Greece, Italy and Spain still witness this construction technique, which emerged again as an efficient solution during the recent years.

Several numerical studies were carried out in the past years to assess the energy performance of buildings equipped with cool roofs. The impact of cool roofs on a single floor detached house placed in different climatic zones of the planet world was calculated for insulated and not insulated dwellings [17]. The cooling energy consumption reduction was 18% and 93% increasing the roof solar reflectance from 20% to 85%. Three typical building models were developed respectively for: a residential building, an office and retails store, differentiated by age (before and after 1980). The impact of cool roof ensured global energy savings from 7% to 25% according to the different age and building type for several US climates [18]. Other studies were focused to limited geographical sites, as Jordan or Honk Kong [19,20]. Other studies faced the cool roof positive impact evaluated as an additional thermal insulation [21]. The results of the analysis revealed that the integrated daily roof heat gain was not dependent on its thermal mass. An energy analysis run proved that the daily heat flow in a roof with SR of 0.65 and a thermal resistance (*R*-value) of 1.1 m^2 K/W was equivalent to the flow in a roof with SR 0.3 and *R*-value 2.2 m^2 K/W.

Limited data from real building application are available. A field campaign was carried out in one house and two school bungalows in Sacramento, California. Cooling energy savings of 2.2 kWh/day were measured increasing the solar reflectance of the roof from 0.18 to 0.73 [22]. The energy savings in the school buildings was about 35%. A study in an experimental building in Rome, Italy, proved that the air temperature of an attic room decreased by 2 °C increasing the albedo of the roof from 14% to 85% and this room was found cooler than an identical room at the floor below, which had no roof at all [23].

Green roofs, also called eco-roofs, use the foliage of plants to protect the building environment. The thermal loads due to the solar radiation and the air temperature are limited before entering the buildings by the vegetation layer. This depends on the absorption of the solar radiation by the plants to support their life-cycle, including: photosynthesis, evapo-transpiration, respiration. Moreover, the soil layer gives an added insulation to the building roof and the water content increases the thermal inertia of the structure. The vegetation characteristics affect, in addiction, the convective and radiative heat transfer through the roof surface.

Green roofs were once typically used in northern climates to improve the insulation performance of the building envelope, but they are also an opportunity in warm climates, because of their thermal behaviour under the solar radiation. Several studies were produced during the past years trying to quantify the effect of green roofs on the energy performance of buildings. The noticeable impact of green roofs during the hot and the cold seasons was analysed in a nursery school in Athens, founding out that energy savings up to 49% could be obtained [24]. The energy and water issues were analysed in two experimental setups in Italy; particular attention was paid to the impact of the foliage on the radiation and the air temperature profiles insisting on the building roof, respect to the undisturbed values [25]. Combined measurements and calculation analyses were performed in order to assess and predict the 60% reduction of the heat flux through a green roof respect to a conventional roof in a hospital building in northern Italy [26]. A case study in Brasil demonstrated that a green roof in an experimental building reduced the heat flux by 92–97% compared to a ceramic and a metallic conventional roof [27]. Specific studies on the substrate materials, foliage characteristics and vegetal species demonstrated the variability of the green roof performances as a function of the adopted technical solutions [28–30].

3. Methodology

The scope of this work consists in the assessment of the energy performances of residential buildings using different roof solutions: standard, cool and green roofs. The study is focused on the Mediterranean area, a mild climatic zone with differences in rainfall levels and air temperature profiles that can lead to different choices of building technologies to achieve the opti-

Table 1
Air temperature and solar radiation data of the selected localities.

Month	*T* (°C) Barcelona	*H* (kJ/h/m²)	RH (%)	*T* (°C) Palermo	*H* (kJ/h/m²)	RH (%)	*T* (°C) Cairo	*H* (kJ/h/m²)	RH (%)
Jan	8.2	288	71	12.7	312	76	14.0	439	67
Feb	9.4	409	68	11.9	454	71	14.5	597	58
Mar	11.1	553	73	13.8	625	79	16.6	736	59
Apr	13.1	744	72	15.7	843	71	21.8	913	45
May	17.0	879	74	19.2	980	77	24.7	1052	40
Jun	20.9	873	74	22.8	1090	71	28.0	1142	45
Jul	23.5	1004	68	25.5	1099	76	28.2	1118	56
Aug	24.1	858	71	27.0	993	73	27.9	1008	60
Sep	21.6	603	74	24.1	741	66	26.6	898	56
Oct	17.3	444	82	21.6	549	74	23.8	630	56
Nov	12.1	287	78	17.2	319	69	19.0	493	61
Dec	9.9	250	65	13.9	272	78	15.3	430	64