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Assessment of the effectiveness of cool and green roofs for the mitigation of the Heat Island effect and for the improvement of thermal comfort in Nearly Zero Energy Building

Elisa Di Giuseppe* and Marco D'Orazio

Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Ancona, Italy

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The effectiveness of cool and green roofs to improve thermal comfort could be strongly dependent on the U -value of the roof itself and on the way it has been constructed (ventilated or unventilated, lightweight or massive, etc.). Recent strict limits on the U -values of building envelopes run the risk of reducing the effectiveness of cooling strategies in roofs which could be employed in warm and temperate climates to reduce surface temperatures and consequently to cool internal environment. In this paper, we experimentally analyse some roof systems (a high-albedo membrane and a green roof) compared to traditional ones in a Nearly Zero Energy Building, in order to provide new information concerning their effect on the internal comfort and the air temperatures of the surrounding environment. Experimental results confirm that, while the effectiveness of green and cool roofs for the mitigation of the Urban Heat Island effect is well established, the use of high-albedo materials on roofing systems with very low U -value is of little effectiveness for internal comfort. The green roof is distinguished by its passive cooling ability due to the evapotranspiration phenomena of the vegetation and the storage capacity of the substrate.

Keywords: cool roof; green roof; NZEB; thermal comfort; Heat Island

Introduction

In a building market that is moving towards Nearly Zero Energy Buildings (NZEBs), increasingly spreading coating materials are used with specific radiative properties, with the aim of reducing surface temperatures reached in the warmer seasons within buildings. In this way, it is believed to achieve a reduction in energy consumption for cooling and improve thermal comfort. However, the use of lightweight and strongly insulated envelopes even in hot and temperate climates is likely to rely entirely on the insulation, the function of containing the heat gains by solar radiation.

This role today, in countries with a warm climate, is mainly carried out by other strategies: envelopes with high thermal inertia (massive roofs and walls), ventilation systems (air gaps and discontinuous roof coverings) and materials with high albedo (buildings painted in light colours). These strategies risk to become less effective if used in strongly insulated envelopes.

Only few studies focus on the effectiveness of the use of materials with high albedo on overinsulated envelopes for the construction of NZEB.

D'Orazio, Di Perna, and Di Giuseppe (2010) have previously shown that an increase in roof insulation thickness decreases cooling potential due to traditional

construction methods of roofs (ventilation, mass and radiative properties).

From the analysis of different real-scale roofing systems with various values of solar reflectance, Miller (2006) observed that the use of a metal cladding with high reflectance coupled to an undermantle ventilation reduced heat fluxes by 45%. However, only 15% of this percentage is due to the radiative properties of the material, while the remaining 30% is due to undermantle ventilation.

Zinzi and Agnoli (2011) analysed the performance of cool and green roofs on non-insulated ($U = 1.4 \text{ W/m}^2 \text{ K}$) and moderately insulated ($U = 0.6 \text{ W/m}^2 \text{ K}$) slabs with the help of Energy Plus software. They were able to obtain savings in consumption compared to traditional roof coverings by up to 13.9% in the case of non-insulated ones and only up to 7.8% in the case of moderately insulated ones.

By comparing two scale models of building in the absence and presence of insulation on the roof slab, increasing the albedo (from 0.30 to 0.70) Simpson and McPherson (1997) showed a reduction in total and peak hourly energy for cooling by only 5% for the insulated roof ($U = 0.19 \text{ W/m}^2 \text{ K}$) and by 28% for the non-insulated one.

Levinson, Akbari, and Reilly (2007), in a roof with thermal transmittance at around $0.25 \text{ W/m}^2 \text{ K}$, analytically found that the energy savings for cooling, associated with the use of reflective materials in roof covering, is reduced

*Corresponding author. Emails: e.digiuseppe@univpm.it, elidigi@gmail.com

111 by 85% compared to that obtained in a high transmittance
 roof. This trend gradually decreases exponentially with
 increasing insulation.

116Q3 In addition, in locations where there is need for both
 heating during winter and cooling in summer, the use of
 material with high SRI could prove to be even counterpro-
 ductive for the reduction of solar gains in the winter phase
 (Suehrcke, Peterson, and Selby 2008).

121 Nevertheless, high-albedo roofs (green and cool roofs)
 are recognized as fundamental strategy that dense urban
 areas can deploy on a large scale, at low cost, to mit-
 126 gate the Urban Heat Island (UHI) effect (Gaffin et al.
 2012). In fact, such materials reach modest temperatures
 when exposed to solar radiation; they reduce heat transfer
 to the adjacent air thereby contributing to the decrease in
 temperature on an urban scale.

The effectiveness of their use in climates with long
 summers and mild winters is supported by numerous
 studies.

131 Among them, Takebayashi and Moriyama (2007, 2009)
 and Takebayashi, Moriyama, and Sugihara (2012) inves-
 tigated the performance of high reflectance roofs and
 green roofs, noting their ability to reduce the surrounding
 temperature with respect to a concrete roof by about 10°C.

136 Furthermore, recent studies confirm that both cool and
 green roofs can contribute considerably to the improve-
 ment of the urban environment (Santamouris 2012; Coutts
 et al. 2013; Kolokotsa, Santamouris, and Zerefos 2013;
 Saadatian et al. 2013).

141 Recently, Gago and Roldan (2013) realized a review
 on different strategies to mitigate adverse effects of UHI,
 highlighting that if the albedo coefficient of construction
 materials is increased, it is possible to achieve direct energy
 savings of 20–70%, while an effort should be made to sys-
 146 tematize all current knowledge concerning the effects that
 greenery has on the urban microclimate.

Therefore, from the literature review, it is clear that
 the role of the radiative properties of building materials
 and that of green roofs is still to be investigated in detail,
 especially in relation to the technological evolution of the
 151 building envelope.

The research that we carried out thus sought to under-
 stand the influence of the type of roof covering (vegetation
 cover, high-albedo material, traditional surface coated in
 156 copper or brick) on roof's temperatures during warm and
 temperate season, also related to indoor thermal comfort
 and UHI effect.

Phases, materials and methods

161 The research was carried out in three successive steps:

- Laboratory measurements of optical properties (emissivity and solar absorption) of different roof covering materials: clay tiles, copper plates, zinc plates and a reflective sheathing.

- Insertion of some of the tested materials (clay tiles, copper plates and reflective sheathing) as roof covering of a building mock-up, also in comparison to a green covering. 166
- Assessment of the *in situ* albedo of the various covering and of their thermal performance. 171

Solar absorption was recorded by using spectropho-
 tometers in visible light (Spectrum Model 554), infrared
 (Spectrum GX 1) and near-infrared (Spectrum One NTS)
 176 ranges. Emissivity was directly measured by using a
 pyrometer (Testo 830).

The *in situ* monitoring was carried out on a real-scale
 experimental building built in 2007 near Ancona (Italy,
 2064 DD). The building is 8.20 m × 10.50 m, totalling
 86.10 m² with a unique volume of around 250 m³. The side
 181 walls were built with multi-layered insulating panels made
 of polyurethane resin ($U = 0.20$ W/m² K). Inside the enve-
 lope, a 30 cm air cavity was created with the help of 22 mm
 OSB panels in order to reduce the impact of solar radiation
 on the walls. The floor was insulated with 20 cm extruded
 polystyrene panels in order to make the building almost
 186 adiabatic.

The roof was divided into modules of the same width
 (1.50 m each) and same length of 6 m on the south slope
 and 3 m on the north slope, in order to obtain a similar size
 191 as that of traditional roofs (Figure 1). The common ele-
 ment among all the roof coverings is the insulation, which
 was made of two crossed layers of EPS panels with a total
 thickness of 12 cm ($U = 0.25$ W/m² K). The roof modules
 were well insulated (12 cm extruded polystyrene) on both
 196 sides to avoid any heat diffusion crosswise.

This research focused on four different roofs installed
 in the building: two ventilated clay tiles and copper
 roofs (respectively named LV6_A and MV6_A) originally
 201 installed in the building, a green roof (MNV_GR) and a
 roof with a reflective sheathing (MV6_RS) installed in a
 part of the existing roofs in 2011 (Figures 2 and 3).

The green roof installed had a culture substrate with
 medium–low thickness (15 cm) and low and evergreen
 206 vegetation of the “officinalis” type for which very little



Figure 1. South view of the experimental building near Ancona (Italy).

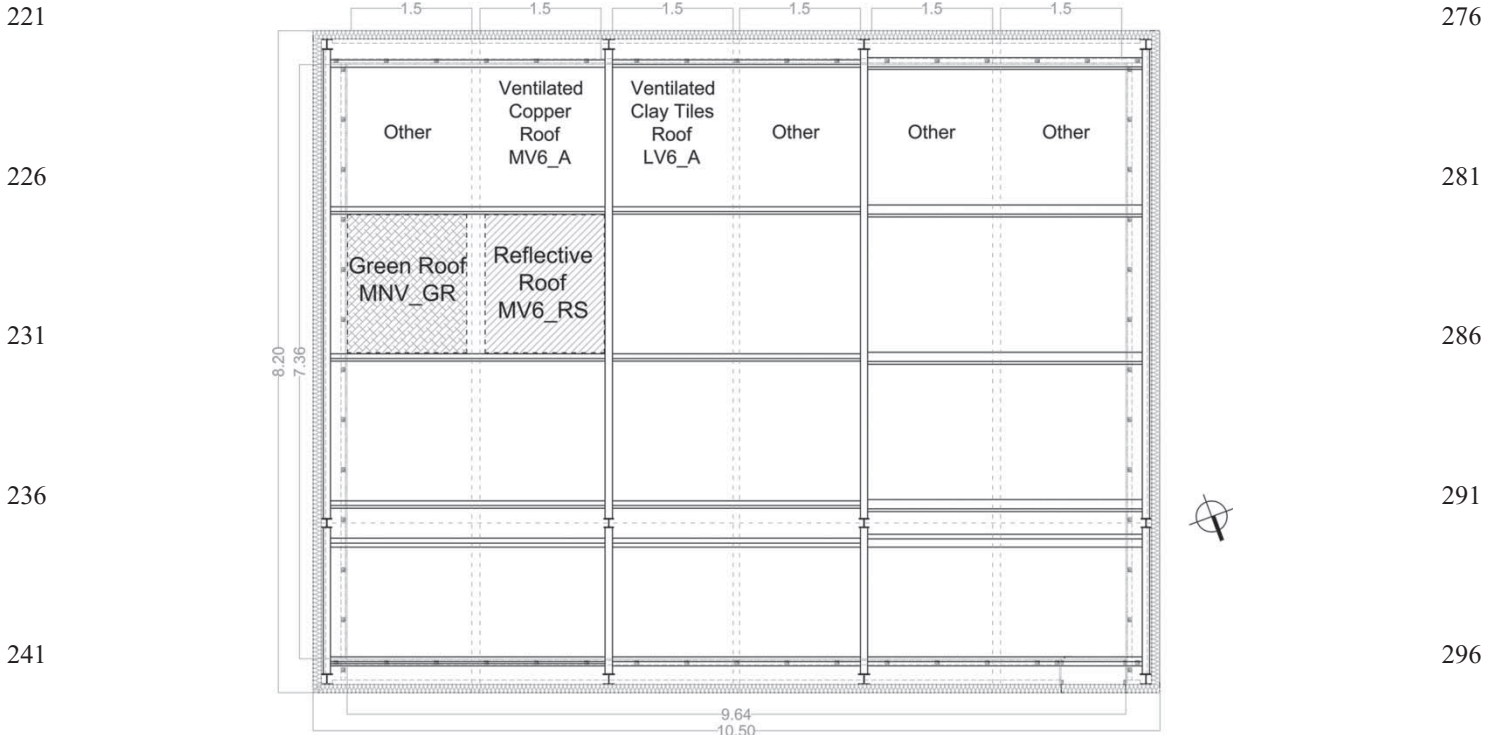


Figure 2. Plan of the experimental building with the schematic position of the original roofs installed in the building (ventilated clay tiles and copper roofs) and the high-albedo roofs (green roof and roof with a reflective covering) installed in 2011.

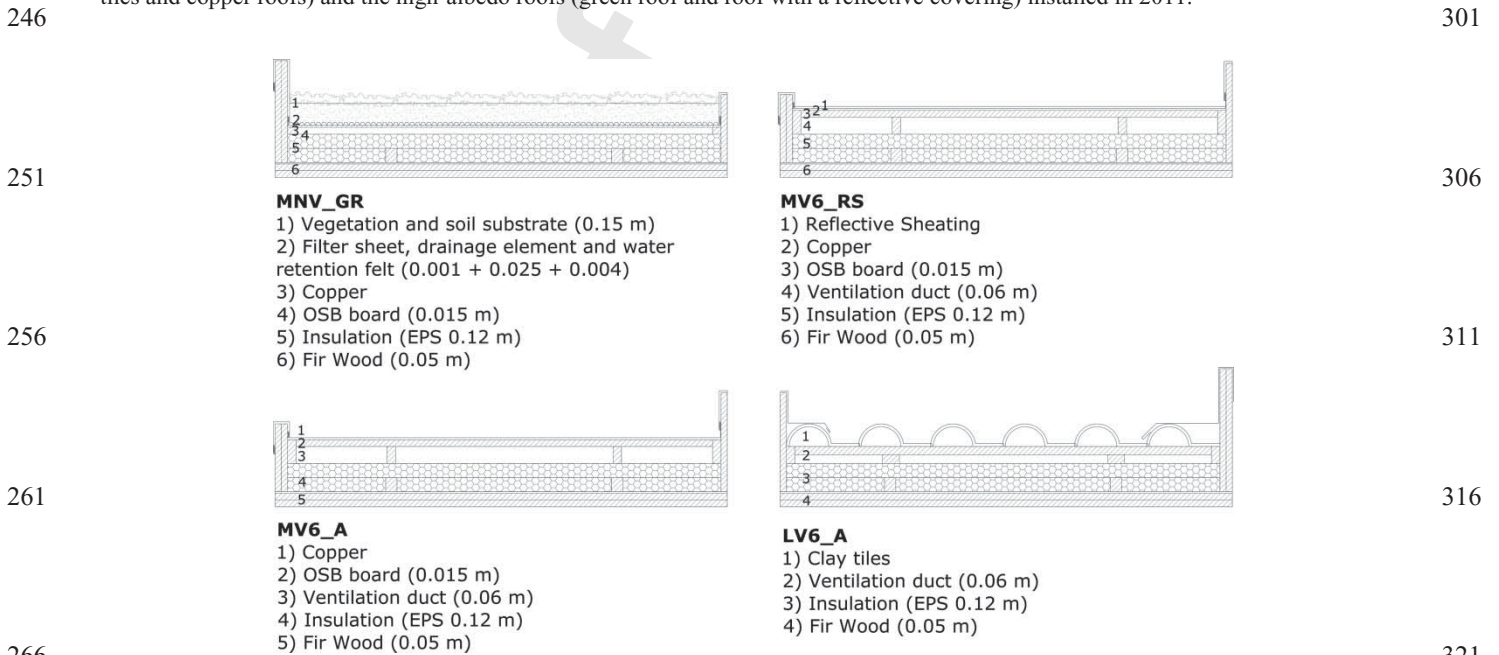


Figure 3. Stratigraphies of the four roofs installed in the experimental building: two ventilated clay tiles and copper roofs (LV6_A, MV6_A), a green roof (MNV_GR) and a roof with a reflective covering (MV6_RS).

maintenance is required. Table 1 shows the materials that constitute the roof.

An automatic drip irrigation system was installed on the green roof in the summer season, which automatically turned on at 6 a.m. every morning for one hour.

External weather conditions were recorded throughout the summer of 2011 by means of a 12-bit datalogger (Elog Lsi-Lastem) to which instruments were connected in order to measure global radiation (DPA 153 Lsi-Lastem), temperature and relative humidity of the air outside (DMA

331 Table 1. Thermophysical properties of the materials composing the green roof. 386

Layer	Thickness (m)	Material	Thermal conductivity (W/m K)	Density (kg/m ³)	Specific heat (J/kg K)	
336 Vegetation and soil substrate	0.150	Lapillus, Compost	0.17 (dry) 0.33 (saturated)	582	1000	391
Filter sheet	0.001	Polypropylene	0.220	910	1900	
341 Drainage, storage and ventilation element	0.002	Polyethylene	0.380	950	2300	
Air (inside the drainage element)	0.023	Air	Thermal resistance = 0.16 W/m ² K			396
Retention felt	0.004	Polypropylene	0.220	910	1900	
346 Roof covering	0.001	Copper	380	8900	382	
OSB board	0.015	OSB	0.130	630	2200	401
Insulation	0.120	EPS	0.035	25	1470	
Roof slab	0.050	Fir wood	0.120	550	2700	



376 Figure 4. Placement of the instrumentation for the albedo measurements on roofs composed of two coupled radiometers: one facing the sky to measure the incident global radiation and the other one towards the roof surface to detect the amount of reflected radiation. 431

381 572.1 Lsi-Lastem), speed and wind direction (DNA 021-024-027 Lsi-Lastem) and rainfall (DQA030 Lsi-Lastem). Thermal data on the roof stratigraphies were also observed in the same period by means of five 12-bit dataloggers (Elog Lsi-Lastem) connected to

- thermal resistances (PT100 Lsi-Lastem) for measuring temperatures within the different layers of the

roof coverings (surface of the insulation, and surface of the covering, slab, ground and air cavities);

- probe for measuring temperature and moisture content in the planted roof soil (DISACC4825 Lsi-Lastem). 436

Temperature and relative humidity of the air (DMA 572.1 Lsi-Lastem) were also recorded inside the building.

441 The accuracy of the probes was $\pm 0.15^\circ\text{C}$ for PT100
 thermal resistances, $\pm 0.5\%$ of mv for the anemometers,
 5% for radiometric probes, $\pm 0.1^\circ\text{C}$ for internal air temper-
 446 ature probe and $\pm 1.5\%$ for internal RH probe, $\pm 0.2^\circ\text{C}$ for
 external air temperature probe and $\pm 1.5\%$ for external RH
 probe. The acquisition rate was set to 10 seconds, while the
 post-processing rate was set to 10 minutes. All the probes
 and measurement connections were calibrated beforehand,
 and the calibration results were noted in order to correct
 the values that were recorded.

451 In order to measure the albedo of roofs, the protocol
 developed by Sailor, Resh, and Segura (2006) was fol-
 lowed. A system of two coupled radiometers (DPA 153
 Lsi-Lastem) was assembled: one facing the sky to measure
 the incident global radiation and the other one towards the
 456 roof surface to detect the amount of reflected radiation. The
 inclination of the instrumentation was then adjusted to 17° ,
 the same as the roof's pitch (Figure 4). The albedo of the
 roof is represented by the ratio of total reflected radiation
 to incident electromagnetic radiation. Radiation measure-
 461 ments were carried out during four days of clear sky in
 the month of September. For the incident radiation, only
 the values which were greater than 100 W/m^2 were con-
 sidered, to avoid the occurrence of errors and dispersions
 of results.

466 **Results**

*Laboratory measurements of optical properties of
 different roof covering materials*

471 The laboratory measurement of solar absorption and emis-
 sivity of different roof covering materials enabled the
 definition of the values listed in Table 2.

Table 2. Laboratory measurements of solar absorption and
 emissivity of different roof covering materials.

Material	Solar absorption	Emissivity
<i>Reflective sheathing</i>	0.10	0.01
<i>Clay tile</i>	0.56	0.86
<i>Polished copper</i>	0.40	0.10
<i>Tarnished copper</i>	0.70	0.40
Prepatinated zinc – dark pickling	0.70	0.50
Prepatinated zinc – clear pickling	0.30	0.30
Polished zinc	0.10	0.20

The reflective sheathing, clay tiles and polished copper,
 whose emissivity and solar absorption values are shown in
 italics in Table 2, are those used then to build roof cover-
 511 ings monitored on site. However, the copper, two months
 after installation in actual weather condition, reached a
 high degree of oxidation (tarnished copper).

516 Measured thermal emissivity was 0.10 for the reflective
 sheathing, 0.86 for clay tiles, 0.10 for polished copper and
 0.40 for tarnished copper. Measured solar absorptivity of
 the reflective sheathing was 0.10, for clay tiles 0.56, while
 its value for copper might have varied from 0.40 to 0.70
 depending on the oxidation degree of the material.

*In situ assessment of roofs albedo and their impact on
 the Heat Island effect*

526 The scatter plots in Figure 5 show the values of incident
 and reflected radiation, measured for the four analysed
 roofs MNV_GR, MV6_A, LV6_A and MV6_RS.

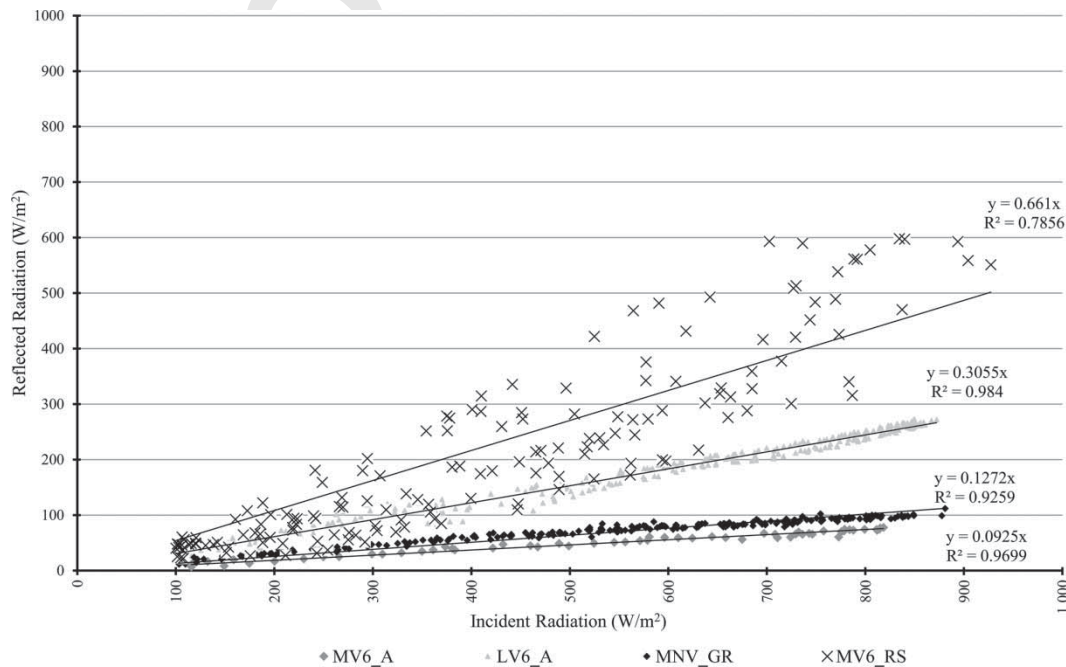


Figure 5. Roofs albedo, represented by the ratio of reflected radiation to incident radiation.

551 The lines that interpolate the points show a linear trend.
 556 The slope of these lines represents the value of albedo: 0.66 for the roof with reflective sheeting MV6_RS, 0.31 for the clay tile roof LV6_A, 0.13 for the green roof MNV_GR and 0.09 for the copper roof MV6_A. Even if for MV6_RS results are more scattered, the value of albedo for the reflective sheathing appears to be comparable with those proposed in the literature where the range varies between 0.65 and 0.80.

561 Concerning the green covering, the value of the resulting albedo is slightly lower than the other data found in the literature (Takebayashi and Moriyama 2007; Sailor 2008). However, it is important to consider that the passive cooling property of a green roof is not only due to its albedo, but also to a combined effect of soil insulation, evapotranspiration and radiative shading of the plant canopy.

566 The solar radiation flux coming into the green roof is a net contribution after solar reflection and absorption of the greenery, which depends on the Leaf Area Index, which is the ratio between the green area and the underneath soil area, and on the short-wave extinction coefficient (k_s).

606 By using the exponential law developed by Palomo del Barrio (1998), we found (in percentage) that the greenery reflected 13 units and absorbed 56 units, calculated as residual term after the transmitted fraction of solar radiation. The solar radiation entering the system could then be estimated as 31% of the incident global solar radiation. The whole procedure is described in detail by D'Orazio, Di Perna, and Di Giuseppe (2012). This result is independent of the fact that the green roof was wet or dry, in agreement with others (Lazzarin, Castellotti, and Busato 2005).

616 *Thermal performance of the roofs*

621 Thermal analysis was carried out in the month of September 2011. The weather conditions in the month of September in Italy are usually highly variable, with sunny and warm days often followed by rainy cold days.

626 Figure 6 shows the main meteorological conditions monitored during a week in September (22–29 September 2011). The first day of the week is marked by high solar radiation (until 818.38 W/m^2) and air temperature (24.70°C), while the following days were cloudy and

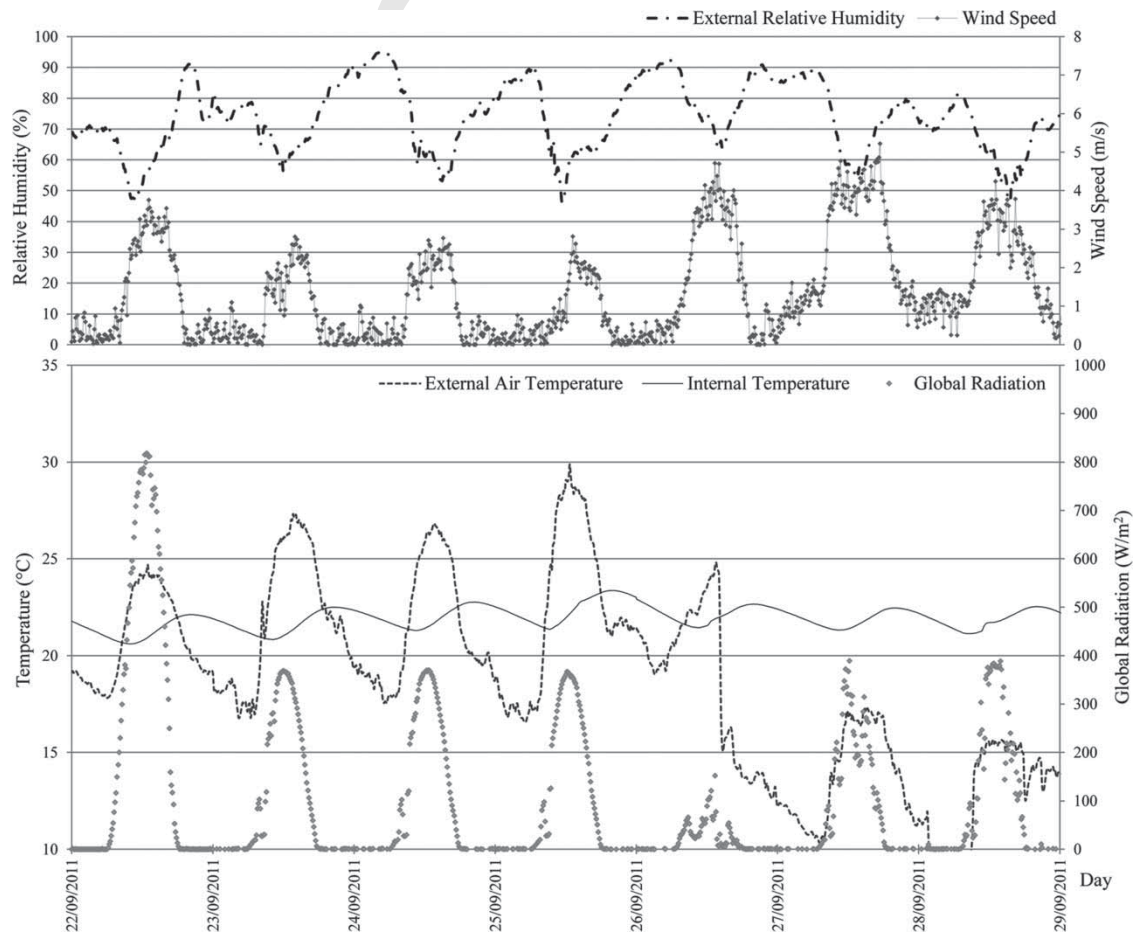


Figure 6. Meteorological conditions monitored during a week (22–29 September 2011).

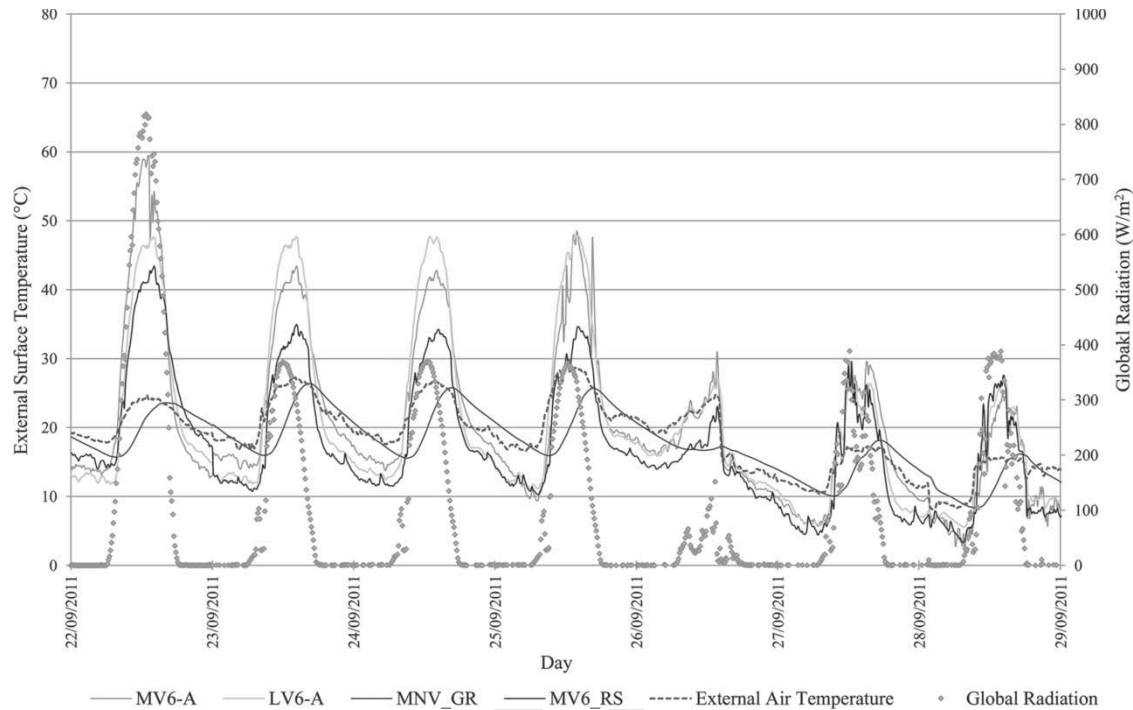


Figure 7. Roofs covering surface temperature trend ($^{\circ}\text{C}$) with respect to the external air temperature and global radiation during a week (22–29 September 2011).

warm. Finally, air temperature decreased until very low values at the end of the week (15°C). During the week it has never rained.

Figure 7 shows the external surface temperatures of the roofs with respect to the external air temperature and total radiation during the week.

Figure 8 focuses on the first sunny and warm day (22 September). As it can be observed, the surface temperatures on the upper side of the substrate of the green roof (MNV_GR) during the day are actually lower compared to the external air temperature and reach a maximum of 23.60°C against an external temperature of 24.70°C . On the contrary, the covering temperatures of the other roofs are undoubtedly higher, with maximum temperature that reaches up to 59.50°C for the roof with copper covering (MV6_A) and goes down to 47.65°C for the ventilated clay tile roof (LV6_A) and 43.42°C for the reflective sheathing (MV6_RS).

The green roof surface temperature is also delayed in time compared to external air temperature because of the thermal inertia of the substrate. Water accumulation during the irrigation phase in the early morning (at 6 a.m.) also contributes to cool the roof.

Surface temperatures of the roofs decrease during the following days of the week according to the lowering of global solar radiation (Figure 7)

The cooling of the surface temperatures in relation to the different reflectance of the surface of the coverings is made evident in Figure 9, which shows the average

and maximum surface temperatures of the surfaces as a function of the albedo on the day in question.

The only exception to the declining trend of the temperature values with the albedo is represented by the green roof, which, as seen above, has a performance strongly conditioned by the evapotranspiration phenomena of the leaves and the substrate.

Figure 10 shows temperatures on the soffit of the wooden slabs on the same day. It can be seen how the differences between the temperatures are rather low in terms of absolute value because of the high insulation of the slabs. However, the green roof (MNV_GR) is able to guarantee a lower internal surface temperature (until 21.98°C), which is also considerably attenuated and delayed in time compared to the other roofs (23.43°C for MV6_A, 22.70°C for LV6_A and 22.91°C for MV6_RS). In particular, the difference in the surface temperatures of the green roof was observed to be up to about 2°C compared to the temperature of the other ventilated roofs.

The temperature of the roof with the reflective sheathing (MV6_RS) is comparable to that of the other two ventilated roofs in the daytime phase, while it decreases during night-time hours, for phenomena of undercooling due to reduced emissivity of the reflective material.

Discussion

The experimental evaluation of the radiative properties of the different materials used as roof coverings has shown

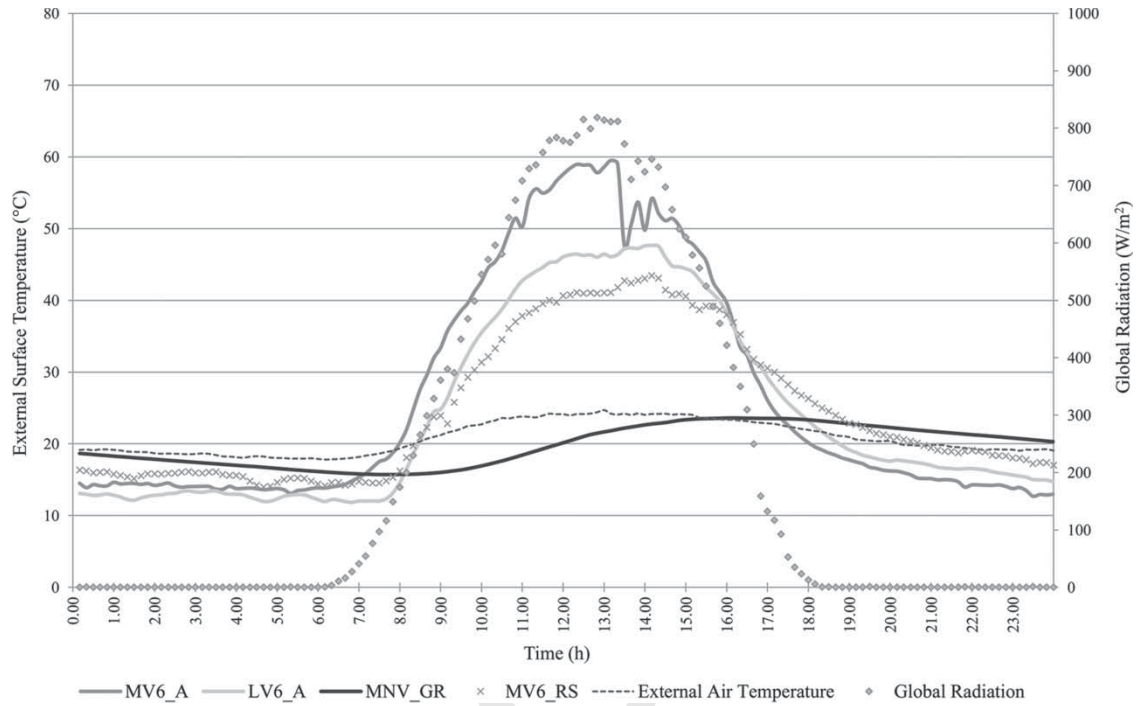
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Figure 8. Roofs covering surface temperature trend (°C) with respect to the external air temperature and global radiation on a bright day (22 September 2011).

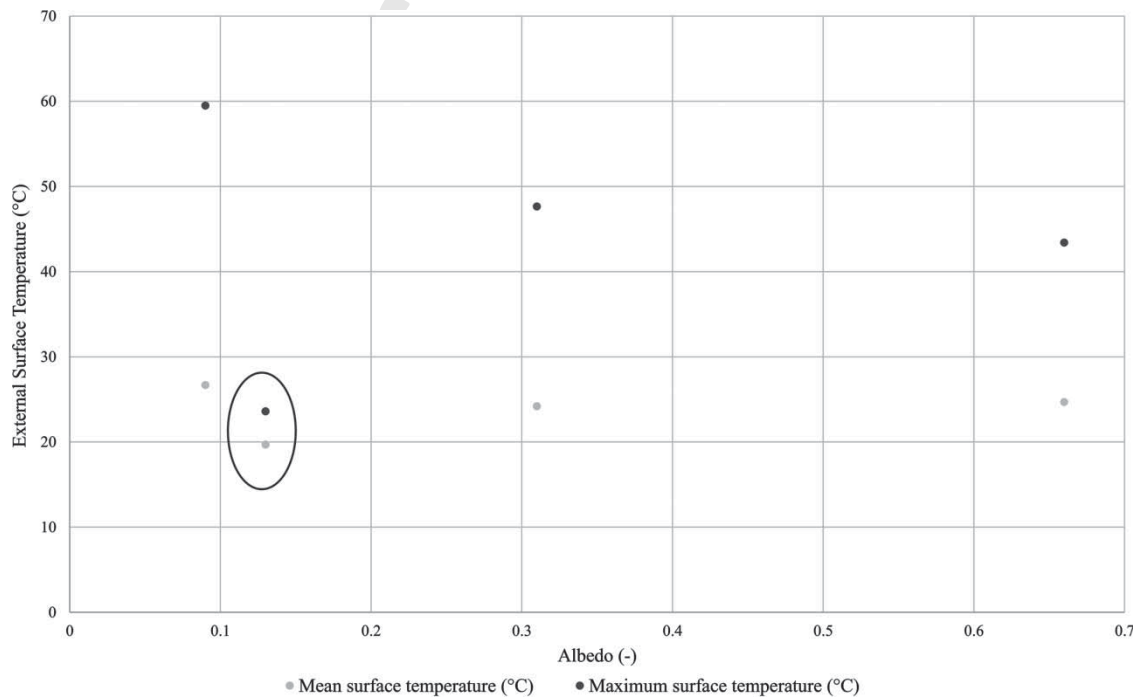
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Figure 9. Average and maximum covering surface temperatures of the roofs as a function of the albedo on the day in question (22 September 2011).

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that traditional materials (clay, copper and zinc) differ substantially due to the characteristics of their emissivity (high values for bricks and low for metallic materials). The reflective sheathing has the lower value, reaching an emissivity of 0.01 in factory conditions.

The absorption coefficient depends on the level of colour saturation of the material and on its ageing. Over time, the metallic materials tend to assume a surface patina that substantially alters their colour, making the saturation similar to that of bricks. The measurement of the

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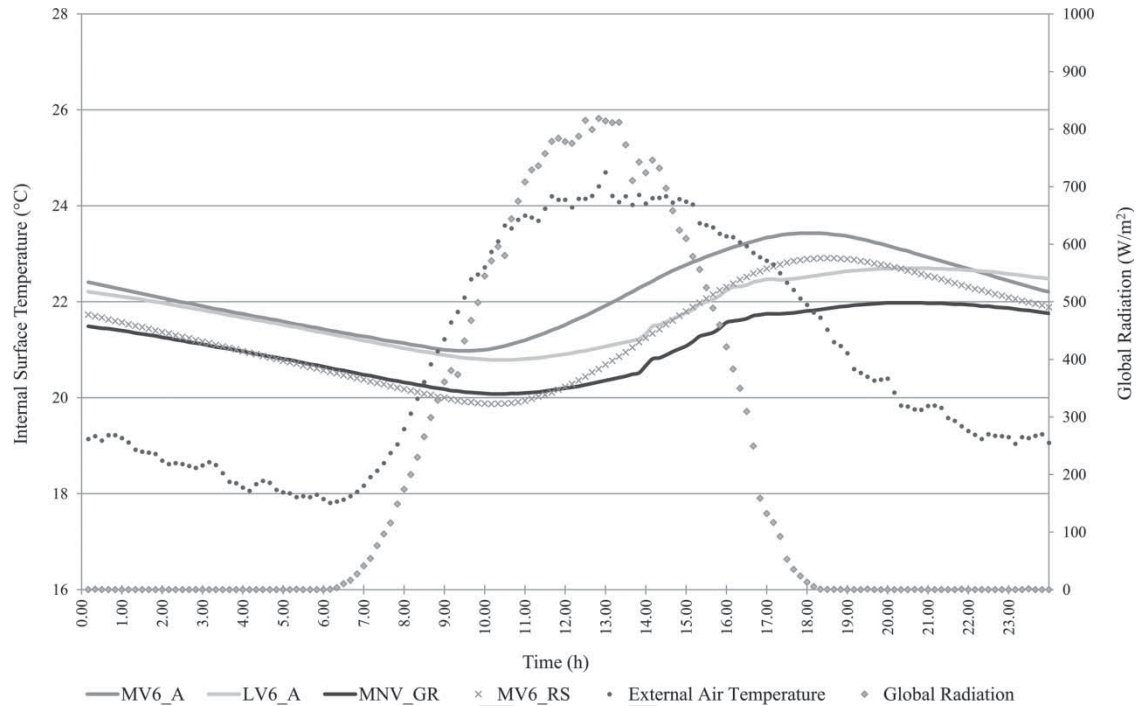


Figure 10. Roofs slab surface temperature trend (°C) on the day in question (22 September 2011).

absorption coefficient of the “new” material is therefore not indicative of the actual radiative properties of the material once put in place, as in the case of copper covering, and is thus subject to weathering, ageing and to variations in colour.

Preliminary measurements of the *in situ* albedo of roof covering materials show that green roof reaches a low value. In fact, the passive cooling property of a green roof is not only due to its albedo, but also due to a combined effect of soil insulation, evapotranspiration and radiative shading of the plant canopy. Experimental results confirm that the plant canopy reflects 13% of incident global solar radiation and absorbs 56%, so that the solar radiation entering the system can therefore be estimated as 31% of the incident global solar radiation.

The measured external surface temperatures of the two ventilated copper and clay tile roofs and of the reflective sheathing, together with the green roof, show a declining trend with an increase in the albedo of the covering. The green roof, for the reasons stated previously, represents the only exception.

Even if there are evident differences in the surface covering temperatures (a maximum of 59.50°C reached by the copper covering, against a maximum of 43.42°C for the reflective sheathing) during the warmer day analysed, as regards the internal slab surface temperatures, they do not turn out to be very different from each other because of the low transmittance of the systems.

Only the green roof guarantees internal slab temperatures, which are considerably attenuated (up to 2°C) and delayed in time compared to the other roofs.

Conclusion

The *in situ* monitoring of roofs with different covering materials (clay tiles, copper, vegetated substrate and reflective sheathing) confirmed a significant reduction in the external surface covering temperatures by increasing the albedo of the roofs. This result confirms that cool and green roof strategies could be effectively adopted for the mitigation of the Heat Island effect.

Nevertheless, the different external temperatures of the roofs become “flattened” internally, where the variances between the temperatures are rather low in terms of absolute value. In particular, the roof with reflective sheathing shows a performance similar to the other ventilated roofs. The use of high-albedo materials on roofing systems with very low *U*-value is then of little effectiveness for internal comfort. The green roof is distinguished by its passive cooling ability due to the evapotranspiration phenomena of the vegetation and the storage capacity of the substrate. It is able to guarantee a lower internal surface temperature (until about 2°C compared to other roofs), which is also considerably attenuated and delayed in time.

A lower temperature of the roof soffit reduces the mean radiant temperature of the attic (which depends on the internal temperature and on that of all the surfaces facing the room), impacting positively with environmental comfort during summer.

These results, relating to a building monitored in Italy, can be trusted in temperate climate, such as the northern Mediterranean, where the need for a significant *R*-value of the envelope in winter must be complemented by a reduction of solar gains in summer.

991 A remarkable thermal insulation is today an essential condition to achieve an NZEB, nevertheless strategies against the overheating in summer, such as green and cool roofs, still require further investigation in these kinds of buildings, taking into account the specific climatic conditions of local environments and also considering their economic feasibility.

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