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Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs

V. Costanzo*, G. Evola, L. Marletta

Department of Industrial Engineering, University of Catania, Viale A. Doria 6, Catania, 95125, Italy

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ABSTRACT

The intensification of the Urban Heat Island effect (UHI) is a problem that involves several fields, and new adequate solutions are required to mitigate its amplitude. The construction sector is strictly related with this phenomenon; in particular, roofs are the envelope components subject to the highest solar irradiance, hence any mitigation strategy should start from them and involve their appropriate design process.

For this purpose, cool materials, i.e. materials which are able to reflect a large amount of solar radiation and avoid overheating of building surfaces have been deeply analyzed in the last years both at building and urban scales, showing their benefits especially in hot climates. However, green roofs also represent a possible way to cope with UHI, even if their design is not straightforward and requires taking into account many variables, strictly related with the local climatic conditions.

In this context, the present paper proposes a comparison between cool roofs and green roofs for several Italian cities that are representative of different climatic conditions. In search of the most effective solution, the answers may be different depending on the perspective that leads the comparison, i.e. the need to reduce the energy consumption in buildings or the desire to minimize the contribution of the UHI effect.

1. Introduction

The urban sprawl, to which global warming is strictly related, has caused a series of environmental hazards that are well-known but difficult to tackle: the Urban Heat Island effect (UHI) is one of them. According to this phenomenon, urban areas experience higher outdoor air temperatures than those measured in rural areas, due to the heat released by human activities, the lack of greenery, the scarcity of air circulation in urban canyons and the great amount of solar radiation absorbed by urban surfaces [1]. The Urban Heat Island effect was first observed in London in the 19th century, as a consequence of the industrial revolution, but in the last decades it has gained increasing attention especially in those countries that experience high solar irradiance in the summer [2].

Indeed, urban surfaces usually present high solar absorptance, low permeability and other thermal properties very favorable to increase urban air temperature. Rizwan et al. [3] carried out an interesting review of previous studies focused on the generation and the mitigation of the UHI phenomenon, finding three possible ways to tackle the problem: reducing anthropogenic heat release, adopting appropriate cooling strategies (e.g., humidification and shading by means of PV modules) and improving roofs' designs.

In particular, it is proven that the roof surface plays a very important role. Indeed, roofs represent about 20–25% of urban surfaces and 60–70% of the building envelope on average in Italy, depending on the building typology. Moreover, the solar radiation impinging on the roofs can easily raise their outer surface temperature up to 50–60 °C, that is to say, 10–15 °C higher than in the surrounding green areas [4].

In this context, many studies have been carried out in order to develop new finishing materials for urban surfaces. As concerns the roofs, the most promising passive strategies seem to be the use of highly-reflective coatings (cool roof) and the placement of a vegetation cover on top of the roof surface (green roof).

The use of highly reflective cool paints for roofs and road pavements has been investigated in a pioneering way by Akbari in various works [5–7], showing the potential energy and money savings in space cooling achieved by using materials with medium–high solar reflectance and high thermal emittance. Considering the sensible heat fluxes measured in the framework of an experimental campaign carried out by the Kobe University, Takebayashi and Moriyama [8] compared the thermal performance

* Corresponding author. Tel.: +39 0957382353; fax: +39 0957381496.
E-mail address: vcostanzo@dii.unict.it (V. Costanzo).

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Nomenclature

Variables

A	Roof surface [m^2]
C_h^g	Sensible heat flux bulk transfer coefficient [–]
$C_{p,a}$	Specific heat of air at constant pressure [J·kg·K^{-1}]
COP	Coefficient of Performance [–]
EER	Energy Efficiency Ratio [–]
F	Net heat flux [W m^{-2}]
g	Solar factor [–]
H	Sensible heat flux [W m^{-2}]
h_c	Convective coefficient [W m^{-2} K^{-1}]
h_p	Height of plants [m]
I_{ir}	Total incoming long wave radiation [W m^{-2}]
I_s	Total incoming short wave radiation [W m^{-2}]
k	Dry soil thermal conductivity [W m^{-1} K^{-1}]
L	Latent heat flux [W m^{-2}]
m_{sr}	Minimum stomatal resistance [s m^{-1}]
PER	Primary Energy Ratio [–]
Q	Thermal energy needs [MWh y^{-1}]
r	Solar reflectance [–]
T	Temperature [K]
U	Thermal transmittance [W m^{-2} K^{-1}]
w	Wind speed [m s^{-1}]

Greek letters

ε	Thermal emissivity [–]
ε_1	View factor [–]
η	Efficiency [–]
ρ	Density of air [kg m^{-3}]
σ	Stefan-Boltzmann constant [W m^{-2} K^{-4}]
σ_f	Fractional vegetation coverage [–]

Subscripts

af	Air-foliage
c	Convective
f	Foliage layer
g	Ground layer
I	Indoor air
o	Outdoor air
s	Summer
so	Outer surface
w	Winter

of different roof finishing layers: traditional concrete tiles, green roofs (both bare soil and with lawn) and highly reflective paints (gray and white colored). They found out that, for the specific climatic conditions of Kobe, green roofs present the lowest incoming sensible heat flux (2 W m^{-2} on average during two typical summer days), followed by the highly reflective white (20 W m^{-2}) and gray (97 W m^{-2}) paints and by concrete tiles (72 W m^{-2}).

On the other hand, Scherba et al. [9] modeled and validated through experimental measurements the heat fluxes released by different roof solutions (dark membrane, cool roof and green roof), together with the shading effect of PV modules installed on them, and found out that both green and cool roofs are able to cut the peak flux by about 70%.

Moreover, Santamouris et al. [10] investigated the effectiveness of various materials (highly reflective and highly emissive light colored materials, cool materials, phase change materials and dynamic cool materials) in reducing their surface temperature when hit by solar radiation, finding that cool materials are the commercially available solution most appropriate both under the energy and the economic point of view. On the other hand, coatings with dynamic optical characteristics are very promising but need further investigation about their aging and degradation.

Through this brief summary, it is clear how the use of cool and green materials are among the most effective technical solutions to reduce the roof outer surface temperature, thus mitigating the UHI phenomenon. As an example, their application allowed to reduce the peak air temperature in an urban park of Athens by about 1–2 °C [11], and also to strongly reduce the cooling energy needs of a building in Italy [12].

However, these studies only consider the roof behaviour in summer. If one takes into account also the winter period, these solutions may imply a reduction in the solar heat gains through the roof, hence an increase in the building energy needs for space heating.

To clarify this issue, the present paper shows the results of annual dynamic simulations for a sample office building in three Italian cities with different climatic conditions. The simulations will compare the energy performance (heat fluxes and primary energy needs) and the external roof temperatures for five different scenarios: the existing roof, green roof without irrigation (dry), green roof with an appropriate irrigation schedule and cool roofs with two different values of solar reflectance (r = 0.65 and r = 0.80).

The aim is to demonstrate that the choice between green and cool roofs has to be made with extreme attention, in relation to the peculiar climatic constraints, namely solar irradiation and precipitation. Moreover, depending on the perspective that drives the comparison – UHI mitigation or energy savings for air conditioning – the choice between the two solutions may be different.

2. Modeling green and cool roofs

2.1. Green roofs: equations and key parameters

Modeling green roofs involves the study of mass and heat transfer through the different layers, as well as elements of plant physiology. Several models are available in the literature: the simplest models only consider the reduction of roof thermal transmittance based on in-situ measurements [13], while other studies analyze more in detail the complex phenomena due to foliage shading and evapotranspiration [14].

Amongst these models, the one developed by Del Barrio [15] divides a green roof in three different layers: the canopy, the soil and the support. By imposing the horizontal homogeneity of the roof slab, heat and mass fluxes are assumed to be mainly vertical, so one-dimensional equations can be adopted to describe the thermal behavior of each layer. This model has been validated through a sensitivity analysis for a concrete roof slab of 10 cm in Athens, and represents the main reference for other one-dimensional models, such as those developed by Kumar and Kaushik [16] or by Lazzarin et al. [17]. On the other hand, two-dimensional models are much less common: an example in the literature is given by Alexandri and Jones [18], aimed to evaluate the thermal effect of green roofs and green walls.

Anyway, nowadays the one-dimensional EcoRoof model developed by Sailor [19] is maybe the most used one, and thanks to its high reliability it has been implemented in the software tool EnergyPlus. Based on the previous work of Frankenstein and Koenig [20], who developed the FASST (Fast All-Season Soil Strength) model, Sailor calculates two different heat fluxes for the green roof, respectively at the foliage surface F_f (see Eq. (1)) and at the ground surface F_g (see Eq. (2)):

$$F_f = \underbrace{\sigma_f[I_s(1-r_f) + \varepsilon_f I_{ir} - \varepsilon_f \sigma T_f^4]}_{\text{radiant\_sky}} + \underbrace{\frac{\sigma_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1}(T_g^4 - T_f^4)}_{\text{radiant\_ground}} + \underbrace{H_f}_{\text{sensible}} + \underbrace{L_f}_{\text{latent}} \quad (1)$$

$$F_g = \underbrace{(1-\sigma_f)[I_s(1-r_g)+\varepsilon_g I_{ir}-\varepsilon_g\sigma T_g^4]}_{\text{radiant\_sky}} - \underbrace{\frac{\sigma_f\varepsilon_g\varepsilon_f\sigma}{\varepsilon_1}(T_g^4-T_f^4)}_{\text{radiant\_foliage}} + \underbrace{H_g}_{\text{sensible}} + \underbrace{L_g}_{\text{latent}} + \underbrace{k\frac{\partial T_g}{\partial z}}_{\text{conductive\_soil}} \quad (2)$$

As it is possible to observe from Eq. (1) and Eq. (2), in both cases the energy balance is split into a radiant term, a sensible and latent heat exchange and a conductive heat flux for the soil. The radiant term considers the heat exchange with the sky (at short and long wavelengths) and the mutual heat transfer between foliage and ground. Actually, this model does not allow the variation of soil thermal properties (solar reflectance, thermal conductivity, specific heat capacity and density) according to the moisture content of the soil media, because of stability issues during the calculation [21]. However, a simplified moisture balance that considers precipitation, irrigation and moisture transport between two soil layers (top and root zones) is already implemented; future improvements in this direction are in any case necessary, as highlighted in [22]. In fact, moisture can leave the soil by means of evaporation, and the vegetation by evapotranspiration: these phenomena are influenced by water runoff in the soil layer due to saturation-excess and infiltration-excess [23].

When working with the Sailor model, EnergyPlus allows the user to define a series of parameters, for both the soil layer and the foliage, to fully characterize the green roof. Olivieri et al. [24] have carried out a sensitivity analysis by varying all the parameters that define the EcoRoof routine in the range allowed by the software, and have found that, for an extensive green roof in the Mediterranean coastal climate, only four parameters have a strong influence on the roof performance and must be carefully considered. These parameters are:

- the height of plants (h_p);
- the Leaf Area Index (LAI), defined as the ratio of the projected leaf area to the overall ground area;
- the minimum stomatal resistance (m_{sr}), which represents the resistance of the plants to moisture transport;
- the dry soil conductivity (k).

The outcomes reported in the next paragraphs are obtained from simulations based on the Sailor model, and on input values for the green roof gathered from Olivieri's work. More specifically, we have assumed the following values for the eco-roof parameters: $h_p = 0.20$ m, LAI = 2, $m_{sr} = 180\ \mathrm{s\,m^{-1}}$, $k = 0.33\ \mathrm{W\,m^{-1}\,K^{-1}}$, $r_f = 0.3$, $\varepsilon_f = 0.9$ and a soil thickness of 20 cm.

2.2. Cool roofs: equations and key parameters

Under steady-state conditions, that is to say without considering the heat capacitance of the roof, the energy balance on the roof surface, written explicitly in relation to the outer surface temperature T_{so} is given below:

$$\underbrace{\frac{T_{so}-T_i}{R_{i\_so}}}_{q_{transferred}} = \underbrace{(1-r)I}_{q_{absorbed}} - \left[\underbrace{\sigma\varepsilon({T_{so}}^4-{T_{sky}}^4)}_{q_{radiant}} + \underbrace{h_c(T_{so}-T_o)}_{q_{convective}}\right] \quad (3)$$

Eq. (3) states that the solar radiation absorbed by the roof surface is partially released to the outdoor environment, both by convection and by infrared radiation. Moreover, heat transfer occurs through the roof; this contribution is proportional to the difference between the outer temperature of the roof and the indoor temperature, and depends on the thermal resistance R_{i_so} associated to the roof layers and to the heat transfer on the inner surface of the roof.

Fig. 1. Picture of the main façade.

The main technical parameters determining the cool roof performance are the solar reflectance r and the thermal emissivity ε. The latter is usually very high for construction materials, and $\varepsilon = 0.9$ can be assumed. As concerns r, it obviously depends on the chemical agents used to produce the cool paint, and can achieve values higher than 0.8. However, it is well known that cool paints usually undergo soiling and weathering in the first months after installation, which significantly reduce their solar reflectance. As an example, Akbari [25] reported on a reduction by about 10% in only two months in the solar reflectance of a white coating having an initial $r = 0.8$; another field study measuring the effects of aging and weathering on ten roofs in California found that the reflectance of cool materials can decrease by as much as 0.15, due to the deposition of soot and dust, mostly within the first year of service [26]. However, Bretz and Akbari [27] also demonstrated that washing the roof surface could almost restore the original solar reflectance.

In Eq. (1) it is also important to make an appropriate choice for the convective coefficient h_c. As demonstrated in Ref. [28] by comparing experimental measurements to simulations, the most reliable algorithm for dry horizontal flat surfaces without obstructions is the Clear Roof algorithm. It is available on EnergyPlus and has been used in this study for the simulation of the cool roofs.

3. Performance comparison: methodology

3.1. Simulation of the energy performance for the sample building

The sample building used for this study is an existing office building situated in the University Campus of Catania (see Fig. 1), that hosts the offices used by teachers at $i_0$ts ground floor, while the basement is occupied by laboratories; the flat roof hosts the air conditioning devices. The S/V ratio of the building is 0.47 $\mathrm{m^{-1}}$, while the ratio between the transparent envelope area and the opaque envelope area is of about 46%.

In this study, the performance of the sample building will be assessed through dynamic simulations in three different representative Italian climatic zones. The cities considered to this purpose and the main data regarding their climate are reported in Table 1.

In the simulations, we decided not to consider the real properties of the envelope in terms of U-value. Indeed, this would penalize the winter performance of the building when simulated in a cold climate, like in Milan. Hence, while keeping the same materials used in the real building, the thickness of insulation was properly changed in order to comply, in each city, with Italian Building Codes on energy saving [29]. This should normalize the results of the energy performance in the different conditions. In particular, the external walls are made of a double leaf of concrete blocks (12 cm) and hollow clay blocks (8 cm), separated by an air gap (17 cm) with

Table 1
Cities considered for the simulation of the roof performance.

	Catania	*Rome*	*Milan*
Latitude	37°31′N	41°55′N	45°29′N
Winter degree days	833	1415	2404
Mean daily temperature in summer	24 °C	22 °C	20 °C
Mean peak temperature in summer	35 °C	33.4 °C	33 °C
Mean daily temperature in winter	11.8 °C	9.4 °C	4.7 °C
Mean peak temperature in winter	26 °C	18.2 °C	15 °C
Mean daily irradiance on the horizontal	28.2 MJ/m^2	27.1 MJ/m^2	24.0 MJ/m2
Peak irradiance on the horizontal	1013 W/m^2	988 W/m^2	960 W/m^2

Table 2
U-values of the building opaque envelope [W m^{-2} K^{-1}].

	Existing	*Catania*	*Rome*	*Milan*
Walls	0.80	0.47	0.39	0.33
Roof	0.70	0.36	0.36	0.29

a layer of polystyrene on the outermost face whose thickness is varied according to the law requirements. The roof is based on a prefabricated structure covered by a layer of mineral wool plus a lightened cement screed (10 cm), a layer of mortar (2 cm) and clay shingles (1.2 cm). The resulting U-value for the opaque envelope components are reported in Table 2.

The windows consist of double glazing filled with argon (4-12-4 mm) on an aluminum frame provided with thermal cutting. They are assumed to be the same in all cases, with U = 2.80 W m^{-2} K^{-1} and g = 0.77.

Other assumptions for the simulation of the building in EnergyPlus are reported in [30]. As an example, it is occupied from Monday to Friday (9:00–18:00) and shows internal gains due to people activity equal to 60 W per person, in addition to those deriving from electrical equipment (150 W per workstation) and lighting systems (6 W m^{-2}). The outdoor air infiltration rate is set to 0.5 h^{-1} during the occupancy period, 0.2 h^{-1} during the remaining time.

3.2. Proposed solutions for the roof

As concerns the behavior of the green roof, two design solutions are considered, characterized by different irrigation schedules:

- GR_1: no irrigation (dry soil)
- GR_2: weekly irrigation (every Monday, Wednesday and Friday, from 06:00 a.m. to 07:00 a.m.).

Actually, the hypothesis of dry soil is not very realistic, but it is still useful to estimate the role played by the soil moisture content in lowering the heat fluxes on the roof. Here, the amount of water used for irrigation purposes is 1.2 kg m^{-2}, according to the experimental campaign carried out by Santamouris et al. [31] for a nursery school building in Athens where grass plants were used for the extensive covering of the roof.

On the other hand, the data concerning rainwater, expressed in millimeters, have been gained by the Agrometeorologic Sicilian Informative Service (SIAS) for the city of Catania, while for Rome and Milan they have been gathered from the Regional Agency for the Environmental Protection (ARPA). Since the EnergyPlus weather files do not contain such information for these locations, the annual precipitation pattern has been added in the form of compact schedules for each location.

As to the cool roof, two different possible solutions are considered:

- CR_1: cool paint with r = 0.65
- CR_2: cool paint with r = 0.80 (white paint)

These values are representative of paints having an average and a high cooling potential, respectively. The thermal emissivity is always ε = 0.90. Actually, a solar reflectance r = 0.80 is difficult to retain over time because of aging and soiling processes. Nevertheless, by means of regular cleaning processes the solar reflectance of the paint can lose only the 10% of the original reflectance value, thus lowering the aging effect [32].

The first step in the analysis of the mitigation potential for green roofs and cool roofs is the calculation of the roof external surface temperature, which is a relevant indicator to evaluate the impact of the technology in terms of UHI effect. Another relevant parameter, that has been determined through dynamic energy simulations, is the convective heat flux released from the roof to the outdoors in summer. The mathematical formulation for the calculation of this heat flux is given below:

$$H_c = h_c A(T_{so} - T_o) \tag{4}$$

$$H_f = (1.1 \times \mathrm{LAI}\rho_{af} C_{p,a} W_{af})(T_{af} - T_f) \tag{5}$$

$$H_g = \rho_{ag} C_{p,a} C_h^g W_{af}(T_{af} - T_g) \tag{6}$$

In particular, Eq. (4) is used for the calculation of the convective heat transfer in both the existing and the cool finishing layers. Eqs. (5) and (6) are used in green roofs for the foliage and ground layers calculations, respectively.

3.3. Calculation of the annual primary energy needs

Another potential impact of the selected technologies concerns the reduction in the energy consumption for both space cooling and heating. In this study, this will be evaluated in terms of Primary Energy, which requires the definition of the specific technology used for air-conditioning purposes. In this work, air-conditioning in summer is always performed through an electrically-driven chiller. As concerns space heating, two different solutions are considered, namely a gas-fired boiler and a reversible air-to-water heat pump.

The investigation is based on the concept of *Primary Energy Ratio* (PER): this is defined as the ratio of the thermal energy delivered to (or extracted from) the conditioned space to the Primary Energy consumption of the air-conditioning device. The value of the PER depends on the processes adopted by the device to produce or extract thermal energy. As an example, in a gas-fired boiler the PER corresponds to the average efficiency η of the boiler, whereas in electricity-driven reversible heat pumps the PER can be calculated by multiplying the average Coefficient of Performance (COP) by the average efficiency for the electricity production and distribution (η_{el} = 0.46).

The overall Primary Energy needs for space heating and cooling can be calculated according to Eq. (7):

$$\mathrm{PE} = \frac{Q_s}{\mathrm{PER}_s} + \frac{Q_w}{\mathrm{PER}_w} \tag{7}$$

where, the two addends represent the PE consumption for space cooling in summer (s) and space heating in winter (w).

Table 3
Mean performance coefficients for different air-conditioning devices.

	Gas-fired boiler	*Reversible air-to-water heat pump*			
	$PER_w = \eta$ [–]	EER [–]	PER_s [–]	COP [–]	PER_w [–]
Catania	0.75	3.65	1.68	3.76	1.73
Rome	0.75	3.86	1.77	3.49	1.60
Milan	0.75	3.89	1.79	3.09	1.42

The mean performance coefficients assumed in this study are reported in Table 3. In the case of the reversible air-to-water heat pump, the variation of the performance coefficient with the outdoor air temperature has been taken into account, according to data provided by the manufacturer. The values reported in Table 3 are average seasonal values.

4. Results and discussion

4.1. Performance at the roof scale and UHI mitigation

4.1.1. Roof surface temperatures

The temperature reached on the building surfaces strongly influences the air temperature in the urban environment. Hence, the calculation of the roof temperature is a basic step to study the effects of the proposed solutions in terms of Urban Heat Island mitigation.

In particular, Fig. 2 shows – for each roof technology – the hourly profile of the roof outer surface temperature resulting from the simulations in three particularly hot days in summer, namely from the 8th to the 10th of August in Catania, from the 14th to the 16th of August in Rome and from the 30th of July to the 1st of August in Milan. The curve of the solar irradiance on the horizontal plane is also reported.

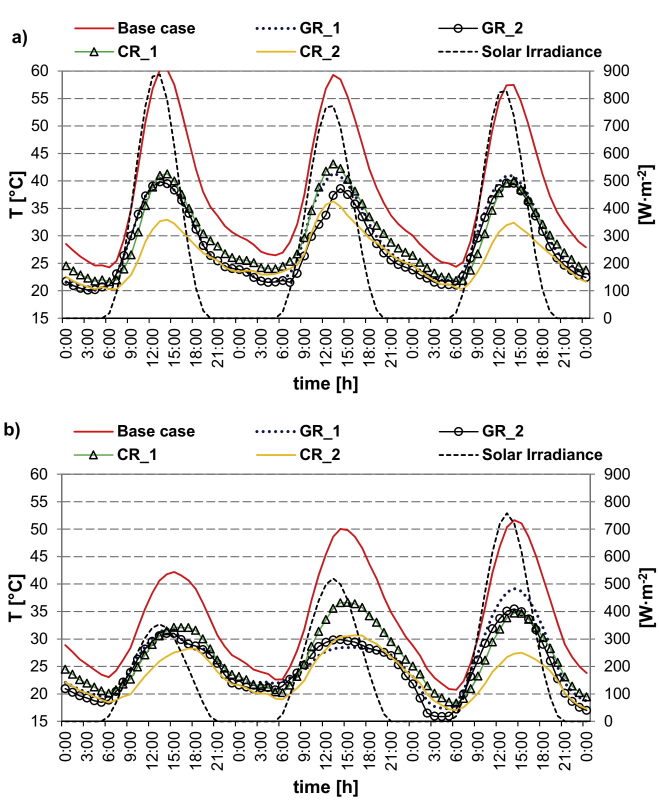

Fig. 2. Outer roof surface temperatures during three hot days in summer. (a) Catania (b) Milan.

Here, it is important to underline that, for the green roofs, the roof temperature is the weighted average of foliage and soil temperatures. Indeed, the outermost layer facing the environment is the vegetated one, thus one could consider this layer for computing the roof temperatures. However, one must take into account that the extensive green roof here considered does not show a very high LAI value, and that during the year the surface covered by the foliage layer is not constant.

Looking at results for the site of Catania (Fig. 2a), the application of a cool paint seems to be the most effective solution in lowering the roof temperature: indeed, a peak reduction by about 25 °C – if compared to the existing finishing layer – is expected for CR_2 (white paint) when solar irradiance is at its maximum. During the afternoon, the expected reduction ranges from 15 to 10 °C. On the other hand, the use of an extensive green roof leads to a trend very similar to that achieved with CR_1; the peak daily values for the green roof are sometimes slightly lower than for the cool roof, with a difference of about 2–4 °C.

Moreover, no significant difference is expected between GR_1 (dry soil) and GR_2 (irrigated soil), except during the second day when GR_1 achieves peak temperatures slightly higher than GR_2.

For the city of Rome the results are very close to those of Catania, thus they are not shown in Fig. 2. The cool paint is still the best solution for reducing the roof temperature, since the peak reduction with respect to the existing roof covering would swing from 12 to 25 °C for CR_2.

A slightly different roof behavior is observed in Milan (Fig. 2.b), because of the lower amplitude of the external heat forces (outdoor dry bulb temperature and solar irradiance). Here, GR_2 (wet green roof) strictly follows (at least during the first two days) the behavior of CR_2. During the last day, GR_1 (dry green roof) shows higher surface temperatures than those achieved by GR_2 (about 5 °C), as it cannot discharge heat by moisture evaporation.

Another way to compare the different technologies is to look at the cumulated frequency distribution of the surface temperatures achieved by the roof during the whole summer season (from the 1st of June to the 30th of September). In particular, Fig. 3 shows the cumulated percentage of time during which the roof temperature is below a certain value.

As it is possible to observe from Fig. 3a, the external roof temperature in Catania is always below 45 °C if green or cool roofs are used, whereas in a traditional roof the external temperature would exceed this threshold for the 25% of time, and it would even reach 60 °C. The results referring to CR_1 and to the green roofs are similar, with a slight preference for GR_2. However, when a paint with high solar reflectance is used (CR_2), the reduction in the external roof temperature is more significant: the peak value does not exceed 35 °C and for the 80% of time the temperature is below 28 °C.

The city of Rome shows a very similar trend, while in Milan for the 80% of time the roof outer temperature is below 40 °C if considering the existing roof, 30 °C in case of green roof, 28 °C and 22 °C respectively for CR_1 and CR_2. For this city, a translation of all the curves towards lower temperature values is observed, because of the milder summer season.

Finally, with the aim of showing the influence that different irrigation schedules could have on the performance achievable by green roofs, the simulations for the irrigated case have been repeated considering two additional scenarios:

(1) same irrigation rate as in GR_2 ($1.2\ kg\ m^{-2}$ every Monday, Wednesday and Friday), but with an additional irrigation period (from 18:00 to 19:00);
(2) higher irrigation rate ($2.4\ kg\ m^{-2}$), but with the same irrigation period (every Monday, Wednesday and Friday, from 6:00 to 7:00).

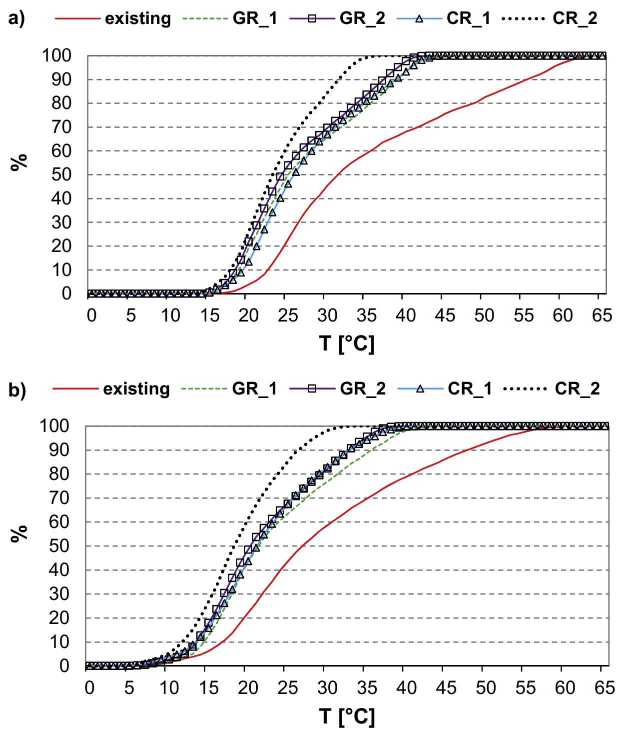

Fig. 3. Cumulated frequency distribution of the outer roof temperature. (a) Catania (b) Milan.

The results of these additional simulations show that the roof temperature is only slightly interested by the longer irrigation schedule. On the other hand, doubling the irrigation rate has almost no effect, since over a certain threshold the soil gets easily saturated.

4.1.2. *Roof heat fluxes*

Still paying attention to the Urban Heat Island effect, the evaluation of the heat flux exchanged between the roof and the outdoors can give a clear idea of the potential of each technology in reducing the UHI intensity within the urban environment. The heat flux is calculated through Eqs. (4)–(6); its value is positive when the heat flux is released from the roof to the outdoors.

In Fig. 4, the sensible heat flux released by the roof is plotted for the same three hot days in summer considered in the previous analysis.

If looking at the results of Catania (Fig. 4a), the simulated peak values for the sample building are reduced by about 70% when using CR_1, and a value close to zero is expected if considering the best performing cool paint (CR_2). This happens because the roof temperature is very often close or even below the outdoor air temperature. On the other hand, green roofs show peak values higher than for a cool paint, but also high negative heat fluxes at night and in the morning hours. This result seems mainly related to evapotranspiration, and is particularly evident during and after irrigation.

In Milan (Fig. 4b), the lower amplitude of the external forcing conditions (outdoor temperature and solar irradiance) leads to results much more comparable between the two cool paints considered, and to a less fluctuating value for the green roofs, whose surface temperature keeps below the outdoor temperature also during the day (for this reason, negative fluxes are expected).

Moreover, Fig. 5 reports the overall sensible heat flux exchanged by the roof with the outdoor air over the whole summer season, measured in $\mathrm{kWh\,m^{-2}\,y^{-1}}$. Here, it is easy to observe how both green and cool roofs induce a dramatic reduction in the overall heat

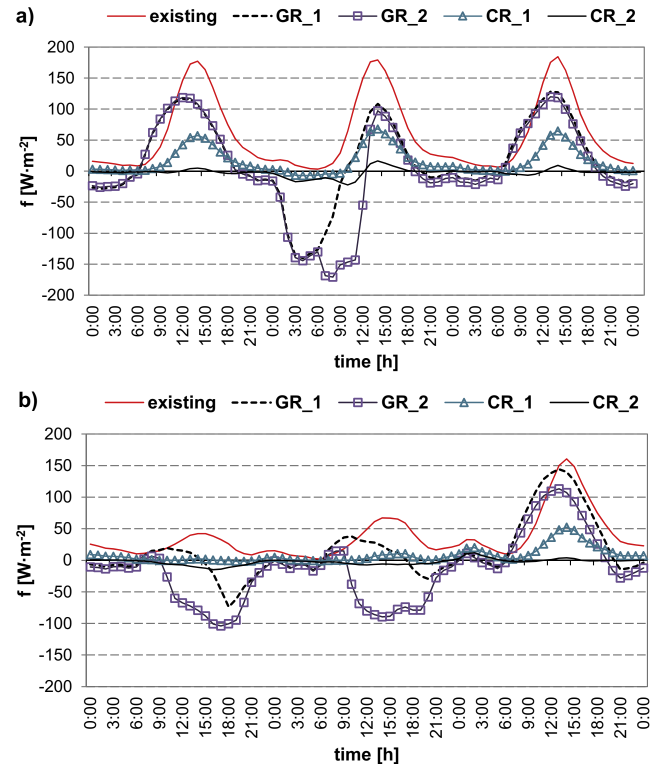

Fig. 4. Roof heat fluxes during the three hottest summer days. (a) Catania (b) Milan.

flux: indeed, GR_1 shows a reduction by about 53%, while GR_2 by even 75% for Catania, whereas the corresponding reductions for Rome are 42% and 58% respectively.

When dealing with cool roofs, a reduction by more than 75% is expected for each city with CR_1, and even negative results (i.e. convective fluxes from the air to the roof) are expected with CR_2.

Finally, the introduction of additional irrigation periods with respect to GR_2 (see Section 4.1.1) determines a strong reduction in the heat flux, especially in Catania, where this decreases from 36 to 20 $\mathrm{kWh\,m^{-2}\,y^{-1}}$ when irrigating the roof twice a day. In Rome and Milan, the expected reductions are by about 15% and 27%, respectively. On the contrary, only low reductions are induced when doubling the irrigation rate.

In conclusion, this comparison shows that both green and cool roofs are good solutions for lowering the roof surface temperature and for reducing the heat fluxes released to the outdoors in summer, thus mitigating the UHI effect. This is true for every city considered in this analysis, despite different climatic conditions. However, the two technological solutions show quite comparable performance when the cool paint has an average solar reflectance

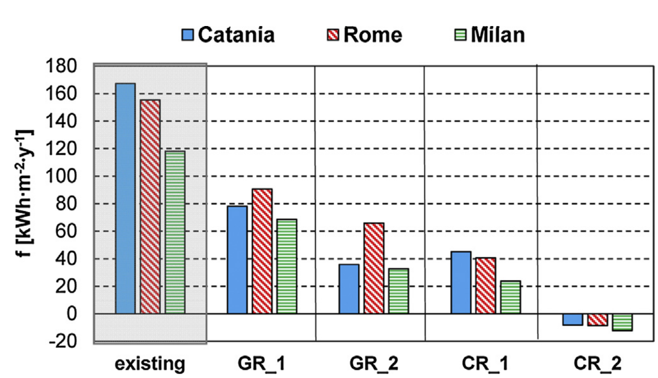

Fig. 5. Overall heat fluxes released by the roof to the outdoor air in summer.

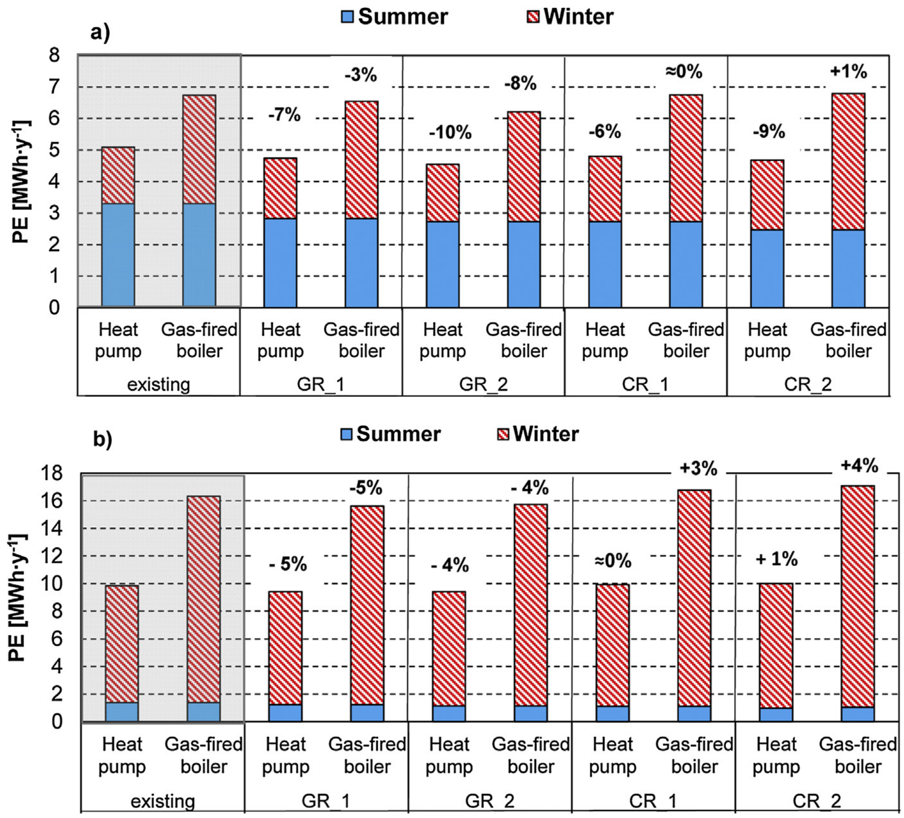

Fig. 6. Overall primary energy needs for heating and cooling. (a) Catania (b) Milan.

value (r = 0.65), while if using a more performing paint (r = 0.80) cool roofs are preferable by far, also because they need low maintenance in comparison with green roofs.

However, the different behavior of the finishing layer may have significant effects in winter. This issue is examined in the next paragraph, by looking at the annual primary energy needs for both space cooling and heating, and by studying the effects on the peak loads for air-conditioning.

4.2. Performance at the building scale

4.2.1. Annual primary energy needs

It is common belief that the cooling needs of buildings always benefit from the application of a green coverage or a cool paint to the roof. However, very seldom the energy analysis of green and cool roofs is extended to the winter and is performed in terms of PE consumption, which is strongly influenced by the choice of the devices for space heating and cooling.

In this study, these issues are considered as explained in Section 3.3, and the main results are shown in Fig. 6.

In particular, for the city of Catania (Fig. 6a), the use of an extensive green roof provided with an irrigation system (GR_2) leads to a reduction by about 10% in the annual primary energy needs for cooling and heating, when using an air-to-water heat pump in winter, or by about 8% when using a gas-fired boiler. The comparison with the dry green roof (GR_1) is carried out only with the aim of estimating the differences with the irrigated one, since it is not possible for the vegetation to grow up in such a hot climate without an appropriate irrigation schedule.

On the other hand, the application of the cool paint is the best solution for reducing the cooling energy needs, as it is possible to observe from Fig. 6a, where the cooling energy needs are considerably reduced (by about 17% for CR_1, and by about 25% for CR_2). However, the annual energy needs decrease by only 6% when performing space heating with a heat pump, and keep almost equal to the original building if using a gas-fired boiler and CR_1. The use of the most reflective paint (CR_2) would lead to a reduction by 9% in the case of the heat pump and an increase by about 1% when a gas-fired boiler is adopted. For the city of Rome, a similar trend is observed, even if the impact of the energy needs for heating is more marked than in Catania. The results are not reported for the sake of brevity.

Finally, Milan shows the highest PE needs amongst the cities considered in this study, and this is due to the high heating loads, whereas cooling loads are almost negligible. In this case, it is interesting to highlight how GR_2 behaves slightly worse than GR_1, because of the additional winter heat losses due to the water content.

Anyway, as observed for Catania and Rome, green roofs are the best solution for lowering PE needs, because they act as a shading device in summer, lowering the heat flux incoming through the roof, and as an insulating layer in winter by mitigating heat losses.

In a cold climate, like in Milan, the insulating role played in winter leads to annual savings of about 5%, while the application of a cool paint leads to an increase of about 3% when a gas-fired boiler is used (see Fig. 6b). In addition, the use of a white paint (CR_2) would not modify the results obtained with CR_1, because of the negligible cooling needs for these climatic conditions.

On the other hand, the PE needs are only marginally interested by the irrigation pattern, since a reduction by about 1% is expected for Catania and Rome, and an increase by 1% for Milan when considering the improved irrigation scenarios discussed in Section 4.1.1.

4.2.2. Peak loads reduction

Another noticeable effect due to the use of these technologies is the reduction of the peak loads for space cooling in summer, as

Table 4
Peak loads for space cooling and heating. Starting values and percentage variations.

		Space cooling—summer			
	Existing [kW]	GR_1 (%)	GR_2 (%)	CR_1 (%)	CR_2 (%)
Catania	7.1	−10	−10	−10	−18
Rome	6.6	−14	−14	−14	−20
Milan	5.7	−16	−16	−16	−21
		Space heating—winter			
	Existing [kW]	GR_1 (%)	GR_2 (%)	CR_1 (%)	CR_2 (%)
Catania	13.5	−5	−3	+6	+10
Rome	17.9	−6	−4	+3	+4
Milan	25.2	−5	−5	+1	+2

described in Table 4. In fact, even if both green and cool roofs reduce the summer peak loads in a similar way for each city considered (from 10% to 20% depending on the existing case and on the solar reflectance value), these two technologies show different winter performance.

Indeed, cool roofs always increase the peak demand for space heating, especially in cities like Catania and Rome that experience higher solar irradiance than Milan in winter. In this way, free solar gains are penalized, so increasing the heating peak loads by about 6% for Catania and by about 3% for Rome when $r = 0.65$ (CR_1), while when using a paint with $r = 0.80$ (CR_2) these values raise up to 10% and 4%, respectively. The increase of the peak heating loads due to cool paints is less significant in Milan.

Conversely, green roofs reduce the heating peak loads of the building in each city considered, and in particular in Milan, where the heating loads are much more important if compared to the cooling ones. In this case, a decrease by about 5% is expected when a green roof is used. In conclusion, the green roof technology seems to be mostly appropriate for reducing both the cooling and the heating peak loads of the air-conditioning devices, thus reducing their size and providing money savings.

5. Conclusions

This paper proposes a comparison between cool roofs and green roofs, with the aim of identifying the best compromise between mitigation of the Urban Heat Island effect and reduction of the primary energy consumption in buildings. The study is based on dynamic thermal simulations of an existing single-story office building. The simulations are repeated in three different climatic conditions in Italy, ranging from the warm climate of Catania (833 winter degree days) to the cold climate of Milan (2404 winter degree days). In the simulations, the thermal transmittance of the envelope is modified according to the climate, in order to comply – in all sites – with the current Italian building codes for the insulation of buildings. This should normalize the energy performance of the building in relation to the outdoor temperatures.

The results show that cool roofs are the most suitable solution for reducing the external roof surface temperature in any climate: if using a very performing cool paint ($r = 0.8$), peak reductions ranging from 15 to 25 °C in summer are expected, while during the afternoon such effect is less pronounced. Green roofs follow a similar trend, at least if compared to cool paints with an average cooling potential ($r = 0.65$).

Moreover, the sensible heat fluxes released by the roof to the outdoor environment are cut down in each city when using both green roofs (from 42% to 75%, depending on the climate) and cool roofs (about 75% when $r = 0.65$, and even more when $r = 0.80$). These results suggest that cool roofs, if $r > 0.65$, are a more effective solution than green roofs to tackle the UHI effect.

On the other hand, if looking at the annual primary energy needs of the sample building, and then by taking into account the efficiency of the specific device adopted for space heating and cooling, green roofs are preferable to cool roofs. This is due to their insulating potential, which reduces the energy needs in winter, whereas cool roofs may determine an increase in the energy consumption for space heating, since they reduce solar heat gains.

Moreover, green roofs and cool roofs are almost equivalent in terms of reduction in the peak cooling load, thus providing energy and economic savings due to the reduced size of the air-conditioning devices. These results are not significantly affected by the irrigation schedule applied to the green roofs.

Finally, it must be highlighted that, thanks to the reduced cooling loads of the building, both cool roofs and green roofs allow a lower rate of heat rejection to the environment from the condenser of the cooling device, thus providing an additional positive effect for the UHI mitigation.

In conclusion, depending on the perspective that leads the comparison, the choice between cool and green roofs can vary: if looking only at the issue of the UHI effect mitigation, cool roofs (especially those with very high solar reflectance values) are to be preferred, also in cold climates like in Milan. Conversely, if looking at the annual primary energy needs of buildings, green roofs perform better thanks to their shading and insulating properties.

These outcomes are coherent with the results of a recent paper by Gagliano et al. [33]. Here, an innovative multi-criteria methodology is introduced to compare several roof solutions under a broad perspective, by assigning a score to different indicators that measure the energy and environmental performance. The proposed comparative procedure indicates that an extensive and moderately insulated green roof is the most effective technology to strongly reduce the energy needs of buildings, while helping in the UHI mitigation, at least in mild Mediterranean areas.

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