

Chapter 2

Assessment of the Green Roofs Thermal Dynamic Behavior for Increasing the Building Energy Efficiencies

Antonio Gagliano, Maurizio Detommaso and Francesco Nocera

Abstract The continuous city growth leads to the intensification of the Urban Heat Island effect (UHI) which involves several consequences for the in-habitant comfort. Countermeasures such as green roofs can mitigate the urban microclimate reducing the roof surface temperature and hence the surrounding air temperature. As most of the existing Italy building stock was built without or with poor thermal insulation, they need of interventions of energy retrofit. In particular, roofs are the component of the building envelope that are mainly engaged of both solar gains and thermal fluxes. Therefore, any interventions refurbishment should include the roof surface. This paper focuses on the analyses of the energy performance and the dynamic thermal behavior of a green roof implemented in an existing house-holiday situated in the south part of Sicily. Moreover, other two refurbishment scenarios that foresee the increase of the roof thermal insulation were analysed. Dynamic simulations have proven that the green roof reduce the energy needs, about 90% in the cooling period and 30% in the heating period; delays and attenuates the outdoor heat wave in comparison with traditional roofs, as well as diminishes the average daily temperature fluctuations. The reduction of the vegetated temperature area results about 10.0 °C lower than the one of a bare roof area.

Keywords Green roof · Energy building simulations · Thermal comfort · UHI

Nomenclature

$C_{e,g}$	Latent heat flux bulk transfer coefficient at ground layer
C_f	Bulk heat transfer coefficient
$C_{h,g}$	Sensible heat flux bulk transfer coefficient at ground layer
$C_{p,a}$	Specific heat ($J\ kg^{-1}\ K^{-1}$)
DF	Decrement factor (–)

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F_f	Net heat flux to foliage layer (W m^{-2})
F_g	Net heat flux to ground surface (W m^{-2})
h_c	Convective heat transfer coefficient ($\text{W m}^{-2} \text{K}$)
h_r	Linear radiative heat transfer coefficient ($\text{W m}^{-2} \text{K}$)
H_f	Foliage sensible heat flux (W m^{-2})
H_g	Ground sensible heat flux (W m^{-2})
$I_{\downarrow}$	Total incoming short wave radiation (W m^{-2})
$I_{\text{ir}}^{\downarrow}$	Total incoming long wave radiation (W m^{-2})
l_f	Latent heat of vaporization at foliage temperature (J kg^{-1})
l_g	Latent heat of vaporization at ground temperature (J kg^{-1})
L_f	Foliage latent heat flux (W m^{-2})
L_g	Ground latent heat flux (W m^{-2})
LAI	Leaf area index (m m^{-2})
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
q_{af}	Mixing ratio for air
$q_{f,\text{sat}}$	Saturation mixing ratio at foliage temperature
$q_{g,\text{sat}}$	Saturation mixing ratio at ground temperature
r^*	Surface wetness factor
r	Short wave reflectance (-)
r_f	Short wave reflectance of the foliage (-)
r_g	Short wave reflectance of the soil surface (-)
s	Thickness (m)
S	Total envelope surface area (m^2)
S_r	Roof surface (m^2)
S_u	Net floor area (m^2)
SM	Superficial mass (kg m^{-2})
t	Transmissivity (-)
T_{af}	Air temperature within the canopy ($^{\circ}\text{C}$)
T_{db}	Dry bulb air temperature
T_f	Leaf temperature ($^{\circ}\text{C}$)
T_g	Ground surface temperature ($^{\circ}\text{C}$)
T_i	Indoor temperature ($^{\circ}\text{C}$)
T_{MRT}	Mean radiant temperature ($^{\circ}\text{C}$)
T_o	Outdoor air temperature ($^{\circ}\text{C}$)
T_{op}	Operative temperature ($^{\circ}\text{C}$)
$T_{\text{op,av}}$	Average operative temperature ($^{\circ}\text{C}$)
T_{si}	Inner surface temperature ($^{\circ}\text{C}$)
T_{so}	Outdoor surface temperature ($^{\circ}\text{C}$)
TL	Time-lag (h)
U	Thermal transmittance ($\text{W m}^{-2} \text{K}^{-1}$)
V	Heated gross-volume (m^3)
W_{af}	Wind speed within the canopy (m/s)
z	Depth (m)

Greek letters

α_f	Short wave absorptance of canopy (–)
α_g	Short wave absorptance of the ground surface (–)
ε_f	Emissivity of canopy (–)
ε_g	Emissivity of the ground surface (–)
ε_l	$E_f + \varepsilon_g - \varepsilon_f \cdot \varepsilon_g$
g	Radiant fraction
λ	Thermal conductivity ($\text{W m}^{-2} \text{K}^{-1}$)
ρ_{af}	Density of air at foliage temperature (kg m^{-3})
ρ_{ag}	Density of air at ground surface temperature (kg m^{-3})
ρ_g	Density of growing medium (kg m^{-3})
ρ	Density (kg m^{-3})
	Stefan-Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$)
f	Fractional vegetation coverage (–)
τ	Time (s)

2.1 Introduction

The improvement of building energy efficiency is at the heart of the EU's transition to a resource-efficient economy and the Europe 2020 strategy for smart, sustainable and inclusive growth.

Energy efficiency measures contribute to the overall resilience to climate change as they play a safeguarding role against adverse/extreme weather events.

Thus, research on innovative energy technologies and passive solutions for improving the energy efficiency of buildings has become a strategic environmental and economic issue.

Various sustainable approaches and environmentally responsive efficient technologies have been proposed to design low-energy buildings [1–5].

In this context, the green roofs represents a suitable solution for improving the roof energy resilience in summer period reducing the cooling loads of both new and existing buildings [4, 6, 7] and for making buildings more sustainable.

The vegetation layer of a green roof realizes photo-synthesis processes, whereas the soil layer allows absorption of rainfall, often resulting in improvements of the water runoff quality [8–10]. Many researches on the green roofs have pointed out further benefits on the environment, such as improving thermal comfort and urban air quality [11], mitigation of the Urban Heat Island (UHI) by reducing “hot” surfaces facing the sky [6], [12–14] as well as noise transmission.

Green roofs are generally built to enhance the energy saving, since they act as a thermal buffer [15, 16] diminish the heat gain of about 70–90% in summer, and heat loss of about 10–30% in winter [17]. The energy consumptions of air conditioning (AC) during the summer are reduced by means of the combined effect of shading

and evapotranspiration [18]. They also reduce and delay the outdoor surface temperature peak and keep the internal conditions within the comfort range [14, 19, 20].

Green roofs, as well as the cool roofs, could show a negative energy balance compared with traditional roofs in the heating period, particularly during spring and autumn when the thermal losses are higher than the traditional roof [19].

As regard mitigation strategies aiming to reduce UHI, the implementation of green and cool roofs have been proposed in literature [5, 6, 13].

However, the mechanisms to reduce UHI through green and cool roofs are different; a green roof acts by the evapotranspiration of soil and plants on rooftops (redirecting available energy to latent heat) [21], while a cool roof increases the reflection of incoming solar radiation by increasing the albedo of roof surfaces. The question of determining the impacts of these strategies of mitigation on the UHI phenomena at city scale remains an open question.

The purpose of this study is to evaluate the improvement of the energy performance of an existing poor insulated building, which has been refurbished by means of the implementation of an extensive averagely insulated green roof.

The research was conducted through dynamic simulations using the DesignBuilder software [22]. The energy performance of the building has been calculated under three different configuration roof configurations that foresee the implementation of a green roof, as well as the installation of two different thickness of thermal insulation (intermediate or well-insulated roofs). The dynamic thermal behavior, the thermal inertia parameters and the thermal comfort were investigated too. The results of the study show the reduction of energy needs, the improvement of the indoor thermal comfort and, the decreasing of the outdoor temperature surface when the green roof is applied.

2.2 Materials and Methods

Green roofs, also named “eco-roofs”, “living roofs” or “roof gardens”, are roofs with plants in their final layer [23, 24]. Two types of green roofs are generally identified: extensive (with soil thickness less than 10–15 cm) and intensive (with soil thickness more than 15–20 cm). As regard the intensive green roof, Karachaliou et al. presented a research on the thermal behavior and the energy performance of this typology of green roofs [25].

Because of their low additional loads, extensive green roofs are most suitable for building retrofitting, i.e. they do not require any additional strengthening [26].

The typical layers from the inside to the outside of an extensive green roofs are: load-bearing slabs (roof deck), thermal insulation, waterproof membrane, root barrier, drainage, filter layer, growing medium and vegetation layer (Fig. 2.1).

The vegetation layer can be constituted by mosses, sedum, graminaceous or other succulents plants, which are very common and suitable plants for using on an extensive green roof.

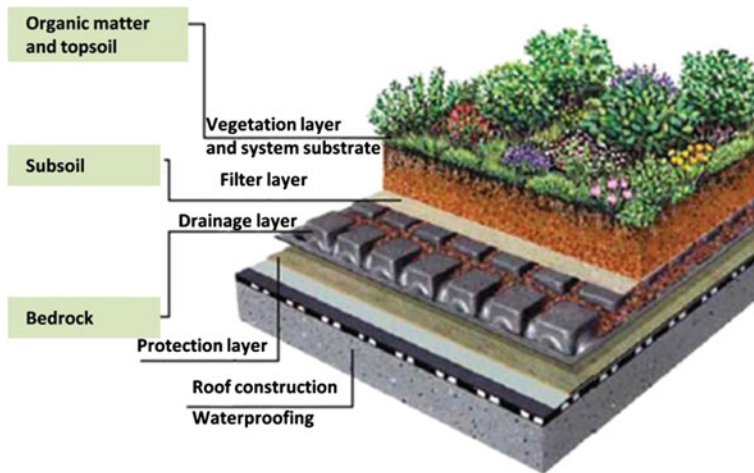


Fig. 2.1 Stratigraphy of extensive green roof [27]

All the above mentioned plants are small plants that grow across the ground rather than upwards offering good coverage and roof membrane protection. Moreover, such plants have the capabilities to store water in their leaves making them high drought resistance. Thus these extensive green roofs could survive also in Mediterranean climates. The systems must be able to retain the necessary quantities of water to support the plants, while draining off the excess. The plant type, the geographical region and the roof itself determine the required amount of water. Besides to build the most correct structure of green roof to support the plants, it is essential to protect the water-proofing from both mechanical damage as well as by the attack by plant roots.

The thermo-physical model of green roof identifies three main components: structural support, soil and canopy (leaf cover). The structural support includes all the layers between the inner plaster and the filter layer whose upper surface is the interface support-soil.

The soil is a complex component because it consists of a solid phase (mineral and organic material), a liquid phase (water) and a gaseous phase (air and water vapor). Data about soils are available in the technical standard EN ISO 13370 (CEN 2007) that provides thermal characteristics of common soils, as well as in the Farouki's database of soils [28].

Values of density, thermal conductivity, specific heat and albedo for eight types of ecoroof soils with different moisture levels, commonly used for green roofs, are available in [29]. A correlation between thermal conductivity and thermal capacity for different kind of soils is presented in [30]. The soil used in the green roofs has contain a modest percentage of organic compost, relevant percentage of sand as well as light material such as pumice or expanded shale.

The canopy is constituted by leaves and air enclosed in the leaf cover, which is characterized by the following parameters:

- Height of plants;
- Leaf area index (LAI) that is the total one-sided area of leaf tissue per unit of ground surface area ($\text{m}^2 \cdot \text{m}^{-2}$);
- Minimum stomatal resistance, that governs the flow of water vapor through the stomates;
- Emissivity, reflectivity, absorbance and transmissivity of the leaves.

The LAI index ranges from 1.0 for sparse vegetation, to 5.0 for dense vegetation of grasses and small plants. This parameter characterizes the canopy–atmosphere interface, where most of the energy fluxes is exchanged [13] (Fig. 2.2).

Various studies have analyzed the thermal performance and the heat exchange phenomena which occur in green roofs [15, 31].

The soil acts as an inertial mass with a high thermal capacity and low thermal transmittance; the foliage behaves as a shading device under which convection provokes heat thermal exchange, but foliage absorbs part of the thermal energy for its vital process of photosynthesis; soil and vegetative layers induce evaporative and evapotranspiration cooling.

Incoming solar radiation is removed by sensible (convection) and latent (evaporative) heat flux from soil and plant surfaces, combined with conduction of heat into the soil substrate and long-wave (thermal) radiation [32, 33].

The thermal balance of extensive green roof indicates that heat fluxes are exchanged of about 50% by evapotranspiration, 30.9% by the long-wave radiative thermal flux and 1.2% accumulated and transferred to the rooms underneath [31, 34]. Green roofs reflect between 20 and 30% of solar radiation, and absorb up to 60% of it through photosynthesis, whereas a percentage below 20% of the heat is transmitted to the growing medium [23].

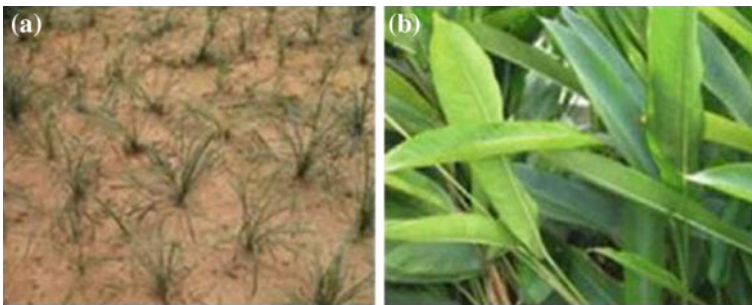


Fig. 2.2 Sparse (a) and large vegetation (b) [23]

2.3 Green Roof Modeling

The energy balance of the canopy is governed by radiative and convective thermal fluxes, evapotranspiration and evaporation/condensation of water vapor. Radiative thermal fluxes include the solar radiation absorbed by the leaves, the long-wave radiative exchanged between the leaves and sky, between the leaves and the soil surface and between the leaves themselves. Convective thermal fluxes occur between the leaves and the canopy air and between the soil surface and the canopy air. Evapo-transpiration includes the water evaporation into the leaves, the vapor diffusion onto the leaves surface and the vapor transport from leaves surface to the air.

The fast all season soil strength (FASST) model developed by the US Army Corps of Engineers is one of the numerical models most applied for simulating the energy balance of the green roofs [35]. The computational model includes: simplified moisture balance, soil and plant canopy energy balance, soil surface T_g and foliage T_f temperatures equations set are solved simultaneously each time step (Fig. 2.3).

The energy balance is divided into a budget for the foliage (1) and a budget for the ground surface (4) [34]. The energy balance on the foliage is based on the following equations:

$$F_f = \sigma_f \left[I_s^{\downarrow} (1 - r_f) + \varepsilon_f I_{IR}^{\downarrow} - \sigma \varepsilon_f T_f^4 \right] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_l} (T_g^4 - T_f^4) + H_f + L_f \quad (2.1)$$

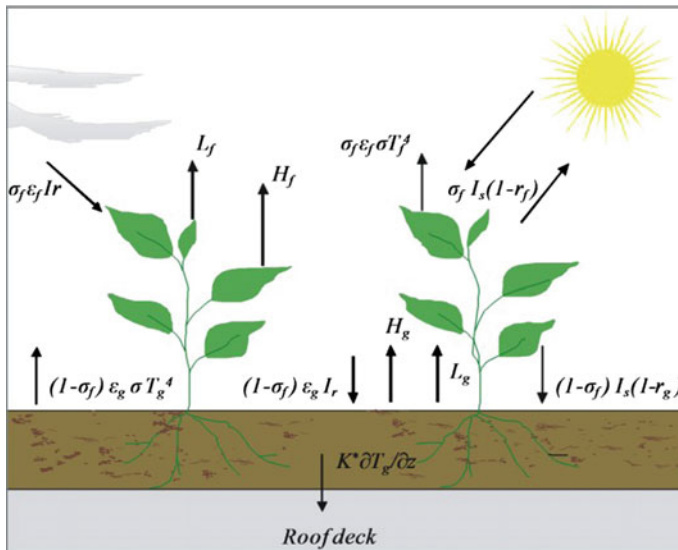


Fig. 2.3 Energy balance of the green roof

$$H_f = (1.1 LAI \rho_{af} C_{p,a} C_f W_{af}) \cdot (T_{af} - T_f) \quad (2.2)$$

$$L_f = l_f LAI \rho_{a,f} C_{p,a} C_f W_{af} r'' (q_{af} - q_{f,sat}) \quad (2.3)$$

Equation (2.2) calculates the sensible heat flux between the leaf surface and air canopy, which depends by the temperature difference between leaf surfaces and canopy, the wind speed as well as the LAI.

Equation (2.3) provides the latent heat flux in the foliage layer, which depends on the transpiration phenomena of the leaves. It is mainly influenced by the stomatal and aero-dynamic resistance of the leaves, soil moisture content, light intensity and vapor pressure difference between the inside of the leaf and the outdoor atmospheric. The energy balance on the ground surface, is characterized by the following equations:

$$F_g = (1 - \sigma_f) \left[I_s^\downarrow (1 - r_g) + \epsilon_g I_{IR}^\downarrow - \sigma \epsilon_g T_g^4 \right] - \frac{\sigma_f \epsilon_f \epsilon_g \sigma}{\epsilon_1} (T_g^4 - T_f^4) + H_g + L_g + K \frac{dT_g}{dz} \quad (2.4)$$

$$H_g = \rho_{ag} c_{p,a} C_{hg} W_{af} (T_{af} - T_g) \quad (2.5)$$

$$L_g = C_{e,g} l_g W_{af} \rho_{a,g} (q_{af} - q_{g,sat}) \quad (2.6)$$

The energy budget on the ground surface (2.4) is mainly influenced by the moisture content, thermal properties of the soil and amount of surface covered of the leafs. The sensible heat flux in the soil layer is given by the Eq. (2.5). It is function of the temperature difference between the soil surface and the air and by the wind speed of the air canopy. Equation (2.6) gives the heat latent exchanged between the ground surface and the air which depends on the difference between the mixing ratio of the soil surface and air and the wind speed of the air within canopy. The end result is a set of two simultaneous equations for temperatures, one for soil and the other for the foliage.

2.4 Methodology

2.4.1 Building Simulations

Green roofs are frequently designated as an efficient technologies that reduce the direct influence of solar radiations, indoor temperature fluctuations, and indoor air temperature peaks [15–18, 36].

The investigations of the effectiveness of the green roof to achieve the above-mentioned objectives requires the use of numerical model that allows to

simulate the influence of the radiative properties and thermal inertia on the energy performance of building.

Nowadays, many software tools are available for building dynamic simulations [22]. In this study the software Design Builder has been used. In Design Builder the green roof module can be implemented as outer layer of a rooftop construction using a “Material: Roof Vegetation”. The calculation method consists in a energy budget analysis that it follows the Fast All Season Soil Strength (FASST) model developed by Frankenstein and Koenig for the US Army Corps of Engineers [34].

This tool carries out accurate thermal analyses and allows very detailed inputs, including: climatic data (including air temperature, solar radiation, relative humidity hourly profiles); construction materials and components in dedicated libraries or manually edited; energy systems’ specifications; time schedules (systems’ management, occupancy, electric lighting, ventilation, etc.).

2.4.1.1 Thermal Dynamic Behavior

The dynamic thermal simulations permits to calculate the energy needs of both in heating and cooling period, the indoor air temperature (T_a), the outdoor (T_{so}) and in-door superficial temperature (T_{si}) and the indoor operative temperature.

The knowledge of these temperatures provides a set of data relating with the performances of the building envelope as thermal inertia parameters, indoor thermal comfort and the mitigation effects on the UHI [37].

As well known building energy performance strongly depends by the thermal inertia of the building envelope components. Buildings envelope with high thermal mass and heat capacity contribute to the reduction and the time delay of the peaks of cooling load [38].

The time lag (TL) and decrement factor (DF) are the two parameters widely used for characterizing the thermal inertia and heat storage capability of buildings.

The Time lag (TL) is measured by the delay of time between the hour when the maximum outer surface temperature occurs and the hour when the maximum inner surface temperature occurs.

$$TL = \tau_{T_{so,max}} - \tau_{T_{si,max}} \quad (2.7)$$

The decrement factor (DF) is the ratio of the amplitude of the inner surface temperature fluctuations to the amplitude of the outer surface temperature fluctuations:

$$DF = \frac{A_{si}}{A_{so}} = \frac{T_{si,max} - T_{si,min}}{T_{so,max} - T_{so,min}} \quad (2.8)$$

Therefore, it is worth to investigate the thermal behavior of the Green Roof with reference the above mentioned thermal inertia parameters.

Further, the temperature reached on the external building surface strongly influences the sensible heat available for transmission to the air or to building envelopes and, consequently the air temperature within the urban area.

2.4.1.2 Thermal Comfort

The purpose of ASHRAE Standard 55, thermal environmental conditions for human occupancy, is “to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space” [39].

Actual thermal comfort is dependent on environmental factors, such as air temperature, air velocity, relative humidity and the uniformity of conditions, as well as personal factors such as clothing, metabolic heat, acclimatization, state of health, expectations, and even access to food and drink [40].

When calculating the thermal indoor climate, the operative temperature can be used as a simple measure for the heat loss from a person. It is the combined effects of the mean radiant temperature (T_{MRT}) and air temperature (T_{dry}).

Mathematically, operative temperature (T_{op}) can be expressed as;

$$T_{op} = (h_r \cdot T_{MRT} + h_c \cdot T_{db}) / (h_r + h_c) \quad (2.9)$$

where, T_{MRT} is the mean radiant temperature for the thermal zone, T_{db} is the mean zone air temperature, h_c is convective heat transfer coefficient; h_r is the linear radiative heat transfer coefficient.

The operative temperature (T_{op}) can also be calculated using the Eq. (2.10) as per Standard 55-2004.

$$T_{op} = \gamma \cdot T_{db} + (1 - \gamma) \cdot T_{MRT} \quad (2.10)$$

γ is the radiant fraction, whose typical value is 0.5.

It can be useful in assessing the likely thermal comfort of the occupants of a building. Normally, whenever T_{op} exceeds desired comfort range, people tries to change the T_{db} set point to achieve a comfortable value of the operative temperature.

2.5 Pilot Study

2.5.1 Reference Building

The reference building is a typical holiday houses situated in the south coast of Sicily (lat. 36°53', long. 4°25'). This typology of buildings (Fig. 2.4) were built at

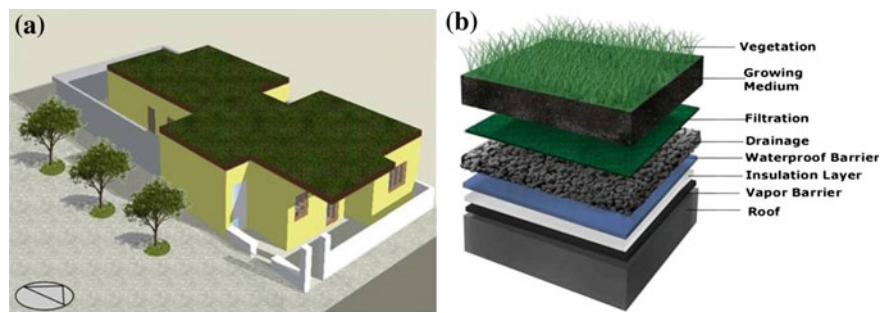


Fig. 2.4 Simulated building **a** 3D view, **b** green roof

least 30 years ago, when thermal insulation of the building envelope was almost totally disregarded in Italy.

The roof is a flat roof in reinforced concrete slabs with thickness of 25 (cm), the opaque vertical closures are characterized by masonries in double brick walls with internal air gap with an overall thickness of 30 (cm). Basic horizontal closure is composed by reinforced concrete slab and upper cement screed, coated with ceramic pavement.

The building is equipped with an air conditioning system, which operates with a set-point temperature of 20 °C during the heating period (December 1st–March 31th) and a set-point temperature of 26 °C during the cooling period (June 1st–September 30th).

As concerns internal gains, electric equipment and lighting: the average occupancy density is 0.04 people·m⁻², the density power for lighting and domestic equipment is 10 W·m⁻² for the entire environment except the kitchen zone where the internal gains are 45 W·m⁻². The air change rate is 0.5 vol/h. The main geometrical feature of this building are reported in Table 2.1.

The thermal transmittance and mass surface of the building components are reported in Table 2.2.

Table 2.1 Geometric feature of the building and characteristic parameters

V (m ³)	S (m ²)	S/V (m ⁻¹)	S _u (m ²)	S _r (m ²)	h (m)
513	530	1.03	151.17	151.17	3.00

Table 2.2 Thermal transmittance and mass surface of building components

Building components	U (W m ⁻² K ⁻¹)	SM (kg m ⁻²)
External masonry in double brick walls (30 cm)	1.27	381
Roof slab	3.17	571
Ground floor	3.77	474
Windows	2.60	–

2.6 Building Retrofits Scenario

A suitable strategy, to improve the energy performance of this typology of buildings, is the refurbishment of the roof considering that usually roofs have a large dispersing surface. Therefore, three scenarios have been investigated, two cases foresee the addition of thermal insulation, with a thickness of 4.0 and 8.0 cm respectively, the third case foresees the implementation of an extensive green roof.

It has been proven that non-insulated green roofs can be advantageous in summer, but they are less favorable in winter when the roof would benefit of a higher thermal resistance [41, 42]. Therefore, we have decided to investigate a green roof averagely insulated with 4.0 cm of thermal insulation, as an efficient way to obtain good performance of both during warmer days and, during colder ones.

2.6.1 Descriptions of the Green Roof

An extensive green roof has been considered because it is compatible with the existing building structures. The vegetation layer can be constituted by mosses, sedum, graminaceous or other succulents plants, which are very common and suitable plants for using on an extensive green roof. All the above mentioned plants are small plants that grow across the ground rather than upwards offering good coverage and roof membrane protection [18]. Moreover such plants have the capabilities to store water in their leaves making them high drought resistance. The thermo-physical properties of vegetation layer and substrate are reported in Table 2.3.

The substrate is a thin layer (10 cm) of porous soil, it is typically a mixture of sand, clay, mineral aggregates and organic matter. The soil is above the filter layer, a geotextile fabric, that filters the soil granules in order to prevent that the empties of the drainage layer are filled. Table 2.4 summarizes the main characteristics of the proposed green roof.

Table 2.3 Thermo-physical properties of vegetation layer

Vegetation layer			Substrate		
Height of the plants	H	0.10 (m)	Thermal conductivity	λ	0.98 ($\text{W m}^{-1} \text{K}^{-1}$)
Leaf area index	LAI	5.0 ($\text{m}^{-2} \text{m}^{-2}$)	Density	ρ_g	1460 (kg m^{-3})
Reflectivity	r_f	0.22	Specific heat	C_p	880 ($\text{J kg}^{-1} \text{K}^{-1}$)
Absorbance	α_f	0.60	Emissivity	ϵ_g	0.90
Transmissivity	t_f	0.18	Absorbance	α_g	0.70
Emissivity	ϵ_f	0.95	Residual moisture content	θ_r	0.01 ($\text{m}^{-3} \text{m}^{-3}$)
Minimum stomatal resistance	r	180 (s m^{-1})	Initial moisture content	θ_{in}	0.15 ($\text{m}^{-3} \text{m}^{-3}$)

Table 2.4 Stratigraphy and thermal properties of the extensive green roof

Layers	s (cm)	λ (W m ⁻¹ K ⁻¹)	ρ (kg m ⁻³)	C _p (J kg ⁻¹ K ⁻¹)
1. Vegetation layer	–	–	–	–
2. Soil layer	10.0	0.98	1460	880
3. Filter layer	0.1	0.22	910	1800
4. Drainage layer	10.0	0.92	900	1000
5. Root barrier	0.5	0.19	1400	1200
6. Waterproof membrane	0.5	0.19	1400	1200
7. Thermal insulation	0.4	0.033	100	710
8. Moisture barrier	0.5	0.23	1100	1050
9. Concrete slab	24.0	2.30	2300	1000

The U-value of this extensive green roof results of 0.55 W m⁻² K⁻¹ and its surface mass (SM) is 762 kg m⁻².

2.7 Energy Performance Simulations

2.7.1 Building Simulations

The climatic conditions, air temperature and relative humidity as well as the solar radiation, are taken by the wheatear database embedded in Energy Plus for the Catania [22]. Figure 2.5 depicts the average daily solar irradiation on an horizontal plane and the outdoor air temperature.

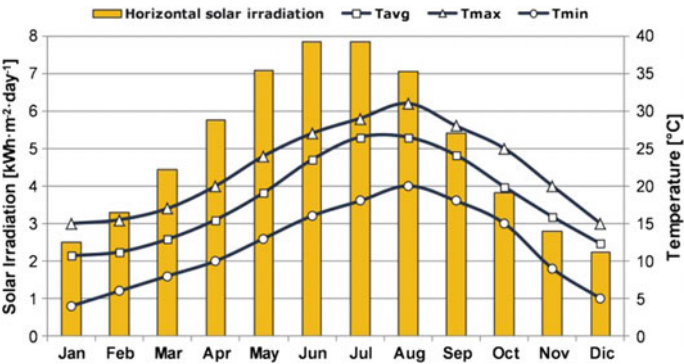


Fig. 2.5 Main average weather data of Catania city

Table 2.5 Thermal transmittance and mass surface of the roofs considered

Roofs	Acronym	Thickness (m)	Insulation thickness (m)	U-value ($\text{W m}^{-2} \text{K}^{-1}$)	SM (kg m^{-2})
Existing baseline roof	TR ₀	0.29	0	3.17	645
Averagely insulated roof	TR ₄	0.34	0.04	0.61	653
Well insulated roof	TR _L	0.38	0.08	0.35	657
Averagely insulated green roof	GR	0.55	0.04	0.55	762

The calculation of the overall building energy performance were carried out from June 1st to September 30th (cooling period) and from December 1st and March 31th (heating period).

The energy performance of the green roof scenario has been compared with the performance of the existing baseline roof and with the other two insulated roof, averagely and well insulated. The main termo-physical characteristics of all the investigated roofs scenario are reported in Table 2.5.

Figure 2.6 shows the comparisons of the heat fluxes exchanged through the roof surfaces for each investigated scenario.

The GR achieves the better results in the cooling period, because the incoming heat flux through the GR is only the 5% than existing baseline roof. The well insulated roof TR_L achieves the best performances in heating period with a reduction of the of heat flux of (83%) compared with the bare roof. During the heating period, it can be noted that the GR achieve performance that are a slightly lower than the well-insulated roof TR_L, which has 4 cm of extra thermal insulation.

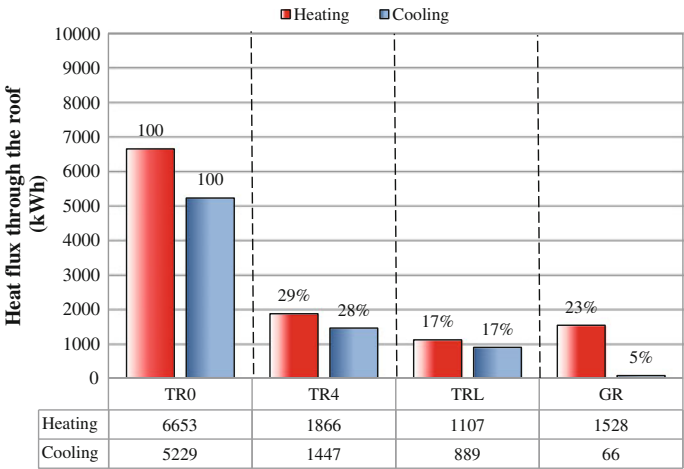


Fig. 2.6 Heat flux exchanged through the roof in heating and cooling period

2.7.2 Energy Needs

The energy needs of the building were calculated of both in the heating and cooling period. The results comparison of the yearly specific energy needs ($\text{kWh}/\text{m}^2\text{y}$) are reported in Fig. 2.7a, b.

As concerns the cooling period, it can be noticed that the reductions of the energy needs achievable with the green roof scenario (GR) are of about 90, 76 and 69%.

When compared respectively with the existing baseline (TR_0), the intermediate and well insulated roofs. As concerns the heating period (from 1st December to 31st March) it is can be noticed that the well-insulated roof allows to achieve better performance than the green roof scenario, while the GR and the intermediate insulated roofs (TR_4) achieve about the same performance. However, the energy deficit between the GR scenario and the well-insulated scenario is just about 3%. The specific energy needs for heating and cooling of the building are summarized in Fig. 2.8.

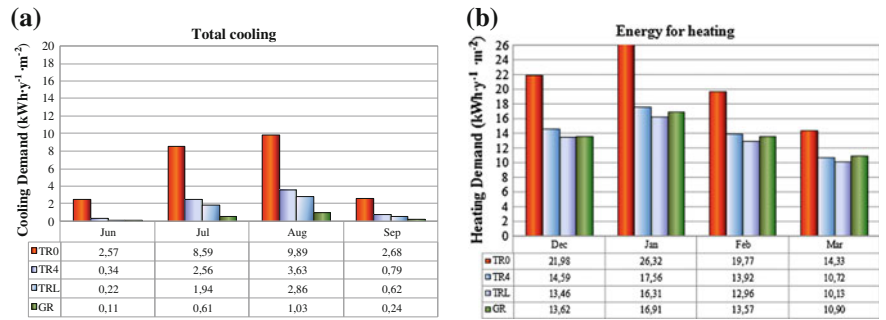
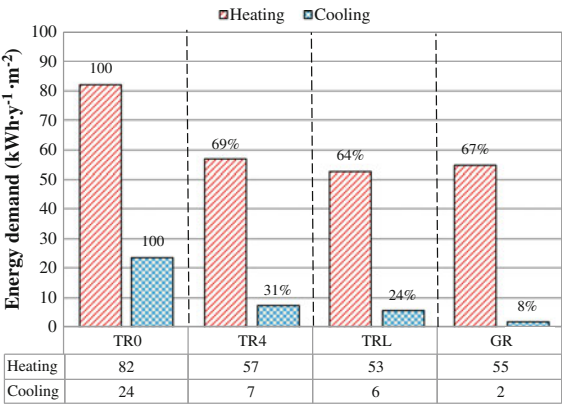


Fig. 2.7 Specific energy needs of each roof scenario: a cooling, b heating

Fig. 2.8 Total energy demand per unit of net floor area



Finally, it is possible to assert that the GR scenario provides the best performance considering an all year round analysis.

Moreover, the reduction of the energy needs in summer period implies the decreasing of the heat discharged through the condenser of the AC plants in the urban area. This aspect surely contributes to mitigate the UHI intensity at micro scale.

2.7.3 Assessment of the Thermal Dynamic Behaviour

With the aim to analyses the effectiveness of the GR to reduce indoor and outdoor superficial temperature fluctuations the hourly and daily profiles of both the superficial, internal (T_{si}) and external (T_{so}) as well as indoor temperature (T_i) were calculated in free running conditions.

The daily temperature profiles of the baseline roof, the well-insulated and the green roofs scenario are reported in Fig. 2.9, during the period (15th July–15th August).

The temperatures of the averagely insulated scenario is not reported, since its thermal dynamic behavior lies between the TR_0 and the TR_L temperature profiles.

It is possible to notice that throughout the period investigated the outdoor superficial temperature of the baseline $T_{so}(TR_0)$ and the well-insulated roof $T_{so}(TR_L)$ are always higher than and $T_{so}(GR)$. The average monthly difference between $T_{so}(GR)$ and $T_{so}(TR_L)$ is of about 7.0 °C, with a maximum daily value of 9.5 °C. Whereas the value of $T_{si}(TR_L)$ and $T_{si}(GR)$ are almost comparable with mean differences of about 1.0 °C. These results indicate the barrier effect of the

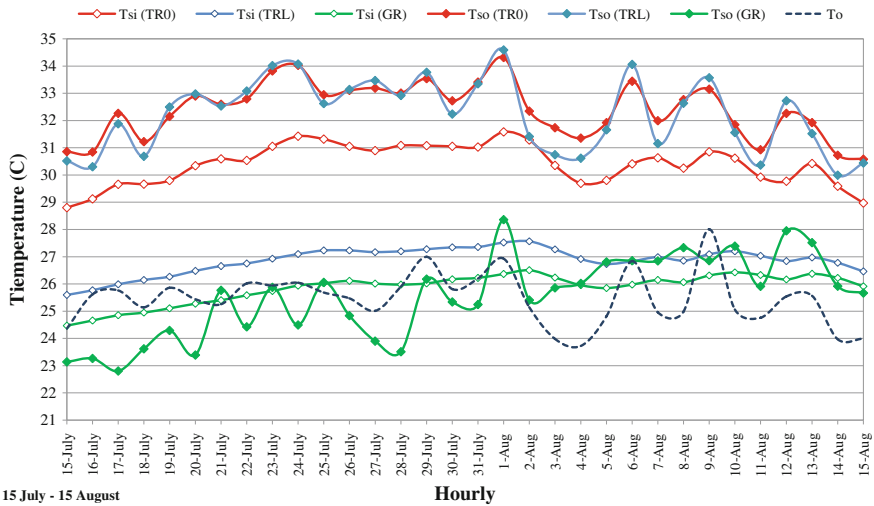


Fig. 2.9 Daily profiles of outer and inner surface temperature

thermal insulations, which allow a very large increase of the superficial external temperature.

These results indicates the very appreciable action of the green roof for mitigate the UHI, thanks to its lowest superficial outdoor temperatures.

Indeed, the lowest temperature on the external surface of the GR reduce the transmission of sensible heat flux from the building to the urban environment.

2.7.3.1 Assessment of the Thermal Dynamic Behaviour

In addition, the time lag and the decrement factors have been calculated for describing the response of the green roof to outer forcing conditions, using the Eqs. 2.7 and 2.8.

Figure 2.10 shows the comparison between the hourly variations of the superficial temperatures, in free running conditions, of the GR, TR₀ and TR_L scenario in a day characterized by the highest peaks of outdoor temperature (10 August).

It is evident the very wide temperature fluctuations of both TR₀ and TR_L when they are compared with the GR. Table 2.5 summarize the main results (Table 2.6).

It is possible to notice that the green roof achieves the lowest peak of outdoor surface temperature ($T_{so,max} = 32\text{ }^{\circ}\text{C}$), that is 13 and 16 $^{\circ}\text{C}$ lower than the other two scenario. On the other hand, the well-insulated roof is characterized by the highest value of peak of the outdoor surface temperature ($T_{so,max} = 48\text{ }^{\circ}\text{C}$).

The well-insulated roof, TR_L, and the green roof scenario, GR, have almost similar values of both time lag and decrement factor.

The well-insulated roof reaches such high value of $T_{so,max}$ because the insulating layer stops the heat flux from the outdoor to indoor causing the overheating of the

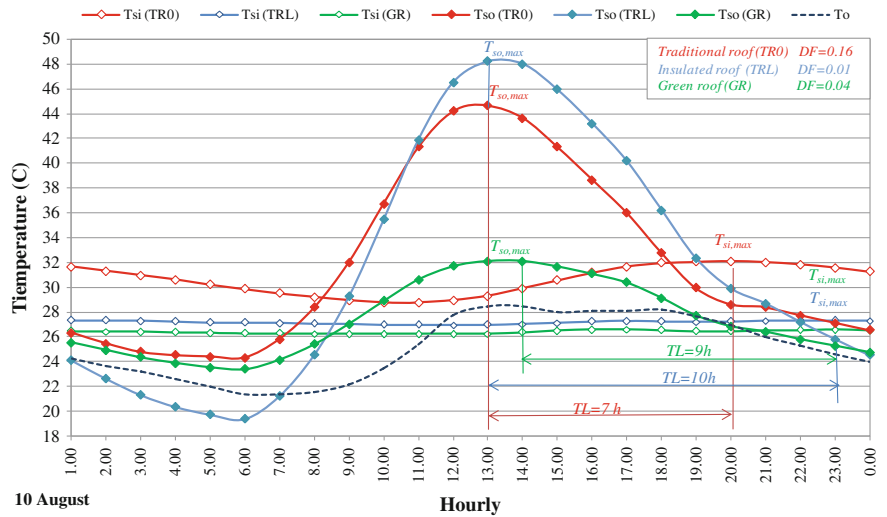


Fig. 2.10 Hourly profiles of the outer and inner surface temperature

Table 2.6 Dynamic thermal parameters

Roof	$T_{so,max}$ (°C)	$T_{si,max}$ (°C)	TL (h)	DF (-)
TR ₀	45 °C (13:00)	32 °C (20:00)	7.0	0.16
TR _L	48 °C (13:00)	27 °C (23:00)	10.0	0.01
GR	32 °C (14:00)	26 °C (23:00)	9.0	0.04

outer surface of the roof and, consequently contribute to increase the local urban warming.

Thereby the main advantage of the GR in comparison with TR_L is its capability to maintain lower external temperatures.

2.7.4 Assessment of Thermal Comfort

This section assesses the effect on the indoor thermal comfort conditions induced by the green roof in comparison with the other roof scenarios considered. The comparison has been performed using the temperature (T_{op}) calculated using Eq. (9).

Figure 2.11 shows the hourly profiles of T_{op} calculated for each scenario during three typical summer days, from 8 to 10 August.

Subsequently, considering the value of 26 °C as a setpoint of the operative temperature, the percentage of hours when T_{op} is higher than 26 °C has been carried out.

Table 2.7 reports, the maximum and the average values of the operative temperatures calculated for each scenario during the investigated period and and, the corresponding predicted mean vote (PMV) as well as the percentage of dissatisfied (PPD).

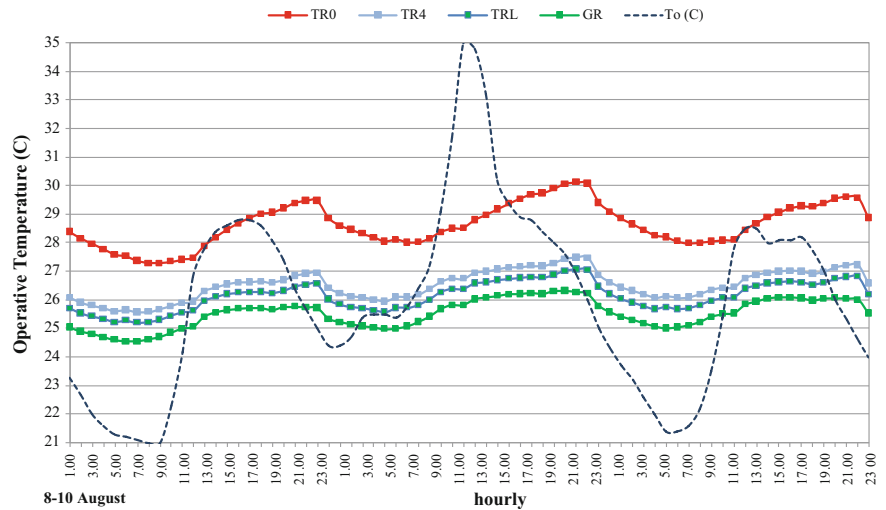


Fig. 2.11 Hourly profiles of the operative temperature

Table 2.7 Average operative temperatures (8–10 August)

Values	TR ₀	TR ₄	TR _L	GR
$T_{op,max}$ (°C)	30.13	27.50	27.08	26.33
PMV/PPD	1.59/56%	0.70/15%	0.56/12%	0.31/7%
$T_{op,av}$ (°C)	28.65	26.53	26.15	25.53
PMV/PPD	1.09/30%	0.38/8%	0.25/6%	0.04/5%
$T_{op,av} > 26$ °C	100%	83%	65%	26%

The PMV was calculated considering the following assumptions: air speed 0.1 m/s; humidity 50%; Metabolic rate 1.1 met; clothing rate 0.5 cloth [43]. Further, the percentage of hours when $T_{op} > 26$ °C is also shown.

It is quite evident that the scenario TR₀ involves the worst performances with thermal sensation between Slightly Warm and Warm when the average or the max values of T_{op} are used.

The intermediate and well-insulated scenarios provide thermal sensations of Slightly Warm or neutral in conjunction with the max or average values of T_{op} .

Otherwise the GR scenario leads to the better results, indeed the neutral thermal sensation is always guaranteed and it complies with ASHRAE Standard 55-2013.

Figure 2.12 shows in psychometric chart the comfort zone boundary and the thermodynamic state of the GR scenario with the $T_{op,av}$.

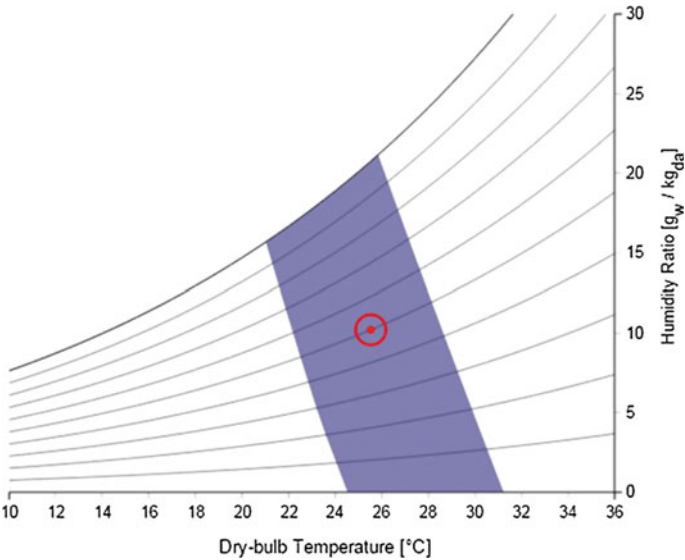


Fig. 2.12 Comfort zone and thermal comfort for GR scenario

2.8 Discussion

The results of this research are in accord with other literature studies that indicate an energy savings for building cooling of a nursery school in Hong Kong of about 75% [32], and of about 70% for a hospital building sites in Vicenza (Italy) [33]. Otherwise, an extensive green roof applied on a nursery school in Athens (Greece) provides a reduction of the building cooling load of about 50% [37].

The dynamic simulations also have proven the reduction of the absolute superficial temperature and their daily fluctuations from 20 to 6 °C, in comparison with the bare roof scenario. This result agree with the reduction of temperature fluctuations calculated by [42] and [44] which have found a temperature reduction from 18 to 6 °C.

The effect of the dynamic properties was investigated for a building sited in Floria-nopolis [14], which calculated a (TL) of about 10 h, that is really comparable with the (TL) of 9 h calculated in this study. The increase of the delay time is also confirmed by experimental study conducted [45].

2.9 Conclusions

The research presented in this paper, investigates the thermal and energy performance of an existing buildings on which it was applied an extensive green roof.

The thermal behavior of such building, has been investigated through dynamic simulations for assessing the energy needs, the variations of the superficial temperature and the indoor thermal comfort. Moreover, other two scenario that foresee the addition of two different thickness of thermal insulation, intermediate and well-insulated, have been investigated and compared with the green roof scenario.

The discussion of the results highlights that the green roof allows to obtain the highest energy saving in summer. The energy savings obtainable are of about 92% and 33% in the cooling and winter period, respect to the bare roofs. Generally, the GR scenario allows to obtain better performances in comparison with the bare roof (TR_0) and the averagely insulated roof (TR_4).

Instead the green and the well-insulated roof (TR_L) allow to achieve comparable energy savings, quite similar thermal inertia parameters, time lag and decrement factors, and to achieve good indoor thermal comfort.

The main advantage of the GR in comparison with TR_L is its capability to maintain lower external temperatures. Indeed differences of the peak values of the outdoor surface of 16 °C between these two scenario have been found.

The well-insulated roof reaches such high value of $T_{so,max}$ because the insulating layer stops the heat flux from the outdoor to indoor causing the overheating of the outer surface of the roof. Thereby, it is possible to highlight that well-insulated roofs allow to achieve substantial energy savings, but on the other hand they act as a catalyser that contribute to increase the local global warming.

As results, the lowest temperature on the external surface of the GR reduces the transmission of sensible heat flux from the building to the urban environment and, obviously contribute to mitigate the UHI effects. Therefore, the benefits of green roof as countermeasure for mitigating the UHI have to include the low outdoor surface temperature and the energy savings in summer period this last benefit reduces the heat discharged by the condenser of the AC plants in the crowded urban environment.

Thus, the energy efficiency improvements of existing buildings may be considered as part of a strategy to pursue and expand the scope of climate change adaptation measures.

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Smart Energy Control Systems for Sustainable Buildings

Littlewood, J.R.; Spataru, C.; Howlett, R.J.; Jain, L.C.

(Eds.)

2017, XVIII, 268 p. 117 illus., 98 illus. in color.,

Hardcover

ISBN: 978-3-319-52074-2