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The retrofit of existing buildings through the exploitation of the green roofs – a simulation study

Gagliano A.[a]*, Detommaso M.[a], Nocera F.[a], Patania F.[a], Aneli S.[a]

[a]*Department of Industrial Engineering, via A. Doria 6, Catania, 95125, Italy*

Abstract

Green roofs have several environmental benefits, such as improving building energy efficiency. As the existing Italy building stock was built before any roof insulation was required, the existing buildings will benefit most by the green roofs. The exploitation of a green roof for retrofitting of an existing house-holiday placed in the south part of Sicily was studied. The building energy performance and the dynamic thermal behavior of the green roof has been evaluated using a transient simulation program. The results of this study indicate a remarkable reduction both of the cooling and heating load respectively of about 80% and 34%. Dynamic simulations have proven essential that the typology of green roof investigated delays and attenuates the outdoor heat wave better of traditional roof diminishing the average daily temperature fluctuations. Therefore, the green roof shows a strong potential for the retrofit of not well-insulated building in Mediterranean area.

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Key words:green roof, thermal inertia, building simulation, energy consumption;

1. Introduction

In summer period improve the energy performance of the building roofs is fundamental, as the most common roof constructions are not able to sufficiently mitigate the effects of the solar radiation [1,2]. In this context, the green roofs represent an interesting technology to reduce the cooling loads both for new or existing buildings [3]. A green roof is a layered system comprising of a waterproofing membrane, growing medium and the vegetation layer. The layer of vegetation protects the roof from the direct solar radiation and cool it through the evaporation [4, 5]. Several studies have shown the positive effects of green roofs both on buildings and on the environment, such as: improving thermal comfort and reducing noise

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* Corresponding author. Tel.: + 39-320-433-2228; fax: +39-095-7382496
E-mail address: agagliano@dii.unict.it

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transmission into the building, improved water run-off quality [6,7,8], improved urban air quality [9], reducing the urban heat island effect by reducing “hot” surfaces facing the sky [10]. Several researchers [11, 12] has discussed the role of green roofs on limiting the Urban Heat Island effect. Green roofs have also been considered as a type of construction that could reduce the heating and cooling loads of buildings and act as a thermal buffer for buildings [13, 14]. The green roofs reduce the energy consumptions for air conditioning during the summer, because of the combined effect of shading and evapotranspiration [15]. With a green roof, the heat gain can be reduced by an average 70-90% in summer, and heat loss was reduced of 10-30% in winter [16]. The energetic benefit of a green roof is usually represented through the reduction of the outdoor surface temperature due both to the effect of vegetation and of the roof thermal transmittance [17]. The green roof, as well as the cool roof, has a greater positive energy balance than the traditional roof during all the year with the only exception of the months of middle season. Indeed, during spring and autumn season the thermal energy flux lost is higher than the traditional roof [18].They also reduce and delayed the outdoor surface temperature peak and keep the internal conditions within the comfort range [19,20]. The objective of this study is to evaluate the energy performance of an existing building placed in the south of Sicily on whose is applied a green roof. This analysis was conducted through dynamic simulations using the Design Builder software [21]. Moreover, it will be carry out the comparison of the thermal inertia factors between the conventional existing roofs (based on traditional techniques). The results obtained indicate the reduction of energy needs for air conditioning of buildings in Mediterranean climates.

2. Material and methods

Two types of green roofs are generally identified: extensive (with soil thickness less than 10 and 15 cm) and intensive (with soil thickness more than 15 and 20 cm) [22, 23].

Because of their low additional loads, extensive green roofs are suitable for building retrofitting, i.e. they do not require any additional strengthening [24]. Moreover, the vegetation layer of extensive green roofs will readily survive in European climates. The typical layers from the inside to the outside of extensive green roofs are: load-bearing slabs (roof deck), vapor barrier, insulation layer, roofing membrane, root barrier, drainage layer with/without aeration and storage water, filter layer, growing substrate/porous soil and vegetation layer.

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. Although different materials with different thermal features composed the support, it can be considered as a unique layer with constant thermal properties and a specific value of thermal conductance. The soil is a complex component because within it there are the solid phase (mineral and organic material), the liquid phase (water) and the gaseous phase (air and water vapor). The leaves and the air within the leaf cover compose the canopy. The characteristic parameters of canopy are height of plants (m), Leaf Area Index (LAI) that is the total one-sided area of leaf tissue per unit of ground surface area. ($m^2 \bullet m^{-2}$), minimum stomatal resistance, that governs the flow of water vapor through the stomates, emissivity, reflectivity, absorbance and transmissivity of the leaves.

The LAI characterizes the canopy–atmosphere interface, where most of the energy fluxes is exchanged [13]. The energy balance of the canopy is governed by radiative and convective thermal fluxes, evapotranspiration and evaporation/condensation of water vapor. The 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. The convective thermal fluxes occur between the leaves and the canopy air and between the soil surface and the canopy air. The evapotranspiration 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 evaporation/condensation of the water vapor from the soil surface and its convective transfer in the surrounding air [25]. 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 [26].

2.1. Mathematical model

The software DesignBuilder, which provides a graphical interface for the numerical code Energy Plus [27], was used to evaluate the dynamic thermal behavior of the green roof. A current advanced implementation of the green roof model developed by Frankenstein and Koenig called named "Fast All Season Soil Strength" (FASST) [28] is available in the Energy Plus program [28,29]. This computational model includes the energy balance for: moisture, soil and plant canopy, soil surface T_g and foliage T_f. This model evaluates the long and short wave radiation exchange within the canopy (multiple reflections, shading); effect of canopy on sensible heat exchange between the ambient air, the leaf and the soil surfaces; thermal and moisture transport in the growing media with moisture inputs from precipitation (and irrigation if desired); evaporation from the soil surface and transpiration from the vegetation canopy. The foliage (F_f) and the soil (F_g) energy balance are given by the following equations:

$$\mathrm{F_f} = \sigma_f\left[I_s^{\downarrow}(1-\alpha_f) + \varepsilon_f I_{IR}^{\downarrow} - \sigma\varepsilon_f T_f^4\right] + \frac{\sigma_f\varepsilon_f\varepsilon_g\sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right) + H_f + L_f \tag{1}$$

$$\mathrm{F_g} = (1-\sigma_f)\left[I_s^{\downarrow}(1-\alpha_g) + \varepsilon_g I_{IR}^{\downarrow} - \sigma\varepsilon_g T_g^4\right] - \frac{\sigma_f\varepsilon_f\varepsilon_g\sigma}{\varepsilon_1}\left(T_g^4 - T_f^4\right) + H_g + L_g + K\frac{dT_g}{dz} \tag{2}$$

where: ε_g and ε_f are the soil and foliage emissivity, T_g and T_f are the soil and foliage temperatures, H_g and H_f are the soil and foliage sensible heat flux; $I_s^{\downarrow}$ is the total incoming short wave radiation; $I_{IR}^{\downarrow}$ is the total incoming long wave radiation; L_g and L_f are the soil and the foliage latent heat flux; α_g and α_f are the soil and foliage short wave reflectivity, σ is the Boltzmann constant, σ_f is the density of the foliage.
The term ε_1 is given by:

$$\varepsilon_1 = \varepsilon_g + \varepsilon_f - \varepsilon_g \cdot \varepsilon_f \tag{3}$$

3. Case Study

3.1. Reference building

The reference building is a single floor residential building located in the marine fraction of Vittoria, Scoglitti, in the south coast of Sicily (lat. 36°53', long. 14°25'). This typology of building, characterized by the poor thermal insulation of the building envelope, is really representative of many holiday houses located in the south cost of Sicily. In particular, the thermophysical characteristics of the roof slab give the opportunity of upgrading its thermal behaviour introducing a green roof. 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 Gela city. Figure 2 shows the plant of the building and a view of the three-dimensional model, which has been created through the CAD tools in DesignBuilder .

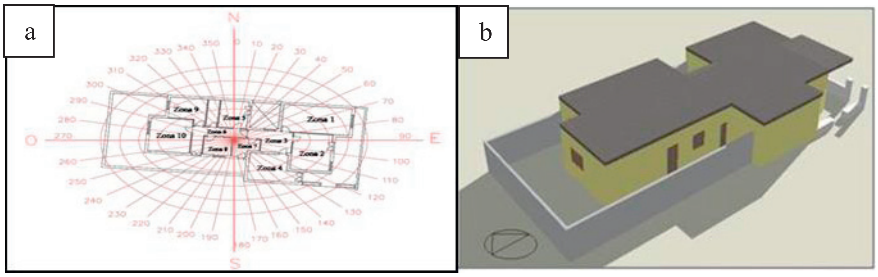

Figure 2. Simulated building (a) plant; (b) 3D view

The load-bearing structure is realized in reinforced concrete (RC).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 a overall thickness of 30 cm. Basic horizontal closure is composed by reinforced concrete slab and upper cement screed, it is coated with ceramic pavement. Windows are realized with wood frame and double glazing (s=3 mm) separated by an air gap (*s*=13 mm). The glasses have low-emissivity coating on the outer glazing (ε=0.2) and no coating on the inner glazing (ε=0.837) and a solar gain factor *g* of 0.74.The U-value of double glazing is 1.98 $W \cdot m^{-2} \cdot K^{-1}$, while the frame thermal transmittance is 3.63 $W \cdot m^{-2} \cdot K^{-1}$. The geometric feature and thermal transmittance of the building envelope components are reported in table 1.

Table 1. Thermal transmittance (U-value) and mass surface of building components (SM).

Geometric feature	Envelope component	U-value [$W\ m^{-2}K^{-1}$]	SM ($kg \cdot m^{-2}$)
Heated gross-volume (V) =513 m^3	*External walls*	1.27	*381*
Total external surface (S) =530 m^2	*Flat roof*	3.17	*571*
Shape factor (S/V) =1.03 m^{-1}	*Ground floor*	3.77	*474*
Net floor area($S_{n)}$=151.17 m^2	*Windows*	2.60	-
Roof Surface (Sr)= 151.17 m^2			

This building is characterized by a very high value of the ratio (Sr/S) that is of about 0.28.

3.2. Building energy model

As previously mentioned the study was carried out with the code Design Builder, that provides the graphical interface at numerical code Energy Plus. 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.)All the building rooms were considered occupied zones equipped with an air conditionig systems (ACs). That is an air conditioning system (chiller) that supplies both heating and cooling, with an average coefficient of performance COP=2.50. The conditioning system 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 summer period (June 1st –September 30th). As concerns internal gains, electric equipment and lighting: the average occupancy density is 0.04 $people \cdot m^{-2}$, 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 h^{-1}.

3.3. Energy needs at the current state

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

Tables 2 and 3 show the different typology of thermal fluxes: transmission through building envelope, external infiltration, internal and solar gains. Moreover, the total energy needs of the building during both the cooling and the heating period are shown. It necessary underline that, in according with the sign convention for thermal loads, negative sign indicates heat loss and positive sign indicates heat gains. For the energy needs the negative sign indicates that energy have to be extracted from the building and with the positive sign that energy have to be provided to the building. The total cooling loads are the sum of sensible cooling and latent loads.

Table 2. Building energy demand for cooling (June 1st-September 30th).

Thermal Fluxes (kWh)	June	July	August	September	Total
Transmission + Infiltration	-863	-455	-367	-703	-2388
Internal + Solar gains	1009	1025	1019	941	3993
Total cooling	-189	-847	-977	-382	-2395

Table 3. Building energy demand for heating (December 1st-March 31th).

Thermal Fluxes (kWh)	December	January	February	March	Total
Transmission + Infiltration	-3699	-3841	-3287	-2713	-13541
Internal + Solar gains	733	755	758	966	3211
Energy for heating	3018	3138	2574	1783	10512

The overall value of energy demand is 1550 kWh for the sensible cooling and 2395 kWh (15.84 kWh·m^{-2}) for total cooling, which include also the latent heat related to external infiltration and internal gains. As concerns the energy demand for heating, the overall value is 10512 kWh (69.54 kWh·m^{-2}), calculated through the energy balance between the heat loss and solar gains from the building envelope and the internal gains. It is interesting point out that the heating energy needs are higher than the cooling energy needs.

4. Building retrofit through a green roof

In order to evaluate the energy savings obtainable through the introduction of the green roof, further simulations have been carried out adding on the existing flat roof the typical layers of an extensive green roof described in the follows.

4.1. Description of the green roof

In this study an extensive green roof has been considered for the previous mentioned reasons and because it is particularly suitable to existing building structures.

The vegetation types used are mosses, sedum, graminaceous and succulents plants that are a very common and suitable plant for using on an extensive green roof. They are small plants that grow across the ground rather that upwards offering good coverage and roof membrane protection.

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, which filter the soil granules in order prevent that the empties of the drainage layer are filled. The thermo-physical properties of vegetation layer and substrate are reported in Table 4.

Table 4. Thermo-physical properties of the vegetation layer and substrate.

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

All the layers between the inner plaster and the filter layer are been considered as an unique solid layer with a conductance of 0.61 $W \cdot m^{-2} \cdot K^{-1}$. The U-value of this extensive green roof is 0.56 $W \cdot m^{-2} \cdot K^{-1}$ and the surface mass (SM) is 781 $kg \cdot m^{-2}$.

4.2. Energy needs after renovation

The calculations were carried out during the cooling period (June 1st to September 30th) and winter period (December 1st to March 31th). The results are shown in tables 5 and 6.

Table 5. Energy demand for cooling of building (June 1st-September 30th).

Building with Green roof	June	July	August	September	Total
Transmission + Infiltration	-979	-960	-900	-880	-3717
Internal + Solar gains	1014	1029	1022	944	4008
Total cooling	-44	-107	-207	-94	-452

Table 6. Building energy demand for heating in kWh (December 1st-March 31th).

Building with Green roof	December	January	February	March	Total
Transmission + Infiltration	-2526	-2701	-2425	-2328	-9980
Internal + Solar gains	733	754	758	966	3210
Energy for heating	1840	1993	1707	1394	6934

The overall value is 269 kWh for sensible cooling and 452 kWh (2.99 $kWh \cdot m^{-2}$) for total cooling. The application of green roof implies the reduction of the total cooling of about 80%. It is very interesting notice that the introduction of the green roof causes the decrease of the heat losses associated with the external infiltration and the increase of the heat losses (from the indoor to the outdoor environment) for transmission of about 50%. Globally, the heat losses from the indoor space to the outdoor environment increases thanks to the decrease (about 80%) of the incoming heat fluxes into the indoor space through the roof surface. Indeed, the green roof acts as passive cooling system as evidenced by the fact that throughout the hours of the day the heat fluxes were outgoing (negative values) [35].

The overall value of energy needs for heating is of 6934 kWh (45.86 kWh·m^{-2}). The heating demand is reduced of about 34% thanks to the significantly reduction of the thermal energy for transmission equal to the 45%. Again, the decrease of the energy needs is mainly due to reduction of the heat losses through the roof surface, which diminishes from 11,467 kWh to 7,899 kWh. Obviously, the high percentages of energy saving obtained are strictly connected with the large extension of the roof surface, which characterizes the reference building analysed.

4.3. Assessment of the thermal dynamic behavior of the green roof

As well known the energy performance of the buildings in cooling period depends strongly by the thermal inertia of the building envelope components. The two most important thermal inertia parameters, which characterize the dynamic behaviour of the building envelope, are the Time Lag (TL) and the Decrement Factor (DF). Therefore the hourly variations of the superficial temperatures have been calculated, for free running conditions, to determine (TL) and (DF) [30] both for the green and traditional roof. These superficial temperatures, calculated during a summer day (10 august), are shown in Figure 4.

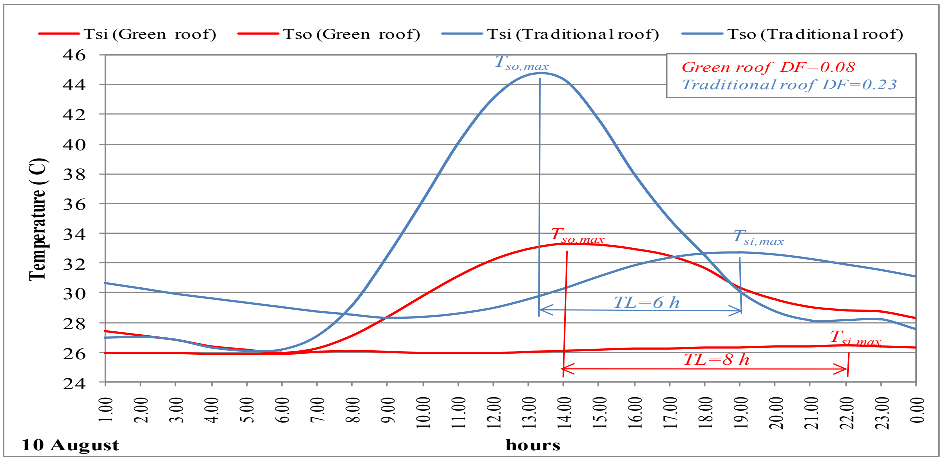

Figure 3. Hourly profiles of outer and inner surface temperature of the two roofs.

The blue lines depict the hourly variation of the outer surface temperature (T_{so}) and the inner surface temperature (T_{si}) of the existing roof, as well as the red line depicts the surface temperatures of the green roof. The traditional roof shows a wide fluctuation of its surface temperatures. The outdoor surface temperature reaches the peak value of about 45°C ($T_{so,max}$), at around 13:00 h, in phase with the maximum daily value of the solar radiation; while the inner surface temperature varies between the minimum value of 26 °C to the max value of 33 °C, which occurs at the 19:00. Thereby the TL of this traditional roof is about of 6 hours.

Instead, the green roof shows lower fluctuation of its superficial temperatures than the traditional roof. The outdoor surface temperature reaches the peak value of about 33,5°C ($T_{so,max}$), at around 14:00 h, which is 12 °C lower than the ($T_{so,max}$) of traditional roof. The inner surface temperature shows a very smooth fluctuation between the minimum value of 26 °C to the max value of 26,3 °C, which occurs at the 22:00. Thereby the TL of this green roof is of about 8 hours, and the (DF) is of about 0.08.

These good values of the thermal inertia factors are surely attributable to the characteristic of the green roofs components. The vegetation layer, which absorbs the solar radiation and exchanges latent and sensible heat by foliage. The soil layer, which contributes with both its thermal mass and the water content to absorb a large amount of heat and delaying the heat transfer from the outside to the inside. The calculated values (Tsi) are almost constant, of about of 26°C, therefore this results indicate the absence of overheating phenomena and favourable conditions of indoor thermal comfort. In addition, the thermal dynamic behavior of the green roof has been highlighted analyzing the variations of the superficial roof temperatures in free running conditions (without ACs).

Figure 4 shows the indoor T_{si} (Gr) and outdoor T_{so} (Gr) daily superficial temperature for the green as well as for the traditional roof T_{si} (Tr) and outdoor T_{so}(Tr), during the period (15st July-15th August).

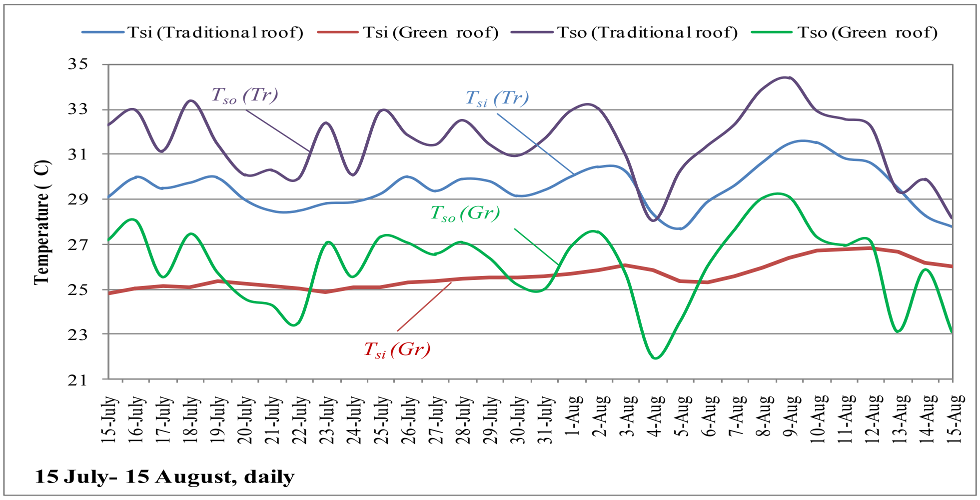

Figure 4. Daily profiles of outer and inner surface temperature of the traditional and green roof.

It is possible to notice that throughout the period investigated not only T_{so}(Gr) and T_{si}(Gr) are always lower than T_{so}(Tr) and T_{si}(Tr), but even T_{so}(Gr) is lower than T_{si}(Tr). The average monthly difference between T_{so} (Gr) and T_{so}(Tr) is of 5.44 °C, with a maximum daily value of 6.70 °C and a minimum of 3.99 °C . Instead the average monthly difference between T_{si}(Gr) and T_{si} (Tr) is 3.89 °C with a maximum daily value of 5.09 °C and a minimum of 1.74 °C.

Moreover, it can be observed the very smooth variation of T_{si}(Gr), that testify the ability of the green roof to attenuate and delay the cooling peak. These results indicates a very good thermal performance of the green roof, and also suggest the possibility to increase the passive cooling effect of the green roof exploiting the nocturnal ventilation to further reduce the cooling load of this building.

4.4. Discussion

The result of the simulations confirm the effectiveness of the green roofs in reducing the energy needs for both cooling and heating. Indeed the installation of the green roof system lead the reduction of building cooling load during the summer period of about 80%; the reduction of the heating load is of about 34%. These results 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% [31], and of about 70% for a hospital building sites in Vicenza (Italy) [32]. Otherwise, an extensive green roof applied on a nursery school in Athens (Greece) provides a reduction of the building cooling load of about 50% [33].

The high-energy savings calculated for this reference study confirm that the green roofs are more effective with non-insulated roof ($U < 1.4\ W \cdot m^{-2} \cdot K^{-1}$) [34]. The dynamic simulations also have proven the reduction of the absolute superficial temperature and their daily fluctuations from 12 °C to 6 °C.

This result agree with the reduction of temperature fluctuations calculated by [31] and [23] which have found a temperature reduction from 20 °C to 6 °C .

The effect of the dynamic properties was investigated for a building sited in Florianopolis [19], which calculated a TL of about 10 h, that is really comparable with the TL (8 h) calculated in this study. The increase of the delay time is also confirmed by experimental study conducted [35].

5. Conclusions

The research presented in this paper, mainly deals the energy performance of an existing house-holiday on which is applied an extensive green roof. Several dynamic simulations were performed through the Design Builder software to calculate the energy needs, evaluate the thermal behavior of the green roof, and determining its thermal inertia properties. The results highlight the significantly improvements of the energy performance of the building after the installation of the green roofs. In fact, a remarkable energy saving was achieved due to the reduction both of the cooling and heating load respectively of about 80 and 34%. Dynamic simulations have proven essential that the typology of green roof investigated delays and attenuates the outdoor heat wave better of traditional roof diminishing the average daily temperature fluctuations from 12 °C to 6 °C. Moreover, the thermal inertia properties are improved: the time lag is of about 8 h and the decrement factor is of about 0.08. The combination of these results highlights the ability of the roof to reduce the heat incoming during day, contributing to maintain comfort conditions inside the building. Globally the results of this study suggest that the use of green roofs could be highly recommended in the refurbishment of the existing buildings.

Further developments of the research foresee the evaluation of the performance of green roof, both in terms of energy savings and indoor thermal comfort, when it is combined with the nocturnal ventilation during the cooling period.

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