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Simulation of the thermal behaviour of a building retrofitted with a green roof: optimization of energy efficiency with reference to italian climatic zones

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Abstract

Running a building energy simulation program (EnergyPlus), simulations were conducted on a 'public housing' building type, in order to evaluate the energy savings achieved by a green roof coupled with different configurations of external wall. EnergyPlus enabled the investigation of the thermal behaviour variations of the building envelope, and the possible consequences, in terms of comfort, on the temperature of the internal spaces. The variation of the energy behaviour of the building envelope type was assessed primarily through the analysis of the operative temperature T° of the elements of surface casing, the trend of the surface heat fluxes on the faces of the elements of internal and external housing, the variation of the operating temperature inside the rooms. The energy savings achieved with a green roof varies considerably in relation to the reference performance obtained without this kind of insulating structure. The main parameters, useful to define the contribution of the green roof to the reduction of the loads of cooling plants, consist of the specific climate and the thermal isolation level of the initial coverage.

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Keywords: green roof; energy performance; energy plus; energy simulations; operative temperature.

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1. Introduction

In traditional building terms, roof is a top surface over an habitable area that protect inhabitants from unwanted weather elements and helps in maintaining comfortable indoor condition, protecting people and property from the sun, wind, rain and snow. In architectural terms, a roof can be sloped or flat but regardless of its configuration, both becomes extraordinarily hot in direct sun exposure, especially during the summertime. The variation in temperature of the roof surface can cover more that 70 degrees from morning till afternoon and this heat gain strongly affects the thermal comfort of the roof-space. The green roof design moved from this requirements in order to provide an efficient and sustainable solution to comfort problems as the indoor operative temperature variation during both summer and winter, the rainwater drainage and retention, and, at the urban scale, the CO_2 and PM absorption, the heat island effect mitigation and a sensible contribution to biodiversity and natural landscape. A green roof is not just a decorative element on the top-floor but is a technical system performing detailed functions and fulfilling certain requirements in a building, as stated by the national standard UNI 11235 (2007).

Therefore, even if green roof design has been primarily applied starting from XVIII and XIX century, in northern Europe regions, it has been recently developed in Mediterranean regions also, as a consistent technology to improve the thermal performances of the building without increasing energy costs, especial for the summer cooling.

Determining the contribution of a green roof to the indoor comfort and to the reduction of the conditioning loads during summertime is the main aim of this research work.

2. Green roof and energy savings

The potential energy savings due to the installation of a green roof vary considerably in relation to the reference performance that it refers to. A crucial parameters in defining the contribution of green roofs to reduce the HVAC loads mainly consist of the specific climate and the insulation level of the roofing type.

Most of the researches on green roof have been carried out in cold climates where green roofs primary spontaneously colonized rooftops but, in the last decade, an increasing amount of green roofs has been built especially in Mediterranean and dry climates (Werthmann, 2008).

The green roof is historically known for its ability to provide thermal insulation in cold climates, and to limit the overheating due to direct sunlight on roofing, in hot climates, as in Santamouris (2009).

More recently, many efforts have been made to quantify the contribution to energy efficiency of "green" technologies such as green roofs and green walls. Simulations based on both mathematical and real models made it possible, using quantitative parameters to calculate the thermal performance of these green envelopes and highlighting their contribution to thermal insulation and thermal inertia. These models also state and the interaction of plants with the local irradiation and mainly moisture and rainfall levels.

Therefore, with the different climatic context, the hydrological design and benefits of green roofs have to be reassessed. In regions characterized by water scarcity, innate conflicts between resource, conscious water management and green roof irrigation have to be evaluated.

3. Green Roof model in Energy Plus

As with a traditional roof, the energy balance of an green roof is dominated by radiative forcing from the sun. This solar radiation is balanced by sensible (convection) and latent (evaporative) heat flux from soil and plant surfaces combined with conduction of heat into the soil substrate.

A step forward, researches have integrate these mathematical calculation models in the most advanced building energy simulation software in order to assess the contribution of the green roof to the global performance of the building, in decreasing total heat flow and internal overheating and consequently reducing the yearly energy bill.

Currently, however, there are few design tools available to assist developers and architects in assessing the likely magnitude of energy savings associated with various implementation options.

The “Green Roof” module was introduced in EnergyPlus in 2007 and it allows user to monitor various characteristic parameters of a green roof, such as the Leaf Area Index (LAI), plant height, stomatal conductance (ability to transpire moisture), and soil moisture conditions (including irrigation).

The Green roof model simulates the heat transfer processes involved on a vegetated roof:

- long wave and short wave radiative exchange within the plant canopy,
- plant canopy effects on convective heat transfer,
- evapo-transpiration from the soil and plants, and
- heat conduction (and storage) in the soil layer

The green roof module accounts for long wave and short wave radiation incident on both soil and vegetative surfaces, evapo-transpiration effects, one dimensional conduction through and storage in the soil, and convection in the canopy-soil surface zone. It also allows for input of precipitation and irrigation schedules, tracking the resulting diurnal and seasonal variations in soil moisture.

4. Climatic database

The location of the building is a determining factor in calculating of the energy performance of the building in use and, consequently, in determining the potential impact on energy consumption due to the roofing system.

A quality climate database is needed for a proper sustainable building design because it strongly influences design strategies, thermal loads analysis and energy consumption. Different climate data has been used recently as a basis for assessing energy performances of buildings and how they operate when the climatic stress increases. Designing zero energy buildings, the consistency and representativeness of climate data become a crucial elements of a successful design, of both buildings and plants.

Unfortunately climatic databases are still scarce, incomplete and difficult to access.

The source of most complete information on Italian climate, is the Air Force Weather Archive, that contains both historical and real-time data but, these are rarely formatted to be directly imported into simulation tools.

So, in order to fulfil the objectives of this research, the weather file has been chosen from the EnergyPlus Weather database directly.

Considering the general aim of this research to assess the contribution of green roof in reducing energy loads in buildings in Mediterranean climate, the simulation have been carried out during the more stressed thermal period, that is in the summer (Runperiod: from June 1st to September 30th) when thermal mass and transpiration could offer a decisive contribution to reduce overheating in indoor space.

5. Reference building

Taking into account the recent indications of Directive 27 (2012) about the exemplar role played by public authorities in promoting energy savings in buildings, a social housing building has been chose as reference building for this study. According to EU Directive 31 (2010), institutions engaged in social, will have to adopt distinctive energy efficiency plans defining objectives and specific actions and the social housing stock, that mainly dates back to 50es and 60es, represents a primary area of application.

The reference building is located in Pisa and it is part of a large housing scheme built by the Civil Engineering Dept. starting from 1948 to face the housing emergency after the II World War.

The masonry building has 3 storeys and a basement, and houses six two-room flats (37.5 m^2) and six three-room flats (48.6 m^2)

Outer walls are made by hollow clay, the clay tiled pitched roof is bear by reinforced concrete beams

Rooms are properly oriented and sufficiently illuminated, but the building envelope (walls, window frames, floors) have heavy thermal losses that badly affect the building energy performance

Therefore, in order to assess the energy performance of the building at the steady state and evaluate the effective contribution of a green roof instead of a standard pitched roof, a medium-efficient building envelope has been designed as refurbishment. External insulation panels (8 cm thickness) has been added to external walls to solve thermal bridges increasing the thermal resistivity. A thermal and acoustic insulation as been added on both face of the internal walls; the inter-storey floor as been thermally and acoustically insulated as well. Windows have an aluminium frame with double argon glazing (6+13+12 type). Outdoor steel blinds operates during the hottest afternoon hours (2:00÷5:00 pm). Windows are considered ‘open’ during the night, to provide a proper ventilation rate (0.8 vol. h^{-1}) and a night free-cooling.

These building elements are invariant in the simulations, therefore only roof floor changes. The simulation have been carried out for the roof-space thermal zone only and not for lower storeys.

Rainfall data in Pisa from 2008 to 2013 have been collected from a local database (Pisameteo), and added to the Energy Plus climatic records. Information about monthly rainfalls during June, July, August and September have been included in the "Roof Irrigation" schedule in EnergyPlus, in order to simulate a natural precipitation (52.6 mm in June, 37.7 mm in July, 36.4 mm in August, and 58.6 mm in September). This correspond to ~0.44 mm h^{-1}, four hour per day in the irrigation schedule.

6. The green roof model

The reference building has a traditional pitched roof with clay roof tiles on a ventilated air cavity (60 mm), an EPS (80 mm) insulation layer on a hollow-core concrete floor.

Seven different types of green floor has been designed in order to assess their energy performances in comparison to the pitched roof, three extensive green roofs and four intensive green roofs. One of the green roof characteristics has been changed per type, in order to evaluate the single contribution of each parameter to the operative temperature variations. A comprehensive and detailed description of the green roof types is in **Errore. L'origine riferimento non è stata trovata.**.

Table 1. Description of the 7 different green roof types that have been simulated.

Model A	Model B	Model C	Model D	Model E	Model F	Model G
extensive irrigated	extensive irrigated	extensive irrigated	intensive irrigated	intensive irrigated	intensive irrigated	intensive irrigated
Plant height 150 mm	Plant height 150 mm	Plant height 150 mm	Plant height 300 mm	Plant height 300 mm	Plant height 300 mm	Plant height 30 0mm
LAI 1	LAI 5	LAI 1	LAI 2	LAI 5	LAI 2	LAI 2
Medium 80 mm	Medium 80 mm	Medium 80 mm	Medium 200 mm	Medium 200 mm	Medium 200 mm	Medium 300 mm
Insulated 80 mm EPS	Insulated 80 mm EPS	Not insulated	Insulated 80 mm EPS	Insulated 80 mm EPS	Not insulated	Insulated 80 mm EPS

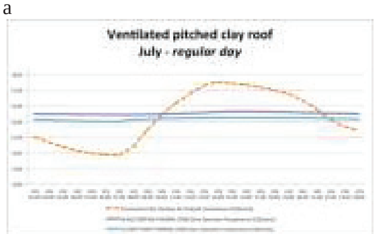
7. Results

Wong et al. (2009) and other researchers reported a difference of the surface temperature between a green roof and a pitched roof around 20°C, or even more during the day, that progressively decreases during the night when green roof temperature is generally 1÷2°C higher because of the thermal inertial and the leaf area that reduce heat losses to the night sky.

Simulation results confirm literature data and in Pisa the simulation shows a maximum surface temperature difference over 25°C during the day in June, and an average of 18° during July-September. During the night, green roof solutions are 2°C hotter, on average. Results in the following figures are expressed per regular day:

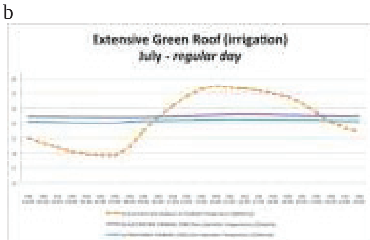
hourly temperatures during the regular day have been calculated as average of the monthly temperature within each hour. The night free cooling generally assures a 1°C decrease of the operative temperature, as results from the comparison of T° trend in the roof-space and stair thermal zones (Fig.1).

a



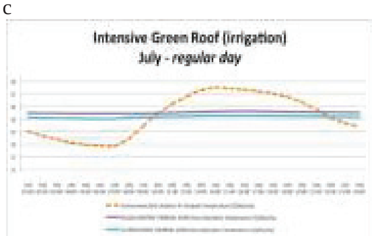
$T°_{med}$ 23.36 $T°_{min}$ 23.01 $T°_{max}$ 23.49

b



$T°_{med}$ 22.60 $T°_{min}$ 22.23 $T°_{max}$22.85

c



$T°_{med}$ 22.21 $T°_{min}$ 21.85 $T°_{max}$ 22.45

Fig. 1. Operative temperature in both the roof-space and stairs Thermal Zones compared with the outdoor air temperature during July; a) Ventilated pitch clay roof; b) Extensive green roof; c) Intensive green roof. Statistical values are reported for the roof-space zone.

Table 2 reports the statistical values of the operative temperature in the roof-space thermal zone.

Table 2. Operative temperature in the roof-space Thermal Zone.

Roof type	Operative Temperature T° $_{med}$	Operative Temperature T° $_{min}$	Operative Temperature T° $_{max}$	Month
Ventilated pitch clay roof	21.68	21.26	21.83	June
Extensive green roof	21.04	20.61	21.33	
Intensive green roof	20.71	20.29	20.99	
Ventilated pitch clay roof	23.36	23.01	23.49	July
Extensive green roof	22.60	22.23	22.85	
Intensive green roof	22.21	21.85	22.45	
Ventilated pitch clay roof	23.52	23.62	23.52	August
Extensive green roof	22.85	23.21	23.67	
Intensive green roof	22.50	22.18	22.74	
Ventilated pitch clay roof	21.65	21.25	21.80	September
Extensive green roof	21.01	20.59	21.30	
Intensive green roof	20.73	20.32	20.32	

8. Heat transfer

Wong et al. (2003) calculated a potential reduction of 60% of heat flux during the summer period, comparing a low insulated flat roof to green roofs. They concluded that the green roof works as an high performing insulation layer because during the most stressing thermal period, therefore the hottest daytime hours, the heat flux reverses its direction and the extra heat is absorbed by the thermal mass of the green roof and then subtracted from the room, avoiding overheating.

But, when the base of the comparison is a well insulated pitched roof, these potential benefits are strongly reduced and benefits of having a green roof are less intense. Results of the present research have demonstrated a notable reduction of the heat flux, on both directions, that are more relevant in cold climate that in hot climate.

9. Operative temperature

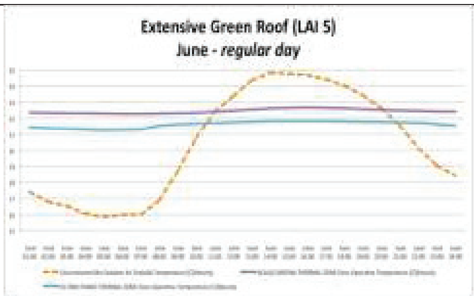
Despite Niachou et al. (2001) demonstrated a 2°C reduction of the operative temperature in the room under the green roof compared to the temperature in a flat roof-space, results of the present simulations have validate a little less sensible decrease:

in general, during the summer season (winter performances have been not investigated) average T° is reduced by 0.6°C÷1°C because of the extensive or intensive green roof respectively (data not shown for June, August, and September). Performance of the green roofs improves during the hottest days, and in July, it is 10÷12% better, especially as regards the minimum temperature. It should be noted that the daily temperature range in Pisa is not so relevant and it is around 9°C (Fig. 1).

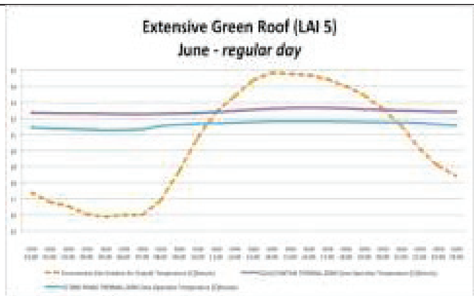
Energy savings, and consequently cost savings, due to the green roof are supposed to rise up when the growing medium thickness, or the LAI value, increases as well. In fact, results have shown just a low benefit:

when the LAI has been enhanced to 5 (LAI from 1 to 5 for the extensive green roof, see Fig. 2 letters a);c);e); LAI from 2 to 5 for the intensive green roof, see Fig. 2 letters b);d);f)), temperatures fall 1°C÷1.20°C down, and when the substrate depth of the intensive green roof has been upgraded to 300 mm, temperatures fall about 1°C down, compared to the pitched roof (**Errore. L'origine riferimento non è stata trovata.**Table 3).

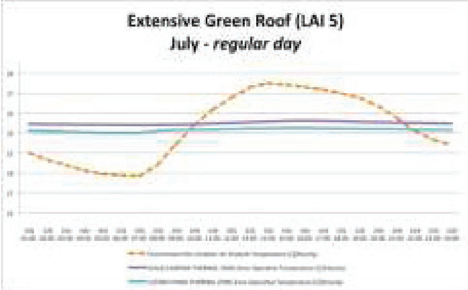
It has to be also remarked that, when solar irradiation is extremely intense as in the Mediterranean climate, a very extensive leaf area limits the long wave radiation of the stored heat back to the sky during the night time. Therefore, the cooling benefit is reduced, especially if no night free cooling strategies are applied. Moreover, because no heavy irrigation was provided to both green roofs, the transpiration process offers just a small contribution to the heat dissipation.Regarding the thermal capacity of the extra thiknees of the medium, due to the reverse thermal flow during the nighttime, an overdepth of the medium could be not performing at best in hot climates.



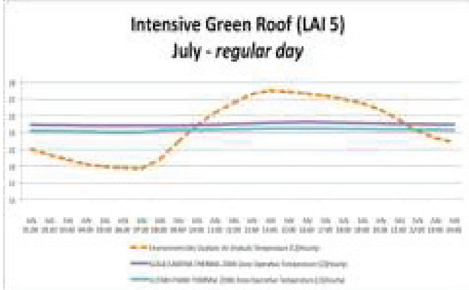
a
T°$_{med}$ 20.64 T°$_{min}$ 20.23 T°$_{max}$ 20.92



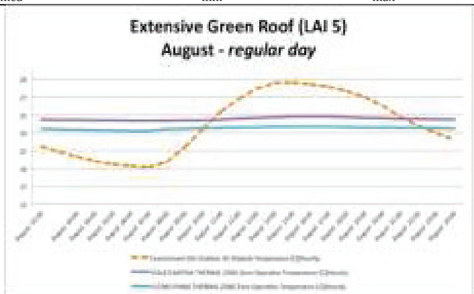
b
T°$_{med}$ 20.50 T°$_{min}$ 20.10 T°$_{max}$ 20.78



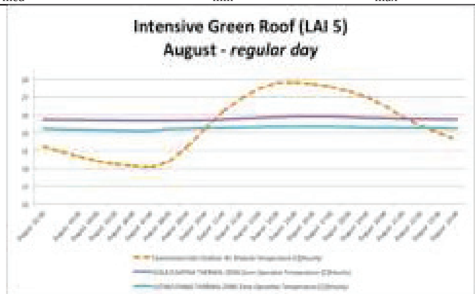
c
T°$_{med}$ 22.21 T°$_{min}$ 21.85 T°$_{max}$ 22.45



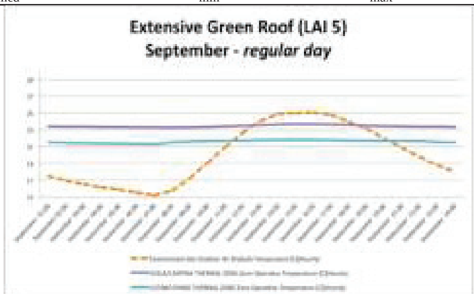
d
T°$_{med}$ 22.02 T°$_{min}$ 21.68 T°$_{max}$ 22.26



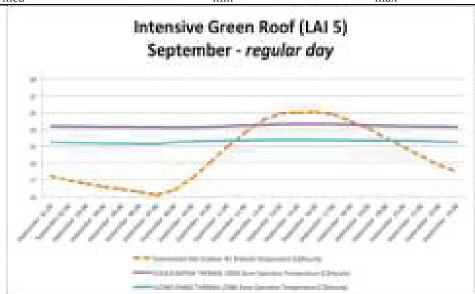
e
T°$_{med}$ 22.50 T°$_{min}$ 22.18 T°$_{max}$ 22.74



f
T°$_{med}$ 22.34 T°$_{min}$ 22.03 T°$_{max}$ 22.58



g
T°$_{med}$ 20.64 T°$_{min}$ 20.24 T°$_{max}$ 20.91



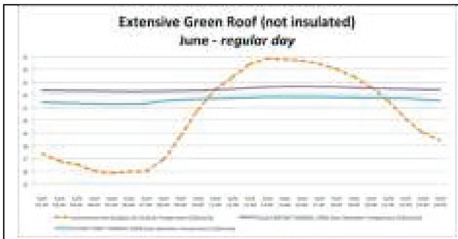
h
T°$_{med}$ 20.57 T°$_{min}$ 20.17 T°$_{max}$ 20.84

Fig. 2. Operative Temperature T° variations between extensive and intensive green roof when LAI increases to 5, for each month. a);c);e) extensive green roof; b);d);f) intensive green roofs. Operative Temperature T° variation between

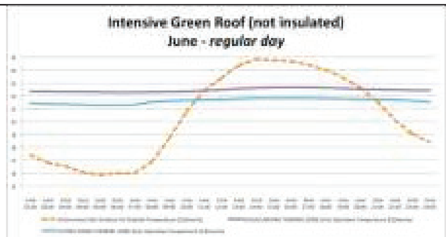
Table 3. Operative temperature under the clay roof and under the intensive green-roof with a 300 mm layer-depth of the substrate.

Statistical values	Operative Temperature T°	Clay roof T°	Intensive greenroof heavy soil T°	ΔT° difference	Month
$T°_{med}$	20.46	21.68	20.62	1.06°C	June
$T°_{min}$	15.86	21.26	20.21	1.05°C	
$T°_{max}$	24.83	21.83	20.90	0.93°C	
$T°_{med}$	23.49	23.36	22.09	1.27°C	July
$T°_{min}$	18.67	23.01	21.74	1.27°C	
$T°_{max}$	28.02	23.49	22.33	1.16°C	
$T°_{med}$	23.62	23.52	22.42	1.10°C	August
$T°_{min}$	19.14	23.21	22.10	1.11°C	
$T°_{max}$	28.63	23.67	22.65	1.01°C	
$T°_{med}$	19.41	21.65	20.70	0.95°C	September
$T°_{min}$	15.22	21.25	20.30	0.95°C	
$T°_{max}$	25.05	21.8	20.98	0.82°C	

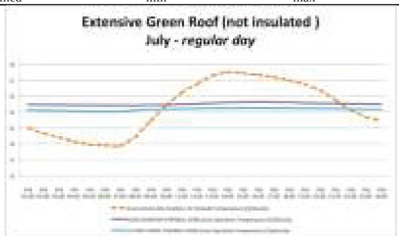
On the contrary, results have demonstrate a sensible influence of the insulation layers to the global performances of the green roof even during the summertime. Temperatures in the green roof-spaces when the insulation layer is removed are 0.25°C÷1.65°C higher compared to the insulated pitched roof (Fig. 3). This is in line with results coming out from several other researches (Fantozzi et al., 2013) that enhanced the relevance of an alternate sequence of layers with a resistivity and heat capacity characteristic in improving the dynamic performance of a building during the summertime.



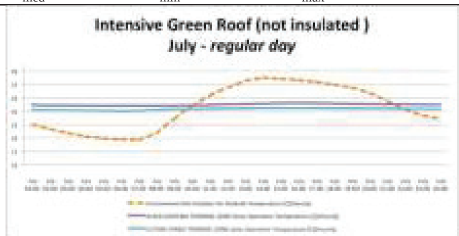
a
$T°_{med}$ 23.14 $T°_{min}$ 22.63 $T°_{max}$ 23.46



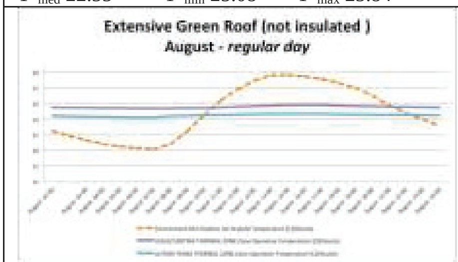
b
$T°_{med}$ 21.78 $T°_{min}$ 21.29 $T°_{max}$ 22.11



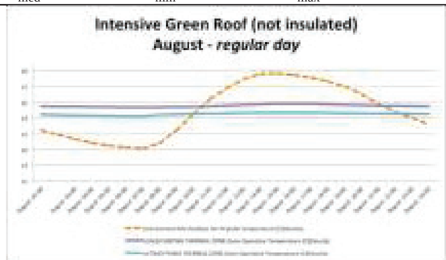
c
$T°_{med}$ 22.55 $T°_{min}$ 25.08 $T°_{max}$ 25.84



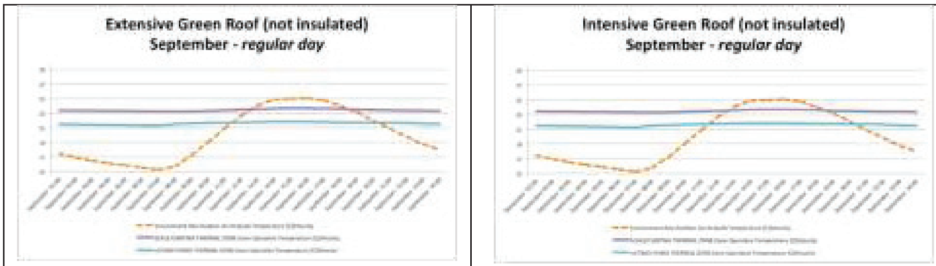
d
$T°_{med}$ 24.00 $T°_{min}$ 23.54 $T°_{max}$ 24.30



e
$T°_{med}$ 25.45 $T°_{min}$ 25.01 $T°_{max}$ 25.72



f
$T°_{med}$ 24.11 $T°_{min}$ 23.69 $T°_{max}$ 24.40



g	h
$T°_{med}$ 22.62 $T°_{min}$ 22.16 $T°_{max}$ 22.92	$T°_{med}$ 21.98 $T°_{min}$ 22.121 $T°_{max}$ 21.66

Fig. 3. Operative Temperature T° variations during each month without insulation layer, LAI =5 . a);c);e);g) extensive green roof; b);d);f);h) intensive green roofs.

10. Conclusions

Results of the present work confirm what Kokogiannakis et al. (2012) already stated, that is buildings that hare insulated according to the most recent and restrictive energy regulations, get moderate benefits from green roofing, relative to an insulated pitched roof.

The “Roof Vegetation” and “Roof Irrigation” modules in EnergyPlus software, are quite detailed and require a certain number of data to perform the simulation at best. Therefore, reliability of the results is strongly affected by the quality of the input parameters and especially of those refer to the growing medium and the vegetable species that have been used. These parameters are influencing the complex algorithm that runs to calculate the processes of convective and sensible heat transfer, longwave radiation absorption, evaporation, transpiration, water infiltration. Even if the heat released or gained due to phase changes of soil water, precipitation heat flux and heat flux due to vertical transport of water in the soil are ignored by the equation right now, the energy balance at the soil surface is mainly influenced by the soil thermal properties, (in addition to the amount of foliage coverage and the amount of moisture in the soil) and these information vary a lot from product to product but they are generally confidential and not easily available on the technical information sheets provided by green roof companies.

Because of the specific research requirements, simulations haven’t considered internal gains due to people or equipment and the thermal influence of any heating/air conditioning plant. To properly describe the performances of a green roof under real operating conditions, these contributions have to be measured.

Measuring the dynamic building reaction to different types of heating/cooling systems (radiant, convective air/water) could be as much interesting, in order to enhance potential high efficient pair to reduce the total energy cost.

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The data processing and the editorial work must be shared, within the competencies of the research groups, equivalently among the Authors.

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