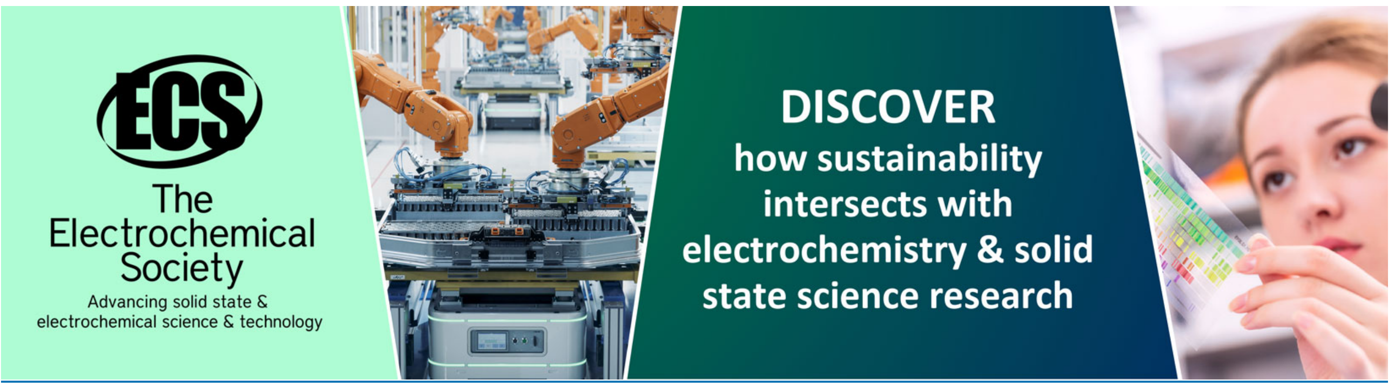
Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Mitigating the cooling need and improvement of indoor conditions in Mediterranean educational buildings, by means of green roofs. Results of a case study



Journal of Physics: Conference Series **655** (2015) 012027 doi:10.1088/1742-6596/655/1/012027

Mitigating the cooling need and improvement of indoor conditions in Mediterranean educational buildings, by means of green roofs. Results of a case study

F Ascione[1], N Bianco1, R F De Masi[2*], F de Rossi[2], G P Vanoli[2]
[1] Università degli Studi di Napoli Federico II, DII – Dipartimento di Ingegneria Industriale, Piazzale Tecchio 80, 80125 Napoli, Italy
[2] Università degli Studi del Sannio, DING – Dipartimento di Ingegneria Industriale, Piazza Roma 21, 82100, Benevento, Italy

*E-mail: rfdemasi@unisannio.it

Abstract. Indoor overheating risk and increased energy demand for cooling are becoming more and more frequent in the building sector of the Mediterranean area. In detail, for the reduction of the energy consumption of educational buildings, characterized by high endogenous gains, the particular boundary conditions affecting their use should be taken in consideration, and thus schedules of occupancy, wide necessity of air-changes for air quality. This paper, with reference to a case study, proposes deep investigations aimed at optimizing the annual energy performance of an educational building of the University of Sannio, located in the Southern Italy. A numerical model of the building has been designed and validated according to monitored data. Starting from the present scenario, after a complete refurbishment of the building envelope, the potentialities of several typologies of green roofs - by considering also the implementation of the adaptive approach in the comfort standard - have been tested. The scope is the optimization of the energy demand for the annual microclimatic control, by avoiding an energy-intensive operation of the air-conditioning devices during the warm season.

1. Introduction

Inappropriate design of buildings, combined with the heat island effect in dense urban areas, as well as the global warming and the necessity of improvement of living standards, have led to an increase (around 46%) of buildings with air-conditioning systems [1]. In the last decennia, peak loads are moving from winter to summer and it implied criticalities for the electricity grids, with increasing costs of energy. For this reason, priority should be given to strategies which enhance the thermal performance of buildings during the summer period, by encouraging, especially, an energy-oriented refurbishment of the existing stock.

Several studies have shown the positive effects of innovative technologies as cool material, cool roofing system and integration of phase change materials (PCM) in different envelope elements. Cool roofs represent an innovative and relatively inexpensive technique proper for reducing the building cooling energy requirements and for improving the indoor thermal comfort conditions. These applications primarily consist of high-reflectance and high-emissivity coatings or membranes, largely investigated, in recent studies, by Cotana *et al.* [2-4]. On the other hand, PCMs are widely investigated technologies and there is a fast developing research area concerning these. Pomianowski *et al.* [5]

have presented a review of PCM technologies developed to serve the building industry. Recently, different solutions have been investigated to increase the efficiency of PCM integration, in terms of improvement of indoor thermal comfort and reduction of energy consumption for cooling [6-8].
Also green roofing systems have shown good potentialities in terms of reduction of the air-conditioning requests, improvement of comfort sensation in the outdoor and indoor environment, better sound insulation and urban water management [9-12]. However, high construction and maintenance costs often do not allow to justify their economic feasibility [13], that is strictly influenced by the chosen type of plants, specific climatic conditions and characteristics of the buildings [14, 15]. Moreover, the coupling with traditional energy efficiency measures should be taken into account for a global optimization of the annual performances.
Here, the main motivations of this paper: it discusses the optimization of the annual energy performance of an educational building in the South Italy. After a complete refurbishment of the building envelope, several typologies of green roof have been tested. After the description of the case study and calibration of the building numerical model, the proposed study consists of three main phases:

a) evaluation of "traditional" insulation measures for the building envelope;
b) energy and environmental analysis of three green roof typologies and economic profitability;
c) assessment overheating risk and indoor thermal conditions according to adaptive approach.

2. The case study: an educational building in Mediterranean climate

The investigated building is located just close to the ancient center of Benevento, a southern Italian city with moderate Mediterranean climate. It is an educational building hosting offices and classrooms of the Economics of the University of Sannio. All the information necessary for the building performance assessment have been obtained through in-situ surveys, interviews with managers and occupants, in-field measurements. In order to simulate the real energy performances, hourly simulations, by means of EnergyPlus [16], have been performed according to procedures of "tailored ratings" [17]. In this section, audit procedure aimed at the numerical modeling are described.

2.1. Building simulation energy modeling

The building (figure 1) has a quite rectangular shape, being placed on a sloped area, so that the articulation of volumes provides a large amount of sun- and wind- exposed roof. It has a global elevation of about 17 m, with four usable floors above the ground. The net conditioned building area is equal to 4'707 m^2. The "surface to volume ratio" (S/V) is equal to 0.41 m^{-1}.

Figure 1. The investigated building of University of Sannio

2.1.1. Characterization of building uses and definition of thermal zones

The numerical model has been defined by combining all detected information about occupancy schedules and installed equipment. A typological floor is shown figure 2. Some areas of the basement are presently interested by renovations; however some classrooms (figure 2a) and a bar/lunch area are already operative. The ground and second floors host mainly classrooms, libraries and offices for teachers. At the first floor, there are mostly offices, a conference room and some laboratories. In the modeling phase, even if diversified depending on the room use, the average air change rate has been defined around 1.5 AHC, for guaranteeing the required comfort conditions established by the standard UNI EN 15251 [18]. In every space, an additional air change rate equal to 0.5 ACH has been considered too, because of the lack of air-tightness.

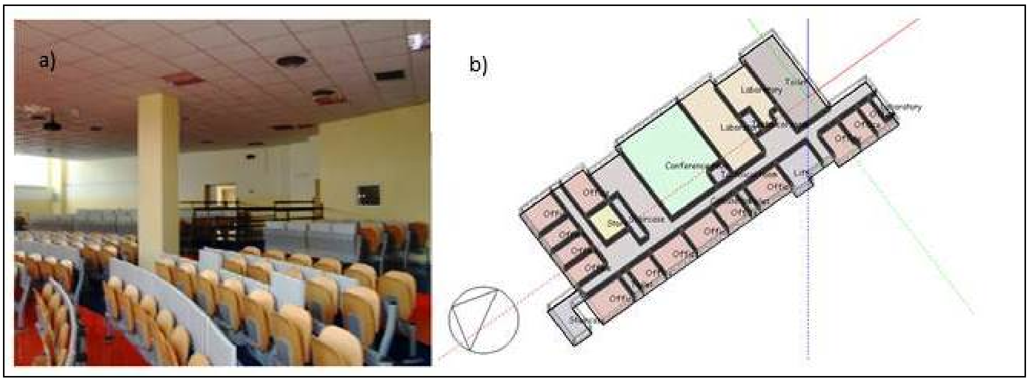


Figure 2. Thermal zones: a) classroom at basement floor; b) geometrical model of 1st floor

2.1.2. Building envelope and technical plant audit

By means of the audit of the building envelope, it is known that the building has a reinforced concrete structure with insulated external walls. The average wall thickness is 0.25 m and the reliable thermal transmittance (U_{wl}) of the vertical wall is 0.55 $W \cdot m^{-2} \cdot K^{-1}$. Ceiling, basement and roofs have mixed structures, given by the parallel presence of concrete beams, joists and interposed hollow bricks, with insulating layers (i.e., 3.0 cm of expanded polystyrene). The thermal transmittance is around 0.76 $W \cdot m^{-2} \cdot K^{-1}$. The window-wall ratio is 27%, with double glazed systems, air filling, aluminum frame and external shading. The evaluated U_W is 2.7 $W \cdot m^{-2} \cdot K^{-1}$. Table 1 summarizes the building HVAC system.

Table 1: Thermal zones and HVAC system

	Thermal zones	HVAC System	Generation system
Basement floor	Education activities	Mixed air/water system	Condensing gas boiler (P_n=388 kW_{th}) Air-cooled chiller (P_n=406 kW_{th}).
	Bar/ dining hall	Autonomous direct expansion systems	Various installed power
I, II and ground floor	Classrooms and offices	Hydronic air-conditioning systems	Air-cooled electric heat pump: heating: P_n= 91.2 kW cooling P_n= 85.5 kW

According to the Italian law, the heating system is turned on from 16th November to 31st March and the building is heated at 20 °C from 8.00 am to 6.00 pm, from Monday to Friday. The cooling set-point is at 26 °C, between 10.00 am and 6.00 pm, also in this case from Monday to Friday, from 1st June - 30th September. A fluorescent lighting system is installed in the whole building.

2.2. Calibration of energy model

The output of simulations have been compared with the billing data of the last five years, according to the "Whole Building Level Calibration with Monthly Data" approach proposed by M&V Guideline [19]. According to this, a model can be declared to be calibrated if:

- ✓ the ERR_{year} (error in the annual energy consumption) is within ±10%;
- ✓ the coefficient of variation of the root mean squared error $CV(RMSE_{month})$ is within ±10%;
- ✓ the mean bias errors (MBE) is within ±5%.

Table 2 shows the evaluated indexes separately for the space heating (E_H) and the electric energy demand for all building uses (E_{el}). A satisfactory convergence is quite evident according to the literature indications, so that the energy model can be considered as well-calibrated. According to the numerical model, by assuming a conventional lower calorific value of natural gas equal to 9.59 kWh/m^3 and by considering the electric efficiency of the Italian system as equal to 0.42 [16], the calculated specific heating demand, in terms of primary energy, is around 32 kWh/m^2, including the energy demand of auxiliaries. Moreover, with reference to the annual electric demand only for the space cooling, the annual primary is equal to 22 kWh/m^2.

Table 2: Calibration indexes evaluation

ERR_{year}		MBE		$CV(RMSE_{month})$	
E_H	E_{el}	E_H	E_{el}	E_H	E_{el}
1.5%	1.5%	2.1%	2.6%	3.7%	10%

3. Optimization of educational building refurbishment

According to the authors, the optimization of refurbishment design should consider at least four issues:

- annual primary energy saving;
- avoided polluting emissions;
- indoor comfort conditions;
- effectiveness under the point of view of the economic feasibility.

These points will be investigated for the proposed case study. More in detail, the annual primary energy saving (DEP expresses in % or kWh/year) will be referred only to the space heating and cooling. With reference to the the avoided emissions of equivalent carbon dioxide (ΔCO_2), the LCA (Life Cycle Assessment) emission factors have been adopted, by assuming for the request of natural gas and electricity respectively 0.237 $tCO_{2\text{-}eq}$/MWh and 0.708 $tCO_{2\text{-}eq}$/MWh [20]. About economic indicators, the discounted pay-back times (SPBs) of efficiency measures and their Net Present Values (NPVs, considering a lifetime equal to 20 years) will be taken into account. Common prices have been assumed for electricity and gas, respectively equal to 0.25 €/kWh$_{el}$ and 0.90 €/m^3 [21].
In order to assess the quality of thermal environments, the discomfort levels have been properly estimated, according to both conventional and adaptive approaches. Thus, firstly the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) have been adopted according to [22-23]. Furthermore, the effect of a less restrictive standard concerning the indoor operative temperature levels has been evaluated. In this regard, several studies underlined that the coupling of adaptive approach and adoption of passive cooling strategies can allow lower cooling consumptions [24].

3.1. Traditional energy saving measures

Presently, the building envelope does not allow levels of thermal resistance completely proper for reducing the energy demand for heating. For this reason, as first step, a complete refurbishment of the building envelope has been studied as summarized in table 3.

Table 3: Interventions and adopted nomenclature

	Technical specification	Nomenclature	C_I [€]
Insulation of the wall (3 cm EPS)	$U_{wl} = 0.37\ W{\cdot}m^{-2}{\cdot}K^{-1}$	[IW]	78’060
Insulation of roof slab (9 cm EPS)	$U_r = 0.29\ W{\cdot}m^{-2}{\cdot}K^{-1}$	[IR9]	74’040
Insulation of roof slab (6 cm EPS)	$U_r = 0.33\ W{\cdot}m^{-2}{\cdot}K^{-1}$	[IR6]	62’934
Low-E glazing (4/16/6 - Argon)	$U_w = 2.20\ W{\cdot}m^{-2}{\cdot}K^{-1}$	[LE]	319’475

Figure 3 shows the expected results. First, the application of 9.0 cm of expanded polystyrene could reduce the heating demand of 9.3% and thus the annual energy demand can be decreased around 6%, meanwhile the polluting emissions of about 5.3%. The reduction of the operational cost is around 1’498 €/year and the DPB (assuming 3% as discounting rate) is greater than 15 years. Conversely, by coupling roof and wall insulations, the annual energy savings and the avoided emissions are around 6% for the solution IW_IR6 and 7% for the second package of energy efficiency measures (EEMs) with wall insulation and the application of 9.0 cm of insulation material for the roof. In both cases, the operational costs are reduced of around 7%.

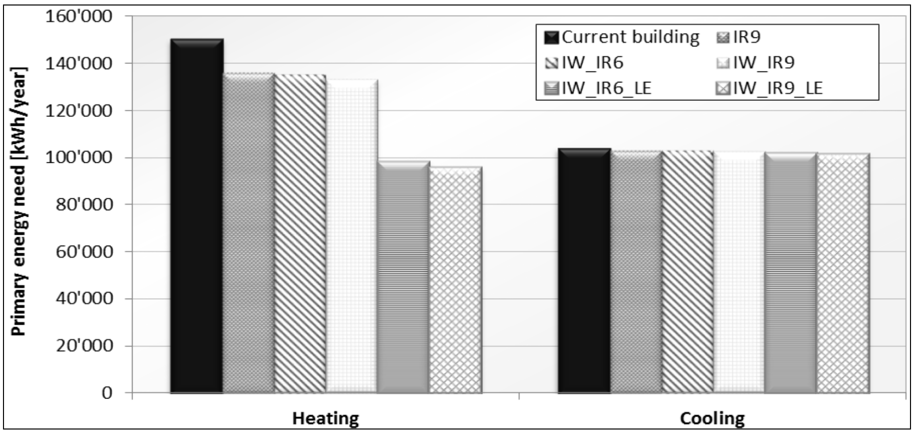


Figure 3. Effect of different refurbishment measures in terms of annual primary energy need

Finally, the previous refurbishment configurations have been coupled with the adoption of low-emissive windows. The overall achievable annual saving is around 21% and 22% when, respectively, 6.0 cm and 9.0 cm are considered for the thickness of the roof insulation. The energy saving implies avoided CO_2 equivalent emissions of about 15.0 tons for the solution IW_IR9_LE and of 14.4 tons for IW_IR6_LE. The operational costs for both configurations are reduced of about 20%. However, the discounted paybacks are always higher than 20 years.
All told, good results can be achieved in terms of energy efficiency and environmental effect. The operational costs can be reduced and it is important for building management. However, the paybacks are quite high and probably suitable incentives’ policies are required for making the retrofit feasible.

3.2. Configuration of simulated green roofs

For the case study here analyzed, three configurations of green roofs have been considered:

- HL-LR means High LAI and Low Stomatal Resistance;
- ML-MR means Mean LAI and Mean Stomatal Resistance;
- LL-HR means Low LAI and High Stomatal Resistance.

Each kind of green roof has been considered as equipped with a layer of 12 cm of polystyrene (3 cm already installed + 9 cm of added insulation during the refurbishment), placed just below the drainage layer. Table 4 shows the main characteristics and the unitary installation costs without considering the cost of insulation for the three simulated configuration.
For the building here investigated, considering the roof surface of the second floor, the area potentially suitable for installation of green roof is of 950 m^2.
Each kind of green roof has been considered as equipped with a layer of 12 cm of polystyrene (3 cm already installed + 9 cm of added insulation during the refurbishment), placed just below the drainage layer. Table 4 shows the main characteristics and the unitary installation costs without considering the cost of insulation for the three simulated configuration.

Table 4. Main characteristics of the vegetation modeled on the roofs

	Dimension	LL-HR	ML-MR	HL-LR
Height of plants [m]	[m]	0.1	0.25	0.40
Leaf Area Index (LAI) [m^2/m^2]	[m^2/m^2]	0.8	2.0	3.5
Leaf Reflectivity [-]	[-]	0.3	0.4	0.5
Leaf Emissivity [-]	[-]	0.95	0.95	0.95
Density of Dry Soil [kg/m^3]	[m^2/m^2]	700	1 100	1 000
Thickness of the Soil [m]	[m]	0.10	0.14	0.18
Minimum Stomatal Resistance	(s/m)	300	200	120
Saturation Volumetric Moisture Content of the soil	(-)	0.40	0.40	0.40
Residual Volumetric Moisture Content of the soil	(-)	0.01	0.01	0.01
Initial Volumetric Moisture Content of the soil	(-)	0.20	0.20	0.20
Installation cost per unit of roof area	[€/m^2]	73	78	83

For the building here investigated, considering the roof surface of the second floor, the area potentially suitable for installation of green roof is of 950 m^2.

4. Green roof: potentiality for an educational building in Mediterranean climate

In this section, the green roof installation will be evaluated. Firstly, a deepening about the energy balance of the overall facility, and thus building and HVAC systems, will be presented. Then, the energy and environmental benefits will be evaluated as well as the economic profitability. The indoor air temperature and the comfort conditions will be also analyzed.

The simulations will be performed by using rain data derived by 10 years of monitoring activity (from 2002 to 2012), with a sampling time equal to 10 minutes. These data have been elaborated and a representative reference year has been defined. Figure 4 shows the cumulative monthly rainfall levels.

In this regard, it is very important the evaluation of a realistic daily rainfall. Indeed, this not only influences the green roofs behavior but also it affects greatly the evaluation of the economic expenditure for the artificial irrigations as underlined by Ascione *et al*. [26].

In order to evaluate the effectiveness of the proposed intervention, in the following sections, the analysis of results has been focused on the energy demand of the second floor. Indeed, with reference to this, the green roof has the greater incidence in terms of energy balance.

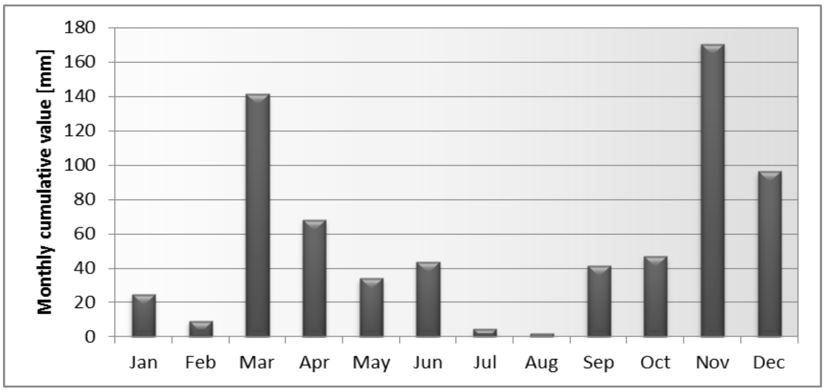


Figure 4. Rainfall for a typical month

4.1. Heat transfer phenomena involved in the building energy balance

The green roof has effects on the energy balance of the building/HVAC system, both during the winter and summer seasons. More in detail, with reference to the heat transfer phenomena, in wintertime, the heat convection of the external side of the roof is greatly reduced by the roughness of the canopy and the quasi-stable air layer within the foliage. Moreover, in the periods characterized by a dry soil, it contributes to increment the envelope thermal resistance.

Conversely, during the cooling period, an attenuation and time shifting of the thermal wave crossing the roof can be obtained because of the thermal mass of the wet soil layer, characterized by significant thickness, wetness and quite high thermal capacity. Moreover, the evapotranspiration phenomenon (and this is the main effect) that interests both vegetation and soil, allows a significant evaporative cooling. The evapotranspiration is directly related to the solar radiation, the soil moisture contents, the stomatal resistance of the vegetation, the resistance of the boundary limit to the vapor diffusion, the amount of foliage (expressed by the leaf area index).

The green roof model implemented in EnergyPlus is based on the studies of Sailor and this slightly modifies the FASST methodology of Frankenstein and Koenig, as described in [26]. The physical formulation is based on two main equations, concerning the energy balance at the atmosphere/foliage interface (F_f, equation 1) and the heat transfer through the soil (F_g, equation 2).

$$F_f = \sigma_f \left[I_s^{\downarrow} \left(1-\alpha_f\right) + \varepsilon_f I_{ir}^{\downarrow} - \varepsilon_f \sigma T_f^4 \right] + \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_g + \varepsilon_f - \varepsilon_f \varepsilon_g} \left(T_g{}^4 - T_f{}^4 \right) + H_f + L_f \tag{4.1}$$

$$F_g = \left(1-\sigma_f\right) \left[I_s^{\downarrow} \left(1-\alpha_g\right) + \varepsilon_g I_{ir}^{\downarrow} - \varepsilon_g \sigma T_g^4 \right] - \frac{\sigma_f \varepsilon_f \varepsilon_g \sigma}{\varepsilon_g + \varepsilon_f - \varepsilon_f \varepsilon_g} \left(T_g{}^4 - T_f{}^4 \right) + H_g + L_g + K \frac{\partial T_g}{\partial z} \tag{4.2}$$

In the equations (4.1) and (4.2), the following terms are:

- H_f: sensible heat flow at the atmosphere/foliage interface, [W m^{-2}];
- H_g: sensible heat flow at the atmosphere/soil interface, [W m^{-2}];
- L_f: latent heat flow at the atmosphere/foliage interface [W m^{-2}];
- L_g: latent heat flow at the atmosphere/soil interface [W m^{-2}];
- s_f: fractional Vegetation Coverage;
- a_f: foliage absorption coefficient;
- a_s: soil absorption coefficient;
- e_f: foliage infrared emissivity;
- e_s: soil infrared emissivity;
- T_f: Temperature of the foliage [K];
- T_s: Temperature of the soil [K];
- z: height or depth [m];
- s:constant of Stefan-Boltzman [W m^{-2} K^{-4}];
- $I_s^{\downarrow}$: total incoming solar radiation [W m^{-2}];
- $I_{ir}^{\downarrow}$: total incoming infrared radiation [W m^{-2}].

Sensible (H_f and H_g) and latent (L_f and L_g) heat flows (where the subscripts "f" and "g" respectively refer to foliage and ground) are calculated as function of LAI, sensible and latent bulk heat transfer coefficients at the ground surface, latent heat of vaporization at the foliage's and soil's temperatures, air velocity and mixing ratio in the canopy. The complete model is available in the technical documentation of EnergyPlus [16].

4.2. Energy-environmental benefits and economic profitability of green roofs

Table 5 shows the comparison between the primary energy requirements of the second floor for the configuration in which only 9.0 cm of insulation has been applied (IR_9) and those with the installation of green roofs as previously described.

Annually, the primary energy saving varies from 2.0% to 3.4% (depending on the type of vegetation), showing the best results for configurations with higher LAI and lower stomatal resistance. Again, with reference to the HL_LR solution, also the emissions are reduced of about 4%. In particular, the savings are mainly due to the reduced cooling need during the cooling season, because the heating savings are always less than 1%; for the summer period, conversely, in case of HL_LR, savings of 7% can be achieved in terms of both primary energy and operating costs. Of course, the HL-LR solution is the one requiring the highest irrigation cost, because of the higher evapotranspiration. Really, the water cost in Italy is quite moderate, around 1.3 €/m^3. By considering the whole year, all solutions are energetically beneficial, even if the costs of artificial irrigation completely nullify the energy savings. In other words, the annual cash flows are disadvantageous.

Table 5. Energy saving, avoided polluting emission and reduction of operational cost (2nd floor)

	Heating [kWh·yr^{-1}]	Cooling [kWh·yr^{-1}]	ΔEP [%]	ΔCO_2 [%]	ΔCE [€·yr^{-1}]
IR9	39'871	26'254	-	-	-
HL_LR	39'545	24'329	3.4	4.0	247
LL_HR	38'889	25'971	2.0	1.7	124
ML_MR	39'290	25'132	2.5	2.3	180

4.3. Thermal comfort analysis

For the whole cooling season, the indexes PMV and PPD have been calculated and it allows the understanding that the solutions ML_MR and HL_LR allow improved comfort conditions at the second floor. More in detail, Figure 5 shows the hourly trends of PPD for an office, facing south-east, for two summer days. It can be seen how the percentage of dissatisfied can be considerably reduced, with indoor operative temperatures more frequently in the range 23-26 ° C. This result is the same for all the investigated thermal zones, by showing that a green roof certainly induces a significant improvement of comfort conditions for the occupants.

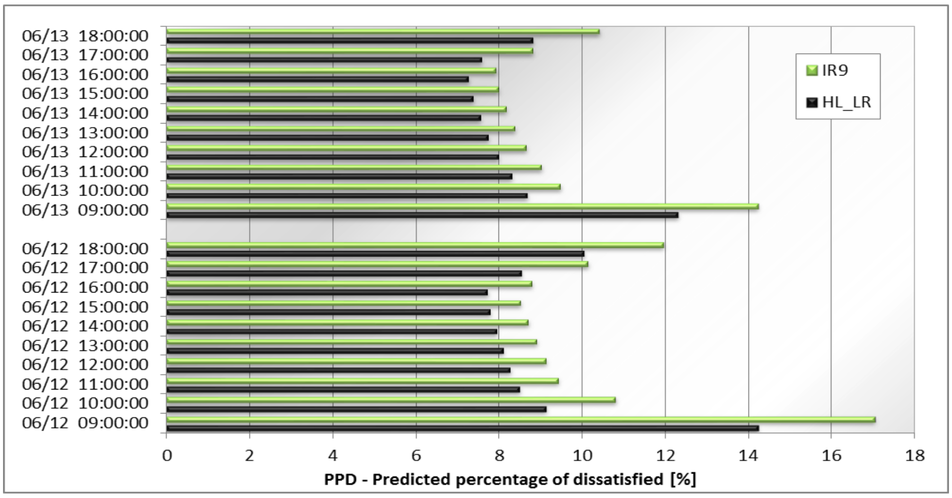


Figure 5. Predicted percentage of dissatisfied for an office with south-west exposure (2nd floor)

5. Indoor thermal conditions according to adaptive approach for traditional slab or green roof

The traditional approach expresses indoor comfort conditions as function of steady temperature levels. Conversely, the adaptive approach takes into consideration temperature levels that are unsteady and follow the variability of the outdoor climate.

The European Committee for Standardization has introduced the adaptive approach in the Standard EN 15251 [18]. The basic equation for the evaluation of the limits of the comfort operative temperature (T_{co}), reliable only for outdoor reference temperatures between 10°C and 30°C, is:

$$T_{co} = 0.33\ T_{rm} + 18 \pm X \tag{5.1}$$

Here, T_{rm} is the running weekly mean temperature, and "X" is a scalar number, ranging between 2 and 4 °C, that provides the acceptability ranges. In this study, the comfort Category I has been considered (i.e., X = 2 °C). It corresponds to the highest level of comfort expectations (PPD < 6%).
According to [18], the adaptive approach should be restricted to the assessment of the summer performances of naturally ventilated and unconditioned buildings.
Thus, firstly, this approach has been applied to the case study, assuming that the HVAC system is turned off at the second floor. In this way, the trend of operative temperatures will be analyzed and the benefits achievable with the installation of green roof will be evidenced.
Then, a hybrid management of HVAC system will be proposed, assuming variable set point temperatures on the basis of the outside temperature. Indeed, since the adaptation takes place also in conditioned buildings provided with "perceived adaptive opportunity" [27, 28], this approach seems reasonable for extending the adaptive criterion to all kinds of buildings.

5.1. Adaptive theory and range of comfort for the climate of Benevento
The definition of reference temperature for Benevento has been applied, and then it was calculated the range of comfort for the operating temperatures, as shown in table 6, for the typical warm season (i.e., from June to September).

Table 6. Running mean temperature and limit values for the operative temperature

Week	T_{rm}	Highest T_{co}	Lowest T_{co}	Week	T_{rm}	Highest T_{co}	Lowest T_{co}
I	23.4	28.5	24.5	X	28.1	30.1	26.1
II	24.5	28.9	24.9	XI	27.9	30.0	26.0
III	25.4	29.2	25.2	XII	27.6	29.9	25.9
IV	26.1	29.4	25.4	XIII	26.9	29.7	25.7
V	27.1	29.7	25.7	XIV	25.5	29.2	25.2
VI	28.0	30.0	26.0	XV	24.8	28.9	24.9
VII	28.8	30.3	26.3	XVI	24.1	28.7	24.7
VIII	28.5	30.2	26.2	XVII	22.9	28.4	24.3
IX	28.4	30.2	26.1				

5.2. Free running building: indoor thermal comfort
The hourly trend of operative temperature has been analyzed, for all rooms of the second floor. By way of example, Figure 6 shows the chart for one day in July for an office with south-west exposure during the occupied hours. The upper and lower limits for the temperatures are respectively 26.2°C and 30.2°C. Each green roof configuration allows lower operative temperatures. More in detail, the configuration HL_LR is able to maintain quite low the oscillations between the hottest hours and the cooler hours, without the use of the air conditioning. Good results are achieved also with the adoption of the ML_MR configuration, even if a high LAI allows much better performance. In the following discussion, the results will concern merely the installation of a green roof with high LAI, because this assures the better energy and environmental performances. Globally, starting from these analyses, it has been noted that the increased inertia induces a reduction of the temperature by 0.3°C to 1.5°C.
In detail, two indices have been introduced to evaluate the hourly temperatures of 2nd floor:

- GTO, global operating temperature index: percentage of hours, in which the operative temperature does not exceed the upper limit (2nd column in table 6) during the working period.
- MTO, mean value for the operating temperature index: this is the percentage of hours in which operative temperature does not exceed the mean value of comfort range (X=0 in equation 9).

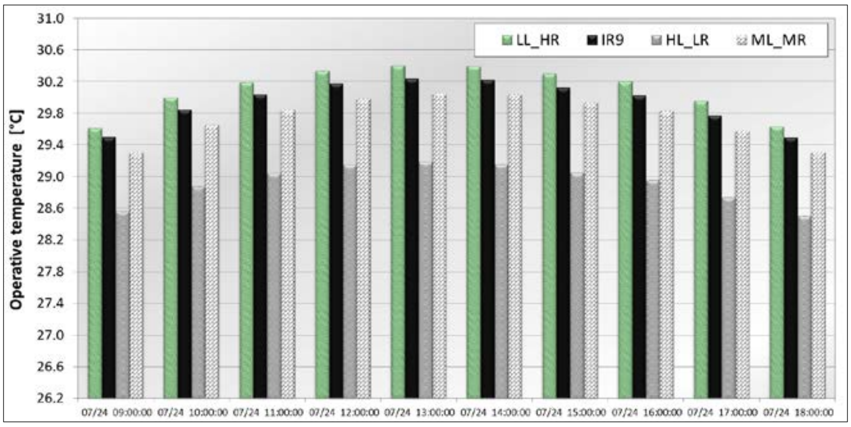


Figure 6. Hourly operative temperatures for an office with south-west exposure (24th July)

Moreover, figure 7 shows that, by referring to the GTO index, the installation of a green roof allows an operating temperature below the maximum allowable temperature, for all occupied hours of the building. This means that - by combining an appropriate strategy of ventilation and the installation of a green roof - the air conditioning could be turned off during the entire summer season. It should be noted that the adaptive theory provides a number of possibilities for the occupants' behavior; a proper natural ventilation must be considered in every case. Furthermore, by considering the MTO index, it is seen that the solution with green roof allows, for about the 80% of the occupancy hours, the achievement of an operating temperature "lower than" or "equal to" the average temperature of the comfort range.

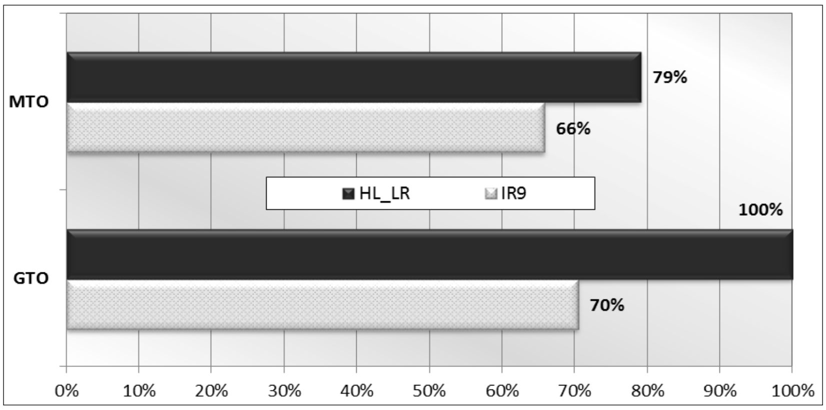


Figure 7. Operating temperature indexes: MTO and GTO

5.3. Energy and environmental benefits and economic profitability by adopting a hybrid approach

At the present time and with reference to the cooling period, the consideration of naturally ventilated office buildings, in the Italian context, is quite unreliable, so that the best potential of the adaptive approach consists in the actual management of air conditioning and cooling systems through variable set-points. For this reason, it has been assumed the consideration of an optimized management of the air-conditioning system, in which the set point temperature is fixed on the average temperature of comfort range defined with an adaptive approach, on a time basis equal to one week. This type of

Journal of Physics: Conference Series **655** (2015) 012027 doi:10.1088/1742-6596/655/1/012027

management can be achieved with an automated system that connects the external temperature to the selected set-point. In the following table 7, for the second floor, the comparison between the configuration with roof insulation and traditional management of the HVAC system and green roof installation and adaptive approach for the thermal comfort, is shown. Annually, the primary energy saving with high LAI roof is around 17%. More in detail, the electricity demand during June and September is reduced of around 60% with this configuration and around 30% during the hottest months. A good result is obtained in terms of reduction of polluting emissions with all configurations. The economic analysis starts to get interesting.

Table 7. Energy saving, avoided polluting emission and reduction of operative costs (2nd floor)

	Heating [$kWh \cdot yr^{-1}$]	Cooling [$kWh \cdot yr^{-1}$]	ΔEP [%]	ΔCO_2 [%]	ΔCE [€$\cdot yr^{-1}$]
High LAI-adaptive comfort	39'545	15'014	17	19	1'287
Low LAI-adaptive comfort	38'889	17'105	15	16	1'115
Med. LAI-adaptive comfort	39'290	16'182	16	17	1'180

Table 8. Performance improvement by adopting a High LAI and Low Stomatal Resistance green roof

	ΔEP [%]	ΔCO_2 [%]	ΔCE [%]
Traditional approach (HVAC on)	3.4	4	0.3
Adaptive approach (hybrid HVAC)	17	19	10

Finally, the energy needs have been compared for the proposed solutions, when the adaptive theory is applied to all configurations. The insulation of the roof slab (IR9) and the adaptive management of air conditioning in summer induce a demand for cooling of 18'119 $kWh \cdot yr^{-1}$.

Therefore, an annual (i.e., heating and cooling) energy savings of 9% can be achieved with the configuration high LAI and adaptive approach for thermal comfort, and the electric demand for cooling is reduced by 10% during the July and August and 30% during the less hot months, with positive effects also concerning the emissions. In conclusion, the green roofs surely allow the attenuation of the heat transfer from the outside to the inside environments, in summer conditions and thus energy and environmental benefits. However, there is not a net economic profitability, so that the design must be very careful. The best configuration of green roof is the one with High LAI and Low Stomatal Resistance. The final results for this type of installation, for the 2nd floor, are summarized in table 8, by comparison with the solution of roof insulation and the same HVAC management.

Conclusions

This paper discusses the potentialities of integration of several typologies of green roofs and the management of the microclimatic control with adaptive models. The investigated building hosts department and classrooms of the University of Sannio and it is located in Benevento (South Italy). The first part of the study has been focused on the calibration of a proper energy model and the evaluation of traditional refurbishment actions applied to the building envelope. Moreover, beyond the definition of various eco-roofs, with reference to both properties of the soil and plants, the energy saving, the avoided polluting emissions and the economic profitability have been evaluated. For the case study, by considering only the second floor of the building (where the great incidence of green roof can be perceived), it was found that the primary energy savings in the summer months, compared to a solution in which a mere insulation is applied, ranges from 2.0% to 3.4% depending on the type of vegetation. The best results are for plants with high LAI and low stomatal resistance. The costs of green roof installation and the needs of irrigation, however, do not provide profitable paybacks.

As further analysis, by applying the adaptive theory to evaluate the comfort temperatures, it was found that in case of green roof with high LAI, even with the HVAC system turned off, the thermal comfort constraints are always fulfilled. This leads to the conclusion that an appropriate strategy for natural ventilation, the application of less stringent comfort temperatures and the installation of a green roof, with high LAI and low resistance stomatal, could completely nullify the demand for the space cooling. By considering a hybrid approach, in which the control temperatures for the active microclimatic are set according to the mean value of the comfort adaptive range, the installation of the aforementioned typology of green roof allows a reduction of primary energy demand for the summer cooling. The saving is of 18% compared to a solution with roof insulation and similar management system, or about 43% compared to a solution with only insulation and a standard management system. In these cases, also the cost-effectiveness of the investment begins to be evident. Although this is not highlighted in this study, also the quality of the external environment can be improved, as investigated in [29-31], not only in terms of reduction of polluting emissions but also relatively to the urban heat island effect. Finally, in order to optimize the building performance in the Mediterranean climate, deep studies are needed about technologies aimed at limiting the energy demand for the air-conditioning in the cooling season.

References

[1] Rodrigues L T, Gillott M and Tetlow D 2013 Summer overheating potential in a low-energy steel frame house in future climate scenarios *Sust. Cities and Society* **7** 1
[2] Cotana F, Rossi F, Filipponi M, Coccia V, Pisello A L, Bonamente E, Petrozzi A and Cavalaglio G 2014 Albedo control as an effective strategy to tackle Global Warming: A case study *Appl. Energy* **130** 641
[3] Pisello A L and Cotana F 2014 The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring *Energy Build.* **69** 154
[4] Pisello A L, Piselli C and Cotana F 2015 Influence of human behavior on cool roof effect for summer cooling *Build. Environm.* **88** 116
[5] Pomianowski M, Heiselberg P and Zhang Y 2013 Review of thermal energy storage technologies based on PCM application in buildings *Energy Build.* **67** 56
[6] Barreneche C, Navarro L, de Gracia A, Fernández A I and Cabeza L F 2016 In situ thermal and acoustic performance and environmental impact of the introduction of a shape-stabilized PCM layer for building applications *Renew. Energy* **85** 281
[7] Castellani B, Morini E, Filipponi M, Nicolini A, Palombo M, Cotana F and Rossi F 2014 Clathrate hydrates for thermal energy storage in buildings: Overview of proper hydrate-forming compounds *Sustainability* **6** 6815
[8] Soares N, Gaspar A R, Santos P and Costa J J 2014 Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates *Energy Build.* **70** 411
[9] Saadatian O, Sopian K, Salleh E, Lim C H, Riffat S, Saadatian E, Toudeshki A, and Sulaiman M Y 2013 A review of energy aspect of green roofs *Renew. Sustain. Energy Rev.* **23** 155
[10] Mentens J, Raes D and Hermy M 2006 Green roof as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape Urban Plan* **77** 217
[11] Versini P A, Ramier D, Berthier E and de Gouvello B 2015 Assessment of the hydrological impacts of green roof: From building scale to basin scale *J Hydrology* **524** 562
[12] Santamouris M 2014 Cooling the cities: A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments *Sol. Energy* **103** 682
[13] Ascione F, Bianco N, de' Rossi F, Turni G and Vanoli G P 2013 Green roofs in European climates. Are effective solutions for the Energy savings in air-conditioning? *Appl. Energy* **104** 845
[14] Berardi U, GhaffarianHoseini A H and GhaffarianHoseini A 2014 State-of-the-art analysis of the environmental benefits of green roofs *Appl. Energy* **115** 411
[15] Bianchini F and Hewage K 2012 Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach *Build. Environ* **58** 152

[16] U.S. Department of Energy 2013 Energy Plus simulation software *Version 8.1.0*
[17] EN 15603: 2008. Standard: Energy Performance of Buildings – Overall Energy Use and Definition of Energy Ratings
[18] UNI EN 15251: 2008. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
[19] U.S. Department of Energy Federal Energy Management Program, M&V Guidelines: Measurement and Verification for Federal Energy Projects Version 3.0, 2008, Boulder, CO.
[20] TERNA Statistical Data (in Italian) http://www.terna.it
[21] The Covenant of Mayors, Committed to local sustainable energy. Technical annex to the SEAP template instructions document: the emission factors http://www.eumayors.eu/
[22] European Commission, Eurostat Statistics for Energy Costs http://epp.eurostat.ec.europa.eu/
[23] ASHRAE Standard 55: 2004. Thermal environmental conditions for human occupancy
[24] UNI EN ISO 7730: 2005. Ergonomics of the thermal environment e analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
[25] Ferrari S and Zanotto V 2012 Adaptive comfort: Analysis and application of the main indices *Build. Environ* **49** 25
[26] Ascione F, Bianco N, De Masi R F, De Rossi F and Vanoli G P 2015 Technical and economic analysis of green roofs to reduce building cooling needs, *Chapter 13 of Eco-Efficient Materials for Mitigating Building Cooling Needs, Design, Properties and Application 1st Edition* (Woodhead Publishing) p 349
[27] Brager G S and Baker L 2008 Occupant satisfaction in mixed-mode buildings *Proc of Conference: Air Conditioning and the Low Carbon Cooling Challenge, Cumberland Lodge, Windsor (London, United Kingdom)*
[28] ThermCo 2009 Interrelation between different comfort parameters and their importance in occupant satisfaction. Report for the Thermal Comfort in Buildings with Low-Energy Cooling European Project http://www.thermco.org/
[29] Salata F, Golasi I, Vollaro E L, Bisegna F, Nardecchia F, Coppi M, Gugliermetti F and Vollaro A L 2015 Evaluation of different urban microclimate mitigation strategies through a PMV analysis *Sustainability* **7** 9012
[30] Salata F, Golasi I, Vollaro A D L and Vollaro R D L 2015 How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study *Energy Build.* **99** 32
[31] Peri G, Rizzo G, Scaccianoce G and Sorrentino G 2013 Role of green coverings in mitigating heat island effects: An analysis of physical models *Applied Mechanics and Materials* **261-262** 251