A new simulation tool for the evaluation of energy performances of green roofs

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Abstract

Among the different adoptable solutions for building envelopes, of particular interest is the green roof which allows us to obtain, at the same time, energy, economic and environmental benefits using solar energy as a source for its operation.

The aim of the proposed study is to evaluate the energy and economic savings achievable through the installation of an additional green roof stratigraphy on a variety of traditional roofs. The analysis was carried out with reference to the climatic conditions of the Calabria region (Italy), classified as Mediterranean.

Such assessment has been achieved by the use of a thermal model in dynamic regime formulated by the authors that allows us to determine the heat transfer in roofs with a green cover. The model is based on two energy balance equations for the vegetation and soil layer. The model has been implemented into the software tool ThermoGR that allows us to evaluate the thermal exchanges of a green roof with indoor and outdoor environments and the seasonal energy savings due to the presence of the green stratigraphy.

The reduction of the thermal load through the roof, due to the green roof, is used to perform an economic analysis based on the calculation of the cost of the energy saved per square meter of roof surface during the air-conditioning period both in summer and in winter. This analysis is used to identify the constructive typologies on which the application of the green roof is more advantageous.

1. Introduction

Greenhouse gas emissions are caused by human anthropogenic activities and to reverse the growing trend, it is important to mitigate the process in all sectors: residential, industrial and transportation.

The building sector is the largest consumer of energy, in which the main requirements are energy demand for space heating, cooling and domestic hot water production and electricity demand to illuminate and power household appliances (Masoso and Grobler, 2010). The continuous growth in energy demand for cooling and heating buildings makes the design and use of sustainable architectural solutions and plant systems for energy refurbishment of existing buildings necessary.

In this context, green roofs can be used to obtain, at the same time, energy, economic and environmental benefits. They are believed to mitigate the urban heat island effect, improve storm water management, filter fine particles, provide aesthetic and social benefits, reduce noise pollution, improve the durability of roofs, provide effective thermal insulation and reduce the cooling loads of buildings. Green roofs are often classified as intensive and extensive, according to the level of maintenance required and the depth of the growing media. The main elements of the stratigraphy are, from the top to the bottom: proper vegetation, lightweight growing media, filter layer, water storage and drainage layer and

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root-barrier whose function is often provided by a waterproof layer.

Different physical phenomena are involved in the green roof energy balance that are not easy to model since they imply heat and mass transfers. Nevertheless, developers and architects need proper tools for assessing the likely amount of energy savings associated with diverse green roof options.

Several authors have proposed thermophysical models in the last few years, often based on energy balance equations. Each model supposes simplifying assumptions neglecting some factors and considering others in more detail.

Del Barrio (Del Barrio, 1998) proposed one of relevant initial models. She divided the green roof system into three main parts: canopy, soil and roof slab. A heat balance calculation was performed for each part in association with boundary conditions at the canopy-soil, soil-roof slab, and roof slab-indoor air interfaces.

Following another approach, Lazzarin et al. (Lazzarin et al., 2005) developed a numerical model. The green roof system has been investigated in dynamic state considering mono-dimensional analysis at the finite differences. The physical system is divided into different segments and nodes. The soil is described with three nodes, while one node describes the drainage layer, the waterproofing sheet and the structural concrete roof. The other elements are neglected for the limited thermal mass. The upper border is the ambient air and the lower one is the room underneath. In the energy and water model, fluxes take place. They depend on the evaporative flux and on the saturation or dryness condition of the soil: if a node reaches the saturation, the excess water drains down to the lower one, while if it becomes completely dry, it recalls the needed water from the same one.

Frankenstein and Koenig (Frankenstein and Koenig, 2004) developed the FASST (Fast All-Season Soil Strength) model. Two heat balances are considered, at the soil surface and at the foliage surface. The main influencing parameters that affect heat transfers for a green roof were considered: foliage height, leaf area index (LAI), fractional vegetation coverage, albedo, stomatal resistance. The heat and mass transfers in the canopy were studied by considering the leaf as a solid body in which air circulates.

Following the study of Frankenstein and Koenig (Frankenstein and Koenig, 2004), Sailor (Sailor, 2008) developed a more accurate energy balance model. In particular, the energy budget is divided into the foliage layer and the ground surface. The model was linearized and the final set of equations are solved simultaneously to obtain the surface temperature of soil and foliage. According to Sailor (Sailor, 2008), moisture leaves the soil through runoff evaporation and evapotranspiration from vegetation surfaces. At each time step, the soil moisture state is updated based on the net inflow of moisture to the soil layer.

Tabares-Velasco and Srebric (Tabares-Velasco and Srebric, 2012) presented a quasi-steady state heat and mass transfer green roof model. It considers heat and mass transfer processes between the sky, plants and substrate. In particular, the formulation presents new equations to calculate substrate thermal conductivity, substrate resistance, and sets stomatal resistance functions to calculate plants transpiration.

On the basis of the work of Del Barrio (1998), Frankenstein and Koenig (2004) and Sailor (2008), Djedjig et al. (2012) reformulated the energy contributions of the energy balance equations and proposed a dynamic model. The thermal behavior of the green roof layers was coupled to the water balance in the substrate that was determined accounting evapotranspiration.

Finally, photosynthesis was included in the thermal balance by Feng et al. (2010).

The literature survey demonstrates the importance of thermal parameters of substrate and drainage layer, such as thermal conductivity and specific heat capacity, which in reality vary as a function of the moisture content. This last dependency is not always taken into account introducing in this way strong simplifications in the modelling.

In this study, energy and economic savings achievable through the installation of an additional green roof stratigraphy on traditional roofs are evaluated. The analysis is carried out with reference to climatic conditions of the Calabria region located in southern Italy. The climate is

Mediterranean, defined as subtype *Csa* according to the Köppen climate classification, characterized by hot and dry summers and wet winters. The choice of a lightweight extensive solution typically does not generate a problem of excessive structural load to be borne by the structural roof.

The evaluation is achieved by using a thermal model in dynamic regime formulated by the authors that allows us to determine the heat transfer in roofs with a green cover. The model is based on two energy balance equations, for the vegetation and soil, and takes into account the sensible and latent heat transfer, the effects associated with the heat capacity of the soil and the photosynthetic activity of plants. Furthermore, the model considers the variation of the substrate thermal properties with the water content.

The model has been implemented into the software tool ThermoGR that allows us to evaluate the heat transfers of a roof toward indoor and outdoor environment. These outputs can be used for the evaluation of building thermal loads through the building cover, in presence and absence of a green roof. The results of simulations, temperatures in the stratigraphy and thermal fluxes are used to assess seasonal energy savings due to the presence of the green cover depending on the roof type (construction, thermal insulation, etc.) and climatic conditions of the considered localities (solar radiation, air temperature, precipitation, etc.).

The assessment of the reduction of the thermal load through the roof cover, due to the green roof, is furthermore used to perform an economic analysis based on the calculation of the cost of saved energy during the air-conditioning period both in summer and in winter per square meter of roof. This analysis provides useful information about energy and economic benefits that can be obtained from each type of studied roof coverage allowing to identify the constructive typologies on which the application of the green roof is more advantageous.

2. The Thermophysical model

The thermophysical model developed by the authors is based on the relevant literature. For their accuracy, the reference model for the formulation of radiative heat exchanges was (Ouldboukhitine et al., 2011), the model of Sailor (2008) was considered as a reference for the definition of sensible and latent heat exchanges. The model has been extended considering the FASST (Frankenstein and Koenig, 2004) for assessing the energy contribution associated with the precipitation, and the work proposed by Feng et al. 2010 (2010) regarding the energy contribution associated with photosynthesis and plant respiration.

The proposed model contains some novelties, or rather refinements, compared with the reference formulations. In particular, the contemporaneity of the following assumptions is considered:

1) the heat storage capacity of the growing media is introduced, through the calculation of the variation of its internal energy;

2) the thermal modelling of the drainage layer, partially filled with water is added;

3) the thermal conductivity and the specific heat of the substrate and of the drainage layer are expressed as a function of the water content;

4) the green roof is considered partially covered by vegetation, defining the fractional vegetative coverage σ_f;

5) the heat flux associated with precipitations and photosynthesis is considered.

The green roof mathematical model is based on two instantaneous energy balance equations for the vegetated and soil layer, expressed as functions of the unknown variables temperature of foliage (T_f) and substrate surface temperature (T_g). The surface energy balance equation for the vegetation is given by:

$$R_{n,f} + H_f + L_f + P_f + P_{hf} = 0 \quad (1)$$

Where $R_{n,f}$ is the net radiative heat exchange, H_f is the sensible heat flux, L_f is the latent heat flux, P_f is the precipitation heat flux and P_{ph} is the heat flux associated with photosynthesis and plant respiration. The same formal equation is written for the soil surface:

$$R_{n,g} + H_g + L_g + P_g + C_g + \frac{\Delta U}{\Delta t} = 0 \quad (2)$$

Where $R_{n,g}$ is the net radiative heat exchange, H_g is the sensible heat flux, L_g is the latent heat flux, C_g is the conductive heat flux, P_g is the precipitation heat flux and ΔU is the variation of internal energy. In particular in the conductive term of the balance, C_g, the variability of the substrate thermal conductivity is expressed by the following relation (Sailor and Hagos, 2011):

$$\frac{K}{K_{dry}} = \frac{1.45 \exp\ (4.411 S_r)}{[1 + 0.45 \exp(4.411 S_r)\ ]} \quad (3)$$

where K_{dry} is the thermal conductivity in dry condition and S_r is the degree of saturation. Furthermore, in the term ΔU the variability of the substrate heat capacity is introduced considering a linear interpolation between the dry C_{dry} and saturated condition C_{sat}:

$$\mathrm{C} = \mathrm{C_{dry}} + \frac{\mathrm{C_{sat}} - \mathrm{C_{dry}}}{\theta_{\mathrm{sat}}} * S_r \quad (4)$$

In both energy balance equations, the unknown variables are the surface temperature of foliage (T_f) and the surface temperature of the substrate (T_g). The system of equations is linearized and solved in order to provide T_g and T_f as output. Once these temperatures are calculated, every energy contribution of the balances can be evaluated.

The formulation has been successively completed by the thermal modelling of the layers underlying the substrate, interposed between the growing media and the internal environment, as shown in fig. 1.

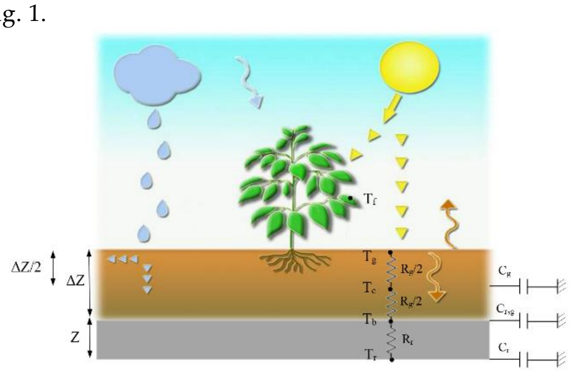

Fig. 1 – Schematic representation of the thermal variables considered in the energy balance

The drainage layer was modelled considering an equivalent thermal conductivity expressed in function of the thermal conductivity of air k_a, water k_w, and drainage material k_p, weighted on the respective areas. In a similar way, an equivalent heat capacity was defined.

The finite difference method was implemented to solve the energy balance in every node between the growing media and the internal environment.

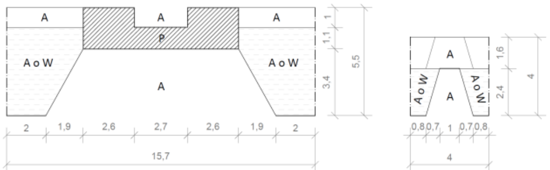

Fig. 2 – Schematic representation of the drainage layer for the thermal modelling. A: Air, W: Water, P: Material (Polystyrene)

Finally the resolution of the system of equations provide the node temperatures T_f, foliage temperature, T_g, surface ground temperature, T_c, temperature at the center of ground, T_b, ground-drainage interface temperature, T_r, drainage-structural roof interface temperature and the node temperature in the layers underlying the foliage-ground-drainage system.

3. The simulation tool ThermoGR

In order to create a user-friendly and useful tool, the mathematical model, written in C++ programming language, was implemented in a new software, named ThemoGR. Furthermore, the C++ subroutine can be coupled with common energy simulation software, some of which do not provide, at the moment, a library for the evaluation of the thermal performance of green roofs. For example, ThemoGR can interact with the Type 56 building model of Trnsys (TRNSYS 17, 2010).

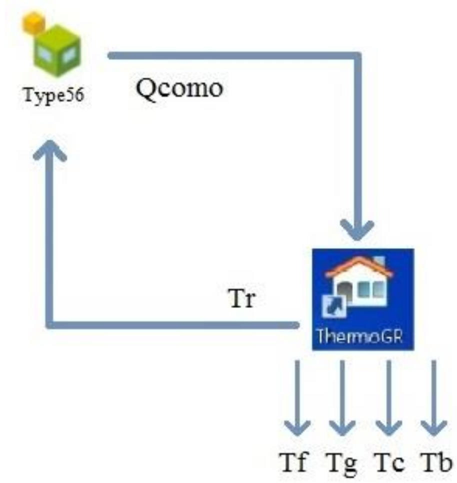

Fig. 3 – Flow Chart on which interaction TRNSYS-ThermoGR is based

In particular, Type 56 calculate the heat flux Q_{COMO} at the drainage-structural roof interface that constitute a data input for ThermoGR that evaluate the node temperature in the foliage-ground-drainage system (see fig. 3). At each time-step, the temperature T_r computed by the tool is then given to Type 56 until this cycle process reaches convergence, namely all thermal variables do not vary.

The ThemoGR is able to perform hourly dynamic simulations. The tool allows the setting of all the involved parameters through six windows for vegetation, substrate, drainage, structural roof and input and output data.

The software requires some input data: climatic conditions of the considered locality, type of structure, parameters defining the characteristics of the vegetated layers (leaf area index, SAI, fractional coverage σf, height of plants, stomatal resistance, albedo, transpiration coefficient, evapotranspiration rate) and of the growing media (albedo, thermal conductivity, heat capacity) and simulation time period. This data can be entered manually in the software or by importing an external text file. The main outputs are temperatures of the different layers, energy contributions of the balance equations of soil and vegetation and heat flux through the entire roof. In the output windows, it is possible to visualize the data and export them into a *txt* or *xls* file. It is furthermore possible for the user to select a proper time range to show and export the simulation results.

4. Application of the simulation tool ThermoGR

Dynamic hourly simulations were carried out by ThemoGR. Simulations aim to evaluate the influence of the installation of a green roof stratigraphy on different types of roof in different localities by determining the entering and exiting heat fluxes from the internal environment. The considered extensive green roof is comprised of the following layers:

- vegetation;
- substrate 8 cm;

- drainage and storage layer in polystyrene 5.5 cm;
- waterproof membrane;

Four types of roof have been considered:

1 precast concrete and pre-stressed reinforced with polystyrene lightening elements;
2 traditional roof with 16 cm hollow flooring blocks;
3 traditional roof with 24 cm hollow flooring blocks;
4 traditional roof with 16cm hollow flooring blocks and thermal insulation;

Fig. 4 – Examples of considered structural roofs. a) precast concrete and prestressed reinforced, b) traditional masonry

Three localities in the Calabria region were considered: Cosenza, Catanzaro and Reggio Calabria. According to the National regulations (DPR 412/93, 1993), the heating period for Cosenza and Catanzaro is from 15th November to 31st March, whereas for Reggio Calabria from 1st December to 31st March. For the summer season, a conventional cooling period from June to September was assumed. Temperatures for heating and cooling periods were set respectively to 20 °C and 26 °C.

4.1 Definition of green roof thermophysical parameters

The input data for vegetation and growing media were determined considering the experimental set-up of the University of Calabria. The main thermal properties of the substrate are: maximum water content 40%, dry density 1060 kg/m^3, saturation density 1360 kg/m^3, specific heat 1227 J/kg K in dry condition, specific heat 1388 J/kg K at saturation, average thermal conductivity equal to 0.27 W/m K. Regarding the vegetation, some in situ measurements carried out in August 2013, allowed us to obtain the following values: vegetation coverage $\sigma f = 0.55$, leaf area index equal to 3, height of plants 12 cm.

4.2 Weather Data

Climatic data of the considered localities have been generated by the use of the software TRNSYS - (TRaNsient Systems Simulation – TRNSYS 17, 2010), using empirical methods and experimental available measurements.

Hourly data of total solar radiation on horizontal surface, humidity ratio and temperature were generated by Type 54a. Type 69b was used to calculate the sky temperature that is necessary to obtain the long-wave radiative exchange with the atmosphere. Type 33 was used for the calculation of wet bulb temperature. In the generation procedure, the hourly values are determined so that their associated statistic are approximately equal to the long-term statistics for the specified locality.

The hourly rainfall data were determined with a proper procedure. It can be observed that the probability of a rainfall event to occur is related to high relative humidity values and small differences between dry and wet bulb temperature of external air $\Delta T = T_{db} - T_{wet.}$ The clearness index k was also considered to refine the selection of the hours in which a rainy event could occur. Particularly, hours with $k > 0.5$ were not taken into account. Concerning the night hours, cloudiness index N was used to assess when the precipitation phenomena happen; hours with $N < 5$ tenths sky cover were not taken into account. Table 1 shows the hours in which a rainy event can occur as a function of temperature difference ranges considering different criteria: with no control (No cont), considering only the control on the clearness index (k) and both k and cloudiness index (N) control.

Table 1 – Number of hours in which rainfall occurs at variation of temperature interval ΔT. The values are determined by three different selection methods.

	0<ΔT<0.5	0<ΔT<1	0<ΔT<1.,5	0<ΔT<2	0<ΔT<3	0<ΔT<4	0<ΔT<5
No cont	582	1242	1952	2730	4253	5434	6333
K	562	1129	1713	2309	3442	4254	4827
N	278	577	890	1191	1732	2074	2303

The ARPACAL (Center for Functional Comprehensive Regional Agency for Environmental Protection of Calabria) database provides the average yearly rainy days for Calabrian cities (ARPACAL). For Cosenza this number is 95, meaning 2,280 hours; therefore the results for the range 0<ΔT<5 were chosen considering both k and N control. The same procedure was applied for Catanzaro and Reggio Calabria. Considering monthly average precipitation values provided by ARPACAL, achieved in 96 years of observation, rain intensity has been linearly related to the cloudiness index N at each hour in which rainy event occurs.

5. Results

Table 2 shows the total ingoing and outgoing specific energy for the three considered localities for the four different types of roof, in summer and winter air-conditioning seasons. The total ingoing specific energy is calculated as the integral of the heat flux entering the indoor environment through the structural roof, whereas the outgoing specific energy is integral of the heat flux that leaves the environment through the same structural roof.

Table 2 – Results of winter and summer simulations

Roof Type	City	Summer air conditioning		Winter air conditioning	
		Ingoing energy [Wh/m²]		Outgoing energy [Wh/m²]	
		Without Green roof	With Green Roof	Without Green roof	With Green Roof
1	CS	6334.47	2424.58	9443.10	8047.43
	CZ	4233.69	1353.61	10156.21	8496.25
	RC	4427.19	1687.09	7339.14	5950.03
2	CS	9239.66	3367.88	19754.34	12440.28
	CZ	6017.96	1871.75	22196.47	13288.19
	RC	6320.34	2342.85	16174.87	9261.57
3	CS	8750.93	3239.61	17992.56	11904.52
	CZ	5602.43	1788.42	20095.71	12720.17
	RC	5911.76	2252.54	14625.46	8877.49
4	CS	4494.70	1786.70	5581.49	5397.82
	CZ	3071.28	1004.97	5885.29	5653.24
	RC	3192.77	1243.68	4237.90	3970.98

It appears the presence of a green roof is beneficial both in summer and in winter, reducing the energy loads if compared to the cases without green roofs. The maximum energy percentage reduction is found for te roof type 2 with values in summer and winter respectively of 64% and 37% in Cosenza, 69% and 40% in Catanzaro and 63% and 43% in Reggio Calabria with an absolute reduction of 5.9 kWh/m² in summer in Cosenza and 8.9 kWh/m² in winter in Catanzaro. In Catanzaro, due to the different climatic conditions, total ingoing specific energy is always lower than Cosenza in summer but the outgoing energy shows higher values in winter. In Reggio Calabria summer ingoing energy is similar to Catanzaro while in winter, it is the lowest of all the considered localities.

The evaluation of the energy saving achievable through the installation of the green roof is followed by an economic analysis to determine the convenience for the user. Usually the installation cost of a green roof varies between 30 €/m² and 70 €/m².

In summer, the presence of a green roof determines the reduction of the total specific ingoing energy to the conditioned environments. The reduction of the thermal load Q is calculated as the difference between the ingoing specific energy without the presence of the green roof (Q_{WGR}) and the value evaluated in presence of the green roof (Q_{GR}).

$$Q = Q^{+}{}_{WGR} - Q^{+}{}_{GR} \quad (5)$$

To determine the primary energy saving a COP equal to 3 was considered assuming the air conditioning plant is supplied by a heat pump. Considering the electricity energy cost C_{el} of 0.19 €/kWh the economic saving *ES* per square meter of roof is evaluable as:

$$ES\left[\frac{€}{m^2}\right] = E_{el}[kWh] * C_{el}\left[\frac{€}{kWh}\right] \quad (6)$$

where E_{el} is the electric energy consumed by the heat pump.

In winter the green roof reduces the outgoing specific energy, so that the reduction of the thermal load is calculated as:

$$Q = \left|Q^{-}{}_{WGR}\right| - \left|Q^{-}{}_{GR}\right| \quad (7)$$

In this case supposing the use of a natural gas boiler with an efficiency of 0.9, for the methane the lower calorific value of 35 MJ/m³ and a cost of 0.83 €/ m³, the achievable economic saving ES, in function of the fuel saving *FS* [m³/m²], per square meter of roof is calculated as:

$$ES\left[\frac{€}{m^2}\right] = FS\left[\frac{m^3}{m^2}\right] * c_{el}\left[\frac{€}{m^3}\right] \quad (8)$$

Results of the economic analysis are shown in table 3. The installation of a green roof provides always energy benefits and consequently economic savings.

Table 3 – Economic saving for the different roof solutions (S=Summer, W= Winter)

	Economic Saving [€/m²]					
	COSENZA		CATANZARO		REGGIO CALABRIA	
	S	W	S	W	S	W
Roof 1	0.25	0.13	0.18	0.16	0.17	0.13
Roof 2	0.37	0.69	0.26	0.85	0.25	0.66
Roof 3	0.35	0.58	0.24	0.70	0.23	0.55
Roof 4	0.17	0.02	0.13	0.02	0.12	0.03

From an economic point of view, the effectiveness increases when the thermal performances of the structural roof decrease. In fact, the traditional roof with insulation, which performs the best from the thermal point of view, allows us to obtain the lowest results in term of economic savings from 17 €cent/m² to 12 €cent/m² in summer and from 2 €cent/m² to 3 €cent/m² in winter. The installation of the green cover on a roof with 16 cm hollow flooring block, characterized by lower thermal resistance, leads to economic savings ranging from 25 €cent/m² to 37 €cent/m² for electric costs in summer and from 66 €cent/m² to 85 €cent/m² for methane costs in winter. It is possible to conclude that in Mediterranean climatic conditions, such as those of the considered cities, the installation of the green roof allows for greater savings if the roof is poorly insulated.

6. Conclusions

An evaluation of energy and economic savings achievable through the installation of an additional green roof stratigraphy on traditional roofs was carried out. Three localities in Mediterranean climatic conditions have been considered.

The evaluation is achieved by the use of a thermal model in dynamic regime formulated by the authors. The model, based on the pertinent literature, contains some refinements given by the contemporary presence of different physical phenomena. In order to predict the thermal behaviour of vegetated roofs, the mathematical model was written in C++ programming language. The C++ code was implemented in a new software, named ThemoGR that permits the user to calculate the outgoing and ingoing heat fluxes from and to the internal environments. The experimental set-up of University of Calabria has been considered to obtain vegetation and growing media parameters to be provided as input data in the simulation tool.

The results of the energy simulations showed that for the three localities, the presence of a green roof is beneficial both in summer and in winter, reducing the thermal loads compared to the cases without green roofs.

The evaluation of the energy saving achievable through the installation of a green roof has been followed by an economic analysis to determine the economic savings achievable per square meter of installed green roof.

It is possible to conclude that in Mediterranean climatic conditions, such as those of the considered cities in Calabria region, the installation of the green roof allows for greater savings if the roof is poorly insulated. The maximum energy reduction was found for the roof type 2 with reduction in summer and winter respectively of 64% and 37% in Cosenza, 69% and 40% in Catanzaro and 63% and 43% in Reggio Calabria

Even though the economic saving evaluated with the simulation tool are not relevant in magnitude, especially if compared to the high installation costs, several other aspects can justify the choice of a green roof. First of all a proper national mechanism of financial support, identifying green roofs as a technology that provides energy savings, could help to spread this type of solution and at the same time reduce the installation costs allowing a quicker return of the investment. Finally, it has also to be considered that the expected lifetime of a vegetated roof is supposed to be more than twice as long as a traditional roof, because they are subject to lower thermal stress and that, added to the economic savings related to the lower energy consumption for the air-conditioning, lead to a smaller payback period.

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