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Enhancing values of roofs albedo for lowering cities' air temperature and electric demand of buildings: a simple economic evaluation

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Abstract. In cities vegetated roofs are becoming more popular because they can mitigate Urban Heat Island phenomena by decreasing the outdoor air temperature in summer. This decrease reduces the electric energy demand for climatization of buildings, which, in front of a milder climate, will recur less to mechanical tools for guaranteeing thermal comfort conditions to occupants. Cities can registered another indirect positive effect: the reduced cooling energy demand, limits the heat released by the climatization systems' external unities toward the urban open spaces, thus lowering the outdoor air temperature. Therefore, the outdoor surface temperature of green, as well as cool roofs, can be assumed as an important design parameter for guaranteeing the sustainability of buildings and their approach toward an nZEB path. Obviously, designers and city planners must have at their disposal simple and effective tools for evaluating the economic feasibility of these two choices. This paper proposes a simple method to assess the economic effectiveness of green or cool roofs. It relies on the appraisal of the number of hours during which a building requires a cooling mechanical support for maintaining the indoor comfort conditions. This duty period of the cooling system is then simply converted into the cost of the needed electric energy.

1. Introduction

European Member States are establishing new challenging targets in order of readdressing their policies toward a less carbon-dependent economy. Such targets are declared in the EU 2030 climate and energy framework [1]. All sectors of the country's economy are deeply involved in this effort and, among them, certainly buildings are called to play an important role because of their relevant incidence on the energy consumption and their climatic pressure exerted on the environment. Obviously, the involvement of buildings in the transition towards a less carbon path should be attained keeping the mind on guaranteeing the indoor thermal conditions of people living and working inside such premises [2, 3], where they spend a high part of their time, particularly in industrialized and post-industrialized countries.

On the other hand, buildings are also called to accomplish the new requirements suggested by the nZEB concepts for these buildings, in which "the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [4]. It is evident that lowering the fossil-fuels related energy demand of building, by pursuing an enhancement of the albedo of their roofs, is perfectly in line with the search for nZEBs.

Additionally, urban contexts with their paved and built areas are responsible for the generation of the so-called Urban Heat Island (UHI) phenomenon that is the difference of air temperatures between the



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urbanized zones and their contiguous rural sites [5]. UHI is a very important physical occurrence that should be properly controlled mainly by suitably modifying the reflectivity characteristics of roofs [6], which affect their outdoor surface temperatures. In fact, cooler roofs induce a reduction of the solar radiation absorbed and transmitted indoors through the building envelope while, at the same time, could effectively contribute to lowering the outdoor air temperature of cities, in this way limiting the UHI phenomena.

One of the most effective ways for limiting the increase in UHI intensity is enhancing the albedo of the building roofs. This can be operatively achieved by installing a vegetated compound or a cool surface onto the roof of buildings. The link between the UHI effects and the albedo of the roofs of buildings has been analyzed several times, particularly referring to the reduction of cooling energy needs determined by the installation of highly-reflective roof surfaces in urban contexts [7].

Clearly, the possible positive effects of a roofs' albedo increasing can be analyzed by the economic point of view. This aspect, along with the related energy and environmental features, has largely been investigated by means of an extensive analysis involving several cities in the United States of America [8]. Particularly referring to the annual electrical energy savings from cooler surfaces, another study [9] analyzed the situation of a typical warm city.

In order of getting useful information from the possible adoption of high-albedo surfaces, it is of crucial importance for technicians and local administrators, the availability of reliable and easily applicable methods of evaluation, which could avoid the utilization of complex computer simulation tools that, among other things, require the knowledge of a large amount of detailed data referring to the local climatic conditions and to the design choices of the involved buildings. On purpose, in this work, a simple method is proposed for assessing the economic effectiveness of installing green or cool roofs in buildings. Such method enables an easy comparison in terms of economic features of different design configurations of the roofs.

Apart the fact that the surface temperatures (internal and external) of the envelope directly affect the energy demand of buildings, there exists a directly link between the value of the temperature of outdoor surfaces of roofs and the risk of determination of UHI phenomena. Clearly, different types of roofs (traditional, cool or green) will determine different values of the outdoor surface temperatures and, then, different risks of onset of UHI effects. On the other hand, the indoor surface temperature of the ceiling directly affects the indoor thermal comfort conditions of people living and working inside the building. Therefore, the proposed method depends essentially on these two physical parameters and aims to evaluate the economic benefits (apart the energy and environmental ones) of cool and green roofs, compared with those of traditional roofs. The method is then applied to the four biggest cities of Sicily, showing different urban densities and local climate conditions.

2. Computing the surface temperatures of roofs

The simplified methodology aimed at assessing the economic benefit, following an enhancement of the albedo values of roofs, requires the determination of the roof outdoor (T_{or}) and ceiling indoor (T_{ic}) surface temperatures of the ceiling of buildings in both conditions. The procedure relies on the energy balance of the building roof, described in equation (1):

$$q_{irr} - q_{ref} - q_{conv} - q_{reir} - q_{cond} = 0 \quad (1)$$

where q_{irr} and q_{ref} are the incoming and reflected components of the solar radiation respectively, q_{conv} is the convective outdoor heat exchange, q_{reir} is the infrared re-irradiated heat flux and q_{cond} is the heat flow rate transmitted indoors by conduction. The maximum value of the monthly mean solar irradiance and the maximum value of the monthly mean air temperature in the summer season are used to compute the terms of the energy balance for each type of roof taken into account. Finally, the characteristic air temperature of a given city is given by the average of those of the different roof typologies, weighted with their percentage extension on the urban contest under analysis. This energy balance allows the evaluation of the so-called "skin temperature" of building roofs that is the outdoor surface temperature, which is directly related to the UHI effect, since the mean air temperature of a given city is certainly affected by the weighted average of the roof typologies present in the urban context.

This simple model has been applied to the four biggest cities of Sicily (Palermo, Catania, Messina and Trapani) that show the prevailing presence of three main typologies of roofs in their urban areas: pitched roofs of brick tiles, pitched roofs of asphalt shingle and flat concrete roofs. Based on the statistical distribution of such types of roofs in each town, it has been possible to determine, by means of the application of Eq. 1 to the three predominant typologies of roofs, the outdoor average temperature of the considered urban contexts, on the base of the roof albedos of such surfaces [15]. This temperature represents a simplified, but reliable, indicator of the UHI effects. As that, we have indicated the average temperature of the urban surfaces with the term $UHI_{\text{precursor}}$.

Table 1. Average outdoor surface temperature ($^{\circ}\text{C}$) of the roofs of the considered towns: *status quo* situation.

Roof typologies	ρ	Palermo	Catania	Messina	Trapani
Pitched roofs of brick tiles	0.35	37.9	37.4	42.6	35.9
Pitched roofs of asphalt shingle	0.21	39.5	38.8	44.4	36.9
Flat concrete roofs	0.30	40.7	39.9	45.7	37.7
$UHI_{\text{precursor}}$		41.3	38.9	42.0	41.3

Afterwards, we have hypothesized the change of the values of the reflectance (albedo) of roofs for the same four towns, by utilizing cool or green roofs as external coverages, due to their well-recognised effectiveness in enhancing the albedo values [6, 11, 12, 13] and, therefore, reducing the value of the outdoor surface temperature of roofs. Specifically, we have supposed three different scenarios: 1) the pitched roofs of brick tiles and asphalt shingles were covered by a cool painting ($\rho=0.79$); 2) only the flat concrete roofs covered by green roofs ($\rho=0.50$); 3) the flat concrete roofs covered by green roofs and the remaining with cool painting.

Table 2. Average outdoor surface temperature ($^{\circ}\text{C}$) of the roofs ($UHI_{\text{precursor}}$): enhanced albedoes.

Roof typologies	Palermo	Catania	Messina	Trapani
Scenario 1	36.5	35.1	39.1	38.1
Scenario 2	39.4	38.5	42.0	39.5
Scenario 3	36.9	35.2	39.2	39.1

The decreasing of the surface temperatures, compared with those of the starting situation, is well evident, as reported in table 2, with a little prevalence of the scenario 1 (cool roofs).

With a similar statistical approach, we have performed an analysis by referring to the typical building module proposed by the Italian regulation standard [10], in order of computing the indoor surface temperatures of the ceilings (table 1) of the selected towns.

3. Simple economic appraisal

The proposed tool simply relies on the appraisal of the number of hours during which a given building requires a cooling mechanical support for maintaining the indoor comfort conditions. This duty period of the cooling system is then converted into the cost of the needed electric energy.

The method is based on the computation of the indoor surface temperature of the building ceiling. This is affected by the physical properties of the roof compound and depends on the damping of the amplitude of the outdoor temperature and on the delay in the time of the arrival at the indoor surface of the thermal wave coming from outdoors (Figure 1).

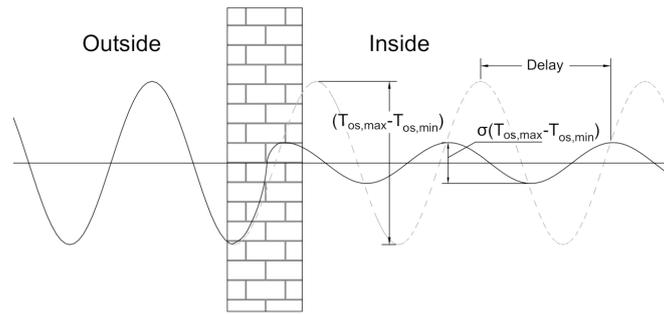


Figure 1. Indoor attenuation and delay of the outdoor heat flux.

The delay D (s) with which a heat wave reaches the indoor surface of the ceiling depends on both the thickness s_i (m) and the velocity v_i (m/s) with which the heat thermal flow crosses each layer i of the roof stratigraphy. That is:

$$D = \sum D_i = \sum (s_i/v_i) \quad (2)$$

The velocity v_i of the heat wave in each layer depends on its thermal conductivity λ_i (W/m K), on its density ρ_i (kg/m³), on its specific heat c_{pi} (J/kg K), and on the pulsation $\omega=2\pi/86400$ (s⁻¹) of the heat wave, and it is calculated as follows:

$$v_i = [\lambda_i/(\rho_i c_{pi}) 2\omega]^{1/2} \quad (3)$$

Finally, the indoor surface of the ceiling, T_{ic} , depends on the maximum ($T_{os,max}$) and minimum ($T_{os,min}$) values of roof outdoor surface temperatures and on the attenuation σ of the heat wave:

$$T_{ic} = (T_{os,max} + T_{os,min})/2 + \sigma (T_{os,max} - T_{os,min})/2 \quad (4)$$

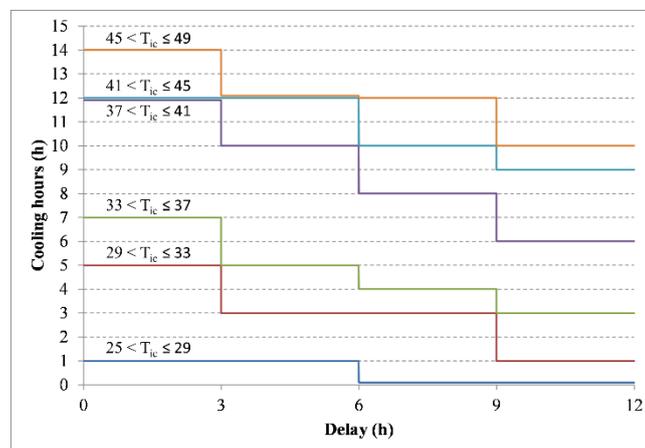


Figure 2. Cooling hours as a function of the delay time of the ceiling compounds.

The economic evaluation of the possible benefits induced by the modification of the reflectance of the roofs has been conducted in a very simplified way, by considering the “air conditioning period” of the buildings, that is the number of hours during which the HVAC systems must operate in order of maintaining the indoor air temperature at the supposed summer comfort value of 25 °C. The COP of the air conditioning system is set at 3.0, according to the statistical Italian characteristics for the installed systems in the building mainly composing the building stocks of the considered towns. The cost of the electric energy has been set at 0.22 €/kWh, according to the Italian average conditions of the energy market. Obviously, the operation time of the air conditioning system directly depends on the delay D

(Eq. 2) and the attenuation σ with which the external thermal heat is transferred to the indoor surface of the ceiling. Figure 2 illustrates this dependence for the selected case.

The application of this method allows the determination of the specific climatization costs (kWh/m^3) for the *ex-ante* and the enhanced albedo situations, for the scenarios reported in table 1 and table 2, respectively.

Figure 3 depicts the corresponding results for Palermo and Messina, characterized by a different urban shapes and built environments (Palermo is more compact, while Messina has a more diffuse layout). In other words, the urban layout strongly affects the costs referring both to the *ex-ante* and the improved conditions.

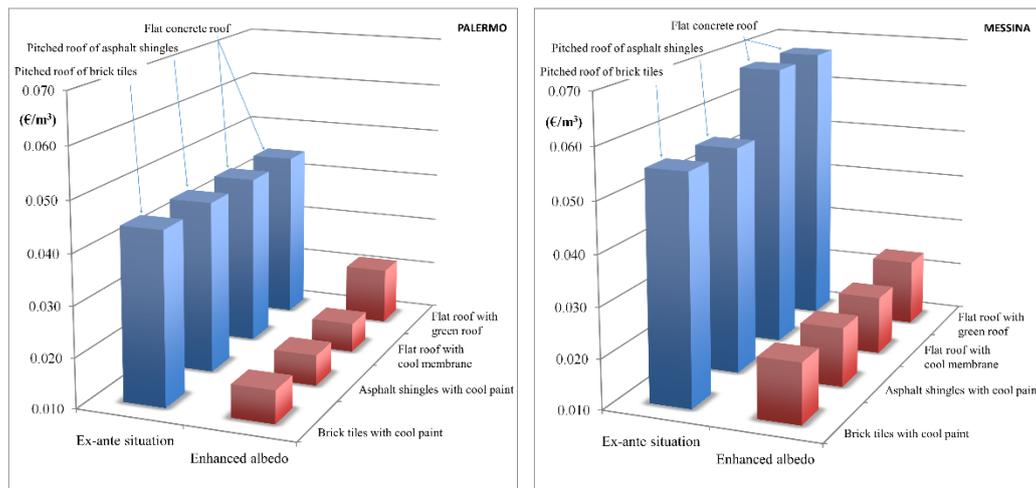


Figure 3. Costs reduction of buildings subsequent to the enhanced values of albedo.

4. Discussions and conclusions

The analysis of figure 3 indicates that the cheaper solution is given by the adoption of cool paints or cool membranes on the existing roofs, while the green roof (*sedum*, in this case) generally shows a smaller decrease of the climatization costs referring to the *ex-ante* situation. Moreover, it must be observed that the green roofs are characterized by a higher investment cost compared with those of cool paints or membrane, then leading to a higher pay-back period.

Obviously, in the present application the results of the green roofs are affected by some relevant simplifications that could affect the generality of the analysis. In fact, the energy behavior of green roofs depends on the type of the employed vegetated species that are characterized by different Leaf Area Index (LAI) values and fractional vegetation coverages. Additionally, the thermal conductivity of the soils will strongly vary with its humidity content. Finally, a standardized method for computing the whole green roof compound is not available so far, despite some popular simulation models incorporate specific routines for this building component [14].

Another simplification of the method consists in assuming the temperature of the indoor surface of the ceiling equals to that one of the indoor air temperature. In other words, the mean radiant temperature of the building enclosure is set at the same value of the air temperature. This simplification is often assumed in the building modeling; nevertheless, it could lead to unrealistic results, particularly in the cases where the building module is characterized by the presence of large radiant surfaces (windows, for example).

Anyway, the method presented here can represent a first and useful contribution in the aim of orienting city's policy makers in choosing more promising solutions in the restoration/retrofitting of large stocks of building.

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