Energy and Buildings 151 (2017) 81–97

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Optimization of roof solar reflectance under different climate conditions, occupancy, building configuration and energy systems

Cristina Piselli[a], Mohammad Saffari[b], Alvaro de Gracia[c], Anna Laura Pisello[a,d,*], Franco Cotana[a,d], Luisa F. Cabeza[b]

[a] CIRIAF – Interuniversity Research Centre, University of Perugia, Via G. Duranti 63, 06125 Perugia, Italy
[b] GREA Innovació Concurrent, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001, Lleida, Spain
[c] Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili,Av. Paisos Catalans 26, 43007 Tarragona, Spain
[d] Department of Engineering, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy

ARTICLE INFO

Article history:
Received 17 March 2017
Received in revised form 6 June 2017
Accepted 18 June 2017
Available online 20 June 2017

Keywords:
Cool roof
Solar reflectance
Energy savings
Optimization
EnergyPlus simulation
GenOpt

ABSTRACT

Cool roofs have been widely proved to represent an effective strategy for building thermal-energy performance improvement during the cooling season. However, their effectiveness along the whole year can be affected by building features and other boundary conditions. The present work aims at assessing the energy performance of high solar reflectance roof solutions in different climate zones, when implemented in a variety of building typologies. Therefore, an optimization study was carried out to select the optimum roof solar reflectance able to minimize building annual HVAC energy consumption. In this work, Italian climate zones were considered as case study conditions. The analysis was performed through dynamic simulation of validated standard ASHRAE building reference models. Moreover, the role of (i) type of HVAC system operating, (ii) presence and intensity of internal gains, and (iii) roof thermal insulation level was evaluated on the resulting optimum roof reflectance capability. Results show that the optimum roof solar reflectance varies under different climate conditions, mainly depending on heating or cooling dominated conditions. However, all further analyzed boundary conditions, i.e. building typology, HVAC system, internal gains, and roof insulation level, affect building energy performance and, therefore, the optimum roof reflectance identification. In the hottest climate, the optimum roof solar reflectance resulted to be consistently equal to the maximum considered, i.e. 0.8, also with varying the other parameters. Moreover, the annual HVAC energy need is more sensitive to roof reflectance in the apartment building, showing 17% of energy savings with standard model characteristics. On the other hand, in heating dominated climates, the optimum roof solar reflectance is more variable, ranging over all the considered values, because it is affected by the additional boundary conditions. On the contrary, the variability of HVAC need due to roof solar reflectance variation is generally lower.

1. Introduction

It is well acknowledged that the building sector in Europe accounts for about the 40% of total energy use and produces the largest contribution of global GHG emissions [1]. Moreover, in the last years the Southern European countries, e.g. Italy, Spain, etc., have been experiencing an increase in cooling energy consumption [2], which is expected to further grow up in next decades [3]. In fact, global warming and climate change are crucial issues significantly affecting the evolution of environment and human attitudes [4]. One environmental consequence is represented by the Urban Heat Island (UHI) phenomenon, namely the air temperature difference between the warmer dense urban environment and the surrounding rural and sub-urban areas. The main causes of such phenomenon and its environmental impact are the replacement of vegetation in the urban area by built surfaces, i.e. buildings and pavements, characterized by low permeability, high solar absorption, and high energy storage and heat release capability, and the anthropogenic heat release [5,6].

On the other hand, buildings represent one of the sectors with the highest potential for improving global energy efficiency and

---

[*] Corresponding author at: CIRIAF – Interuniversity Research Centre, University of Perugia, Via G. Duranti 63, 06125 Perugia, Italy.
E-mail address: anna.pisello@unipg.it (A.L. Pisello).

http://dx.doi.org/10.1016/j.enbuild.2017.06.045
0378-7788/© 2017 Elsevier B.V. All rights reserved.

sustainable development through relatively low cost strategies [7]. The enhancement of buildings fabric and systems with active and passive energy efficient technologies [8–10] or the education of occupants' behavior toward aware energy attitudes [11,12] can lead to improvements in buildings energy performance. In last decades, the challenge to cut down buildings energy consumption has led to the development of Net Positive [13] or Net Zero Energy Buildings (NZEB) [7] in compliance with the requirements of the EPBD (Energy Performance of Building Directive) 2010/31/EU of the European Union [14]. In such buildings, strongly insulated envelopes are always used with the aim of containing heat losses in the cold season and preventing heat gains by solar radiation in the hot season. Instead, high albedo materials for reducing cooling energy consumption are relatively less used as building envelope coating, because their effectiveness may be lowered when coupled with highly insulated envelopes [15,16].

However, cool materials may be effective and low cost solutions for building energy performance improvement in summer and UHI mitigation, when considered as both building skins and urban applications [17–20]. In fact, such materials are able to lower the heat released to the indoor ambient air and to the outdoor urban environment, since they present high thermal emittance and higher solar reflectance properties compared to conventional construction materials. For instance, Zinzi [21] analyzed the effectiveness of cool materials for façade applications in residential buildings in the Mediterranean region through dynamic simulation. Results showed cooling energy saving potential up to 2.9 kWh/m^2 per 0.1 increase of solar reflectance. Similarly, Marino et al. [8] simulated the indoor thermal comfort improvements and energy savings obtained by applying cool paints on walls and roof external surface, for various Italian and European cities. They were found to be up to 60%. With the aim of developing innovative cool materials for the building envelope, Antonaia et al. [22] studied the performance of high reflective commercial products not specialized for buildings, characterized by good technical properties. The sole white acrylic paint showed good values of solar reflectance (77%–80%) and thermal emittance (92%). Samani et al. [23], instead, compared cool coating with other passive cooling techniques for tackling overheating in prefabricated buildings in hot climates, finding potentialities for all considered techniques. With the aim of preventing cool surfaces darkening, Werle et al. [24] developed a cool, self-cleaning cement-based surface using TiO_2, demonstrating that photocatalytic activity is effective in keeping surfaces clean and, therefore, ensuring the maintenance of initial cool properties. Concerning cool materials UHI mitigation capability, Peron et al. [25] studied the effect of different mitigation technologies in Venice mainland (Italy) through numerical simulation. Outdoor air temperature reduction of about 4 °C was obtained by implementing cool materials and green permeable surfaces on roofs and pavements. Similar results in Italy were found by Noro and Lazzarin [26] in Padua, where they monitored and simulated the microclimate variation in a square by applying cool and green pavements. Instead, Park et al. [27] investigated pedestrians' exposure to near-roadway air pollution in idealized street-canyons, when applying building roof cooling, using a coupled CFD-chemistry model. In the presence of roof cooling, the street-canyon wind vortex strength is intensified and the air temperature near the building roof is decreased.

Among built surfaces, roofs represent about the 20%–25% in the urban area [28] and are also characterized by a higher view factor to the incoming solar radiation, especially during summer season. Therefore, cool roofs have a great potential for both building energy saving and UHI mitigation, when efficiently designed, in particular in the Mediterranean area [29]. For instance, in an in-field experimental and numerical analysis carried out in Athens, Greece, Stavrakakis et al. [30] demonstrated that cool roof ensures annual energy savings up to 7.4%, when applied in a school building with heat pump cooling system. Switching to the urban scale, Li and Norford [31] evaluated the Urban Heat Island mitigation effect of cool roofs in the tropical climate of Singapore. Results of numerical analysis showed that the reduction of near-surface air temperature and surface skin temperature due to cool roofs is significant during daytime, but almost negligible during nighttime. On the other hand, Zhang et al. [32] calculated, through a sophisticated Earth system model, that the global adoption of cool roofs in urban areas can affect the UHI everywhere, with a global annual mean temperature decrease up to 1.6 °C.

Considering in particular the Italian climate context, Zinzi and Agnoli [29] simulated the effect of cool and green roofs in the energy performance of residential buildings in different Mediterranean cities. They showed that cool roofs are the most effective strategy for the center and southern Mediterranean area, mostly in insulated houses, where the increase in heating demand is restrained. Therefore, the coupling of highly reflective coating and efficiently designed insulation seems to optimize the building annual energy performance. A similar analysis was carried out experimentally by Di Giuseppe and D'Orazio [16] for a real-scale prototype building in the northern Mediterranean city of Ancona (Italy). In this case, the effect of cool roofs on the internal comfort was found to be small with roofing systems characterized by low U-value. Different results were found by Gagliano et al. [33], who compared the energy and environmental behavior of cool, green, and traditional roofs via dynamic simulation also based on the level of thermal insulation. Green and cool roofs were shown to provide higher energy savings and environmental benefits than highly insulated standard roofs, which require a higher thickness of thermal insulation than the other two typologies to maximize their performance. Moreover, to develop durable and suitable materials for Italian historic buildings applications, different innovative cool tiles products were developed in recent works [34–37]. Moving to a more comprehensive analysis focused on the performance of cool roofs in different Italian climate contexts, Costanzo et al. [38] showed the suitability of cool roofs for annual energy saving in three Italian cities and, therefore, with different insulation levels and with different air-conditioning systems. Results confirmed the effectiveness of cool coatings in reducing energy needs for space cooling. However, the use of such materials in heating dominated regions should be preliminarily evaluated in association with high insulation levels and very efficient heating systems. Instead, Zinzi et al. [39] defined an energy-rating scheme for cool roofs application in residential buildings in different Italian climate zones based on numerical calculation results.

In this view, also the current Italian building regulation [40] (*Decreto interministeriale 26 giugno 2015 – Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici*) requires the use of relatively high reflectance coatings for both flat and sloped roofs in new constructions and buildings subjected to energy requalification. In fact, as previously shown, it is well acknowledged that cool roofs are able to reduce cooling energy requirement of buildings in the Mediterranean area. Nevertheless, in the coldest climate contexts of northern Italy, which are typically heating dominated climates, cool roof may not be the optimum solution for minimizing the annual building energy consumption. In fact, cool roof decreases heat gains through the roof and, therefore, higher amount of heat is required from the air-conditioning system during the cold season to maintain comfort conditions. To the best of the authors' knowledge, existing studies in literature focus on seasonal or annual performance of such systems in a single case study [30,31,41], while only few of them focus on the different impact of such solution in the various Italian climates [38,39]. However, none considers the insulation level in each climate according to the updated Italian