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The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring

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ABSTRACT

Cool roofs represent an innovative and relatively inexpensive technique to reduce building energy requirements for cooling and to improve indoor thermal comfort conditions. These applications primarily consist of high-reflectance and high-emissivity coatings or membranes commonly applied to the flat roofs of non-residential buildings located in both hot and mild climates. This paper discusses the possibility of applying an innovative "cool roof" solution, consisting of a prototyped cool clay tile, on a traditional residential building in central Italy to improve the thermal conditions of the indoor environment that is adjacent to the roof. In particular, the results of a two-year continuous monitoring campaign are presented. The building was monitored for an entire year in the original configuration and for another entire year in the optimized configuration, with the final objective of quantifying both the summer benefits and the winter penalties of such a solution in residential buildings in temperate climate conditions. The year-round analysis shows that the proposed cool roof solution produces a maximum effect of decreasing summer peak indoor overheating of the attic by up to 4.7 °C. The corresponding winter maximum overcooling reduction is 1.2 °C. These experimental results show that this innovative cool roof solution can be implemented on traditional sloped roofs with a clay tile covering, producing substantial benefits in summer and relatively small penalties in winter for residential buildings, even in temperate climates.

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1. Introduction

Cool roof strategies are progressively catalyzing the attention of the scientific community and the market due to their effective role in reducing building energy requirements for cooling and peak electricity demands, and mitigating urban heat island effects [1].

A cool roof technology generally consists of a roof system with a coating characterized by high solar reflectance and high thermal emissivity. When the roof is exposed to solar radiation, these two characteristics render the roof's external surface colder compared with the same roof with lower reflectance and levels of emissivity [2]. Consequently, the solar heating load that enters the indoor thermal zone is decreased.

In recent years, important experimental and numerical studies have been carried out to demonstrate cool roof efficacy in different climatological contexts [3,4] and for different construction and occupancy typologies. In particular, Kolokotsa et al. [5] analyzed the performance of a cool roof applied on a laboratory building in Crete, Greece. The dynamic simulation results showed a year-round energy conservation of 19.8% due to the cool coating application, a value greater than the benefits achievable by traditional retrofit interventions, such as those with increased envelope insulation or with window improvements. Synnefa et al. [6] evaluated the impact of the application of a cool roof membrane on the flat roof of a school building in Athens. The validated simulation results showed a 1.5–2 °C reduction in terms of indoor air temperature in summer and a reduction of approximately 0.5 °C in winter. Additionally, a 40% reduction of the cooling energy load was reported compared with a 10% increase in heating demand. Bozonnet et al. [7] studied the cool roof effect in a free-floating public housing building by using calibrated dynamic simulations in summer conditions. This group showed that the cool roof is able to decrease the daily attic peak operating temperatures by up to 8.4 °C for non-insulated roofs, even in a moderate climate condition such as that of Poitier in central France. Additionally, this research showed that the operational and occupancy conditions could significantly affect the performance evaluation of free-running areas [8,9], making the cool roof effect more difficult to identify. Another coupled experimental and numerical study was carried out by Kolokotroni et al. [10] in which the important variables were taken into account to determine the cool roof efficacy in a university building in the moderate London climate. This group reported an operative temperature decrease of 2.5 °C, with a consequent summer comfort improvement in free-floating conditions. However, this summer benefit should be compared with the relative heating penalty in the London climate, which corresponded to 10% for that case study. Particularly

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Nomenclature

BC	base case scenario
CR	cool roof scenario
$J_{OH\text{-}m}$, $J_{OC\text{-}m}$	monthly overheating and monthly overcooling indeces
n	the number of days i in each considered month m
m	the subscript m represents the month considered in the calculation
OH_m, OC_m	monthly overheating decrease and monthly overcooling increase indeces
S_{mean}, $S_{\min}$, $S_{\max}$	indexes describing the monthly daily average of overheating and minimum and minimum peaks of the indoor operative temperature
$T_{in,\text{mean}}$	mean attic operative indoor temperature calculated in the monitored year
t_m	time period of each considered month m
$T_{op,\min\text{-}i}$ $T_{op,\max\text{-}i}$, $T_{op,mean\text{-}i}$	minimum, maximum, and average values, respectively, of the operative temperature in the attic of each day i
$T_{out,\min\text{-}i}$ $T_{out,\max\text{-}i}$, $T_{out,mean\text{-}i}$	minimum, maximum, and average values, respectively, of the outdoor temperature of each day, i, during the month m
$T_{op}(\tau)$	the attic operative indoor temperature
$T_{out}(\tau)$	the outdoor dry bulb temperature

in those climate areas, which are characterized by cold winters and hot summers, important elements such as roof insulation, building occupancy, internal gains, and the inter-building context [11–13] play strategic roles in determining cool roof efficacy.

Spanning the boundaries of cool roof application to evaluate the impact of such a technology at the regional scale, Boixo et al. [14] analyzed both the environmental and economic effects of diffuse cool roof applications in Andalucía, Spain. Their results suggest that such a technology should be encouraged even in that region. However, few contributions exist on the topic of cool roof potentials applied to residential buildings. One of these contributions, by Synnefa et al. [3], consisted of an accurate dynamic simulation study aimed at investigating the cool roof effect in terms of the thermal comfort conditions and energy demand for heating and cooling and it took into account the same flat-roof house located in several climate conditions around the world. In varying climatic boundary conditions, this group showed that the cooling demand reduction was anywhere from 18% to 93%, and the hours of relative discomfort decrease by anywhere from 9% to 100%. The corresponding heating penalty was lower than the cooling benefit for the considered locations, demonstrating that the proposed cool roof coating could represent a relatively cheap and effective solution to reduce building energy requirements over a wide variety of climates.

Given the increase of the summer energy load and the peak energy demand for cooling throughout the Mediterranean basin, as well the recent Italian interest in promoting solutions for reducing cooling requirements by mitigating solar gains [15], important cool coating analyses were carried out to explore the possible effects of such a technology in the Italian climate. Particular attention was paid to residential buildings for which specifically focused design strategies can produce notable energy reduction through the exploitation of climatic natural resources, i.e., natural ventilation, careful building orientation, etc. [16]. To this aim, in their numerical study, Zinzi and Agnoli [16] showed how improvement of the roof technology, through the implementation of cool roofs in residential buildings, is able to reduce the number of hours with operative temperatures higher than 28 °C by more than 80%. Important findings also focused on the application of cool coatings, which are specific coatings developed in the last few years, which have high reflectance in the near infra-red region of the solar spectrum [17–19], to windows shutters in Italian residential buildings [20].

Most of the cool roof studies and applications were focused on cool paints and membranes implemented over flat roofs as the most economical and easy to apply cool roof technology [21]. Given the intrinsic variety of the typical constructions around the world, and, in particular, given the Italian constraint on improving the energy performance of existing buildings that are typically characterized by sloped roofs covered with clay tiles, [22], this research focuses on the possibility of application of cool roofs to existing residential buildings with sloped roofs, where common reflective coatings and membranes are not presently applicable. To this aim, the innovative contribution of this work consists of the investigation of the effect of new cool clay tiles when applied over the roof of a traditional residential building located in the temperate climate area of central Italy. Therefore, a clay tile with optimized reflectance and emissivity properties was prototyped and applied to the sloped roof of the case study house [23]. The effectiveness of such an innovative cool roof technology was carried out through a two-year continuous monitoring campaign, specifically conceived to quantify both the expected summer benefits and the relative winter penalties, given the peculiarity of the climate of central Italy, not yet been investigated in the literature.

This paper specifically focuses on the analysis of the experimental results from the monitoring campaign. The year-round effects of the prototyped cool roof system are investigated in terms of thermal behavior of the roof and thermal performance of the attic.

2. Methodology

The evaluation of the brick tile performance was carried out through an experimental monitoring campaign, whose results are analyzed by means of concise analytical indices defined for the purpose. The main steps of the research are schematically described as follows:

(i) Development of the prototype: preliminary in-lab experimental analysis for the elaboration of the industrial prototype of "cool tile".
(ii) Continuous monitoring of the Base Case (*BC*) scenario: year-long continuous monitoring of the thermal performance of the roof and the attic in *BC* configuration.
(iii) Continuous monitoring of the Cool Roof (*CR*) scenario: year-long continuous monitoring of the thermal performance of the roof and the attic in *CR* configuration.
(iv) Data analysis procedure: analytical procedure to evaluate the year-round benefits and penalties that are imputable to cool roof implementation.
(v) Analysis of the results.

The experimental part of the research was carried out through a combination of in-lab and in-situ analysis. The purpose of the preliminary in-lab analysis was the elaboration of the prototype of an innovative reflective tile using measurements of reflectance and emissivity to determine the Solar Reflection Index (SRI) properties of the tiles [24,25]. The in-situ analysis consisted of the study of the two-year continuous monitoring results with respect to the effect of tile on the indoor thermal behavior of the case study building, which represents the main contribution of this work.

2.1. Laboratory characterization of the prototype

The development of the prototype consists of a preliminary in-lab experimental campaign aimed at characterizing the

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