

Thermal-energy analysis of roof cool clay tiles for application in historic buildings and cities



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ARTICLE INFO

Article history:

Received 21 November 2014
Received in revised form 6 February 2015
Accepted 10 March 2015
Available online 23 March 2015

Keywords:

Cool roofs
Urban heat island
Energy efficiency in buildings

ABSTRACT

More than 90% of historic buildings have traditional clay tiles as roof covering exposed to solar radiation, largely impacting buildings' thermal-energy performance and urban climate, since most of historic buildings are located in dense urban contexts. In this view, the optimization of these traditional elements could represent a key research issue, with the purpose of building energy retrofit and the constraint to preserve architectural heritage. This paper concerns the year-round analysis of the thermal-energy performance of a typical 16th century historic residential building located in central Italy where an innovative cool clay tile is installed in a continuously monitored two-floor residential unit. Main results show that the proposed tiles, having good visual similarity with respect to the classic tiles, represent an effective solution to improve building energy efficiency during the cooling season and, if applied at larger scale, they could represent an effective UHI mitigation technique. In particular, maximum primary energy saving for cooling is 51%, while heating energy penalty is lower than 2%. The combined multi-scale analysis finally showed how these tiles represent an effective non-invasive strategy to (i) optimize thermal-energy performance of historic buildings even in temperate climate, and to (ii) mitigate urban climate.

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Nomenclature

Abbreviations

T_{op}	operative temperature (°C)
T_{air}	indoor air temperature (°C)
T_m	mean radiant temperature (°C)
$Q_{heating}$	energy requirement for heating (kWh)
$Q_{cooling}$	energy requirement for cooling (kWh)

1. Introduction

Dense and highly populated urban environment, typical of city centers around the world (Salata, De Lieto Vollaro, De Lieto Vollaro, & Mancieri, 2014), are responsible for specific “urban microclimate” phenomena such as urban heat island (Borbora & Das, 2014). Such phenomena impact both human attitudes and health conditions, produce non-negligible increase of buildings energy need for cooling and CO_{2eq} gases emissions (Tsilini, Papantoniou, Kolokotsa, & Maria, 2015; Coma, Pérez, Castell, Solé, & Cabeza, 2014). An

acknowledged methodology to reduce urban overheating is represented by bioclimatic design and passive high albedo (Wang & Akbari, 2014) or “green” solutions (Goussous, Siam, & Alzoubi, 2014).

The investigation of innovative passive low-impact solutions for building energy efficiency in summer are becoming always more important especially in urban areas where more than half of the world's population lives (Paolini, Mainini, Poli, & Vercesi, 2014). In fact, in urban areas, anthropogenic heat released by constructions increases in summer (Gros, Bozonnet, & Inard, 2014) given the huge households energy requirement for cooling (Bellia, De Falco, & Minichiello, 2013) and their increased level of indoor thermal comfort expectation (Moreno, Castell, Solé, Zsembinszki, & Cabeza, 2014).

In this view, building scale and district scale solutions such as urban landscaping, high albedo surfaces and vegetated areas showed to be successful in mitigating urban heat island effect, producing both direct and indirect benefits in urban livability and improvement of building energy efficiency. A specific acknowledged technique in this field is represented by cool roofs (Dimoudi et al., 2014; Gros et al., 2014). These roofs, in fact, present high solar reflectance and high thermal emittance and they are able to reflect the solar radiation, with the consequent reduction of roof overheating and solar gain entering the attic through the roof (Synnefa, Saliari, & Santamouris, 2012). The benefits of this technique have

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been widely investigated all over the world during last decades through both numerical and experimental studies (Kolokotsa et al., 2012). Main results showed important benefits in terms of energy saving for cooling in residential buildings (Synnefa, Santamouris, & Akbari, 2007a) and office buildings (Levinson & Akbari, 2010). Cool roofs and cool materials in general, also present important inter-building benefits at larger scale, by reducing urban overheating especially in dense urban environment (Pisello, Castaldo, Poli, Cotana, & Cotana, 2014; Santamouris, Synnefa, & Karlessi, 2011) and by mitigating global warming (Cotana, Pisello, Moretti, & Buratti, 2014; Cotana et al., 2014b). Given the high potential of cool coatings and cool membranes, which reached competitive cost–benefits balance, the principal application of cool roofs concerned high reflectance materials for application over flat roofs of new or non-historic buildings all over the world, also for the easier and cheaper installation procedure (Bozonnet, Doya, & Allard, 2011).

In this view, the recent registered increase of cooling demand in Italy and the huge amount of cultural heritage buildings in dense urban areas opened the perspective of cool roof application in those buildings which are considered very difficult to improve in terms of energy efficiency, given the rigorous architectural preservation measures. This research lack showed to be even more urgent, since most of historic buildings are located in ancient city centers, typically also affected by local peculiar climate conditions such as urban heat island phenomenon (Busato, Lazzarin, & Noro, 2014; Giannopoulou et al., 2014). In this specific field of application, therefore, cool roof solutions, should be specifically designed in order to preserve the architectural heritage, and at the same time, to reduce cooling energy consumption or to optimize indoor thermal comfort in free-floating conditions. With the purpose to reduce the visual impact of these applications, that are typically light in color (Pisello, Cotana, Nicolini, & Brinchi, 2013; Ferrari, Libbra, Muscio, & Siligardi, 2013), recent research contributions described the elaboration of cool coatings with high reflectance capability but with similar visible appearance to the one of existing traditional roof covering (Synnefa, Santamouris, & Apostolakis, 2007b).

Given the Italian peculiar characterization of roof covering, basically concerning clay tiles for more than 90% of sloped roof surfaces, this key research focus was specifically directed toward the development of “cool” clay tiles with classic visual appearance, in order to be suitable for application in traditional or hedged-in buildings (Pisello et al., 2013; Libbra, Tarozzi, Muscio, & Corticelli, 2011; Libbra, Muscio, Siligardi, & Tartarini, 2012). Particular attention has been paid to historic buildings. In fact, historic buildings in Italy are often occupied by households or public and private offices, where low-efficiency solutions are mainly implemented. Therefore, even larger importance should be dedicated to passive solutions, which could be sufficient by themselves to maintain indoor thermal comfort in many Italian climate conditions. Additionally, in those thermal zones where internal gains are typically not too large, e.g. bedrooms, connections areas, etc. or where the occupancy is limited to specific short periods of the day, strategic passive methods could represent a key improvement solution (Ghaffarian Hoseini et al., 2013).

In this panorama, as already mentioned, given the large majority of buildings with clay tile covering, the study of cool roof solutions suitable for application in historic buildings represents a key environmental issue, in particular for multiple benefits such as (i) cooling energy saving, (ii) reduction of summer peak loads and grid request, and mitigation of climate change phenomena at urban and larger scales.

In this view, starting from previous contribution by the author about the prototyping process of cool clay tiles for historic buildings (Pisello et al., 2013), their comparative performance is evaluated in a typical historic residential building in the city center of Perugia,

Italy, located in central Italy temperate climate area. The comparative assessment between traditional and innovative tiles is carried out through calibrated and validated dynamic simulation method. In fact, the case study building has been continuously monitored during summer 2013 in order to calibrate and validate the dynamic simulation model of the palace (4-floor building), where the apartment is located. The thermal-energy assessment is finally operated in order to estimate both summer benefits and winter penalties of the innovative tile in the attic thermal zone. By enlarging the applicability perspective to district level by considering all the residential buildings located within the urban walls of the historic city area, the effect of the proposed tile is also assessed in terms of (i) electricity need for cooling, (ii) consequent reduction of carbon emission and (iii) money saving.

2. Methodology

This research starts from previous findings concerning the elaboration and in-lab characterization of innovative reflective clay tiles for application to existing or historic buildings (Pisello et al., 2013). The most performing tile samples are here collected and described through the dynamic simulation engine (UIUC, LBNL, 2005) and their performance is then evaluated. The building-scale performance of these selected tiles is assessed during the course of the year in order to study their effect in optimizing the attic thermal performance and its energy efficiency by taking into account primary energy requirement for cooling and heating. The case study duplex apartment has been continuously monitored in order to calibrate and validate the dynamic simulation model of the construction, representative of residential construction typicality in historic Italian city centers. Therefore, by assuming similar results in other equivalent historic buildings with residential use, an economic and environmental analysis is carried out. In particular, the corresponding CO_{2eq} emission reduction due to the cooling energy saving is estimated at historic district level.

The detailed research procedure is reported as follows:

- (i) Choice of high performing cool tiles, suitable for application in historic buildings, after in-lab analysis and optimization of highly reflective coatings for clay tiles (Pisello et al., 2013).
- (ii) Choice of the case study historic building, where implementing the numerical and experimental campaign. The choice was guided by in-situ observation and inspection in order to evaluate the construction typicality of ancient city centers.
- (iii) Thermal continuous monitoring of the building by means of thermal probes positioned in the main floor and in the attic, in order to allow the calibration procedure. The main thermal zones of the duplex apartment were monitored, in order to describe both the thermal behavior of the lower and the upper floor, adjacent to the roof, more sensitive to the application of cool tiles.
- (iv) Elaboration of the dynamic simulation model and calibration-validation iterative procedure. Materials and boundary conditions were described within EnergyPlus environment and specific iterative calibration procedure was performed. Given the specific considerations on historic buildings, and the lack of information about envelope systems and materials, several assumptions were carried out by mean of in-field analysis.
- (v) Selection of the final reliable prediction model, after iterative calibration procedure.
- (vi) Year-round thermal-energy performance simulation of 4 scenarios, i.e. the case study apartment with the 4 selected tiles. Indoor thermal behavior and primary energy requirement of the attic were selected as the key variable to study in order to identify the effect of the clay tiles.



Fig. 1. Aerial view of the city historic center (a) where the case study is located (b)

- (vii) Analysis of the results in both free floating and controlled thermal conditions of the attic. The free floating analysis aimed at determining the passive cooling contribution produced by the cool clay tiles. The analysis of the results from numerical analysis was useful to evaluate possible energy optimization opportunities at building and urban scale.
- (viii) Geographical analysis of the urban environment with similar characteristics with respect to the case study building. GIS systems were used to identify the urban historic area where the effects of the proposed study could be generalized and applied.
- (ix) Preliminary urban-scale assessment of the issue: economic and environmental perspective. By assuming the equivalent conditions of the case study within the ancient walls of the city, a reference global surface of residential buildings covered by clay tiles' roof was identified and an overall environmental and economic assessment was carried out.

Given the specific peculiarities of historic buildings and the lack of technical details about materials characteristics and design document, the model calibration is performed by considering observations carried out by mean of in-field analysis. In particular, occupancy and the interaction of the constructions located in close proximity of the apartment represented the calibration parameters. The methodology proposed in (ASHRAE, 2002) was pursued by selecting indoor air temperature as calibration parameter, while more advanced calibration techniques based on energy management system and HVAC requirement (Hopkins, Lekov, Lutz, & Rosenquist, 2011; O'Neill & Eisenhower, 2013; Milaii & Zmeureanu, 2013) were considered as not applicable in such building type, given also the experimental data monitored in only free floating conditions.

3. Case study

3.1. Criteria for the case study selection

The analysis of the effect of the proposed cool tiles for historic buildings is evaluated in a traditional residential four-floor building in the historic center of Perugia, in central Italy. The building, such as the roof typology, has been chosen for its typicality in Italian ancient urban context and for the possibility to continuously monitor the attic, i.e. the thermal zone adjacent to the optimized roof. Additionally, the implementation of the campaign is motivated by the extremely low thermal performance of such attics in summer, since most of historic buildings have non-insulated and highly absorptive walls and roofs. Therefore, also the impact at district scale of the proposed tile is assessed, by focusing on the ancient city center included within the Middle-Age urban walls.

About the specific tile, the main selection criterion consisted of tile reflectance capability, together with the chance to apply such roof covering in historic buildings, according to the constraints

imposed by the public office for architectural preservation of the city of Perugia, Italy, where the building is located. In particular, the local policy of architectural heritage preservation requires the implementation of clay-based tiles with similar visual appearance with respect to traditional, original ancient tiles. Additionally, while elaborating the cool coating, only “natural” pigments could be used and the original iron-based yellow, red, and brown pigments were used for preparing the colored cool coating for tiles. Therefore, the three main constraints considered in the analysis consisted of: (i) the material of the tile, (ii) the composition of the coating to apply over the clay tile, and (iii) the color/visual appearance of the surface exposed to solar radiation were considered while selecting the low-impact cool covering for historic buildings. To this aim, 4 clay tiles' typologies (Pisello et al., 2013) were evaluated and compared in terms of their thermal-energy performance in the attic in summer and winter conditions in the climate of Perugia, Italy.

3.2. Description of the building

Before the beginning of the dynamic model elaboration in simulation environment, an architectural field survey was completed about the entire residential unit. The monitored residential unit is a 112 m² apartment occupying two floors of an ancient palace in the historic center of the city (Fig. 1). The palace original structure and layout dates at 16th century. A major renovation of the building, and the division of the overall surface in 12 residential units was carried out in 2000. During that retrofit intervention, the attics of the building were retrofitted, the clay tiles were partially renovated, and some roof windows were installed, in the monitored apartment as well (Fig. 2). No insulation panel was applied in order to preserve the original stone façade of the building and the internal appearance of the roof. The windows were substituted and wood frame new windows with double glass system were installed. The monitored apartment is a duplex apartment where the lower floor occupies 75 m² and the upper floor, i.e. the attic, occupies 37 m². In the lower floor, there are: the kitchen, the living room open space, one large bedroom, one bathroom, a connection area and a small terrace. The attic is an open space living room or bedroom for hosts, with a bathroom. Given the huge wall structure, and the massive inter-building concentration in the dense area, the house is pretty dark, since daylight and solar gains are obstructed by the presence of surrounding buildings.

3.3. Analysis of the urban context

Since the purpose of the study was to propose and to evaluate the year-round effects of a cool clay tile for application in historic buildings, the analysis at urban scale is aimed at assessing the overall energy, environmental and economic consequences of the application of such non-invasive tiles in all the residential buildings within the ancient city walls. To this aim, geographic

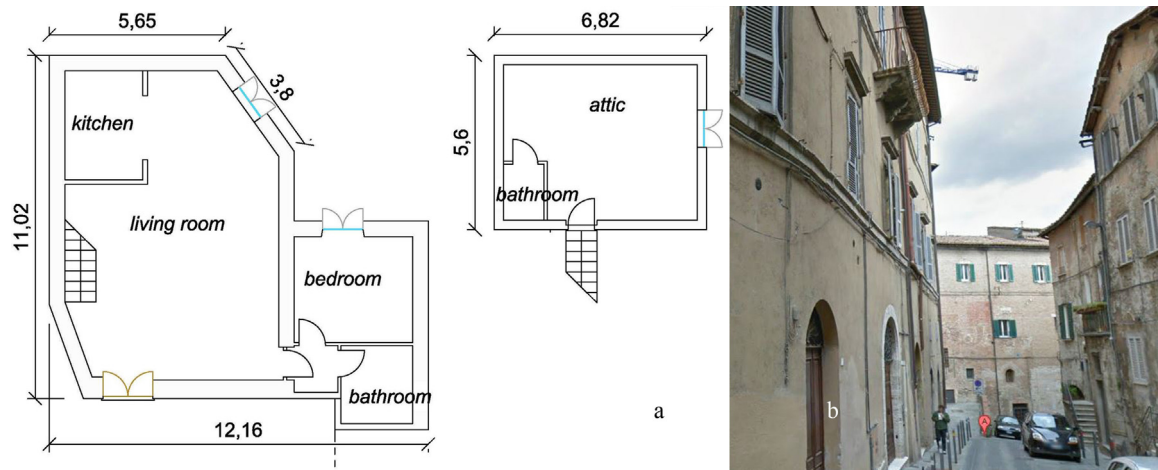


Fig. 2. Case study complex building. Plan of the two floors—measures in meters (a) and view from the street (b).

methodology was used in order to outline the wall line and to quantify the available roof surfaces covered by clay tiles within the line space. Consistently with the research objectives, the considered roofs were the only roofs of residential buildings were the attic thermal zones were occupied by dwelling activities. In this view, geographical systems analyses were combined with field inspection of the sites and analysis of the urban local regulation reporting the final uses of buildings in each investigated area of the city.

3.4. Modeling and calibration procedure

The first model of the building, before the calibration, precisely reported all the characteristics of the apartment. After the analysis of the first output during the monitored period, many modifications were necessary in order to reach suitable values of the driving calibration parameters, i.e. RME and $C_V(\text{RMSE})$ (ASHRAE, 2002; Pisello et al., 2014). In order to minimize the sources of discrepancy due to weather peculiar condition of the monitored period, a dedicated custom-made weather file was developed by considering the key weather parameters monitored by mean of a dedicated weather station located in close proximity to the case study building. All the details of instruments and weather parameters are reported in previous works by the same author (Cotana et al., 2014a,b). In fact, the monitored air temperature, in both the attic and the lower floor open space showed that the indoor environment was just quite a little affected by daily temperature and sun radiation fluctuation. The thermal capacity of the 1 meter thickness walls, the low solar gain due to the dense urban geometry of the city center, the presence of internal covered courtyards at each floor of the palace, separating each apartment from the outside environment, guided the iterative calibration procedure.

In fact, the first model reported both RME and $C_V(\text{RMSE})$ higher than 3°C , with larger discrepancies during the central hours of the day, when the model predicted an air temperature increase due to solar gains and outdoor overheating, that the real building does not register. Therefore, model 2 was elaborated by increasing the thermal insulation of doors and by decreasing the solar gain entering the windows. Model 3 was elaborated, starting from model 2, by completely withdrawing indoor thermal gains due to occupancy. This choice was motivated by the fact that the apartment occupancy during the monitored summer was very low in terms of timing schedule and internal gains due to activities. Occupants were only two people, rarely cooking or turning on high gain equipment, e.g. computers, etc. Model 4 was elaborated by enlarging the wall thickness of 0.2 m, accounting for further thermal capacity of the overall structure of the walls and ceiling partially modified

during the course of the centuries, and difficult to identify, given the completely absence of technical design documents. Last model, the final model 5, was elaborated by reducing the natural infiltration of model 4 from 0.7 vol/h to 0.2 vol/h. This was motivated by the important protection of the surrounding buildings and residential units facing the only three windows of the monitored apartment. This model presented a RME of -0.9°C , and a $C_V(\text{RMSE})$ of 1.2°C , calculated on 10-min time step measured air temperature of both the attic and the living room thermal zone of the residential unit by mean of equations (1–2, ASHRAE, 2002). The main characteristics of the envelope are reported in Table 1.

$$\text{MBE} = \frac{\sum_{i=1}^{N_p} (M_i - S_i)}{\sum_{i=1}^{N_p} M_i} \quad [-] \quad (1)$$

$$C_V\text{RMSE}_{(p)} = \frac{\sqrt{\sum_{i=1}^{N_p} ((M_i - S_i)^2 / N_p)}}{\bar{M}_p} \quad [-] \quad (2)$$

where

$$\bar{M}_p = \frac{\sum_{i=1}^{N_p} M_i}{N_p} \quad [\text{kW h}] \quad (3)$$

M_i, S_i = measured and simulated data at instance i respectively;
 p = time interval—duration of the monitoring for calibration period;
 N_p = number of values in interval p ; and \bar{M}_p = average measured data.

After the definition of the calibrated model ready for performing thermal-energy assessment of the cool clay solution, the TMY reference weather file of the city was used in order to generalize the results by considering Typical Meteorological Year data (EnergyPlus, 2015).

3.5. Characteristics of the tiles

The elaborated tiles compared in this analysis were 4 clay tiles (Fig. 3) coated with different techniques, and in-lab tested through spectrophotometer and emissometer (Pisello et al., 2013).

- Tile A is the natural un-coated clay tile, which original color is brown-red, and it appears as a new tile, before natural or artificial aging process.
- Tile B is obtained from natural Tile A, by coating this same tile with, first, a titanium dioxide engobe and, second, with a pigmented top coat with commercial white opaque stabilized potassium silicate-based binder and mineral pigments in these

Table 1
Main thermal–technical features of modeled façade elements.

Facade elements	Layers	Thermal properties (EN ISO 6946)
External walls	1. Masonry—heavyweight dry [0.5 m] 2. Masonry—heavyweight dry [0.5 m] 3. Gypsum plastering [0.02 m]	U value: 0.904 W/(m ² K) K_m internal heat capacity: 151 kJ/(m ² K)
Internal partitions	1. Gypsum plasterboard [0.015 m] 2. Brickwork, inner leaf [0.1 m] 3. Gypsum plasterboard [0.015 m]	U value: 1.847 W/(m ² K) K_m internal heat capacity: 129 kJ/(m ² K)
Sloped roof	1. Brick tile [0.03 m] 2. Air gap [0.02 m] 3. Waterproof membrane [0.005 m] 4. Brickwork, inner leaf [0.5 m] 5. Cement plaster [0.03 m]	U value: 2.180 W/(m ² K) K_m internal heat capacity: 81 kJ/(m ² K)
Floor	1. Gypsum plasterboard [0.015 m] 2. Concrete block [0.20 m] 3. Neoprene [0.005 m] 4. Ceramic/clay tile [0.01 m]	U value: 1.323 W/(m ² K) K_m internal heat capacity: 148 kJ/(m ² K)
Windows and roof windows	1. Generic clear glass [0.006 m] 2. Air gas camera [0.012 m] 3. Generic clear glass [0.006 m]	U value: 2.685 W/(m ² K) Direct solar transmission: 0.604 Light transmission: 0.781 Total solar transmission SHGC: 0.703

quantities: 7.2 g of iron oxide-based yellow, 0.6 g of red in 100 g of opaque binder.

- Tile C is obtained from Tile A, with the same engobe of Tile B, but with different pigmented top coat mixture. This top coat presents the same commercial white opaque stabilized potassium silicate-based binder of Tile B, but it is characterized by different mineral pigments quantities: i.e. 7.2 g of iron oxide-based yellow, 1.4 g of red, 1 g of brown in 100 g of opaque binder. It presents a darker color than Tile B, and the visual appearance is very much similar to the one of original clay tile (Tile A).
- Tile D is obtained from Tile A, with the previously mentioned engobe, and it is covered through a thin layer of top coat, where the binder is a self-made sodium silicate-based binder in water. It presents the same relative presence of pigments of Tile C, because of the good visual appearance result of Tile C, but very lower concentration of this pigments. In particular, given the transparency of the new self-made binder, lower concentration of pigments was necessary to obtain similar visual appearance. In fact, the pigment quantity was: 0.72 g of yellow, 0.14 g of red, and 0.16 of brown pigment in 100 g of binder. The solar reflectance characteristics of the tiles, calculated with reference to the solar spectrum in (ASTM G173, 2003), described in the dynamic simulation model, are reported in Table 2.

4. Analysis of results

4.1. Comparative thermal analysis of the roof scenarios

The overall year-long characterization of the 4 scenarios is reported in Fig. 4. In the graphs, the monthly average main parameters are described with reference to the outdoor dry bulb temperature of the case study city, as reported in the simulation

weather file. The thermal set-point was setup on the indoor air temperature T_{air} of the attic, which winter set-point corresponds to 20 °C and the summer set-point corresponds to 26 °C. It is evident that winter energy requirement for heating is very much higher than summer cooling need of the attic in the climate context of Perugia. Additionally, the thermal behavior of the attic shows that, when the air-conditioning system is operative, the temperature profiles does not vary very much, with varying tile reflectance. Nevertheless, non-negligible difference is registered in terms of mean radiant temperature T_{rad} in July, when Scenario Tile A presents higher T_{rad} by 1 °C. In winter, on the contrary, the same difference is less than 0.1 °C.

The daily analysis carried out in winter (January 21st) in Fig. 5 reports the thermal and energy trends in January 21st for the 4 scenarios, and consistent results are showed with respect to the monthly values. Additionally, the profiles of July 7th are also showed in Fig. 6 for summer analysis purpose. The graphs reports an important difference in terms of cooling requirement of the optimized Tile B with respect to the natural red clay Tile A, which presents the highest energy requirement for cooling. This discrepancy is even more important during the afternoon, when the reflective tile contributes to the overheating reduction of the West-oriented roof face and of the downward indoor environment, while the traditional tile produces important energy requirement, i.e. extra 37%, to maintain the air temperature at 26 °C. Mean radiant temperature T_{rad} of the attic is very much impacted by the roof overheating, which determines also hotter thermal perception in terms of operative temperature T_{op} by almost 1 °C, mainly producing higher discomfort conditions for attic occupants.

Fig. 7 reports the distribution of the attic year-round air temperature in different thermal 1 °C-ranges as quantitative categorical values. The height of each column indicates the size of the

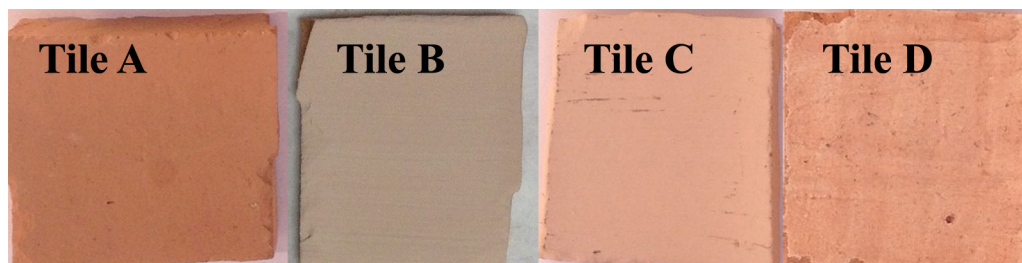


Fig. 3. The chosen 4 tile prototypes for the thermal-energy analysis.

Table 2
Solar reflectance and emittance of the chosen tile samples.

Tiles	UV reflectance [%]	VIS reflectance [%]	NIR reflectance [%]	SOL reflectance [%]	Thermal emittance [%]
Tile A	8.8	31.1	65.9	45	88
Tile B	8.1	59.1	81.8	67	88
Tile C	7.7	48.4	73.1	58	88
Tile D	20.1	40.0	74.7	58	88

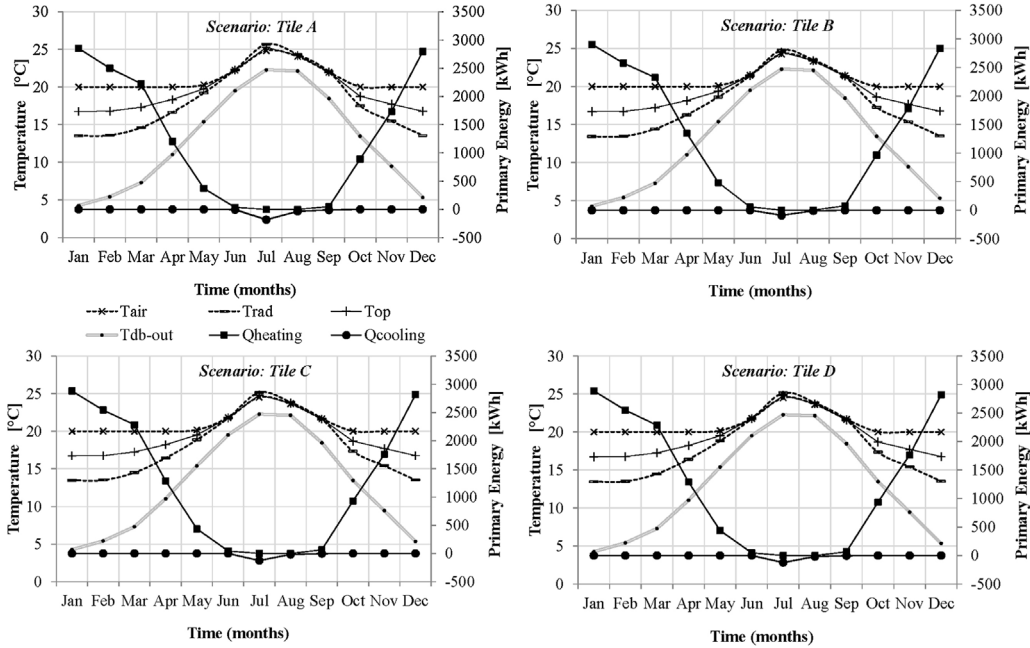


Fig. 4. Year-round characterization of the 4 scenarios.

air-temperature values' group, for each tile typology (different color), in each temperature category. The graph shows how the application of the B optimized tile is able to increase the most probable temperature value in summer overheating period by 35%, i.e.

from 500 h to 327 h in the temperature range $26^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$. Additionally, huge overheating conditions are almost negligible since Tile B is characterized by only 39 h over 30°C versus 109 h of Tile A. On the contrary, in winter, the cumulative number of hours when

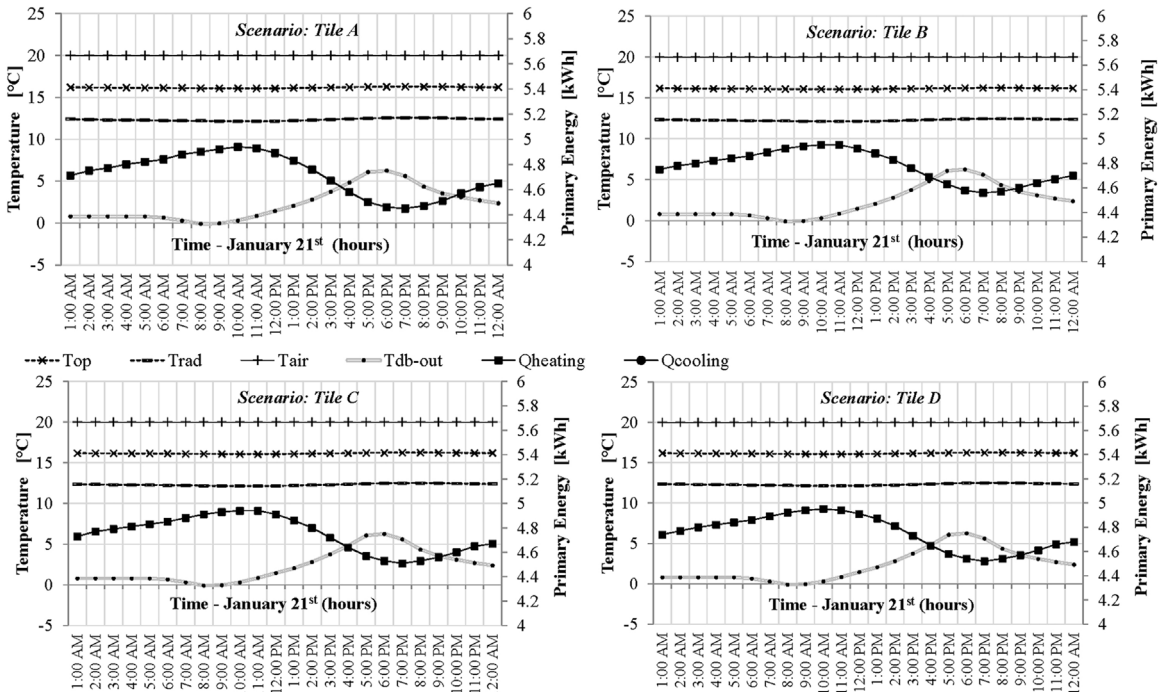


Fig. 5. Daily characterization of the 4 scenarios in winter (January 21st).

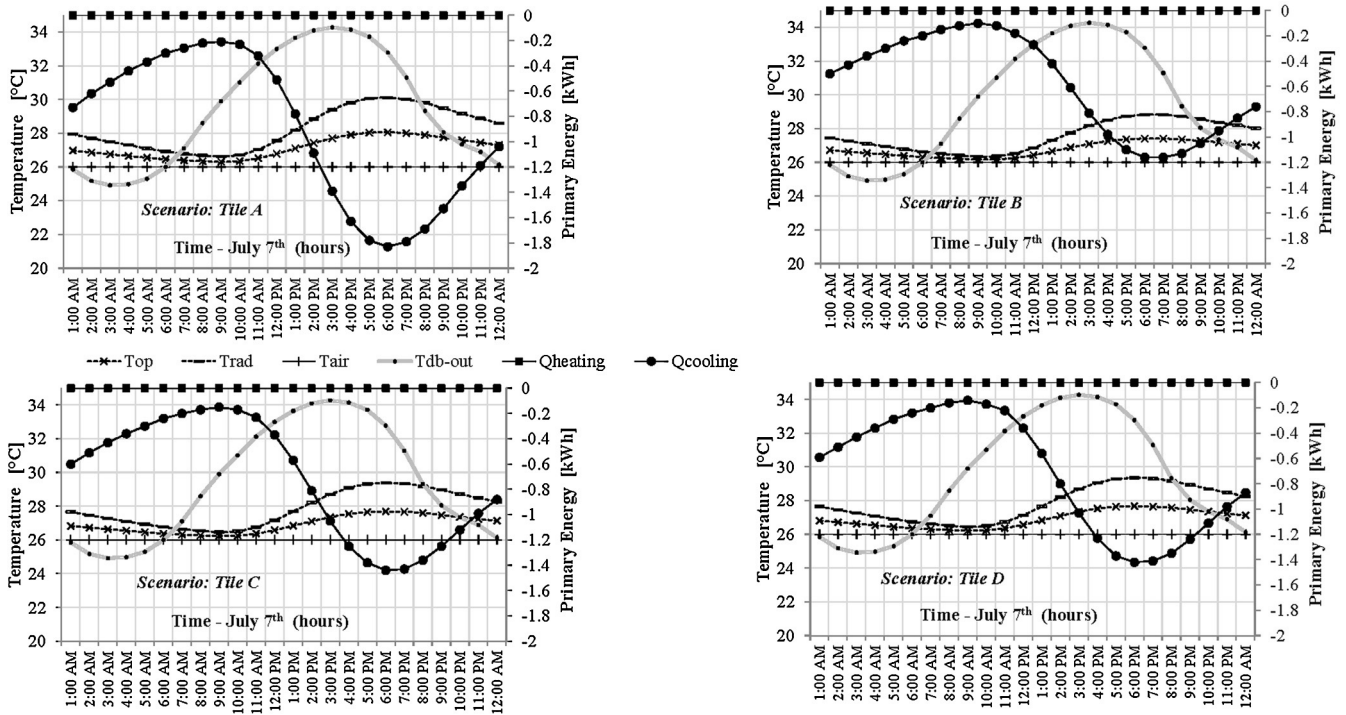


Fig. 6. Daily characterization of the 4 scenarios in summer (July 7th).

the heating system should be turned on, i.e. when T_{air-in} is lower than $18\text{ }^{\circ}\text{C}$, decreases by 3.6% (5128 h vs. 5315), from Tile A to Tile B.

4.2. Energy analysis for heating and cooling

The primary energy requirement for heating and cooling is reported in Fig. 8, for the attic thermal zone, when the 4 scenarios are simulated. In order to analyze a HVAC-independent configuration, the only primary energy requirement performance indicator was mentioned in this analysis. As mainly visible, the energy consumption for heating is not clearly impacted by the tile variation. The main difference is registered in January, the coldest month, but it is always lower than 2%, even while comparing Tile A with Tile B, which present the largest reflectance difference. In summer conditions, the energy requirement for cooling is radically impacted by the cool tile application. Tile B is able to decrease this need of 51%,

Tile C and Tile D of 33% and 32% respectively, with respect to Tile A scenario.

4.3. Thermal analysis in free floating conditions

The indoor operative temperature T_{op} , the air temperature T_{air} and the mean radiant temperature T_{mr} of the attic thermal zone are here analyzed in order to evaluate the impact of the proposed tile in summer and winter condition. To this aim, the same calibrated model is now run by turning off all the air conditioning systems in the monitored apartment, in order to simulate free floating conditions of the case study.

Fig. 9 reports the number of hours when the attic is hotter than $26\text{ }^{\circ}\text{C}$ in summer and when it is colder than $20\text{ }^{\circ}\text{C}$ in winter. It is possible to see that the number of winter non-comfortable hours is very much higher than summer overheating for the climate of Perugia. In such heating-dominated climate, cool roof application

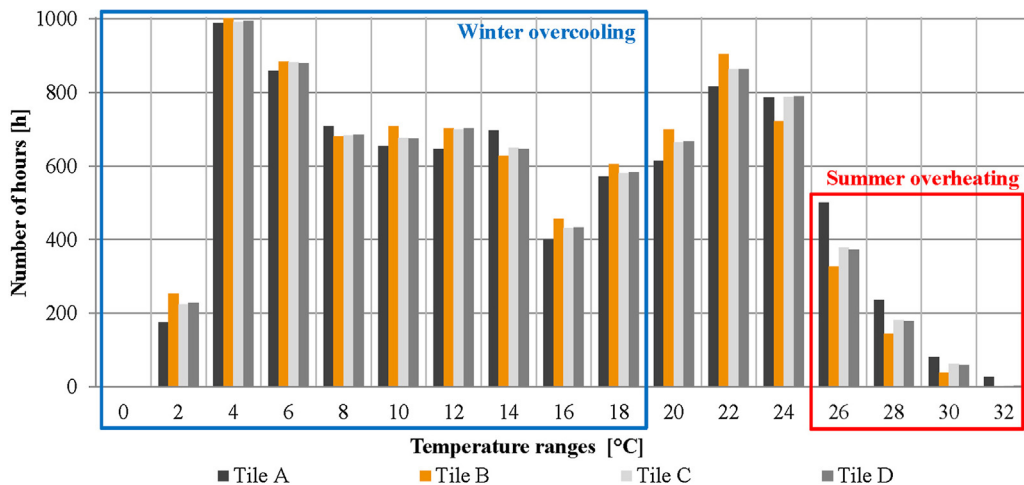


Fig. 7. Distribution of attic indoor air temperature during the course of the year.

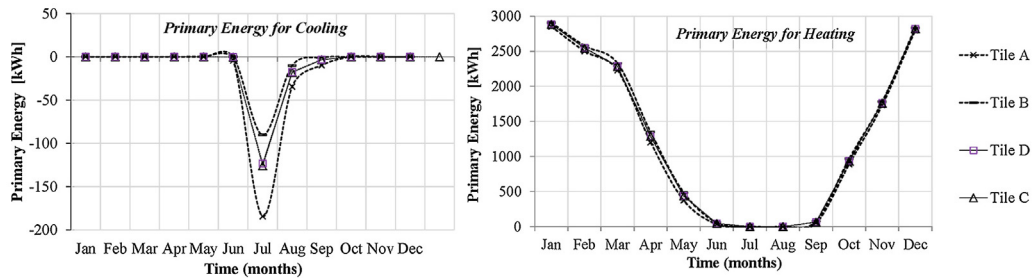


Fig. 8. Comparison between the 4 scenarios in terms of primary energy requirement.

Table 3
Degree hours in terms of operative indoor temperature top of the attic.

Scenarios	Degree hours [$^{\circ}\text{C} \times \text{h}$]	
	Winter	Summer
Tile A	55,957	993
Tile B	57,920	465
Tile C	57,074	659
Tile D	57,174	645

could be considered as useless or even penalizing from a generic energy point of view. On the contrary, cool tiles' effect in winter is almost negligible, increasing the overcooling hours by only 1%. Also, from a technology point of view, design and implementation of winter plants should not take into account about cool tiles. On the other hand, summer overheating could be radically affected by cool tile as passive cooling technique. In fact, the number of hours when the attic is hotter than 26°C in terms of T_{op} , decreased by 40% from Tile A to Tile B, and of 25% for Tiles C–D with respect to Tile A.

Degree hours (DH) in winter and summer are also calculated, as reported in Table 3. The degree hours are calculated as the product of hourly temperature difference between actual temperature and temperature set-point in winter and summer, i.e. 20°C and 26°C , respectively. In this analysis, the effect of cool roof application is even relatively higher, given that the degree hours difference is around 4% in winter and 53% in summer, by comparing Tile A and Tile B. This shows that the cool roof application is even more effective in decreasing indoor operative temperature peaks during the hottest hours of the day.

4.4. Economic and environmental impact of the cool tiles at district scale

As previously mentioned, the proposed tile is thought to be implemented in historic buildings at urban scale. To this aim, a preliminary evaluation of the district effect of such application in the city center of Perugia is dealt with in this section. Geographical techniques allowed to quantify the overall available roof surfaces covered by clay tiles occupied by the only residential buildings with dwellings occupying the attic thermal zones. Fig. 10 represents the geographical boundary of this analysis (thick line covering the city ancient walls). In this geographical boundary, about 240,000 square meters of roof with the selected characteristics were estimated. Equivalent dwelling energy requirement to the one of the chosen case study building were assumed, for simplicity of calculation and with the final aim to find out the order of magnitude of the effects produced by the cool tile. Therefore, by assuming a summer energy saving of 3.97 kWh/m^2 as previously calculated for the only period July–August where non-negligible differences were found, the energy saving at district level corresponded to 952,000 kWh. By considering the only economic point of view, it corresponded to an overall money saving of 195,301 euro that could be invested by public administrations or private citizens. Additionally, since the majority of electricity demand in summer is concentrated in the central sunny hours of the day, the reduction of this energy demand also produces non-negligible further benefits non-investigated here. Going back to the single building scale, assuming the energy consumption for cooling equivalent to the case study ones, each attic of 100 m^2 showed to save around 397 kWh in the period July–August, with a corresponding direct money saving of 81.3 euro for the only July–August period every year.

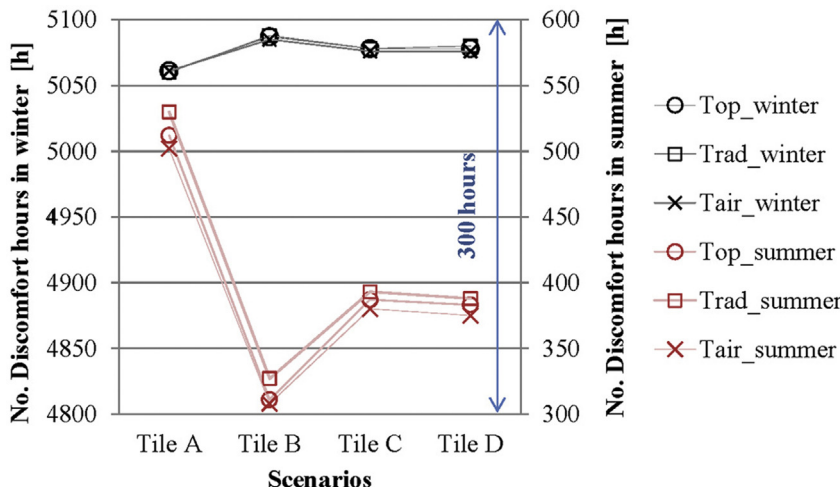


Fig. 9. Number of hours where temperature is outside the set-point range.



Fig. 10. Geographical boundary of the historic district where residential units were considered.

By considering now the emission factor for electrical consumption in Italy corresponding to $0.386 \text{ kg}_{\text{CO}_2\text{eq}}/\text{kWh}$, the application of the cool clay tile could be estimated at district scale (Fig. 10) for residential buildings. By assuming the same energy saving for cooling in July–August in Perugia, the application of the clay tile would be able to reduce carbon emissions by $367 \text{ t}_{\text{CO}_2\text{eq}}$ for the only period July–August compared to the traditional clay tiles.

It should be also said that the economic price of the prototyped tile is equivalent to the one of “fake aged” tiles at the moment. Therefore, the application of the proposed cool tile does not produce any further investment in retrofits interventions requiring roof covering renovation.

5. Conclusions

Dense urban environment is nowadays characterized by local microclimate phenomena such as urban heat island, responsible for increasing buildings’ energy demand and compromising human livability of urban city centers. In order to deal with this environmental and economic issue, effective passive solutions were investigated and applied in dense city centers, such as urban gardens and high albedo surfaces exposed to solar radiation, e.g. pavements and building roofs. In this view, given the key role played by building surfaces, cool roofs were largely implemented with the threefold benefit to: save energy for cooling, and mitigate local and global climate change phenomena.

A peculiar situation is represented by historic city centers where high construction density and huge architectural constraints for preserving heritage buildings, contributed to address this environmental issue with more difficulty. Recent research developments in this field were focused on the development of non-invasive cool coatings, pavements and roof elements, without impacting the visual appearance of buildings and other urban surfaces. In this panorama, during the very recent years, researchers started to think about the development of cool clay tiles, since these elements are installed over more than 90% of traditional roofs in cities of Mediterranean countries, typically characterized by huge energy need for cooling. Starting from previous findings, the present research dealt with the analysis at building and district scale of the thermal-energy and environmental performance of a new cool clay tile for

historic buildings. To this aim, a residential building was selected as case study, and how much this passive cooling technique could impact the urban energy requirement for cooling in summer hottest months is estimated. More in detail, a residential unit in a 16th Century building has been continuously monitored in summer 2013, in order to calibrate and validate the dynamic simulation model of the building. Four scenarios have been compared in terms of primary energy requirement for heating and cooling, and indoor temperature profiles were also analyzed. Results showed that the prototyped cool tiles were able to decrease the energy requirement for cooling up to 51%, with good performance in terms of visual appearance. The corresponding winter penalty was found to be less than 2%. Number of hours with too cold or too hot temperature were also analyzed in free-floating conditions. The cool tile was able to decrease summer overheating hours by 30%, with major contribution in lowering daily peaks. The increase in the corresponding winter overcooling hours was only by 1%. By extending the results of the study to the Middle-Age wall district in the historic Italian city, and by assuming an equivalent thermal-energy behavior of residential buildings with occupied attics, a total district energy saving for cooling in the only hottest months July–August was estimated to be about 952 MWh, with a corresponding economic benefit of almost 200 k€. This corresponded to around 370 $\text{t}_{\text{CO}_2\text{eq}}$ of avoided carbon emissions for the only period July–August produced by the cool tile compared to the traditional clay tiles.

These results provided some insides into urban heat island anthropogenic causes, such as buildings’ cooling increasing need, in ancient dense city centers. The analysis presented in this work showed that in those typical historic buildings where no insulation and no envelop improvement is applicable for architectural preservation constraint, specific cool tiles could represent an effective strategy to reduce building energy consumption in summer and the relative peak electricity demand at city scale. Future developments of this work will consider different roof typologies and occupancy schedules in order to consider a wider variability of case studies at both building and urban scale. The proposed tile could be considered as an effective solution even in those climates where heating requirement prevails on cooling need, like the case study location. In fact, that cooling need could be reduced up to be

eliminated in some period of the year, through the integration of passive sustainable strategies in historic residential buildings.

Acknowledgment

The author acknowledgments are due to the “CIRIAC program for UNESCO” in the framework of the UNESCO Chair “Water Resources Management and Culture”, for supporting her research.

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