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Cool clay tiles in Italian residential districts: investigation of the coupled thermal-energy and environmental effects

Anna Laura Pisello[1], Veronica Lucia Castaldo[1], Federico Rossi[1], Franco Cotana[1]

[1] *Department of Engineering – University of Perugia, Italy. Via G. Duranti 93– 06125 – Perugia (Italy); CIRIAF - Interuniversity Research Center on Pollution and Environment «Mauro Felli», University of Perugia, Italy. Via G. Duranti 67– 06125 – Perugia (Italy).*

Abstract

Passive strategies for environmental sustainability and energy reduction in construction industry are becoming increasingly important in both the scientific community and the industrial world. Particularly, cool roofs showed acknowledged contribution in cooling energy saving and reducing urban overheating phenomenon, such as urban heat island. Additionally, high albedo strategy has shown also promising benefits from a global scale perspective, by counteracting global warming measured by means of CO_2eq emissions' offset.
In this view, the present research work combines experimental, numerical, and analysitical analysis approaches with the purpose of estimating the environmental and energy impact of the application of cool clay tiles over the roof of a residential area with single family buildings located in central Italy, where a continuous monitoring setup has been operating since 2010.
The multiscale and multipurpose investigation demonstrated a global year-round CO_2 emission compensation by more than 700 tons, of which the 15% is produced by the passive cooling contribution at building scale and the remaining part is produced by the climate mitigation technique.
The work therefore showed that local energy saving strategies must be combined with larger scale models for performing an exhaustive environmental analysis.

Keywords: Global Warming; Cool roof; Dynamic simulation; Building energy efficiency; Albedo; Urban Heat Island; Cool clay tile.

1. Introduction and research background

The overall energy need imputable to buildings reaches around the 40% as final energy use, being responsible for a key portion of the total energy requirement worldwide [1]. A non-negligible increase of this value was also registered in office and residential buildings in particular, also given the growing technology content and the higher indoor comfort expectations of the occupants in developed countries [2]. These data become even more alarming in developing countries, where the energy need of constructions corresponds to about a half of the global energy need.
In this view, key research improvements are under work in progress in both the construction design and scientific community aimed at reducing the energy need for lighting, cooling, and heating, by keeping constant, or even improve, the indoor environmental quality [3]. At the same time, the whole life cycle impact of construction is nowadays under deep investigation with the aim of reducing the effect of the whole construction chain in terms of CO_2eq offset as further measure against climate change and global warming trends [4-5].
In particular, several passive strategies with multiscale benefits were developed and optimized by highlighting their beneficial effects at building scale, in terms of energy saving potential, and at larger scale such as greenery over building envelopes, e.g. green roofs and walls [6-7].
In the same field, several important studies were performed for optimizing the solar reflectance capability of building surface materials, with the purpose of minimizing the building summer overheating and the consequent cooling energy need. Such highly reflective coatings were named "cool" materials, due to their considerable cooling potential within different climate boundary conditions, building features and occupancy levels, as proved by research studies worldwide, even in continental climate areas [8-9]. Over the years, several case study buildings were monitored with the aim of quantifying the realistic energy reduction potential and thermal comfort improvement due to the application of cool envelopes. To this aim, experimental monitoring campaigns were performed also in colder climate conditions [10-11]. Such studies always demonstrated a global annual benefit due to highly reflective roofs with non-significant

winter penalties. Therefore, after the acknowledgement of this effect, additional studies were performed with the purpose of investigating the impact of both aging and weathering phenomena on the passive cooling potential attributable to the most commonly used cool materials i.e. coatings, membranes, and paintings [12].
Given the capability of the outdoor environmental conditions to affect the durability and therefore the passive cooling potential of such cool materials, a huge research effort is currently focusing on the development of experimental test procedures able to reproduce such microclimate boundary phenomena with different weather and environmental stresses, i.e. pollution concentration. By shifting the perspective from the single building scale to the settlement scale, high albedo technologies were therefore demostrated to be able to considerably contribute to the mitigation of global warming [13-14]and also of local overheating phenomena, i.e. heatwaves and urban heat island [15-16].
In this scenario, several numerical models were implemented with the purpose of quantifying the impact of highly reflective surfaces as offset of CO_2eq emissions [13].
In fact, it was proved that high albedo materials can decrease the quantity of energy absorbed by the Earth upper surface layer by consequently reducing the overall warming path attributable to anthropogenic heat sources [17]. Such a contribution can compensate the negative effects of the greenhouse gas emissions; therefore, the benefits achieved by applyng highly reflective surface materials such as cool pavings and roofs can be determied in terms of offset of CO_2eq. To this purpose, a new tailored methodology to quantitavely determine the potential of high albedo surfaces in abating the CO_2eq emissions depending on the site location (i.e. latitude), the climate zone and the weather conditions, the surface orientation and slope, i.e. building roofs and pavements, was proposed in [13]. Such an innovative method could be used in order to quantify the further environmental benefit of highly reflective surfaces at urban scale, in terms of potential of CO_2eq emission offset. Morevoer, it helps to determine the mitigation capability of different buildings or whole areas by specifying the surfaces'geometry and location.
Starting from the above presented research background, the present work aims at bridging the gap between the analysis at single-building level and a more global approach. Therefore, building upon existing research efforts about (i) innovative cool roof technologies, and (ii) the potential of highly reflective surfaces in mitigating the global warming phenomenon, this work aims at assessing the coupled environmental and energy effects of a cool clay tile tailored for application in historical architectures for its low visual impact.
Therefore, a residential neighborhood situated in Italy was chosen as a case study, and three main building typologies were identified to assess the energy performance in numerical simulation environments, by focusing in particular on the electricity consumption for cooling.
In this paper, the impact of the highly reflective clay tiles is assessed at first by quantifying the summer cooling energy saving potentiality. Therefore, the energy reduction is converted into the CO_2eq emissions avoided by reducing the summer electricity demand. Such a benefit in terms of environmental impact is finally coupled with the benefit computed by using an energy balance model developed by the authors [13]. The same method is therefore used for a prototype residential district whose energy behaviour is improved by applying cool clay tiles able to reduce their impact, combining the energy saving potential and the mitigation of the global warming in terms of CO_2eq emissions offset.

Nomenclature	
C-I	building category (i.e. constructed before 1980)
C-II	building category (i.e. constructed between 1977 and 2000)
C-III	building category (i.e. constructed after 2001)
CO_2eq	equivalent carbon dioxide
SRI	solar reflection index
h_c	convection coefficient

2. Materials and methods

2.1. Research framework

The present paper consists of a multifunctional and a multipurpose procedure coupling numerical analysis, analytical methods, and final environmental assessment, with the aim of assessing the performance of a case study settlement and the possible energy and environmental saving attributable to the application of cool tiles, by shifting the perspective from the single-building level to the urban scale. The numerical analysis aimed at implementing dynamic simulation models calibrated by means of continuously monitored data of the case study reference building. The analytical tool [13] was implemented to investigate the contribution imputable to high albedo solution in terms of CO_2eq offset of the settlement roofs in the considered prototype village. The final environmental assessment was performed in order to couple the energy-environmental benefits due to cooling energy saving together with the ones related to the high albedo technology as climate change mitigation techniques, as acknowledged in previous works [14]. The innovative contribution of the work consists, therefore, of (i) the implementation and integration of such proposed tools and procedures, (ii) their application at settlement level to a residential district characterized by sloped roofs covered by clay tiles, whose framework could ensure a massive results' extension to all the similar context, and (iii) the replication of the study for multiple building categories, characterized by different architectural characteristics and construction period, typically affecting the Italian building environmental and energy performance.

3. The cool clay tile prototype

The development of the innovative cool tiles was performed to combine the necessity of improving their passive cooling capability and simoultanoulsly minimizing the exterior impact of the cool coating appereance. This is motivated by the fact that the case study village consists of a suburban district characterized by traditional architectures located on a hill. Such a tile was selected according to previous works of the authors [18], where a first in-lab characterization was carried out to evaluate the solar reflectance and thermal emittance of multiple clay tile samples. Such properties are in fact both characterized by a significant impact on the cooling capability of such tile, expressed in terms of Solar Reflection Index-SRI [19].
The cool clay tile optimization was performed starting from an already commercialized composite material consisting of the clay tile covered by an engobe layer. The engobe represents a sort of coating that is applied over the tile before the cooking process into the industrial ovens and that is able to preserve its optic-energy characteristics also after such oven-produced thermal stress. Therefore, already commercialized tiles usually present several engobes typically designed for several aesthetic purpose, e.g. face antique appearance, coloring, finishing, etc. This engobe has been characterized with IR-reflective pigments. Therefore, the optic-energy performance of the tiles to be applied on the case study residential buildings' roofs of the selected district is the same of light color clay tile typically applied over traditional sloped roofs but presents a relatively higher solar reflectance capability, as reported in Table 1.

Table 1. Optic characteristics of the cool clay tile.

Tiles characteristics	Value
UV reflectance:	8.1%
VIS reflectance:	59.1%
NIR reflectance:	81.8%
Total Solar Reflectance:	67.0%
SRI=80 [16], h_c= 5 W $m^{-2}K^{-1}$	80

4. Dynamic thermal-energy analysis at building scale

The residential district selected for the purpose of this work was firstly mapped by means of GIS techniques, and the main technical and architectural features were identified. The preliminary GIS assessment helped the authors to consider and evaluate several building typologies and to cluster them with respect to the period of construction as the selected main driver for the energy behavior in Italy. In fact, the first energy efficiency regulation applied to constructions in Italy was published in 1976. Therefore, all the antecedent buildings (i.e. designed before 1976 and constructed before 1980) that were not retrofitted had to be considered as non-insulated buildings, as the continuously monitored one. Therefore, a first main building category was identified, i.e. 1st category, of non-insulated buildings constructed before 1976. Afterwards, two additional categories were identified by using the same approach, i.e. a category including buildings built between 1980 and 2000, and a third category of houses built after 2000, characterized by very high European energy standards, as indicated in recent directives and statistics [20].
Therefore, the three identified building categories are as follows:

- C-I: Buildings antecedent 1976;
- C-II: Buildings dated back to 1980-2000;
- C-III: Recent buildings built after 2000.

The continuously monitored data reported and analysed in previous works [21] helped to calibrate the models designed in this paper and to finally extend the results up to district level. More in details, an outdoor weather station positioned in the case study district was dedicated to this work, being able to continuously monitor the main outdoor microclimate parameters: outdoor dry bulb temperature [°C], wind velocity [m/s] and main direction [°], global solar radiation over a horizontal plane [W/m^2], direct solar radiation [W/m^2], superficial temperature over the roof slopes [°C], and air relative humidity [%]. At the same time, an indoor attic floor microclimate monitoring station was also installed in the prototype building, being able to monitor: indoor air temperature [°C], relative humidity [%], internal surface temperatures [°C], air velocity [m/s], and globe-thermometer temperature [° C]. More details about the experimental equipment are given in previous works for the same authors [22-23].
The collected experimental data were used in the dynamic thermal-energy analysis to calibrate the reference numerical

model (i.e. house in C-I) according to [24] and to extend the results to all the other identified building categories as the purpose of the work, after properly refining the models in order to describe all the buildings' typologies, i.e. C-II and C-III.
Buildings indoor occupancy was modelled by accounting for simplified schedules, according to [25]. EER of 1.5 and continuous operational setup scheme were assumed for the cooling system. The summer indoor air temperature setup was assumed to be 26°C by referring to the European reference standard EN 15251 [26-27]. Electric and thermal energy consumption of 10 houses per category was collected and the average category building was defined. Therefore, the annual calibration procedure was performed by considering a dedicated weather file elaborated during the course of 2013, to which the energy consumptions were referred.

5. Environmental modeling at global scale

The assessment of the environmental impact of the cool tiles in terms of CO_{2eq} offset included different steps.
Firstly, the relation between the change in the Earth albedo and the average atmospheric temperature was quantified by means of the analytical model provided in [13], which was applied to the case study settlement sloped surfaces [13]. Such a model [13] consists of four main phases:

(i) Comparison of the modification of the mean albedo of the Earth to the one of the mean atmospheric temperature by means of a dedicated tailored analytical procedure;
(ii) Assessment of the mitigation of global warming in terms of CO_2eq offset, by assuming that the measured temperature rise is generated exclusively by the observed increase of CO_2 level;
(iii) Evaluation of the effect on the climate generated by the peculiar roof treatment and calculation by considering the experimentally measured characteristics of solar reflectance of the considered tiles;
(iv) Quantification of the potential mitigation of the global warming in terms of offset of CO_{2eq}.

This effect is therefore coupled to that one generated by the energy reduction achieved by the cool tile implementation. Additionally, in order to evaluate the potential of the proposed solution in mitigating the global warming at district scale, the combined effect is also assessed.
To this purpose, the surface of the roof in every house was evaluated and the area and the inclination-orientation characteristics were taken into account in the mathematical model [13], given that it is the first currently available model able to consider such geometrical characteristics of surfaces with varying albedo. Therefore, experimental spectrophotometer albedo values provided by previous studies were considered. Moreover, data about the latitude and longitude, specifically referring to the real Italian residential buildings selected as case study village, were used as input for the model.

6. Description of the case study

The selected case study neighborhood is constituted by 106 villas situated in the green belt of Perugia, a city located in central Italy within the moderate climate zone (Figure 1). Such settlement corresponds to a wide architectural variety characterizing the hill where the houses are located, since they were built starting from the 60s to current years. Therefore, three main building categories, according to the time of construction, were identified and modeled for the purpose of this work.

Figure 1. Aerial view of the case study village.

The building clustering was carried out firstly by GIS techniques and then by in situ inspection and multiple surveys to the building facilities. Possible energy retrofits were asked to the building owners and taken into account in the building clustering. Finally, realistic electric and thermal energy consumption data of 30 houses, i.e. 10 houses per category, were collected for the purpose of the calibration of the dynamic simulation models up to an acceptable

approximation rate, according to [28].
For the motivations previously exposed, Category 1 (i.e. C-I) included those buildings made, designed, and constructed before 1980, without any following retrofit. It included 52 buildings out of 106. Category 2 (i.e. C-II) included those buildings constructed within the period 1980-2000, and it was represented by 39 buildings out of 106. The final Category 3 (i.e. C-III) included the most recent constructions built after 2000, and it included the few remaining 15 houses. In Table 2, some general information of the building architecture and categories are reported. I
Moreover, the main buildings' thermal and technical characteristics were differentiated within the dynamic simulation engine for energy assessment purposes. In particular, the thermal insulation capability of both the transparent and the opaque envelope components was differentiated according to statistical data of the Italian construction stock and according to in situ inspections. Table 4 finally reports the main boundary conditions used for the simulation on an annual base.

Table 2. Technical information about the evaluated buildings architecture and category.

Building categories	Building architecture general details
<1976 (C-I) [1977;2000] (C-II) >2001 (C-III)	120 m^2 (Ground floor area) 100 m^2 (First floor area) 60 m^2 (Second floor area) Masonry resistant structure

Table 2. Main thermal properties of the building envelope for each category.

Building category	Envelope properties
C-I	Opaque external partition (No insulation panels) WALLS: Thermal transmittance: 1.87 $W/m^2 K$ Internal heat capacity: 150 kJ/m^2K ROOF: Thermal transmittance: 2.01 $W/m^2 K$ Internal heat capacity: 207 kJ/m^2K GROUND FLOOR: Thermal transmittance: 1.67 $W/m^2 K$ Internal heat capacity: 163 kJ/m^2K Windows (single clear glass 6 mm) Thermal transmittance: 5.78 $W/m^2 K$ Solar factor: 0.82 Direct solar transmittance: 0.78 Lighting transmittance: 0.88
C-II	Opaque external partition WALLS: Thermal transmittance: 0.72 $W/m^2 K$ Internal heat capacity: 150 kJ/m^2K ROOF: Thermal transmittance: 1.35 $W/m^2 K$ Internal heat capacity: 126 kJ/m^2K GROUND FLOOR:

	Thermal transmittance: 0.98 W/m^2 K Internal heat capacity: 80 kJ/m^2K Windows (double clear camera 3-14-3 Air) Thermal transmittance: 2.72 W/m^2 K Solar factor: 0.76 Direct solar transmittance: 0.71 Lighting transmittance: 0.81
C-III	Opaque external partition WALLS: Thermal transmittance: 0.33 W/m^2 K Internal heat capacity: 150 kJ/m^2K ROOF: Thermal transmittance: 0.29 W/m^2 K Internal heat capacity: 16 kJ/m^2K GROUND FLOOR: Thermal transmittance: 0.34 W/m^2 K Internal heat capacity: 27 kJ/m^2K Windows (double lowE camera 6+13+6 mm - Arg) Thermal transmittance: 1.49 W/m^2 K Solar factor: 0.57 Direct solar transmittance: 0.47 Lighting transmittance: 0.75

Table 4. Main case study settlement boundary conditions used for the dynamci simulation.

Climate boundary conditions	Location
Daily average dry bulb temperature (maximum/minimum peak): *Winter:* 7.8°C - 1.8°C *Spring:* 15.9°C - 7.4°C *Summer:* 27°C - 16.5°C *Fall:* 17.7°C - 10.4°C Eliophany: 5.8 h/day Rainfall rate: 850 mm	Perugia (Italy) Elevation above sea level: 522 m Latitude: 43°06’59.09” Longitude: 12°18’38.79” Degree Days: 2204

7. Discussion of the results

7.1. Cooling energy reduction assessment

The electricity energy requirement in summer was selected as the key parameter to be analyzed. Figure 2 shows the profile of the requirement for cooling of the multiple building categories in the “cool-roof” and “non-cool roof” scenario. In particular, the estimated reduction of the electric energy for cooling due to the application of cool clay tiles was converted in CO_2eq avoided emissions [13]. The main results for each building category, i.e. C-I, C-II, and

C-III are reported in Table 4.
In particular, the annual energy reduction due to the application of the cool tile is equal to 11.8% for category I, 12.7% for category II, and 13.0% for category III. Therefore, C-III buildings are detected to require more electricity than C-I buildings, i.e.7.5% more. Therefore, significant penalties are generated by the insulated envelope in the hot season in the evaluated buildings.
In Figure 3, the energy balance through the building envelope is depicted for C-I (a), C-II (b), and C-III (c), by taking into account the energy required for heating, cooling, lighting, and for all the appliances and the internal gains due to the occupancy level, the solar gains, and the envelope infiltrations. The graphs show that buildings belonging to C-III, i.e. built after 2001, are characterized by the best performance of the building envelope from an energy balance perspective since they present generally lower energy requirements, and thermal losses and gains are therefore less affected by the outdoor boundary conditions variability.

Table 4. Energy reduction due to cool tiles and related avoided emissions of CO2eq.

Electric energy saving due to cool tiles [kWh/year]					
C-I		C-II		C-III	
Non-cool tiles: 27157.2	Cool tiles: 23960.4	Non-cool tiles: 28657.0	Cool tiles: 25021.2	Non-cool tiles: 29784.1	Cool tiles: 25912.5
CO_2eq avoided emissions					
11.8%		12.7%		13%	

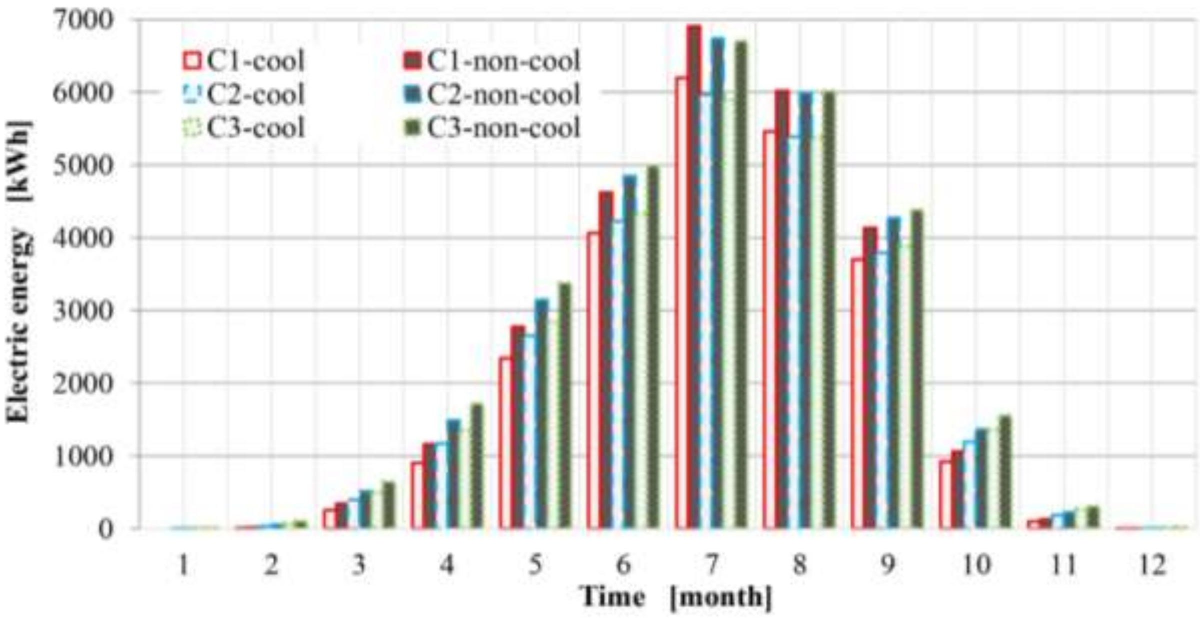

Figure. 2. Electricity requirement for cooling in different building categories and envelope configuration.

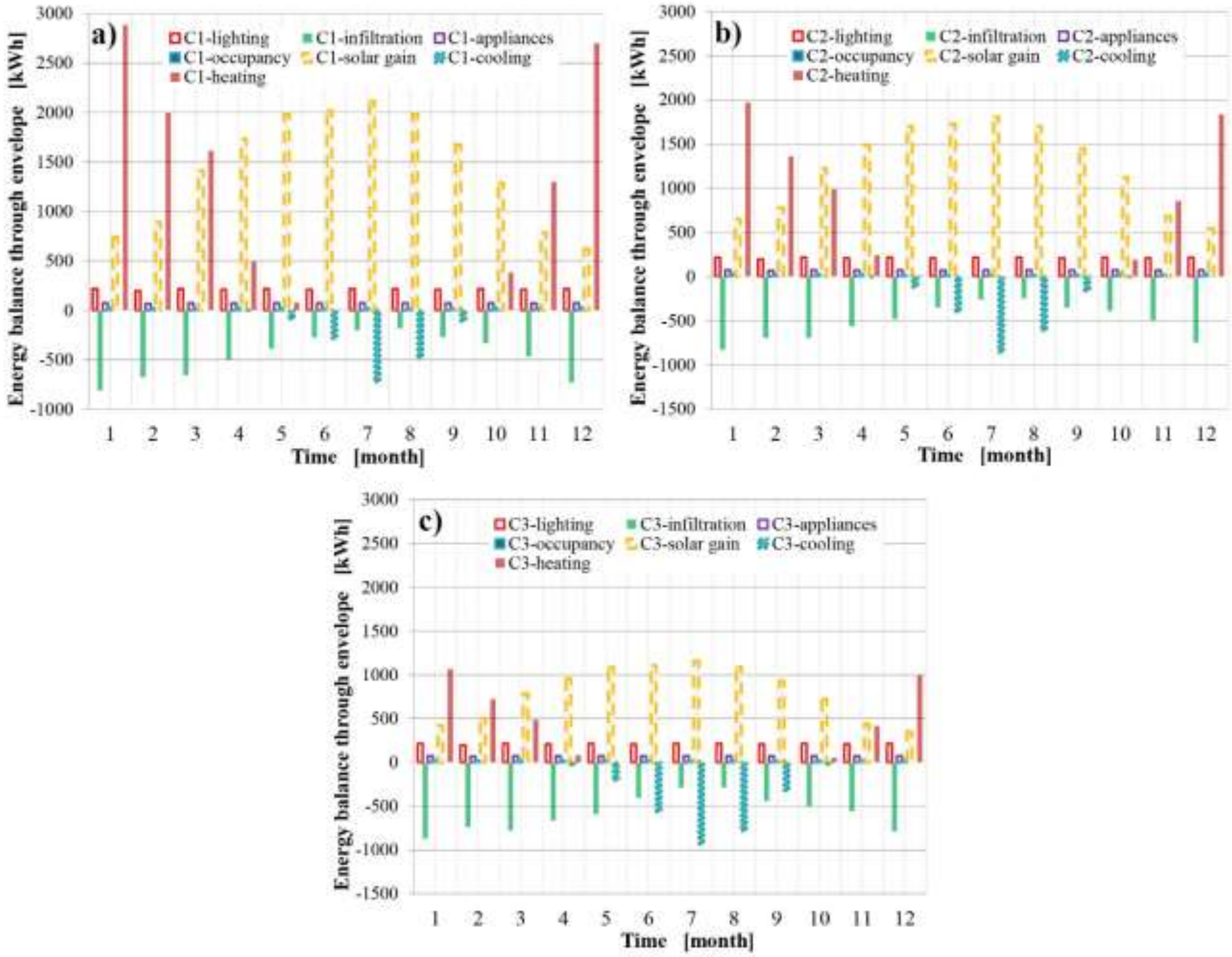

Figure. 3. Energy balance trough the building envelope for C-I (a), C-II (b), and C-III (c).

7.2. Assessment of the environmental impact

The analytical model developed in [13] was applied to the selected case study area in order to determine the total environmental impact of the proposed cool tiles in the increase of the albedo of the evaluated district.

To this purpose, each roof surface included in the geometrical building model elaborated for the dynamic energy simulation was considered also in the analytical methodology. Moreover, also reference roof configurations were defined in the developed energy balance tool. However, the realistic features of each roof i.e. geometry, orientation, slope, and surface extension were taken into consideration.

The analysis results show how the application of the highly reflective clay tiles on the village roofs leads to a CO_2eq emissions offset by 631 tons per year, generated by the additional reflected radiation contribution.

Therefore, the total emissions avoided were computed by taking into account the whole neighborhood with the different buildings categories by taking into account the emissions avoided annually given the cooling energy saving. In details, the database Eco-invent 3 was taken into account for evaluating the equivalent CO_2 emissions avoided (corresponding to 0.386 kgCO_2eq/kWhel) [29].

More in details, all the residential buildings characterized by low-reflective clay tiles require about 2,976,558.4 kWhel/year for cooling. The same buildings but with the highly reflective clay tiles require around 12.3% less. The optimized settlement configuration therefore requires 2,610,456 kWhel/year, with a consequent calculated energy saving equal to 366,102.7 kWhel/year at district level.

Therefore, the benefit generated by the reduction of the energy requirement for cooling from an environmental perspective is equal to 141.3 tons of CO_2eq/year. Such a value is then coupled with the offset of CO_2eq emissions computed by using the model for contributing to the increase of the Earth albedo. The application of the cool clay tiles can offset 772.3 tons of CO_2eq/year by taking into account the overall settlement contribution i.e. 106 houses.

Figure 4 shows the comparison between the primary energy requirements for cooling for the different evaluated building categories within the “cool” and “non-cool” configuration of the building roof. Additionally, in Figure 5(a, b) the comparison between the total CO2eq emissions due to the building HVAC operation and the total CO_2eq emissions offset guaranteed by the different type of roof cover is illustrated in terms of tons of CO_2eq. In particular,

CO_2eq emissions reduction of 354.00, 265.50, and 102.12 tons are calculated for C-I, C-II, and C-III, respectively, thanks to the application of high albedo tiles at the settlement scale.
Lastly, Figure 5c shows the net balance between the CO_2eq emissions produced by the building HVAC and the CO_2eq emissions offset for the evaluated settlement. It is evident how the net balance for the “cool” configuration of the buildings of the selected case study village is negative compared to the “non-cool” scenario since the CO_2eq offset is greater compared to the CO_2eq emissions due to the HVAC operation for the benefic passive cooling action produced by the application of the cool tiles,which leads to reduce cooling energy requirements.

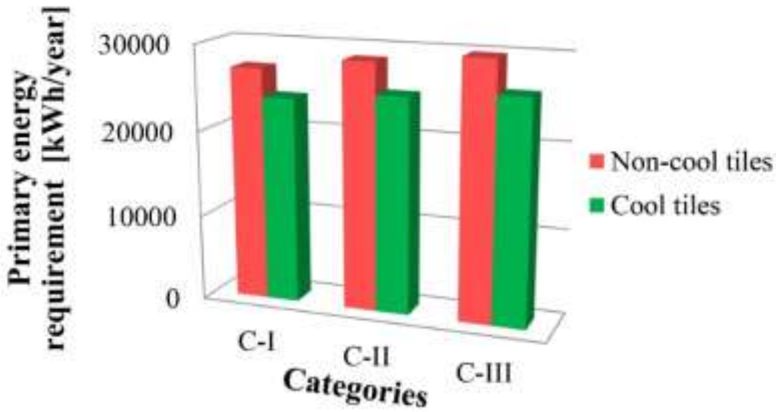

Figure. 4. Global cooling primay energy need for building categories and roof configuration.

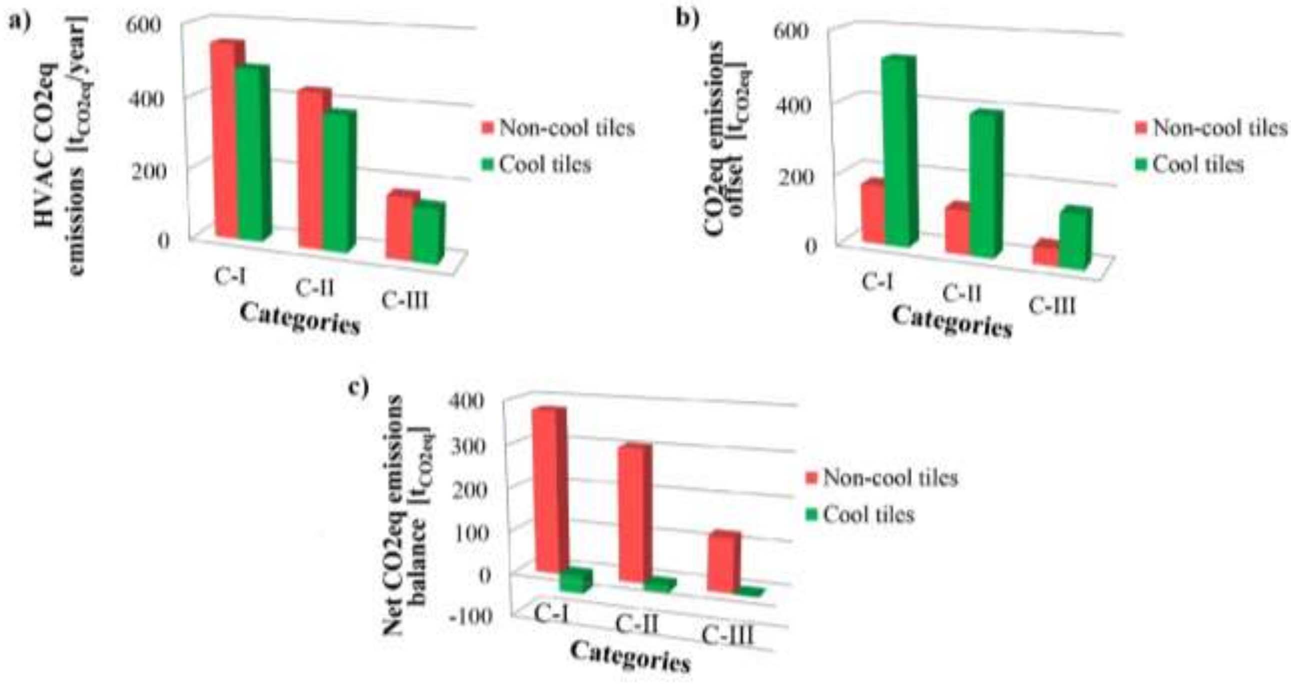

Figure. 5. Net CO_2eq emission balance (c) between the CO_2eq emissions produced (a) and the CO_2eq emissions offset (b) generated for the case study settlement.

8. Conclusions

The present work consisted of the coupled assessment of the (i) energy and (ii) environmental impact generated by the application of a higlhy-reflective and low-visual impact clay tiles in a neighborhood in central Italy. In particular, a historic traditional settlement was selected as representative of typical Italian residential buildings, where cool roofs usually cannot be applied due to the several aesthetic and visual constraints imposed by national regulations preserving the quality of local landscape and environment.
Therefore, the selected case study area included 106 detouched houses characterized by sloped roofs covered by traditional red coloured tiles. Such tiles were therefore optimized with the aim of reducing the summer cooling electricity requirement and calculating the related offset of CO_2eq emissions by using coupled (i) preliminar

experimental campaign and (ii) analytical model. Such an analytical tool, which was implemented in a previous work, was used to determine the relation between the highly reflective surface and the correspondent potentiality in terms of tons of CO_2eq offset.
The coupled experimental and numerical methodology applied allowed to detect that the high albedo tile, in spite of its low impact in terms of exterior appereance, can guarantee around 13% of electric cooling energy saving for the case study settlement with different building categories.
Such an energy reduction was calculated to be about 141.2 tons of CO_2eq/year, by taking into account the average rate of emissions of Italian national cooling electrical systems and grid effectiveness. Such a benefit from an environmental point of view, when combined to the one produced by the implementation of the cool solution, was found to be around 772 tons of CO_2eq/year, for the case study settlement.
The achieved results show, therefore, how cool roof solutions can be taken into consideration for application even in such typical and traditional residential areas due to their key cooling energy saving potential and coupled considerable effect from an environmental perspective.

9. Future developments

The present research represents a “prototypical study” aimed at assessing the combined environmental and energy imact of cool roofs, and presents therefore many limitations. First, the assessment of the residential building categories in the case study neighborhood was performed by evaluating all the building features by performing indoor surveys around only 40% of the houses. However, the whole neighborhood was considered into the analysis and realistic assumptions were made by directly observing the houses outdoor features. Therefore, the classification of the selected houses in building categories helped to simplify the problem geometry, with no significant effect on the method reliability.
Future development of the study could first consider a more realistic and a less semplified configuration of the buildings. Morevoer, an in-field evaluation of the building envelope technologies can permit a more precise modeling for the purpose of the dynamic simulation. Further efforts could also focus on the cost-benefit analysis of the cool clay tiles implemementation and on the assessement of the potential financial benefits attributable to such a proposed solution, by taking into account the mechanism of EU ETS for the emission credits trading.

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