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Cool Clay Tiles in Italian Residential Districts: Investigation of the Coupled Thermal-Energy and Environmental Effects

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Abstract

Passive strategies for environmental sustainability and energy reduction in the construction industry are becoming increasingly important in, both, the scientific community and the industrial world. Particularly, cool roofs demonstrate acknowledged contribution in cooling energy saving and reducing urban overheating such as urban heat island. Additionally, high albedo strategy has shown promising benefits from a global perspective by counteracting global warming measured by means of CO_2eq emission offset. In this view, the present research work combines experimental, numerical, and analytical analysis approaches to measure the impact on energy and the environment from the application of cool clay tiles over the roof of a residential buildings located in central Italy, consistently monitored since 2010. The purposeful investigation demonstrated a consistent CO_2 emission compensation of more than 700 tons, 15% of which is produced by the passive cooling contribution of buildings and climate mitigation techniques. The work, therefore, incidicated 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

The overall energy needed and used up in buildings amounts to up to 40% of the total energy needed world-wide ("Annual Energy Outlook", 2011). A major increase of this percentage was also registered for office and residential buildings in particular given the developing technology used and requirements of indoor comfort for developing countries occupants (OECD, 2003). The data given become even more alarming in developing countries especially where the energy needed for construction was noted to have amounted to half of the global energy needed.

In this view, key research improvements are currently a 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 improving, the indoor environmental quality (Salata, Vollaro, Lietovollaro, & Mancieri, 2015). Similarly, the whole life cycle assessment of buildings is now under deep investigation with the aim of reducing the effect of the whole construction chain in terms of CO_2eq as a way of mitigating climate change and global warming trends (Pisello & Asdrubali, 2014; Synnefa, Santamouris, & Akbari, 2007). In particular, several passive strategies with great benefits were developed and optimized by highlighting their effects at building scale, in terms of energy saving potential and at larger scale such as green building envelopes, e.g. green roofs and walls (Malys, Musy, & Inard, 2016; Razzaghmanesh, Beecham, & Salemi, 2016).

In the same field, several important studies were undertaken to optimize 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 are 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 (Kolokotroni, Gowreesunker, & Giridharan, 2013; Pisello, Piselli, & Cotana, 2015) . 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 in colder climate conditions (Hosseini & Akbari, 2014; Paolini, Zinzi, Poli, Carnielo, & Mainini, 2014). These studies demonstrated an annual benefit from highly reflective roofs with non-significant winter penalties. Consequently, additional studies were done to investigate the impact of aging and weathering phenomena on the passive cooling potential. Cool materials, such as coatings, membrances and painting, were recoginzed as the most commonly (Sleiman, Ban-Weiss, Gilbert, François, Berdahl, Kirchstetter, Levinson, 2011).

Given the capability of outdoor environmental conditions to influence the durability and passive cooling potential of such cool materials, large research efforts are currently focused on the development of experimental test procedures to reproduce microclimate boundary phenomena during different weather and environmental stresses, i.e. pollution concentration. By shifting the perspective from a single building scale to a larger settlement scale, high albedo technologies were therefore demostrated to be able to considerably contribute to the mitigation of global warming (g (Akbari, Menon, & Rosenfeld, 2008; Cotana, Rossi, Filipponi, Coccia, Pisello, Bonamente, & Cavalaglio, 2014) as well as local overheating phenomena, i.e. heatwaves and urban heat island island (Santamouris, 2015; Wang & Akbari, 2015). In this scenario, several numerical models were implemented with the purpose of quantifying the impact of highly reflective surfaces as an offset of CO_2eq emissions (Cotana et al, 2014).

It was proven that high albedo materials can decrease the quantity of energy absorbed by the Earth's top surface layer by consequently reducing the overall warming path attributed to anthropogenic heat sources (OReskes, 2004). Such a contribution can compensate for the negative effects of the greenhouse gas emissions. Therefore, the benefits attained by applying highly reflective surface materials, such as cool pavings and roofs, can be determied in terms of offset of CO_2eq. For this reason, 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 (Cotana et Al., 2014). Such an innovative method could be used in order to quantify additional environmental benefits of highly reflective surfaces, at an urban scale, in terms of potential of CO_2eq emission offset. Moreover, it helps to determine the mitigation capability of different buildings or whole areas by specifying the surfaces'geometry and location.

Beginning with the aforementioned research background, the present work is an attempt at bridging the gap between the analysis at single-building level and a global approach. Therefore, building upon existing research efforts on (i) innovative cool roof technologies, and (ii) the potential of highly reflective surfaces in mitigating the global warming phenomenon, this work is an assessment of environmental and energy effects of a cool clay tile tailored for application in historical architecture 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 potential. 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 (Cotana et Al., 2014). The same method is therefore used for a prototype residential district with an energy behaviour that is improved by applying cool clay tiles. This results in a reduction in their impact and 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 that groups 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 attributed to the application of cool tiles, perspective is shifted from a single-building level to the urban scale. The numerical analysis is an attempt to implement dynamic simulation models adjusted by means of continuously monitored data of the case study. The analytical tool (Cotana et Al., 2014) was implemented to investigate the contribution of a high albedo solution in terms of CO_2eq offsets of the settlement roofs in the considered prototype village. The final environmental assessment was performed to groups the benefits of cooling and energy saving together with the ones related to the high albedo technology as climate change mitigation techniques as acknowledged in previous works (Akbari et Al. 2013). The innovative contribution of the work consists, therefore, of (i) the implementation and integration of such proposed tools and procedures, (ii) their application from settlement level to a residential district characterized by sloped roofs covered by clay tiles (iii) the replication of the study for multiple building categories that are 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 is an attempt to improve their passive cooling capability and simultaneously minimize the exterior impact of the cool coating appearance. This is inspired 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 (Pisello, 2014), where a first in-lab depiction was carried out to evaluate the solar reflectance and thermal emittance of multiple clay tile samples. Such properties are considered to have a significant impact on the cooling capability of the tile which is expressed in terms of Solar Reflection Index-SRI (Akbari, 2001).

The cool clay tile optimization was performed starting from a 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 designed for several aesthetic purposes such as face antique appearance, coloring, finishing, etc. This engobe has been characterized with IR-reflective pigments. Therefore, the application of optic-energy performance of tiles on residential buildings' roofs of the selected district is the same as that of lightly-colored clay tile typically applied over traditional sloped roofs. However, the latter 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 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 as well as cluster them with respect to the period of construction as the selected main driver for the energy behaviour in Italy. In fact, the first energy efficiency regulation applied to construction in Italy was published in 1976. Therefore, all the predecessor buildings (i.e. designed after 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. 1^{st} 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 ("Energy Performance of Buildings Directive", 2005).

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 (Pisello & Cotana, 2014) helped calibrate the models designed in this paper and finally extend the results up to district level. Moreover, an outdoor weather station positioned in the case study district was dedicated to this work 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/m2], direct solar radiation [W/m2], 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 (Pisello, Castaldo, Piselli, Fabiani, & Cotana, 2016; Pisello, Castaldo, Fabiani, & Cotana, 2016). The collected experimental data were used in the dynamic thermal-energy analysis to calibrate the numerical model reference (i.e. house in C-I) according to (Mustafaraj, Marini, Costa, & Keane, 2014) and to extend the results to all the other identified building categories after properly refining the models to describe all the buildings typologies, i.e. C-II and C-III.

Indoor occupancy of buildings was modelled by accounting for simplified schedules according to (Feng, Yan, & Hong, 2015). 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 ("Indoor Environmental Input Parameters for Design", 2012; "Revision of EN 15251", 2012). 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 consumption 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 (Cotana et al., 2014), which was applied to the case study settlement sloped surfaces (Cotana et al., 2014). Such a model consists of four main phases:

(i)Comparison of the modification of the mean albedo of the Earth to that of mean atmospheric temperature through a 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 from the observed increase of CO_2 level;
(iii)Evaluation of the effect on the climate generated by the peculiar roof treatment. Measured by considering the experimental characteristics of solar reflectance of the considered tiles;
(iv)Quantification of the potential mitigation of global warming in terms of offset of CO_2eq.
This effect is therefore coupled to one generated by energy reduction achieved by cool tile implementation. Additionally, to evaluate the proposed solution in mitigating global warming at district scale, the combined effect is also assessed. For this reason, the surface of the roof in every house was evaluated and the area and the inclination-orientation characteristic taken into account in the mathematical model of Cotana and others (2014). This is the first currently available model capable of considering geometrical characteristics of surfaces with varying albedo. Therefore, experimental spectrophoto meter 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 characterized by a hill where the houses are located since they were built starting from the 60s. Therefore, three main building categories, according to the time of construction, were identified and modeled for this work.

Figure 1. Aerial view of the case study village.

The building cluster was carried out firstly using GIS techniques and then by in-situ inspection and multiple surveys to building facilities. Possible energy retrofits were considered in the building clustering. Finally, realistic electric and thermal energy consumption data of 30 houses, 10 per category, were collected to adjust the dynamic simulation models up to an acceptable approximation rate according to (”Ashrae Guideline”, 2002). For reasons previously mentioned, category 1 (C-I), included those buildings made, designed, and constructed before 1980 without any following retrofit. This category included 52 buildings out of 106. Category 2 (i.e. C-II) included buildings constructed from 1980-2000 and was represented by 39 buildings out of 106. The final category, category 3 (C-III), included the most recent constructions built after 2000 as well as the few remaining 15 houses. In Table 2, some general information of the building architecture and categories are reported. 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 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 3. Mainthermal 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

Continued on next page

Building category	Envelope properties
C-II	**Opaque external partition** WALLS: Thermal transmittance: 0.72 W/m^2 K Internal heat capacity: 150 kJ/m^{2}K ROOF: Thermal transmittance: 1.35 W/m^2 K Internal heat capacity: 126 kJ/m^{2}K GROUND FLOOR: Thermal transmittance: 0.98 W/m^2 K Internal heat capacity: 80 kJ/m2K **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^{2}K ROOF: Thermal transmittance: 0.29 W/m^2 K Internal heat capacity: 16 kJ/m^{2}K GROUND FLOOR: Thermal transmittance: 0.34 W/m^2 K Internal heat capacity: 27 kJ/m^{2}K **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 dynamic 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 during the 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 (Cotana et al., 2014). 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 require more electricity than C-I buildings (7.5% more). Therefore, significant drawbacks are created by the insulated envelope in the hot season in the evaluated buildings.

In Figure 3, the energy balance of 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 all the appliances and internal gains due to the occupancy level, solar gains, and envelope infiltrations. The graphs show that buildings belonging to C-III, built after 2001, are characterized by the best performance of the building envelope from an energy balance perspective since they generally present lower energy requirements. Thermal losses and gains are therefore less affected by the outdoor boundary conditions’ variability.

Table 5. Energy Reduction Due to Cool Tiles and Related Emissions of CO_2eq.

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%	

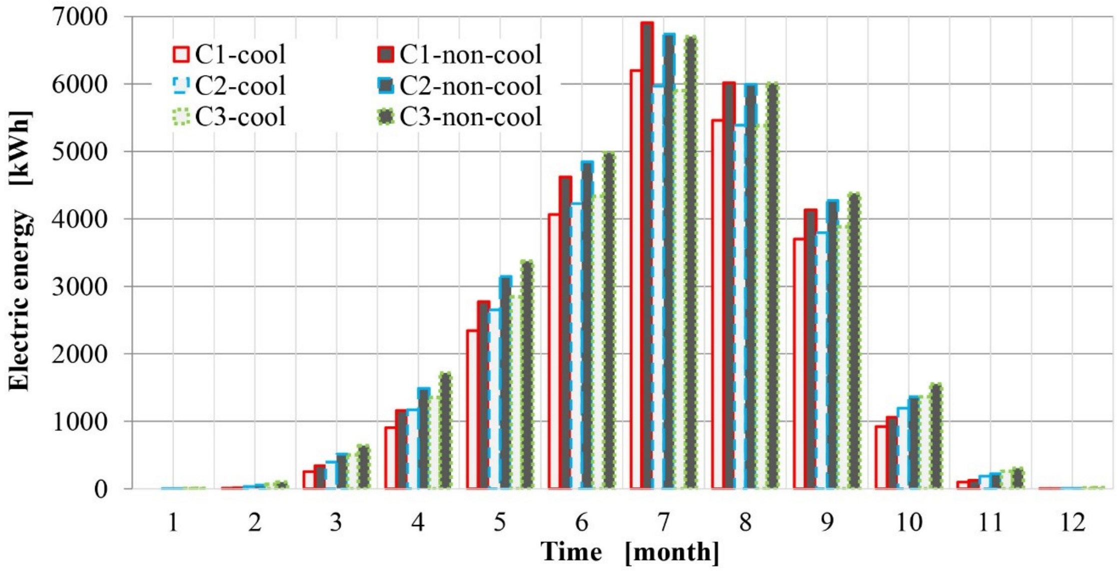

Figure 2. Electricity requirement forcooling in different building categories and envelope configuration.

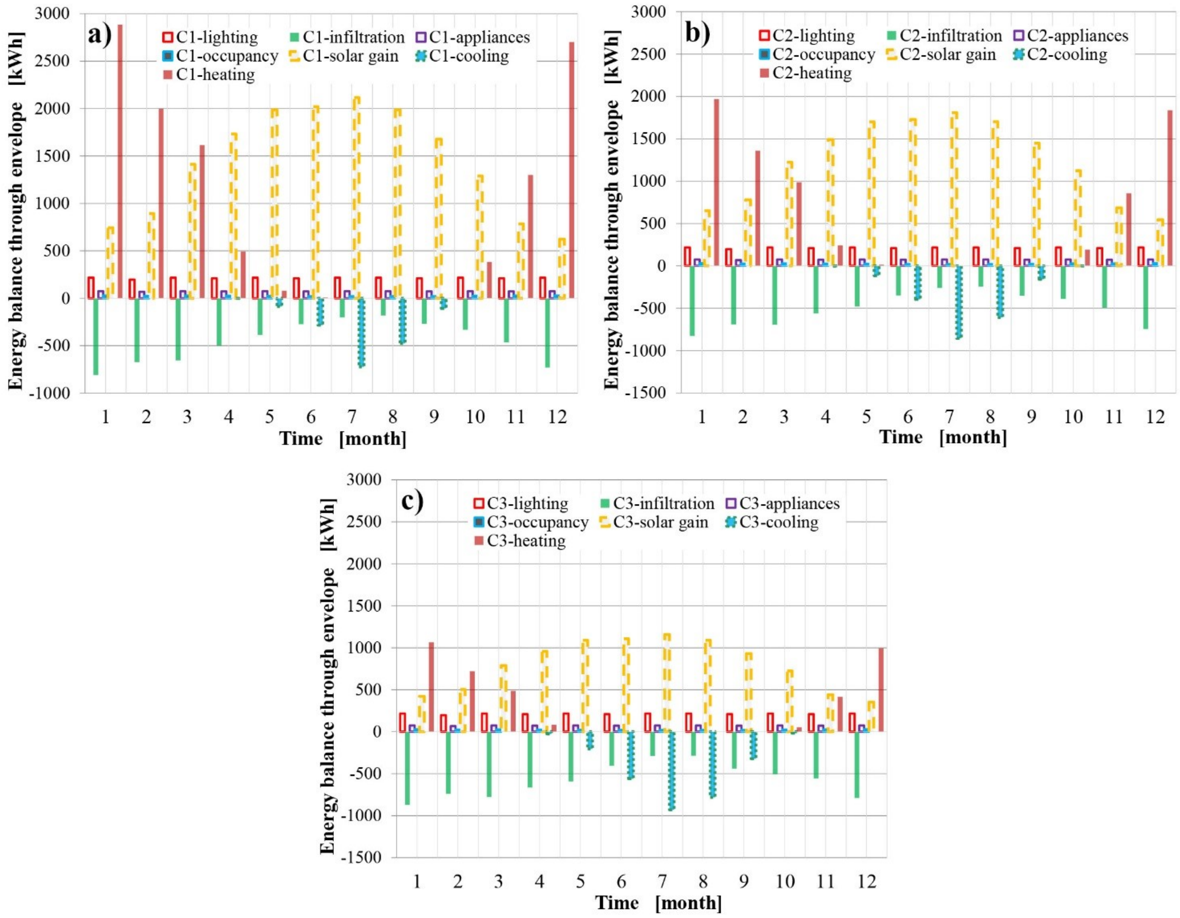

Figure 3. Energy balance through the buildingenvelope for C-I (a), C-II (b), and C-III (c).

7.2. Assessment of the Environmental Impact

The analytical model developed in (Cotana et al., 2014) was applied to the selected case study area in order to determine the total environmental impact of the proposed cool tiles and increase of the albedo of the evaluated district. For this reason, each roof surface included in the geometrical building model used for the dynamic energy simulation was considered in the analytical methodology. Despite the fact that roof configurations were defined in the developed energy balance tool, the realistic features of each roof, such as geometry, orientation, slope, and surface extension, were taken into consideration.

The analysis results show how applying highly reflective clay tiles on village roofs leads to a CO_2eq emission offset of up to 631 tons per year, which is generated by the additional reflected radiation. Therefore, the total emissions evaded were computed by taking into account the whole neighborhood with the different building categories as well as the emissions avoided annually given the cooling energy saving. More specifically, the database Eco-invent 3 was taken into account to evaluate the equivalent CO_2 emissions evaded (corresponding to 0.386 kgCO2eq/kWhel) (GmbH, 2013). Moreover, all the residential buildings characterized by low-reflective clay tiles require about 2,976,558.4 kWhel/year for cooling. The same buildings, yet those 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 equivalent 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 counterbalance 772.3 tons of CO_2eq/year by taking into account the overall settlement contribution of 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 CO_2eq 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. Finally, 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.

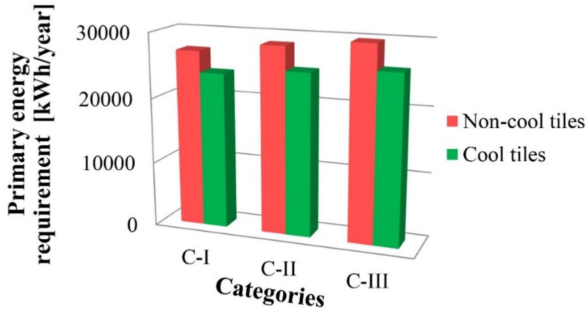

Figure 4. Global cooling primay energyneed for building categories and roof configuration.

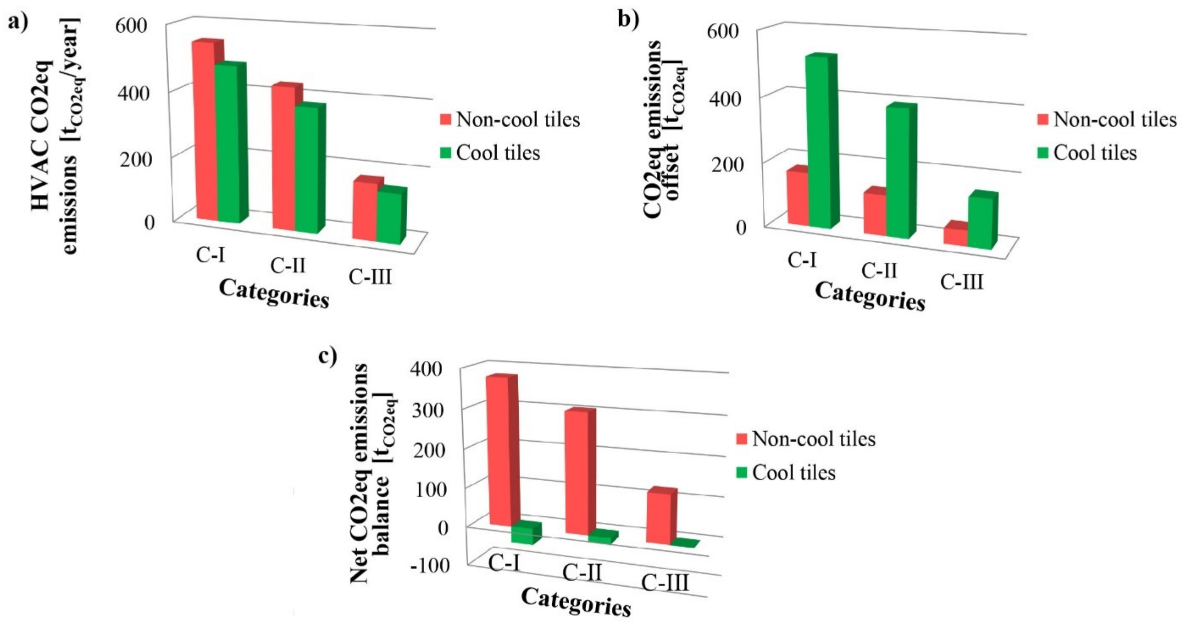

Figure 5. Net CO_2eq emission balance (c) between the CO_2eq emissions produced (a) and the CO_2eq emissions offset (b) generated for the case study settlement.

8. Conclusion

The present work consists 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 utilized 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) preliminary experimental campaign and an (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 indicate how cool roof solutions can be taken into consideration for application even in 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 presents a "prototypical study" aimed at assessing the combined environmental and energy impact of cool roofs and presents many limitations. Firstly, the assessment of the residential building categories in the case study neighborhood was undertaken by evaluating all the building features and 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 simplify the problem geometry without significant effect on the reliability of the method. Future developments for the study could consider a more realistic and a more complex configuration of the buildings. Moreover, 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 implementation and on the assessment 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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References

1. Akbari, H., Menon, S., & Rosenfeld, A. (2008). Global cooling: Increasing world-wide urban albedos to offset CO2. *Climatic Change*, 94(3-4), 275-286. doi:10.1007/s10584-008-9515-9

2. *Annual Energy Outlook 2011 With Projections to 2035.* (2011). Washington: Us Energy Information Adminisitration: Dept of Energy. Retrieved from https://www.eia.gov/outlooks/aeo/pdf/0383(2011).pdf.

3. *Ashrae guideline: Measurement of energy and demand savings.* (2002). Atlanta, GA: ASHRAE. Retrieved from http://www.eeperformance.org/uploads/8/6/5/0/8650231/ashrae_guideline_14-2002_measurement_of_e

nergy_and_demand_saving.pdf

4. Cotana, F., Rossi, F., Filipponi, M., Coccia, V., Pisello, A. L., Bonamente, E., . . . Cavalaglio, G. (2014). Albedo control as an effective strategy to tackle Global Warming: A case study. *Applied Energy*, 130, 641-647. doi:10.1016/j.apenergy.2014.02.065

5. Energy Performance of Buildings Directive. (2005). *Structural Survey,* 23(1). doi:10.1108/ss.2005.11023aab.001

6. Feng, X., Yan, D., & Hong, T. (2015). Simulation of occupancy in buildings. *Energy and Buildings*,87, 348-359. doi:10.1016/j.enbuild.2014.11.067

7. GmbH, B. (2013). Ecoinvent 3.0. Retrieved from https://www.ecoinvent.org/database/older-versions/ecoinvent-30/ecoinvent-30.html

8. Hosseini, M., & Akbari, H. (2014). Heating energy penalties of cool roofs: The effect of snow accumulation on roofs. *Advances in Building Energy Research,* 8(1), 1-13. doi:10.1080/17512549.2014.890541

9. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. (n.d.). doi:10.3403/30133865u

10. Kolokotroni, M., Gowreesunker, B., & Giridharan, R. (2013). Cool roof technology in London: An experimental and modelling study. *Energy and Buildings*, 67, 658-667. doi:10.1016/j.enbuild.2011.07.011

11. Malys, L., Musy, M., & Inard, C. (2016). Direct and Indirect Impacts of Vegetation on Building Comfort: A Comparative Study of Lawns, Green Walls and Green Roofs. *Energies*, 9(1), 32. doi:10.3390/en9010032

12. Mustafaraj, G., Marini, D., Costa, A., & Keane, M. (2014). Model calibration for building energy efficiency simulation. Applied Energy, 130, 72-85. doi:10.1016/j.apenergy.2014.05.019

13. OECD. (2003). OECD Statistics. Retrieved 2016, from https://stats.oecd.org/

14. Oreskes, N. (2004). The Scientific Consensus on Climate Change. *Science*, 306(5702), 1686-1686. doi:10.1126/science.1103618

15. Paolini, R., Zinzi, M., Poli, T., Carnielo, E., & Mainini, A. G. (2014). Effect of ageing on solar spectral reflectance of roofing membranes: Natural exposure in Roma and Milano and the impact on the energy needs of commercial buildings. *Energy and Buildings*, 84, 333-343. doi:10.1016/j.enbuild.2014.08.008

16. Pisello, A. L. (2014). Optic-Energy Performance of Innovative and Traditional Materials for Roof Covering in Commercial Buildings in Central Italy. *Advanced Materials Research*, 884-885, 685-688. doi:10.4028/www.scientific.net/amr.884-885.685

17. Pisello, A. L., & Asdrubali, F. (2014). Human-based energy retrofits in residential buildings: A cost-effective alternative to traditional physical strategies. *Applied Energy, 133*, 224-235. doi:10.1016/j.apenergy.2014.07.049

18. Pisello, A. L., & Cotana, F. (2014). The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring. *Energy and Buildings*, 69, 154-164. doi:10.1016/j.enbuild.2013.10.031

19. Pisello, A. L., Castaldo, V. L., Fabiani, C., & Cotana, F. (2016). Investigation on the effect of innovative cool tiles on local indoor thermal conditions: Finite element modeling and continuous monitoring. *Building and Environment*, 97, 55-68. doi:10.1016/j.buildenv.2015.11.038

20. Pisello, A. L., Castaldo, V. L., Piselli, C., Fabiani, C., & Cotana, F. (2016). How peers' personal attitudes affect indoor microclimate and energy need in an institutional building: Results from a continuous monitoring campaign in summer and winter conditions. *Energy and Buildings*, 126, 485-497. doi:10.1016/j.enbuild.2016.05.053

21. Pisello, A. L., Piselli, C., & Cotana, F. (2015). Influence of human behavior on cool roof effect for summer cooling. *Building and Environment,* 88, 116-128. doi:10.1016/j.buildenv.2014.09.025

22. Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces. (n.d.). doi:10.1520/e1980

23. Razzaghmanesh, M., Beecham, S., & Salemi, T. (2016). The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening*, 15, 89-102. doi:10.1016/j.ufug.2015.11.013

24. Revision of EN 15251: Indoor Environmental Criteria. (2012). *REHVA Journal*, 5-11.

25. Salata, F., Vollaro, A. D., Lietovollaro, R. D., & Mancieri, L. (2015). Method for energy optimization with reliability analysis of a trigeneration and teleheating system on urban scale: A case study. *Energy and Buildings*, 86, 118-136. doi:10.1016/j.enbuild.2014.09.056

26. Santamouris, M. (2015). Regulating the damaged thermostat of the cities—Status, impacts and mitigation challenges. *Energy and Buildings*, 91, 43-56. doi:10.1016/j.enbuild.2015.01.027

27. Sleiman, M., Ban-Weiss, G., Gilbert, H. E., François, D., Berdahl, P., Kirchstetter, T. W., . . . Levinson, R. (2011). Soiling of building envelope surfaces and its effect on solar reflectance—Part I: Analysis of roofing product databases. *Solar Energy Materials and Solar Cells*, 95(12), 3385-3399. doi:10.1016/j.solmat.2011.08.002

28. Synnefa, A., Santamouris, M., & Akbari, H. (2007). Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings*, 39(11), 1167-1174. doi:10.1016/j.enbuild.2007.01.004

29. Wang, Y., & Akbari, H. (2015). Development and application of 'thermal radiative power' for urban environmental evaluation. *Sustainable Cities and Society*, 14, 316-322. doi:10.1016/j.scs.2014.07.003