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# **Coupling of Solar Reflective Cool Roofing Solutions with Sub-Surface Phase Change Materials (PCM) to Avoid Condensation and Biological Growth**

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**Abstract**

Cool roofs are effective solutions to counter the overheating of building roofs, inhabited spaces below and urban areas in which buildings are located thanks to their capability of reflecting solar radiation. Nonetheless, the relatively low surface temperatures that they induce can cause condensation of humidity and leave the surface moistened for a long time during the day, thus, promoting the growth of bacteria, algae and other biological fouling. This can cause a quick decay of the solar reflective performance. Biological growth is countered by surface treatments, which may be toxic, forbidden in many countries and may vanish quickly. It can also be countered by lowering the thermal emittance and thus decreasing heat transfer by infrared radiation and consequently leading to night undercooling. However, this can decrease the performance of cool roofs. An alternative approach, which is analyzed in this work, is to embed in the first layer below the cool roof surface a phase change material (PCM) that absorbs heat during the daytime and then releases it during nighttime. This can increase the minimum surface temperatures, reduce the occurrence of humidity condensation and biological growth. In this work, preliminary results on the coupling of a cool roof surface with a PCM sublayer are presented. Results are obtained by carrying out a theoretical investigation on commercial materials and taking into account the time and patterns of evolution of the environmental conditions.

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**Keywords**

cool roof; phase change material; PCM; condensation; biofouling

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**1. Introduction****1.1. Cool Roofs and Their Lifespan**

Cool roofs are roofing solutions reflective of solar radiation thanks to their high solar reflectance, or albedo. They can prevent overheating of both individual buildings and entire urban areas. Their potential has been quantitatively investigated in the USA since the 1980s in response to both the urban heat island (UHI) effect and the need of reducing electric energy and peak power absorption for air conditioning (Taha, Akbari, Rosenfeld, & Huang, 1988). Many studies have followed evidencing the effectiveness of gradually increasing the albedo of a city by choosing high-albedo surfaces to replace darker materials during routine maintenance of roofs. Proven as well

was the usefulness of establishing sponsored incentive programs, product labeling, and standards to promote the use of high-albedo materials for buildings (Rosenfeld, Akbari, Romm, & Pomerantz, 1998). Surveys on cool roofing materials were completed (Berdahl & Bretz, 1997) and strong savings of cooling energy and peak power were shown (Akbari, Bretz, Kurn, & Hanford, 1997). Additionally, the researcher paid attention to the long-term performance of high-albedo roof coatings (Akbari et al., 1997). Steps were then taken by cities in the warm half of USA towards the incorporation of cool roofs in the revised ASHRAE building standards and the inclusion of cool surfaces as tradeable smog-offset credits in Los Angeles (Rosenfeld et al., 1998). Eventually, this resulted in the culmination of prescriptive requirements such as the inclusion of cool roofs in energy codes like Title 24 of the California Code of Regulation (Levinson, Akbari, Konopacki, & Bretz, 2002).

Cool roof technologies, in the USA, have spread worldwide. Among many others, studies demonstrating their potentialities were undertaken in Europe (Synnefa, Santamouris, & Livada, 2006; Zinzi, 2010). The Cool Roofs Project as well was co-funded by the European Union to promote high-albedo surface as a UHI mitigation strategy and a measure for reducing cooling loads (Synnefa & Santamouris, 2012). Moreover, a hot theme in both Europe and the USA is the contribution to offset CO<sub>2</sub> production that can be achieved by increasing the albedo of urban surfaces (Akbari, Menon, & Rosenfeld, 2008). The usefulness of cool roofs was also investigated with regard to cold climates, such as in Montreal (Touchaie & Akbari, 2013). While cool roofs have shown to significantly reduce the contribution to the UHI in the hot season, the penalization introduced in regions with cold winter often seems negligible in terms of either energy needs for heating or lower heat released, thus, warming the outer urban environment (Magli, Lodi, Contini, Muscio, & Tartarini, 2016).

### Nomenclature

$c$  specific heat (J/(kg°C))

$c_l$  specific heat of the liquid/high temperature phase (J/(kg°C))

$c_s$  specific heat of the solid/low temperature phase (J/(kg°C))

$d_l$  mass density of the liquid/high temperature phase (kg/m<sup>3</sup>)

$d_s$  mass density of the solid/low temperature phase (kg/m<sup>3</sup>)

$h_{ce}$  external convective heat transfer coefficient (W/(m<sup>2</sup>°C))

$h_{ci}$  internal convective heat transfer coefficient (W/(m<sup>2</sup>°C))

$h_{re}$  external radiative heat transfer coefficient (W/(m<sup>2</sup>°C))

$h_{ri}$  internal radiative heat transfer coefficient (W/(m<sup>2</sup>°C))

$I_{sol}$  solar irradiance (W/m<sup>2</sup>)

$k$  thermal conductivity (W/(m°C))

$k_l$  thermal conductivity of the liquid/high temperature phase (W/(m°C))

$k_s$  thermal conductivity of the solid/low temperature phase (W/(m°C))

$L$  total thickness (m)

$q_{sl}$  latent heat (J/kg)

$T$  temperature (°C)

$T_{air}$  ambient air temperature (°C)

$T_{air}$  ambient air temperature (°C)

$T_{dp}$  dewpoint temperature (°C)

$T_e$  external effective temperature (°C)

$T_i$  internal temperature (°C)

$T_{me}$  mean absolute external temperature (K)

$T_{se}$  external surface temperature ( $^{\circ}\text{C}$ )

$T_{sky}$  sky temperature ( $^{\circ}\text{C}$ )

$T_{sl}$  phase change temperature

$T_{sol/air}$  sol-air temperature ( $^{\circ}\text{C}$ )

t time (s or day)

$v_{wind}$  wind velocity (m/s)

x coordinate across thickness (m)

$Dq_i$  change of the entering heat flow rate per unit surface ( $\text{W}/\text{m}^2$ )

$DT_{sl}$  half amplitude of the phase change interval ( $^{\circ}\text{C}$ )

$e_{ter}$  (external) thermal emittance ( $0 < e_{ter} < 1$ )

$r_{sol}$  (external) solar reflectance ( $0 < r_{sol} < 1$ )

$\sigma_0$  Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$ )

Moreover, cool roofs can in fact be seen as a technological rediscovery of ancient concepts. In Mediterranean areas, roofs and walls of buildings have been white since thousands of years. On the other hand, today we know that a white or very light color is not an objective term of evaluation but just a qualitative indicator. Thus, current cool roof technologies are based on measurement of materials performance and calculation of resulting benefits. More specifically, we know that a cool roof must have high solar reflectance, *i.e.* the ratio of reflected and incoming solar radiation. It should also have high thermal (or infrared) emittance such as the ratio of radiation emission in thermal (or far) infrared and maximum theoretical emission at the same surface temperature. Both solar reflectance and thermal emittance are measured as a percentage or a fraction of the unit. The higher the solar reflectance, the lower the fraction of solar radiation that is absorbed by a surface is. Such an absorbed radiation can then be returned to the atmosphere by convection with the air and by thermal radiation. In the absence of wind, heat removal mainly occurs through thermal radiation provided that the thermal emittance is high. In contrast, low solar reflectance may cause the surface to overheat and, consequently, lead to heat transmission to the roof structure and living spaces below. This contributes to building overheating and to the correlated UHI effect either directly, in terms of heat transfer to the external air by convection, or indirectly, due to the removal of the transmitted heat from the living spaces by means of the air conditioning systems. The latter contribution is augmented by the compressor power absorption which increases with the external air temperature.

Two different families of cool roofing solutions can be identified: cool white technologies for flat roof coverings, such as the example in Figure 1. These, by far, are the ones more commonly used. Cool color technologies for sloped roofs, as well, are designed to show a reflection spectrum in the visible range ( $0.4\text{-}0.7 \mu\text{m}$ ) as needed to obtain a desired color. At the same time, a reflection capacity in the near infrared (NIR,  $0.7\text{-}2.5 \mu\text{m}$ ) where solar radiation falls by more than 50% remains invisible to the human eye.

Cool white roofing solutions have many types: field applied coatings (paints, fluid applied membranes, etc.), reinforced bitumen sheets made of modified bitumen (elastomeric or plastomeric), single-ply sheets and membranes (thermoset or thermoplastic), tiles (ceramic, concrete, etc.), asphalt or bituminous shingles, pre-painted metal roofs, and built-up roofing. They can show initial solar reflectance as high as 80-85% and thermal emittance range of 80% to 95% for non-metallic materials (CRRC, 2015; US EPA, 2015; ECRC, 2015). On the other hand, it is very difficult to retain the initial reflectance value due to chemical and physical deterioration of materials and, above all, soiling caused by pollutant deposition and biological growth (Berdahl, Akbari, Levinson, & Miller, 2008; Berdahl, Akbari, & Rose, 2002; Bretz & Akbari, 1997; Sleiman et al., 2014). That being mentioned, the reflectance and emittance of opaque building elements are of the most superficial matters. These elements consist of a surface layer or a coating with thickness as low as a few tenths of millimeters with properties generally unaffected by the underlying substrate. Therefore, a superposed layer of atmospheric suspensions and/or grown up organic matter may strongly affect the reflective performance. Both initial and aged values of solar reflectance are thus provided in



Figure 1. Flatroof with cool white waterproofing membrane (Tecnopolo building of the University of Modena and Reggio Emilia, Modena, Italy).

the framework of the CRRC rating program which is obtained by natural exposure in three locations with different climate for at least three years (Sleiman et al., 2011). The development of matrices and white pigments chemically and physically stable permits avoiding degradation of the reflectance, such as that associated to yellowing of the surface. However, several approaches are exploited to reduce soiling, such as controlling the surface porosity and roughness, and possibly applying super-hydrophilic, super-hydrophobic surface treatments or self-cleaning coatings based on photo-catalysis (Diamanti et al., 2013). A few approaches, mentioned in the following section are also available to limit biological growth.

## 1.2. Biological Growth and Deterioration of Building Surfaces

As anticipated above, the deterioration of cool roofs and external building surfaces is due to several causes: aging and weathering, soiling and deposition of atmospheric black carbon, dust, organic and inorganic particulate matter as well as microbiological growths (Mastrapostoli et al., 2016; Sleiman et al., 2014). It is often difficult to distinguish between non biological and biologically-mediated weathering of materials: the two processes can occur concurrently, each one contributing to the overall deleterious effects (Gaylarde & Morton, 2003). The development of microbial communities on wetted surfaces is called biofilm, and it becomes gradually a more complex system (Characklis & Marshall, 1990). Biofilms on building surfaces can contain cyanobacteria, heterotrophic bacteria, algae, fungi, lichens, protozoa, and a variety of small animals (arthropods) and plants (briophyte) (Gaylarde & Gaylarde, 2005). Biological growth is influenced by both external conditions and intrinsic characteristics of the building material (Tomaselli, Lamenti, Bosco, & Tiano, 2000). External conditions are represented by rainfall, wind, sunlight, temperature and humidity as these determinate the water availability, an essential element to the microbial metabolism: wet surfaces promote autotrophic organism growth, therefore a higher susceptibility to bio fouling occurs in rainy regions as well as during heavy rain seasons (Tran et al., 2014). The issue arises also in humid climates due to the low surface temperatures of cool roofs and persistent condensation of atmospheric moisture. On the other hand, high temperatures induce water evaporation by heating the materials, making wind essential for the drying phenomenon. Altogether the climatic conditions determine, depending on the geography position, the moisture and light conditions that define the micro-climate on building surfaces, which is the major environmental factor influencing biological growth (Ariño, Gomez-Bolea, & Saiz-Jimenez, 1997). If moisture is

high enough, and lighting and temperature conditions are suitable, colonization of the surface of new buildings can occur very quickly (Wee, 1992). Also, the building design and the orientation of the building surface influence external factors of bio growth: the north-facing facades, which are wetter and less sunny, get colonized faster (Ariño et al, 1997). More details on biological growth are given by Ferrari (2015).

In order to limit biological growth, surface treatments based on biocides can be used, but their effects may however vanish quickly and may be toxic and forbidden in many countries. Biological growth can also be countered by lowering the thermal emittance and thus decreasing heat transfer by infrared radiation to the sky and the consequent night undercooling. Nonetheless, this can also decrease the performance of cool roofs. The alternative approach to counter biological growth on cool roofs and similar building surfaces that is analyzed here is to embed in the first layer below the cool roof surface a phase changing material that absorbs heat during the daytime and then releases it in the nighttime. This can increase the minimum surface temperatures, thus reducing humidity condensation and biological growth. In this work, preliminary results on the coupling of cool roofs and PCMs are presented after being obtained by theoretical investigation on commercial materials and taking into account the time of evolution of environmental conditions in a sub-Mediterranean climate with low wind and relatively high humidity.

## **2. Phase Change Materials and Their Coupling with Cool Roof Surfaces**

Latent heat storage technologies that use phase change materials (PCM) embedded in lightweight building elements are considered an interesting alternative to sensible storage by heavyweight constructions (Zalba, Marin, Cabeza, & Mehling, 2003; Khudhair & Farid, 2004; Mavrigiannaki & Ampatzi, 2016). These materials can undergo a phase change, typically melting or solidification, and therefore exchange more heat with the environment in terms of latent heat rather than sensible heat storage capacity. In recent times the attention has also been drawn by the coupling of PCMs with cool roofs, studied by either numerical simulation or experiments. Experimental results, by Karlessi and others (2011), demonstrated that PCM incorporated in building coatings yields lower surface temperatures than either common coatings or cool infrared-reflective coatings. The numerical investigation by Aguilar and others AR (2013) extended previous work by considering the impact of PCM embedded in roofing module on cooling energy and showed that solar reflectance is the parameter with the biggest impact. Nonetheless, PCMs may be worthwhile in locations where the reflectance undergo a sharp decrease due to soiling. Moreover, they verified that simulation is a powerful tool for the involved multi-parameter analyses. Roman and others (2016) showed through simulation that a PCM allows a sharp decrease of through-roof heat gain at a wide range of albedo. In (Chou, Chen, & Nguyen, 2013) the coupling of a metal sheet cool roofing structure with a PCM was studied in order to absorb the downward heat flow induced by incident solar radiation and then release it back to the environment by convection during the nocturnal cycle. Experimental and numerical analyses showed that the downward thermal flow through the roof into the house can be significantly reduced. Another study was aimed at the development and prototyping of a cool polyurethane-based membrane with PCM inclusion for roofing applications (Pisello et al., 2016). In another, PCM cool roof system was created using PCM doped tiles (Chung & Park, 2016). Experimental results showed that such tiles, during the summer, allow a decrease of surface temperature while maintaining low room temperatures.

Generally speaking, most of the studies have shown that PCM can even both positive and negative peaks of surface temperature and thus improve thermal comfort and reduce cooling energy demand. None, however, seem to have yet paid attention to the specific issue of using PCM to limit condensation and biological growth on cool roof surfaces. This is therefore the topic of investigation in this work.

## **3. Model and Case Study**

In order to parametrically investigate the thermal behavior of a cool roof coating coupled with a PCM, a one-dimensional mathematical model of the roof system was implemented in the Matlab programming environment. The model, based on a finite-volume approach with implicit discretization of the time derivatives, takes into account

the cyclical variability of the boundary conditions (temperature, solar irradiance, heat transfer coefficients) and the temperature dependence on the thermophysical properties of materials. It has been used to identify the time periods during which the external surface temperature falls below the dew-point and the risk of humidity condensation occurs. In this way, a comparison of the situation with and without a PCM layer below the cool roof surface has been carried out considering surfaces with relatively low thermal emittance.

A flat roof was considered in this study. Hourly weather data on air temperature, sky temperature, wind velocity, solar irradiance and dew-point temperature were obtained over the whole year from the TRNSYS programming environment (TMY data). Representative time evolution patterns are shown in Figure 2.

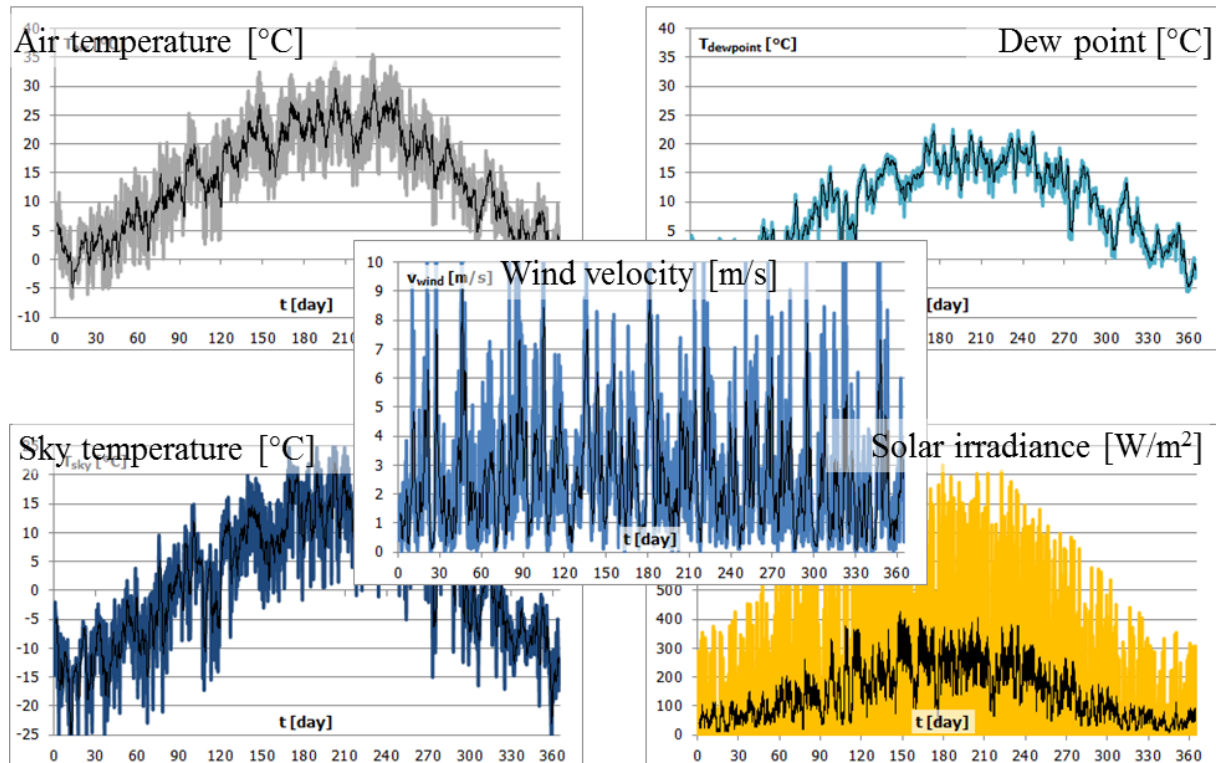


Figure 2. Ambient conditions over the year for Bologna, Italy (data from TRNSYS, the black lines represent the daily average).

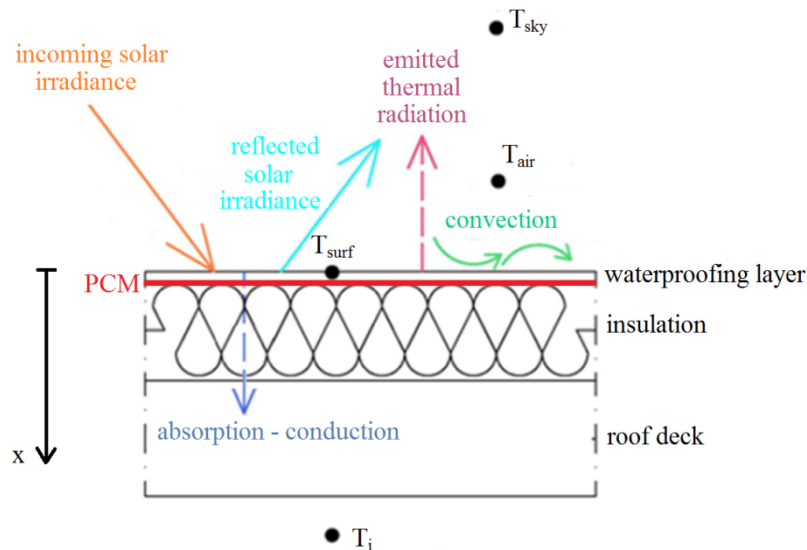


Figure 3. Roof structure and surface heat transfer processes.

The heat transfer process is depicted in Figure 3. More specifically, the boundary condition at the external surface of the solid matter ( $x=0$ ), delimiting the external environment from the waterproofing layer, is expressed as

$$(h_{ce} + h_{re}) [T_{sol/air}(t) - T(t)_{x=0}] = -k \frac{dT(t)}{dx} \Big|_{x=0} \quad (1)$$

where the so-called sol-air temperature  $T_{sol/air}$  ( $^{\circ}\text{C}$ ) is calculated as follows: from the effective external temperature  $T_e$  ( $^{\circ}\text{C}$ ) and the absorbed fraction of the solar irradiance  $I_{sol}$  ( $\text{W}/\text{m}^2$ ) that results from the surface solar reflectance  $\rho_{sol}$  ( $0 < \rho_{sol} < 1$ ):

$$T_{sol/air}(t) = T_e(t) + \frac{(1 - \rho_{sol})I_{sol}(t)}{h_{ce} + h_{re}} \quad (2)$$

The effective external temperature  $T_e$  ( $^{\circ}\text{C}$ ) is in turn the average of air and sky temperatures,  $T_{air}$  and  $T_{sky}$  ( $^{\circ}\text{C}$ ), weighted by the external convective and radiative heat transfer coefficients,  $h_{ce}$  and  $h_{re}$  ( $\text{W}/(\text{m}^2\text{C}^{\circ})$ ):

$$T_e(t) = \frac{h_{ce}T_{air}(t) + h_{re}T_{sky}(t)}{h_{ce} + h_{re}} \quad (3)$$

Air temperature and sky temperature, as well as the solar irradiance and, consequently,  $T_e$  and  $T_{sol/air}$ , are function of the time  $t$  (s). The convective heat transfer coefficient  $h_{ce}$  is evaluated from the wind velocity  $v_{wind}$  (m/s) according to ISO 6946 (ISO, 2007a):

$$h_{ce}(t) = 4 + 4v_{wind}(t) \quad (4)$$

The radiative heat transfer coefficient  $h_{re}$  is again evaluated according to ISO 6946 at the mean absolute external temperature  $T_{me}$  (K), also considering the thermal emittance  $\epsilon_{ter}$  ( $0 < \epsilon_{ter} < 1$ ), as

$$h_{re} = \epsilon_{ter} 4\sigma_0 T_{me}^3(t) \quad (5)$$

where  $\sigma_0$  is the Stefan-Boltzmann constant ( $\sigma_0 = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$ ), and

$$T_{me}(t) = \frac{1}{2} [T_{sky}(t) + T(t)_{x=0}] \quad (6)$$

An explicit approach is generally followed to evaluate the radiative heat transfer coefficient from the calculated surface temperature.

Concerning thermal interaction between the roof structure and the inhabited space below, the indoor temperature  $T_i$  ( $^{\circ}\text{C}$ ) was assumed to be controlled by an appropriate air conditioning system and kept constant at a level adequate to thermal comfort, e.g.  $T_i = 27^{\circ}\text{C}$  for the summer period in the analyses presented here. The boundary condition at the internal surface ( $x=L$ ), delimiting the roof structure from the indoor space, is expressed as

$$(h_{ci} + h_{ri}) [t(t)_{x=L} - T_i] = k \frac{dT(t)}{dx} \Big|_{x=L} \quad (7)$$

Constant values obtained from ISO 6946 were used for both the internal convective coefficient  $h_{ci}$ , taken equal to  $0.7 \text{ W}/(\text{m}^2\text{C}^{\circ})$ , and the internal radiative coefficient  $h_{ri}$ , evaluated equal to  $5.5 \text{ W}/(\text{m}^2\text{C}^{\circ})$  by a formula analogous to eq. (5) for the typical value of the thermal emittance of inner building surfaces, equal to 0.9, and an internal absolute mean temperature of  $27^{\circ}\text{C} = 300 \text{ K}$ .

The same model used in a previous work was exploited for the heat transfer in the solid matter comprised between the external surface ( $x=0$ ) and the internal one ( $x=L$ ), including the PCM layer (Barozzi, Corticelli, Libbra, Muscio, & Tartarini, 2009). In fact, the thermal behaviour of a PCM can be mathematically modeled through different approaches. The one adopted here is based on the definition of a fictitious equivalent material whose specific heat  $c$  ( $\text{J}/(\text{kg}\times^{\circ}\text{C})$ ) is a function of temperature. Heat absorbed or released by such a fictitious material must be equal to that absorbed or released by the actual material for the same increase or decrease of temperature. This seems consistent with the literature which shows that currently available PCM do not change phase at a precise temperature level, but rather over a more or less narrow temperature interval (Carbonari, Grassi, Perna, & Principi,

2006; Farid, Khudhair, Razack, & Al-Hallaj, 2004; Schossig, Henning, Gschwander, & Haussmann, 2005; Tyagi & Buddhi, 2007; Zalba et al., 2003). Moreover, the slope of heat absorption or release in the phase change interval is often similar to a gaussian distribution about the central temperature. In the industrial practice, either the central value or the amplitude of the phase change interval are modulated through an appropriate formulation of the PCM (ex: the phase change temperature of paraffin depends on the length of the molecular chains, which can be modulated in terms of statistical distribution about an assigned average value in order to obtain the desired properties).

Going into detail, the equivalent specific heat  $c$  of a PCM with latent heat  $q_{sl}$  (J/kg), specific heat  $c_s$  (J/(kg×°C)) of the solid phase (or the low temperature phase in solid-solid transitions) and specific heat  $c_l$  (J/(kg×°C)) of the liquid phase (or the high temperature phase) is represented in this study by a gaussian distribution in a range with amplitude  $2 \times \Delta T_{sl}$  about the nominal phase change temperature  $T_{sl}$  (°C) (see Fig. 3). This is described by the following relationship:

$$c(T) = c_s + (c_l - c_s) \cdot \left( \frac{T - T_{sl}}{2\Delta T_{sl}} + \frac{1}{2} \right) + \frac{q_{sl}}{\Delta T_{sl}} \cdot \frac{2}{\sqrt{\pi}} \cdot \exp \left[ - \left( \frac{T - T_{sl}}{\Delta T_{sl}/2} \right)^2 \right] \quad (8)$$

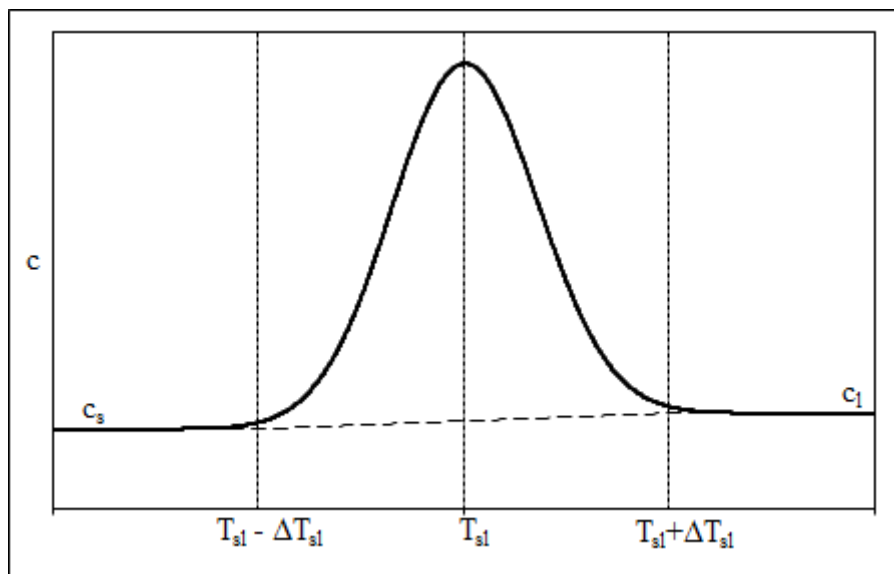


Figure 4. Effective specific heat of the PCM.

The thermal conductivity  $k$  (W/(m°C)) and other thermophysical properties which may vary significantly during the phase transition can also be modelled by assuming, over the phase change temperature interval, a linear variation between the values for the solid and the liquid phases, e.g.  $k_s$  and  $k_l$  (W/(m°C)):

$$k(T) = k_s + (k_l - k_s) \cdot \left( \frac{T - T_{sl}}{2 \cdot \Delta T_{sl}} + \frac{1}{2} \right) \quad (9)$$

Nonetheless, for the time being, certainly reliable data on the PCM are missing, so the properties of the solid and liquid phases are assumed to be equal for sake of simplicity, in view of their relatively low differences.

The properties of common building materials as reported in ISO 13786 (ISO, 2007b) for a thick concrete structure with thermal insulation were used for the different layers (see Tab. 1), whereas a commercial PCM board, DuPont Energain (Energain, 2016), was considered for the PCM to be introduced between the waterproof coating and the thermal insulation layer below with a thickness up to 10 mm. More specifically, a product developed by DuPont and called Energain® was considered, that is a composite PCM wallboard constituted of 60% of microencapsulated paraffin included in a polymeric structure; such a mixture is laminated by aluminium. Since the literature raises doubts on the material specifications (Energain, 2016), these were integrated with experimental data from a third party (Du et al., 2012) (see Tab. 2).

Table 1. Properties of the reference roofstructure – Raw data from (ISO, 2007b).

Layer	Th. conductivity k (W/(m°C))	Mass density d (kg/m <sup>3</sup> )	Specific heat c (J/(kg°C))	Thickness s (m)
Waterproofing	1.00	1200	1500	0.005
PCM	See Tab. 2		1400	0 – 0.010
Thermal insulation	0.04	30		0.100
Concrete	1.80	2400	1000	0.200

Table 2. Properties of the PCM panel – Raw data from Du et al. (2012); Energain (2016)

Latent heat $q_{sl}$	70 kJ/kg
Phase change temperature $T_{sl}$	24.5°C
Half-amplitude of the phase change interval $\Delta T_{sl}$	9.5°C
Specific heat $c_s \cong c_l$	2.3 kJ/(kg°C)
Thermal conductivity $k_s \cong k_l$	0.16 W/(m°C)
Mass density $d_s \cong d_l$	1001 kg/m <sup>3</sup>

#### 4. Results

The model has been used to identify the time periods during which the external surface temperature  $T_{se}$  (°C) falls below the dewpoint  $T_{dp}$  (°C), thus explaining the risk of humidity condensation. The process is depicted in Figure 4, where the surface temperature is plotted for a short mid-summer period in case of absence of PCM and presence of a PCM layer with 10 mm thickness.

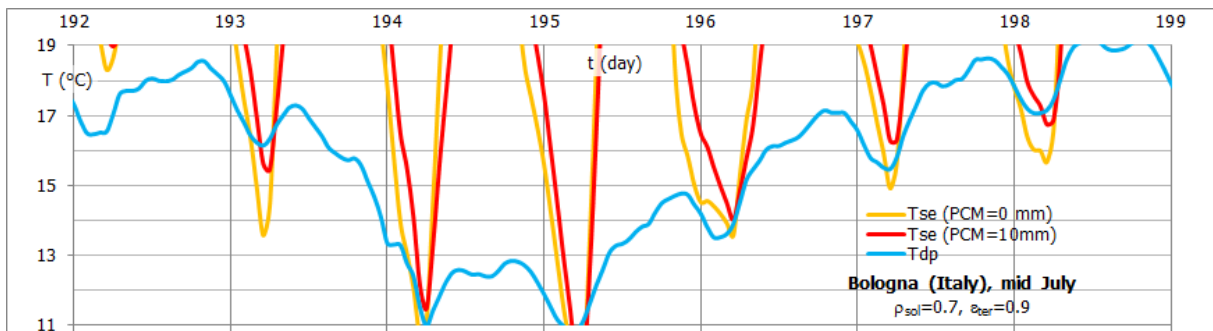


Figure 5. Time evolution patterns of dew point surface (with and without PCM) temperatures: the risk of condensation exists where the surface temperature falls below the dew point temperature.

The frequency of the risk of condensation is represented in Figure 5-a) for a cool roof with thermal insulation but without PCM below the surface. It is then shown in Figure 5-b) and Figure 5-c), respectively, that the risk becomes lower with a 5 mm PCM layer, and much lower with a 10 mm PCM layer. In Figure 5-d) the risk of condensation is represented for a cool roof with thermal insulation and without PCM, but with thermal emittance 0.6 instead of 0.9; in this case one can observe that the reduced thermal emittance limits heat loss toward the sky during the night-time and, consequently, yields a risk of condensation similar to that provided by a 10 mm thick layer of PCM. Nevertheless, it was also found that an always positive change  $Dq_i$  (W/m<sup>2</sup>) of the heat flow entering the inhabited space is obtained with respect to a cool roof surface with typical emittance of 0.9, that is an increased entering heat flow (see Fig. 6), whereas a cool roof surface with emittance 0.9 coupled with PCM causes an oscillating change  $Dq_i$  of the entering heat flow but with null average.

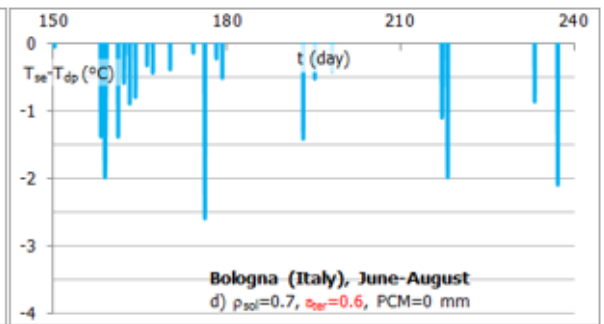
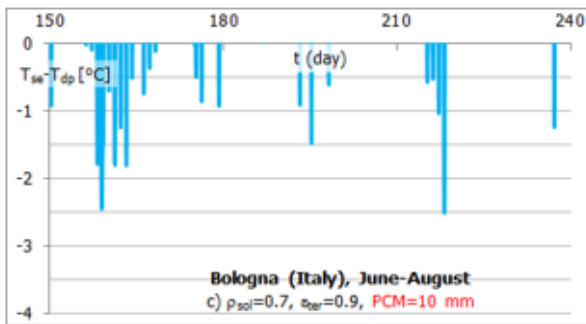
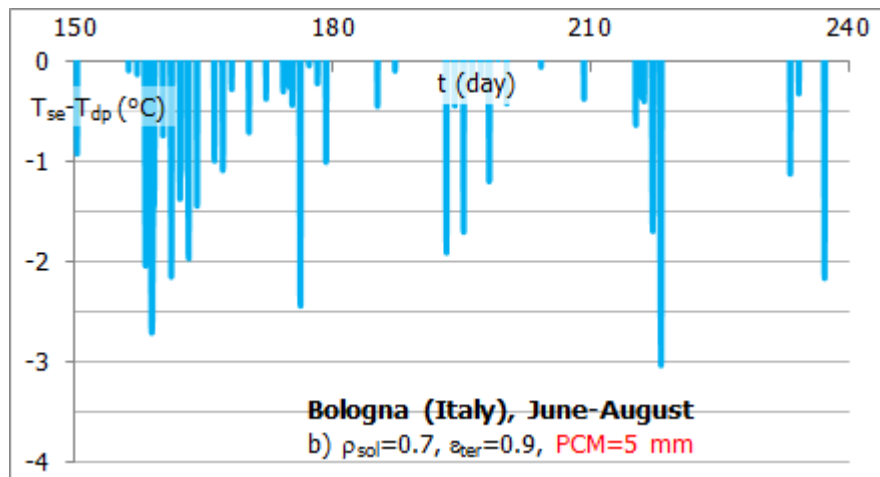
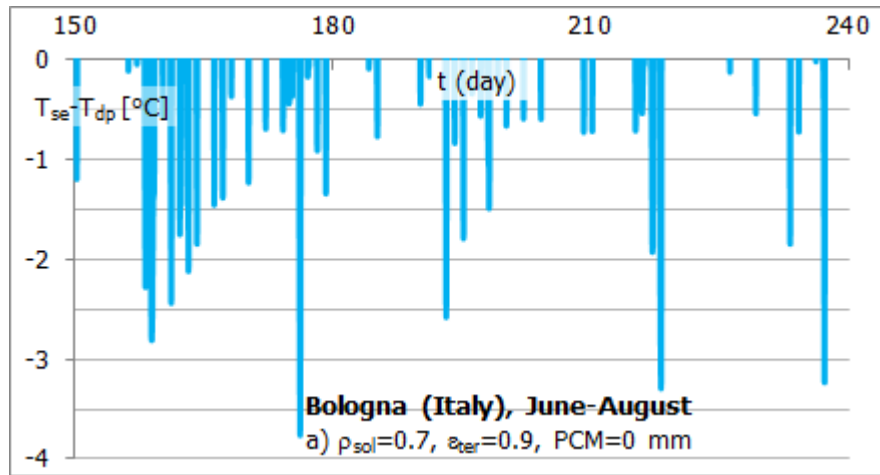


Figure 6. Risk of condensation for a) a typical cool roof, b) a cool roof coupled with 5 mm PCM, c) a cool roof coupled with 10 mm PCM, d) a cool roof with thermal emittance lower than usual.

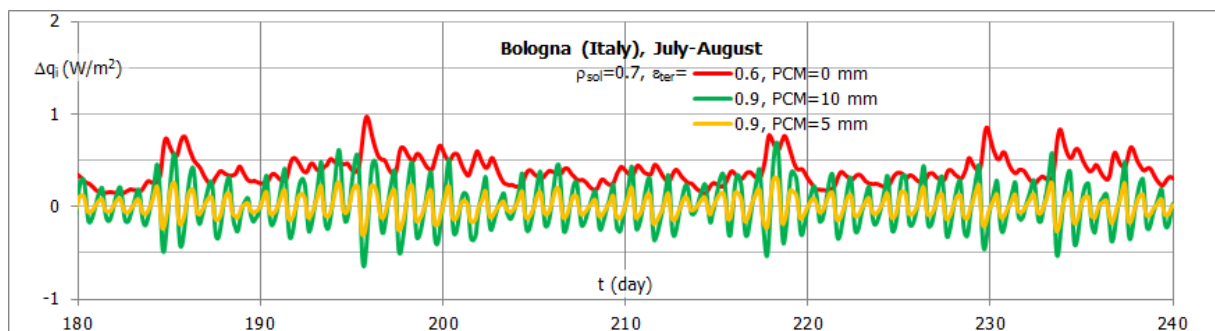


Figure 7. Change of the heat flow entering the inhabited space with respect to a typical cool roof with  $\rho_{sol}=0.7$ ,  $e_{ter}=0.9$ .

## 5. Concluding Remarks

In this work, it was shown that a PCM can actually increase the nighttime surface temperature of a thermally-insulated cool roof without affecting the overall performance of the cool roofing product. Heat is accumulated in the daytime by the PCM and then released in the night-time, increasing the minimum temperature and thus reducing the risk of falling below the dewpoint temperature, with the start of humidity condensation. Limiting humidity condensation may help preserve the cool roof surface from biological growth, especially for insulated roofs. A similar result can also be provided by a decrease of the thermal emittance at the external surface, but with a penalization of the cool roof performance in terms of heat transmitted to the inhabited space below and also maximum surface temperatures.

A relatively high mass fraction of PCM must be installed in the outer layer, either integrated in a waterproofing membrane or, as a board, placed just below the membrane, or below an outer metal sheet in insulated sandwich components. Effective results were in fact found only for a PCM board with thickness 10 mm and percent content of PCM around 60%. A lower amount of dispersed PCM may lead to an ineffective contribution.

In upcoming work, ambient data for different climatic conditions will be taken into account, considering either arid or very humid climates. Moreover, the analysis will focus on the choice of the phase change temperature, which must be slightly higher than the expected dew point temperature and should probably be optimized depending on the location. A more detailed model of the PCM is also under development, to be supported by experiments. Eventually, integration of the proposed solution in comprehensive dynamic models is a long-term objective.

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## References

1. Aguilar, J. C., Smith, G. B., Gentle, A. R., & Chen, D. (n.d.). Optimum integration of albedo, sub-roof R-value, and phase change material for cool roofs. *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France*. P.1315-1321 Retrieved from [http://www.ibpsa.org/proceedings/BS2013/p\\_1105.pdf](http://www.ibpsa.org/proceedings/BS2013/p_1105.pdf)
2. Akbari, H., Bretz, S., Kurn, D. M., & Hanford, J. (1997). Peak power and cooling energy savings of high-albedo roofs. *Energy and Buildings*, 25(2), 117-126. doi:10.1016/s0378-7788(96)01001-8
3. Akbari, H., Konopacki, S., & Pomerantz, M. (1999). Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. *Energy*, 24(5), 391-407. doi:10.1016/s0360-5442(98)00105-4
4. Akbari, H., Menon, S., & Rosenfeld, A. (2008). Global cooling: Increasing world-wide urban albedos to offset CO<sub>2</sub>. *Climatic Change*, 94(3-4), 275-286. doi:10.1007/s10584-008-9515-9
5. Ariño, X., Gomez-Bolea, A., & Saiz-Jimenez, C. (1997). Lichens on ancient mortars. *International Biodegradation & Biodegradation*, 40(2-4), 217-224. doi:10.1016/s0964-8305(97)00036-x
6. Barozzi, G. S., Corticelli, M. A., Libbra, A., Muscio, A., & Tartarini, P. (2009). Building Structures with high thermal inertia based on phase change materials. *International Journal of Heat and Technology*, 27, 121-126.
7. Berdahl, P., & Bretz, S. E. (1997). Preliminary survey of the solar reflectance of cool roofing materials. *Energy and Buildings*, 25(2), 149-158. doi:10.1016/s0378-7788(96)01004-3

8. Berdahl, P., Akbari, H., & Rose, L. S. (2002). Aging of reflective roofs: Soot deposition. *Applied Optics*, 41(12), 2355. doi:10.1364/ao.41.002355
9. Berdahl, P., Akbari, H., Levinson, R., & Miller, W. A. (2008). Weathering of roofing materials – An overview. *Construction and Building Materials*, 22(4), 423-433. doi:10.1016/j.conbuildmat.2006.10.015
10. Bretz, S. E. & Akbari, H. (1997). Long-term performance of high-albedo roof coatings. *Energy and Buildings*, 25(2), 159-167. doi:10.1016/s0378-7788(96)01005-5
11. Building components and building elements. Thermal resistance and thermal transmittance. Calculation method. (n.d.). doi:10.3403/00942964u
12. Carbonari, A., Grassi, M. D., Perna, C. D., & Principi, P. (2006). Numerical and experimental analyses of PCM containing sandwich panels for prefabricated walls. *Energy and Buildings*, 38(5), 472-483. doi:10.1016/j.enbuild.2005.08.007
13. Characklis, W. G., & Marshall, K. C. (1990). *Biofilms*. New York: John Wiley.
14. Chou, H., Chen, C., & Nguyen, V. (2013). A new design of metal-sheet cool roof using PCM. *Energy and Buildings*, 57, 42-50. doi:10.1016/j.enbuild.2012.10.030
15. Chung, M. H., & Park, J. C. (2016). Development of PCM cool roof system to control urban heat island considering temperate climatic conditions. *Energy and Buildings*, 116, 341-348. doi:10.1016/j.enbuild.2015.12.056
16. Cool Roof Rating Council. (n.d.). Retrieved 2015, from <http://www.bing.com/cr?IG=C2FB2C67C46B43D3B9040A1A81E4FE0E&CID=24B9ED466A196C3B3839E1006BE46D1C&rd=1&h=tCnW5yHhwKCRwC9CQiZPmQRATFmZBNLIFiumWEhvn8&v=1&r=http://coolroofs.org/&p=DevEx.LB.1,5491.1>
17. Diamanti, M. V., Paolini, R., Zinzi, M., Ormellese, M., Fiori, M., & Pedefferri, M. P. (2013). Self-cleaning ability and cooling effect of TiO<sub>2</sub>-containing mortars. *Technical Proc. of the NSTI-Nanotech 2013 – 2013 NSTI Nanotechnology Conference and Expo.*, 3, 716-719.
18. DuPont. Energain Data Sheet – Measured Properties. (n.d.). Retrieved 2016, from [http://energain.co.uk/Energain/en\\_GB/assets/downloads/documentation/download/Energain®\\_Datasheet\\_UK.pdf](http://energain.co.uk/Energain/en_GB/assets/downloads/documentation/download/Energain®_Datasheet_UK.pdf)
19. ENERGY STAR — The Simple Choice for Energy Efficiency. (n.d.). Retrieved from <https://www.energystar.gov/>
20. Farid, M. M., Khudhair, A. M., Razack, S. A., & Al-Hallaj, S. (2004). A review on phase change energy storage: Materials and applications. *Energy Conversion and Management*, 45(9-10), 1597-1615. doi:10.1016/j.enconman.2003.09.015
21. Ferrari, C., Santunione, G., Libbra, A., Muscio, A., Sgarbi, E., Siligardi, C., & Barozzi, G. S. (2015). Review on the influence of biological deterioration on the surface properties of building materials: Organisms, materials, and methods. *International Journal of Design & Nature and Ecodynamics*, 10(1), 21-39. doi:10.2495/dne-v10-n1-21-39
22. Gaylarde, C. C., & Gaylarde, P. M. (2005). A comparative study of the major microbial biomass of biofilms on exteriors of buildings in Europe and Latin America. *International Biodeterioration & Biodegradation*, 55(2), 131-139. doi:10.1016/j.ibiod.2004.10.001
23. Gaylarde, C., & Morton, G. (2003). Biodeterioration of Mineral Materials. *Encyclopedia of Environmental Microbiology*. doi:10.1002/0471263397.env135
24. Ichinose, M., Inoue, T., & Sakamoto, Y. (2009). Long-term performance of high-reflectivity exterior panels. *Building and Environment*, 44(8), 1601-1608. doi:10.1016/j.buildenv.2008.10.003

25. John, D. M. (1998). Algal growths on buildings: A general review and methods of treatment. *Biodeterioration Abstracts*, 2, 81-102.
26. Karlessi, T., Santamouris, M., Synnefa, A., Assimakopoulos, D., Didaskalopoulos, P., & Apostolakis, K. (2011). Development and testing of PCM doped cool colored coatings to mitigate urban heat island and cool buildings. *Building and Environment*, 46(3), 570-576. doi:10.1016/j.buildenv.2010.09.003
27. Khudhair, A. M., & Farid, M. M. (2004). A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Conversion and Management*, 45(2), 263-275. doi:10.1016/s0196-8904(03)00131-6
28. Le Du, M., Zalewski, L., Lassue, S., Dutil, Y., & Rouse, D. (2012). Thermophysical characterization of a composite phase change material: The specific case of Energain. Proceedings of the 12th International Conference on Energy Storage.
29. Levinson, R., Akbari, H., Konopacki, S., & Bretz, S. (2002). Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. doi:10.2172/813562
30. Magli, S., Lodi, C., Contini, F., Muscio, A., & Tartarini, P. (2016). Dynamic analysis of the heat released by tertiary buildings and the effects of urban heat island mitigation strategies. *Energy and Buildings*, 114, 164-172. doi:10.1016/j.enbuild.2015.05.037
31. Mastrapostoli, E., Santamouris, M., Kolokotsa, D., Vassilis, P., Venieri, D., & Gompakis, K. (2016). On the ageing of cool roofs: Measure of the optical degradation, chemical and biological analysis and assessment of the energy impact. *Energy and Buildings*, 114, 191-199. doi:10.1016/j.enbuild.2015.05.030
32. Mavriagiannaki, A., & Ampatzi, E. (2016). Latent heat storage in building elements: A systematic review on properties and contextual performance factors. *Renewable and Sustainable Energy Reviews*, 60, 852-866. doi:10.1016/j.rser.2016.01.115
33. 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
34. Pisello, A., Fortunati, E., Mattioli, S., Cabeza, L., Barreneche, C., Kenny, J., & Cotana, F. (2016). Innovative cool roofing membrane with integrated phase change materials: Experimental characterization of morphological, thermal and optic-energy behavior. *Energy and Buildings*, 112, 40-48. doi:10.1016/j.enbuild.2015.11.061
35. Roman, K. K., Obrien, T., Alvey, J. B., & Woo, O. (2016). Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities. *Energy*, 96, 103-117. doi:10.1016/j.energy.2015.11.082
36. Rosenfeld, A. H., Akbari, H., Romm, J. J., & Pomerantz, M. (1998). Cool communities: Strategies for heat island mitigation and smog reduction. *Energy and Buildings*, 28(1), 51-62. doi:10.1016/s0378-7788(97)00063-7
37. Schossig, P., Henning, H., Gschwander, S., & Haussmann, T. (2005). Micro-encapsulated phase-change materials integrated into construction materials. *Solar Energy Materials and Solar Cells*, 89(2-3), 297-306. doi:10.1016/j.solmat.2005.01.017
38. 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

39. Sleiman, M., Kirchstetter, T. W., Berdahl, P., Gilbert, H. E., Quelen, S., Marlot, L., . . . Destailhats, H. (2014). Soiling of building envelope surfaces and its effect on solar reflectance – Part II: Development of an accelerated aging method for roofing materials. *Solar Energy Materials and Solar Cells*, 122, 271-281. doi:10.1016/j.solmat.2013.11.028
40. Synnefa, A., & Santamouris, M. (2012). Advances on technical, policy and market aspects of cool roof technology in Europe: The Cool Roofs project. *Energy and Buildings*, 55, 35-41. doi:10.1016/j.enbuild.2011.11.051
41. 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
42. Synnefa, A., Santamouris, M., & Livada, I. (2006). A study of the thermal performance of reflective coatings for the urban environment. *Solar Energy*, 80(8), 968-981. doi:10.1016/j.solener.2005.08.005
43. Taha, H., Akbari, H., Rosenfeld, A., & Huang, J. (1988). Residential cooling loads and the urban heat island—the effects of albedo. *Building and Environment*, 23(4), 271-283. doi:10.1016/0360-1323(88)90033-9
44. Thermal performance of building components. Dynamic thermal characteristics. Calculation methods. (n.d.). doi:10.3403/30313353
45. Tomaselli, L., Lamenti, G., Bosco, M., & Tiano, P. (2000). Biodiversity of photosynthetic micro-organisms dwelling on stone monuments. *International Biodeterioration & Biodegradation*, 46(3), 251-258. doi:10.1016/s0964-8305(00)00078-0
46. Touchaei, A. G., & Akbari, H. (2013). The climate effects of increasing the albedo of roofs in a cold region†. *Advances in Building Energy Research*, 7(2), 186-191. doi:10.1080/17512549.2013.865558
47. Tran, T. H., Govin, A., Guyonnet, R., Grosseau, P., Lors, C., Damidot, D., . . . Ruot, B. (2014). Influence of the intrinsic characteristics of mortars on their biofouling by pigmented organisms: Comparison between laboratory and field-scale experiments. *International Biodeterioration & Biodegradation*, 86, 334-342. doi:10.1016/j.ibiod.2013.10.005
48. Tyagi, V. V., & Buddhi, D. (2007). PCM thermal storage in buildings: A state of art. *Renewable and Sustainable Energy Reviews*, 11(6), 1146-1166. doi:10.1016/j.rser.2005.10.002
49. Wee, Y. (1992). The occurrence of *Ficus* spp. on high-rise buildings in Singapore. *International Biodeterioration & Biodegradation*, 29(1), 53-59. doi:10.1016/0964-8305(92)90006-a
50. Zalba, B., Marin, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications. *Applied Thermal Engineering*, 23(3), 251-283. doi:10.1016/s1359-4311(02)00192-8
51. Zinzi, M. (2010). Cool materials and cool roofs: Potentialities in Mediterranean buildings. *Advances in Building Energy Research*, 4(1), 201-266. doi:10.3763/aber.2009.0407