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COOL ROOFS
COST BENEFIT ANALYSIS

Volume 1 - Cool Roofs : International Progress, Technology, Market, and Legislative Frame

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Image on the cover page: infrared aerial orthophoto of the CBD of Parramatta. Parramatta Urban Overheating Project, UNSW Built Environment.

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Executive summary

This study is performed to report on the state of the art of reflective roofing technologies, widely known as cool roofs, and the advances for the new generation of cool roofing materials. The main categories of products available on the market are discussed as well as the general market trends. Then, we discuss the benefits at building and urban scale of cool roofs in terms of energy savings and ambient temperature reductions. We also report on the limitations and disadvantages of the technology. Further, we document policies and programs that support the adoption of cool roofs in North America (USA, Canada, and Mexico) and the European Union, including the performance assessment and testing framework implemented with the Cool Roofing Rating Council (CRRC) in the USA, and European Cool Roofs Council (ECRC) in Europe. Then, we present some relevant projects implementing and assessing the performance of cool roofs. Thus, in this executive summary, we offer a synthesis of the contents presented in detail in the extended report. Finally, a survey was conducted and analysed to collect information on the existing cool roof installations in Australia, and the performance, current market, and characteristics of cool roof products from cool roof commercial stakeholders in Australia.

The whole study involved the following sections:

Cool Roofing Technologies. A cool roof is an opaque roofing system that is characterized by high solar reflectance (SR), to minimize the amount of solar radiation absorbed and high thermal emittance (TE) to maximize the amount of heat that is radiated away in the infrared portion of the electromagnetic spectrum. As a result, cool roofs exhibit a surface temperature increase lower than that of a conventional roofing system. A cool roof, due to its lower surface temperature, decreases the heat penetrating into the building and contributes to decreasing the air temperature as less heat is transferred via convection from the cooler surface to the ambient air. Many cool roofing materials are commercially available such as coatings, membranes, built-up roofs, metal roofs, tiles and asphalt shingles, and there is a cool option for almost every type of roof. Cool white or light-coloured roofing products demonstrate superior performance in terms of their radiative properties with high initial SR and TE values (usually SR > 0.65 and TE > 0.8) and a significant cooling potential exhibiting surface temperatures that are by 30-35 °C lower, compared to dark coloured conventional roofing material. Cool coloured materials may have the same colour as conventional materials but present higher SR because they highly reflect in the non-visible near-infrared (NIR) part of the solar spectrum. For instance, a cool black coating with SR = 0.27 will stay by 10 °C cooler compared to a conventional black coating (SR = 0.05). They are used on steep-sloped roofs or other visible surfaces to meet the aesthetic/design preferences for darker colours and prevent potential visual discomfort problems. In addition, innovative materials for heat mitigation in the built environment with advanced radiative and thermal properties have been developed, and their performance is investigated. Fluorescent cool coloured materials stay cooler under the sun as they re-emit some of the absorbed solar radiation as invisible NIR radiation (fluorescence effect). Thermochromic materials are dynamic materials that change their solar reflectance (colour) reversibly as a function of temperature, having high solar reflectance (white or light-coloured appearance) in summer and low solar reflectance (dark coloured appearance) during the cold period, minimizing the heating penalty and optimizing the energy performance throughout the year. The first generation of these materials suffered from significant ageing, as they faded and lost their reversibility after some time when exposed to outdoor conditions, with a new generation of such materials under development. Directionally reflective and retroreflective materials have tailored radiative properties preventing glare problems and overheating due to unwanted reflection. Daytime radiative cooling is one of the most promising cool material technologies due to its high cooling potential. These materials have SR approaching 1 (i.e., almost perfect reflection) and TE also close to 1 in the atmospheric window (8-13 μm), while they have a very low TE in the rest of the 4 – 80 μm thermal infrared spectrum to maximize long-wave radiative loss to the sky and thus may have a negative thermal balance, decreasing surface temperatures to sub-ambient levels. Also, Phase Change Materials (PCMs), which can store and release large amounts of heat in latent form when they go through a change in their physical state (from solid to liquid and vice versa), have been incorporated in cool materials. During the daytime, the PCM absorbs part of the heat through the melting process and at night, the PCM solidifies and releases the stored heat. The net effect is a reduction of the daytime surface temperature of the material and increased durability due to lower temperature swings.

Benefits of cool roofs at building scale: Installing a cool roof on a new or existing building can significantly improve the energy efficiency resulting in cooling energy savings that may range from 2% to 44% and peak cooling energy savings between 3% and 35% depending on local climate, radiative properties of the building envelope, building characteristics, type and use, etc. These reductions result in corresponding cost savings and prevent unwanted electricity shutdowns during heatwaves. Moreover, in buildings without air conditioning, the reduced heat transfer from the cooler roof results in lower indoor air temperatures ranging averagely from 1-3°C and improved thermal comfort conditions. This is an important social benefit, especially for low-income households suffering from energy poverty and exposure to extreme overheating conditions and heat-related health risks. In addition, a cool roof is likely to have a longer lifetime, resulting in reduced waste going to landfills due to the significantly lower surface temperatures and the reduced diurnal temperature fluctuations compared to a conventional dark roof. Combining solar panels with a cool roof can increase the output of a photovoltaic system due to the reduced transferred heat. A large cool roof surface area (e.g., on commercial or industrial buildings) has been found to decrease local air temperatures 0.5-1.5 m above the roof, thereby further decreasing rooftop HVAC energy consumption due to lower intake temperature. Finally, building owners can see increased property value from energy efficiency measures such as cool roofs that lead to lower energy consumption and lower running costs.

Main disadvantages and problems: Cool roofs may cause an increase in demand for building heating in the winter. This heating penalty is usually offset by the cooling energy savings in the summer. Cool roof impact is reduced during winter as less solar radiation arrives on the roof (due to increased cloud cover, lower solar radiation intensity, fewer hours of sunshine, snow cover) to be absorbed or reflected. Installing a cool roof on a residential building in 27 cities worldwide with varying climatic conditions resulted in a heating penalty (0.2–17 kWh/m^2 year) that is less important than the cooling load reduction (9–48 kWh/m^2 year). Cool roofs are evidently more advantageous in locations with long cooling seasons and short or no heating season. Cooling energy use and cost savings greatly outweigh potential heating energy use and cost penalties for warmer climates with significant amounts of solar radiation incident on the roof. In colder climates, cool roofs may cause heating load increases, and factors such as local energy prices should be considered in order to determine if a cool roof is a cost-effective solution. Optimizing roof albedo in combination with insulation levels for specific climatic conditions and buildings can cost-effectively reduce energy consumption for heating and cooling. For buildings with high internal gains, such as commercial or industrial buildings, that might result in significant cooling loads throughout the year, the installation of a cool roof is beneficial even in colder climatic conditions. Finally, it should be highlighted that cool roofs present an attractive solution as cooling savings are expected to be even more important in future climatic conditions due to global warming and because of the environmental benefits they provide in terms of mitigating the urban heat island effect, improving outdoor thermal comfort and air quality and decreasing heat-related mortality.

Another potential negative impact of cool roofs is that they can be more susceptible to moisture accumulation and risk of condensation when used in colder climates. Condensate may affect the energy efficiency of the building envelope (reduced thermal resistance) and potentially cause environmental and health concerns to the building occupants (e.g., mould growth). In warm, humid climatic conditions, cool roof surfaces may be more susceptible to algae or mould growth. A properly designed cool roof can significantly improve the moisture performance of the roofing assembly and, at the same time, provide energy efficiency and environmental benefits. Cool roofs should always be considered in the context of their surroundings as light from a bright white roof may reflect into windows of neighbouring taller buildings, potentially causing building users glare and visual discomfort and unwanted heat. Moreover, white roofs may not meet the building owners' aesthetic/design preferences for darker colours in cases where the roof is visible from the street level. In all such cases, cool coloured materials can be used.

Performance assessment and monitoring – Testing and accreditation framework & infrastructure: The performance of cool roofs is determined by their SR and TE. Alternatively, the Solar Reflectance Index (SRI) can be used, which is an index that combines both SR and TE in a single value and indicates how "cool" a material is. The SR, depending on the material and the specific application, can be measured using a spectrophotometer equipped with an integrating sphere, a reflectometer or a pyranometer. Infrared emittance can be measured with an emissometer or an FTIR spectrometer. The SRI is calculated based on measured SR and TE values. Ageing of cool roof products can be evaluated via a) natural weathering, i.e. exposure of samples to outdoor ambient conditions at Weathering Test Sites, for a period of at least three years, b) artificial weathering with the use of weathering chambers that accelerate the degradation of materials in a reasonably fast time c) a laboratory accelerated aging method that incorporates features of soiling and weathering and simulates three years of natural soiling in a few days. Good practice procedures for all these measurements, methods and calculations are defined in various international, U.S0 and European standards.

The Cool Roofing Rating Council (CRRC) in the U.S. and the European Cool Roof Council (ECRC) in the EU operate rating programs for the radiative properties of roofing products. Their purpose is to provide a uniform and credible system for rating and reporting the radiative properties (i.e. SR, TE, and SRI) of Roofing Products by granting them a Label, indicating one or more radiative property ratings reported by Accredited/Approved Testing Laboratory reports. In the framework of these two (independent) programs, Manufacturers and Sellers have the opportunity to label roofing products with the measured values of their Initial and Aged Radiative Properties. These properties are determined and verified through testing by Accredited/Approved Testing Laboratories and a process of random testing of rated products. Any roofing product can be tested as long as it is in compliance with the specifications and requirements defined in the Product Rating Manual. The product rating program does not specify minimum or target values for any radiative property.

<u>Suboptimal and Ineffective Products in the Market</u>: The following factors may contribute to sub-optimal or poor performance of cool roofs: a) the installation of unsuited roofing materials, such as simple white paint instead of a cool roof coating, b) the lack of (credible) performance data that prevents the selection of appropriate products (e.g. products with poor ageing performance or sub-optimal initial radiative properties such as low infrared emittance) d) installation failures when manufacturers' instructions are not followed. These failures can be minimized if credible cool roof performance data are available and by following the manufacturers' installation and maintenance instructions closely.

<u>Cool roof policies</u>: Worldwide, policies on the adoption of cool roofs have been modelled on those developed and applied in the USA, where cool roofs were first introduced in building codes (while their use in vernacular architecture in the Mediterranean and other areas largely proceeds building codes). In the U.S., model codes for commercial and multi-family residential buildings, such as ASHRAE 90.1 and the IECC, require cool roofs in warmer climate zones. These model codes are widely adopted across the U.S. Individual states may adopt their own requirements for cool roofs (e.g., California Title 24). Where allowed by state law, municipalities may also adopt requirements for cool roofs via their building codes (e.g., New York, Chicago, Denver, Washington DC). Localities may also encourage cool roofs via the adoption of green codes. Green codes often allow for measures to be justified by their broader environmental benefits, in addition to their potential effect on building energy consumption. Programs such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) and ASHRAE 189.1 encourage the use of cool roofs to reduce urban heat island effects.

There are a wide variety of incentives and voluntary programs encouraging the use of cool roofs as well. These programs may overlap with existing energy efficiency incentive schemes or may be specific to heat mitigation (e.g., Louisville, Kentucky's cool roof rebate program). There are also several international efforts to accelerate the use of cool roofs for thermal comfort, improved health, and energy savings. The Million Cool Roofs Challenge is a philanthropic initiative to create local champions for cool roofs in ten countries experiencing an acute lack of access to cooling services. The champions are existing organizations, universities, and companies that demonstrate the local performance, build the supply chain for cool roof materials, implement cool roofs at scale, and advocate for supportive policies, programs, and targets. The Challenge, which concludes in November 2021, is introducing cool roofs into new markets and helping to test a variety of business/implementation plans for scaling the market.

The CRRC has been a critical component in the growth of the cool roof marketplace across all building sectors and is explicitly cited in most U.S. model, state, and municipal codes.

Similarly, the development of the cool roof market in Europe is being spearheaded by the European Cool Roofs Council (ECRC). The ECRC was founded in 2011 to develop scientific knowledge and research in relation to a "cool roof" technology and to promote the use of cool roof products and materials in Europe, including developing a product rating programme for such products and materials. The introduction of cool roofs in European Member States has been implemented at the national level, with the first programs developed in

Greece and Italy. In several European Countries, cool roofs are generally supported with incentives like any other building efficiency intervention, and in Greece and Italy, their use is specifically promoted for public buildings. In Italy, for all buildings, designers are required to perform an assessment of the benefit of a cool roof (solar reflectance greater than 0.65 for flat roofs or 0.30 for pitched roofs).

Cool roofs adoption and market penetration: Cool roof products have been available in the United States for certain categories since the early 1980s. In the late 1990s, cool roofs were added as a credit option to several major energy codes, notably California Title 24 and ASHRAE 90.1. Cool roofs remain a compliance option for many energy efficiency standards and incentives. Starting in 2001, Chicago adopted a cool roof policy that explicitly referenced cool roofs' ability to mitigate urban heat islands. The adoption of cool roofs has similarly proceeded on these two tracks. Increased adoption of model energy codes that require cool roofs by states and municipalities has helped drive the commercial, multi-family, and institutional markets, particularly in the Southern U.S. The increasing use of green certifications, most notably LEED, has also been beneficial for cool roof adoption, particularly among higher value building classes.

Cool roof implementation faces a number of obstacles that have slowed progress. Heat mitigation is rarely pursued in a coordinated fashion, in favour of an approach spread across many agencies and actors. Awareness of cool roof options and benefits, particularly in the residential market, remains relatively low in North America. The structure of the market, specifically residential roofing, is quite diffuse and hard to change with policy. There remains a lack of regulatory frameworks for properly valuing and adopting cool roofs, as well as a lack of public and private financing for those investments.

The global cool roof coatings market size was estimated to be worth USD 3.59 billion in 2019 and is expected to register a revenue-based CAGR of 7.1% over the forecast period. The rising adoption of green building codes by the emerging economies across the globe is anticipated to further fuel the demand for cool roof coatings. North America held the largest market share of more than 34% in terms of revenue in 2019. Increasing awareness regarding building energy consumption, coupled with the implementation of the Leadership in Energy and Environmental Design (LEED) green building certification initiative, is likely to drive the regional demand for cool roof coatings. The Asia Pacific is projected to be the fastest-growing region in the near future on account of the increasing acceptance of green building codes. The growing construction industry in the emerging economies of Asia Pacific and increased infrastructure spending by the governments of India and China are the key factors responsible for driving the product demand over the forecast period. Finally, the global roof coating market is dominated by big international players such BASF SE (Germany), Akzo Nobel N.V. (Netherlands), or Sika AG (Switzerland), and several more companies that invested in R&D over the years.

Cool Roof Market Report: The last section conducted a survey to collect information on the existing cool roof installations in Australia, and the performance, current market, and characteristics of cool roof products from cool roof commercial stakeholders in Australia. Collectively, the following conclusions have been drawn from this section:

- All stakeholders sell cool roof materials, within which around half provide installation, consulting, and supervision services.

- Most stakeholders only install cool roofs domestically or only possess a small portion of business in the international market. On average, each stakeholder installs 12909 m^2 cool roof in Australia every year.
- Most stakeholders only sell cool roofs domestically or only possess a small portion of business in the international market. The average annual sales volume of these products in Australia is 10.7 million Australian Dollars (turnover) or 14840 tons (quantity of sale).
- The number of products in descending order is membrane, paint, spray, and metal.
- Half of the surveyed products can only be applied for retrofitting roofs; 12% can only be used to replace the original roof, while 38% can be used for both purposes.
- Most cool roof products have a thickness of 200 microns to 500 microns under wet conditions. After being dried, the thickness decreases by 8-200 microns on average.
- The average solar reflectance and the thermal emittance of the collected cool roof products are 0.83 and 0.90, respectively.
- The average cost for the 14 cool roof products is 13 AUD/m^2.

1. Introduction

This report delivers the first development on Part 1, including a literature review on cool roofing materials, policy around the world, and testing procedures and rating infrastructure.

This report covers all the available knowledge on different aspects of cool roofs. Including the first (white roofs) and second generation of cool roofing materials (near infrared reflective), which have been now available on the market for many years, to the recent advances in the enhancement of the performance delivered by the new generations of cool materials and in particular: thermochromic materials, daytime radiative coolers, and retro-reflective materials. These offer superior performance with respect to the second generation of materials.

We discuss the benefits and performance of cool roofs at building and urban scales. The benefits at the building scale include cooling energy savings and improved indoor thermal comfort (for buildings that are not hyper-insulated). Further, a reduction in the exterior surface temperature yields decreased thermal stress-strain cycles compared to an otherwise identical black roof. The benefits at the urban scale relate to a drop in ambient temperature during the hot season, which leads to indirect cooling energy savings as the inlet temperature is reduced and improved indoor and outdoor thermal comfort. We also present relevant case studies documenting the performance of buildings with cool roofs.

Then, we provide an overview also of the main problems affecting cool roofs: performance loss due to ageing (i.e., weathering, soiling, and biological growth), a heating penalty in cold climates, condensation (for some buildings with high indoor moisture generation and cold climates), and possible first-cost premiums. We also cover the factors affecting the performance of cool roofs, such as insulation level (i.e., the difference between black and cool roof decreases with increasing roof insulation), climate and incoming solar radiation (due to climate and cloudiness or shades from other buildings and roof pitch).

We present a detailed analysis of the current cool roof policies and legislation in North America, Europe, and the rest of the world. Performance assessment and testing infrastructures were implemented in North America (Cool Roofing Rating Council) and EU (European Cool Roofs Council) with solar reflectance and thermal emittance measurements before and after three years of natural exposure by accredited laboratories at defined exposure farms. This framework, led by the industry, enabled the development of a market with certified properties.

Then, we present the current implementation and market development in USA, EU, and global context, considering the current obstacles and problems to the growth of the cool roof market: nobody owns the problem of urban heat, a lack of awareness of cool roofing solutions, a lack of comprehensive policy guidance or regulatory frameworks, and limited financing/incentives, which is a common issue for any energy efficiency measure. Finally, we present exemplar cool roof installations.

2. Technology development

2.1. Existing cool roof materials & technologies

This section gives an overview of existing cool materials for roofs. The concept of cool roofs is explained, and the main parameters that characterize cool roofs are defined. Well established and commercially available cool roofing types are covered as well as advanced cool materials that have been developed and/or are under development in recent years. Their main features are documented, and their performance is analysed in terms of their radiative properties, Solar Reflectance Index (SRI) and their ability to reduce surface temperatures. The technologies that have been used to develop advanced cool roofing materials are detailed, and their level of maturity is estimated by means of technology readiness levels. A critical review of the advantages and limitations of the cool roof technologies is included.

2.1.1 The cool roof concept

Cool roof definition

The sun's energy represents the main source of heating acting upon a roof surface. Most of the sun's energy falls between the wavelengths of 300 nm and 2500 nm. The invisible ultraviolet (UV) range (300-400nm) contains about 5% of solar energy, the visible range (VIS) from 400 to 700nm contains about 43% of the sun's energy, and about 52% of the solar energy falls in the invisible, near-infrared part (NIR) between 700 and 2500nm (ASTMG173 [1]). When solar radiation falls on a horizontal opaque surface (i.e., a roof), a part of it is reflected or scattered in the VIS region, determining the specific colour and gloss of the surface and reflected in the NIR region. The remaining portion of incident solar energy is absorbed by the surface. The roof re-emits some of this absorbed solar energy to the outdoor environment as thermal infrared radiation. In addition, the roof surface exchanges energy by convection with the air above the roof as a function of the heat transfer coefficient and of the temperature difference between the ambient air and the material surface. Finally, heat is conducted through the layers within the roof (insulation etc.) from the warmer side to the cooler side. The conduction induced heat flows through the roof. Hence, the energy needed for heating or cooling depends on the non-radiative properties of the material, i.e., the thermal resistance and thermal capacity and the temperature difference on either side of it.

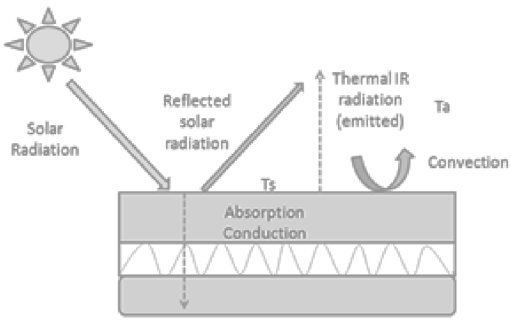


Figure 1. Energy balance of a roof exposed to solar radiation [2].

A cool roof is an opaque roofing system with a net radiative heat gain and thus a surface temperature increase lower than that of a conventional roofing system. Cool roofs are highly reflective to minimise the amount of solar radiation absorbed and converted into heat and highly emissive to maximize the amount of heat that is radiated away.

Cool roof properties

The main physical properties and metrics that are used to characterise cool roofs are explained below:

Solar reflectance (SR) is a measure of the ability of a surface to reflect solar radiation and represents the ratio of reflected to incident solar radiation. Also referred to as albedo, it designates the reflectance of a surface in any direction (i.e., hemispherical) over the solar spectral range (280-2800 nm), including specular and diffuse reflection components. It is measured on a scale of 0 to 1 (or 0–100%).

Solar absorptance (SA) is a measure of the ability of a surface to absorb solar radiation and represents the fraction of absorbed to incident solar radiation. It is measured on a scale of 0 to 1 (or 0–100%). If a surface is opaque, solar absorptance equals 1 – solar reflectance.

Infrared or thermal emittance (TE): Infrared emittance is a measure of the ability of a surface to release absorbed heat by emitting thermal radiation. It specifies how well a surface radiates energy away from itself as compared with a black body operating at the same temperature. Infrared emittance is measured on a scale from 0 to 1 (or 0–100%). High thermal emittance helps a surface cool by radiating.

Solar Reflectance Index (SRI) is an index that combines both solar reflectance and infrared emittance in a single value and indicates how "cool" a material is. SRI quantifies how hot a flat surface gets relative to a standard black (reflectivity 5%, emittance 90%) and a standard white surface (reflectivity 80%, emittance 90%). The calculation of this index is based on a set of equations (ASTM E1980 [3]) that require values of solar reflectance and infrared emittance for specific environmental conditions. The SRI has a value of zero (for the standard black surface) and of 100 (for the standard white surface).

From the definition of the SRI, it is expected that very hot materials can actually have negative values, and very cool materials can have values greater than 100. Several SRI calculators have been developed and available online (LBNL Heat Island Group SRI calculator excel sheet [4]).

Ageing of materials that comes from their natural exposure due to weathering, soiling and biological growth affects their performance over time by changing the initial values of solar reflectance and infrared emittance. When assessing the performance of a cool roof, the **aged radiative properties,** i.e., the aged solar reflectance, infrared emittance and SRI, should be considered.

Additional terminology related to innovative advanced cool materials will be explained in the corresponding sections where each technology is described.

A cool white surface typically has an initial SR above 0.75 and TE above 0.8. Dark coloured surfaces are characterized by lower values of SR (about 0.5-0.2) and high values of emissivity (above 0.8). Construction materials are characterized by high thermal emittance values, with the exception of metallic materials that have low values of thermal emittance and therefore stay warmer. It should be noted, though, that the thermal emittance of a roof is determined mainly by the upper layer. This means that if a metal roof that has a low emittance is covered by an appropriate material with high thermal emittance (e.g., coating), the thermal emittance of the roof will be increased. The dominant factor in determining the thermal performance of a cool roof under the sun is its solar reflectance. The thermal emittance has a significant but secondary impact [5,6].

Cool materials are characterized by high solar reflectance and high infrared emittance. These two properties result in affecting the temperature of a surface [5,7]. A surface with high solar reflectance and infrared emittance exposed to solar radiation will exhibit lower surface temperature compared to a similar surface with lower SR and e values. If the cool surface is on the building roof, this would result in decreasing the heat penetrating into the building, and it would contribute to decreasing the temperature of the ambient air as less heat would be transferred via convection from the cooler surface (Fig. 2).

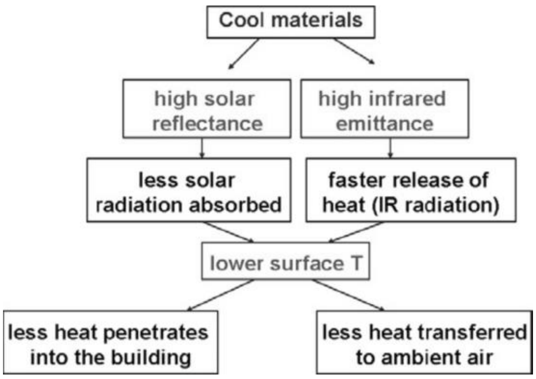
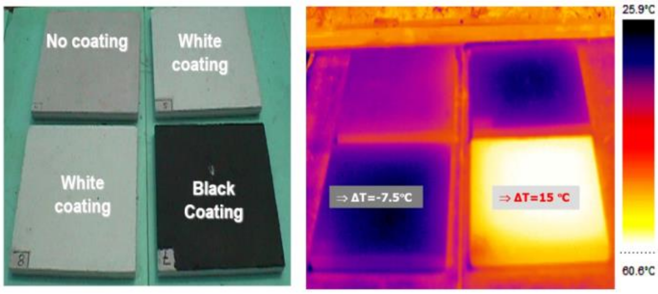


Figure 2. The basic principles of cool materials (Source: [8]).

In **Figure 3**, the impact of solar reflectance on the thermal performance under hot summer conditions is demonstrated using infrared thermography. The figure shows four identical concrete tiles, two of which have been covered with cool coatings with a solar reflectance of more than 0.80, one has been covered with a black coating (SR = 0.05), and the last one is left uncoated and has an off-white colour (SR = 0.65). In the infrared image (Fig. 3b), it can be seen that the application of a cool coating results in a lower surface temperature by 7.5 °C compared to the uncoated but light-coloured tile. In contrast, the application of a coating with high solar absorptance results in increasing the surface temperature by 15 °C [5].



a b

Figure 3. *Visible (a) and infrared (b) images of four concrete tiles painted with cool white coatings. A black coating and an unpainted off-white one. The difference in solar reflectance translates into a significant difference in surface temperatures—source: [5].*

2.1.2 Cool roof technologies

Roof systems are made of one or more material layers. The surface exposed to the sun is the one that determines if a roof is cool or not. A large number of cool roofing materials with high solar reflectance and infrared emittance values are commercially available, representing different surface options. Nowadays, there is a cool option for almost every type of roof (e.g., CRRC Rated Products directory and ECRC Cool Roofs Database [9,10]). In addition, research in the field of advanced materials for heat mitigation in the built environment has been ongoing for more than 15 years, and a number of innovative materials with advanced radiative and thermal properties aiming to reduce solar and heat gains and increase heat losses have been developed and tested demonstrating significant cooling potential [8,11]. The main features, the cooling performance and advantages and limitations of existing and most notable cool roof technologies are presented and discussed in the sections below.

White or light-coloured roofing materials

Common usage

White or light-coloured cool roofing products are characterized by high visible and NIR reflectance and high thermal emittance. To achieve the desired high solar reflectance, they usually contain white or other light-coloured pigments such as titanium dioxide. White or light-coloured materials are usually applied on low slope roofs to avoid potential problems of glare; however, there are cool white and light coloured products also for steep-sloped roofs. The most commonly used cool roofing product categories include coatings, membranes, built-up roofs, metal roofs, tiles and asphalt shingles, and their technical characteristics are described in Annex A [2,10,12].

Performance

The performance of white or light-coloured cool roofing materials is determined by their solar reflectance and thermal emittance values. **Table 1** gives representative solar reflectance and infrared emittance values of commercially available conventional and cool roofing materials. The SRI and maximum surface temperature values based on ASTM 1980 are also reported to estimate the thermal performance of these products under hot summer conditions. Databases with information about the performance of cool and conventional commercial roof products in terms of their solar reflectance and infrared emittance are available by the US Cool Roof Rating Council and the European Cool Roofs Council [10,14].

In addition, several experimental studies [5,15,16] have shown that a conventional dark coloured roof with low solar reflectance and high infrared emittance (e.g. dark coloured asphalt shingle, dark coloured membrane, black coating etc.) can reach a peak temperature under hot summer conditions of about 70- 80 °C, surfaces with medium to high solar reflectance and low infrared emittance (e.g. unpainted metal roofs, aluminium coatings) reach temperatures up to 60– 75 °C, and cool roofs with high solar reflectance and infrared emittance (cool white coatings, white membranes, etc.) reach temperatures of about 40- 45 °C, depending on local conditions.

Table 1. Representative values of solar reflectance and infrared emittance of commonly used conventional and cool roofing materials. SRI and maximum surface temperature values based on ASTM 1980 are also reported.

Material	Solar reflectance	Infrared emittance	Solar reflectance Index	$T_{surface\ max}$ (C)
Coatings				
White	0.7 -0.85	0.8 -0.9	84-113	51 – 42
Aluminum	0.2 -0.65	0.25-0.65	-25 – 72	55 – 92
Black	0.04-0.05	0.8 -0.9	-7 – 0	82 – 85
Asphalt shingles				
White (grey) asphalt shingle	0.2-0.3	0.8-0.90	15 – 28	70 -77
Black	0.04	0.8-0.90	-7 - -1	83 – 85
Tiles				
Terracotta ceramic tile	0.25-0.4	0.85-0.9	23 – 45	65 -74
White clay or concrete tile	0.6-0.75	0.85-0.9	71 -93	47– 56
Grey concrete tile	0.18 -0.25	0.85-0.9	14 - 25	73 – 77
Membranes				
White membrane	0.65-0.85	0.8 -0.9	76 – 107	42-53
Black	0.04- 0.05	0.8-0.9	-7 – 0	83-85
Metal roof				
unpainted	0.2-0.6	0.05-0.35	-48 – 53	63-101
Painted white	0.6-0.75	0.8-0.9	69 – 93	47-56
Dark conventionally coloured	0.05-0.1	0.8-0.9	-6 – 6	80-85
Built-up roof				
With asphalt	0.04	0.8-0.9	-4 - -1	83-85
With dark gravel	0.08.-0.2	0.8-0.9	-2 – 19	75-83
With white gravel	0.3-0.5	0.8-0.9	27 – 58	60-72
With white coating	0.75-0.85	0.8-0.9	93 – 113	42-48
Modified bitumen				
With mineral surface capsheet	0.10-0.2	0.85-0.95	4 – 21	74 - 81
White coating over mineral surface	0.6 – 0.75	0.85-0.95	71 – 94	47-55

Figure 4 shows the solar spectral reflectances of representative cool white or light coloured roof products. White materials have quite similar reflectance curves. They absorb strongly in the UV region (300-400nm). They

have a very high reflectance in the VIS region because of the TiO2 used and high reflectance in the NIR part that decreases slowly with the wavelength. The reflectivity of the white asphalt shingle is quite lower.

The definition of a cool roof does not specify minimum or target values for any radiative property. Nevertheless, various programs, codes or legislation aiming to promote the use of cool roofs have specific performance requirements. Table 2 summarizes the criteria set in the ENERGY STAR (US EPA Energy Star [17]), which is an energy efficiency product qualification program, LEED (USGBC, Leedv.4), a green building program and California Title 24, which is an energy efficiency standard for buildings.

Cool white or light-coloured roofs demonstrate superior performance in terms of radiative properties and a very high cooling potential (except for low emissivity metal or aluminium coatings and asphalt shingles). The main drawbacks and limitations related to cool white materials are outlined below, as they will be analysed in other sections:

- Potential increase of heating loads during the heating season
- Performance loss due to ageing
- Potential glare problems or failure to meet the aesthetic preferences of building users

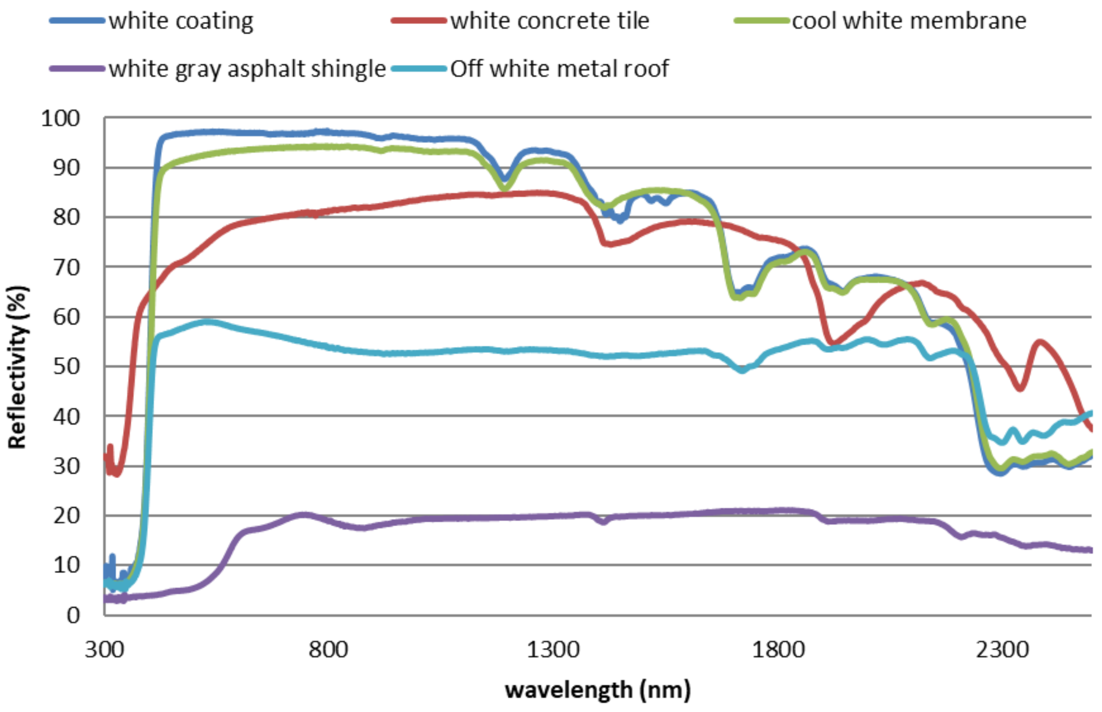


Figure 4. Spectral reflectance curves of representative cool white or light-coloured roof products.

Table 2. Minimum requirements for cool roofs by different programs/ standards by roof slope

	Low Slope Roofs (pitch ≤ 2:12)					Steep Slope Roofs (pitch ≥2:12)				
Program/ Code	$SR_{initial}$	SR_{aged}	TE	$SRI_{initial}$	SRI_{aged}	$SR_{initial}$	SR_{aged}	TE	$SRI_{initial}$	SRI_{aged}
Energy Star	0.65	0.50	-	-	-	0.25	0.15	-	-	-
LEED	-	-	-	82	64	-	-	-	39	32
California Title 24	-	0.55-0.63	0.75	-	64-75	-	0.2	0.75	-	16

Cool coloured roofing materials

The need for cool non-white products to meet the aesthetic/design preferences of darker colours and avoid potential glare problems has led to the research and development of cool coloured materials usually applied on steep-sloped roofs or other visible surfaces such as pavements. A cool coloured surface absorbs in the visible spectrum (400-700nm) to appear of a specific colour, while it is highly reflective in the non-visible near-infrared part of the spectrum (700-2500nm). This results in an overall higher solar reflectance than a conventionally coloured surface of the same colour (same visible reflectance) that absorbs in the visible and near-infrared part, considering that about 50% of the solar energy falls in the NIR part of the spectrum. Cool coloured materials can therefore be defined as spectrally selective materials that exhibit a moderate or low visible solar reflectance, a high near-infrared reflectance resulting in a moderate solar reflectance and high thermal emittance.

Figure 5 shows a standard and a cool black coating and their respective spectral reflectance curves. They present similar very low reflectance values in the visible part of the spectrum (as they are black). Still, a significantly higher reflectance characterises the cool black coating in the NIR part (SR_{NIR} = 0.39) than that of the standard black (SR_{NIR} = 0.10). This results in an overall higher solar reflectance for the cool black coating (SR=0.27) than the SR of 0.05 for the standard black coating.

This difference in their solar reflectance values translates into a difference in their surface temperature when they are exposed to peak summer conditions, reaching a value of ΔT=10˚C. Cool coloured products are developed with the use of spectrally selective pigments that are characterized by high NIR reflectance values or high NIR transmittance values.

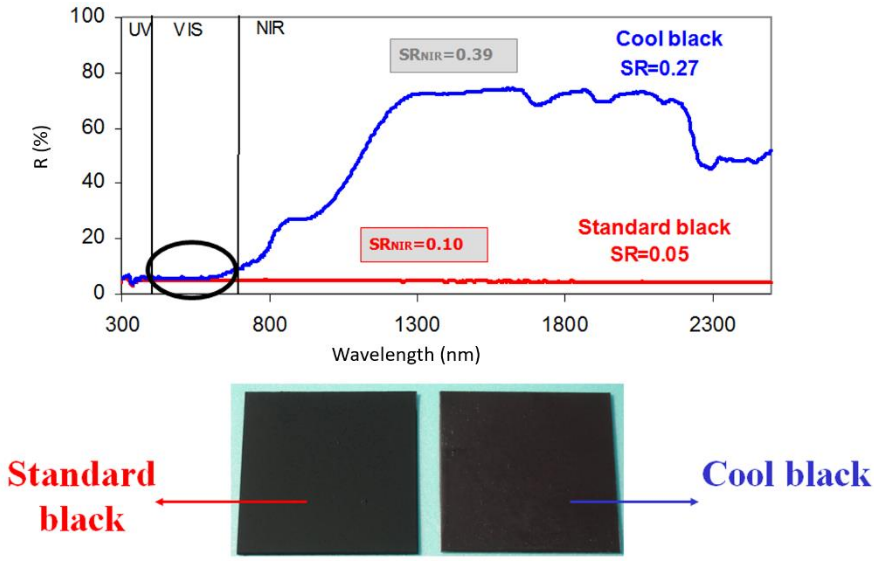


Figure 5. *The spectral reflectance of a standard and a cool black coating. They are characterized by similar reflectance values in the visible part of the spectrum, but the cool black coating has a reflectance that is significantly higher in the near-infrared (NIR).*

The basic method for creating a NIR infrared reflective coating consists of:

a) developing a cool topcoat with coloured NIR reflecting pigments (one coat system)

b) developing a topcoat with NIR infrared transmitting pigments over a NIR-reflective basecoat (e.g., titanium dioxide rutile white) (two coat system). The first option may be applied over opaque substrates that are either NIR reflective or absorbing (provided that the topcoat has sufficient thickness). The second option may be applied over opaque substrates that reflect NIR radiation [22–24]. For the topcoat formulation, a transparent binder (acrylic, fluoropolymer etc.) and colour pigments with appropriate properties (refractive index, spectral absorption and backscattering, pigment volume concentration, particle size etc.) should be selected.

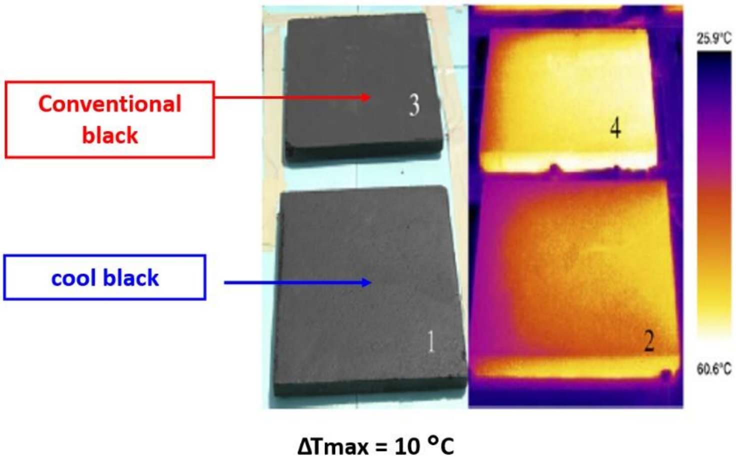


Figure 6. *Visible and infrared images of a cool (1, 2) and standard (3, 4) black coating. (Source: adapted from [25])*

The spectral reflectance of the composite material depends mainly on the reflectance of the substrate, the thickness of the coating, the roughness of the surface and the potential backscattering of the pigments determined [26–29]. Research analyzing the optical characteristics of pigments has provided necessary data for the appropriate selection of pigments leading to the development of cool coloured materials [30–32]. A database reporting the solar spectral radiative properties of standard and cool pigmented coatings is available [4,31].

Several techniques have been used for manufacturing cool coloured roofing materials, and their performance has been evaluated in terms of their solar reflectance and NIR reflectance. The development and evaluation of cool coloured coatings, metal, concrete and clay tiles and asphalt shingles roofing materials are extensively documented in the literature [28,33–42]. In all the studies, a significant increase of the NIR reflectance and the solar reflectance is reported for the cool coloured materials compared to similarly coloured conventional materials of the same type.

Table 3 reports representative solar reflectance values for standard and cool coloured materials of the same type and colour. The most notable increase is observed in dark-black colours reaching relative increases of above 400%. Standard black roofing materials have a solar reflectance of 0.04-0.05, and cool black roofing materials such as coatings or concrete tiles were found to reach solar reflectance values of 0.27 and 0.41, respectively (**Table 3**). In most studies, minor or no changes in the infrared emittance between cool coloured and conventional roofing materials were reported.

Table 3. Representative solar reflectance values for cool coloured and conventional similarly coloured roofing materials of the same type (from [33,34]).

Product	Solar reflectance	
	Standard	Cool coloured
Black asphalt shingle	0.04	0.18
Gray asphalt shingle	0.27	0.36
Black concrete tile	0.04	0.41
Terracotta concrete tile	0.33	0.48
Gray metal roof	0.32	0.49
Dark brown metal roof	0.08	0.27
Black coating	0.05	0.27
Blue coating	0.18	0.33

As expected, cool coloured roofing materials have a significantly greater cooling potential than colour matched standard roofing material. As previously stated and shown in **Figure 6**, the increased reflectance of the cool coloured material results in lower surface temperatures compared to similarly coloured conventional materials. Maximum surface temperature reductions reported under peak summer conditions may reach values of about 10°C-14°C, while the minimum reductions reported are in the order of 3°C-5°C [34–36]. This means that less heat will penetrate into the building, and less sensible heat will be released in the ambient air. The magnitude of the achieved temperature decrease is found to be linearly correlated with the solar reflectance increase [34].

Cool-coloured roofing products are commercially available and cover almost all roof product types. Their performance is characterized by their solar reflectance and infrared emittance. As is the case for cool white or light coloured roofing materials, the definition of a cool coloured roof does not specify minimum or target values for these properties. In **Table 2**, the minimum requirements for steep slope cool roofs as specified by various programs and standards are presented, indicating the radiative properties values typically required for such products.

Cool coloured materials present a significant advantage as they are available in a large variety of colours and product categories. Compared to white or light coloured materials that have higher visible and NIR reflectance values, they present a lower cooling potential, cooling energy savings and heating penalties. Cool coloured materials have been found to present a good long-term performance compared to conventionally coloured material when exposed to outdoor conditions. The loss in solar reflectance for painted metal and clay and concrete tiles was of the order of 6% of the initial reflectance for 2½ year exposure [33].

As reported by Santamouris and Yun [11], current research activities in the field of NIR reflecting coatings focus on two areas:

a) The development of IR reflecting pigments of higher spectral reflectance to further enhance the performance of cool coloured materials; and

b) The development of advanced super-hydrophobic (SH), near infrared reflecting coatings presenting advanced self-cleaning and anti-soiling properties to increase the solar reflectance but also the long term performance of the materials.

Fluorescent materials

To further decrease the surface temperature of a cool coloured NIR reflective material under the sun, researchers have developed fluorescent materials. The phenomenon of fluorescence is the emission of light - electromagnetic radiation, when incident radiation or particles are absorbed by a material, causing excitation of its atoms, which then reemit almost immediately. In most cases, the emitted electromagnetic radiation has a longer wavelength and, therefore lower energy than the absorbed radiation, and the phenomenon of fluorescence ceases as soon as the exciting source is removed. The efficiency of the fluorescence process is given by the quantum yield, which is defined as the ratio of the number of photons emitted to the number of photons absorbed.

Fluorescent cool coloured materials stay cooler under the sun by reflecting near infrared solar radiation and by instantly re-emitting some of the absorbed ultraviolet or visible solar radiation as invisible NIR radiation (fluorescence) (Berdahl et al.,2016). Fluorescent cool coatings have been prepared by mixing fluorescent pigments (ruby or Egyptian blue into clear acrylic and then applying the pigmented acrylic to a bright white substrate (an aluminium panel painted white). The white substrate assists in enhancing the absorption by the fluorescent topcoat as it reflects the excitation radiation that passes through the topcoat, and also it reflects upwards the NIR radiation emitted downward [43,44]. Other colours may be developed via mixing or layering fluorescent and non-fluorescent pigments with appropriate optical characteristics [44].

The performance of the fluorescent coatings is characterised by their effective solar reflectance (ESR) and the fluorescence contribution, i.e. the effective solar reflectance minus the solar reflectance (ESR-SR) from which the quantum yield can be estimated. The ESR is the fraction of incident solar radiation rejected via reflection and fluorescence and can be measured by comparing the temperature in the sun of the fluorescent material to those of non-fluorescent reference specimens of known solar reflectance [45]. The developed lightly doped ruby-pigmented coatings over a white substrate were found to have ESR values of about 0.81, Fluorescence contribution of 0.16 and quantum efficiency of 0.83 ± 0.10 [43]. The developed washed Egyptian blue coating over a white substrate was found to have an ESR value of about 0.57, Fluorescence contribution of 0.17 and quantum yield of 0.72 [44].

In terms of thermal performance, Berdahl et al. [43] spread a layer of synthetic ruby crystals on a white surface to obtain a red coating with 6.5^{o}C lower surface temperature in the sun compared to conventional red material. These results indicate that the tested pigments are suitable for manufacturing fluorescent cool coloured material that will stay cooler in the sun than non-fluorescent cool-coloured surfaces of the same colour and NIR reflectance.

Quantum Dots

Quantum dots are another type of nanoscale material that could be classified as cool fluorescent materials. They are nanosized (2–10 nm) inorganic particles that can absorb light at specific wavelengths and emit electromagnetic radiation at different wavelengths. Their main advantage is that their optical properties can be tailored for specific applications by tuning, e.g. their size and surface chemistry, making it possible to develop quantum dots with higher cooling potential than conventional fluorescent materials [46,47].

Garshasbi et al. [48] have investigated the fluorescent cooling potential of quantum and found that they reject almost 54 W/m^2, corresponding to 8.5% of the absorbed radiation. They calculated that the surface temperature of quantum dots samples showed up to 2 °C surface temperature reduction by photoluminescence effect compared to its corresponding non-fluorescent reference sample.

Experimental results have shown a fluorescent cooling potential of CdSe/ZnS QDs sample of abound 2.5 °C, increased by another 8.1 °C by applying the near-infrared reflective basecoat, which is due to the rejection of incident solar irradiations at the wavelengths longer than absorption edge wavelength of QDs.

To our knowledge, no fluorescent cool coloured material applications on buildings or the urban fabric have been implemented to date, so the technology is TRL 3-4 (technology validated in the lab). In IEA [6], it is suggested that cool coloured roofs performance standards could be used for fluorescent cool-coloured material as they both aim to create cool, non-white NIR reflecting surfaces for the roof.

Fluorescent materials and quantum dots are a promising technology that presents a significant potential for cooling energy savings and mitigation of urban overheating. However, it is a technology still under development. Santamouris and Yun [11] report that current research activities related to fluorescent materials focus on modulating and adjusting the fluorescent properties, quantum yield and edge wavelength of quantum dots.

Thermochromic materials

One of the main drawbacks of cool white or coloured materials is the potential increase in heating loads during the cold season due to their high solar reflectance. Ideally, roofing systems should be highly reflective when buildings are in a cooling mode and highly absorptive when buildings are in heating mode [49] to minimize this heating penalty and optimize the energy performance throughout the year.

Thermochromic materials are dynamic materials that change their solar reflectance (colour) reversibly as a function of temperature, having high solar reflectance (white or light-coloured appearance) in summer and low solar reflectance (dark coloured appearance) during the cold period [50–54]. The effect of thermochromism can also be used to modulate infrared emissivity dynamically [55].

A large number of thermochromic materials exist using different mechanisms of colour change. According to Garshasbi and Santamouris [56], thermochromic materials can be divided into two categories:

a) thermochromic materials based on dyes like Leuco dyes or dyes embedded in a polymer matrix, and

b) non-dye thermochromic materials such as quantum dots, plasmonics, photo crystals, conjugated polymers, Schiff bases, and liquid crystals.

The available literature suggests that, to date, dye-based thermochromic materials are the most suitable for developing temperature-induced colour-changing materials for building envelope applications. Our analysis will focus on this category, namely on Leuco dyes that have mainly been investigated by researchers for such applications. A detailed review can be found in [47].

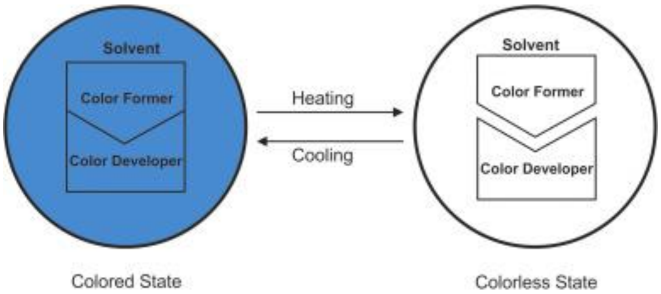


Figure 7. Thermochromism in Leuco dyes (Source: [47])

The use of different types of dyes and solvents can modulate the colour transition temperature of the thermochromic material. With the appropriate selection of the components, the thermochromic performance can be optimized for building envelope (roof) applications by having a dark colour (high solar absorptance) when the building is in heating mode and a white/light colour when the building is in cooling mode. To protect the thermochromic system from ageing and maintain the properties of the surrounding chemicals, microencapsulation is used, which is the encapsulation of the mixture in microcapsules of less than 15 μm. The thermochromic dyes are usually applied over an appropriate substrate, such as a white concrete tile, as they can transmit or absorb light [11,47,52,54,57,58].

The performance of thermochromic coatings is characterized by its high solar reflectance in the colourless phase and its low solar reflectance in the coloured phase, the transition temperature and transition time. No performance standards have been defined for this technology.

The performance of the thermochromic materials based on Leuco dyes has been tested and evaluated by many projects indicating the potential of such materials for energy savings in buildings and heat mitigation in the built environment [52,59–62]. In all cases, as expected, the solar reflectance was found to be higher at higher temperatures and low at low ambient temperatures. Many studies suggest the use of TiO_2 to increase the solar reflectance of the TC coatings [52,61,63]. In most studies for building or heat mitigation applications, the transition temperature of the TC material is about 30°C [52,60,61].

Microencapsulated thermochromic dyes have been added to conventional white coatings [53,59]. It was found that the coating reflects more solar energy for high outdoor temperatures and is 4°C cooler than the conventionally coloured coating [53]. Thermochromic coatings with and without TiO_2 and a colour-changing temperature of 30°C have been developed and applied on concrete tiles. Their performance was experimentally investigated against colour-matched, cool coloured (NIR reflecting) conventional coatings. It was found that the addition of TiO_2 significantly increased the solar reflectance of the TC coatings at the white phase, reaching a value of 43% and that, as expected, the solar reflectance of the coatings at the colourless phase was considerably higher than the reflectance at the coloured phase.

Recorded temperature differences under summer conditions between TC and cool coloured coatings range from 2.2 °C to 9.2 °C and between TC coatings and conventional coatings from 4.2 °C to 11.4 °C. **Figure 8** shows the brown set of coatings TC in both states, cool coloured and conventional, and the temperature difference measured with infrared thermography [52]. Perez et al. [60] have developed a smart reversible thermochromic mortar based on ordinary white Portland cement and organic microencapsulated thermochromic pigments, with temperature transition at 31 °C, which is found to present 0.32 and 0.38 solar reflectance at 20 and 40 °C, respectively. A novel roofing system integrating multifunctional films containing thermochromic powders and/or nano-TiO_2 particles and traditional roofing materials (aluminium, wood, plastics, and asphalt concrete) was fabricated. The system exhibited a significant increase in solar reflectance with values of 40%, 48%, 39%, and 40% for aluminium, wood, plastics, and asphalt concrete, respectively, while its surface temperature was 3.5 °C −10 °C lower than that of conventional roof coatings depending on the roofing material [61].

A

B

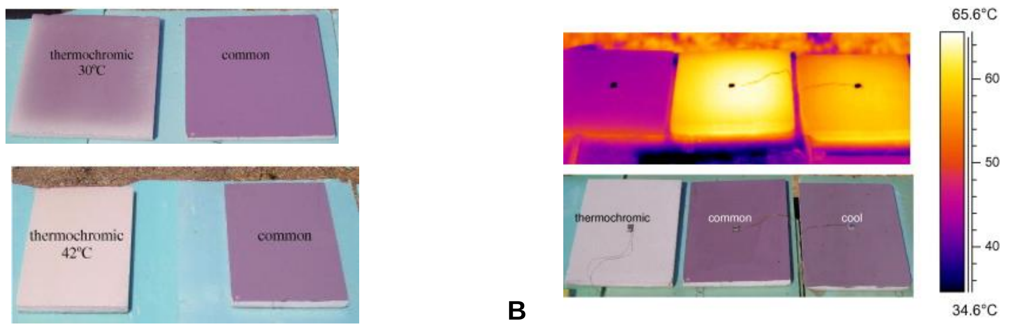


Figure 8. The transition phase of thermochromic brown coatings (SRcoloured phase =0.55, SRcolourless phase = 0.76) (A) . Visible and infrared images showing the temperature differences under peak summer conditions among the TC, cool coloured and conventional brown coating $\Delta T_{(cool\text{-}thermochromic)}$=9.2°C and $\Delta T_{(conventional\text{-}thermochromic)}$ =11.3°C (B) (Source: Santamouris et al., 2010)

Zheng et al. [63] have developed thermochromic coatings using different Leuco dyes combined with TiO_2 and evaluated their energy performance via simulations compared to light-coloured conventional coatings. They found that all TC coatings presented higher energy savings. Energy performance calculations in 7 U.S. geographic locations show that the energy savings for TC material could reach up to 5.4% in winter and 13.3% in summer [64].

Fabiani et al. [65] developed a thermochromic solvent-based coating using 5 μm microencapsulated Leuco-based thermochromic pigments applied over a soiled polyurethane-based membrane and tested it against a traditional dark envelope and a cool configuration using a prototype building. They found a reduction of about 0.2 K and 0.5 K on the average indoor air temperature in summer for the high and low insulation configuration, respectively and a maximum indoor temperature increase of about 0.5 K and 0.6 K in winter for the high and low insulation configuration. They also demonstrated that the cool roof results in a 5.87% increase in the thermal loads during the colder months, while the thermochromic roof has a reduced heating penalty of 0.07% [66].

TC coating, incorporating titanium dioxide, exhibits a 0.24 switching in solar reflectance. Energy performance calculations show that such coating could lead to energy savings up to 40% and 8% with respect to conventional and static cool roofs. The energy saving potential of thermochromic cool roofs to optimize the thermal response of residential buildings in the Mediterranean Basin has been investigated via dynamic simulation. It was found that the thermochromic materials exhibit potential annual energy savings up to 8.5% and 19% with respect to cool and conventional roofs, respectively, when the solar reflectance switches from 0.15 to 0.75 [67].

Current Research

The main obstacle in using dye-based thermochromic materials in outdoor environmental conditions, on building envelopes or the urban fabric, is that they suffer from significant ageing, as they fade and lose their reversibility after some time. Thermochromic coatings exposed to outdoor conditions for ten days were found to have a faded coloured phase and an increase in their solar reflectance. In parallel, the tone of the colourless phase became darker and solar reflectance was decreased [52]. Accelerated ageing studies on thermochromic coatings showed significant colour fading and irreversible photodegradation during as little as 200 h [68] and 96h [69] of testing. The interaction with solar radiation causes the polymer chains' breaking and/or crosslinking, leading to altered chemical and mechanical properties and loss of the reversible thermochromic effect [51]. This phenomenon is not well understood; however, it is believed due to an irreversible photochemical reaction caused by UV light, the reduction of molecular oxygen and the generation of reactive oxygen species (ROS) [47].

Current research in thermochromic materials focuses on investigating the photodegradation phenomenon related to thermochromic dye systems and possible solutions and techniques to improve their performance, e.g., using appropriate UV filters [51]. In addition, researchers investigate the potential of using non-dye thermochromic materials as alternatives to thermochromic materials based on dyes to avoid the problem of photodegradation and exploit the significant thermochromic properties they present. Thermochromism of quantum dots, plasmonics, and photonic crystals is associated with nanoscale quantum, plasmonic, and photonic effects, while thermochromism of conjugated Polymers, Liquid Crystals, and Schiff Bases is associated with the molecular rearrangements by temperature change. This category of materials is still under investigation and development (TRL 2 or 3) for roof applications and has not yet been tested on building roofs. For this reason, our analysis of thermochromic materials has focused on dyes. A comprehensive review of non-dye thermochromic materials can be found in Garshasbi and Santamouris [47].

Directionally reflective materials and retroreflective materials

Directionally Reflective Materials

Aiming to avoid unwanted reflection from white or light-coloured surfaces that may cause glare problems and/or be absorbed by neighbouring taller buildings or other surfaces or people, causing them to get hotter, the use of directionally reflective (DR) retroreflective materials have been proposed.

Directionally reflective materials (DRMs) are roofing materials with tailored radiative properties in separate directions simultaneously. They are engineered to have a high solar reflectance to the sun's rays direction and low solar reflectance (dark colour) from the ground level. A DRM can be developed by applying a white coating in one direction of an asphalt shingle [70]. Then it can be installed on a steep slope roof with the white side facing the sun and the coloured side facing the ground level (street). They present a durable alternative to thermochromic materials as they are more reflective when the sun angle is high during summer and less reflective when the sun angle is low during winter. A model has been developed to estimate the performance of DRMs in terms of their summer and winter reflectance values [71]. IEA [6] suggests that performance standards for cool-coloured materials on steep roofs should also apply to DRMs.

Retroreflective Materials

Retroreflective (RR) materials mostly reflect the incident radiation in the same direction as the incoming radiation (i.e. the reflected beam has the same direction as the incident beam) [72]. Existing retroreflective materials are used for road safety, signs, and route markers that should be highly visible under low light conditions. Still, no materials are commercially available for building envelope use. The performance of a solar-reflective material is characterized by its solar spectral bi-directional reflectance distribution function [73]. Retroreflectance can be assessed by three methods [73]:

a) measuring retroreflection with a coincident light source and light detector, such as those in a fibre spectrophotometer

b) measuring bi-directional reflectivity, or at least the angular distribution of reflected light, with a goniometer or

c) using calorimetry to gauge directional-hemispherical solar reflectance from the temperature in the sun, then subtracting from this value directional-hemispherical solar reflectance measured in a spectrophotometer fitted with an integrating sphere. However, no performance standards for this technology have been set.

Available technologies for developing retroreflective material for building envelopes include some categories of commercial retroreflective sheeting materials, typically used in traffic control. These include embedded lens glass bead, encapsulated lens glass bead, unmetallized microprism and unmetallized cube-corner microprism and other technologies such as prismatic sheet, glass beads over paint, tiles coated with microspheres and a granule-surfaced asphaltic roofing shingle [73].

Many studies on retroreflective applications focus on estimating the impacts on building envelopes (mainly facades), demonstrating an important cooling potential [74–77], and their application on horizontal surfaces (canyon pavements) has also proven to be effective in mitigating the UHI effect [74].

Daytime radiative cooling materials (Super cool materials)

Daytime radiative cooling is one of the most promising cool material technologies due to its high cooling potential. Daytime radiative cooling material can have a negative thermal balance, decreasing surface temperatures to sub-ambient levels. Radiative cooling is a passive cooling technique that involves the natural emission of infrared (IR) radiation of terrestrial objects to the cold (3 K) outer space through the atmospheric window, i.e., wavelengths of 8 to 13 μm at which the atmosphere is transparent to infrared radiation.

A radiative cooler absorbs shortwave (solar) and longwave (thermal) radiation, emits longwave radiation and exchanges heat (gain or loss) with the ambient air. The ideal daytime radiative cooler must be characterized by:

a) the maximum possible (near unity) solar reflectance to reduce solar heat gains; and

b) a spectrally selective thermal emittance with a maximum value (near unity) in the atmospheric window (8-13μm) and low emittance (near zero) in the rest of the 4 – 80 μm thermal infrared spectrum to maximize long-wave radiative loss to the sky. This will result in a negative thermal balance leading to a surface temperature below that of the ambient air during daytime. In parallel convective heat transfer from the ambient air to the surface should be minimized by appropriate shielding/ cover [78].

The main parameters determining the performance of a daytime radiative cooler are its solar reflectance, emittance in the atmospheric window (8-13μm), emittance in the rest of the thermal infrared spectrum, daytime radiative heat loss rate, and daytime sub-ambient temperature depression. No standards have been defined for daytime radiative coolers [73].

In the past, several radiative cooling technologies have been developed and evaluated consisting of commercially available materials such as polymers, paints, metals or composite materials, using a radiative cover shield on top of a cooler. Their cooling performance was limited as their radiative properties could not be tuned to approximate the desired values. They were mainly capable of achieving sub-ambient temperatures only during nighttime without solar radiation [79]. Recent developments in photonic/plasmonic and metamaterial technologies have allowed the development of radiative coolers with enhanced performance able to achieve sub-ambient surface temperatures during the daytime. Santamouris & Feng [80] performed a thorough review of daytime radiative cooling materials and have identified 21 different technologies classified in four major technological clusters:

a) Multilayer Planar Photonic Structures. They consist of two parts: the reflector, which aims to maximize the reflectance between 300 and 2500 nm, and an emitter that seeks to achieve a high emissivity in the atmospheric window (8 and 13 μm). Materials such as metal mirrors of aluminium or silver have been used as reflectors or structures of alternative levels of varying refractive index or a combination of a metal mirror with a thin film composed of alternative levels of variable refractive index [78]
b) Metamaterials and 2D-3D photonic structures. A number of metamaterials and 2D-3D photonic structures, such as metamaterial structures based on multilayer all-dielectric micro-pyramid structures [81], dielectric resonator metasurfaces [82], and 2D metal-dielectric photonic structure [83] have been developed, presenting at the same time high solar reflectance values and emissivity values in the atmospheric window close to one. This type of material cannot be considered for building applications due to its high fabrication cost and reduced scalability.
c) Polymers for Radiative Cooling: Polymeric photonic coolers are polymers (e.g. Polyethylene, acrylic resin etc.) doped with nanomaterials- EM resonators (e.g. crystalline SiC and SiO2 nanoparticles, black carbon particles etc.), that are collectively excited, resulting in a high emissivity in the atmospheric window wavelengths where the particles resonate.
d) Paints for Radiative Cooling. Paints using photonic components such as microspheres of SiO2 have been used as radiative coolers, demonstrating an emissivity in the atmospheric window higher than 0.95 while its solar reflectance was equal to 0.97 [84,85]. Paints and other passive radiative materials present a good heat mitigation solution for the built environment as they can be easily produced and implemented, and their costs are reasonable. The ageing of paints may limit their performance.

The performance of the proposed daytime radiative coolers has been evaluated experimentally and via simulations and has shown impressive results. Although the results cannot be compared among them due to the differences in the testing conditions and simulation assumptions, they indicate the potential of this technology. The tested multiplanar photonic systems may present a net cooling power between 40 and 127 W/m^2 and a sub-ambient surface temperature between 5 °C and 8.2 °C [86,87]. Metamaterials and 2D-3D photonic structures were found to have a net cooling capacity of 120 W/m2 and reach a surface temperature of-15 °C below the ambient one during daytime [83]. Polymer-based coolers present daytime surface temperatures varying between 6 °C up to 12-25°C below the ambient temperature [88,89]. Paint base radiative coolers reached 6-12°C cooler temperatures than the ambient temperature [84,90]. A study has evaluated the cooling potential of innovative and traditional mitigation strategies to improve outdoor thermal comfort in a single street in Sydney, Australia. Using a combination of microclimate modelling and experimental data, they found that photonic daytime radiative cooling applied to solar control devices exhibited the highest cooling performance among all mitigation strategies used individually, providing a maximum air temperature and surface temperature decrease of 1.6°C and 24.2°C, respectively [91].

Advanced radiative coolers appear to be the most promising technology for urban heat mitigation; however, they present several limitations. First, their application on building roofs may increase heating loads and decrease indoor thermal comfort conditions as the lower surface temperature during winter will contribute to additional heat losses. In addition, there is evidence that the cooling potential of radiative coolers decreases in high humidity conditions because the transmission in the 8-13 μm band decreases [92], and therefore considering climate conditions when designing radiative cooling materials is extremely important [93]. The potential glare problems due to the high solar reflectance and the failure to meet the aesthetic preferences of the users should be considered. Finally, another significant consideration in the design of the radiative coolers is to minimize the heat gains from the warmer ambient air to the surface of the cooler through the convection process, with the use of appropriate shielding/cover.

Researchers are exploring and proposing solutions for these obstacles, such as the use of self-adaptive radiative coolers to avoid overcooling problems, the use of Asymmetric Electromagnetic Window (AEW) technologies to improve the performance of photonic systems in humid climates, and the development of coloured radiative coolers for enhancing the optical conditions in the environment of the cooler [94,95].

Cool composite materials using Phase Change Materials (PCM)

With the aim to further decrease the surface temperature of cool materials and increase their durability, phase change materials (PCMs) have been used. PCMs have the ability, in a relatively small volume, to store and release large amounts of heat in latent form when they go through a change in their physical state (from solid to liquid and vice versa). Heat storage and its recovery occur isothermally, preventing temperature swings. During the daytime, the PCM absorbs part of the heat through the melting process and at night, the PCM solidifies and releases the stored heat. The net effect is a reduction of the daytime surface temperature of the material. The PCM's upper and lower phase transition temperatures must be selected appropriately to be within the operational temperature range for a given application [96]. When PCMs are incorporated in building envelope material, they can increase thermal capacity and thus reduce and delay the peak heat load transferred into the building, reducing room temperature fluctuation, improving thermal comfort conditions and decreasing cooling needs [97–100]. When used in pavements, PCMs decrease the convective heat flow to the ambient environment and mitigate the heat island intensity. In addition, integrating PCMs in asphalt and concrete pavements has increased their durability [101].

There are several ways to incorporate PCMs in building materials. Microencapsulation, the enclosure of PCM in a thin, high molecular weight polymeric film, improves PCMs performance by providing increasing heat transfer area, reduction of PCMs reactivity towards the outside environment and control of the changes in the storage material volume as phase change occurs [102]. The factors affecting the degree of the potential decrease of a material integrated with PCMs surface temperature include the volume of the PCMs in the whole mixture, the melting temperature of the PCMs, the method used to incorporate PCMs into the material, the thermal and optical characteristics of the materials and the local climatic conditions [11].

The combination of PCMs with cool roof technologies may result in enhanced performance for the roof as the high solar reflectance of the cool roof will reduce solar heat gains into the building and decrease the release of heat into the ambient air, on the other hand, the PCM technology can store a high amount of heat coming from the roof surface optimizing its release and in addition moderate the temperature fluctuations in the cool roof [103–106].

PCM doped cool coloured (NIR reflecting) coatings were developed by incorporating microencapsulated phase change material into an appropriate binder system, and their performance was experimentally investigated against cool coloured and conventional materials of the same colour in outdoor summer conditions. It was demonstrated that the PCM NIR reflecting coatings can be cooler by 7.8°C and by 2°C compared to conventional and cool coloured coatings of the same colour, respectively [107]. A PCM cool roof system was developed using PCM doped tiles covered with a shape stabilized PCM produced by mixing a hydrophilic paint with microencapsulated PCM and tested against other roof materials.

The results indicated that the PCM doped tiles significantly reduced building surface temperatures and indoor test chamber temperatures in summer conditions while demonstrating the lowest diurnal variation. They were found to reduce the heating penalty during winter conditions compared with a cool paint maintaining a higher chamber air temperature [104]. A simulation-based study has demonstrated that integrating PCMs in both cool and non-cool roof membranes can reduce building energy requirements in both summer and winter conditions, especially in non-insulated roof configurations. For the case of PCMs integrated into the cool membrane, a 10.4% and 9.4% cooling energy saving was found with and without considering the roof insulation, and the heating energy saving is equal to 5.4% and 8.4% with and without considering the roof insulation [103]. Another simulation-based study showed that the application of PCM and cool roof technologies together can significantly reduce the thermal stress of a cool roof membrane and reduce the annual energy needs [106]. A cool roof waterproof membrane combined with shape stabilized PCMs was developed, and its performance in terms of durability over time due to the PCM was studied using accelerated weathering testing. Membranes with PCM were found to conserve mechanical and optic-energy performance better when incorporating up to 25 wt% [105].

3. Benefits and Performance

3.1. Level of knowledge of the use and benefits of the technology

As previously mentioned, two properties determine whether a roof is cool or not: Solar reflectance (SR) and thermal emittance (TE). A cool roof is a roofing system characterized by [108]:

a) High solar reflectance, which measures the ability of a surface to reflect solar radiation. Solar reflectance designates the total reflection from a surface, considering the hemispherical reflectance of radiation integrated over the solar spectrum, including specular and diffuse reflection. It is measured on a scale of 0 to 1 (or 0-100%).

b) High infrared emittance, which measures the ability of a surface to release, absorbed heat. It specifies how well a surface radiates energy away from itself compared with a black body operating at the same temperature. Infrared emittance is measured on a scale from 0 to 1 (or 0-100%). The thermal emittance of a roof is determined mainly by the upper layer, which means that if a metal roof with a low emittance is coated with a high emissive material, the roof's emissivity will increase.

A clean, smooth white surface (e.g. a white elastomeric coating) reflects both the visible and the NIR radiation strongly, achieving a reflectivity of 0.85. A black asphalt shingle may have a reflectivity of 0.05. However, because a significant portion of energy falls in the invisible NIR region, the visible properties of a surface do not always indicate how cool it will be under sunlight.

Cool roof products and technologies are produced for building applications related to the construction sector. Financial and legislative schemes are needed to assess comprehensive renovation procedures to support a deeper penetration of sustainable (and cool roof in particular) technologies [52]. In addition, Cool roofs provide several quantifiable benefits. By reducing temperatures in homes, especially at peak hours of heat, they mitigate heat-related mortality and illnesses. By decreasing air conditioning, cool roofs save residents money on electric bills. Thanks to this reduction in energy usage, which means lower demand for power generation, and the decrease in HFCs emitted directly by air conditioners during operation, cool roofs also significantly lower greenhouse gas emissions. However, cool roofs can result in significant energy savings for those who do.

3.1.1. Benefits on the energy, environmental, health, amenity and urban heat island mitigation of cool roofs use at the urban scale

Cities are especially vulnerable to the impacts of climate change: extreme heatwaves, flooding, water scarcity and droughts can impact the health, infrastructure, local economies, and quality of life of city habitants. The land cover for housing, roads and car parks (soil sealing) increases the absorption of energy from the sun, and it contributes to higher urban temperatures, thus generating the urban heat island effect. At the same time, natural drainage is decreased, which, particularly during heavy rains, can lead to urban floods. Through appropriate and resilient urban design, the impacts of climate change can be reduced using green infrastructures such as forests, parks, wetlands, cool materials for walls, roofs, and pavement. Such approaches also lead to significant co-benefits, including improved air quality, energy savings, support for biodiversity and enhanced quality of life, and employment opportunities [35]. Benefits in using cool materials include:

- Reduce the energy consumption
- Mitigate the urban heat island effect
- Reduce power plant emissions, including carbon dioxide, sulphur dioxide, nitrous oxides, and mercury, by reducing cooling energy use in buildings
- Mitigate heat-related mortality and illnesses
- Social benefits, e.g. improving indoor comfort for spaces that are not air-conditioned.

Mitigate the urban heat island effect

Cool Materials can help in the mitigation of the urban heat island effect. The main characteristics of cool material are high reflectivity and emissivity of visible and IR light spectrum. Because of these characteristics, the radiation, by a great percentage, returns instantly to the environment instead of being absorbed by the building elements.

Reduce power plant emissions, including carbon dioxide, sulphur dioxide, nitrous oxides, and mercury, by reducing cooling energy use in buildings

While there are lower environmental and indoor temperatures, the need for cooling energy will be reduced. This reduction, eventually, will lead to lower energy productions from power plants, and as a result, the levels of hazardous emitted gases will progressively be reduced (and the greenhouse effect development will be delayed)

Social benefits

Energy poverty has a serious impact on the quality of life of low-income households. Existing statistics show that low-income families in Europe live in houses characterized by lower thermal and environmental standards. Cool roofs can improve the indoor comfort of low-income households, especially during summer overheating and reducing heat-related mortality. Also, the improvement of the outdoor comfort conditions contributes to citizens' health and wellbeing.

3.1.2. Benefits of cool roofs at building scale

When a cool material is installed on the roof of a building, it decreases its surface temperature. Thus, less heat is transferred into the building interior spaces resulting in lower cooling needs if the building is air-conditioned and lower indoor temperatures if the building does not have any cooling system. A brief overview of the methodologies used for determining the impact of cool materials at the building scale will be presented. A literature review of studies reporting the performance of cool roofs in terms of cooling energy savings and indoor thermal comfort improvement will be conducted to cover different climatic conditions and building typologies worldwide. Results from experimental studies involving the application of cool materials and the pre and post-installation assessment will be included. The factors affecting the performance of cool roofs in terms of cooling energy savings will be discussed. In addition, other direct benefits of cool roofs, such as the increased lifetime of the roof due to less thermal stress, will be reported, and relevant examples will be provided.

3.2. Methodologies to quantify the impact of cool roofs at building scale

The impact of cool materials at the building scale can be quantified by many different approaches, experimentally or via numerical modelling and simulation. Although there are a lot of variations in the employed methodologies depending on the scope of the research, available means, and project limitations, some guidelines can be defined. Many cool roof case studies have been conducted in residential and non-residential buildings [109–116]. The experimental assessment involves the monitoring activities performed in existing buildings in a two-step process involving the building with:

a) the conventional roof (the reference case); and
b) the cool roof after the installation of the cool material.

This method consists of the following steps, after the identification of the building on which the cool roof will be applied:

a) An audit of the building must be conducted. Data should be collected to assess the impact of the cool roof, including weather conditions in the area, air temperature inside the building, surface temperatures on and below the roof surface, AC and total building power consumption, operation schedules and other building configurations and use data etc.). Ideally, the experimental period should cover one full year for pre and post-intervention periods.
b) The radiative properties of the roof, i.e. the solar reflectance and infrared emittance, should be measured before and after the intervention.
c) Statistical analysis of collected data to determine the impact of the cool roof at building scale, including, for example, statistical analysis to assess the differences in the roof surface temperature, indoor air or operative temperature, cooling energy use under similar weather conditions pre and post cool roof installation, development of statistical models to relate AC energy use and demand to outdoor-indoor air temperatures difference, calculation of AC daily energy savings and demand reduction
d) A cost-benefit analysis may quantify if installing a cool roof is beneficial for the specific case on a monetary basis.

Several experimental studies aiming to assess cool roof impacts in terms of thermal comfort and energy consumption involve using test cells [35,117]. This method consists of using at least two identical test cells, usually without openings, to only account for the cool roof influence, one of which is covered by a conventional material and is used as a reference and the other is covered by the cool roofing material.

Whole building energy simulation methods that describe the behaviour of a multiple zone building for an entire year have been used for quantifying the benefits of a cool roof at building scale with short computational time [18,118,119]. This is an advantageous methodology when an experimental campaign cannot be carried out or, for example, when a sensitivity or parametric analysis must be performed or in cases where the benefits of a cool roof must be assessed under different climatic conditions, with different building typologies and characteristics (increased insulation, system efficiencies etc.), or for comparisons of cool roofs with other energy saving measures. The following process is usually followed:

a) Collect all available data on the building (plans, building configuration, building use, systems, bills etc.) or assumptions if it is a theoretical case
b) input data on the initial and final roof solar reflectance and emissivity (measured or from existing databases),
c) Input of appropriate climatic data (hourly values)
d) Data analysis and calculation of energy savings, indoor temperature reduction, surface temperatures or other desired output parameters.

This methodology uses whole building dynamic simulation software (e.g. TRNSYS, Energy Plus etc.) that require detailed input and give hourly values of the selected output parameters. There are several web-based cool roof calculators allowing a quick estimation of annual energy and monetary savings associated with choosing a cool roof instead of a dark roof for a large number of cities in the US (ORNL Cool Roof Calculator [120]) and in Europe (EU Cool Roofs Toolkit). Both methods have been combined, and collected experimental data may be employed to calibrate and validate the developed building model to assess the cool roof impact on a building [112]. This is a good alternative in cases where some monitoring activities can be performed, but for example, the pre and post cool roof installation monitoring periods are short and correspond to different outdoor conditions that cannot be directly compared.

Finally, to quantify thermal comfort improvements from installing a cool roof, computational fluid dynamics (CFD) techniques involving heat and mass transfer analysis in buildings have been used [38]. CFD models are based on the resolution of the Navier–Stokes equation and require very detailed input to build the model and its boundary conditions. They provide a detailed output of the flow field, such as air temperature, air velocity etc. Some commonly used CFD software are PHOENICS and FLUENT.

3.2.1. Reduction of cooling energy use

Installing a cool roof on a new or existing building can significantly improve the energy efficiency during the cooling season and throughout the year, as reported by annual HVAC or energy cost savings. Several research studies have attempted to quantify the potential energy savings attributed to applying a cool roof in residential and non-residential buildings. Haberl and Cho [121]performed a literature review on cool roof studies, and they reported cooling energy savings varying from 2% to 44% and averaged about 20%. They also report peak cooling energy savings from cool roofs between 3% and 35%, depending on ceiling insulation levels, duct placement and attic configuration. Lower peak electricity demand saves on total electrical use. It can reduce demand fees that some utilities charge commercial and industrial building owners and assist in preventing unwanted electricity shutdowns on hot summer days. Further, most HVAC systems are designed based on peak summer cooling loads; therefore, reduced peak electricity loads will lead to downsizing HVAC systems, which can operate more efficiently throughout the year, including the heating season [108,109,122].

In a recent literature review, including more than 100 international studies employing simulation and experimental methods regarding the thermal performance of reflective materials applied to building components, it was reported that daily cooling energy decrease varies between 1% and 80% depending on the climate and the building construction characteristics [123]. The sections below present simulation-based studies for residential and non-residential buildings and different climatic conditions focusing on the cooling savings.

A simulation study aimed to assess the impact of using cool roofs on the energy loads of residential buildings for various climatic conditions (27 cities around the world). SR was increased from 0.2, corresponding to a conventional material, such as grey concrete, to 0.60, corresponding to an aged cool roof or a cool coloured roof and b) to SR=0.85, corresponding to a cool white roof. The decrease in the cooling loads for an increase in SR by 0.4 varies between 6.8 and 29 kWh/m^2 and for a higher increase by 0.65 between 8.4 and 48 kWh/m^2. Regarding peak cooling loads, it was shown that increasing SR by 0.65 can achieve savings that vary between 10.7% and 27% [18].

Levinson and Akbari [124] conducted a simulation-based analysis of cool roofs applied to four commercial building prototypes: new/old office buildings and new/old retail stores. Roof insulation values for old and new prototypes were R- 19 and R-7, respectively, and the roof solar reflectance was changed from 0.2, corresponding to weathered conventional grey roofs to 0.55, corresponding to weathered cool roofs. Energy use savings and penalties and other cool roof impacts were estimated for 236 US locations. The savings for all evaluated locations and building types were then scaled up to a national level using US building stock and building density data. Cool energy use savings per unit conditioned roof area varied from 3.30 kWh/m^2 in Alaska to 7.69 kWh/m^2 in Arizona, with an average of 5.02 kWh/m^2 nationwide.

A study for California houses estimated the impact of cool NIR reflective coatings for tiles on annual cooling energy savings [35]. For a typical 139 m^2 house, increasing the solar reflectance of the roof by 0.3 by applying cool coloured coatings on tiles was calculated to present whole-house peak power savings of 230 W in Fresno, 210 W in San Bernardino, and 210 W in San Diego. The corresponding absolute and fractional cooling energy savings are 92kWh/year (5%), 67kWh/year (6%), and 8 kWh/year (1%), respectively.

Wang et al. [118] compared the electricity consumption of a single-story retail shed with different coatings for six locations worldwide (Durban, South Africa, Kuala Lumpur, Malaysia, Lisbon, Portugal, Miami, and Phoenix, US, and Shanghai, China). The highly reflective coatings significantly reduced the energy consumption in hot climates in a range of 25–38%. The cooling load savings when increasing the solar reflectance to 0.6 were estimated for a hospital and an office building during the summer conditions in Iran's hot and humid areas. Simulation results show that a light coloured roof reduced the cooling load by 10% for both the hospital and the office building [125]. Gao et al. [119] used simulations to estimate the effect of cool roofs on a standard-compliant Chinese office and residential building prototype in seven Chinese cities (Harbin, Changchun, Beijing, Chongqing, Shanghai, Wuhan, and Guangzhou). An aged grey roof of SR= 0.2 was substituted by an aged white roof of SR= 0.6. The results for the office building show that its annual cooling load was reduced by 2.3 kWh/m^2 (Harbin) to 12.4 kWh/m^2 (Guangzhou). The annual energy load savings ranged from −1.5 kWh/m^2 (Changchun) to 10.5 kWh/m^2 (Guangzhou) and were positive everywhere but Harbin and Changchun. For the residential building, the annual cooling load reduction ranged from zero (in Harbin and Changchun, where the residential building was not cooled) to 10.9 kWh/m^2 (Guangzhou).

Compared to other energy efficiency interventions (such as green roofs), cool roofs are very efficient, especially for high albedo roofs and warmer climates [126,127]. However, results are nonconclusive as the characteristic boundary, and initial conditions under which the various experimental and simulation studies have been carried out are different. Therefore, although they give important information, they cannot be easily compared [128]. Moreover, life-cycle operational energy savings and costs should be considered.

Finally, taking into consideration that global warming is expected to increase building cooling demand [129,130] significantly, the importance of considering possible future climate scenarios in building energy performance design is highlighted, and cool roofs present an attractive solution as cooling savings are expected to be even more critical in future climatic conditions.

3.2.2. Improvement of thermal comfort conditions inside an unconditioned building

If a building is not air-conditioned, the reduced heat transfer from the cooler roof results in lower indoor air or operative temperatures and improved thermal comfort conditions (e.g. reduced hours of discomfort calculated for a threshold temperature). Various monitoring and simulation studies indicate a decrease in indoor temperature ranging averagely from 1-3°C and a significant reduction in discomfort hours [18,35,110,112,131]. Hernández-Pérez et al. [123] summarize space temperature reductions measured or simulated from many experimental and simulation studies and report that a reflective material reduces indoor air temperatures around 1–7 °C.

In the previously mentioned study by Synnefa et al. [18], the increase of the solar reflectance of the roof of a residential building by ΔSR= 0.4 and ΔSR =0.65 was found to decrease the maximum temperatures inside the non-air-conditioned residential building by 0.8 - 2 °C for the first scenario and between 1.2 and 3.7 °C for the second, for the 27 cities that were examined. The indoor thermal comfort conditions were improved as shown by the estimated decrease in the hours of discomfort considering a threshold temperature of 27°C, that was reported to be between 5% and 97% for a roof solar reflectance of 0.6 and between 9% and 100% for SR of 0.85.

Using scale model experimental measurements of building temperature and heat flux, the effects of cool coloured tiles have been assessed in hot climatic conditions in the city of Riverside, California. Under typical summer conditions, installing cool coloured tiles that increase the roof's solar reflectance by 0.3 results in a peak roof surface temperature reduction by 5–14 °C and a peak ceiling heat flux decrease of 13–21%. The absolute decrease in attic air temperature was about 6.2°C [35].

An experimental study to evaluate the effect of cool roofs in improving internal thermal comfort in residential buildings in Italy has been conducted [132]. The measurements reported were carried out during summer conditions at an experimental residential building. The roof was covered by paint with a measured solar reflectivity of 0.86, and measurements were carried out before and after applying the paint on the roof. The room temperature under the roof was found to be higher than 27 °C for 99.8% of the time, while in the room below, it was 64%. After installing the cool roof, the percentages were, respectively, 58% and 48%, indicating a significant improvement of thermal comfort in the space under the cool roof.

Another experimental study was carried out for a residential building in Townsville, Australia. The building is of timber frame and clad construction and has a corrugated steel roof. A reflective white paint with SR=0.8 was applied to the roof, and measurements have shown that the interior temperatures reduced relative to the ambient temperature; before painting, the interior temperature was 2.1 °C above ambient and after the interior temperature was 0.8 °C above ambient with the corresponding improvement in thermal comfort for the occupants [110].

The impact of cool roofs in hot and humid climates was studied in two schools in Hyderabad and Nagpur, India [131]. Two classrooms of two unconditioned Indian school buildings of the same size, function, and occupancy from both the school buildings were monitored for ten weeks. The application of the cool coating increased the solar reflectance of the first school by 0.2 and by 0.4 for the second school. An average reduction and peak reduction in indoor air, roof under the deck, and roof surface temperatures of 2.1 °C, 5.0 °C and 12.3 °C and 4.3 °C, 10.0 °C and 26.3 °C were detected for the school in Hyderabad and 1.5 °C, 4.0 °C and 9.5 °C, and 3.3 °C, 4.2 °C, and 25.2 °C for the school in Nagpur. For a case-study building in Portugal [133], in the summer, it was found that an increase in the envelope solar reflectance from 0.5 to 0.9 reduced the maximum indoor free-float temperature between 2.0 °C and 4.7 °C in old construction (without thermal insulation), and between 1.2 °C and 3.0 °C in new construction (with thermal insulation).

The impact of cool roofs in reducing the air temperature and improving thermal comfort conditions inside unconditioned buildings during summer overheating is a significant social benefit, especially because a large percentage of low-income housing worldwide is characterized by lower thermal and environmental standards and inappropriate indoor environmental conditions. Thus, low-income households are exposed to extreme overheating conditions and heat-related health risks [130,134,135]. Cool roofs can contribute to the Improvement of indoor comfort of low-income households and reduce heat-related mortality [136].

3.2.3. Cool roof case studies

Five case studies have been implemented within the framework of an EU funded project called Cool Roofs, aiming to demonstrate cool roof potential in different building typologies and climatic conditions, improve the thermal conditions in non-air-conditioned buildings, and reduce the energy consumption in air-conditioned buildings. The methodology followed in all cases includes building monitoring activities under free-floating conditions pre and post cool roof application and experimental data to perform calibrated simulation and estimate annual energy and thermal performances.

Case Study 1 – School building

The first case study examines the impact of a cool roof on a 410 m^2 school building in Athens, Greece [112]. The building structure was reinforced concrete with no envelope insulation. The building does not have AC equipment installed, and it is naturally ventilated via its windows. The solar reflectance of the roof has changed from 0.2 (cement and gravel screed) to 0.89 after applying a white elastomeric cool coating, and the emissivity was 0.89. The analysis has shown that after the cool roof application, the indoor air temperature was reduced by 1.5–2 °C during summer and 0.5 °C during winter. The annual cooling energy load reduction was 40%, and the heating penalty was 10%. Lower reductions of 35% and 4% were estimated when considering the building to be insulated. A significant decrease in the surface temperature, reaching a maximum of 25°C during summer, is recorded after the ‘Cool Roof’ application.

Case Study 2 – Laboratory and office building

The second CR case study was carried out in Heraklion, Crete, Greece, and involved a 50 m^2 one-floor laboratory and office building [113]. The building envelope had increased insulation. The roof had a solar reflectance of 0.2, and after the application of a cool white coating, it was increased to 0.89. The infrared emittance was 0.89 for both cases. The analysis of the calibrated simulation results showed energy conservation equal to 19.8% for the whole year and 27% for the summer period. The difference in the indoor temperature reaches 1.5 °C in the summer months, and it is reduced to 0.5 °C in the winter period.

Case Study 3 – Laboratory and office building

The third case study involved cool roof application on a 700 m^2 roof of a single-story office/laboratory building with no insulation in Trapani, Sicily, Italy [137]. The initial roof external finishing was of grey concrete tiles (SR=0.25) on which a water paint based on a mixture of milk and vinegar was applied (SR=0.86, e=0.89). A reduction of 54% in cooling energy demand was registered for the actual building and 24% for the insulated variant. An average reduction of the operative temperature of 2.3 °C was calculated for the studied case during the cooling season. The cool roof significantly reduces discomfort hours since a temperature of 27 °C was reached for less than 15% of the period compared to the initial case of above 55%.

Case Study 4 – Duplex apartment

The fourth case study involves the investigation of the performance of a cool roof on a part (a duplex apartment) of a residential social housing low-rise building in Poitiers, France [116]. The studied building was well insulated mechanically ventilated with no air conditioning. An asphalt coating covered the initial roof, and the cool roof installed had a solar reflectance of 0.88 and a thermal emittance of 0.90. A decrease up to 10 °C of the surface temperature was registered. The operative temperature within the attic shows a significant reduction with an average value of 30.8 °C for the initial coating and 22.4 °C for the cool roof. The room's average operating temperature below the roof varies from 24.9 °C for the initial coating to 24.2 °C for the cool roof.

Case Study 5 – Office room in a university building

The fifth case study involves the application of a cool coloured coating on a 137 m^2 flat roof in a naturally ventilated office university building in the area of London, UK [138]. The building envelope is insulated, and the roof was initially covered by an asphaltic material (SR=0.1). The chosen cool roof coating was a cool coloured coating with an in situ measured reflectance of 0.6 and a thermal emittance of 0.88. The choice of a coating with a lower solar reflectance was optimum for a moderate climate with high heating loads such as London's. The maximum operative temperature was reduced by 2.2 °C and the average operative temperature by 2.5 °C, improving significantly thermal comfort. It was also found that heating load was increased, and the cooling load was decreased with an overall energy demand reduction between 1 and 8.5%.

Commercial buildings in California

Akbari et al. [109] have monitored the cooling energy use savings from increasing roof solar reflectance of commercial buildings in California: a retail store in Sacramento, an elementary school in San Marcos, and a cold storage building in Reedley. The increase in solar reflectance was 0.61, 0.54 and 0.61, respectively. Results showed that installing a cool roof reduced the daily peak roof surface temperature by 33–42 °C. The estimated average daily savings in cooling energy use for the retail store was 72 Wh/m^2 (52%), and the peak demand reduction was found to be 10 W/m^2 (50%). The estimated daily savings in cooling energy use and peak demand for the school were about 42–48 Wh/m^2 (17–18%) and 5 W/m^2 (12%), respectively. The cold storage facility had daily cooling savings of 69 W h/m2 (4%) and peak demand reduction of 5–6 W/m^2 (6%).

Warehouse building in Brisbane, Australia

A study has been performed aiming to quantify the impact of a 1004 m^2 cool roof of a single-storey 'warehouse-style retail building in sub-tropical Brisbane, Australia [110]. The radiative properties of the initial roof were SR= 0.2 and TE=0.25, and after the cool roof application, the corresponding values were SR= 0.875 and TE= 0.9. Before and after the cool roof installation, experimental monitoring results were used to perform a calibrated simulation. Results indicate an average 4% increase in hours within the ceiling void at a temperature in the design set point range of (21–23 °C) accompanied by a 7.5% and 9% reduction of hours where the ceiling void space temperature exceeds the ranges 29° < T ≤ 32 °C and ≥ 32 °C respectively. The cool roof achieved a 13% (2.84 MWh) reduction in cooling energy consumption, without heating penalty in the specific case. In addition, the energy efficiency potential of cool roof technology applied to similar retail buildings across Australia was examined for seven different limes, from cool temperate (Canberra) to hot-humid summer and warm winter climate (Darwin). In all cases cooling energy savings have been found, with the greatest reduction occurring in tropical, subtropical and desert environments where an energy saving of 2.8–8.4 kWh/year/m^2 was estimated.

Semi-detached house near the equator

The impact of a cool roof on a low-income single-storey semi-detached house in Jamaica, which is near the equator and is characterized by high solar irradiance, is examined by Kolokotroni et al. [114]. The building was monitored before and after applying a cool coating with SR- 0.82 and e=0.90. Internal ceiling surface temperature and internal air temperature were reduced by 6.8 °C and 2.3 °C, respectively. Experimental data were used to perform calibrated simulation, and a cooling load reduction of 188kWh/m^2/year corresponding to about 38% was estimated. A field study quantified the direct energy savings from installing cool roofs on commercial buildings in Hyderabad, India [111]. The roof area is 700 m^2. When the roof solar reflectance changes from 0.1 (black roof) to 0.70 (white coating), the annual energy saving achieved was 20–22 kWh/m^2 for roof area coated with white paint of commercial building and an air-conditioning energy use reduction by 14–26%. The corresponding values from changing the roof solar reflectance from 0.30 (grey concrete roof) to 0.70 (white coating) are in the range of 13 – 14 kWh/m^2, corresponding to an air-conditioning energy-use reduction in the range of 10 – 19%.

3.2.4. Increased lifetime of the cool surface

Many studies have shown that the application of a cool roofing material replacing a conventional "hot roof" results in lower surface temperatures as high as 30°C as well as significantly reduced diurnal temperature fluctuations [112,116,137]. **Figure 9** shows the hourly values of surface temperature for a whole year of a school building that initially had a conventional roof installed (SR=0.2) (A), and then a cool roof was applied (SR=0.85). The daily fluctuations of the surface temperature are significantly greater for the reference roof. During summer, the average daily fluctuation of the surface temperature for the reference roof is 28 °C, while for the cool roof, it is only 10 °C. The degradation of materials is associated with chemical reactions that progress faster with higher temperatures. Furthermore, extreme changes in surface temperature impose stresses due to differential thermal expansion causing the roofs to damage. Therefore, a cool roof is likely to have a longer lifetime, resulting in reduced waste conveyed to landfills [19,21].

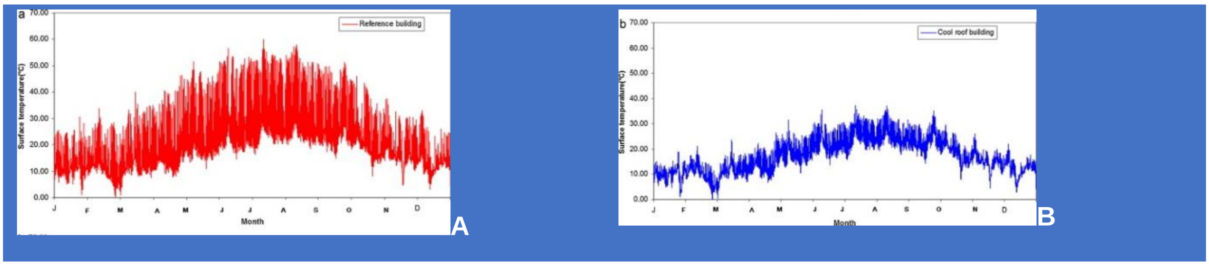


Figure 9. Hourly values of surface temperatures for a building with a conventional hot roof installed (reference) (A) and with a cool roof (installed) (Source: [112]).

3.3. Factors affecting the performance of cool roofs

Although in all cases, a cool roof is found to reduce cooling loads, there is a great variation in the building energy performance depending on the specific boundary conditions in terms of local climate, radiative properties of the building envelope, building characteristics, type and use, HVAC systems, sky view factor etc.

- Heating penalty. As cool roofs deliver cooling energy savings by reducing solar heat gains through the roofing assembly, heating energy needs are increased by reduced roof surface temperature during the heating season. The ratio of the cooling energy savings to the healing penalties – for the same building with identical insulation level – depends on how much the climate is heating or cooling dominated as well as on the internal heat gains (e.g., in buildings in cold climates that require air conditioning even during the heating season because of high internal heat gains a cool roof can still deliver savings).
- The impact of ageing – Weathering, soiling, and biological growth can cause significant solar reflectance losses, reducing the cool roof savings.
- The influence of thermal resistance. A perfectly insulated roof (e.g., more than 300 mm of thermal insulation) does not transfer heat, and thus, the influence of the roof reflectance on the building performance is negligible. On the other hand, an uninsulated roof is affected mainly by the optical-radiative properties of its exterior surface.
- Solar availability. A roof in a climate with high radiation intensity and full solar exposure (unshaded and flat) displays the maximum cool roof savings. Factors that decrease the amount of solar radiation arriving on a roof surface, such as air pollution or cloud cover, are expected to affect the efficiency of a cool roof, decreasing its cooling potential. In addition, when planning to opt for a cool roof, potential sun blockage by trees, buildings, or topography should be considered

These aspects here presented simply discussing the energy balance are presented more in detail in the section on the limitations of cool roofs.

3.3.1. Additional cool roof benefits

Lower intake temperature will decrease HVAC energy consumption

Cool roofs may present an additional cooling benefit, involving the influence of a large roof surface area, such as that of a commercial or industrial building, on local air temperatures 0.5-1.5 m above the roofs, and thereby on the performance of rooftop HVAC equipment since it will result in decreasing the temperature lift between the source and the output [154]. Few studies have been conducted on this issue, reporting decreased above roof temperatures over large cool roofs compared to conventional roofs ranging from 0.3 °C to 3.3°C [154–157]. Green et al. [158] performed measurements of above-roof temperature variations at three shopping centre buildings in NSW. Based on the experimental data, they developed a model to estimate air temperatures above hot or cool roof surfaces and implemented it in a set of case-study simulations that revealed that above-roof air temperatures can have a large effect on the predicted performance of cool roofs and should be taken into account in building simulation studies. They report that in cases where cooling equipment and ventilation inlet ducts were both located on the roof, the electricity savings and gas 'penalties' attributable to cool roofs would have been underestimated by 44–85% (61% on average) if above-roof air temperature variations had not been modelled accurately. Only a limited set of studies has been performed on this aspect, all covered by Green et al. [158] (available also as a CRC LCL report).

Improvement of the photovoltaic panel performance

Combining solar panels with a cool roof represents the integration of sustainable technologies that can increase the output of a photovoltaic system. In terms of temperature, when all other parameters are constant, the higher the temperature, the lower the voltage output. The photovoltaic panels' temperature will increase because of the heat transferred from the roof they are placed on. Installing a cool roofing material will reduce the roof temperature, reducing the heat transferred to the PV module, which could be really beneficial for the PV performance [159]. However, the evidence of this aspect is limited to a few experimental studies without an extensive appraisal.

Increase in property value

Building owners may experience increased property value from energy efficiency measures that lead to lower energy consumption and lower running costs. In addition, according to several studies, highly rated energy efficiency properties and green-certified buildings present an overall higher property value and sell at a premium [6]. Moreover, at district and city scale cool roofs contribute to mitigating the urban heat island effect and its impacts, thus directly impacting the quality of life and health of citizens, especially the vulnerable people (i.e. elderly people or low-income people living in inappropriate households). As an example, Leadership in Energy and Environmental Design (LEED), the U.S. Green Building Council's voluntary green building certification system, recognises cool roofs' benefits regarding increasing sustainability, awards points for heat island reduction under the Sustainable Sites Credit when cool roofs are used.

4. Disadvantages and Problems

4.1. Main disadvantages and problems

Cool roofs application results in significant energy and environmental benefits at the building, urban, and global scale. There are, however, limitations and disadvantages related to cool roofs. This section will address the main criticism associated with cool roofs, which is the potential increase of energy needs during winter, i.e. the heating penalty. By conducting a review of available studies, we will analyse the performance of cool roofs during winter and examine the impact of increasing the roof albedo in colder climates. Another potential negative impact of lower surface temperatures from cool roofs that will be reported is the susceptibility to condensation within the roof assembly. The potential aesthetic limitations of cool roofs and the problem of glare will be presented. Specific examples will be given, and possible solutions or methods to avoid these problems and disadvantages will be discussed.

4.1.1. Heating penalty - cool roofs in cold climates

Cool roofs may cause an increase in demand for building heating in the winter. Except for extremely cold/polar climates, the additional energy for heating demand in winter is typically more than offset by the cooling energy savings in the summer. The reduction of the roof solar absorptance results in lower roof surface temperatures as more solar radiation is reflected away from the roof, and less heat is transferred into the building through the roof. This is beneficial under hot climatic conditions but may lead to increased heating loads and annual heating energy use in climates that have a heating season. Several factors minimize the "winter heating penalty" of cool roofs in many cases [143], such as:

- The sun is generally at a lower angle in the winter months than it is in the summer months, which means that solar radiation is less intense during the winter.
- In some areas, snow cover during the winter makes the underlying roof colour irrelevant because it prevents sunlight from reaching the roof surface [143].
- Heating loads and expenditures are typically more pronounced in the evenings and are not aligned with the daytime benefit of a darker roof in winter.
- Many commercial buildings have a low surface area-to-volume-area ratio, so heat losses in winter are often fully offset by interior heat sources from human bodies, electric lighting, and office equipment. Occupancy patterns in some commercial buildings may be such that space cooling is used in all seasons, and in such cases, reducing solar heat gain contributes to building energy savings year-round.

All the above factors result in less solar radiation (energy) arriving on the roof to be absorbed or reflected during winter, and so the cool roof impact is reduced. The surface temperature of concrete slabs on which different types of cool white or light-coloured coatings and a black coating were applied was monitored from August to October in Athens, Greece. The maximum mean daily surface temperature differencbetween the white cool tiles and the black tile was about 20 °C in August and dropped to 9 °C in October [5]. Moreover, in a similar study evaluating the thermal performance of cool coloured coatings compared to conventional coatings of the same colour, the maximum surface temperature difference dropped significantly from August to December (**Figure 10**).

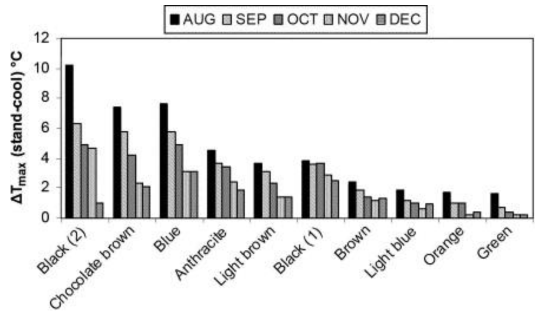


Figure 10. The maximum surface temperature difference (ΔTmax) between each cool and its coloured matched standard coating during daytime [34].

The mean maximum temperature difference between the standard and cool black (2) coating was 6.5 °C during August and dropped to 0.5 °C for December [34]. These observations indicate that the impact of cool materials is reduced during winter. Moreover, in some areas, snow cover hides the roof underneath, and therefore the roof solar reflectance does not play any role in the thermal balance.

Below we present some representative studies that have evaluated the impact of cool roofs on cooling and heating energy loads in different climatic conditions. A simulation study was conducted to assess the effect of using cool roofs on the energy loads of residential buildings for 27 cities around the world. It was found that when increasing the solar reflectance from 0.2, corresponding to a conventional material such as grey concrete, to 0.85, corresponding to a cool white roof, the heating penalty (0.2–17 kWh/m^2 year) is less important compared to the cooling load reduction (9–48 kWh/m^2 year) for the climates studied (**Figure 11**). For the building chosen and the climates examined in this study, even in the cases where heating loads are more important than cooling loads, the decrease in cooling loads always exceeded the increase in heating load (except for the case of Mexico City), although in some cases this distinction was small.

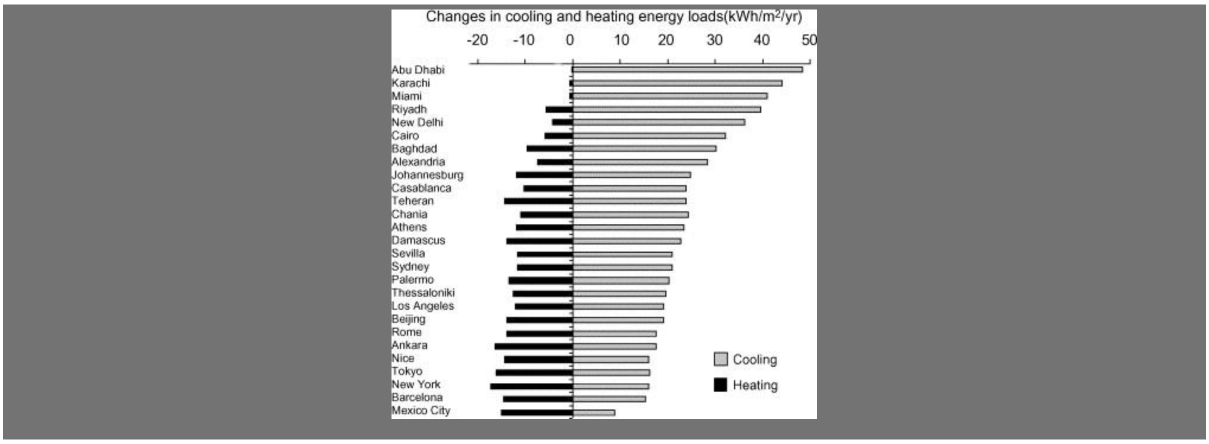


Figure 11. Climate effect on cooling and heating load changes for a change in roof solar reflectance of 0.65 [18].

In the same study, a parametric analysis was performed, which showed that two main factors affecting the energy savings resulting from using cool coatings in residential buildings were the climate and the U-value of the roof. The study found that the annual reduction in cooling load is a linear function of changes in roof solar reflectivity for each location and each roof U-value considered. The benefits of cool roofs are more important in low or non-insulated buildings [18].

Akbari and Konopacki [160] evaluated correlations between building location heating degree-days (HDD) and cooling degree-days (CDD) and energy use savings achieved by the installation of cool roofs for 240 different locations across the United States. Three building types (6 variants): new/old residential, new/old office building and new/old retail have been considered as they offer the most savings potential. New buildings had higher levels of insulation. The solar reflectance of the conventional roof was 0.2 and changed to 0.5 and 0.6 for the residential buildings and commercial buildings, respectively. The simulation analysis results are summarized in the table below. Considering even the extreme cases where HDD>8000 and CDD<200, cooling energy use savings from increasing roof solar reflectance ranged from 4–11% (old)and 1-8% (new), 4-8%(old) and 2-4% (new), 6-11% (old)and 4-7% (new) and heating penalties from 0-2% (old and new), 0-3% (old) and 0-6% (new), 0-6% (old) and 0.-10% (new) for residential, office and retail buildings respectively.

In another study [124], four commercial building prototypes a) new office (1980+), b) old office (pre-1980), c) new retail (1980+), and d) old retail (pre-1980) were simulated in order to estimate the annual heating and cooling energy uses in 236 US cities covering a large range of climatic conditions. Higher values of envelope insulation characterized the “new” prototypes compared to the “old” prototypes. It was considered that a weathered conventional grey roof with SR = 0.20 was substituted by a weathered cool white roof with SR = 0.55. It was demonstrated that the cool roof retrofit results annually in:

a) A cooling energy saving per unit conditioned roof area ranging from 3.30 kWh/m^2 in Alaska to 7.69 kWh/m^2 in Arizona and 5.02 kWh/m^2 nationwide.
b) A heating energy penalty ranging from 0.003 therm/m^2 in Hawaii to 0.14 therm/m^2 in Wyoming and 0.065 therm/m^2 nationwide
c) An energy cost saving ranging from 0.126/m^2 in West Virginia to 1.14/m^2 in Arizona (0.356/m^2 nationwide).

Table 4. Estimated annual cooling energy use savings and heating penalties range from increasing the roof solar reflectance for new (1980+) /old (Pre-1980) residential, office and retail buildings by ranges of Cooling Degree Days (CDD) and Heating Degree Day

		Residential		Office		Retail	
		Old	New	Old	New	Old	New
Cooling savings (kW h/m2)	200<CDD<500	4.02	0.55	5.57	1.56	7.6	2.01
	CDD>5000	8.6	3.6	8.2	2.8	10.9	3.76
Heating penalty (therm/m^2)	HDD<500	0	0	0	0	0	0
	5500<HDD<6000	0.17	0.05	0.11	0.05	0.02	0.01

Several other studies have attempted to estimate the impact of cool roofs at temperate/ cold climatic conditions. In Europe, a case study using calibrated simulation has examined the impact of applying a cool coloured coating on a 137 m^2 flat roof in a naturally ventilated office university building in the area of London, UK [138]. The building envelope is insulated, and the roof was initially covered by an asphaltic material (SR=0.1). The chosen cool roof coating was a cool coloured coating with an in situ measured reflectance of 0.6 and a thermal emittance of 0.88. The choice of a coating with a lower solar reflectance was found to be optimum for a moderate climate with high heating loads such as London's. The heating load was increased, and the cooling load was decreased with an overall energy demand reduction between 1 and 8.5%.

In another study, an innovative cool fluorocarbon coating was applied on a 1685 m^2 industrial building internal heat gains due to electric lights and equipment. The building is located in the Netherlands, where the climatic conditions are characterized as temperate. The solar reflectance of the roof was changed from 0.3 to 0.67. With the use of calibrated simulation, they found that installing a cool roof decreases cooling loads by 73% and increases the heating load by only 5% [142].

The effect of cool roofs on a standard-compliant Chinese office and residential building prototype has been estimated using simulation techniques in seven Chinese cities spanning five climate zones ranging from severe cold and cold climatic conditions (Harbin, Changchun, and Beijing) to hot summer/cold winter, and hot summer/warm winter conditions (Chongqing, Shanghai, Wuhan, and Guangzhou) [119]. An aged grey roof with SR= 0.2 was substituted by an aged white roof of SR= 0.6. For the office building, it was found that the annual heating load was increased by 1.0 kW h/m^2 (Chongqing) to 4.2 kW h/m^2 (Changchun) while reducing its yearly cooling load by 2.3 kW h/m^2 (Harbin) to 12.4 kW h/m^2 (Guangzhou). Annual conditioning (heating plus cooling) load savings ranged from −1.5 kW h/m2 (Changchun) to 10.5 kW h/m2 (Guangzhou) and were positive everywhere but Harbin and Changchun. For the residential building, the annual heating load increase ranged from 0.2 kW h/m2 (Guangzhou) to 4.7 kW h/m2 (Shanghai). In contrast, the cooling load reduction ranged from zero (in Harbin and Changchun, where the residential building was not cooled) to 10.9 kW h/m2 (Guangzhou)). Annual conditioning load savings ranged from −2.2 kW h/m2 (Changchun) to 10.7 kW h/m2 (Guangzhou) and were positive everywhere but Harbin and Changchun.

It has been demonstrated through whole-building simulation analyses that modelling snow accumulation on cool roofs during the winter periods can lower heating penalties to acceptable levels as snow accumulation provides an additional layer of insulation and increases the roof's solar reflectance regardless of their actual radiative properties. The energy consumption has been simulated for several prototype office and retail buildings in four cold-climate cities in North America: Anchorage, Milwaukee, Montreal, and Toronto. In Anchorage, the simulated annual heating energy consumptions of the old retail building with a dark versus a cool roof (without snow) are 123.5 and 125.8 GJ/100 m^2, respectively (a 2.3 GJ/100 m^2 heating penalty for the cool roof). With snow, the heating penalties decreased to 1.2 GJ/100 m^2, leading to an annual energy savings of 7 \$/100 m^2 of roof area. For an old retail building in Montreal and Toronto, a cool roof can save up to \$62/100m+ and \$37/100m^2, respectively. For a new, medium-sized office building with natural gas heating fuel, a cool roof would save \$4/100m^2 in Montreal, \$14/100m^2 in Milwaukee and Anchorage, and \$10/100m^2 in Toronto. For most building types and climates, simulations showed that a cool roof saves overall energy expenditure even without snow. However, snow can effectively reduce the heating penalties for buildings with cool roofs—as seen in all simulated climate regions—contributing to an increase in annual energy expenditure savings [143].

The impact of insulation levels and roof albedo on temperature and heat flux has been investigated via calibrated simulation in the North Eastern United States for a period of a whole year. The objective was to identify the optimal combination of roof insulation and roof reflectivity in terms of reducing energy consumption and minimising cost. Results show that although roof solar reflectance plays a significant role in reducing the heat conducted into the building during the cooling season, insulation thickness plays the dominant role in preventing heat loss from the buildings in the heating season. The physical reason for this discrepancy between summertime benefits and wintertime penalties of cool roofs, even though the Northeastern US has about five times more heating degree days than cooling degree days, is related to the negligible impact of albedo during peak heating periods (which occur during nighttime and in winter when the insolation periods are short), as opposed to its prominent role during peak cooling periods (occurring in the afternoon and the summer when the insolation periods are long). The results demonstrate that high albedo roofs with thicker insulation can cost-effectively reduce energy consumption for heating and cooling in buildings. It also highlighted that cool roofs will help moderate extreme heat in cities as even with higher insulations, cool roofs are still advantageous, particularly for mitigating the urban heat island effect and its consequences as higher albedo roofs resulted in significant reductions in the sensible heat transferred from the roofs to the atmosphere [153].

The reported literature demonstrates that several factors, such as building location, roof solar reflectance, building type, construction characteristics, and use, play a role in determining the potential energy use savings and peak demand reductions achieved by the installation of cool roofs. It is evident that the installation of cool roofs is more advantageous in locations with long cooling seasons and short or no heating season. Cooling energy use and cost savings greatly outweigh potential heating energy use and cost penalties for warmer climates with significant amounts of solar radiation arriving on the roof. In colder climates, cool roofs may cause significant heating thermal load increases. However, it has been demonstrated that heating penalties are overestimated in studies that do not consider the effect of snow that raises the albedo of a conventional roof. Moreover, in order to determine if a cool roof is a cost-effective solution in these cases, local energy prices must also be considered.

The roof solar reflectance has a predominant effect on the performance of cool roofs, and the annual reduction in cooling load is found to be a linear function of changes in roof solar reflectance for a specific location and building. Building construction characteristics and, in particular, insulation levels significantly impact the benefits and the penalties of cool roofs. Old buildings with low or no insulation are expected to have higher cooling energy use savings and higher heating thermal penalties. Optimizing roof albedo in combination with insulation levels for specific climatic conditions and buildings can cost-effectively reduce energy consumption for heating and cooling.

The building type, occupant levels and building play a determining role in the potential savings from cool roofs. Cool roofs can result in higher cooling energy use savings and heating energy use increases for residential buildings than commercial buildings because the impact of envelope contributions to energy loads is higher. Commercial buildings, however, provide more relative cooling energy use savings when compared to heating penalties, in particular buildings with longer operation schedules, e.g. retail stores and/or increased internal gains that might result in significant cooling throughout the year, making the installation of a cool rood beneficial even colder climatic conditions. Although here we have analysed only the direct impacts of cool roofs, the benefits they provide in terms of mitigating the urban heat island effect, improving outdoor thermal comfort and air quality and decreasing heat-related mortality should always be considered.

Finally, taking into consideration that global warming is expected to increase building cooling demand [129,130,135] significantly, the importance of considering possible future climate scenarios in building energy performance design is highlighted, and cool roofs present an attractive solution as cooling savings are expected to be even more important in future climatic conditions [143].

4.1.2. Condensation

Another potential negative impact of cool roofs is that they are potentially more susceptible to moisture accumulation and the risk of condensation when used in colder climates. Moisture from the indoor air can be accumulated within the roofing assembly. In cold climates, there is less heat available to dry out the roof, and moisture may build up. Due to the lower surface temperatures of cool roofs compared to dark roofs, the drying potential is reduced, increasing the risk of condensation. In addition, lower temperatures during the night due to high infrared emittance values may cause the roof temperature to drop below the dew point, causing condensation of moisture in the roof assembly. If moisture accumulates over time, it could damage those materials. Moreover, moisture in the roofing assembly affects the energy efficiency of the building envelope (reduced thermal resistance) and may cause environmental and health concerns (e.g. mould growth) to the building occupants.

A simulation study has evaluated two roofing compositions (typical and self-drying, without a vapour barrier) with solar reflectance 0.12 (black roof) and 0.8 (white roof) for a period of five years. The simulations indicated that in warm climatic conditions (Phoenix), both typical and self-drying roofing systems can be used with either black or white surfaces. In temperate climatic conditions (Chicago), only white roofs can be installed on the self-drying roofs and in very cold climatic conditions (Anchorage); black surfaces were recommended for both roofing systems [161].

Another simulation study has attempted to compare the hygrothermal behaviour of black (solar reflectance 0.12) and white (solar reflectance 0.8) flat modified-bitumen roofing systems for the climatic conditions of Toronto, St. John's, Saskatoon, Seattle and Wilmington. It was concluded that black roofs experienced lower moisture content than white roofs in all climates. In St John's and Saskatoon, the study recommended black roofs to decrease the risk of moisture accumulation. For Toronto, Seattle, and Wilmington, it was found that white roofs have low risk of moisture damage and result in a net yearly energy saving compared to buildings with black roofs [162].

A comprehensive study on the hygrothermal behaviour of cool roofs has been conducted, analyzing the risk of accumulation and mould growth for various roof assemblies in different climates and locations within the US [163]. Four different types of roofing systems have been considered a) typical, b) smart, c)self-drying, and d) smart-vented roofs in residential and commercial buildings. The study found that moisture performance of standard and cool roofs for office buildings was similar in hot climates, and moisture accumulation problems were never experienced during the 5-year analysis period. Residential buildings with cool roofs and conventional vapour retarders were found to present a risk of moisture accumulation and mould growth in very cold cities. This risk was decreased when using smart vapour retarders or self-drying roofs. It was demonstrated that cool roofs did not face any moisture accumulation with the smart-vented system, even in very cold weather conditions like Anchorage. Finally, it was demonstrated that snow accumulation on the roof could effectively reduce the risk of condensation and moisture problems for cool roofs in cold climates.

Cool roof surfaces may be more susceptible to algae or mold growth than hot roofs in warm, humid climatic conditions. This problem may be alleviated by using special chemicals in roof coatings that prevent mould or algae growth for a few years. A well-designed roof assembly is essential to reduce the risk of condensation and mould growth, which may cause damage to the roof. Properly designed cool roofs can significantly improve the moisture performance of the roofing assembly and, at the same time, provide energy efficiency and environmental benefits.

There is little risk of moisture buildup in consistently hot and dry climates. In winter months in cooler climates, all roof structures will develop some moisture that will dry out in warmer summer months. This “self-drying principle” is a long-standing roof design feature in North America. Without proper design and installation, both dark and cool roofs can accumulate moisture in colder climates. Solar reflective roofs maintain lower temperatures than dark roofs and will typically take longer to dry out throughout an annual cycle than a dark roof. However, there are many factors that contribute to moisture problems in the roof system, such as:

- How well sealed the attic is from the space between it. The better the seal, the lower the attic moisture.
- The moisture content of the air in the building - if it is high then we expect more attic moisture problems.
- How well vented is the attic space - generally, more venting will mean less moisture issues (with the exception of further north on the West Coast where too much venting with cold saturated outdoor air may lead to moisture issues in any roof structure).
- Whether there are existing roof leaks allowing water intrusion.

4.1.3. Performance losses due to ageing

The performance of a cool roof highly depends on its radiative properties and mainly its solar reflectance. A parametric analysis conducted by Synnefa et al. [18] showed that the annual reduction in cooling load is found to be linear function ($R^2 = 1$) of changes in roof solar reflectance for a specific location and building. As expected, a decrease in solar reflectance will limit the performance of a cool roof.

Aging, i.e. weathering, soiling and biological growth, diminishes the solar reflectance of cool roofs. The ageing effect mainly depends on the type of roofing material, the characteristics of the local climate and the initial value of solar reflectance [19]. The analysis of solar reflectance values of a large number of commercial roofing products, after natural exposure at three US weathering test sites with different climatic conditions, including Arizona (hot and dry climate), Florida (hot and humid climate) and Ohio (temperate and polluted), showed that products with high initial solar reflectance tended to lose reflectance, while those with very low initial solar reflectance tended to become more reflective as they aged.

For typical cool roofing material with initial solar reflectance values ranging from 60%- 80%, the mean absolute loss in solar reflectance is reported to be 0.13 for Florida, 0.05 for Arizona and 0.1 for Ohio. For higher values of initial solar reflectance (SRinitial>80%) the corresponding reductions were 0.24, 0.8 and 0.17 [144]. It was reported that absolute solar reflectance losses were largest for field-applied coating, modified bitumen and single-ply membrane products and smallest for factory-applied coating and metal products [144]. Similar results were found for European conditions, Japan, China, and Brasil [145]. The solar reflectance of two school roofs in Athens (Greece) covered with white elastomeric coatings with initial albedos of 0.71 and 0.74 dropped by 0.17 and 0.24 respectively, after four years of exposure[146]. After the natural exposure of 16 roofing materials for four years in Milan and Rome, it was concluded that a low sloped cool roof with an initial albedo of 0.80 is subject to a loss of 0.27 in Milan and of 0.19 in Rome. Materials with an initial albedo of 0.20–0.30, instead, were almost showing the initial values even after exposure [145].

Reductions in the initial solar reflectance of 0.15-0.25 were recorded for cool roofing materials in Japan [147]. Washing and cleaning practices were found able to restore the initial albedo or a percentage of it in some cases [21]. This loss in solar reflectance results in a reduction in the performance of the cool roof. The daily temperature difference between the ambient air and acrylic elastomeric coatings increased by 5 °C on average (4-9 °C) due to their exposure to outdoor conditions and their solar reflectance reduction with an increase in cooling loads [146]. Paolini et al. [148] report that ageing by 0.14 and 0.24 reduces cool roof cooling load savings of 14–23% in Roma or 20–34% in Milano, respectively and that an aged roof (albedo = 0.56) may be even 16 °C hotter than when new (albedo = 0.80). Aging was found to reduce the cool roof energy savings by 8.8% in Xiamen or 15.8% in Chengdu, China [149]. Most studies report the deposition of black carbon soot particles and biological growths as the main causes of reflectance decrease [150–152]. A roof may lose approximately 25% of its initial solar reflectance over the first 3-4 years after installation, with minimal additional loss in solar reflectance afterwards [144–146].

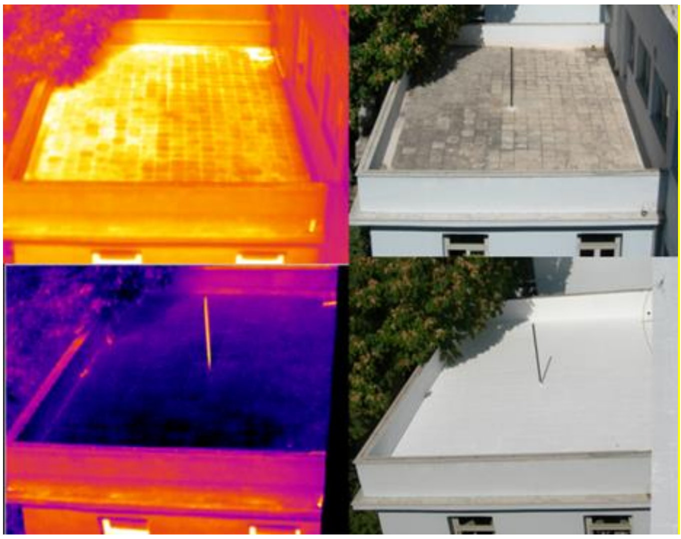


Figure 12. The impact of ageing on the thermal performance of a cool roof. The aged cool roof (above) is by several degrees hotter compared to the recently retrofitted cool roof (below), as revealed by infrared thermography.

4.1.4. Potential glare problems

Another potential problem of cool roofs is the effect of glare. Under sunny conditions, light from a bright white roof may reflect into windows of neighbouring taller buildings, potentially causing building users glare and visual discomfort and unwanted heat. This is not expected to be a significant issue as cool white roofs exhibit diffuse reflection, which means that light from a surface such that a ray incident on the surface is scattered at many angles rather than at just one angle, as in the case of specular reflection. To conclude, cool roofs should always be considered in their surroundings. In instances where glare problems may occur, building owners can opt for a cool coloured roof to improve reflectance without significantly affecting neighbouring buildings. We note that information on these issues is more anecdotal – due to the nature of complaints, a comprehensive appraisal is missing.

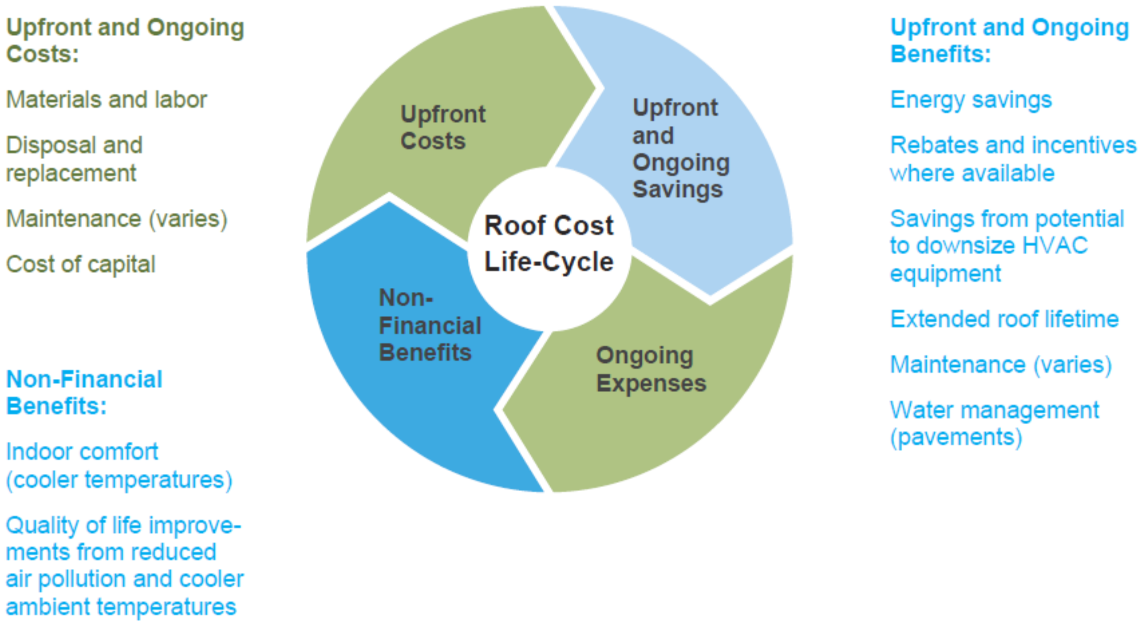
4.1.5. Failure to meet the aesthetic preferences of building users

White roofs may not be as aesthetically pleasing as roofs with a more neutral or darker colour. Therefore white coloured cool roofs are mainly installed in low slope roofs or surfaces that are not visible from the ground. For steep slope roofs or other surfaces visible from the ground, cool coloured materials can be used to satisfy the colour preferences of the building owners and, at the same time, provide the energy and environmental benefits of cool roofs. Also, this aspect is unsystematically and episodically reported, without statistical information on its significance.

4.1.6. Possible first cost premiums

Upfront-cost premiums will vary, particularly in new markets with fewer product options, but highly reflective roof options are generally cost-competitive with traditional roofs in established markets. The simple economic payback[1] of choosing highly reflective roof options ranges between 0 and 6 years based on building energy-cost savings alone [164]. The labour required to install cool roofs is about the same as for non-cool roofs. Other factors to consider when evaluating cost-effectiveness include changes in the expected life of the roof, expected maintenance/cleaning, roof material disposal at the end of service life, and replacement costs. There is an upfront cost premium when applying a cool coating to an otherwise functional roof which is typically paid back with energy savings, longer roof service life, and other benefits. **Figure 13** illustrates some of the lifetime costs and benefits to consider when evaluating cool roofing installations. From an economic perspective, switching to a cool roof is most advantageous when a new roof is installed or an existing roof needs to be replaced. Repairs to an existing functional roof, e.g., when waterproofing, can also be cost-effective to shift to a highly reflective solar roof. **Table 5** shows approximate cost premiums for cool products by roofing type in the USA.

[1] Payback is defined as the amount of time it takes for benefits generated to equal costs incurred.



Source: Global Cool Cities Alliance
Note: Maintenance costs may go up if the roof is regularly washed (a fairly uncommon choice) or may go down because the roof does not experience as much thermal expansion and contraction as a dark colored roof.

Figure 13. Typical life-cycle costs of cool roofs. Source: Global Cool Cities Alliance

Table 5. Approximate cost premiums for cool roofing products.

ROOF MATERIALS	TYPICAL NON-COOL SURFACE	COOL ALTERNATIVE	US$ PER M²
Built-Up Roof	Mineral aggregate embedded in flood coat	Light-colored aggregate, like marble chips, gray stag	0.00
	Asphaltic emulsion	Field-applied coating on top of emulsion	8.61 to 16.14
	Mineral surfaced cap sheet	White mineral granules	5.38
Metal	Unpainted metal	May already be cool	0.00
		Factory-applied white paint	2.15
	Painted metal	Cool-colored paint	0 to 10.76+
Modified Bitumen	Mineral surface cap sheet	Factory-applied coating, white mineral granules	5.38
	Gravel surface in bitumen	Light colored gravel	0.00
	Metallic foil	May already be cool	0.00
		Field-applied coating	8.61 to 16.14
	Asphalt coating	Field-applied coating on top of asphaltic coating	8.61 to 16.14
Shingles	Mineral granules	White granules	0.00
		Cool-colored granules	3.77 to 8.07
Sprayed Polyurethane Foam	Liquid applied coating	Most coatings are already cool to protect the foam	0.00
	Aggregate	Light colored aggregate	0.00
Thermoplastic Membranes	White, colored, or dark surface	Choose a white or light colored surface	0.00
Thermoset Membranes	Dark membrane, not ballasted (adhered or mechanically attached)	Cool EPDM formulation	1.08 to 1.61
		Factory cool ply or coating on dark EPDM	5.38
Tiles	Non-reflective colors	Clay, slate (naturally cool)	0.00
		Cool colored coatings	0.00

Source: U.S. Department of Energy (2012)

4.1.7. Effects of insulation

Roof solar reflectance and insulation in the roof structure reduce heat flow into a building. The similarity in their effect on heat flows has, in some cases, led to policies that allowed increased surface solar reflectance to be traded off for lower insulation levels, given the relative ease of changing roof colour compared to adding insulation in an existing structure. Some building codes allow for a reduction in insulation levels when a solar reflective surface is installed. However, recent research in a climate characterized by hot summers and cold winters in the United States finds that insulation and surface reflectance are complementary, not substitute, solutions for building efficiency and comfort. Building heat flows during summertime are driven by roof surface colour, and heat flows during winter are correlated to insulation level [153].

Many research studies show that the benefits of cool roofs are more important in low or non-insulated buildings, as it is the case for old construction buildings [34,112,137].

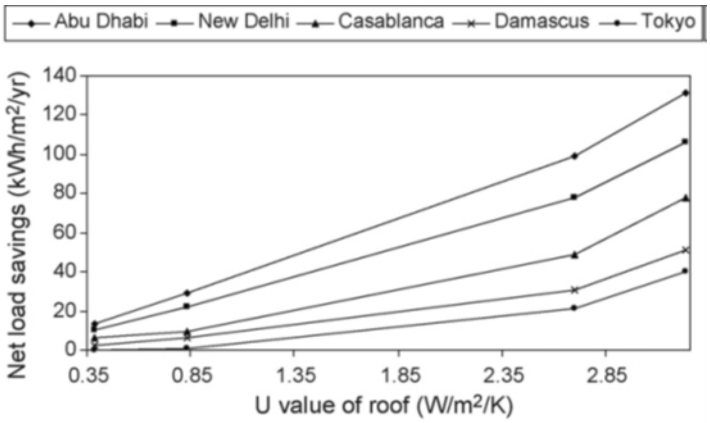


Figure 14. The effect of U-value on the net energy savings resulting from changing the roof reflectance by 0.4 [18].

It is not suggested, though, that cool roofs interventions are used instead of insulation. Actually, cool roofs paired with appropriate levels of roof insulation will assist in keeping buildings more energy-efficient and thermally comfortable [153]. However, it indicates that it can be a low cost and easy to install solution to reduce cooling loads and improve thermal comfort conditions in cases where there are limitations in the possible interventions (e.g. traditional buildings) or budget limitations (e.g. low-income houses, slums etc.).

5. Cool Roofs Policies and Legislation

5.1. Introduction

Cool roof initiatives have been implemented in the past two decades in leading cities as an effective strategy to counter the urban heat island effect and reduce cooling loads in buildings [165]. While the cool roof movement began to take shape in the late 1990s as a policy program, the nature of its inclusion in policies has evolved. While initially, building owners were provided credits and rebates to incentivize the inclusion of a cool roof strategy in their building, it has gradually evolved into a requirement as part of the building code in many cities worldwide [166].

Cities and urban areas are increasingly considering the potential impacts of addressing cool roofs on their urban environment. The urban local governments that govern them have often spearheaded the initiatives. Recognizing that cities can learn from each other, global networks that promote cool cities have been formed, such as the Global Cool Cities Alliance and the Cool Cities Network. The Global Cool Cities Alliance (GCCA) was launched in 2010 to accelerate a worldwide transition to cooler, healthier cities. Its mission is to advance urban heat island mitigation policies and programs to promote more efficient and comfortable buildings, healthier and more resilient cities, and cancel some of climate change's warming effects through global cooling [167].

The Cool Cities Network supports city efforts to reduce the impact of the urban heat island effect, working in partnership with C40: Cities of Climate Leadership and the Global Cool Cities Alliance. Cities participating in the network have prioritized three focus areas around which they actively share policies and strategies. The focus areas are:

- Urban Heat Island data monitoring and measurement – collecting and using UHI data to target future action
- Heat health vulnerability – considering the populations most vulnerable to health impacts from UHI and identifying strategies to reduce heat-related vulnerability
- Integrating heat into long-term planning - integrating urban heat assessments and strategies to address it into long-term planning
- Green and cool solutions - evaluating green and cool solutions and their implementation

5.2. Cool Roofs Policies in North America

Cities around the world have adopted and are implementing policies to encourage the use of cool roofs, including incentives, requirements, awareness-raising campaigns, and procurement specifications. Municipalities may build cool roofs into broader efforts to spur energy efficiency, allow them to comply with a performance standard, or be a specific requirement of a stand-alone prescriptive approach. This section will review a selection of cool roof language in model codes, municipal mandates, green building certification schemes, and voluntary incentive programs.

5.2.1 Model Codes

Model codes refer to standards developed by international organizations that are then adopted by state and local code bodies in the United States. Since 1999, several widely used building energy-efficiency standards, including ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California's Title 24, have adopted cool roof credits or requirements for certain types of buildings and climate zones [165]. Provisions for cool roofs in energy-efficiency standards promote their building- and climate-appropriate use and also stimulate the development of energy-saving cool-roof technologies.

5.2.1.1 ANSI/ASHRAE/IES Standard 90.1

Cool roofs have been included in ASHRAE's Energy Standard for Buildings except Low-Rise Residential Standard 90.1 since 1999 as a credit and have evolved over the intervening years. The 2019 revision requires high albedo roofs in ASHRAE climate zones 0-3 (**Figure 15** and **Figure 16**) within the Prescriptive Compliance pathway.

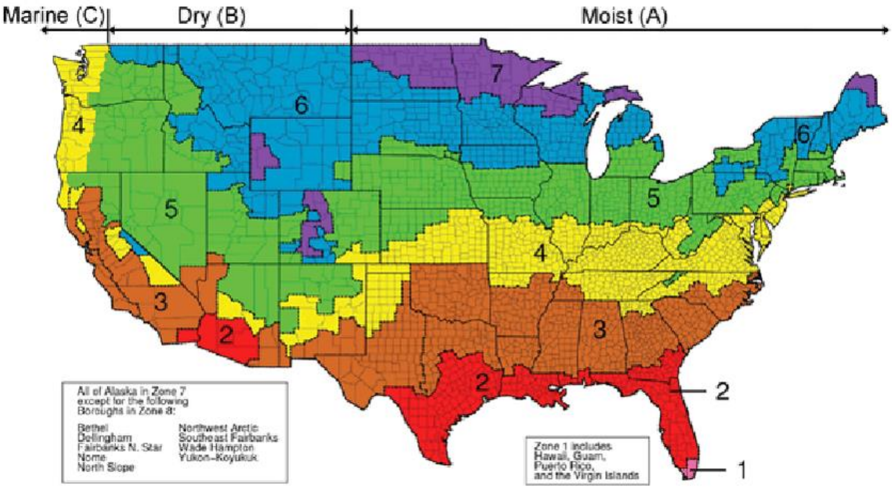


Figure 15 ASHRAE Climate Map: U.S. Source: ASHRAE

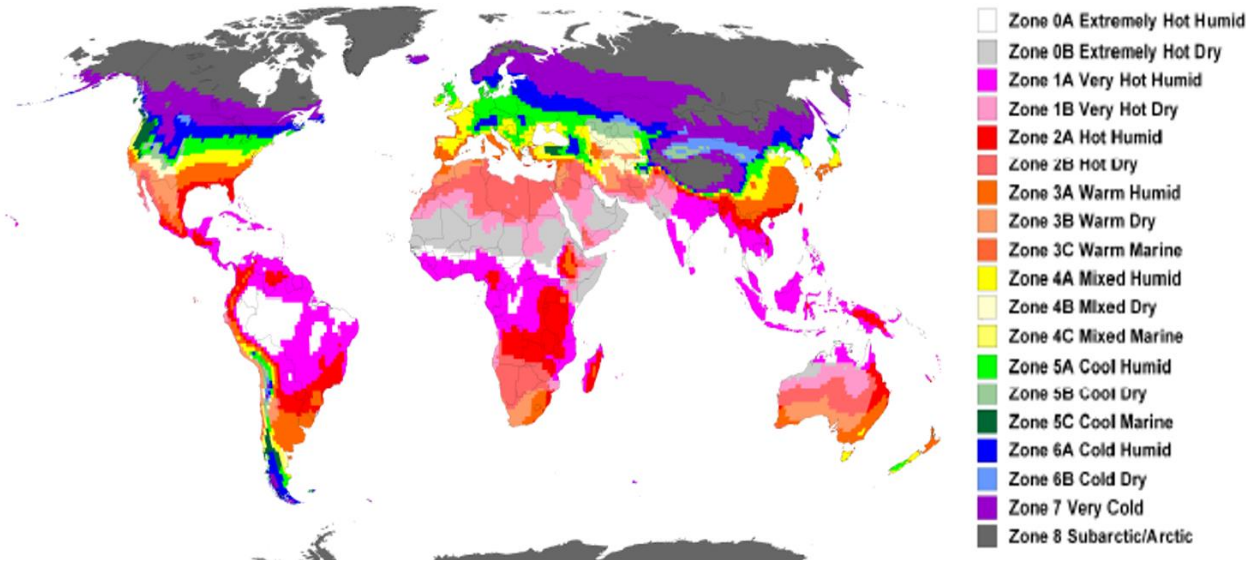


Figure 16 ASHRAE Climate Maps: World. Source: ASHRAE

There are three methods for meeting the cool roof requirements, listed in Section 5.5.3.1.1. A roof must meet one of the following requirements:

- A minimum 3-year aged solar reflectance of 0.55 and 3-year aged thermal emittance of 0.75 as calculated using the ANSI S100 Standard (previously referred to as the CRRC-1 Standard [168]);
- A minimum Solar Reflectance Index of 64, calculated using aged solar reflectance and thermal emittance as calculated by ANSI S100; or
- Insulation levels that meet or exceed those listed in the standard.

Standard 90.1 includes a number of exemptions to the requirements for some ballasted roofs, when 75% or more of the roof area is covered by vegetated roof that is at least 63.5mm deep, when 75% of the roof is shaded during peak sun angle on June 21 (northern hemisphere) by permanent structures or solar photovoltaic panels, roofs with a slope greater than 2 units over 12 units (2:12), low-sloped metal roofs (Climate Zone 2-3), roofs covered by asphaltic membranes (Climate Zones 2-3) and roofs over ventilated attics, semi-heated spaces or uncooled spaces.

ASHRAE 90.1 is an important standard that underpins a significant number of existing U.S. energy codes, and so the inclusion of cool roofs as a credit, and then as a requirement, has been helpful in spreading the use of cool roofs in warm climates. There are a few things to consider when adopting 90.1 language for cool roofs. First, the Standard includes an explicit tradeoff between increased insulation and the surface properties of the roof (solar reflectance and thermal emittance). This may not be an appropriate trade-off in all climates and, based on more recent research, may ignore the fact that roof surface characteristics and insulation act symbiotically in both summer and winter[153]. Second, potential adopters of ASHRAE 90.1 cool roof language should closely review the exemptions to the requirement to ensure they are in line with their desired outcomes. Some exemptions, such as for shade from permanent structures and the use of a vegetated roof, are common and appropriate. Some exemptions, such as for ballasted roofs, may apply when only energy impacts are considered but may complicate efforts to use cool roofs to mitigate urban heat. Exemptions for certain uncoated metal and asphalt roof products may have some, perhaps debatable, justification when only considering energy impacts but would negatively affect indoor conditions in uncooled spaces.

5.2.1.2 ANSI/ASHRAE/IES Standard 90.2

ASHRAE's *Energy-Efficient Design of Low-Rise Residential Buildings Standard 90.2* was overhauled in the 2018 version and switched from prescribing specific energy efficiency measures to establishing performance targets for residential low-rise buildings. This approach gives designers broad flexibility to meet the targets in any way they see fit. Efficiency is determined using the Energy Rating Index (ERI), which is substantially similar to the existing HERS Index. The ERI runs from 0 (a net-zero energy building) to 100 (a home that complies with the 2006 version of Standard 90.2). As such, cool roofs are not explicitly required under the code itself.

5.2.1.3 International Energy Conservation Code (IECC)

The IECC covers commercial and most multi-family structures (excludes one- and two-family residential structures). Section C402.3 of IECC 2018 requires cool roofs in Climate Zones 1, 2, and 3 on low-slope roofs (less than 2units over 12 units) directly above cooled conditioned spaces. There are two ways to prescriptively comply with this requirement: use roofs that have a 3-year-aged solar reflectance of 0.55 and a 3-year-aged emittance of 0.75 or have a 3-year aged solar reflectance index (SRI) of 64. If aged values are not available via the ANSI/CRRC S100 process, they may be determined by the following equation:

$$R_{aged} = [0.2+0.7(R_{initial}-0.2)]$$

Section 402.3 includes several exemptions to the requirement, including portions of the roof covered by renewable energy technologies, vegetated roof installations, roof decks and walkways, skylights, roof equipment such as HVAC systems, portions of a roof that are shaded by permanent structures during peak sun angle on June 21, and heavily ballasted roofs. The IECC does not include exemptions for uncoated metal roofs or asphaltic membranes that currently exist in ASHRAE 90.1.

5.2.2 Green Codes and Certifications

Cool roofs are also featured in a number of green codes and certifications. In these cases, cool roofs are valued for their ability to mitigate the urban heat island in addition to building energy efficiency gains.

5.2.2.1 Leadership in Energy and Environmental Design (LEED)

LEED is the U.S. Green Building Council's (USGBC) voluntary green building certification and has been an important driver of cool roof installations on commercial and institutional buildings. LEED Version 4.1, released in 2019, awards up to 2 points for heat island reduction as part of the Sustainable Sites Credit in Building Design and Construction, Building Operations and Maintenance, Neighbourhood Development or Residential rating systems. Requirements vary slightly by credit and are summarized below. Requirements include both roof and non-roof areas and include exemptions for vegetated roofs. Each rating system calls for the use of aged SRI but allows initial values to be used if the products have not completed a three-year aging process as defined by ANSI/CRRC S100 Standard.

- Building Design and Construction (BD&C) applies to buildings tha2t are newly constructed or going through a major renovation. BD&C awards 1 point for healthcare facilities and parking undercover and 2 points for all other structures for roofs that meet or exceed the values in **Table 6**.
- Building Operations and Maintenance (O&M) applies to existing buildings that are undergoing improvement work with minimal construction. O&M may be applied to existing buildings, schools, retail, hospitality, data centres, warehouses and distribution centres and awards 1 point for roof area that complies with **Table 1** above.
- Neighbourhood Design (ND) applies to new land development projects or redevelopment projects containing residential uses, nonresidential uses, or a mix. Projects can be at any stage of the development process, from conceptual planning to construction. Under this rating system, up to 1 point may be awarded under the Heat Island Reduction Credit. To comply, at least 75% of roof area must meet or exceed the SRI values in **Table 6**.
- Residential applies to single-family homes and multi-family buildings and awards 1 point for roofs that meet the values in **Table 1**. For multifamily structures, 1 point can be awarded when 50% of the total hardscape area (pavement and roof) comply with the requirements and 2 points if more than 75% of the total hardscape areas are compliant.

Table 6 Cool roof requirements in Sustainable Sites Credit BD&C

	Initial SRI	Aged SRI
Low Slope (<=2:12)	82	64
Steep Slope (>2:12)	39	32

5.2.2.2 ASHRAE Standard 189.1 / International Green Construction Code2

Standard 189.1/IgCC is a model green code that allows users to consider the impacts of measures beyond their effects on energy use. As of the 2017 Revision, ASHRAE 189.1 Section 5.3.5.3 requires that at least 75% of roof area on buildings and parking structures have a minimum aged SRI of 64 when the roof has a slope of less than or equal to 2:12 and an SRI of 25 if the slope is greater than 2:12. This requirement applies to roofs in Climate Zones 0 to 3 and 4a and 4b. Total roof area excludes roof penetrations, areas covered by renewable energy systems, areas designed to capture heat for building energy technologies, vegetated roof areas, and rooftop decks and walkways. Exemptions include projects where an annual energy analysis simulation demonstrates that the total annual building energy cost and total annual CO2e, as calculated in Section 7.5.2, are a minimum of 2% less for the proposed roof than for a roofing material complying with the SRI requirements. While the aged SRI requirements could be more stringent, the inclusion of cooler climate zones

[2] These two standards are shown together to reflect that, in 2015, ASHRAE and ICC reached an agreement to have ASHRAE develop all technical provisions of the IgCC.

(4a and 4b) is an important step to recognize the energy, UHI, and climate change mitigation benefits of cool roofs in cooler climates.

5.2.3 Selected State and Municipal Codes

5.2.3.1 California Building Energy Efficiency Standards (Title 24, Part 6)

California Title 24, Part 6 contains requirements for the thermal emittance, three-year aged reflectance, and Solar Reflectance Index (SRI) of roofing materials used in new construction and re-roofing projects. Section 140.3 describes the prescriptive requirements for building envelopes. The cool roof requirements apply to new construction and to retrofits or additions that replace or re-coat at least 2,000 ft^2 (186 m^2) of roof space for nonresidential buildings and 1,000 ft^2 (93 m^2) of roof space for residential buildings, or 50% or more of the roof surface (whichever is larger). These requirements apply to nonresidential, high-rise residential, and low-rise residential buildings across California's 16 climate zones (**Figure 17**).

Additionally, Title 24, Part 6 establishes requirements for how cool roof products are tested, rated and labelled (Section 10-113). This section designates the Cool Roof Rating Council as a supervisory entity responsible for administering California's rating program for roofing products. Minimum surface property requirements are shown in **Table 7** below. Products that are not certified per the requirements in Section 10-113 may use default aged values shown in **Table 8**.

There are a number of exemptions to these requirements. Wood-framed roofs in Climate Zones 3 and 5 are exempt, provided the U factor of the roof is sufficiently low (below 0.034). Roofs with sufficient mass (greater than 25lb/ft^2).

Title 24, Part 6 has been hugely influential for the advancement of the cool roofing market in the U.S. As a massive market, the requirement helped establish a robust demand for the products, which has resulted in greater innovation, price competition, and product availability that have generated benefits beyond California. The strong focus on testing, rating, and labelling directly led to the growth of the Cool Roof Rating Council, whose certifications are now globally recognized good practices and that underlie almost all of the U.S. cool roof requirements and voluntary programs.

However, Title 24, Part 6 does articulate a trade-off mechanism between roof surface characteristics and roof insulation levels which may not be appropriate to adopt. Ramamurthy et al. 2015, A field study and model analysis of black and white roof membranes over various insulation levels at the Princeton University campus, showed that the relationship between roof reflectivity and insulation is symbiotic, not a tradeoff [153]. The research highlights the inter-connected role of roof surface reflectivity and insulation in roofing systems and finds that reflectivity is the variable that minimizes heat flux during the summer and that insulation levels are the driving variable during winter. In other words, to have a high-performance roofing system that minimizes heat gain in the summer and heat loss in the winter, you need both insulation and a highly reflective roof surface. Beyond the technical issues, establishing a tradeoff between insulation and reflectivity unnecessarily creates competition between these industries, resulting in slow market development and policy adoption.

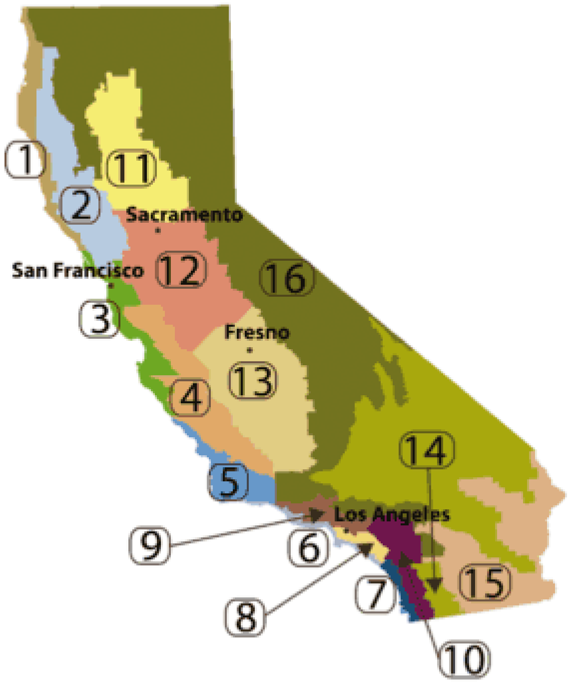


Figure 17 California climate zones. Source: Lawrence Berkeley National Laboratory.

Table 7 Surface property requirements in California Title 24, Part 6

	CA Climate Zone	Aged Solar Reflectance	Aged Thermal Emittance	Aged SRI
Non-residential buildings				
Low Slope Roofs	1 – 16	0.63	0.75	75
Steep Slope Roofs	1-16	0.2	0.75	16
High-rise residential / hotels				
Low Slope Roofs	9, 10, 11, 13, 14, 15	0.55	0.75	64
Steep Slope Roofs	2 – 15	0.2	0.75	16

Table 8 Default values for uncertified products

	Solar Reflectance	Thermal Emittance
Asphalt Shingles	0.08	0.75
All other roofing products	0.10	0.75

5.2.3.2 New York City Cool Roof Law

Local Laws 92 and 94, part of the broader Climate Mobilization Act, mandate that any roof undergoing major construction (i.e., new construction, extensions, or modifications that require a permit) be covered in either solar panels or a green roof system. Simple roof repairs and membrane replacements do not trigger the sustainable roof requirement. If triggered, the legislation requires that all available roof areas be covered in either solar panels or a green roof system, excepting space required by New York City Fire Code and utilized by mechanical equipment. Local Law 94, which has mandated cool roofs since 2012, has been updated to increase the stringency of solar reflectance and thermal emittance for low slope roofs and to extend cool roof requirements to steep slope roofs (**Table 4**). The law includes most of the exemptions included in the IECC, but also has some specific exemptions based on the unique conditions in a dense urban area. For example, roof areas used for recreation, walking, or wood decking must have an initial solar reflectance of only 0.3. Local Law 94 includes a number of exemptions relevant to buildings situated in dense urban cores where roofs are used frequently by the public. It would be a stronger law had the city chosen aged, rather than initial values for their requirements.

Table 9 Roof surface performance requirements in NYC Local Law 94 (2019). Source: NYC.gov

	Low Slope (<=2:12)	Steep Slope (>2:12)
Solar Reflectance	0.7	0.25
Thermal Emittance	0.75	0.75
SRI	82	39

5.2.3.3 Denver Green Roof Ordinance

The Denver Green Roof Ordinance requires green or cool roofs on new buildings that are 2,223 m^2 or larger, roof permits for existing buildings larger than 2,223 m^2 and roof additions of 2,223 m^2 or larger. Residential buildings of under 5 stories (19 meters). **Table 10** summarizes the cool roof requirements.

Table 10 Cool roof requirements in Denver's Green Building Ordinance

Low-sloped Roofs (Slope less than 2:12)				
	Initial Minimum Reflectance	3-Year Minimum Reflectance	Initial SRI Minimum	3-Year SRI Minimum
Low-slope roofs (except for materials specified below)	0.70	0.55	78	64
Low-slope metal roofs	0.50	not available	not available	not available
Low-slope concrete pavers or a concrete surface or stone roofs	0.20	not available	not available	not available
Character-defining roof	*Per section 3.02(a) of the Rules and Regulations*			

Steep-sloped Roofs (Slope 2:12 or steeper)				
	Initial Minimum Reflectance	3-Year Minimum Reflectance	Initial SRI Minimum	3-Year SRI Minimum
Steep-slope roofs (except materials specified below)	0.25	0.15	39	32
Clay or concrete roof tile installed on elevated battens	None required	not available	not available	not available
Character-defining roof	*Per section 3.02(a) of the Rules and Regulations*			

There are many of the standard exemptions to the cool roof requirement, but one unique exemption is for roof sections visible from a public vantage point (like a publicly accessible street, park, or campus), so long as this portion does not exceed 10% of the total roof area. The ordinance also includes language specific to recovers of existing roofs to address concerns about excess moisture accumulation and resulting damage. Where a roof recovery or replacement is introducing a cool roof for the first time, roofs must demonstrate that they meet International Building Code 1203.2 ventilation requirements (for steep slope roofs) or a Class III vapour retarder in addition to an air barrier at the roof deck. Alternatively, the roofing system must be designed by a certified roof consultant, architect or engineer who will submit a report that calculates dew-point and highlights the vapour and air barriers included to minimize condensation in the roof system. For building owners of eligible buildings may choose to pay a fee into the city's Green Building Fund as an alternate compliance pathway. In practice, most have opted to adopt green, cool and other eligible roof technologies rather than paying into the Fund.

Denver's roof law reflects its location in a 4-season, cool climate with the inclusion of language intended to reduce the chance that switching to a cool roof surface over an existing roof system does not lead to moisture problems, including ventilation, vapour retarders, and air barriers. Developers can opt-out of the requirements if they submit a report from a roofing consultant or architect that concludes that a cool roof would present a high risk of moisture problems. While well-meaning, the law does not fully detail what information, modelling, or other analyses must be done to make that conclusion and thus represents a potential compliance loophole.

5.2.3.4 Los Angeles Residential Cool Roof Law

In late 2014, the Los Angeles Green Building Code added a requirement that roofing material used in residential buildings meet the following criteria (**Table 11**). The requirement does not apply when roofs are being repaired, replacements covering less than 50% of the total roof area, roof area covered by solar photovoltaics. A rebate issued by the local utility, Los Angeles Department of Water and Power, was developed to ease the transition for homeowners. A rebate of \$0.20/ft^2 (\$2.15/m^2) was offered to comply with the new ordinance. An enhanced refund of \$0.30/ft2 (\$3.23/m^2) was available if the resulting SRI was above 35 for steep slope roofs and 85 for low slope roofs.

Table 11 Roof surface performance requirements in Los Angeles

	Aged Solar Reflectance	Aged Thermal Emittance	Aged SRI
Low slope (<=2:12)	0.63	0.75	75
Steep slope (>2:12)	0.20	0.75	16

While it is important for major roofing markets to adopt standards for the radiant properties of residential roofs, the requirement for solar reflectance is set fairly low. Los Angeles County subsequently adopted a similar steep slope requirement but set the performance level for solar reflectivity at 0.25. Products with solar reflectance above 0.3 are increasingly available and cost-effective. That said, the enforcement of the cool roof law is also notable. Since the city lacked the resources and permitting requirements to effectively enforce the Cool Roof law at the point of installation, they instead focused on the relatively small number of large supply houses to ensure that roof product inventories complied. This was largely effective at minimizing the amount of non-compliant products available, particularly after Los Angeles County adopted its steep slope solar reflectance requirements.

5.2.4 Incentives and Other Voluntary Programs

5.2.4.1 Louisville, KY Cool Roof Rebate

The Louisville program builds off of an analysis that determined, at a 500-meter resolution, the most vulnerable and highest opportunity areas for passive cooling measures such as cool roofs. Based on the findings, the city adopted a rebate program to spur the adoption of cool roofs in the areas with the greatest vulnerability to heat. The Cool Roof Incentive Program is managed by the city's Office of Advanced Planning and Sustainability and offers a rebate of \$1 per square foot (~\$9.30 per m^2) of cool roof installed, with a goal of incentivizing at least 100,000 square feet of cool roofs on both residential and commercial buildings. Buildings located in Metro Council Districts identified as high heat island areas based on the Urban Heat Management Study (2016) and receive 70% of the available funding for the Fiscal Year 2020-21. The program is funded out of municipal budgets. Since launching in 2017, the City has distributed close to \$500,000 in cool roof incentives, with over 60% of that amount going to roofs in high-heat target districts. Beginning in fiscal year 2020, the program allocates 70% of the available incentive funds for cool roofs in the high-heat districts.

5.2.4.2 Toronto Eco-Roof Incentive Program

The program has been in since 2009 and has been fully subscribed and re-funded several times. The program provides grants to support the installation of green roofs and cool roofs on existing and some new Toronto homes and buildings. There are two grant categories under the Eco Roof Incentive Program: Green Roof Incentive, which provides \$100/m^2 installed and up to \$1,000 for a structural assessment, and the Cool Roof Incentive, which provides \$5 /m^2 for a cool roof with a new membrane or \$2/m^2 for a cool roof coating over an existing roof.

The rebate program is paid for, in part, by cash-in-lieu payments made by developers. Toronto's Green Roof Bylaw sets out a graduated green roof requirement for new developments that are greater than 2,000 m^2 in gross floor area. The requirement ranges from 20-60% of the available roof space of a building. The Bylaw includes an option for developers to seek approval to pay \$200/m2 as cash-in-lieu instead of constructing the required green roof. All funds collected as cash-in-lieu are directed to the Eco-Roof Incentive Program. Between 2009 and 2018, the program had received 500 applications and supported a total of 336 projects. Those projects have resulted in 1000 MWh per year in energy savings 220 metric tons of greenhouse gas emissions reduced per year.

5.2.4.3 Mexico Cool Roof Voluntary Industry Standard

In 2015, following a national impact analysis and 3 years of development, a voluntary standard for testing cool roof characteristics and performance requirements was approved by the National Commission on Energy Efficiency (CONUEE). The standard, PROY-NMX-U-000-SCFI-2015, was developed via a collaborative process involving the Mexican Paint and Coatings Association (ANAFAPyT), Energy Efficiency in Buildings Coalition (AEAEE/ALENAR), the Mexican government (CONUEE), research institutions (CENIDET) and other stakeholders. The standard utilizes ASTM testing standards for initial solar reflectivity, thermal emittance, and SRI. For testing aged performance, the standard measures the initial whiteness of the product sample. An iron oxide mixture is then dispersed on the sample, let to dry for 3 hours, rinsed, left to dry for another 24 hours and then measured again. To meet the standard, product manufacturers must also officially declare the life span of the products being certified. The standard has been used on a number of large roofing projects to date, and efforts are underway to develop a national mandatory standard for cool roofs.

5.2.4.4 San Antonio Under 1 Roof Program

The Under 1 Roof Program replaces worn and damaged roofs with new, energy-efficient light-coloured shingle roofs for qualified homeowners of single-family homes. It is managed by San Antonio's Neighbourhood and Housing Services Agency, and a mix funds its approximately \$2 million budget by the municipal budget and local philanthropic support. Under 1 Roof is a need-based grant program that prioritizes low-income homeowners (i.e., making less than 80% of the area's mean income), veterans, and heat-vulnerable populations. Under the program, the City of San Antonio Places a restrictive covenant on the property requiring homeowners to maintain ownership and occupancy for five (5) years after project completion. Further, residents who do not qualify for the program are encouraged to apply for the Cool Roof Rebate, an alternative provided by CPS Energy for homeowners who install a roof with qualifying materials. Analyses of the program have found up to a 13℃ decrease in attic temperature during the summer and $1,200 in annual energy savings in some households [169].

5.3. Cool Roofs Policies in Europe

5.3.1. Policy Landscape in EU (ECRC)

Cool roof development in Europe is being spearheaded by the European Cool Roofs Council (ECRC). The ECRC was founded in 2011 to develop scientific knowledge and research related to a “cool roof” technology and promote the use of cool roof products and materials in Europe, including developing a product rating programme for such products and materials. The foundation of the ECRC was supported by the IEE Project COOL ROOFS a) (IEE/07/475/SI2.499428) [10]. The (ECRC) advocates that Cool Roof products can make an important contribution to mitigating climate change, reducing the urban heat island effect and increasing the sustainability of buildings. For this reason, the ECRC promotes the certification of Cool Roof products and their use across Europe.

With the help and guidance of the ECRC, a Policy Landscape Assessment (PLA) has been created in Europe, followed by the most important regional, national and local initiatives in Europe. The overall objective of the PLA was to give an overview of existing and forthcoming policies that do or may affect the accelerated introduction of Cool technologies. It consisted of two parts:

- The review of existing policy: to reveal strengths and opportunities that existing policies present. Cool Materials and any significant gaps that might exist in that policy map.
- The study of upcoming policies: to assess how many and at what level those policies in development may affect the accelerated introduction of Cool Materials in the given geography.

The PLA assessed policies in energy, environment, health, and industry to see where Cool Materials can offer solutions and where these policy areas can offer opportunities for Cool Materials, such as financial incentives that can improve their marketability and competitiveness. The PLA also analysed lessons learned from the introduction of Cool Material standards in other parts of the world. In short, the assessment helped shape our thinking by considering the strengths, weaknesses, opportunities, and threats faced by promoters of Cool Materials in these markets. This assessment helped answer the question “how far has policy moved to help promote Cool Materials,” which in itself is the first step in amending policy further in favour of Cool technologies. Ultimately the PLA led to recommendations on the most effective ways to support and promote Cool Materials. In that process, the most relevant stakeholders were examined.

5.3.2. Policy landscape assessment: Critical steps

The PLA has six steps, as outlined in **Table 12:**

Table 12 Steps of The Policy Landscape Assessment

Steps of The Policy Landscape Assessment	
Step 1	Develop a Cool Material story and glossary. The story was designed to resonate with policy-makers to bring to life how Cool Materials as a technology can contribute to meeting policy objectives. The glossary formed a basis for identifying policies relevant to Cool Materials. This glossary was also used in the CEN/CENELEC Workshop Agreement CEN/WS 107 "Mitigation of Urban Heat Island effects with cool materials"
Step 2	Define strict geographical and policy "domain" boundaries for scope of the Assessment. By policy "domain" we mean environment and energy policy for example. Within this, clarify the policy domains (and sub-domains) that are most relevant to Cool Materials.
Step 3	Conduct desk research and interviews on those existing policies and upcoming policies of significance to Cool Materials and collect information on key stakeholders.
Step 4	Gather and analyze data.
Step 5	The last step of the Policy Landscape Assessment was to summarize the findings, draw conclusions and recommend action steps.

5.3.3. Recommended actions in relation to policy advocacy

The previously elaborated findings lead to the following recommendations to Cool Material advocates:

1. Develop a "Share and Re-Apply" strategy: Identify best financial mechanisms that exist at national, regional, local level or outside the EU and advocate for re-application in other countries and if possible at the trans-national level like the European Union.

2. Define the right standardization strategy for Cool Materials at EU level and the principles of an appropriate labelling or certification system. Policy advocates

3. Need to assess the existing standards that affect the technology and how they impact Cool Materials, and whether other standards are needed. In that process, the study findings advise to consider leveraging the following standards:

    a. The Greek Cool Roof technical standard
    b. The Italian standard based on the EN ISO 13790 about the evaluation of cooling systems
    c. The US standard (ASTM) for cooling materials
    d. The work of "Lead market initiative" to widen the scope of design standards for buildings via "Eurocodes" to cover sustainability, even if it is likely to take several years.

4. Prioritize the upcoming policies that entail the highest opportunity to influence based on (a) impact on Cool Materials and (b) achievability or "lower hanging fruits" meaning level of difficulty to amend.:

a. EU Energy labelling Directive 2017/1369 was adopted de in July 2017, replacing the former Energy Labelling
b. Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU. Together, the directives promote policies that will help achieve a highly energy efficient and decarbonised building stock by 2050 and create a stable environment for investment decisions while enabling consumers and businesses to make more informed choices to save energy and money
c. The Greek Cool Roof technical standard, to update the minimum criteria and support Cool Materials
d. The French RT 2012 building regulations, to take into account Cool Materials in the calculation methods
e. The British building regulations, to include temperature change considerations
f. The Italian building code to include Cool Materials as an energy efficiency technology

As part of this recommendation, the next step was completed and revealed the following priority policies across the EU on Cool Materials (**Table 13**):

Table 13. The various policies in EU countries

Geography	Prioritized policies
EU	• EU energy efficiency labelling • EU energy star – though on hold • EPBD recast - Energy Performance of Buildings • EU lead market initiative – though on hold
Greece	• Energy upgrading of public buildings • Building regulations for energy efficiency • CR technical standards
France	• RT 2012 updated building regulations for existing buildings • Building codes – renovation • High energy performance - renovation label
Italy	• The Budget Law 2018 • The Guidelines for Energy Performance Contracts (EPC) • The Decree 26 "Minimum requirements"
UK	• The Green Homes Grant – Zero targets • Building Regulations & minimum standards
Austria	• Building refurbishment programme
Bulgaria	• Mandatory certification of buildings • National Programme for Energy Efficiency in Residential Buildings

Design a consistent and persistent communication strategy targeted to policymakers and policy stakeholders: in all communication, there is a need to position – consistently – Cool Materials as "part of the solution" toward buildings' energy efficiency, highlighting other functional benefits as well as societal benefits from reducing energy demand to improving inhabitants' comfort with minimal extra costs.

5.3.4. Findings from existing policies and success stories

From all the potential policies (concerning energy, environment, industry, health & safety, and financial incentives) that could impact Cool Materials positively or negatively, we examined a total of 66 policy reports. These ranged from policy recommendations (white papers) and regulations, technical codes and standards and financial incentives. Of those 66, 15 covered policies made outside the EU covered EU policies and the rest covered national policies – some of which refer to national implementation schemes of EU policies. In terms of policy breakdown, most policies relate to more than one policy "domain" - 41 policy reports relate to energy, 35 to the environment, 22 to industry, 17 to health & safety, and 20 to financial incentives.

Figure 18 provides an overview of the received reports with the number of existing policies per policy domain and the level of impact of those policies on CR. For clarification, "red" means that the examined policy potentially has a negative impact on Cool Materials, "yellow" means neutral and "green" means that the examined policy has a positive impact on Cool Materials and their take up into the European market. If we map all policy reports, this is the overall picture (Figure 18), showing that most policies affect Cool Materials in energy, environment, and industry.

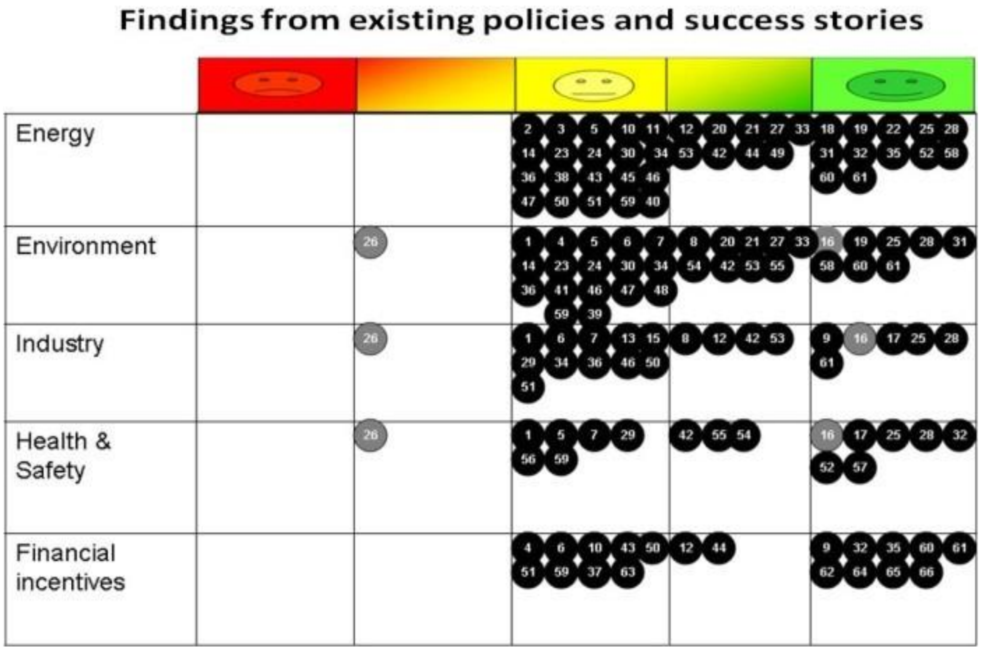


Figure 18. Findings from existing policies and success stories.

5.3.5. Learning from success stories

Beyond evaluating policies that have an impact on Cool technologies, research was also conducted on success stories of the market introduction of other technologies, services, models in Europe and elsewhere (e.g., the "US Energy Star") whose promotion might shed light on the ideal process for Cool Materials.

a) **Raise benefits from functional to societal**. This is important to demonstrate wider policy relevance. For example, the Passive House and Casa Clima concepts linked their energy efficiency benefit with broader issues like climate change, Sustainable Development and even positive quality of life. Therefore the learning for Cool Materials is to elevate benefits from simple “energy efficiency” to enhanced “quality of life” (i.e. comfort) - without degrading the key benefit.

b) **Technology should represent great value** – meaning it should come with functional benefits beyond its core. The example of London Green Roofs illustrates other benefits beyond energy efficiency and climate change mitigation (i.e., biodiversity, reduction of water surface runoff volumes and rates of rainfall leaving roofs, sound insulation and air quality improvements) [170]. Therefore, alongside Cool Materials being a top energy efficiency technology, it should also communicate additional benefits like reduced humidity in the house, easy and inexpensive to maintain, etc.

c) **Benefits must be measurable**. The US LEED rating scheme measures and quantifies various parameters beyond energy efficiency and demonstrates that LEED buildings use a quarter less energy than non- LEED buildings. In the case of Cool Materials, manufacturers need to measure and demonstrate the improvement in energy efficiency and measure the impact of indoor air quality and/or mitigation of the urban heat island phenomenon. Improvements need to be measurable primarily as commercial, and public clients will want to prove that by using Cool Materials, they can demonstrate clear and measurable progress toward meeting specific goals.

d) **Financial incentives are key to kick-start such a technology.** The research finds that this is partly because of existing business models [builders will continue to use the same materials and systems until they have a compelling reason to change] and/or the power of marketing [changing minds of the multitude of potential clients requires a sizeable marketing budget]. As an example, CASA Clima in Italy offers 55% reduction in personal income tax for energy saving expenses, which is hoped to energize household owners to take advantage of energy efficiency technologies like Cool Materials.

e) In the US, there is a policy set up specifically for Cool Roofs via the US Energy Star. The Energy Star is a **voluntary program** involving manufacturers, testers, consumer organizations, local authorities, energy companies etc. It is designed to provide information and other incentives to all partners to convince end consumers and ‘partners’ to use and push Cool Roofs [171,172]. On top of the federal energy star system, several cities, counties and states have developed codes and standards either encouraging or requiring cool roofs on certain types of buildings, as previously mentioned. Beyond that, many energy companies and local authorities have put in place interesting incentive schemes (like Austin Energy, Florida Power and Light, California’s Pacific Gas & Electric). The EPA has announced the sunsetting of the cool roof Energy Star program in 2022.

f) **Target the right influencer.** To determine which actor is the main “influencer,” one has to determine who in each circumstance has the greatest purchasing power influence. In the FacilitiesNet example, a construction executive is the target for use of Cool Materials as it is he who will win rebates [17,173]. The person who will convince people to invest in Cool Materials rather than buying a new car or investing in alternative energy efficient technology is the person Cool Material advocates should focus attention and efforts on. Critically the actor with the greatest purchasing power influence may differ by geography. In some areas, the top influencers might be architects, construction companies, or public procurement officers. In another jurisdiction, the influencer might be real estate agents or local regulators. Once this particular influencer is identified for the specific geography, our learning is to ensure that this “ambassador” is involved and motivated to act on behalf of Cool Materials.

g) In the US Energy Star for Cool Roofs, US regulators have included all “partners” in their communications. In this way, the system convinces end consumers and ‘partners’ from manufacturers, testers, consumer organizations, local authorities, lenders, energy companies, contractors, and architects, to use and push Cool Roofs [174].

5.3.6. Opportunities or risks

Based on the findings, these are the most significant risks – that can be turned into opportunities.

Weak on financial incentives

In relation to financial incentives, based on research, it appears that there are only a few or relatively weak policies providing financial incentives for building owners and intermediaries to choose Cool Materials. Those financial incentives that do rarely exist ever focus on Cool Materials by themselves, and they are often decided on year by year (and even then, only if there is money in the national budget, which is a definitive challenge in today’s cash-strapped Europe). Perhaps more importantly, those financial incentive policies that exist focus on benefits for end-users, but not for Cool Material market actors like construction companies or architects, which could play a strong role in deciding whether or not to use Cool Materials. In other words, they do not provide adequate incentives for construction companies or architect/engineering offices to push end-users to build with Cool Materials.

Therefore, in some markets, it remains a mystery as to how the eligible end-users could learn and how to take advantage of such incentives. Cool Material advocates must explore whether they should more effectively reach out to these third-party suppliers like construction companies, architects, and engineers to promote the materials with end-users. There do not seem to be many standards or certification policies relating to Cool technology, except Cool Roof specific standards in Greece. Further, it is unclear whether the standardization route or the certification route would be more appropriate in many geographical regions.

Insufficient momentum

Existing policies are insufficient to create the momentum necessary for the market to demand Cool Materials. Indeed, Cool Materials need policies (requirements/incentives) that stimulate entrepreneurship these materials: policies that trigger the attention of housebuilders, entrepreneurs and architects to think about Cool Materials automatically when thinking of roofs on buildings. One example is the US Energy Star for Cool Roof products which clearly stimulates companies that sell/ apply/install, or maintain Cool Materials. What is missing in Europe is business stimulation like construction companies or utilities to be stimulated to recommend Cool Materials to their clients when building houses distribution centres (though there is a movement afoot in France that could help create such incentives via French energy saving certificates). Further examples could be training encouragement through public procurement or credits (such that for 2010 all new buildings need to prove energy efficiency standards or use Cool Materials as in the case of state buildings in certain US cities).

5.3.7. Guidelines and general recommendations

The installation of Cool Materials in cities and towns offer social, environmental, and financial benefits with a clear Return on Investment. Calculators to determine the amount of climate change mitigation per application have been designed to allow regulators, construction executives, and building owners to measure the potential effects of applying these materials. Yet their take-up in several geographies has been rather slow. For this reason, regulators considering solutions to reduce energy consumption, mitigate climate change, improve living conditions, and encourage a more environmentally-friendly construction industry are urged to put in place supportive policies (from codes, standards and requirements to financial incentives) that encourage the use of Cool Materials.

Regulatory and voluntary policies designed to encourage these materials have helped Cool Materials become cooler. The structure and methodology of our case study Policy Landscape Assessment will help construction practitioners, policy-makers, academics, and NGOs conduct their own PLA to examine policies affecting the promotion of Cool Materials and offer policy suggestions to accelerate their market penetration. The outcome of the PLA has shown that where policies have been put in place, the take-up of Cool Materials has been strong (particularly in the US). The Assessment has also shown that there are very few policies in place in the European Union that create the necessary drive and incentive for encouraging Cool Materials in construction. On a positive note, the Assessment has also demonstrated that no policy obstacles are presenting a negative impact on Cool Materials. Overall, therefore, one can say that building awareness of the broad benefits of Cool Materials with policy-makers, stakeholders and the construction industry is the first big step: a very large one without which little advocacy work can be done effectively.

The Centre for Process Innovation in the UK declared there is a “Catch-22” situation confounding efforts to mitigate climate change in that regulators refrain from developing climate change policies fearing business resistance, yet the business world find it challenging to scale up investment in low carbon technologies without long term climate policies [175]. One can argue that Cool Materials face their own Catch 22 in that construction practitioners wait for policy incentives before installing Cool Materials. Yet, policymakers will not design policies in support of the materials until they learn from the market about the benefits of the materials. To break this cycle, two organizations have been set up to provide objective and comprehensive information to all stakeholders on the benefits and workings of Cool Materials: the Cool Roof Rating Council in the US [9] and the EU Cool Roof Council in Europe [10].

5.4. Cool Material and Cool Roofs Policies in Greece

5.4.1. Policies on Energy Efficiency

Under Article 5 of Directive 27/2012/EE on the exemplary role of public bodies' buildings, Greece decided to renovate 3% of the total floor area of heated and/or cooled buildings owned and occupied by the central government without applying the alternative approach. Moreover, a list of heated and/or cooled central government buildings with a total useful floor area of over 500 m^2 was published. Directive 2010/31/EU of the European Parliament were transposed into national law by Law 4122/2013 'Energy efficiency of buildings – transposing Directive 2010/31/EU of the European Parliament and of the Council, and other provisions' (Government Gazette, Series I, No 42, 19-02- 2013).

Article 9 of this law provides for establishing a national plan to increase the number of nearly zero-energy buildings, which may include different goals depending on the category of use of the building and notifying it to the European Commission. A study is currently being completed following the reporting requirements set out in the EPBD Directive (2010/31/EU). Specifically, the study includes:

a) Specifications of the technical characteristics of nearly-zero energy buildings, taking into account national, regional or local conditions, including an indicator of primary energy use in Energy Efficiency Trends and Policies in Greece 28 kilowatt-hours per square meter per year (kWh/m^2/year),

b) information on the policies and financial or other measures taken to promote nearly-zero energy buildings, including details of national requirements and measures for the use of energy from renewable sources in new buildings and existing buildings undergoing a major renovation. Moreover, Article 10 of Law 4122/2013 provides for measures, funding programmes and other means to improve the energy efficiency of new and existing buildings. In establishing incentives, the cost-optimal energy efficiency levels and the costs and benefits of energy efficiency investments to society are considered. The joint decision of the Ministers for Finance, Environment, Energy and Climate Change and of any other competent minister, specifying the measures stated in Article 10, is pending.

The list of heated and/or cooled central government buildings in accordance with Article 5 of Directive 2012/27/EC was posted on YPEKA's website on 31 December 2013. The list contained heated and/or cooled buildings of central government with a total useful floor area of over 500 m^2.

The identification of the bodies of the central government was based on the definition of the Central Administration provided in Article 2 of Law 3871/ 2010 'Financial management and accountability' (Government Gazette, Series I, No 141) in accordance with which the Central Government is comprised by the Presidency of the Republic, the Ministries, the Decentralized Administrations and the Independent Authorities. Finally, Article 5 of the Directive sets the necessary framework for public bodies at regional and local levels to be encouraged to play an exemplary role regarding the energy efficiency of buildings. Here, an overview of the existing and new measures for mobilising investments for the renovation of residential and tertiary sector buildings is presented.

5.4.2. Regulation on the Energy Performance of Buildings

Law 3661/2008 'Measures to reduce energy consumption in buildings and other provisions' (Government Gazette, Series I, No 89, 19-05-2008) harmonizes Greek legislation with Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings (OJ L1, 4.1.2003).

Law 3661/2008 incorporates all the provisions of the Directive, provides for the adoption of a Regulation on the Energy Performance of Buildings and distinguishes five main themes: definition of minimum energy performance requirements and the method for calculating energy performance (Article 3) of new and existing buildings (Articles 4 and 5), issue of energy performance certificate (Article 6), inspections to boilers and air-conditioning systems (Articles 7 and 8), provision of qualified and accredited energy inspectors (Article 9). The regulation on the energy performance of buildings (KENAK) introduced an integrated energy design in the sector of buildings to improve the energy efficiency of buildings, energy savings and environmental protection through specific actions:

1. Preparation of a study on the Energy Performance of Buildings
2. Establishing minimum requirements for energy efficiency in buildings
3. Energy Rating of Buildings (Energy Performance Certificate)
4. Energy inspections to buildings, boilers and heating and air conditioning systems

The Study on the Energy Performance of Buildings replaces the study on heat insulation and is prepared for every new or existing building (over 50 m^2), which undergoes a complete renovation and is be based on a specific methodology covering:

1. The requirement to meet minimum standards on the design, envelope and electromechanical installations of buildings and
2. Its comparison with the reference building. Reference building means a building with the same geometry, position, orientation, use and operating characteristics as the building concerned, which also meets minimum standards and has specific technical characteristics.

5.4.3. SAVE and SAVE II programme for local government organizations

The purpose of the 'SAVE' (ΕΞΟΙΚΟΝΟΜΩ) program is the implementation of actions and proven best practices for reducing energy consumption in the urban environment, with emphasis on the building sector (municipal buildings of 1st-grade local authorities) and the upgrade of public spaces, on the one hand, and in the area of municipal and private transport and energy-intensive municipal facilities, on the other, through the implementation of technical interventions and actions to raise awareness and mobilize citizens, the local government, businesses and bodies.

The call for the continuation of the program was published in March 2012. The «SAVE II» (ΕΞΟΙΚΟΝΟΜΩ II) provides financing to energy saving interventions in existing municipal buildings and infrastructure of 1st-grade local authorities, including open building facilities (swimming pools, sports facilities etc.). It does not grant funding to projects launched by municipalities or municipal units (municipalities formerly included in the 'Kapodistrias' plan), which are subsidized by the program.

The program 'Standard demonstration projects on the use of Renewable Energy Sources and Energy Saving Actions in new, under construction or existing buildings, gyms and swimming pools owned by local authorities and municipal enterprises of local authorities' grants financing to demonstration projects using Renewable Energy Sources and Energy Saving Actions in new, under construction or existing buildings, gyms and swimming pools owned by local authorities and municipal enterprises of local authorities. Furthermore, the participation of Greek municipalities in the European initiative 'Covenant of Mayors', which aims at integrated energy planning at the local level and achieving specific environmental objectives, is supported and promoted at the central and regional levels.

5.4.4. Saving at home' program

The 'Saving at Home' program is aimed at providing financial incentives for energy-saving interventions in the residential building sector with a view to reducing energy needs. The types of housing that the program can subsidize are Single-family houses, Apartment blocks for the part of the block which relates to all the apartments in the building, Individual apartments.

The proposal (combination of interventions) for energy upgrade, which is submitted with the application, should cover the following requirement, which is the minimum energy objective of the program: it must upgrade by at least one energy class or, alternatively, provide annual primary energy savings greater than 30% of the reference building consumption (kWh/m^2). Beneficiaries were categorized based on income and societal criteria in 3 different categories, and the level of subsidy and low-interest loan was differentiated accordingly. The applications completed by June 2016 as part of the 'Saving at home' program amounted to 51,659 of a total budget of €529million. 83 % of the completed applications involved the replacement of window frames, 53.9 % thermal insulation and 71.6 % upgrade of the heating system and domestic hot water supply. The total area of renovated residences amounts to 5.2 million m^2 resulting in total annual primary energy savings of 853.6 GWh.

5.4.5. Energy upgrading of social housing buildings - 'Green pilot urban neighbourhood' programme

The program's objective is to upgrade four industrial buildings to nearly zero energy buildings and optimize the local microclimate. The program will present the pilot demonstration and innovative implementation of integrated development and green and sustainable urban housing units. The main criteria for the selection of Neighbourhoods were the economic level of residents, the potential energy savings in the buildings and the prospects for significant improvement of the local microclimate. The implementation plan of projects for each Neighbourhood includes the following stages:

Stage 1: Information, social and business awareness and involvement

Stage 2: Energy recording of buildings and microclimate conditions

Stage 3: Energy study and drafting of specifications issue

Step 4: Tender notice for the projects

Step 5: Evaluation of proposals and selection of contractors

Stage 6: Construction, supervision and delivery of project

Stage 7: Evaluation of benefits and demonstration activities This program is based on voluntary agreements.

5.4.6. ‘Saving at home II’ programme

This is the follow up of the ‘Saving at home’ Programme’ it involves the implementation of interventions to improve the energy performance of residences that are proved to have low energy performance and belong to low-income owners who cannot fully fund their own energy upgrade of their residence, or in which interventions going beyond the minimum required levels of energy performance will be implemented. This program started in 2018 and is funded by the European Union (European Regional Development Fund (ERDF) and National Resources, through the Regional Operational Programmes (ROP) and Operational Programme ‘Competitiveness, Entrepreneurship, Innovation’ (OP-CEI) of NSRF 2014-2020. The total public expenditure of the programme amounts to EUR 292.18 million (EUR 248.06 million from the OP-CEI Operational Programme ‘Competitiveness, Entrepreneurship, Innovation’ and EUR 44.12 million from the ROPs -Regional Operational Programmes).

5.4.7. Improving the energy efficiency of SMEs

This measure aims to support micro, small and medium-sized enterprises in order to improve their energy efficiency. It provides financial incentives. The action involves:

- Interventions in the building envelope: thermal insulation, window frames/glazing, shading systems.
- Upgrade of internal electrical installations and power distribution systems.
- Upgrade of systems for the production and distribution of thermal energy both for cooling/heating purposes and in production. (e.g., hot water/steam generating equipment and systems, waste heat recovery equipment, etc.).
- Upgrade or inclusion of new materials and equipment to reduce energy losses.
- Upgrade of lighting equipment. - Installation of energy management systems.
- Energy inspections and/or energy audits before and after assessing the energy outcome.
- Certification of the energy management system according to ISO 50001.
- Project consultant. - Other interventions, as specified in the guide. Interventions do not include production equipment. Specific objectives (desired outcomes) and eligible budget limits will be set for each of these interventions. The action is funded by the European Union [European Regional Development Fund (ERDF)] and National Resources, through the Operational Programme ‘Competitiveness, Entrepreneurship, Innovation’ (OP-CEI) 2014-2020. The total budget of the action amounts to EUR 64.06 million, and the total public expenditure amounts to EUR 32.3 million.

5.4.8. Energy upgrading of public buildings

This measure aims at energy upgrading of energy-intensive public buildings, exploiting the potential for energy savings and improving energy efficiency in the building sector, with public sector buildings being an example of mobilising the entire economy. The upgrades will, inter alia, include:

- Energy upgrading and energy savings interventions include adding insulation, replacing window frames and glazing with new certified, energy-efficient ones, replacing burner systems/boilers/piping with a RES system, replacing old air conditioning systems and passive solar systems, etc.
- RES projects such as the construction of high-efficiency cogeneration of heat and power facility, construction of a facility for making use of the heat produced from the HECHP and/or RES facility for cooling purposes, etc.

Specific requirements for the energy upgrade of public buildings will be defined to implement interventions that exceed the minimum required energy efficiency levels or, if economically and technically feasible, their upgrading to energy classes B+, A, A+, or to Nearly Zero Consumption Buildings. Meeting the energy target will be ensured by conducting an energy audit by an energy inspector both before and after the implementation of the interventions. The programme is funded by the European Union [European Regional Development Fund (ERDF)] and National Resources, through the Regional Operational Programmes (ROP) and Operational Programme 'Competitiveness, Entrepreneurship, Innovation' (OP-CEI) and the Operational Programme 'Transport Infrastructure, Environment and Sustainable Development' (OP-TIESD) of NSRF 2014-2020. The total public expenditure of the operation amounts to EUR 244.93 million. The public expenditure as part of the call titled 'Energy Upgrading and Energy Savings Actions and Utilisation of Renewable Energy Sources (RES) in Sports Facilities' amounts to EUR 27 million.

5.4.9. Holding Fund under the name 'Infrastructure Fund – Projects for the energy upgrade of public buildings

The Holding Fund under the name 'Infrastructure Fund' - which was set up with Ministerial Decision No 6269/29.11.2017 (Government Gazette, Series II, No 4159), aims at maximising the use of the Financial Instruments to cover the financial gap, inter alia in the fields of Energy Saving and Promotion of Renewable Energy Sources (RES). As part of the Fund, resources from the Operational Programme 'Competitiveness, Entrepreneurship, Innovation' (OP-CEI) relating to these areas will be drawn, in conjunction with national resources from a European Investment Bank (EIB) loan and repayments of the JESSICA financial instrument for the period 2007-2013. The liquidity of public and private entities will be strengthened through the Infrastructure Fund, for the implementation of projects with favourable funding conditions. In the energy sector, the projects that will be financed by the Infrastructure Fund and are related to the resources to be allocated by OP-CEI will concern projects for the energy upgrading of public buildings, as well as projects for the production and distribution of energy from RES.

The Fund draws resources from the Operational Programme 'Competitiveness, Entrepreneurship, Innovation' (OP-CEI), in conjunction with national resources from a European Investment Bank (EIB) loan and repayments of the JESSICA financial instrument for the period 2007-2013. The total resources of the Fund amount to EUR 450 million, while the resources of OP-CEI in the energy sector amount to EUR 128.7 million. [26]

5.5. Energy efficiency policies that advance Cool Roofs in Italy

The Budget Law 2018 confirmed the tax deduction scheme (Ecobonus) to incentivize energy renovation of the existing building stock and introduce some new features concerning, for some specific cases, new rates of deduction, new eligible actions and/or new technologies and/or performance requirements. Other important changes relate to sample checks on all interventions and significant updates on credit transfer rules. The eligible actions, the relative rates and deductions or the maximum expenses are summarized in **Table 13**. Expenses for replacing heating systems with hybrid systems or condensing hot air generators can be deducted at a 65% rate. Hybrid systems are composed of a heat pump integrated with a condensation boiler, assembled in a factory and designed by the manufacturer just to work together.

Following the changes introduced by the Budget Law, ENEA has designed and launched the new website (http://finanziaria2018.enea.it), which requires compiling a single-sheet form to access the Ecobonus, with sections and fields describing the technical aspects and occurred expenses, for all theeligible actions. The procedure automatically calculates energy savings for the most common actions implemented individually and in a single housing unit, in order to help users when they are not obliged to apply to a technician (windows replacement, installation of solar panels to produce domestic hot water, replacement of conventional boilers with heat pump boilers, replacement of heat pumps with condensing hot air generators or with high-efficiency heat pumps, and installing a biomass heating system) [176]. Investments and energy savings achieved in 2017 by technology are shown in **Table 14**: in terms of achieved energy savings, the main contribution derives from the replacement of windows and shutters (584 GWh/year on over 1,300), while over a quarter of savings was achieved thanks to interventions on walls, slabs and roofs (about 350 GWh/year).

Table 14. Ecobonus: investments (M€) and energy savings (GWh/year) by technology, 2017. Source: ENEA.

Year	2017		2017	
Technology/action	M€	%	GWh/y	%
Walls	384.6	10.3%	146.6	11.3
Slabs and roofs	412.3	11.1%	193.6	14.9
Windows and shutters	1,736.4	46.6%	583.8	44.9
Solar thermal	50.3	1.4%	36.6	2.8
Solar shading	183.9	4.9%	25.6	2.0
Condensing boilers	633.5	17.0%	223.2	17.1
Geothermal plants	3.1	0.1%	0.5	0.0
Heat pumps	234.8	6.3%	61.3	4.7
Building automation	20.3	0.5%	10.1	0.8
Other	64.4	1.7%	20.0	1.5
Total	3,723.7	100%	1,301	100

The Guidelines for Energy Performance Contracts (EPC) for the buildings of the public administration,developed by ENEA, are intended to provide public administrators with a tool to support and guide the drafting of energy performance contracts specific to the individual project, consistent with the latest legislation, such as Legislative Decree 50/2016 (New Code of Public Contracts), Ministerial Decree 11 October 2017 concerning the Minimum Environmental Criteria of the assignment ofdesign and works services, the EUROSTAT and ANAC guidelines, and implementing decrees of the Ministry of Infrastructure and Transport.

From a technical point of view, the energy audit plays a fundamental role both in the design phase and in the management and control phase of the Energy Performance Service: the Guidelines provide that its drafting is the responsibility of the public administration so that it can be aware of the energy status and the potential for improvement of its buildings, and so it can therefore make an unhurried decision in terms of the technical and financial convenience of the projects to improve the building's performance, which represents the fundamental of the contract, to be determined before, after and during the execution of the contract, referring to the actual use of the building and the climatic conditions of the location.

The Decree 26 June 2015 “Minimum requirements” sets performance requirements for primary energy for new buildings or those subject to major renovation that are more stringent by 15% compared to the previous standards and will be progressively stricter in 2017, 2019, and 2021. The Decree established the characteristics of a Nearly Zero Energy Building (NZEB). The Italian NZEB standard requires compliance with other minimum requirements in addition to the overall limit on primary energy consumption: useful thermal performance indexes, to be compared with the limit values of the reference building, the overall average heat transmission transfer coefficient, theequivalent summer solar area per unit of useful area, the performance of the winter and summer air conditioning systems and the production of domestic hot water, the limits on the transmittances of the dispersing elements.

In 2017, ENEA launched a national NZEB Observatory that allowed statistics on the number and type of NZEBs, information on regional policies, public and private initiatives for information and training and the state of research in the sector. From an initial estimate, based on the data of NZEB buildings with an Energy Performance Certificate (called APE in Italy) in a sample of regions (Lombardia, Piemonte, Abruzzo, Marche), the Italian NZEBs (according to the 2015 standards) in 2016-2017 period are approximately 600, mainly new (80%) and residential buildings (88%). Despite the still limited number, there is a rapid increase in NZEBs, also due to the even more stringent obligations imposed in advance concerning the deadlines of 2019 and 2021 [177].

5.6. Energy Efficiency Policies in France

In France, the first thermal building code (RT) was implemented in 1974 and has been updated and strengthened six times since then. The last update is particularly ambitious, with a maximum consumption of 50 kWh/m^2 for five end-uses. Still, three-quarters of the current building stock was built without building codes. As a result, and even with the great efforts made since the year 2000, the average performance of the building stock in terms of energy consumption per m^2 is one of the worst in Europe. Today the potential for energy savings in these older buildings is huge, while the building sector is one of the top priorities in the energy efficiency policy roadmap in the country. The specific building-related energy saving goals have been set in the Energy Transition Act of 2015: 28% reduction of final energy consumption in 2050 compared to 2012 level;

retrofit of 500,000 existing dwellings each year, of which vulnerable consumers should occupy half. The French government offers a mix of policy regulation, incentives and support targeting both residential and commercial buildings.

5.6.1. Building codes “RT 2012”-new buildings

The thermal regulation 2012 (“RT2012”) aims at specifying requirements regarding the thermal performance of new buildings. All new buildings whose building permit was lodged after January, 1st 2013 must have a primary energy consumption below a threshold of 50 kWhEP/m^2/year on an average basis (energy performance level equivalent to the ‘low consumption building’ level of labels under the previous thermal regulation, RT 2005). The threshold of 50 kWhEP/m^2/year encompasses consumption of heating, cooling, lighting, domestic hot water produced and auxiliary equipment (pumps and fans). It varies according to geographical location, altitude, nature of the use of the building, average surface area of the dwellings and greenhouse gas emissions. The law for energy & green growth (“Loi pour la transition énergétique et la croissance verte”) from August 2015 has announced the integration of GHG emitted by new buildings over their life cycle from 2018. Experimentation was launched in November 2016 to experiment a new label including both energy & environmental criteria that are called "Bâtiment à énergie positive et réduction carbone".

5.6.2. Building codes – renovation

The thermal regulation of existing buildings applies to existing residential and tertiary buildings during renovations planned by the contractor. It is based on Articles L. 111-10 and R.131-25 to R.131-28 of the Code of Construction and Housing, as well as their implementing decrees. The main goal of this regulation is to ensure a significant energy performance improvement for all buildings undergoing refurbishment. It differs depending on the size and age of the building and on the type of refurbishment implemented. Global RT (for heavy refurbishment of buildings with a surface of more than 1,000 m2), An overall performance target is set for renovated buildings built after 1948.

After work, the overall energy consumption of the building for heating stations, hot water, cooling, auxiliary and lighting should be lower than the baseline consumption of the building. This corresponds to the consumption that would have the same building for imposed performance of structures and equipment that compose it. In addition to this requirement:

- For non-residential buildings, the work should lead to a gain of 30% on energy consumption compared to the previous state;
- For housing, the regulation introduces a maximum value of consumption. The energy consumption of the renovated building for heating, cooling and hot water should indeed be less than a threshold value which depends on the type of heating and climate.

Since 1st April 2008, these buildings are also required to undergo a technical and economic feasibility study regarding the various energy supply solutions whenever implementing a renovation. This latter requirement also applies to buildings built before 1948 and undergoing a major renovation.

5.6.3. Element-by-element RT

For buildings with a surface area of less than 1 000 m^2 or buildings with a surface area of more than 1 000 m2 undergoing minor renovation, the Regulation sets a minimum performance level for replaced or installed elements. For each element that can be installed or changed, the order of May 3, 2007 gives the minimum performance criteria required. This Regulation does not, however, apply to buildings consisting of so-called 'old' ('anciennes') walls.

5.6.4. 'High energy performance - renovation' label

A label has been created for the renovation of buildings. It includes two levels for buildings for residential use:

- The 'high energy performance - renovation, HPE renovation 2009' label for renovated buildings reaching a conventional primary energy consumption* below 150 kWhEP/m^2/year on average;

- The 'low energy consumption building - renovation, BBC renovation 2009' label for renovated buildings reaching a conventional primary energy consumption* below 80 kWhEP/m^2/year on average; this label also includes a level for buildings for non-residential use, 'low consumption building - renovation, BBC renovation 2009' for building reaching a conventional primary energy consumption* 40% below reference conventional consumption.

*On the following 5 uses: heating, cooling, hot water production, lighting, ventilation.

5.7. Energy Efficient Policies in the UK

Historically, the UK has relied on building regulations, Supplier Obligations and EU Product standards to deliver energy savings in the buildings sector. The UK Building Regulations have provided a means of driving energy efficiency improvements and energy savings in homes and non-domestic buildings since building regulations were introduced in the 1970s. Energy Efficiency Obligations have been operational since 1994 (see overview section) and require domestic energy suppliers to promote and install domestic energy efficiency measures. This scheme has focused on fitting every home in the UK with a Smart Meter by 2020. The Clean Growth Strategy aims for homes to be EPC B and C by 2035. Following the coronavirus pandemic, improving energy efficiency in homes will form a core part of the UK government's economic recovery. The Green Homes Grant is a £2 billion scheme providing grants to homeowners and local government to retrofit homes. The Green Homes Grant Skills Training Competition aims to support this scheme by improving the quality and accessibility of training for the skills needed to retrofit homes.

5.7.1. Building Regulations 2016

The Department of Communities and Local Government (CLG) is responsible for making changes to the Building Regulations. They have a role in setting objectives and fair building standards; publishing statutory guidance on how to meet the Building Regulations; overseeing the building control system and statutory appeals system, and supporting the building control service and others who use the system to ensure compliance.

New homes and new non-domestic buildings are targeted by the Building Regulations. The Building Regulations 2016 (Amendment) transpose Article 8 of Directive 2014/61/EU of 15 May 2014 on measures to reduce the cost of deploying high-speed electronic communications networks, which requires that all new buildings, and buildings undergoing major renovation works, have the necessary in-building physical infrastructure to enable connections to superfast broadband. It is also a requirement, under Article 4(1) of Directive 2010/31/EU that minimum standards are reviewed at periods of not more than five years.

UK Building Regulations on energy performance have been required since the 1970s. The UK regulations due to Part L 2002, 2006, 2010 all pre-date the 2010 Energy Performance of Buildings Directive (recast), which requires Member States to set requirements for buildings, or building units are set with a view to achieving cost-optimal levels.

When building work is carried out to existing properties for which Part L of the building regulations applies, including extensions, conversions, renovation of the building envelope and replacement boilers and windows. These require new buildings to meet a minimum standard for thermal transmittance for walls, roofs, windows and doors, together with efficient heating systems. Existing buildings must meet similar standards, when extensions are planned together with standards for replacement heating systems (e.g. the requirement to fit a high efficiency condensing boiler for gas-heated homes).

5.7.2. The Green Homes Grant

To stimulate economic recovery from the coronavirus pandemic and to meet national net-zero targets, the UK government introduced the Green Homes Grant. The grant scheme is worth a total of £2 billion and provides local authorities and homeowners with funds to retrofit or renovate homes with energy-efficient and low-carbon technologies. The following energy-saving projects are covered:

1. Insulation of solid walls, cavity walls, under floors, lofts, flat roofs, room in the roof, insulating a park home,
2. Air source heat pumps
3. Ground source heat pumps
4. Hybrid heat pumps
5. Solar thermal
6. Biomass boilers

The Green Homes Grant was extended until March 2022 and will receive additional funding of £1bn.

5.8. Energy Efficient Policies in Austria

The building refurbishment programme, first implemented in 2009 and ongoing, aims at the thermal refurbishment of residential and commercial buildings that were built more than 20 years ago. The budget for granting subsidies is made available for the following measures:

- Insulation of outer walls

- Insulation of the upper ceiling and roof
- Insulation of the lower ceiling and the basement floor
- Refurbishment or replacement of windows and outer doors
- Replacement of fossil heating systems: installation of solar thermal plants, biomass boilers, heat pumps, connection to the district heating grid or local heating grid (residential buildings only)
- Installation of heat recovery systems (commercial buildings only)
- Installation of shading systems (commercial buildings only)

In the Austrian federal states, the enhancement of thermal quality of residential buildings and the expansion of efficient heating systems are supported by the funds earmarked for residential building subsidies. The level of subsidy is dependent on the achieved thermal quality and the efficiency of the heating system. In addition to requirements relating to final energy, new construction subsidies are subject to increased requirements on primary energy demand and CO_2 emissions. The nature of the support differs among the federal states and is provided in the form of loans, grants and/or subsidies. The renovation offensive of the Austrian government ("Sanierungsscheck") is the most important incentive system for households and businesses for the reduction of energy consumption. The subsidy is a unique and non-repayable grant.

In 2016, 10,100 private renovation projects and 310 projects in the business sector were submitted. The Austrian Government offered € 43.5 Mio. for the thermal refurbishment of buildings. According to the responsible ministries, from 2009 to 2015, investments of 4.2 billion Euro could be triggered with subsidies of approx. € 590 million. The average subsidy amounted to approximately 4,200 € over the last years. Final energy savings amounted to 1,9 PJ in 2014 and to 1,76 PJ in 2015. The cumulative contribution shall amount to 24 PJ between 2014 – 2020. This calculation is based on data in the annual reports by the provinces in the context of energy efficiency monitoring.

5.9. Energy Efficient Policies in Bulgaria

In Bulgaria, the current ongoing measures in the Households sector are 18, including financial, legislative and informative measures. The measures in the Households sector are mostly normative, mandatory certification of buildings, labelling of electrical appliances, energy efficiency standards for electrical appliances, procedures and rules for share distribution of heat energy in multi-family residential buildings, etc. The innovative measures in force in the sector are the financial measures. Among them is the expansion of the administrative, functional and financial capacity of the EE and RES Fund for finance of projects for utilization of renewable energy and by increasing the grant for energy efficiency measures in households. Another new measure with high impact is the National Programme for Energy Efficiency in Residential Buildings. The program aims to carry out renovation of multifamily residential buildings through the implementation of energy efficiency measures and aims to ensure better living conditions for citizens in multifamily buildings, better thermal comfort and higher quality of the living environment. Financial support is 100% grant. There are incentives for the creation of homeowners' associations within the meaning of the Law on Condominium Management to participate in this program. The financial resources of the program are 2 billion BGN to the end of 2017, and its territorial scope includes all the 265 municipalities in Bulgaria.

5.10. Cool Roof Programs and policies in Asia and South Africa

5.10.1. Cool Roof Programs and policies in India

Cool roof programs have been gaining momentum in Indian cities in the past decade. Green building rating systems such as Leadership in Energy and Environmental Design (LEED), Green Rating for Integrated Habitat Assessment (GRIHA) and the Indian Green Buildings Council (IGBC) rating systems highlight cool roofs as a key strategy in reducing the energy consumption in buildings. As awareness of cool roof concepts has grown, their usefulness in addressing thermal comfort in low-income households and for vulnerable populations has come to the forefront. Cool roof initiatives in Indian cities thus far have been tackled from a variety of angles:

- a design-led approach to drive momentum for policy change, such as in Delhi;
- a pilot project-led approach to make a case for the benefits of cool roofs as in Indore and Surat, or
- policy-led programs to drive action, as in Ahmedabad.

Other cities such as Hyderabad are also making progress towards instituting their own cool roof policies. While each approach has its advantages, a clear, comprehensive strategy is needed for sustained action and results in the city environments. While the subject of cool roofs is addressed in the national level National Building Code (NBC) and the Energy Conservation Building Code (ECBC), city governments have most strongly addressed it, often with support from local NGOs and institutional partners. Different sections of Indian cities are controlled and managed by different city, state and regional agencies.

"Cool Roofs for Cool Delhi": A Design Manual to Promote Cool Roofs - 2011

As a large metropolis and the national capital, Delhi is the site of attention and action by decision-makers. In 2011, the Bureau of Energy Efficiency commissioned Environmental Design Solutions to develop a "Cool Roofs for Cool Delhi" design manual with the support of the Delhi national capital territory government and the Shakti Sustainable Energy Foundation. The manual is structured to be a source of information for key stakeholders – decision-makers, citizens and industry – on the benefits of adopting cool roofs in buildings in Delhi. The manual describes different elements of a cool roof initiative, from materials to case studies of energy savings in buildings with cool roof techniques. The manual has a special focus on low-tech, low-cost solutions that can be applied to vulnerable communities. Through the manual, Delhi hoped to provide solutions to cities for mitigating greenhouse gas emissions through converted white cool roofs.

Indore and Surat "Cool Roof Project": Pilot Projects to Showcase Benefits of Cool Roofs

The Indian cities of Indore and Surat are among the fastest-growing cities in India. With populations of 1.9 million and 4.4 million in 2011, the two cities are expected to be impacted by growing heat stress and power demand. The city governments of Indore and Surat, with the support of TARU Leading Edge and the Rockefeller Foundation, in 2011 embarked upon a project to address the potential of cool roofs in the two cities. With buy-in from the city decision-makers and stakeholders, the program focused on displaying successes through pilot case studies on residential buildings in the two cities. The program worked to leverage these local success stories into a compelling case for a cool roof policy development process in the cities of Surat and Indore. Cost-benefit analyses of the implemented locations showed the city government, real estate developers, and technology providers the impact of cool roofs on thermal comfort for vulnerable populations in each city and ways to incorporate cool roofs into future building projects. Through a series of workshops and seminars, cool roof techniques were promoted to broader audiences, including local businesses. Covering over 100 households and 40,000 square feet in Indore and Surat, the Cool Roof Project used simple products such as lime concrete, china mosaic tiles, and broken earthen pots, helping to reduce temperatures and the associated costs of electricity and water.

Cool Roof Standards in India

Energy Conservation Building Code: The Energy Conservation Building Code, 2017 requires commercial building roofs with a minimum solar reflectance of 0.6 through the prescriptive path or whole building simulation path to prove a minimum expected reflectance of 0.6. While the ECBC does not specify cool roof requirements for different climate regions, it does state: “Roofs with slopes less than 20 degrees shall have an initial solar reflectance of no less than 0.6 and an initial emittance no less than 0.9”. Solar reflectance shall be determined in accordance with ASTM E903-96, and emittance following ASTM E408-71 (RA1996). Rating systems in India, including the Indian Green Building Council (IGBC), Leadership in Energy and Environmental Design (LEED) and the Green Rating for Integrated Habitat Assessment (GRIHA), require mandatory ECBC norms compliance as a prerequisite for buildings applying for rating [42].

Table 15. Testing Standards

	Standards
ECBC	ASTM E 903-96, ASTM E408-71 (RA 1996)
LEED India	ASTM Standard E1980-01, ASTM E 408-71 (1996) e1, ASTM E 903-96, ASTME1918-97, ASTM C1371-04, ASTM C1549-04
GRIHA	The GRIHA rating system adopts the provisions of the National Building Code 2005, the Energy Conservation Building Code 2007 announced by the Bureau of Energy Efficiency and other IS codes

5.10.2. Cool Roof Programs and policies in South Africa

In 2014, South Africa launched a multi-agency effort to address the benefits of cool roofs in the country. The South African National Energy Development Institute (SANEDI) and the Association of Architectural Aluminium Manufacturers of South Africa (AAAMSA), together with the South African Department of Energy and the U.S. Department of Energy’s Global Superior Energy Performance Partnership (GSEP) initiative, formed the South African Cool Surfaces Association (SACSA). Through interagency cooperation efforts, the South African cool surfaces program aims to:

- Develop testing systems for product compliance
- Establish a worker training initiative in cool roof technique installation
- Conduct demonstrations of cool paint on low-income houses to improve thermal comfort for residents as well as reduce energy consumption

The South African Cool Surfaces Association (SACSA)

The South African Cool Surfaces Association (SACSA) was established in 2014. SACSA is a non-profit organization that implements and communicate accurate radiative energy performance rating systems for roof and other surfaces, support research, and serve as an educational resource for information on roofing. The South African Cool Surfaces Association (SACSA) was created to develop accurate and credible methods for evaluating and labelling the solar reflectance and thermal emittance (radiative properties) of surfaces, including roofing products, and disseminate the information to all interested parties. The South African Cool Surfaces Association is a non-profit organization, administered by AAAMSA, that aims to:

- Represent the interests of industry, government and the consumer to the benefit of all
- Disseminate the information to all interested parties
- Create employment opportunities through training
- Develop accurate and credible methods for evaluating and labelling the solar reflectance and thermal emittance of roofing and other building surfaces products to:
    - Verify compliance with the National Building Regulation SANS 10400: XA Energy Usage in Buildings
    - Commercial EE Building Envelope- eligible to apply for 12L EE Tax incentive which benefits to consumers
    - Assists professionals to make informed decisions during rational design
    - Promotes energy efficiency by providing a baseline for product development and improvement – Provides performance comparison

The Cool Surfaces Project is the South African involvement and participation in and contribution to the US DOE GSEP Cool Roofs and Pavements Working Group. This initiative is a multilateral collaboration that seeks to improve building energy efficiency and comfort as well as to address urban heat and climate change.

5.10.3. Cool Roof Programs and policies in China

China surpassed the United States in 2010 to become the world's largest energy consumer and accounted for 71% of global energy consumption growth in 2011. China's energy mix is carbon-intensive, using coal to supply 71% of the 85 quadrillion BTU (90 EJ) it consumed in 2008. The U.S. Energy Information Administration predicts that China's electricity generation will increase to 10.5 trillion kW h by 2035, over triple the production in 2009. Facing challenges of energy security, global climate change, and environmental pollution, China has prioritized renewable energy and energy efficiency. In The Twelfth Five-Year Plan for National Economic and Social Development of the People's Republic of China released in July 2012, the government set year-2015 targets of reducing energy consumption per unit per-capita GDP by 16%, CO_2 emission per unit per-capita GDP by 17%, national emission of SO_2 by 8%, and national emission of NO_x by 10%, all relative to year2010 levels. Improving building energy efficiency is an important element of the government's strategy for saving energy. In 2008, Chinese buildings consumed 655 Mtce (million tonnes coal equivalent), accounting for about 23% of national energy use. Air conditioning was responsible for 11% of annual energy use in residential buildings in 2008, and 19% of annual energy use in public buildings in 2005. One way to raise building energy efficiency is to select a ‘cool’ roof with high solar reflectance (ability to reflect sunlight, spectrum 0.3–2.5 mm) and high thermal emittance (ability to emit thermal radiation, spectrum 4–80 mm). By minimizing solar absorption and maximizing net thermal emission, such a roof stays cooler under the sun, reducing heat flow into the building (Levinson et al., 2005). A cool roof on an air-conditioned building can save energy and reduce power-plant emissions of CO2, SO2, and NOx, while a cool roof on an unconditioned building can lower indoor air temperature and improve indoor comfort.

Building construction in China's urban areas has surged over the past decade, increasing building stock floor area to 20.4 billion m^2 by 2008. This presents many opportunities to specify and apply the climate-appropriate use of energy-saving cool roofing products when roof waterproofing is first installed, and when it is replaced at the end of its 10–20 year service life. In 2010, the United States Department of Energy (DOE) and China's Ministry of Housing and Urban-Rural Development (MOHURD) formed the U.S.-China Cool Roof Working Group to evaluate the potential benefits of cool roofs in China. In 2011, Lawrence Berkeley National Laboratory (Berkeley, California, USA) partnered with Chongqing University (Chongqing) and the Guangdong Provincial Academy of Building Research (Guangzhou) to further investigate cool roof science and policies within the U.S.-China Clean Energy Research Center Building Energy Efficiency (CERC-BEE) Consortium [119].

U.S.-China Clean Energy Research Center Building Energy Efficiency (CERC-BEE)

The U.S. – China Clean Energy Research Center Building Energy Efficiency Consortium (CERC-BEE) was initiated between the United States and China and formally established by protocol between the U.S. Department of Energy and Chinese Ministry of Science and Technology in 2009.

Achievements include improved energy efficiency in new and existing buildings, reduced greenhouse gas emissions, increased indoor comfort, and reduced stress on the electric grid. CERC-BEE teams include U.S. national laboratories, U.S. and Chinese universities, research institutes, and industry partners. Lawrence Berkeley National Laboratory leads the U.S. participation in the program.

Share projects in China

Through more than a dozen high-visibility, cost-shared projects, we are conducting research and development on building energy efficiency (BEE) technologies and strategies in the United States and China that will be applicable worldwide. As new construction proceeds around the globe, collaborative BEE research efforts are helping to lock in the tremendous potential energy savings for the long term. In equal amounts, U.S. funds will be used exclusively to support work conducted by U.S. institutions and individuals, and Chinese funds will support work conducted by Chinese institutions and researchers. Together with the U.S. and Chinese research-industry teams:

- Focus on real-world impact through the early commercialization of technologies and by developing intellectual property, software, tools, guidebooks, codes, policies, and more
- Bring new technologies to market
- Create a sustainable platform and build lasting partnerships

- Cover the whole business model by involving various stakeholders such as government, academia, and the private sectorCool Roof Programs and policies in Japan

5.10.4. Cool Roof Programs and policies in Japan

Since 2000, the City of Tokyo has been taking measures to mitigate the impacts of the urban heat island effect, including covering roofs and walls with greenery in order to lower the surface temperature of buildings. To further these efforts, the Tokyo Metropolitan Government passed the Nature Conservation Ordinance in 2001, requiring the greening of building roofs and walls and ground-level greenings for all new construction and existing buildings undergoing renovations. According to the Nature Conservation Ordinance, greening areas must be provided on the premises and on rooftops when buildings are newly constructed, repaired or extended to an area larger than 1,000 m2 for private facilities and 250 m2 for public facilities. Plans must also be submitted to include rooftop greenery for new construction with a total floor area exceeding 10,000 m^2.

The first stage of the Nature Conservation Ordinance required 20% green coverage for buildings with a gross floor area of over 1,000 m2. In 2009, the ordinance was further strengthened by requiring buildings over 5,000m2 to provide 25% green coverage; buildings between 1,000 – 5,000 m^2 are still required to continue to meet 20% green coverage. To popularize the Ordinance, the City of Tokyo conducted media outreach and advertised the conservation ordinance and compliance requirements widely and has played a leading role in keeping public awareness high. [48]

5.11. Global Pilot Programs which forward cool roofs

Pilot programmes worldwide are summarised in the following table.

Table 16 programmes worldwide

Country	Name	Short Description
South Africa	Cool Roofs	This project is aimed at scaling cool roof solutions in RDP (government subsidised) homes throughout South Africa. In each municipality selected, the team intend to deploy at least 25,000 square metres of cool roofing and spread awareness of the benefits of cool roofs among the communities. Working with a professional labour management company, SANEDI will train unemployed local residents to apply the specialised coating in their communities.
Niger	COROPIN	This project is designed to stimulate the private sector and create a market for cool roof solutions and products in Niger while raising awareness and fostering demand for cool roofing solutions.
Cote d'Ivoire	Cool Roof Transform Project	It is led by Social Tech in partnership with MonArtisan. The team will mobilise schools and the surrounding communities to recycle plastic waste and sell it to recyclers, thereby generating the funds to deploy cool roofing. They will then tap into MonArtisan's network of painters to apply the coating. The team aim to fund the first 40,000 sqm of cool roofing as a demonstrator project, with the remaining 60% financed by the income generated from the recycling.
Senegal	Cool Roofers	This project is aimed at deploying highly reflective paint to roofs in households and public buildings in low-income neighbourhoods in Dakar. The initial pilot project aimed at coating five buildings will kick off a more comprehensive strategy of technology transfer, training and support to local partners, eventually scaling to 50 buildings in the locality
Mexico	Cool Means	The team aim to deliver access to cooling in low-income households in Mexico by integrating commercial paints in the standard housing designs of Echale and New Story. The project will begin with a pilot building to identify and test material supplies, prototype installation methodologies, deliver preliminary training and collect data to validate performance predicted with the simulation tools.
Bangladesh	Cool to be Cool	The team aim to conduct a randomised controlled trial comparing three different strategies for reducing indoor temperature in low-income households in Dhaka, including indigenous insulating materials such as dense coir and bamboo mats. This will use a mixed-method approach, with community engagement and focus group discussions supplementing the quantitative testing.
Rwanda	Cooling Rwanda 2020	This project is designed to alleviate cooling challenges in Kigali and beyond, beginning with a number of demonstrator projects and awareness campaigns in homes and a variety of government, commercial, and public buildings.
Indonesia	Cool Roofs Tangerang	The team will run a pilot project deploying cool roof materials on six residential, community and public buildings in the Tangerang municipality of Indonesia. This benchmark project will then be replicated in other municipalities and cities within Indonesia to achieve 1 million square metre coverage

Philippines	Sumasalamin Sa Sun	The aim of this initiative is to test a business model for providing services to paint corrugated metal roofs in the Philippines with a high-quality reflective coating.
Kenya	Topps Seal Coating to Create Reflective Roof Surfaces	The project will focus on recruiting and training young people to carry out pilot cool roof projects on key community buildings such as schools and medical clinics. They then plan to scale the project across the country through partnerships with NGOs, national and county-level governments.

6. Performance Assessment and Testing

6.1. Performance assessment and testing in North America

6.1.1. Cool Roof Rating Council Overview

In 1998, the Cool Roof Rating Council (CRRC) was established to develop accurate and credible methods for evaluating and labelling the solar reflectance and thermal emittance (radiative properties) of roofing products sold in the United States and to disseminate the information to all interested parties. Many of the required tests by the CRRC rely on standards or protocols promulgated by ASTM International (www.astm.org), International Standard Organization (ISO) and the American National Standards Institute (ANSI) (www.ansi.org) and are articulated in the ANSI S100 Standard [168,178]. The actual testing protocol and calibration of the apparatus are set forth in standards promulgated by the International Organization for Standardization (www.iso.org), American Nation Standards Institute (http://www.ansi.org) and the International Electrotechnical Commission (www.iec.ch).

Cool surface testing is an interconnected system of public and private stakeholders that allows for accurate and reliable testing of roofing materials according to local requirements and standards. These stakeholders include:

- Accredited Independent Testing Laboratories (AITLs)– facilities that test the radiative properties of roofing materials. In some cases, these labs may also perform aging and weathering tests.
- Test Farms – facilities where product samples are installed outside and monitored over months or years to determine changes in radiative properties resulting from exposure (i.e., aged ratings).
- Laboratory Accreditation Bodies – agencies or organizations that evaluate lab procedures, staff, and equipment to ensure proper protocols and standards;
- Standards Organizations – national and international bodies that publish standards and facilitate the process for establishing and modifying those standards over time.
- Code bodies – local, regional, and national bodies that adopt requirements for building safety, energy use, and/or sustainability.

Establishing an independent, non-profit, certification governing body, in this case, the CRRC is important to oversee and manage the testing and certification process, update procedures, validate and verify the accuracy of results from testing laboratories and weathering facilities, maintain databases of product testing results, and produce the results and labels for product packaging. The CRRC is a collection of manufacturers, suppliers, testing laboratories, and advocacy groups, including consumer interests, governmental organizations and educational institutions. This membership diversity is reflected in the CRRC Board of Directors, a balanced and representative mix of all types of participants (e.g., manufacturers, testing laboratories, consumer groups, research institutions, technical experts, and policy groups). One of the primary roles of the CRRC is to develop policies and manage a uniform program for the certification and labelling of cool roof products and maintain a publicly accessible database of all certified products for the public to access.

6.1.2. Responsibilities of the Certification Governing Body

The CRRC establishes an effective testing and certification regime by conducting the following activities:

1. Selecting cool surface product attributes for testing and certification (e.g., solar reflectance and thermal emittance)
2. Ensuring that cool surface products are produced with consistent quality and meet the certified performance requirements;
3. Create a process to label products for the marketplace.

Each of these activities is described in more detail below.

6.1.3. Selecting Cool Roof Product Attributes for Performance Testing and Certification

While the CRRC is primarily interested in the testing and certification program for radiative properties of roofing materials, governing bodies in other regions may also include:

- The water infiltration performance of a cool roof is a measure of the resistance; under standard condition, a cool roof product can resist before failing.
- Scratch resistance of the cool roof surface
- Fire resistance of the cool coating and surfaces
- Elasticity of the cool roof product membrane to account for seasonal expansion and contraction due to thermal temperature cycling.

The CRRC considered several program details in consultation with industry, building science experts, and other stakeholders including:

- How long can the test results be used for certification, and thus how often does a manufacturer need to retest and recertify cool roof products?
- What physical changes to a cool roof product can be made without triggering the need for retesting?
- How will test results be reported for each attribute including units (e.g., SI or IP), the number of decimal places reported, and where and what order the attributes are listed on a label?
- Are the attributes and the metrics for those attributes appropriate for all of the use cases and climatic conditions in the jurisdiction covered by the testing entity?
- What exact equipment will be needed by testing labs, and is there a straightforward and unambiguous process for a testing laboratory to acquire and set up test apparatus, to calibrate testing equipment and conduct the tests efficiently across a number of cool roof products (multiple product types in market place, paints, membranes, shingles, tiles and etc.) from multiple manufacturers?
- What is the cost for testing and certification and how does that impact the price of the end product to the consumer? Could that cost be passed along from all manufacturers to the consumer? If so, are the costs comparable across all manufacturers?

- Are there international standards, experience and examples that can be drawn upon for establishing the attributes and the testing protocols, and is this experience applicable to the economy?

6.1.4. The Role of Testing Laboratories and Test Farms

While the CRRC establishes and manages the testing program, the actual testing is undertaken by Accredited Independent Testing Laboratories (AITL) and Approved Test Farms. An AITL is a testing laboratory that is accredited3 for compliance with ISO/IEC Standard 17025 to test roofing products and is completely independent of any roofing product manufacturer or roofing product seller.

Round Robin Testing

As part of ongoing compliance with accreditation, AITLs and Testing Farms are provided with prepared test samples from the CRRC, without advanced notice, and shall test and report the findings on those samples to the CRRC in accordance to set criteria. The intent of the periodic evaluation is to ensure consistency and competency of the testing laboratory by evaluating the test results against pre-determined test results of those same samples. The CRRC notifies the testing laboratory of the results at the completion of each test and of any corrective actions that may be necessary.

Weathering Tests

Weathering farms should be accredited for compliance with ISO/IEC Standard 17025 to weather and test roofing products and shall be independent of any roofing product manufacturer or roofing product seller. Accredited Independent Testing Laboratories are also responsible for reporting radiative properties' results after a period of aging and weathering outdoors (often referred to as aged radiative properties). Age testing is done at an approved test farm which AITL may operate. Such a program helps evaluate the performance of a material under normal usage conditions. AITLs forward product samples for weathering exposure directly to approved test farms after testing for initial radiative properties. After testing samples for aged radiative properties, AITLs are responsible for holding weathered product samples for 90 days or until aged radiative properties are approved by the organization. AITLs must use the most current test method applicable to the roofing product type for measuring the solar reflectance and thermal emittance of aged products.

6.1.5. Specific Requirements for Accredited Independent Testing Laboratories

The CRRC has the responsibility of selecting which AITL's are included in the program based on the lab's ability to demonstrate certification under either ISO-17025 or ISO25 through submission of the following information:

- Evidence of certification by an accrediting entity listed by the Governing Body as complying with ISO Guide 58. This list should be published by the organization for public access.
- A listing of test methods that the accrediting entity has found the AITL capable of performing. The AITL may only use such tests for the purpose of this certification Program.

[3] Accredited is defined as achieving third-party evaluation accreditation by an organization that is itself accredited to ISO 17011.

- An AITL must provide a statement of independence that shows it has no significant ownership or commercial interest in a supplier or roofing product company and is not owned by such a company.

6.1.6. Specific Requirements for Test Farms

In order to participate in the CRRC program, a test farm must meet the following criteria:

- demonstrate certification under ISO 17025.
- have exposure farms at locations as specified by the CRRC. Generally, these are chosen to reflect the range of climatic and exposure conditions that roofing materials would likely be installed in. In the U.S., this includes a hot/dry region, a hot/humid region, and a cool/urban location.
- produce a list of exposure methods that an accrediting body has found the Test Farm capable of performing.
- provide a statement that shows it has no significant ownership or commercial interest in a supplier or roofing product company and is not owned by such a company.

6.1.7. Ensuring that cool surface products are produced with consistent quality and meet the certified performance requirements

The second key task of the CRRC is to ensure that products tested by the program are of consistent quality to meet the performance requirements. The CRRC works with the AITLs and Test Farms to ensure quality control and undertake random testing of products already rated by the program.

Quality Control

All quality control records and the quality control plan are made available to the CRRC upon written request. Cool roof product manufacturers and sellers should have an appropriate quality control plan in place that ensures their roofing products maintain the radiative properties at or above the values they received from the certification program. A manufacturer should designate at least one employee as quality control manager at each plant and shall provide the certification governing body with each of these individuals' name and contact information to the CRRC.

Random Testing of Rated Products

The CRRC periodically selects roofing products it has rated, obtain them from the marketplace or from the point of manufacturing, and have them tested by an AITL. Products are considered to fail periodic testing if the tested radiative properties from the accredited testing laboratory are more than 0.05 lower than the certified radiative properties. The CRRC will not request samples more frequently than once a year unless a product fails the first test and must be retested.

6.1.8. Create a process to label products for the marketplace

A third key role for the CRRC is to create and maintain a means for educating the market on the test results for each product – primarily through the use of a visible label on product packaging. Labelling helps inform the marketplace and also facilitates the inclusion of radiative properties into building codes, voluntary programs, and incentives. Visible certification showing that a credible laboratory verified the product met established attributes provides purchasers of cool roofs with important assurances about their investment in energy-efficient products. An example from the U.S. Cool Roof Rating Council and European Cool Roofs Council are shown in **Figure 19**.

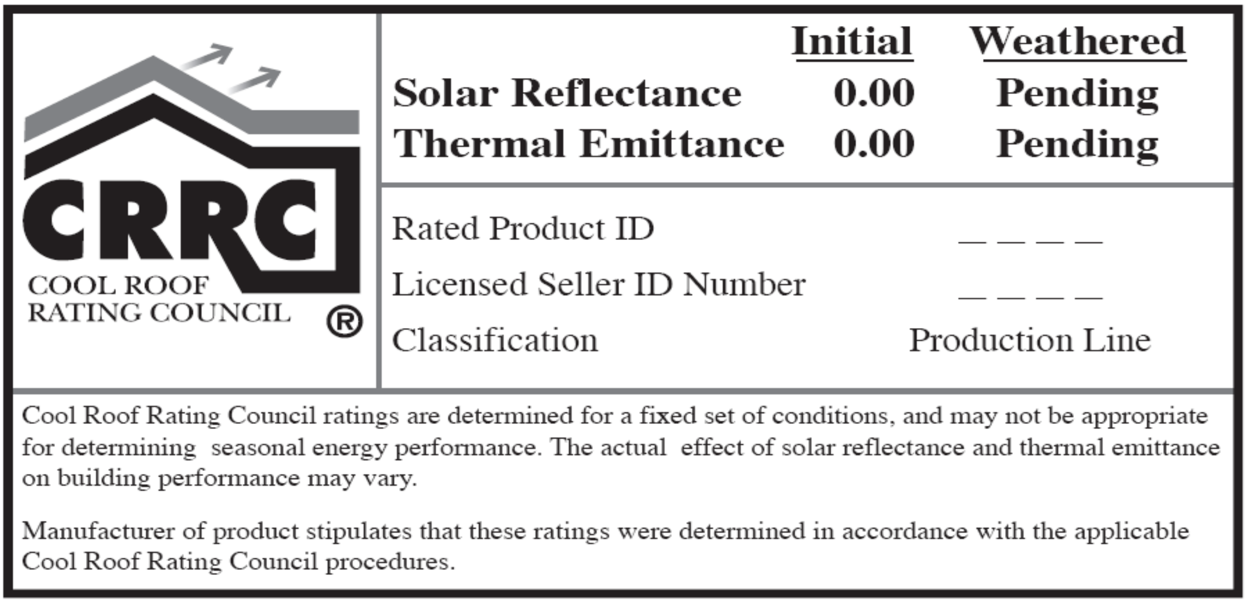


Figure 19 Sample CRRC product label. Source: CRRC

Labels include the manufacturer, model number and the results of the tests for the selected attributes in units familiar to the consumer. It also includes enough detail to trace the original certification that indicates the standard which the product was tested, a name (to provide traceability), the manufacturing facility, the performance level achieved, the series or model name of the product and other information pertinent to that product. The label information should match the data in the CRRC certified products database. The CRRC provides the template for the labels to the manufacturer with guidance on when, where, and how long it is to be affixed.

6.2. Performance assessment and monitoring in EU – ECRC Testing and accreditation framework & infrastructure

This section will describe the methods and standards used for assessing the performance of cool roofs with a focus on the EU. A critical review of available standards for the measurement of solar reflectance and infrared emittance will be presented. Practices and standards for assessing the long term performance of cool roofs will be documented, and their limitations will be discussed. The main features of the European Cool Roofs Council's Product Rating Program will be reported. The focus will be given on ECRC Testing and accreditation framework

& infrastructure. The problems encountered in the framework of the development process of the ECRC Product Rating Program and the key factors that affected the decisions made by the ECRC on the above-mentioned issues will be discussed.

6.2.1. Measurement methods of cool roofs radiative properties

Here, the most commonly used rating techniques for cool roofing materials are presented. There are several methods for measuring the solar reflectance and the infrared emittance of a surface. This section focuses on the techniques adopted by the European Cool Roofs Council (ECRC) and are described by specific technical standards.

Methods to measure solar reflectance

Solar reflectance, depending on the material and the specific application, can be measured using a spectrophotometer, a reflectometer and a pyranometer.

a) Spectrophotometer with an integrating sphere

The first method involves the use of a spectrophotometer equipped with an integrating sphere. This method is used for measuring the total spectral hemispherical reflectance, as the integrating sphere collects both specular and diffuse radiation, for a small area (approximately 0.1 cm2) of a flat and uniform test sample, over the spectral range of approximately 250 to 2500 nm. European laboratories most commonly use spectrophotometric methods. Good practice procedures for the spectrophotometric measurement of the optical properties of materials are defined by ASTM E903, which is the standard adopted by the ECRC and the US Cool Roof Rating Council (CRRC), and other technical standards such as EN14500, CIE130 and ASHRAE74.

The solar reflectance can be calculated from the spectral values of reflectivity by weighted-averaging, using a standard solar spectrum as the weighting function. The ASTME903 [179] standard specifies that the air mass 1.5 beam-normal solar spectral irradiance described in ASTM E891-87 is used. ASTM has replaced this standard with ASTMG159, which is replaced by ASTM G173. Irradiance standard data are also tabled in ISO 9050 and EN 410 [180]. Levinson et al. [181] a clear-sky Air Mass 1 Global Horizontal spectral irradiance (AM1GHwas evaluated under the atmospheric conditions specified in ASTM G173. When used to calculate solar reflectance, it better predicts solar heat gain and cool roofs' energy savings.

The choice of the standard solar irradiance spectrum is very important as it can lead to differences in the determination of the solar reflectance of cool roofing materials, especially for spectrally selective materials (e.g. NIR reflective materials). This can be explained if we examine the spectral characteristics of the different spectra. The NIR solar irradiance (700-2500nm) as calculated for the ASTM E891 is by 8.6% higher than that of the EN410 standard, which explains the differences observed between the solar reflectance values calculated with the two standards and the fact that a higher difference is observed for the NIR reflective samples [182]. These differences contribute to the measurement method's total uncertainty, indicating that the use of a single solar spectrum would provide comparable and “fair” results in the framework of a product rating programme [182].

b) Reflectometer

Measurement of solar reflectance with a portable solar reflectometer involves the measurement of the reflectance of a flat and uniform surface of about 2 cm^2. The portable solar reflectometer measures near normal–hemispherical reflectance by illuminating a surface with diffuse light and sensing light reflected at near-normal incidence. The measurement procedure is described in ASTMC1549. In Europe, the use of portable reflectometer methods for measuring solar reflectance is not widespread apart from their use in the measurement of colour (Hutchins, 2009).

c) Pyranometer

For in situ measurements (large surfaces, roofs) of the solar reflectance, a pyranometer can be used. The procedure is described in ASTM E1918 and requires mounting the pyranometer on an arm and a stand that places the sensor at the height of 50 cm above the surface to minimize the effect of the shadow on measured reflected radiation. A critical review of the above-mentioned methods to measure solar reflectance can be found in Levinson et al. [183]. For flat but non-uniform (heterogeneous) samples, statistical methods are needed in order to determine the solar reflectance. The CRRC-1 Test Method #1 proposed by the US Cool Roof Rating Council uses a Portable Solar Reflectometer and requires multiple measurements at different locations on a single sample. The mean solar reflectance of the test surface is determined by averaging the solar reflectances of these randomly located spots. With this method, for samples with a high degree of variation in the solar reflectance, the convergence rate is slower than typical variegated materials and requires a large sample size to estimate the solar reflectance with the required accuracy. Hooshangi et al. [184] proposed a Modified Monte Carlo (MMC) method that can increase the convergence rate to estimate the mean solar reflectance. Additionally, for rough and/or non-uniform surfaces, the ASTM E1918 method using a pyranometer can be used with a square or round 10 m^2 sample surface. Akbari et al. [185] proposed a method (variant to ASTME1918) to estimate the solar reflectance of low and high-profiled tile assemblies of about 1 m^2 using a pyranometer and a pair of black and white masks.

Moreover, Synnefa et al. [182] conducted interlaboratory testing aiming at investigating the suitability of different measurement methods and standards in determining the radiative properties of roofing materials. The regression analysis performed on the results showed a strong correlation between the SR determined by a spectrophotometer (ASTM E903) and a reflectometer (ASTM C1549). A strong correlation was also found between the determination of SR with a spectrophotometer with a large diameter integrating sphere and by both reflectometers (ASTM C1549) and spectrophotometers with a small diameter integrating sphere.

Methods to measure infrared emittance

a) Emissometer

The infrared emittance of a surface can be determined by using a portable device (emissometer) that measures the hemispherical emittance in the range of 5-80 μm, approximately. This procedure is described in ASTM C1371. This instrument is best suitable for measurements of opaque, highly thermally conductive materials near room temperature and provides an estimate of the thermal emittance of a surface with an accuracy of 0.02. Several techniques can be used in order to determine the infrared emittance of samples with low conductivity or in situ measurements etc., (Devices and Services). In Europe, another emissometer (TIR100-2, Inglass) that measures the total directional emissivity of nearly any surface is also used by some laboratories. The TIR100 technique is mentioned as the 'TIR principle' in the European Norm EN 16012. Finally, another European standard for the measurement of infrared emittance is EN1596.

b) FTIR Spectrometer techniques

In addition to these methods and standards that are suitable for measuring an average infrared emittance, there are other techniques and instruments such as Fourier Transfer Infra-Red (FTIR) spectroscopy that provides a detailed spectral measurement of the emittance as a function of wavelength, λ in the of 2.5 – 100 μm. They come mainly from the glass industry and the blinds and shutters industry (e.g. EN 12898).

Several factors cause uncertainty in the measurement of emissivity, such as the sample temperature and surface geometry, which affect the measurement. Synnefa et al. (2013) have found that the ASTM C1371 and EN15976 standards give comparable results (r^2=0.991) for infrared emittance of flat roof products.

Solar Reflectance Index calculation

The Solar Reflectance Index (SRI), an index that combines both solar reflectance and infrared emittance in a single value, indicates how "cool" a material is. It measures the relative Ts of a surface with respect to the standard white (reflectivity 5%, emittance 90%) and standard black (reflectivity 80%, emittance 90%) under the standard solar and ambient conditions. The calculation of this index is based on a set of equations (ASTM 1980E-01) that require values of solar reflectance and infrared emittance for specific environmental conditions. The SRI has a value of zero (for the standard black surface) and of 100 (for the standard white surface) and is calculated as follows:

$$\text{SRI} = \frac{Tblack - Tsurface}{Tblack - Twhite} x100$$

where Tblack, Twhite and Tsurface are the steady-state temperatures of the standard black, white and material surface, respectively. SRI calculators have been developed and available online (LBNL Heat Island Group SRI calculator excel sheet).

A European standard for calculating the SRI has been recently developed (EN 17190) by CEN, the European Committee for Standardization, one of the official European Standardization Organizations, with the assistance of the ECRC that participated in the corresponding CEN technical Committee as liaison organization. The standard presents a calculation method of the Solar Reflectance Index and the determination of solar reflectivity and thermal emissivity, referring to the ASTM standards commonly used for cool roof radiative properties determination. Having a European Standard for the determination of SRI was an important step in promoting cool roofs in Europe.

6.2.2. Assessment of the ageing of cool materials

The most commonly used experimental procedures for determining the ageing of roofing materials properties consist of the following exposure methods [186]:

a) Natural weathering:

It consists of exposing samples to outdoor ambient conditions (direct sunlight and other weather elements). There are a number of exposure sites (weathering farms) around the world, representing different climatic conditions, which can be used for the purpose of assessing the exterior durability of materials. Exposure specifications (e.g. angle and orientation of exposure) and environmental conditions (ambient weather, air pollution, solar radiation etc.) should be monitored reported as they affect the results significantly. The duration of exposure for roofing materials is usually three years. There are several standards related to materials' natural weathering, such as ASTM G7, ISO 877, ISO 2810.

b) Artificial weathering:

This type of weathering tests are used to accelerate the degradation and study the material's behaviour under controlled environmental conditions in the lab and in a reasonably fast time. There is a large number of commercial artificial weathering acceleration procedures available involving the use of light sources, e.g. UV lamps or filtered xenon arc lamps, to simulate the effect of sunlight. Temperature monitoring and control are performed by a black panel temperature sensor that controls the specimen's surface temperature and simultaneously by the chamber air temperature control to determine the specimen temperature. The effects of outdoor moisture are simulated by direct, pure water spray and by relative humidity control. Some commonly used standards for artificial weathering are ISO11341 and ASTM G155 - 13. Although accelerated weathering gives results in a short time (months), it has the drawback that it does not consider soiling or biological growth that could potentially contribute to the ageing of the material when exposed to outdoor conditions.

c) Laboratory Ageing protocol that simulates 3 year natural weathering

A laboratory accelerated aging method that incorporates features of soiling and weathering has been developed in order to meet the industry's demand for a method that provides accurate ageing results in a shorter time to speed up the introduction of new and better-performing products in the market and assist in the implementation of cool roof requirements. The method consists of spraying a calibrated aqueous soiling mixture of black carbon, salts, dust and organic surrogates onto preconditioned samples of roofing materials and then exposing the soiled samples to UV radiation, heat and water in a weatherometer. Three soiling mixtures were optimized to reproduce the site-specific solar spectral reflectance features of roofing products exposed for 3 years in a hot and humid climate (Miami, Florida); a hot and dry climate (Phoenix, Arizona); and a polluted atmosphere in a temperate climate (Cleveland, Ohio). A fourth mixture was designed to reproduce the three-site average values of solar reflectance and thermal emittance attained after 3 years of natural exposure, which the Cool Roof Rating

Council (CRRC) uses to rate roofing products sold in the US. The method id found to reproduce the three-year aged values of solar reflectance in a few days (Sleiman et al., 2014). This accelerated aging method has been transformed to an ASTM standard (ASTM D7897). The US CRRC, apart from the obligatory three-year weathering at the 3 previously mentioned weathering test farms, has established the Rapid Ratings Program, which is based on the laboratory-aging practice in ASTM D7897.

A variant of the accelerated ageing lab protocol in ASTMD7897 was tested to reproduce the aging conditions in Italian urban areas (Rome and Milan) for roofing materials and façade finish coats with good results, proving that ASTM D7897 can be adapted to mimic weathering and soiling out of the U.S.A. [145].

6.2.3. ECRC Testing and accreditation framework

Overview of the ECRC Product Rating Program

The European Cool Roof Council operates a rating program for the radiative properties of roofing products. This ECRC product rating program aims to provide a uniform and credible system for rating and reporting the Radiative Properties of Roofing Products by granting them an ECRC Label, indicating one or more radiative property ratings reported by ECRC Accredited/Approved Testing Laboratory reports. In the framework of this program, Manufacturers and Sellers have the opportunity to label roofing products with the measured values of their Initial and Aged Radiative Properties. These properties are determined and verified through testing by Accredited/Approved Testing Laboratories and a process of random testing of rated products. Any roofing product can be tested as long as it is in compliance with the specifications and requirements defined in the ECRC Product Rating Manual (ECRC Product Rating Manual). The ECRC product rating program does not specify minimum or target values for any radiative property. The ECRC Product Rating Program was launched in 2016. During its 4th year of operation, the total number of rated products was 17 and in total 5 companies had their products rated (**Figure 20**).

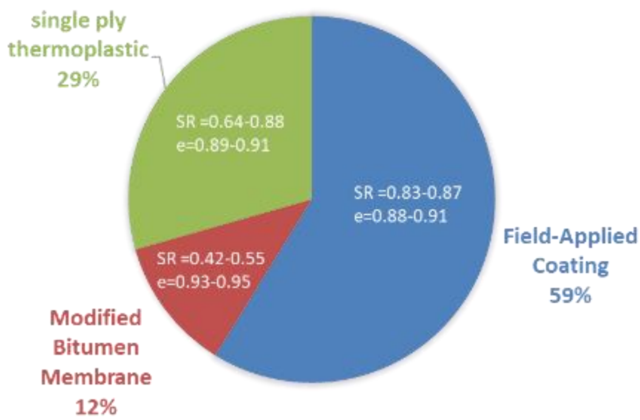


Figure 20. Distribution of product rated per roof product type

Accredited/ Approved laboratories

To get an ECRC product rating, product testing must be conducted by an accredited or approved testing laboratory participating in the ECRC Product Rating Program. Accredited laboratories must be European testing laboratories that are ISO17025 accredited to test the Radiative Properties of Roofing Products according to the procedures defined in the ECRC Product Rating Manual. In an effort to assist laboratories that do not yet have the ISO17025 accreditation to participate in the ECRC Product Rating Program, the ECRC also decided to accept the so-called “approved” laboratories. An ECRC Approved Testing Laboratory is an independent testing laboratory, that has initiated the procedures for ISO17025 accreditation for at least one of the measurement methods for determining the radiative properties of roofing materials, and it has received formal recognition by the ECRC for having demonstrated technical competency to perform specific types of tests, in accordance with the specifications and requirements described in the ECRC Product Rating Manual. The “approved” testing laboratory status is applicable only for one year and only if at a national level there is no other Accredited Laboratory to perform the specific type of measurement. Accredited or approved testing laboratories participating in the ECRC Product Rating Program receive a specific logo as displayed in the figure below.

Figure 21. Logos of the accredited and approved testing laboratories participating in the ECRC Product Rating Program

Testing procedures

For the measurement of the roof products radiative properties the following standards are accepted by the ECRC Product Rating Program:

a) Solar reflectance

- ASTM E903 - in conjunction with ASTM E891 air mass 1.5 beam normal spectrum
- ASTM C1549 for ASTM E891 air mass 1.5 beam normal
- CRRC-1 Test Method #1 (ANSI/CRRC S100) (for variegated roof products and tiles)
- Template method (ANSI/CRRC S100) (for tiles)

b) Infrared Emittance

- ASTMC1371
- EN 15976

For low conductivity materials, the Slide Method as described in the Devices &Services Technical Note TN 11-2 or TN 04-01 andTN10-2 shall be used and for profiled products according to the method described in the Devices &Services Technical Note TN 11-3

c) SRI

The SRI is calculated according to ASTME1980 for medium wind conditions.

The decision to select the specific standards for the ECRC product rating program was based on two main factors:

a) the results of the interlaboratory comparison that was conducted by the ECRC (Synnefa et al., 2013). As previously mentioned it was demonstrated that the use of different standards and different solar spectral irradiance data leads to differences in the determination of the solar reflectance value. Therefore, the use of a single solar spectrum would provide comparable and "fair" results in the framework of a product rating programme.

b) many ECRC members have their products also rated by the US CRRC. If the ECRC had adopted different standards from those accepted by the CRRC it could potentially result to the situation that the same product having different radiative values in the ECRC and the CRRC databases.

The ECRC Product Rating Manual contains all the specifications related to testing of roofing materials (standards, sample preparation specs etc.)

Status of the aged product rating

In order to assess a cool roof product's long-term performance, it is necessary to measure the aged product's radiative values. In this framework, the ECRC is currently integrating three-year natural weathering at Weathering Test Sites (WTSs) in the ECRC product rating program.

The ECRC has defined the requirements that WTSs need to fulfil, described below.

The ECRC will accept in its program companies or organizations that

a) are ISO17025 accredited (Accredited Weathering Test Sites) or

b) have initiated the process for ISO17025 accreditation(Approved Weathering Test Sites)

To conduct outdoor natural weathering exposure activities for products that are in the process of obtaining an Aged Rating, according to ECRC approved methods (ASTMG7), as defined in the ECRC Product Rating Manual. The status of Approved WTSs is only applicable for 1 year and was defined to assist WTS planning to get the ISO17025 accreditation to participate also in the ECRC Product Rating program. Weathering tests of roofing products will be conducted in three different climatic regions representing the anticipated cool roof market in Europe (**Table 17**). Details on the weathering exposure specifications are included in the ECRC

Product Rating Manual. The ECRC has identified two weathering test sites that fulfil the requirements mentioned above (**Figure 22**) and is signing agreements with them to proceed and launch its aged product rating program.

Table 17. Weathering Test Sites characteristics

Climate type	Name	General description	Average monthly temperatures (°C)	Precipitation (mm)	Solar radiation (MJ/m^2)
Csa	Mediterranean	Mild with dry hot summer	>22 during its warmest month and between 18 & −3 in the coldest month & at least four months averaging > 10	driest month < 30 - 40 & with <1/3 that of the wettest winter month.	>5000
Cfa	Humid Subtropical	Mild with no dry season, hot summer	>22 during its warmest month and between 18 & −3 in the coldest month & at least four months averaging > 10	No significant precipitation difference between seasons. No dry months in the summer.	>5000
Cfb	Marine west coast	Mild with no dry season, warm summer	>−3 °C for the coldest month & <22 for all months & at least four months averaging > 10	No significant precipitation difference between seasons	<5000

[1]Köppen climate classification

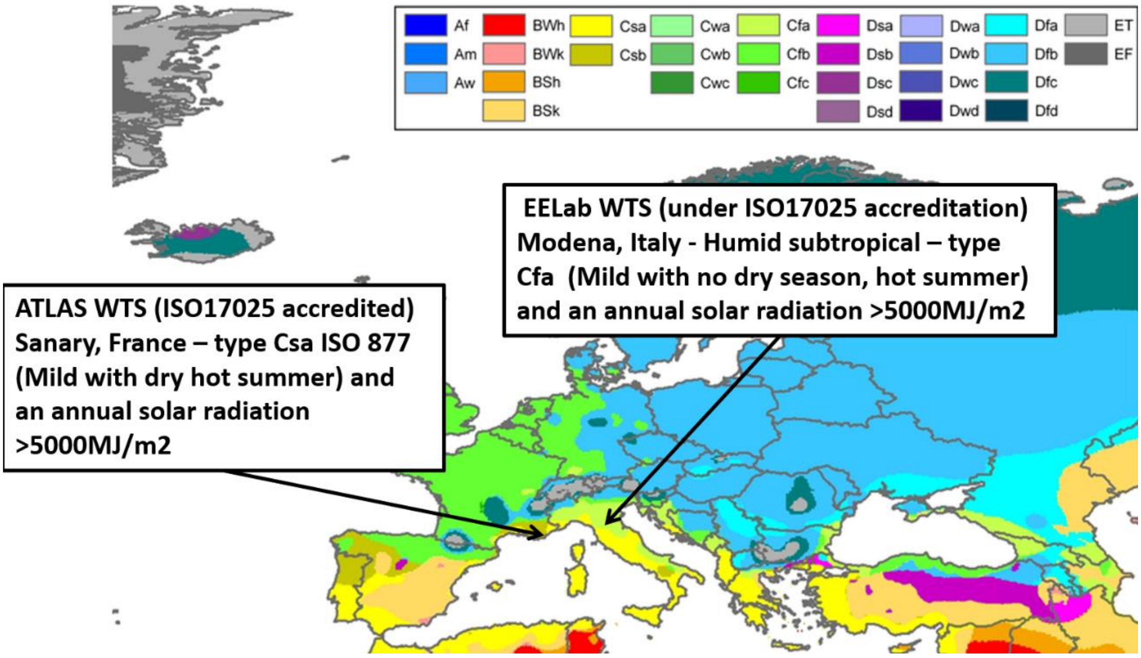


Figure 22. The European Weathering Test sites that will participate in the ECRC Product Rating Program

The ECRC has recently decided to adopt the ASTMD7897 until 3-year aged values are available based on the positive results of recent studies [145]. We are not sure if ASTM lab aged values will be representative of 3-year aged values at the 2 European WTSs and we know that Lab aged values will be different from 3-year aged ones for a product. However, this method will estimate aged radiative properties of products given that the first 3-year aged values will be available in 3 years time, and it will assist in “educating” the market that aged values are important. ISO-accredited/approved laboratories will perform the process, and it will be optional. It will not substitute 3 -year ageing, and lab aged values will be replaced once 3-year aged values are available.

Product Rating Process

The main steps of the ECRC Product Rating Process are described below:

1. The Manufacturer /Seller obtains a unique company and product identification from the ECRC
2. The Manufacturer / Seller submits the samples to be tested in an ECRC Acredited/ approved testing laboratory (ATL) according to the ECRC Product Rating Manual specifications
3. Once all measurements have been carried out, the Initial Test Results Report is sent to the Manufacturer by the lab
4. The Manufacturer /Seller submits an application to the ECRC
5. If the application is approved by the ECRC the Manufacturer will receive a Rated Product Notice and the product will be listed in the ECRC Rated Products Database and receive the Rated Product label. (3 year aged radiative values are noted as “pending”)
6. After initial rating testing, the product samples are sent by the ATL to the Weathering Test Sites (WTSs) the Manufacturer / Seller has indicated to undergo 3 year natural exposure
7. After the 3-year weathering, WTSs will remove the specimens from the exposure rack and communicate with the Manufacturer / Seller to coordinate sending the weathered product specimens to the selected ATL
8. The Manufacturer/ Seller will coordinate with the selected ATL for aged testing
9. The ATL will perform the aged testing and will return an Aged Test Results Report and Application to the Manufacturer /Seller
10. The Manufacturer / Seller will submit a completed Aged Product Rating Application and Test Results Report form to the ECRC.
11. Upon acceptance and approval of the Aged Product Rating Application, the ECRC: a. Issues an Aged Rated Product Notice in which the label and logo for the product are attached b. Uploads aged product information on the rated products database

It should be noted that until the Aged product rating program is officially launched, the ECRC implements only the Initial Rating of products, i.e. steps 1-5.

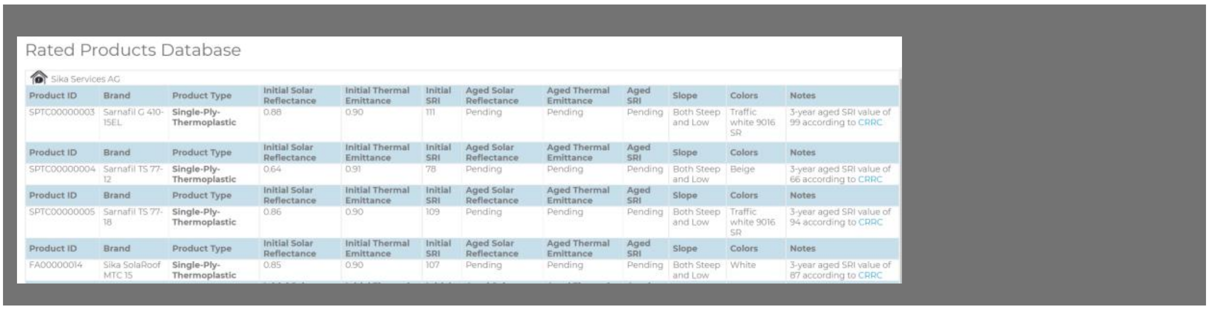
The ECRC database and Label

When the ECRC approves a Roofing Product rating, the Roofing Product will be added to the online ECRC Rated Roofing Products database, and the Manufacturer / Seller is authorized to print the ECRC product Label with its initial and aged ratings and relevant information including:

- Initial & aged* values for Solar Reflectance,
- Initial & aged* values for Infrared Emittance

- Initial & aged* values for SRI
- Manufacturers and/or Seller's name
- Rated Roofing Product ID number,
- Date of measurement at the ATL

The aged radiative property ratings and SRI values will be listed as "pending" until the three-year weathering process and aged testing is completed. The contents of the ECRC Rated Products database are shown in **Figure 23**. The ECRC rated product label is shown in **Figure 24**.



Rated Products Database

Sika Services AG

Product ID	Brand	Product Type	Initial Solar Reflectance	Initial Thermal Emittance	Initial SRI	Aged Solar Reflectance	Aged Thermal Emittance	Aged SRI	Slope	Colors	Notes
SPTC00000003	Sarnafil G 410-15EL	Single-Ply-Thermoplastic	0.88	0.90	111	Pending	Pending	Pending	Both Steep and Low	Traffic white 9016 SR	3-year aged SRI value of 99 according to CRRC
SPTC00000004	Sarnafil TS 77-12	Single-Ply-Thermoplastic	0.64	0.91	78	Pending	Pending	Pending	Both Steep and Low	Beige	3-year aged SRI value of 66 according to CRRC
SPTC00000005	Sarnafil TS 77-18	Single-Ply-Thermoplastic	0.86	0.90	109	Pending	Pending	Pending	Both Steep and Low	Traffic white 9016 SR	3-year aged SRI value of 94 according to CRRC
FA00000014	Sika SolaRoof MTC 15	Single-Ply-Thermoplastic	0.85	0.90	107	Pending	Pending	Pending	Both Steep and Low	White	3-year aged SRI value of 87 according to CRRC

Figure 23. Example of the ECRC rated products database

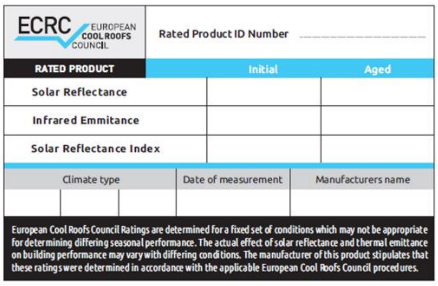


Figure 24. The ECRC rated products label

Quality Assurance procedures

The ECRC has in place two different procedures to assure the quality of its Product Rating Program:

a) Interlaboratory testing comparison (ILC) for the laboratories that participate in the ECRC Product Rating Program. It involves the measurement and reporting of the radiative properties of a set of the same samples conducted by all the laboratories, according to the procedures and specifications of the ECRC Product Rating Manual. This annual activity ensures consistency and competence of the laboratory by evaluating the test results against the other laboratory values.

b) Random testing of rated products: It consists of periodically selecting Rated Roofing Products, obtaining them from the marketplace or from the point of manufacturing, and have them tested by an ECRC Accredited or Approved testing laboratory to compare results obtained with the radiative properties in the ECRC rated products database. In cases of encountered inconsistencies, corrective actions are taken.

7. Implementation and Market Development

7.1. Implementation and Market Development in North America

7.1.1. Cool Roofs in the U.S.

Cool roof products have been available in the United States for certain categories since the early 1980s. Much of the early focus on cool roofs was an energy-efficient option for building envelopes. **Figure 25** summarizes key moments in the development of cool roof policy in the U.S. In the late 1990s, cool roofs were added as a credit option to several major energy codes, notably California Title 24 and ASHRAE 90.1. In parallel, the roofing industry, government, and code officials developed a testing, certification, and labelling regime to support the new cool roof language in the energy codes. The Cool Roof Rating Council and its operations are covered in greater detail in the next section.

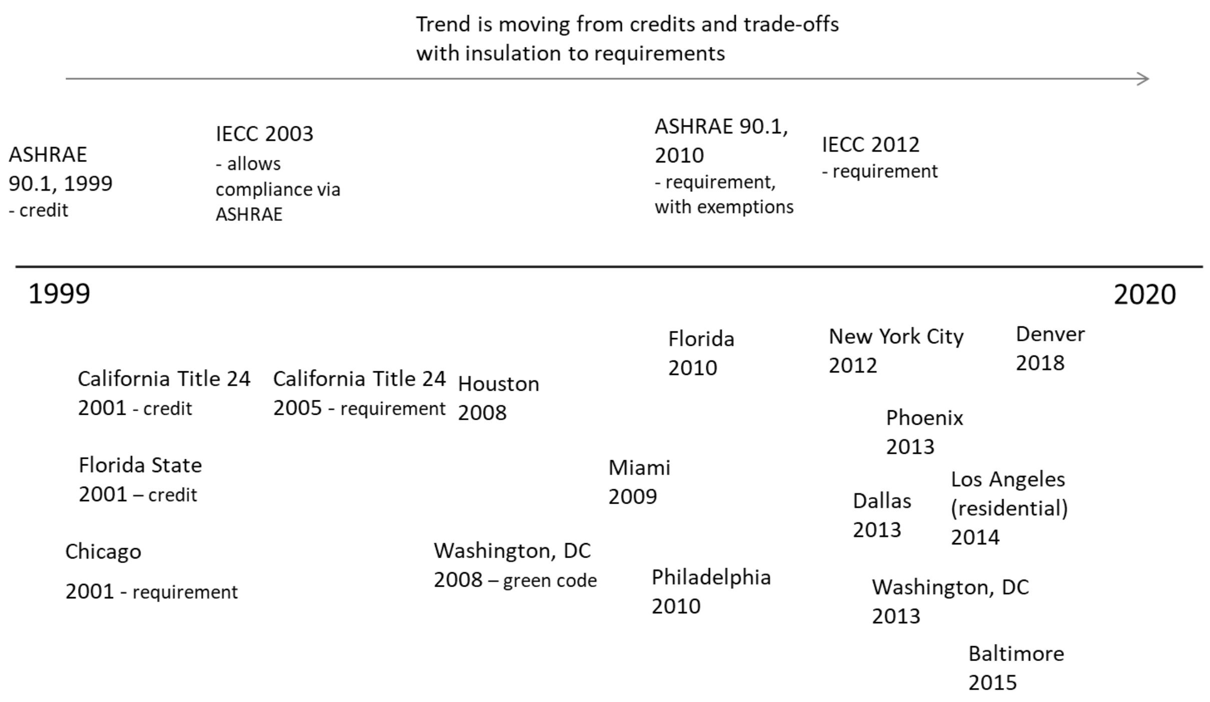


Figure 25 Key Moments in U.S. cool roof policies.

The focus on the energy efficiency benefits of cool roofs shifted slightly in 2001. Chicago, mostly considered a cold-weather town (and located in ASHRAE Climate Zone 5), had endured a catastrophic heatwave in 1995 that killed 739 people. Post-disaster analyses found that the majority of the deaths took place in neighbourhoods that lacked green space and were characterized by little ventilation and black roofs[187–189]. In response, the city adopted a requirement for cool roofs on certain buildings to help build heat resilience and potentially lower air temperatures. The recognition of the benefits of cool roofs has remained split between energy and non-energy effects, particularly when dealing with mandatory policy mechanisms. This has led to an undervaluing of the total potential beneficial impact of large-scale adoption of cool roofs in the U.S.

The adoption of cool roofs has similarly proceeded on two tracks. Increased adoption of model energy codes that require cool roofs by states and municipalities has helped drive the commercial, multi-family, and institutional markets, particularly in the Southern U.S. The increasing use of green certifications, most notably LEED, has also been beneficial for cool roof adoption, particularly among higher value building classes (e.g., Class A real estate). In some market segments like singly ply membrane products, highly solar reflective products are the majority of new installations. This is driven mainly by awareness of cool roof benefits by sophisticated facility managers and first cost parity with black roofing products.

7.2. Organization, associations and workshops in EU and Global

According to the European Cool Roofs Council - ECRC reports, the majority of the key market players claim to be aware of the cool roof technology (70%), but not all are familiar with the term “cool roofs” (57% unaware). Public buildings (47%) are seen as the most suitable application for cool roof products, followed by private residencies (26%) and mass constructions (21%). The core target audience for cool roof products is pinpointed to be architects and engineers (48%), the public administration building services (19%), homeowners (17%) and government ministries (13%).

In the EU, The CEN Workshop is a flexible working platform, open to the participation of any company or organization, inside or outside Europe, for the rapid elaboration of consensual documents. CEN Workshops offer an efficient mechanism and approach to standardization, an international environment tailor-made for the needs of organizations, where they can find a solution to their standardization and specification requirements. This concept provides a unique opportunity for any party faced with finding other market players with similar interests and developing and validating the results in an open area.

7.3. Cool Roof Coating Market and Global Production

The global cool roof coatings market size was estimated to be worth USD 3.59 billion in 2019 and is expected to register a revenue-based CAGR of 7.1% over the forecast period. The growth is attributed to the energy savings offered by this product. The rising adoption of green building codes by the emerging economies across the globe is anticipated to further fuel the demand for cool roof coatings. Rising concerns regarding rising carbon emissions and energy consumption encourage governments to implement environmentally responsible buildings. This factor is expected to create growth opportunities for the cool roof coating market in the near future.

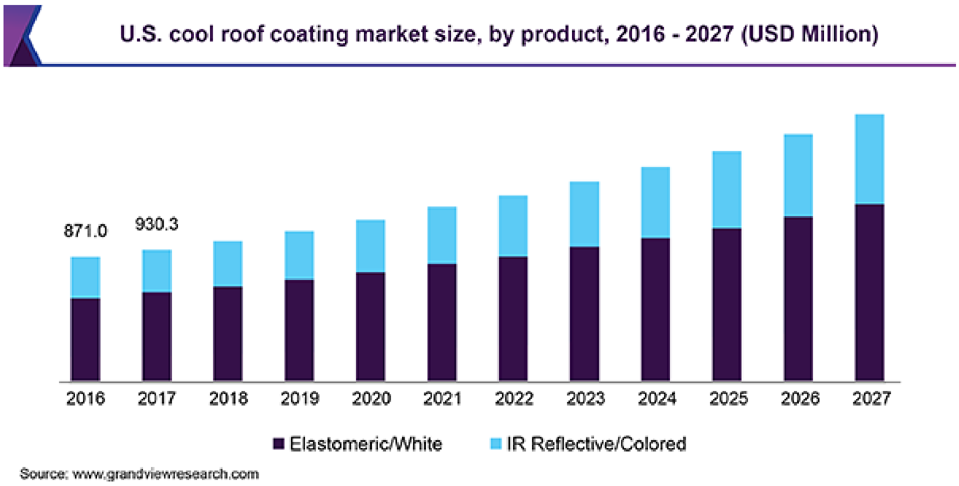


Figure 26. U.S. cool roof coating market size, by product, 2016- 2027 (USD Million)

North America held the largest market share of more than 34% in terms of revenue in 2019. Increasing awareness regarding building energy consumption, coupled with implementing the Leadership in Energy and Environmental Design (LEED) green building certification initiative, is likely to drive the regional demand for cool roof coatings.

The Asia Pacific is projected to be the fastest-growing region in the near future on account of the increasing acceptance of green building codes. The growing construction industry in the emerging economies of Asia Pacific and increased infrastructure spending by the governments of India and China are the key factors responsible for driving the product demand over the forecast period.

Recently, China launched the 13th Five-Year Plan, which includes the construction of more than 50 new civilian airports and the development of airports located in Harbin, Urumqi, Kunming, Chongqing, Shenzhen, Chengdu, and Xi'an. Similarly, the government of India launched its 100 smart cities by 2020 plan, which includes the construction of offices, residential buildings, hotels, retail, sanitation, urban transport, schools, and hospitals. These factors are expected to drive the regional product demand in the forthcoming years.

The market ecosystem includes various stakeholders involved in the supply chain of the roof coating industry, starting from raw material suppliers, research & development, and manufacturing. Post this, the marketing and sales of the products take place, which is only possible if an efficient distribution channel is developed. Finally, the end products are made available to the consumers. The global market for roof coating market is dominated by players such as BASF SE (Germany), Akzo Nobel N.V. (Netherlands), RPM International Inc. (US), PPG Industries, Inc. (US), The Sherwin-Williams Company (US), Hempel A/S (Denmark), The Dow Chemical Company (US), Wacker Chemie AG (Germany), Sika AG (Switzerland), and Nippon Paint Holdings Co., Ltd (Japan).

On the basis of type, the roof coating market is segmented into elastomeric, bituminous, acrylic, epoxy, silicone, and others, including polyvinylidene fluoride, modified silane-based coating, and polyurethane. The elastomeric segment is projected to grow at the highest CAGR from 2017 to 2022. The dominant market position of the elastomeric coating segment can be attributed to its compatibility with almost all types of roof structures. Elastomeric roof coatings have superior elastic properties and are hard-wearing in cold as well as warm areas; these coatings expand in warm weather when the roof expands and contract when the roof contracts in cold weather. Moreover, an elastomeric roof coating is resistant to fungi and mildew, which cause damage to roofs with time.

The roof coating market, by end-use sector, is segmented into residential and non-residential. The non-residential segment is further divided into commercial, hospitality, healthcare, and others. The demand for roof coating in the residential sector is minimal as compared to that in non-residential, mainly due to the lack of awareness in this market. The demand for roof coating in the non-residential sector is higher as safety concerns are greater in non-residential constructions such as hospitals and hotels.

In 2016, the North American region accounted for the largest share of the global roof coating market. However, as the roof coating market in developed countries is maturing, the Asia Pacific market, particularly the developing markets in countries such as China and India, is projected to grow at the highest rate from 2017 to 2022. The Asia Pacific is a hub for foreign investments and booming residential & non-residential construction sectors, largely due to the low-cost labour and cheap availability of land. The increase in demand for roof coating can largely be attributed to the region's rising population with high disposable incomes and the construction opportunities in this region. Moreover, increasing demand for sustainable & eco-friendly construction drives the roof coating market in the region. However, the high production cost of roof coatings is one of the major restraints that limit the growth of the market.

The global roof coating market is dominated by players such BASF SE (Germany), Akzo Nobel N.V. (Netherlands), RPM International Inc. (US), PPG Industries, Inc. (US), The Sherwin-Williams Company (US), Hempel A/S (Denmark), The Dow Chemical Company (US), Wacker Chemie AG (Germany), Sika AG (Switzerland), and Nippon Paint Holdings Co., Ltd (Japan). These players adopted various strategies such as new product launches, expansions & investments, joint ventures, and mergers & acquisitions to increase their share in the roof coating market [190].

8. Exemplar Cool Roof Installations

8.1. Market Overview: Existing Cool Roofs Installations

This chapter provides examples of Cool roof installations in Europe. These installations were made under the study of the European Cool Roof Council ECRC.

8.1.1. Mercado Central de Pescados, Merca Madrid

The fish market in the Spanish capital is a place where shopkeepers, wholesalers, restaurant chefs and individual customers buy fresh or frozen fish and seafood every day. To ensure adequate storage conditions for this kind of temperature-sensitive goods, an ice factory also delivers 20 tons of ice for trading stands each day. Maintaining a low temperature inside is a key factor for business success for this kind of facility. On the other hand, one of the biggest concerns for facility owners is cost reduction in air conditioning and ice production. The whole roof surface of 33,000 m^2 covered with a bitumen membrane was cleaned and primed before applying COOL-R. During the renovation process, two layers of waterproofing coating were applied. The first one in grey was used as an undercoat layer, and the second one in white was the final layer with highly reflective properties. The main products/systems used:

1. COOL-R Primer
2. COOL-R Highly Reflective Waterproofing Coating, layer 1 in grey
3. COOL-R Highly Reflective Waterproofing Coating
4. layer 2 in white

Figure 27. Fish market Cool Roof

Benefits

The temperature under the roof was reduced by 7 °C, which improved thermal comfort inside the building and secured proper storage conditions for temperature-sensitive goods. At the same energy consumption by the air conditioning system was reduced, optimizing the maintenance cost of the facility.

8.1.2. School buildings, Kaisariani, Athens, Greece

The use of cool materials for heat island mitigation has gained a lot of interest during the past few years. Cool materials are characterized by high solar reflectance and infrared emittance values. To maximize cooling energy savings, high albedo roof coatings should maintain the above properties for the service life of the coating. The weatherisation of the cool roofs in two buildings in Athens, Greece is analysed. The optical properties of the aged and new cool roofs are measured and compared. The impact of ageing in the two buildings' energy performance is estimated. The buildings under investigation are two non-insulated schools located in Kaisariani, a densely built urban area near the centre of Athens, Greece. These two buildings were selected because cool materials were applied in 2008. The procedure followed is divided into the following steps:

- Measurement of the roofs' albedo. The two roofs under ageing conditions.
- Thermal imaging of the roofs' surfaces to detect heat patterns and temperature changes

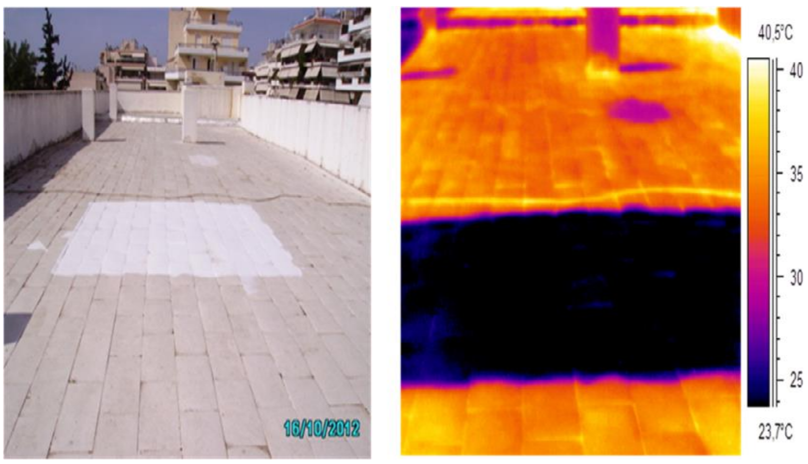


Figure 28 Thermal imaging of the roof's surface

Benefits

The analysis shows a decrease of almost 25% of the cool roofs' albedo after four years of exposure to the outdoor environment. The solar reflectance of the school A roof has changed from 0.5 (existing cool roof) to 0.55 (cleaned cool roof) and finally to 0.74 after the new application of the same cool coating, while the albedo of the school B has shown an alteration from 0.54 to 0.71 for the existing and the new cool coating application respectively. In both school roofs, the surface temperature has a significant decrease between the part of the existing cool coating and the application of the new part (school A ΔT= 12 K, school B ΔT= 7 K). The application of new cool roof coating can decrease the energy demand for cooling by 72% compared to the aged cool roof.

8.1.3. Industrial Building, Netherlands

Rejection of solar gains is the aim of passive cooling strategies in any type of building and any climatic region. The extent of cool materials' applicability depends on the external climatic conditions and internal heat gains. To minimize the energy demand for cooling, the cool material is applied in an industrial building in Oss, Netherlands. The specific building is in Northern climatic conditions (temperate marine climate) where the heating penalty of cool materials is of great significance. This study includes laboratory testing (spectral reflectance measurements, calculation of the solar reflectance, measurement of the infrared emittance, calculation of the solar reflectance index, calculation of maximum surface temperature, accelerated ageing of the samples) and field testing after the application of FC coating on the roof of the building. The field testing measurements (measurement of the roof's albedo, thermal imaging of the roof, thermal imaging of the interior spaces, measurement of indoor temperature and humidity) were performed in two phases, i.e. before (1st Phase) and after (2nd Phase) the FC coating application on the roof. The main products used are a tetrafluoroethylene monomer fluorocarbon coating (FC coating) in a water-borne formula.

Figure 29 Cool Roof of the building, before/after

Benefits

The value of the roof albedo has changed from 0.3 to 0.67 after the application of the cool coating. There is an increase of 120% of the roof's albedo. Regarding the heating and cooling loads, there was a decrease of 73% for cooling while there was a minor heating penalty of 5%.

8.1.4. Aparthotel Vila Petra, Portugal

The existing aparthotel building in the South of Portugal needed rehabilitation. The actual roof waterproofing was a double bituminous layer and had to be replaced, and there was also a need to increase the thermal Insulation. The client requested an economical refurbishment solution.

Figure 30 Roof of Aparthotel

The aqueous coating Sikagard®-570 W PELE ELÁSTICA Térmico, based on styrene-acrylic dispersion, was chosen as the right waterproofing product. After drying, it becomes an elastoplastic layer with excellent crack-bridging properties even at low temperatures and with good thermal properties.

Benefits

The analysis shows an increase in reflectance (as topcoat). Also, the product managed to reduce the energy which needs the building in the summer period, and it improved the thermal comfort inside of the building, mainly under the rooftop.

9. Suboptimal and Ineffective Products in the Market

9.1. North America

The widespread reliance on the CRRC, and its robust quality control procedures, has resulted in a U.S. market with very few products that do not consistently meet the radiative performance listed on their labels. The largest contributor to sub-optimal performance is installation and design failures. These can be minimized through the use of good design guides and by closely following manufacturers' instructions for preparation, application, and maintenance.

9.2. EU Market - only major categories or features

This part will report any sub-optimal or ineffective cool roof products by analysing the main features that diminish their performance and providing the relevant data. For example, aluminium coatings, traditionally advertised as reflective cool products, have lower performances than white roof products due to their lower emissivity values. In addition, based on the European effort to promote cool roofs, experiences from cool material failures will be compiled and presented through specific examples. The reasons for the performance failure will be analysed, and advice will be provided on avoiding such situations that could negatively affect the users' opinion on cool roofs efficiency. Examples of such failures include installing materials that are inappropriate for a specific use of surface, the use of cool materials with poor long-term performance due to lack of aged radiative properties data, etc.

A) Aluminium roof coatings

Aluminium coatings have traditionally been advertised as reflective coatings. They mainly consist of an asphaltic binder and aluminium metal pigment flakes. They are characterized by medium to high solar reflectance with values ranging from 0.3 – 0.6, depending most likely on the percentage of aluminium pigment exposed at the coating surface [13,26]. The spectral reflectance of various aluminium roof coatings is shown in **Figure 31**. It can be observed that the spectral curves are quite similar and tend to increase with increasing wavelength and suddenly drop at around 800 nm. Aluminium coatings have a high solar reflectance in the UV (300-400nm) range compared to white or light coloured coatings that are highly absorptive in this range.

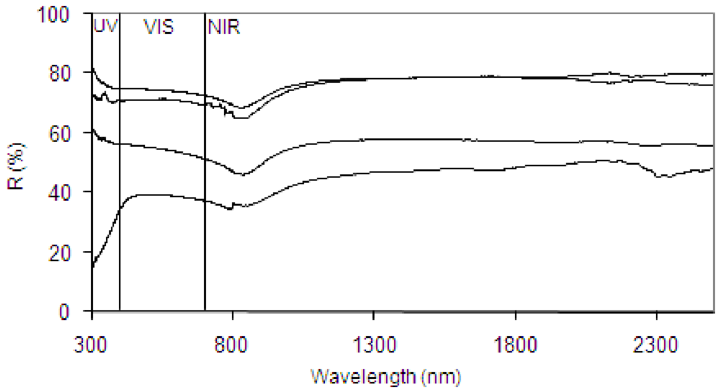


Figure 31. Spectral reflectance of various aluminium roof coatings (Adapted from [5]).

Although all building materials are characterized by high values of infrared emittance, usually above 0.85, the aluminium content in this type of coatings has the offsetting effect of lower infrared emittance ranging usually from 0.25 to 0.65 [5,108]. Cool roofs should be highly reflective to minimize the amount of solar radiation absorbed and converted into heat and highly emissive to maximize the amount of heat that is radiated away. Although aluminium coatings have values of solar reflectance, which are significantly higher than the performance of a black material (SR = 0.05), the low value of their infrared emittance significantly limits their performance.

An experimental study conducted during hot summer conditions in Athens, Greece, measured the performance of different types of reflective coatings (white and aluminium ones). It was found that during the day, the aluminium coatings had a higher surface temperature compared to the white coatings, with aluminium coatings being warmer by 15°C. During the night, the predominant factor affecting the thermal performance is the infrared emittance of the samples and aluminium coatings were by 5°C warmer than the cool white coatings. It is evident that higher surface temperatures observed for aluminium coatings will translate in lower performances in terms of energy savings and indoor thermal comfort improvement when these coatings are applied on building roofs.

B) Use of non-appropriate materials on roofs

In some cases, due to lack of knowledge or avoiding costs, building owners might apply inappropriate materials on their roofs to make them more reflective, such as simple white paint instead of a cool roof coating. Coatings might look like thick paints, but they are specifically manufactured for roofs and have the right properties in order to be weather resistant and protect the roof surface from ultra-violet (UV) light and chemical damage, extending its life. It is important to consult a roofing manufacturer or a cool roof product manufacturer before installing a cool roof on an existing roof. In Greece, there is a traditional practice involving the application of a white limestone paint like mixture on building envelopes during summer to keep them cooler. This practice is very effective in reducing surface and indoor temperatures, as limestone presents very high solar reflectance and infrared emittance values. However, it has very poor ageing performance and presents a major problem of chalking [191].

C) Cool roofing materials with no or inappropriate performance data

In Europe, before the foundation of the European Cool Roofs Council, there were several products in the market advertised as reflective. Some of these products did not present any performance data, i.e. measured values of solar reflectance, infrared emittance or SRI, and they were only based on having a white colour. Other material presented data with no reference to specific measurement standards and parameters. For example, one manufacturer was advertising values of reflectivity of 0.95. After further investigation, it was revealed this value referred to the reflectivity of the product in the visible spectrum (400-700nm) and that it did not represent the solar reflectance (300-2500nm). In other cases, manufacturers presented data from private laboratories with little information on the standards used or the labs measurement procedures and performance. It was impossible to assess the performance of these products, compare performances and decide on their effectiveness in terms of cooling potential. This confuses potential cool roof users, and choosing ineffective cool roof products due to the lack of appropriate performance data may reduce the credibility of cool roofs technology to the public. This highlights the absolute necessity of having in place a uniform and credible system for rating and reporting the Radiative Properties of Roofing Products.

D) Cool materials with poor ageing performance

A cool white roofing material will lose its initial solar reflectance due to ageing, i.e. weathering, soiling and biological growth. The degree of loss in solar reflectance depends on several parameters, such as the type of roofing material, the characteristics of the local climate and the initial value of solar reflectance [19](Berdahl et al., 2008a), and it is different for each material. This loss of solar reflectance decreases the cooling potential of a cool roof in terms of decreasing surface temperatures, indoor temperatures and cooling savings [148].

In the framework of a study conducted in Athens, Greece, 14 different cool reflective coatings from the international market have been studied, and their radiative properties and thermal performance were experimentally investigated. These coatings were applied on concrete slabs and were exposed to outdoor conditions for a period of about 3 months. Significant differences in the solar reflectance of otherwise similar white roof coatings have been observed as shown in the figures below. This translated into a decrease in their thermal performance. Actually, the most important change in the thermal behaviour was observed for an acrylic elastomeric coating (S16), which was the coolest coating during the daytime period of the first month of the experiment, but became a lot warmer during the second and third month of the experimental period (**Figure 32**). In **Figure 33** the effect of ageing on the thermal performance of the samples is shown. On the vertical axis appears the difference between the maximum daily temperature of the surface of the two coating samples and the ambient air (to exclude the influence of weather conditions). On the horizontal axis is the time of exposure (3 months). Although the time of exposure is relatively short, the surface temperature of the coating in **Figure 33A** clearly shows an increasing trend compared to the second coating (**Figure 33B**). This example highlights the importance of measuring and reporting aged radiative properties data for all cool roofing materials.

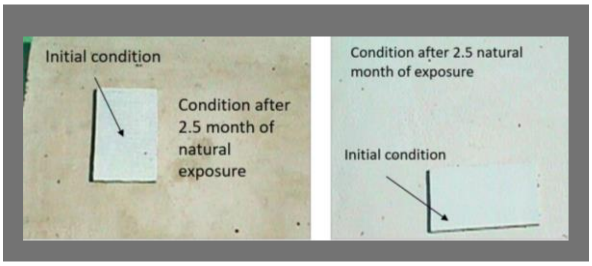


Figure 32. The surface appearance of the cool coating with poor (A) and good (B) ageing performance after 2.5 months of exposure to outdoor conditions in comparison with their initial colour.

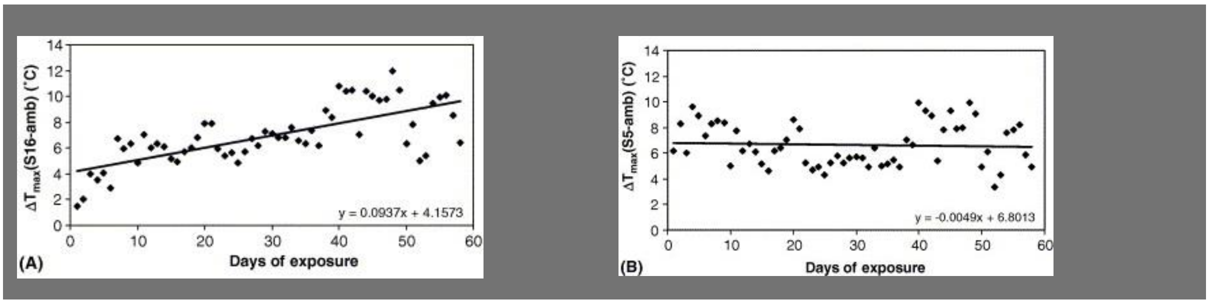


Figure 33. The effect of weathering for the two coating samples (S16) with poor (A) and good S5 (B) ageing performance: Difference between the maximum daily temperature of the surface of S16 (A) and S5 (B) and the ambient air vs. the days of exposure.

E) Improper or no installation of cool roof products

When installing a cool roof, it is of primary importance to follow the guidelines of the cool roof product manufacturer or have a roof professional to install the cool roof. Poor installation of a cool roof may cause significant problems on the roof and decrease the performance of the cool roof, resulting in a cool roof failure.

Apart from the obvious previous statement, cool material failures may result if conventional materials are installed instead of cool ones. For example, in the framework of a project led by the National and Kapodistrian University of Athens (NKUA), cool coloured materials were chosen to be installed in a municipality. A sample of the selected NIR reflective material was tested by the laboratory of NKUA and was found to meet the project standards. After installation, measurements of the thermal performance of the installed materials were found to be a lot worse than expected and similar to the initial situation prior to the installation of cool coloured materials. Further investigation involving the measurement of samples extracted from the project site revealed that the radiative properties of the installed samples were similar to the radiative properties of conventional materials. It was found that the contractor aiming to make a profit had installed similarly coloured conventional material and not the NIR reflective ones. Although this is a rare case, it highlights the importance of post cool material installation assessment.

10. Current Obstacles and Problems

10.1. Current Obstacles and Problems to Cool Roof Market Growth in North America

A number of barriers have slowed the progress of cool roof installations and supportive policies. Many of the barriers associated with implementing energy efficiency in buildings are also factors for slow progress in implementing cool roofs. For example, both urban cooling and building energy efficiency face challenges due to differences between who pays for and who benefits from the measures (also referred to as the "principal-agent problem" or "split incentives"). However, cool roofs and other passive cooling measures face some unique barriers.

10.1.1. No one owns the problem of urban heat

With the exception of the creation of a Chief Heat Officer position for Miami-Dade County in May 2021, there is no central authority in cities responsible for policymaking, funding, and implementing solutions to address the challenges of heat on urban systems. Instead, the response to heat (or cooling) is often siloed within different agencies and organizations and may not be pursued in a coordinated way. This also makes it challenging to properly value the overall social benefits of the heat mitigation potential of cool roofs.

10.1.2. Lack of awareness of cool roofing solutions

While product availability is not an issue in the U.S. market for any of the cool roof product types, there remains a lack of awareness among key stakeholders. Consumers, particularly residential building owners, typically engage the market when a roof problem requires immediate repair and may not be inclined to do extensive product research. Contractors may be unwilling to install products they are not familiar with. Since many roof interventions do not trigger the permit process (especially in the residential roofing market), it may also be challenging to effectively implement municipal programs to raise awareness, provide incentives, or require cool roofs. Beyond product awareness, there is a general lack of understanding of the full set of economic benefits of cool roofs, which leads to sub-optimal policy.

10.1.3. Residential roof markets are difficult to change with policy

Cool roofs have made great progress in commercial, institutional and similar building sectors but have been slower to penetrate the residential market. The residential cool roof market will be key to achieving the scaled deployment needed to reduce urban air temperatures but is a challenging market to change with policy. Because many roof repairs and replacements can happen without a building permit, the municipality may not have an opportunity to influence residential roof buying decisions. The residential roofing market is characterized by many small contractors and tradespeople that may not be aware of or have access to cool roof performance information. Homeowners often make decisions when a roof system has already failed for some reason and may have the time for research or an extensive discussion about options with the contractor. There may also be Neighbourhood covenants or other restrictions on lighter coloured shingles on visible steep-sloped roofs.

10.1.4. Lack of comprehensive policy guidance or regulatory frameworks

While there are numerous examples of good practices and policies to promote urban cooling, there are few, if any, examples of cities taking a fully integrated approach to the challenge of urban heat. Cities have mainly been opportunistic to address urban heat and have generally not taken a systematic, multi-stakeholder approach to the challenge. There is a need to incorporate cool roofing more systematically into broader urban design, planning, zoning, regulatory, procurement, and building code processes.

10.1.5. Limited financing/incentives

There have been insufficient financial resources dedicated to supporting and sustaining municipal passive cooling efforts. The difficulty associated with monetizing the benefits of many urban cooling solutions like cool roofs, along with the challenge of aggregating small and fragmented urban cooling solutions on public and privately owned buildings, has made it hard to attract private capital or fund via municipal bonds or other mechanisms.

Financing and financial incentives for cool roofs do not capture or value the broad social benefits beyond the building on which the roofs are installed. In addition to building energy savings, many passive cooling solutions generate substantial non-energy benefits (including health, comfort, resilience, employment etc.). For example, a study on three diverse American cities estimates that energy efficiency benefits of passive cooling solutions like reflective roofs represent approximately 25 – 30% of the total estimated economic benefit generated by their use [192]. Quantitative analyses that assess costs and benefits more comprehensively are helping demonstrate that wide adoption of cost-effective urban cooling solutions can deliver large financial and economic benefits to cities and their residents and keep the cities livable in a warming world [192].

10.2. Current Obstacles and Problems to Cool Roof Market Growth in Europe

Roofs present a very high fraction of the exposed urban area. It is estimated that urban areas occupy almost 1% of all land, and the total roof area of the urban world is close to 3.8×10^{11} m^2.

There are two types of roofs, low-slope or flat roofs with an inclination of less than 9.5° from the horizontal, and steep-slope roofs with a tilt of more than 9.5° from the horizontal. Low-slope roofs are found usually on commercial, industrial, warehouse, office, retail, and multi-family buildings, as well as some single-family homes, while steep-slope roofs are found most often on residences and retail, commercial buildings and are generally visible from the street. Most cool roofs focus on the low-sloped roofing sector, but cool roof options are also available for the steep-sloped sector. Main roof products include single-ply membranes, modified bitumen roofs, coatings, built-up roofs, metal roofs, shingles and tiles. A cool option is for all these roof types that exist or has recently been developed.

For steep-slope roofs that are typically non-white and visible, cool coloured materials have been developed addressing the desire for different appearances and potential glare problems. These cool coloured materials have been developed by using infrared reflective pigments and other techniques. Therefore, there are plenty of alternatives available concerning the materials for cool roof applications.

The main issue that needs to be underlined in a cool roof installation is verifying that the cool roof product will perform as “cool” after its installation and for a specific period. This is confirmed by the aged materials’ properties as included in the cool roof’ materials database (ECRC, CRRC). In the past, cool roof materials' problems we attributed to a significant aging process after their installations [193,194]. For that reason, it is recommended to have labels that show the cool roofs’ properties (solar reflectance, infrared emittance, SRI) at the initial and aging stage (after 3 years). Accelerated aging protocols have been developed to reduce the time required for the ageing procedure and measurements of materials. In this direction, the ASTM D7897-15 (ASTM method) is an accelerated pollution test method for cool roofs, which has been established in the United States. A similar accelerated pollution test method exists in Japanor antifouling civil engineering materials introduced by the Public Works Research Institute in Japan (PWRI method)[195,196]. The development of initial and aged cool roof products rating programs has significantly increased market trust.

11. UNSW _ Department of Industry, Science, Energy, and Resources (DISER)_cool roof energy efficiency study Questionnaire No.1_Cool Roof Market Report

11.1 Introduction

This survey was conducted to support the study named Cool Roofs Cost Benefit Analysis. The questionnaire (attached in the **Annex B**) was designed to collect information on the existing cool roof installations in Australia, and the performance, current market, and characteristics of cool roof products from cool roof commercial stakeholders in Australia. The information for 16 cool roof products from 10 stakeholders covering spray, paint, membrane, and the metal sheet has been gathered from 2nd June 2021 to 21st July 2021, see **Table 18**. The detailed analysis is presented in the following sections.

Table 18 The information for 16 cool roof products from 10 stakeholders covering spray, paint, membrane, and the metal sheet has been gathered in this questionnaire.

Stakeholder No.	Product No.
1	1A
	1B
2	2A
3	3A
4	4A
5	5A
6	6A
7	7A
	7B
8	8A
	8B
	8C
	8D
	8E
9	9A
10	10A

11.2 Cool roof service and market

11.2.1 Cool roof services overview

Regarding the cool roof services the ten stakeholders are providing, all stakeholders are selling cool roof materials; 50% installs cool roof; 60% provides cool roof project consultation (It includes roof inspection service, cool roof strategy design and product selection, cool roof maintenance consultation, etc) and 50%

can supervise cool roof project, as shown in **Figure 34**. Apart from these services, some also offer end-to-end project management, calculation of return on investment, and data prediction.

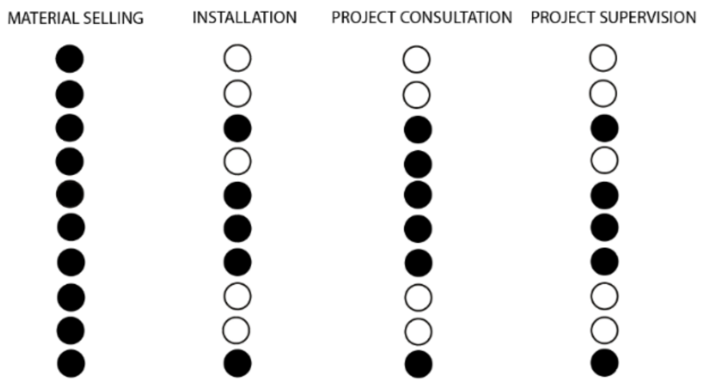


Figure 34 Cool roof services provided by the ten stakeholders (each stakeholder's response is lined in a row, and solid black circles indicate their selected services).

11.2.2 Cool roof installation

As shown in ***Figure 35***, for the six stakeholders who install cool roofs, one started the installation service before 2000, having installed around 200,000 m^2 cool roofs worldwide. Two have installed approximately 750,000 m^2: one started from 2000, and the other started from 2005. Two have installed around 0.1-0.4 million square meters: they started from 2001 and 2015 respectively. The last one started very recently in last year, and the total area of the cool roof it has installed is around 100 m^2. Among these six stakeholders, three install cool roofs only within Australia; two of them install mainly in Australia with an international share of less than 10%. Only one stakeholder has the majority of the installation in the international market (75%). On average, each stakeholder installs 12909 m^2 cool roof in Australia every year, see **Figure 36.**

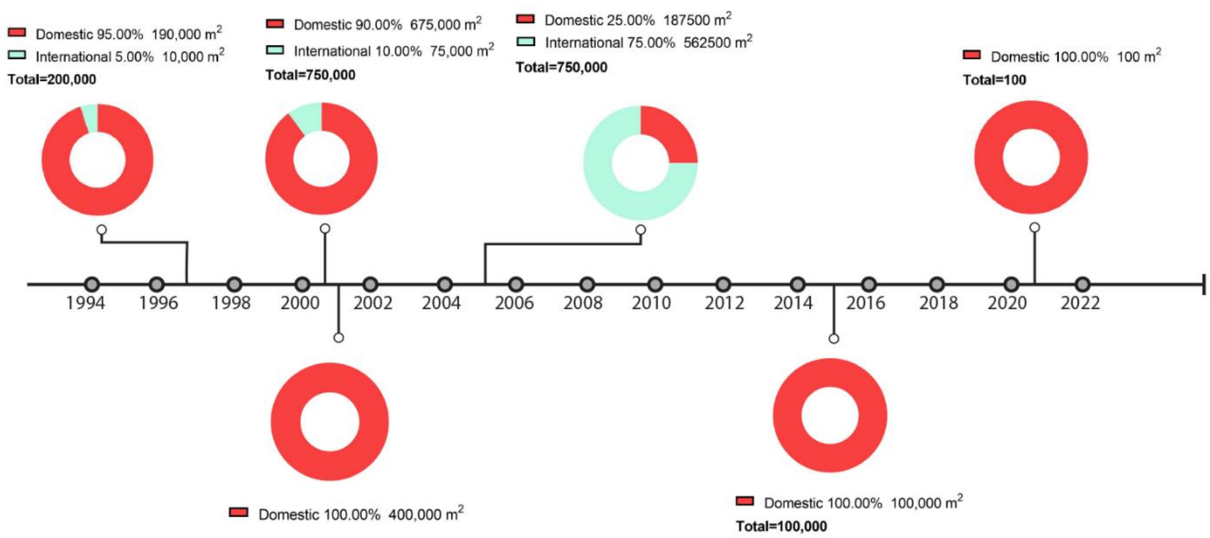


Figure 35 Date of when each stakeholder started the cool roof installation service, the total area the cool roof each stakeholder has installed (m^2), as well as the share of domestic and international installation.

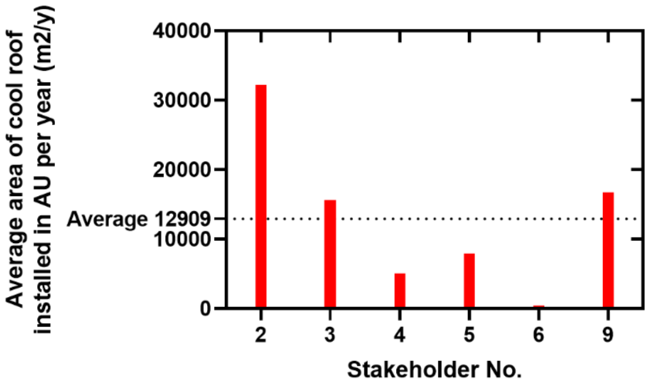


Figure 36 Average area of cool roof installed in Australia by each stakeholder per year.

11.2.3 Cool roof material selling market

The annual sales volume of 14 products has been collected, see

Figure *37*. Some are provided in the form of annual turnover: the maximum sale is around 39.6 million, which is the total turnover for products 1A and 1B, and the minimum is approximately 0.6 million for product 10A; the average annual sales volume of these products in Australia is 10.7 million (products of No.1 series were calculated as one product). Others are provided in the quantity of annual sales: large volumes are reported for products 7A and 7B, with the annual sales volumes of around 87300 and 1655 tons respectively, while the other three volumes are around 30-220 tons. The average annual sales volume for these products in Australia is 14840 tons (products of No.8 B-E series were calculated as one product).

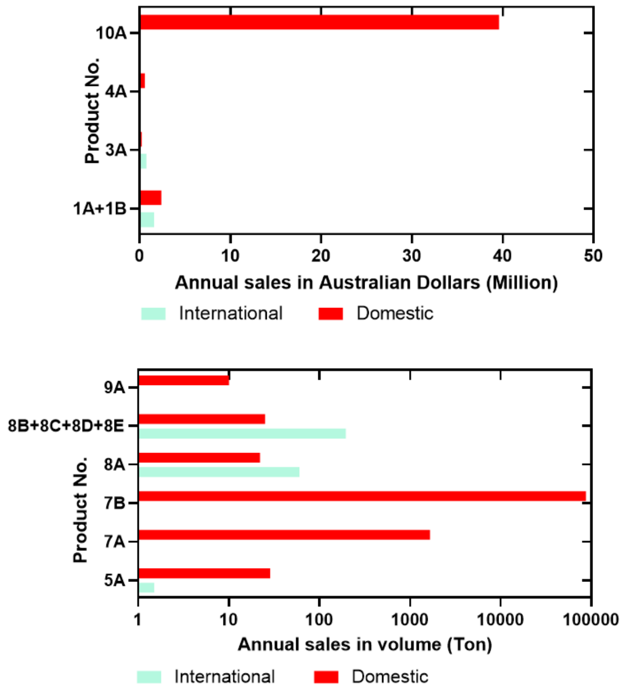


Figure 37 Annual sales of 14 products in Australian Dollars or volume.

When analyzing the share of domestic and international selling of cool roof, products from two stakeholders, No.3 and No. 8, have export outweighing the domestic sale while the rest ones all have a larger domestic market than the international, within which two only have domestic sale (see **Figure 38**).

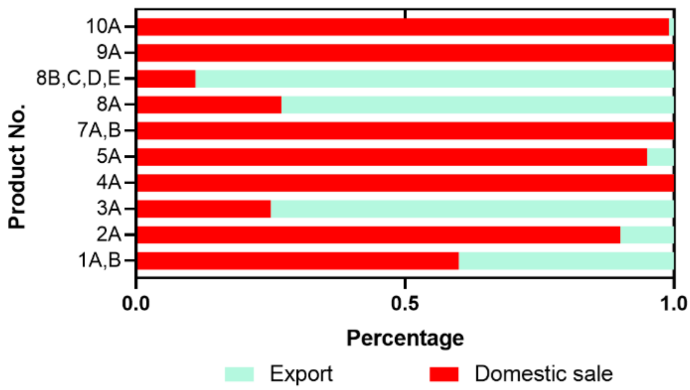


Figure 38 Share of domestic sale and export of cool roof selling.

11.3 Cool roof materials

11.3.1 Cool roof material types and scope of application

Among various cool roof material types listed in the questionnaire, spray, paint, membrane, and metal sheet count for 44%, 69%, 75%, and 25%, see **Table 19.** Other material types provided by the stakeholders include precoated concrete, asphalt, brick, timber, canvas, PVC, polycarbonate, and fibreglass.

Table 19 Material type of the 16 cool roof products.

Product No.	Spray	Paint	Membrane	Metal sheet
1A	√	√	√	
1B	√	√	√	
2A	√	√		
3A	√	√	√	√
4A			√	
5A	√		√	
6A	√	√	√	
7A				√
7B				√
8A		√	√	
8B		√	√	
8C		√	√	
8D		√	√	
8E		√	√	
9A	√		√	

Among the 16 collected cool roof products, 38% can be applied both for roof retrofitting and replacement; 50% can only be applied for retrofitting roofs, while 12% can only be used to replace the original roof, see **Table 20**.

Table 20 The suitability of various cool roof products for roofing retrofit or replacement.

Product No.	Retrofit	Replacement
1A	√	
1B	√	
2A	√	√
3A	√	√
4A	√	√
5A	√	
6A	√	√
7A		√
7B		√
8A	√	√
8B	√	
8C	√	
8D	√	

8E	√	
9A	√	
10A	√	√

1.1. Cool roof layer thickness

As shown in **Figure 39**, most cool roof products have a thickness of 200 microns to 500 microns under wet conditions. After dried, the thickness decreases by 8-200 microns on average. Two products (No.7A and No.7B) have extremely small thicknesses: only 25-38 microns. It should be noted that some products can have substrate-dependent thicknesses and are therefore not covered in this analysis.

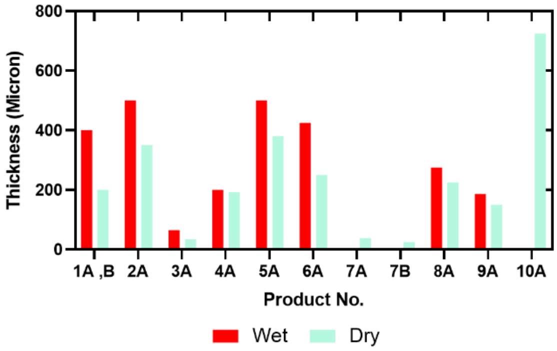


Figure 39 Thicknesses of eight cool roof products in wet and dry conditions.

11.3.2 Colour and optical properties of cool roofs

A white-colored cool roof is a common and major type dominating the market, while most of the manufacturers also provide coloured cool roofs. Regarding the optical properties of the cool roofs we have collected, some products were provided with both the reflectance and the thermal emittance, while some others were featured with the solar reflective index (SRI), as shown in **Figure 40**. Products 2A, 6A, and 9A have both solar reflectance and thermal emissivity higher than 0.9. The total solar reflectance and thermal emissivity of products 3A and 5A are within the range of 0.8-0.9. Products 7A and 7B both have a thermal emittance in the range of 0.8-0.9, while the solar reflectances are 0.77 and 0.55, respectively. For products 4A, 8A-8E, provided were SRI: the light-colored materials of around 113 and the dark-colored material of less than 30.

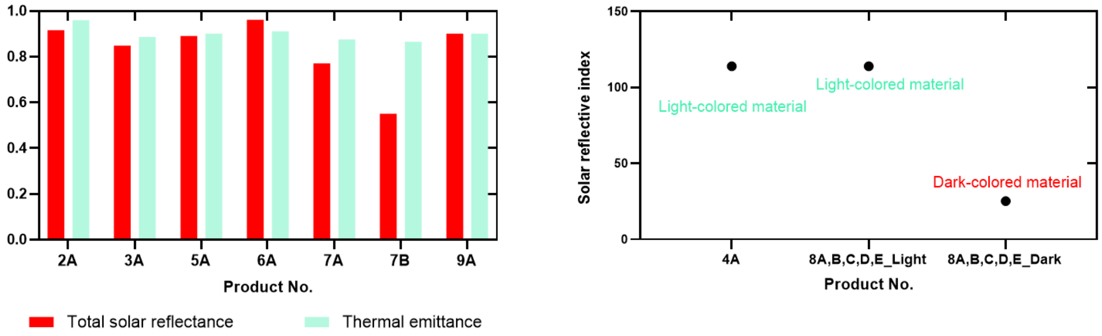


Figure 40 The total solar reflectance and thermal emissivity of 7 products and the solar reflective index of 3 other products.

11.3.3 Cost of the cool roof

The standard cost of the cool roof material in Australian Dollard per square meter has been collected for 14 products, as shown in **Figure 41**. The highest price collected is 32.5 AUD/m^{2,} while the lowest one is 2.5 AUD/m^2. The average cost for the 14 cool roof products is 13 AUD/m^2.

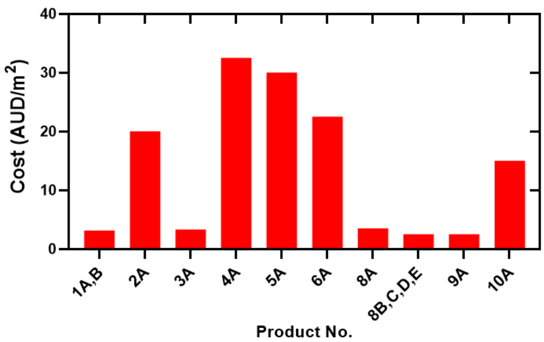


Figure 41 Cost of 14 cool roof products.

11.4 Conclusion

1) All stakeholders sell cool roof materials, within which around half provide installation, consulting, and supervision services.

2) Most stakeholders only install cool roofs domestically or only possess a small portion of business in the international market. On average, each stakeholder installs 12909 m^2 cool roof in Australia every year.

3) Most stakeholders only sell cool roofs domestically or only possess a small portion of business in the international market. The average annual sales volume of these products in Australia is 10.7 million Australian Dollars (turnover) or 14840 tons (quantity of sale).

4) The number of products in descending order is membrane, paint, spray, and metal.

5) Half of the surveyed products can only be applied for retrofitting roofs; 12% can only be used to replace the original roof, while 38% can be used for both purposes.

6) Most cool roof products have a thickness of 200 microns to 500 microns under wet conditions. After being dried, the thickness decreases by 8-200 microns on average.

7) The average solar reflectance and the thermal emittance of the collected cool roof products are 0.83 and 0.90, respectively.

8) The average cost for the 14 cool roof products is 13 AUD/m^2.

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13. Annex A. Main cool roofing product categories and their technical characteristics

Coatings. Coatings look like thick paints, and they can protect the roof surface from ultra-violet (UV) light and chemical damage, extending its life. They have a life expectancy of 5 to 20 years. Cool white coatings have typically solar reflectance values above 0.7 and an emissivity above 0.85. This results in superior thermal performance. They are mainly classified as elastomeric or cementitious. Cementitious coatings contain cement particles. Elastomeric coatings include polymers to reduce brittleness and improve adhesion. Some coatings contain both cement particles and polymers. The important distinction is that elastomeric coatings provide waterproofing, while cementitious coatings are pervious and rely on the underlying roofing material for waterproofing. Manufacturers also use coatings in order to make more reflective surfacing materials such as membranes, metals, granules, etc. Another category of light coloured solar reflective materials is aluminium coatings, silver in colour, that contain aluminium flakes in an asphalt-type resin. Aluminium flakes enhance the solar reflectance to above 0.5 for the most reflective coatings, and although such value is significantly higher compared to the performance of a black material (SR = 0.05), the aluminium content has the offsetting effect of lower infrared emittance, usually ranging from 0.25 to 0.65 [5,13].

Single-ply membranes. A single-ply membrane is a roofing system that consists of pre-fabricated sheets made of polymers or rubber. A grey single-ply membrane can have an initial reflectance of 0.20, while a white one can have an SR of 0.80 and above. They have emissivity values above 0.85. Their life expectancy ranges from 10 to 20 years. They are mainly used for low slope roofs. There are two main types of single-ply materials: a) Single-Ply Thermoplastic: flexible sheet membranes consisting of compounded plastic polymers. When heat is applied to their surface, the thermoplastic seams are welded together, making the material seamless and effective. Most thermoplastics are manufactured to include a reinforcement layer (usually polyester grids and/or glass fleece) for extra durability, dimensional stability and strength.

There are various types of single-ply thermoplastics; the most common are PVC and TPO membranes. b) Single-Ply Thermoset: Thermosets are materials (usually EPDM) that cannot be hot-air welded because they do not melt but change their physical characteristics when heated up too high. Instead, adhesives tapes or contact cement must be used to seal the seams between adjacent membranes. They are typically black and must be formulated differently or coated to make them reflective.

Reinforced Bitumen Sheet made of Modified Bitumen. It is a factory-produced flexible layer of bitumen with internal or external incorporation of one or more carriers, supplied in roll form ready for use. It is topped with a surfacing material. The Radiative Properties of modified bitumen are determined by the surfacing material. Modified bitumen surfaces can be pre-coated at the factory to make them cool. Modified bitumen with a mineral surface has a reflectance of 0.1–0.2, but if a white coating is applied on top, the solar reflectance reaches a value of 0.65–0.7. Thermal emittance in all cases is high, about 0.90. The life expectancy of a modified bitumen roof is 10 to 30 years. They are used for low slope roofs.

Built-Up Roofs. Built-up roofing consists of built-up layers of coated asphalt and insulation applied on-site and can be covered with a capsheet (or surfacing material). There are several ways to make the cap sheet, and it is usually black or dark coloured, but it can be formulated differently, i.e. using reflective marble chip or other light coloured option instead of dark gravel or using reflective mineral granules (if a mineral surface sheet is used) or coated to make it reflective. Coating a built-up roof initially covered by a smooth black surface with a smooth, white surface can increase the solar reflectance from 0.04 to 0.8. The life expectancy of a built-up roof is 10 to 30 years, and they are intended for low slope roofs.

Metal Roofs: Prepainted metal refers to a metal sheet on which a coating material has been applied by coil coating in a factory prior to rolling and profiling to its final shape. Prepainted metal roofing products can be rolled and formed to produce a variety of profiles and a variety of textures. Prepainted metal roofing products are characterized by high durability and a life expectancy from 30 to 50 years. While unpainted or dark painted corrugated metal roofs have very low values of solar reflectance ranging from 0.05 to 0.5, a white painted metal roof can have a solar reflectance of 0.6 – 0.7 on average. It is important to point out that an unpainted metal roof is characterized by low emissivity values ranging from 0.05 to 0.30. A prepainted roof, however, achieves an emissivity value of 0.8 – 0.9. A metal roof is used on low or steep slope roofs.

Tiles: Roofing tiles can come in many shapes: curved, flat, fluted, or interlocking, and in many styles. They can be made of clay, natural stone, or concrete. The colour of a tile may be dispersed throughout its mass, or it may be applied in the form of a coating. Advantages of tiles include fire safety and durability. Disadvantages include increased weight and cost compared with low-cost asphalt shingle roofs. Tile roofs often have enhanced air circulation compared to other roofing types because ambient air can circulate below as well as above the tile. A dark coloured concrete tile can have a solar reflectance of 0.05 - 0.35, while a white one can reach a value of 0.70. Dark coloured clay tiles have, on average solar reflectance values of 0.2 -0.4, while a white clay tile can have a SR of 0.70. . Emissivity values for all cases is high and above 0.8. Tiles can also be glazed to provide waterproofing or coated to provide customized colours and surface properties. These surface treatments can transform tiles with low solar reflectance into cool roof tiles. The life expectancy of a tile roof exceeds 50 years, and they are intended for steep slope roofs.

Asphalt shingles A type of roof covering consisting of an organic or fibreglass mat saturated with bitumen. Small rock granules, aggregate, are added to one side of the shingle in order to protect against natural elements such as sun and rain. Depending on whether the shingle base is organic (paper felt) or fibreglass, the granules are composed of asphalt cement, a mineral stabilizer like limestone and sand-sized mineral granules. This can be coloured and can be formulated to improve Solar Reflectance. The solar reflectance of all conventional asphalt shingles is rather low (0.04- 0.15) due to the limited amount of pigment in the granule coating, the surface roughness and the fact that the very absorptive black substrate is not totally covered. “White” shingles (actually grey in colour) can have a reflectance of about 0.25-0.30. They are a low-cost solution, and they offer very good resistance even in the harshest climatic conditions. The life expectancy of asphalt shingles is 15 to 30 years, and they are intended for steep slope roofs.

14. Annex B. Questionnaire No.1

https://www.smartsurvey.co.uk/s/SEYZQQ/

UNSW _ Department of Industry, Science, Energy and Resources (DISER)_cool roof energy efficiency study No.1

1. Survey respondent

1. Your name *

2. Date *

DD/MM/YYYY

3. Email *

2. Company

4. Company name *

5. What cool roof services are you providing?

	You are providing
Cool roof material selling	☐
Cool roof installation	☐
Cool roof project consultation	☐
Cool roof project supervision	☐

Others (please specify):

6. If you are installing cool roofs, when did you start the installation service?

DD/MM/YYYY

How many areas of the cool roof have you installed (approximately) (m2)?

7. If you are selling cool roof materials, what is your annual sales volume (AUD)?

What is the share of domestic sales and exports?

3. Cool roof material

8. Cool roof product name *

9. Material type of the cool roof

	Spray	Paint	Membrane	Metal sheet
Material type	☐	☐	☐	☐

Others (please specify):

10. Thickness of the cool roof (Micron)

	Thickness
Wet	
Dry	

Others (please specify)

11. Optical properties

Solar reflectance (If you have separate reflectances in UV, VIS and NIR, please specify below)	
Emittance	
Colour	

12. Cost (AUD/m2) *

13. Suitable for roof types *

	Retrofit (any type)	Replacement
Suitable for roof types	☐	☐

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