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State-of-the-Art Review–Effects of Using Cool Building Cladding Materials on Roofs

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Abstract: Cool roofs are roofing systems designed to reflect significant solar radiation, reducing heat absorption and subsequent cooling energy demands in buildings. This paper provides a comprehensive review of cool roof technologies, covering performance standards, material options, energy-saving potential, and hygrothermal considerations. The review examines provisions in current codes and standards, which specify minimum requirements for solar reflectance, thermal emittance, and solar reflectance index (SRI) values. These criteria often vary based on factors like roof slope, climate zone, and building type. Different cool roof materials are explored, including reflective paints and coatings that can be applied to existing roofs as cost-effective solutions. Several studies demonstrated the energy performance benefits of cool roofs, showing significant reductions in cooling loads, indoor air temperatures, peak cooling demand, and overall cooling energy consumption compared to traditional roofs. However, hygrothermal performance must be evaluated, especially in cold climates, to optimize insulation levels and avoid moisture accumulation risks, as reduced heat absorption can alter moisture migration patterns within the building envelope. While cool roofs provide substantial energy savings in hot climates, further research is needed to validate modeling approaches against real-world studies, investigate the impact of seasonality and green spaces on cool roof efficacy and urban heat island mitigation, and explore energy savings potential, moisture control, and condensation risks in cold and humid environments.

Keywords: cool roofs; roofing materials; energy performance; hygrothermal performance; construction

1. Introduction

The Canadian climate, with its cold winters and surprisingly hot summers, poses a unique challenge when it comes to optimizing building performance. Traditional roofing systems may excel in one season but underperform in the other, leading to suboptimal energy usage and occupant discomfort. Cool roofs offer a promising solution that could help strike a balance between the competing demands of heating and cooling. They are designed with materials that have high solar reflectance (the ability to reflect sunlight) and high thermal emittance (the ability to radiate absorbed heat), and these properties allow cool roofs to stay cooler than traditional roofs, reducing the amount of heat transferred to the building below.

The rooftop energy balance for a cool roof is depicted in Figure 1. The white roof has an enhanced reflectivity (albedo) of the surface and this in turn influences the exchange of longwave radiation, the convection heat flux from the roof, and the conduction heat flux into the building. The high reflectivity of white roofs contributes to mitigating the urban heat island effect by reducing the convection heat flux due to lower surface temperatures. During the summer, cool roofs can significantly reduce the amount of heat absorbed by the building, leading to lower cooling loads and energy bills. This can be particularly beneficial in urban areas, where the urban heat island effect can exacerbate the demand for air conditioning.

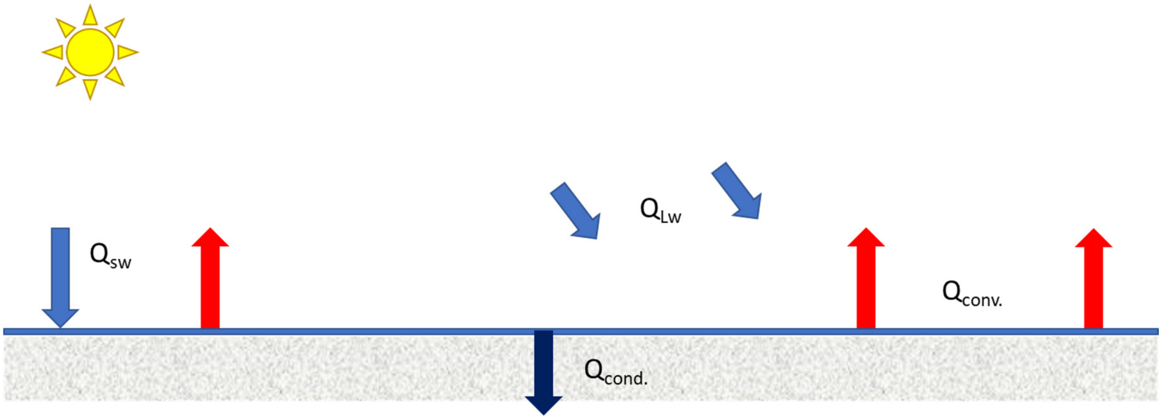


Figure 1. Energy balance diagram for a cool roof. Qsw = short wave radiation from the sun absorbed by the surface. QLw = long wave exchange between the roof surface and surroundings. Qconv. = Convective heat flux and Qcond. = Conductive heat flux.

By mitigating this effect, cool roofs can contribute to a more comfortable and sustainable living environment for Canadians. Additionally, cool roofs can help reduce peak electricity demand, which is crucial for preventing power outages and reducing greenhouse gas emissions from power plants during periods of high energy consumption. However, the potential drawbacks of cool roofs in colder climates, such as increased heating requirements during the winter, could be a point of concern. The balance between the energy savings from reduced cooling and the potential heating penalties must be carefully evaluated to ensure that cool roofs deliver net positive results for buildings. Furthermore, cool roofs can provide additional benefits beyond energy savings, such as improved indoor comfort, reduced urban heat island effects, and extended roof service life due to lower surface temperatures. These co-benefits should be considered when evaluating the overall impact of cool roofs in Canadian climates. To maximize the benefits of cool roofs in Canada, it is essential to consider the specific climate conditions, building characteristics, and occupant needs. Proper insulation levels, HVAC system sizing, and maintenance practices can help mitigate potential heating penalties and ensure optimal performance throughout the year. Additionally, advancements in cool roof technologies, such as spectrally selective coatings and materials that adapt to seasonal changes, could further enhance the effectiveness of cool roofs in diverse climates.

This report provides a comprehensive literature review on roofing materials with higher solar reflectivity and heat emissivity, called “cool roofing materials”. Figure 2 presents the roadmap of this report. The literature review aims to explore four key aspects related to cool roofs in Canadian conditions: a) Provisions in current codes and standards, b) different cool roof materials, c) energy performance of cool roof buildings, and d) hygrothermal performance of cool roof buildings. Details for each aspect are discussed in the following section.

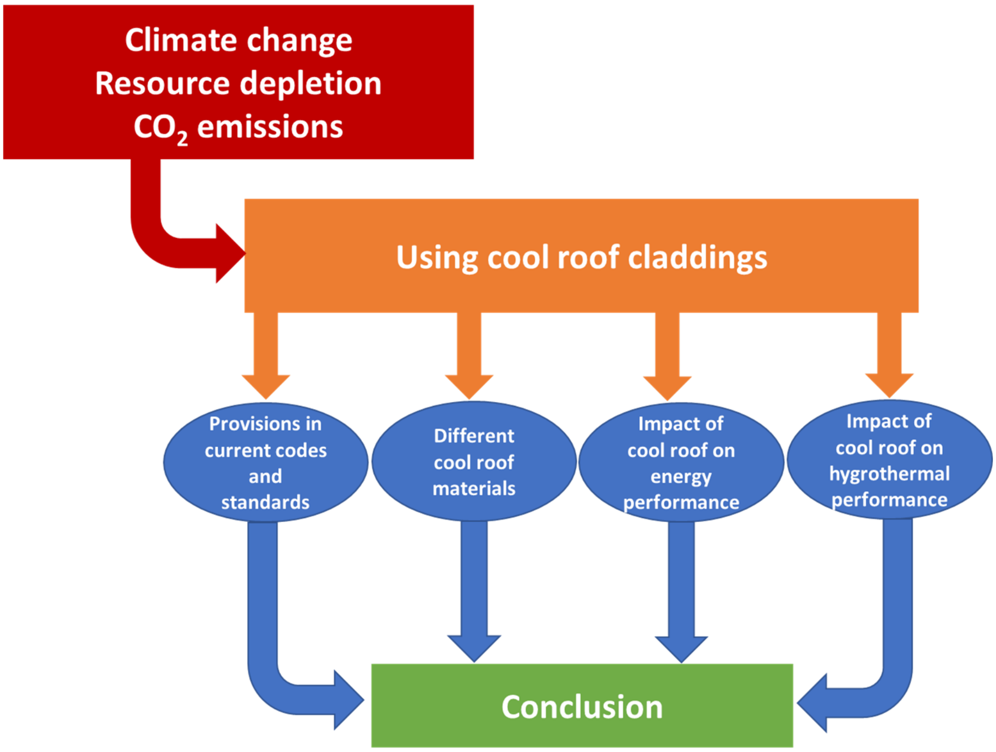


Figure 2. Roadmap presenting the focus of the report.

2. Literature Review

2.1. Provisions in Current Codes and Standards

Building codes serve as comprehensive guidelines that govern various aspects of building design and construction. These codes typically cover structural integrity, safety measures, and energy efficiency requirements, tailoring specific provisions based on the intended use or type of building. Cool roofs have become an increasingly important strategy for improving energy efficiency and mitigating buildings' urban heat island effect. Various building codes, standards, and green construction programs have incorporated cool roof requirements to promote their adoption. These provisions typically specify minimum values for solar reflectance and thermal emittance, or a combined solar reflectance index (SRI), to ensure roofing materials have sufficient heat-rejecting properties. The specific criteria often vary based on factors such as building type, roof slope, climate zone, and whether it's new construction or a re-roofing project. Major codes and standards like the International Energy Conservation Code (IECC), ASHRAE 90.1 and 90.2, California Title 24, and the International Green Construction Code (IgCC) have mandated cool roof requirements, while organizations like the European Cool Roofs Council (ECRC) provide recommendations. Details of various codes and standards are discussed in the following sections.

2.1.1. International Energy Conservation Code (IECC)

The IECC specifies cool roof requirements separately for commercial and residential buildings. For commercial buildings under Section C402.3, a minimum 3-year aged solar reflectance of 0.55 and minimum 3-year aged thermal emittance of 0.75 are mandated. As for residential buildings covered in Section R401.2.1, the minimum aged solar reflectance is 0.55 in Climate Zones 2-3, while a higher value of 0.63 is required in Climate Zone 1. The minimum aged thermal emittance for residential roofs is 0.75 across all climate zones. The requirements aim to reduce cooling loads and energy consumption in buildings by reflecting more solar radiation and emitting absorbed heat efficiently. The IECC provides exceptions for certain roof areas, such as those covered by photovoltaic systems, vegetated roofs, or shaded areas. Additionally, the code allows for trade-offs between cool roof performance and increased insulation levels to provide flexibility in meeting energy efficiency goals.

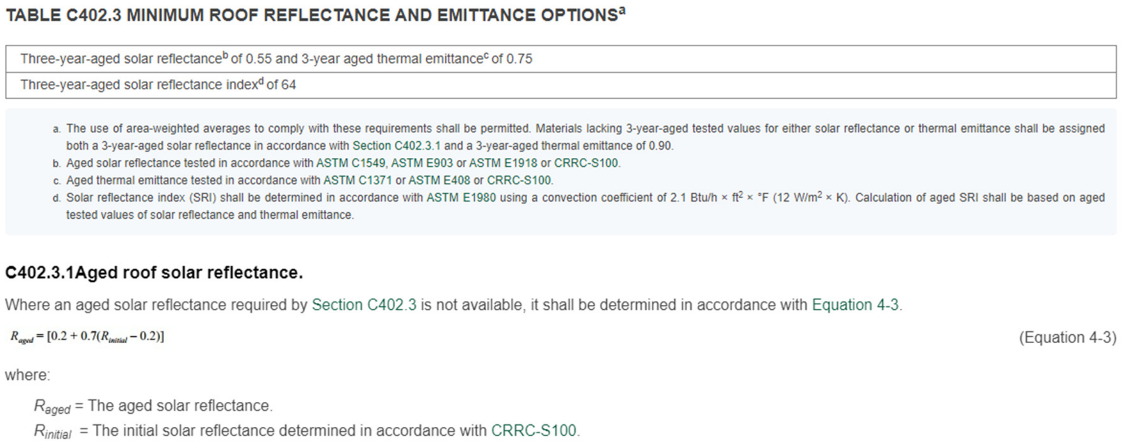


TABLE C402.3 MINIMUM ROOF REFLECTANCE AND EMITTANCE OPTIONS[a]

Three-year-aged solar reflectance[b] of 0.55 and 3-year aged thermal emittance[c] of 0.75
Three-year-aged solar reflectance index[d] of 64

a. The use of area-weighted averages to comply with these requirements shall be permitted. Materials lacking 3-year-aged tested values for either solar reflectance or thermal emittance shall be assigned both a 3-year-aged solar reflectance in accordance with Section C402.3.1 and a 3-year-aged thermal emittance of 0.90.
b. Aged solar reflectance tested in accordance with ASTM C1549, ASTM E903 or ASTM E1918 or CRRC-S100.
c. Aged thermal emittance tested in accordance with ASTM C1371 or ASTM E408 or CRRC-S100.
d. Solar reflectance index (SRI) shall be determined in accordance with ASTM E1980 using a convection coefficient of 2.1 Btu/h × ft^2 × °F (12 W/m^2 × K). Calculation of aged SRI shall be based on aged tested values of solar reflectance and thermal emittance.

C402.3.1Aged roof solar reflectance.

Where an aged solar reflectance required by Section C402.3 is not available, it shall be determined in accordance with Equation 4-3.

$$R_{aged} = [0.2 + 0.7(R_{initial} - 0.2)] \quad \text{(Equation 4-3)}$$

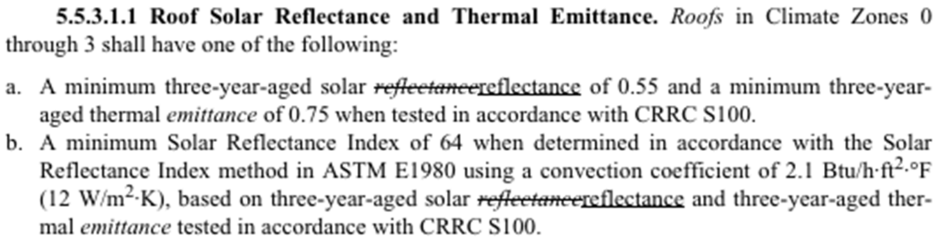
where:

R_{aged} = The aged solar reflectance.
$R_{initial}$ = The initial solar reflectance determined in accordance with CRRC-S100.

Figure 3. Snapshot of section 402.3 of IECC.

2.1.2. ASHRAE Standard 90.1 (Energy Standard for Buildings Except Low-Rise Residential)

ASHRAE 90.1 establishes cool roof criteria for buildings other than low-rise residential. The 2010 version requires a minimum aged solar reflectance index (SRI) of 64, while the 2013 and later editions have a more stringent SRI of 82. Alternatively, these standards permit meeting a minimum aged solar reflectance of 0.55-0.70 along with a thermal emittance of 0.75. The SRI is a combined measure of solar reflectance and thermal emittance, providing a more comprehensive evaluation of a roof's ability to reject solar heat gain. ASHRAE 90.1 also includes exceptions for certain roof types, such as ballasted roofs, vegetated roofs, and roofs with integrated renewable energy systems. These exceptions recognize the unique characteristics and potential benefits of these roof systems.



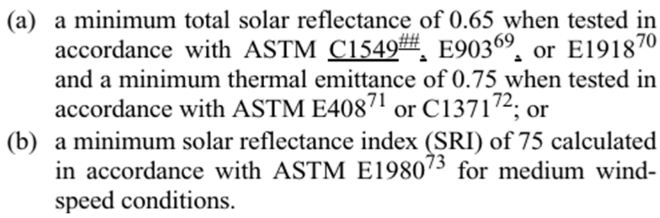
5.5.3.1.1 Roof Solar Reflectance and Thermal Emittance. *Roofs* in Climate Zones 0 through 3 shall have one of the following:

a. A minimum three-year-aged solar ~~*reflectance*~~reflectance of 0.55 and a minimum three-year-aged thermal *emittance* of 0.75 when tested in accordance with CRRC S100.
b. A minimum Solar Reflectance Index of 64 when determined in accordance with the Solar Reflectance Index method in ASTM E1980 using a convection coefficient of 2.1 Btu/h·ft^2·°F (12 W/m^2·K), based on three-year-aged solar ~~*reflectance*~~reflectance and three-year-aged thermal *emittance* tested in accordance with CRRC S100.

Figure 4. Snapshot of section 5.5.3.1.1. of ASHRAE 90.1.

2.1.3. ASHRAE Standard 90.2 (Energy Standard for Low-Rise Residential Buildings)

Specifically for low-rise residential buildings, ASHRAE Standard 90.2 mandates a minimum solar reflectance of 0.65 and a minimum thermal emittance of 0.75 for cool roofs. As an alternative compliance path, it allows achieving a minimum solar reflectance index (SRI) of 75. The standard recognizes the importance of cool roofs in reducing cooling loads and energy consumption in residential buildings, which can have a significant impact on overall energy use and greenhouse gas emissions. The SRI compliance option provides flexibility for manufacturers to develop products that meet the combined performance criteria.

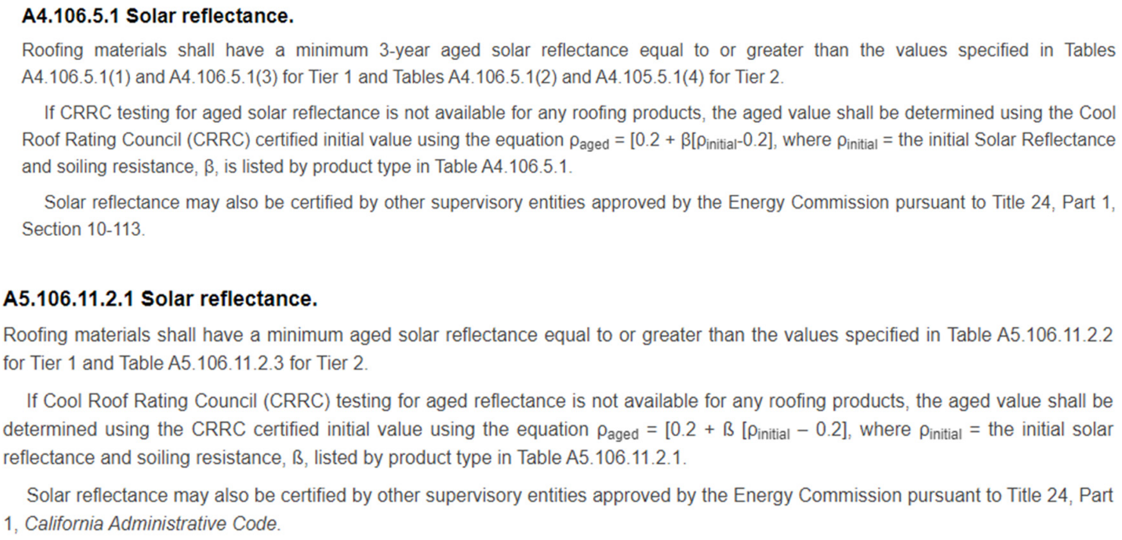


(a) a minimum total solar reflectance of 0.65 when tested in accordance with ASTM C1549[##], E903[69], or E1918[70] and a minimum thermal emittance of 0.75 when tested in accordance with ASTM E408[71] or C1371[72]; or
(b) a minimum solar reflectance index (SRI) of 75 calculated in accordance with ASTM E1980[73] for medium wind-speed conditions.

Figure 5. Snapshot of section 5.3.1.2. of ASHRAE 90.2.

2.1.4. California Title 24 Building Energy Efficiency Standards

The cool roof provisions in California's Title 24 have different criteria based on roof slope in Sections A4.106.5 (Residential) and A5.106.11.2, (Non-residential). For low-slope roofs with a pitch of 2:12 or less, a minimum aged solar reflectance of 0.63 is required. Whereas for steeper roofs over 2:12 pitch, the requirement is a minimum aged SRI value ranging from 16 to 26 depending on the specific climate zone. This distinction recognizes the varying solar exposure and heat transfer characteristics of different roof slopes. The higher SRI requirements for steeper roofs aim to compensate for the increased solar heat gain due to their orientation. Title 24 also includes provisions for cool roof exceptions, such as for buildings with specific space conditioning requirements or renewable energy systems.



A4.106.5.1 Solar reflectance.

Roofing materials shall have a minimum 3-year aged solar reflectance equal to or greater than the values specified in Tables A4.106.5.1(1) and A4.106.5.1(3) for Tier 1 and Tables A4.106.5.1(2) and A4.105.5.1(4) for Tier 2.

If CRRC testing for aged solar reflectance is not available for any roofing products, the aged value shall be determined using the Cool Roof Rating Council (CRRC) certified initial value using the equation $\rho_{aged} = [0.2 + \beta[\rho_{initial}\text{-}0.2]$, where $\rho_{initial}$ = the initial Solar Reflectance and soiling resistance, β, is listed by product type in Table A4.106.5.1.

Solar reflectance may also be certified by other supervisory entities approved by the Energy Commission pursuant to Title 24, Part 1, Section 10-113.

A5.106.11.2.1 Solar reflectance.

Roofing materials shall have a minimum aged solar reflectance equal to or greater than the values specified in Table A5.106.11.2.2 for Tier 1 and Table A5.106.11.2.3 for Tier 2.

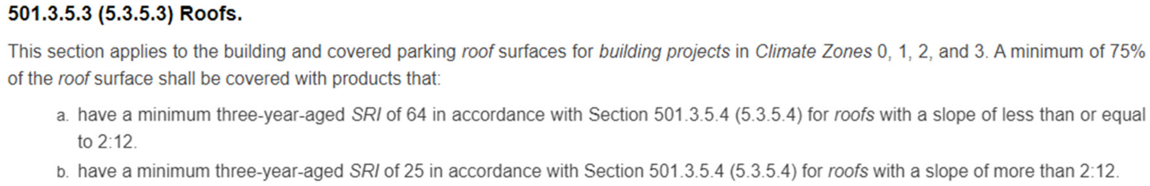
If Cool Roof Rating Council (CRRC) testing for aged reflectance is not available for any roofing products, the aged value shall be determined using the CRRC certified initial value using the equation $\rho_{aged} = [0.2 + ß\ [\rho_{initial} - 0.2]$, where $\rho_{initial}$ = the initial solar reflectance and soiling resistance, ß, listed by product type in Table A5.106.11.2.1.

Solar reflectance may also be certified by other supervisory entities approved by the Energy Commission pursuant to Title 24, Part 1, *California Administrative Code*.

Figure 6. Snapshot of section A4.106.5.1. (Residential) and A5.106.11.2.1(Non-residential) of California Title 24 Building Energy Efficiency Standards.

2.1.5. International Green Construction Code (IgCC)

Section 501.3.5.3 of the IgCC related to cool roofs calls for a minimum aged solar reflectance of 0.55 and a minimum aged thermal emittance of 0.75. Alternatively, it permits achieving a minimum aged solar reflectance index (SRI) of 64 as a compliance option. The IgCC is a model code focused on promoting sustainable and energy-efficient construction practices. The cool roof requirements align with other energy codes but provide a comprehensive framework for green building design and construction. The IgCC also includes provisions for vegetated roofs and other sustainable roofing systems as alternatives to cool roofs.



501.3.5.3 (5.3.5.3) Roofs.

This section applies to the building and covered parking *roof* surfaces for *building projects* in *Climate Zones* 0, 1, 2, and 3. A minimum of 75% of the *roof* surface shall be covered with products that:

a. have a minimum three-year-aged *SRI* of 64 in accordance with Section 501.3.5.4 (5.3.5.4) for *roofs* with a slope of less than or equal to 2:12.

b. have a minimum three-year-aged *SRI* of 25 in accordance with Section 501.3.5.4 (5.3.5.4) for *roofs* with a slope of more than 2:12.

Figure 7. Snapshot of section 501.3.5.3 of the International Green Construction Code (IgCC).

Table 1. Review of current Codes and Standards.

Code/Standard	Cool Roof Requirements
IECC (International Energy Conservation Code)	Commercial: Minimum 3-year aged solar reflectance 0.55, thermal emittance 0.75 (C402.3).

	Residential: Minimum aged solar reflectance 0.55 (0.63 in Climate Zone 1), thermal emittance 0.75.
ASHRAE 90.1	Commercial: Minimum aged SRI 64 (2010) or 82 (2013+), or Minimum aged solar reflectance 0.55-0.70, thermal emittance 0.75. Exceptions for certain roof types.
ASHRAE 90.2	Residential: Minimum solar reflectance 0.65, thermal emittance 0.75, or Minimum SRI 75.
California Title 24	Low-slope roofs: Minimum aged solar reflectance 0.63. Steep roofs: Minimum aged SRI 16-26 based on climate zone.
IgCC (International Green Construction Code)	Minimum aged solar reflectance 0.55, thermal emittance 0.75, or Minimum aged SRI 64.

2.2. ASTM Standards for Solar Reflectance

ASTM has developed several standards to measure the solar reflectance (ability to reflect sunlight) of roofing materials and other construction surfaces:

- ASTM E1918 - Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field.

This standard outlines a method to measure the solar reflectance of roofs and other low-slope surfaces on-site using a pyranometer to measure incoming and reflected solar radiation.

- ASTM E903 - Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres.

This laboratory test method uses an integrating sphere to measure the solar reflectance spectrum of materials across wavelengths representing the solar spectrum.

- ASTM D7897 - Standard Practice for Laboratory Soiling and Weathering of Roofing Materials to Simulate Effects of Natural Exposure on Solar Reflectance and Thermal Emittance.

This practice provides a way to artificially soil and weather roofing samples in the lab to replicate aged conditions after 3 years of use, allowing measurement of long-term solar reflectance.

- ASTM E1980 - Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces.

This standard outlines how to calculate a solar reflectance index (SRI) value, which indicates the steady-state temperature of a surface relative to standard white (SRI=100) and black (SRI=0) surfaces under standard conditions.

These ASTM standards allow measuring initial and aged solar reflectance of roofing products in the lab and field to support the development, testing, and labeling of cool roofing materials with high solar reflectance to reduce urban heat island effects and building cooling loads.

2.3. Different Cool Roof Materials

The second focus of this review is on the diverse range of materials available for cool roofs. Cool roof materials consist of a variety of options, from reflective paints and coatings to specialized tiles and shingles. Each material comes with its own set of characteristics, such as solar reflectance index (SRI), thermal emittance, durability, and cost. Reflective paints and coatings are among the simplest and most cost-effective options for achieving a cool roof effect. These coatings are applied to existing roofs, providing a reflective surface that reduces heat absorption. Other types include Specialized Tiles and Shingles and they often combine reflective surfaces with durable and weather-resistant properties.

Santamouris et al. [1] provided a comprehensive overview of the measurement methods and benefits of using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort. The authors assessed four cool materials: (a) highly reflective and emissive light-colored materials, (b) cool colored materials, i.e., colored materials with increased near-infrared and thus overall solar reflectance compared to similarly colored conventional ones, (c) phase change materials and (d) dynamic cool materials. The results showed that the increasing albedo brought significant benefits, such as energy savings worth \$15 million per year, reduced smog-related expenses by \$76 million per year, and potential global CO2 emission reductions equivalent to about \$500 billion. Levinson et al. [2] investigated the effects of soiling and cleaning on the solar reflectance and heat gain of light-colored polyvinyl chloride (PVC) roofing membranes. The study analyzed 15 white or light-gray PVC membrane samples taken from roofs across the United States. The results showed that black carbon and organic carbon were the main contaminants reducing the solar reflectance of the membranes. Soiling decreased the solar reflectance ratio to 0.41-0.89, indicating a significant loss of reflectance. Soiling increased the solar absorptance ratio to 1.4-3.5, meaning the solar heat gain was up to 3.5 times higher than an unsoiled membrane. In terms of cleaning, the authors revealed that wiping removed much of the black carbon but was less effective for organic carbon. Rinsing and washing removed nearly all remaining soil, except for isolated biomass spots. After cleaning, the solar reflectance ratio increased to 0.94-1.02, and the solar absorptance ratio decreased to 0.9-1.3, indicating near-complete restoration of the original reflective properties. Bretz et al. [3] investigated practical issues for using solar-reflective materials to mitigate urban heat islands. They found that solar-reflective or high-albedo alternatives to traditionally absorptive urban surfaces like rooftops and roadways can reduce cooling energy use and improve urban air quality at almost no cost. In Sacramento, California, it was estimated that 20% of the area is dark roofing and 10% is dark pavement. The overall albedo of Sacramento could potentially be increased by 18% by using solar-reflective surfaces, producing significant energy savings and increased comfort. The authors suggested labeling materials by temperature rise, incentive programs, outreach, and building code changes to promote solar-reflective surfaces and mitigate urban heat islands.

Dornelles et al. [4] investigated the effect of natural weathering on the solar reflectance of cool and standard-colored coatings over 18 months in São Carlos, Brazil. The study exposed 20 coated ceramic tile specimens (12 standard and 8 cool coatings) to natural weathering conditions and measured their spectral reflectance every 3 months. The results showed that there was a significant reduction in solar reflectance for all samples exposed to weathering, except dark green and black coatings which showed a slight increase. Light-colored coatings like white experienced higher reflectance reductions (up to 27.9% for one sample) compared to darker shades. Further, it was noted that soiling from dust, soot deposition, and biological growth had a major impact on reducing the reflectance of white coatings. UV radiation degradation was more significant for darker colors, leading to a slight increase in their reflectance as accumulated dust was more reflective. The authors suggested the development of durable cool coatings, especially white ones, that can maintain high solar reflectance over an extended period to maximize the benefits of cool roofs in reducing building heat gains and cooling loads. Levinson et al. [5] discussed four phases of research on cool materials, from highly reflective white materials to the incorporation of near-infrared reflective pigments and nano-materials. The results demonstrated the significant benefits of cool tile roofs, such as reductions in roof surface temperature (up to 12K), attic air temperature (up to 6.2K), and ceiling heat flux (up to 3.7 W/m2). These thermal improvements further translate to whole-house peak cooling power savings of 210-230 W and annual cooling energy savings of 8-92 kWh/yr (1-6%). Moreover, the potential statewide benefits in California were estimated at 240 MW peak power reduction and 63 GWh/yr energy savings, worth \$15 million per year in energy costs and \$76 million per year in reduced smog-related expenses. Tian et al. [6] reviewed the latest advancements in cool roof research, focusing on super cool roofs, temperature-adaptive roofs, and crucial issues related to their application in urban areas. The study compiled findings from experimental and modeling studies on the thermal performance and energy savings potential of super cool roofs and temperature-adaptive roofs across different climates and building types. The authors also discussed key factors influencing the performance of these advanced cool roof technologies, such as material properties, manufacturing methods, and urban environmental conditions. The results showed that super cool roofs with solar reflectance greater than 0.96 and thermal emittance greater than 0.97 achieved surface temperatures up to 30°C below common roofs and 11.5°C below ambient air temperature during the day. In dry climates, super cool roofs resulted in a net radiative cooling power of 150 W/m2, and large-scale urban implementation of super cool roofs reduced peak urban heat island intensity by 3.2-3.5°C in Kolkata.

Cao et al. [7] investigated the effects of increasing roof albedo (cool roofs) on outdoor air temperatures in Guangzhou, China during summer heat waves and typical summer conditions. They found that during heat waves, cool roofs can reduce daytime urban heat island intensity by roughly 1°C. During summer, cool roofs provided peak daytime temperature reductions of 0.8°C across the urban area. Further, the temperature reduction from cool roofs was found to be greater during heat wave episodes when temperatures were higher (34.1°C vs 31.4°C) and ventilation was lower (33% reduction) compared to typical summer episodes. The authors suggested that the cool roofs can provide significant reductions in outdoor urban air temperatures in the hot and humid climate of Guangzhou, with larger benefits occurring during more stagnant heat wave conditions. Tamhid [8] investigated the thermal energy performance of providing a cool roof system combined with a solar photovoltaic (PV) system to enhance the ambient internal temperature and energy-saving potential for a composite tropical climate in the city of Amroha, India). The results illustrated that cool roof materials like high albedo coatings, green roofs, and phase change materials can significantly reduce the roof surface temperature by 15-25°C compared to traditional roofs and further lead to a reduction in indoor ambient temperatures by 5-10°C. The authors showed that for the case study house, combining a cool roof (green roof and cool tile coating) with a solar PV system led to a 9-10°C reduction in indoor ambient temperature compared to 5 years prior. The authors suggested that the cool roof technologies combined with rooftop solar PV can provide significant energy savings and indoor thermal comfort benefits in composite tropical climates like Amroha, despite an initial investment cost. Miller et al. [9] investigated the potential of cool roof coatings as a residential demand-side management (DSM) strategy for reducing peak electricity demand in tropical Australia. The authors employed numerical simulations using building energy rating software (BersPro 4.2) and a field experiment to evaluate the impact of cool roof coatings on energy consumption and peak demand. A case study house in Townsville, Australia was monitored before and after the application of a cool roof acrylic coating (solar reflectance 0.88). Simulations showed cool roof coatings (solar reflectance 0.9) consistently reduced peak cooling demand by 10-40% compared to dark roofs (solar reflectance 0.15), regardless of construction details. Field measurements confirmed cool roof coatings reduced roof cavity temperatures, closely aligning them with ambient temperatures when combined with reflective foil insulation. The study concluded that while cool roofs can effectively reduce residential cooling loads and peak demand, quantifying the network-level benefits for demand side management is challenging due to diverse building characteristics and occupancy patterns not accounted for in simulation tools.

Kolokotroni et al. [10] investigated the impact of applying a cool roof coating (increasing the roof albedo from 0.1 to 0.6) on an office building in London, UK through field measurements and simulation modeling. Field measurement results showed that after applying the cool roof coating, the open office area was on average cooler by 1.7°C during clear sky periods when solar radiation was high. In terms of modeling results, simulations showed that increasing the roof albedo from 0.1 to 0.6 would reduce the maximum internal air temperature by 1.3°C and average air temperature by 2.1°C in July. Further, a slight decrease was noted in overall annual energy demand (heating + cooling) when using the cool roof with an albedo of 0.6 compared to 0.1, for the case of maintaining 21°C in winter and 25°C in summer. The parametric analysis showed that increasing roof albedo from 0.1 to 0.9 improved summer indoor comfort by reducing air temperatures above 25°C by 25% and operative temperatures above 25°C by 30%. Mastrapostoli et al. [11] studied the cooling potential of a cool fluorocarbon (FC) coating applied to the roof of an industrial building in Oss, Netherlands under temperate climatic conditions. Results showed that FC coating increased the roof albedo from 0.3 to 0.67 after application and lower Indoor temperatures were noted. Energy simulations depicted a 73% decrease in cooling load but a minor 5% heating penalty when using the FC cool roof coating. The authors highlighted the cooling benefits of the high-reflectance FC coating when applied to an industrial building roof in a temperate climate, reducing cooling loads while slightly increasing heating needs. Di Giuseppe et al. [12] investigated the impact of roof reflectivity and building envelope thermal transmittance on the Urban Heat Island (UHI) effect through numerical simulations in typical Italian urban contexts. The authors noted that adopting cool roof materials with high solar reflectance can mitigate outdoor air temperatures by up to 2°C, depending on the building envelope configuration and geographical location. They concluded that the combination of low roof reflectivity and highly insulated envelopes results in the highest outdoor air temperatures, exacerbating the UHI effect.

Pisello et al. [13] presented an innovative cool roofing membrane that incorporates phase change materials (PCMs) into a polyurethane matrix. They mixed paraffin-based PCMs with melting points of 25°C and 55°C into the membrane. The authors found that the PCM inclusion slightly decreased solar reflectance due to increased surface roughness. They noted that a membrane with 35 wt.% PCM concentration exhibited the highest phase change enthalpy of around 14.1 J/g for melting and 13.9 J/g for solidification, nearly doubling the values for lower PCM concentrations. It was concluded that the innovative cool membrane with integrated PCMs combines the benefits of cool roofs and latent heat storage for improved building energy efficiency and indoor thermal comfort. Berdahl & Bretz [14] conducted a preliminary survey of the solar reflectance of cool roofing materials. They performed solar reflectance measurements on various roofing materials including coatings containing aluminum pigments, asphalt shingles, and clay tiles. The spectral reflectance data showed that aluminum coatings have a trade-off - higher solar reflectance from more exposed aluminum flakes, but lower infrared emittance. Even typical 'white' asphalt shingles were found to have low solar reflectance around 21%, as they are manufactured by pressing coated rock granules into the asphalt. The results highlighted the importance of quantifying both solar reflectance and convection coefficients to accurately predict roof temperatures and associated cooling energy penalties for different roofing materials.

Table 2. Review of different cool roof materials.

Year	Location	Focus	Key Findings	Ref.
2011	USA	Cool materials for urban heat island mitigation	Increased albedo from cool materials leads to significant benefits: $15M in annual energy savings, $76M in annual reduced smog expenses, and potential global CO2 emission reductions equivalent to $500B.	[1]
2005	USA	Effects of soiling on solar reflectance of roofing	Soiling reduces solar reflectance and increases heat gain of roofing membranes. Cleaning methods vary in effectiveness.	[2]
1998	Sacramento, California	Practical issues of using solar-reflective materials	Solar-reflective surfaces can reduce cooling energy use and improve urban air quality at almost no cost. Increased albedo could potentially save energy and improve comfort.	[3]
2015	São Carlos, Brazil	Impact of natural weathering on cool coatings	Weathering reduces the solar reflectance of coatings, especially for light colors due to soiling. UV radiation degradation was more significant for dark colors. Development of durable cool coatings recommended for maximizing cool roof benefits.	[4]
2007	USA (California)	Advances in cool roof research	Cool tile roofs provide significant thermal improvements, leading to energy and cost savings. Statewide benefits in California are estimated at reduced peak power and energy savings worth millions annually.	[5]

2023	Kolkata	Advancements in super cool roofs	Super cool roofs achieve substantial surface temperature reductions compared to common roofs, resulting in net radiative cooling power and reduced urban heat island intensity. Large-scale implementation has significant benefits in urban cooling.	[6]
2015	Guangzhou, China	Effects of cool roofs on urban temperatures	Cool roofs reduce urban heat island intensity during heat waves and typical summer conditions. Greater reductions were observed during heat waves with higher temperatures and lower ventilation.	[7]
2023	Amroha, India	Combined cool roof and solar PV system	Cool roof technologies combined with rooftop solar PV significantly reduce roof surface and indoor ambient temperatures, providing energy savings and thermal comfort benefits in tropical climates.	[8]
2015	Townsville, Australia	Cool roof coatings for peak demand reduction	Cool roof coatings consistently reduce residential cooling loads and peak demand. Field experiments confirm reduced roof cavity temperatures and energy savings.	[9]
2013	London, UK	Impact of cool roof coating in temperate climates	Cool roof coatings reduce internal air temperatures in buildings during periods of high solar radiation. Simulations show reductions in maximum and average air temperatures, with slight decreases in overall annual energy demand.	[10]
2014	Oss, Netherlands	The cooling potential of cool coatings in a temperate climate	Cool roof coatings significantly reduce roof surface temperatures and cooling loads in industrial buildings, with minor increases in heating needs.	[11]
2017	Italy	Role of roof reflectivity in mitigating UHI effect	Cool roof materials mitigate outdoor air temperatures, reducing the urban heat island effect. The combination of low roof reflectivity and highly insulated envelopes exacerbates the UHI effect.	[12]
2016	-	Innovative cool roofing membrane with PCMs	Cool roofing membrane with integrated PCMs combines the benefits of cool roofs and latent heat storage for improved building energy efficiency and indoor thermal comfort.	[13]
1997	-	Solar reflectance survey of cool roofing materials	Various roofing materials exhibit different solar reflectance properties. Aluminum coatings show a trade-off between reflectance and infrared emittance. The importance of quantifying reflectance and convection coefficients is highlighted.	[14]

2.4. Energy Performance of Cool Roof Buildings

The third aspect of this review delves into the energy performance of buildings with cool roofs in Canadian winter conditions. While cool roofs are known to reduce cooling loads in warmer climates, their impact on heating loads during winter months is less understood. By maintaining lower roof temperatures, cool roofs can help reduce the temperature differential between indoor and outdoor environments, potentially leading to energy savings in heating.

Gao et al. [15] investigated the thermal and energy performance of near-infrared reflective cool tile roofs in the urban built environment in China. The study used scale model houses with concrete tile roofs coated in different materials (black, white, cool color, standard color) to measure roof surface temperatures, attic air temperatures, and heat fluxes. The results showed that the cool tile coatings reduce roof surface temperature by 12K, attic air temperature by 6.2K, and ceiling heat flux by 3.7 W/m2 compared to standard coatings. For a 1500 ft2 house, the cool tile coatings provided whole-house peak cooling power savings of 210-230 W and annual cooling energy savings of 8-92 kWh/yr. The authors suggested the increased use of cool roofs in both public and residential building energy efficiency standards in hot-summer climates in China. Synnefa et al. [16] investigated the impact of using cool roof coatings on the cooling and heating loads and indoor thermal comfort conditions of residential buildings for various climatic conditions. The study used simulations with TRNSYS thermal software to estimate cooling load reduction, peak cooling demand reduction, and indoor thermal comfort. Results showed that increasing roof solar reflectance from 0.2 to 0.85 reduced cooling loads and peak cooling demand by 25-93% and 11-27% respectively. In terms of thermal comfort, in non-air-conditioned buildings, increasing roof solar reflectance from 0.2 to 0.85 results in decreased hours of discomfort (>27°C) by 9-100% and reduced maximum indoor temperatures by 1.2-3.3°C. The authors concluded that the application of cool roof coatings is an effective and easy technique that contributes to the energy efficiency and thermal comfort of buildings, especially in hot climates. Bozonnet et al. [17] investigated the impact of cool roof coatings on the thermal performance of a low-rise residential building without air conditioning in Poitiers, France. The results illustrated that applying a cool coating (solar reflectance 0.88, thermal emittance 0.90) reduced the mean external roof surface temperature from 30.2°C to 19.8°C during summer. Also, the mean indoor air temperature difference was reduced to 0.47°C after the application of cool coating. It was further noted that the cool roof coating reduced operative temperatures compared to the conventional roof by up to 3°C in the attic space and by around 1°C in the room under the roof. The authors suggested the use of cool roof coatings to improve indoor thermal comfort during summer in residential buildings, with greater benefits for poorly insulated constructions in the French climate.

Hosseini & Akbari [18] investigated the effect of cool roofs on energy consumption in cold climates in Canada: Anchorage, Milwaukee, Montreal, and Toronto, while accounting for the insulating impact of snow cover. The authors used DOE-2.1E building energy simulation software to model several prototype office and retail buildings with different construction vintages and HVAC systems. Results showed that in Anchorage, for an old small office with gas heating, a cool roof led to a heating penalty of 1 GJ/100m2 when considering late winter packed snow, but an annual energy expenditure savings of $18/100m2. For an old retail building in Montreal with gas heating, cool roofs saved up to $62/100m2 annually after accounting for snow insulation effects. In Toronto, cool roofs saved $37/100m2 per year for an old retail building with gas heating when including snow impacts. The study concluded that the cooling energy savings from cool roofs outweighed any heating penalties in these cold climates when properly accounting for the insulating effect of snow on the roof surface. Hosseini et al. [19] investigated the energy performance of cool roofs under the impact of actual weather data in the cold climate of Montreal, Canada. They conducted a large-scale building performance simulation study (3906 simulations) to explore the uncertainty in energy performance when using typical meteorological year (TMY) weather data compared to 30 years of actual meteorological year (AMY) data from 1960-1989. Results showed that there was a 3-29% deviation in predicted space conditioning energy demand when using TMY data compared to the 30-year AMY data for different cool roof designs with varying insulation levels (R-2.4 to R-15.4) and solar reflectance (0.1 to 0.9). Cool roofs with the lowest insulation level (R-2.4) had the largest overestimation in space conditioning energy demand when using TMY versus AMY data. The authors found that the majority of cool roof designs evaluated using TMY data tended to overestimate energy demand compared to AMY data, leading to more conservative designs. Garshasbi et al. [20] performed a comprehensive study to evaluate the energy impact of cool roofs in Australia, considering both building-scale and urban-scale applications across different building types and climate zones. The authors employed Mesoscale climate modeling to estimate the impact of city-scale cool roof implementation on urban climate. They also conducted building performance simulations using EnergyPlus for 17 building types across various Australian cities to quantify cooling/heating loads, indoor temperatures, peak electricity demand, and AC system efficiency under different cool roof scenarios. Results showed that the cool roofs significantly reduced cooling loads, with annual savings up to 90.3 kWh/m2. Further. indoor air temperatures during summer were reduced by up to 3°C with cool roofs and peak electricity demand was reduced by up to 27% by cool roof implementation. The authors highlighted the significant energy-saving potential of cool roofs in Australia, particularly when implemented at both building and urban scales across different building types and climates.

Parker et al. [21] conducted a detailed experimental study to evaluate the energy savings potential of reflective roof coatings in residential buildings across different climate conditions and building characteristics in Florida. The study monitored 9 residential buildings before and after applying reflective roof coatings like white elastomeric, ceramic, or cementitious coatings. For the results, they measured roof surface temperatures, attic air temperatures, ceiling heat fluxes, air conditioning energy use, interior temperatures, and meteorological conditions. For a site with typical insulation, 19% cooling energy savings were observed with the reflective roof coating. For gravel roof and tile roof constructions, 8 kWh/day and 11.6 kWh/day respectively were noted. The authors highlighted the importance of reflective roof coatings across different Florida in terms of reduction in demand for cooling energy and peak demand savings. Pisello [22] investigated the thermal energy performance of cool clay roof tiles for application in historic buildings and cities. The study used a calibrated simulation model of a residential unit in a 16th-century building in Perugia, Italy to compare four tile scenarios - natural red clay tile (Tile A), white cool tile (Tile B), cool colored tile (Tile C), and another cool colored tile (Tile D). The results showed that during summer months, the cool Tile B reduced the mean radiant temperature in the attic by 1°C compared to the natural Tile A. Tile B was able to decrease the primary energy requirement for cooling in the attic by 51% compared to Tile A. Tile C and Tile D reduced the cooling energy need by 33% and 32% respectively, compared to Tile A. Further, by extrapolating to the historic district, the authors estimated the annual cooling energy savings of 952 MWh and 370 t CO2-eq. emissions avoided by using cool tiles instead of traditional clay tiles on residential buildings with occupied attics. Sedaghat et al. [23] explored energy-efficient building solutions like bio-phase change materials (Bio-PCMs) and cool roof coatings for hot regions like Kuwait, Australia, and India. They used TRNSYS simulations and experimental measurements on portable cabins. The results showed that applying an aluminum foil cool roof coating reduced the cooling energy consumption of the cabins by around 15% compared to the base case without cool roofs in Kuwait. Further, increasing the solar reflectance index (SRI) from 72 to 100 for the roof surface resulted in progressively higher cooling energy savings, up to around 20% reduction. Moreover, the usage of Bio-PCMs layers results in an increase of annual total energy savings from 17-22% compared to the base case without PCMs in Kuwait’s climate. The authors recommended the use of cool roof coatings and phase change materials as passive techniques to reduce cooling loads and overall energy consumption in hot climate regions like Kuwait.

Piselli et al. [24] investigated the optimum design of roof solar reflectance and thermal insulation levels to minimize building annual HVAC energy consumption across different climate zones worldwide. The authors used EnergyPlus building simulation software coupled with the GenOpt optimization program to model and optimize the performance of a small office building prototype. They varied roof solar reflectance (from 0.1 to 0.8) and insulation thickness (from 0 to 0.25m) to find the optimum configuration minimizing annual HVAC energy use. Results showed that in hot and warm climates like Abu Dhabi, New Delhi, and Mexico City, the optimum configuration was a cool roof (solar reflectance 0.8) with little to no insulation (0-0.03m thickness). In cold climates like Moscow and Tampere, the optimum was a dark roof (solar reflectance 0.1-0.5) with maximum insulation (0.25m) to reduce heating loads. Finally, in mild climates like Sydney, Rome, and San Francisco, the optimum was a cool roof (0.8) with minimal insulation (0-0.03m) as cooling loads dominated. The authors concluded that in the majority of climates, the optimum roof design to minimize HVAC energy use was a cool roof with little to no insulation, except in very cold climates which required dark roofs and high insulation levels. Qu et al. [25] investigated the cooling effect and energy savings of a cool white coating used on the roof of scale model buildings in Beijing, China. The study used four identical scale model buildings with concrete roofs - two with the cool white coating applied and two left unpainted. Measurements were taken for solar reflectance (albedo), thermal emittance, roof surface temperatures, and ceiling heat fluxes. The results showed that the cool white coating resulted in an increase of solar reflectance by 0.493 (lab) or 0.459 (field) compared to unpainted roofs, solar reflectance index (SRI) by 67.5 (lab) or 62.3 (field), and reduced roof surface temperatures by 25.5°C (lab) or 23.5°C (field). Further, for a model house, the cool white coating provided an annual peak cooling demand reduction of 0.1 kWm-2yr and an annual cooling energy savings of 6.8 kWhm-2yr-1 (lab) or 6.4 kWhm-2yr-1 (field). He et al. [26] investigated the thermal and energy performance of cool roofs in the Shanghai area through field experiments and building energy simulations. Results showed that compared to a common roof, the maximum outer surface temperature reduction for the cool roof was 14.5°C in summer daytime and 12.6°C in winter daytime. The average daily heat flux reductions were 1.9 W/m2 for the cool roof compared to the common roof. Further, for a 23-story office building in Shanghai, applying a cool roof reduced annual cooling load by 7.1% and overall energy consumption by 3.8% compared to a common roof. The results highlighted the potential of cool roofs as passive cooling techniques to improve building energy efficiency and reduce cooling demands in the hot summer climate of Shanghai.

Vakilinezhad & Khabir [27] evaluated the thermal and energy performance of cool envelopes combined with retroreflective and thermochromic coatings on typical low-rise residential buildings in hot-arid and hot semi-arid climates. In the hot-arid climate, results showed that the retroreflective coating with high solar reflectance on the building envelope is the most optimal coating to decrease annual cooling loads by 26%. In the hot semi-arid climate, combining retroreflective and thermochromic coatings on the building envelope is the most optimal alternative to decrease annual cooling loads by 18% and heating loads. The authors provided guidance on selecting the most suitable cool coatings for building envelopes to reduce energy consumption in hot arid and semi-arid regions. Fayad et al. [28] discussed the benefits and considerations of using white roofing materials in emerging economies. They found that the white roofs reflect a substantial portion of incident solar radiation, reducing heat gain into buildings and providing net annual energy savings of 23-34% in hot climates like Saudi Arabia and Kuwait, even accounting for increased heating needs. The authors further pointed out that regular cleaning is required to maintain high reflectivity and energy savings (Figure 8).

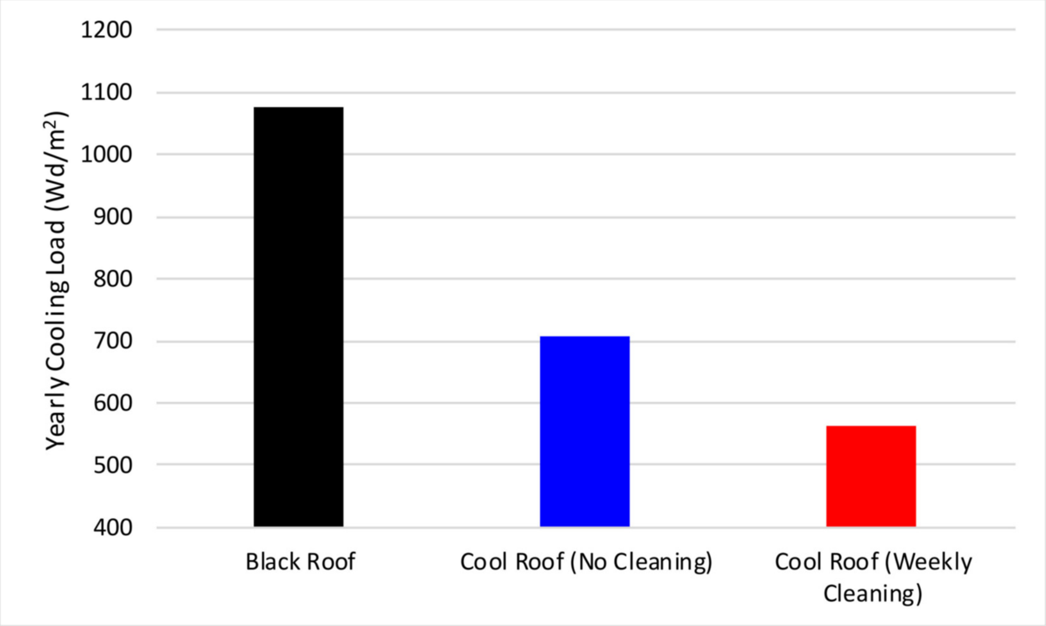


Figure 8. Comparison of the yearly cooling energy load of conventional/black roof and white roof based on no cleaning condition and weekly cleaning condition for Saudi Eastern Province climates. Source: Fayad et al. [28].

Costanzo et al. [29] investigated the performance of cool roofs as a passive cooling strategy in different climates and for varying insulation levels in Italy. The study used EnergyPlus simulations of an existing low-rise office building in Catania (hot-humid climate) with different cool paint coatings applied to the roof ($r = 0.25, 0.45, 0.65, 0.85$). The results showed that applying commercial cool paint ($r = 0.45$) reduced the peak cooling load by 14% and improved thermal comfort conditions during summer. Using a high-performance cool paint ($r = 0.85$) further decreased the peak cooling load by 44%. However, cool roofs also increased the peak heating load in winter by 4.7% for $r = 0.45$ and 14.7% for $r = 0.85$, due to lower heat gains through the roof. For poorly insulated buildings, the annual primary energy (PE) consumption increased by 5-9% when using cool paints, as the heating penalty outweighed the cooling savings, especially in colder climates like Milan. With improved envelope insulation levels, cool roofs reduced annual PE consumption in Catania and Rome when using a heat pump for heating, but still increased PE use in Milan due to the severe winter. The authors suggested the adoption of cool roofs in hot climates like Catania and Rome, especially for well-insulated buildings using efficient heating systems, as they effectively reduce cooling loads while mitigating the urban heat island effect. Barozzi & Pollastro [30] investigated the thermal and energy performance of cool roof coatings in temperate climates through an experimental campaign using three outdoor test cells (C1, C2, C3) in Milan, Italy with C1 being a conventional warm roof, C2 having a cool roof coating ($r = 0.45$), and C3 being a vented roof system. The results showed that the cool roof coating in C2 reduced the external surface temperature by 21°C on average compared to C1 during summer. However, after 12 months of exposure, the solar reflectance of the cool coating degraded by 46%, much higher than expected, due to fouling and pollution at the test site. In terms of indoor thermal comfort during summer, C2 performed better than C1 but worse than the vented roof C3 at night due to its lower thermal wave phase shift. During intermediate seasons, C1 showed the best thermal comfort. For energy consumption, in the first summer (2014), C2 reduced cooling energy use by 22% compared to C1 and 18% compared to C3. However, in the second summer (2015) after coating degradation, the cooling savings of C2 dropped to only 11% versus C1 and 9% versus C3. In winter, C2 increased heating energy use by around 5-15% compared to C1 and C3 due to lower heat gains. The authors suggested adopting cool roofs in hot climates with routine maintenance to preserve their high solar reflectance and achieve sustained cooling energy savings.

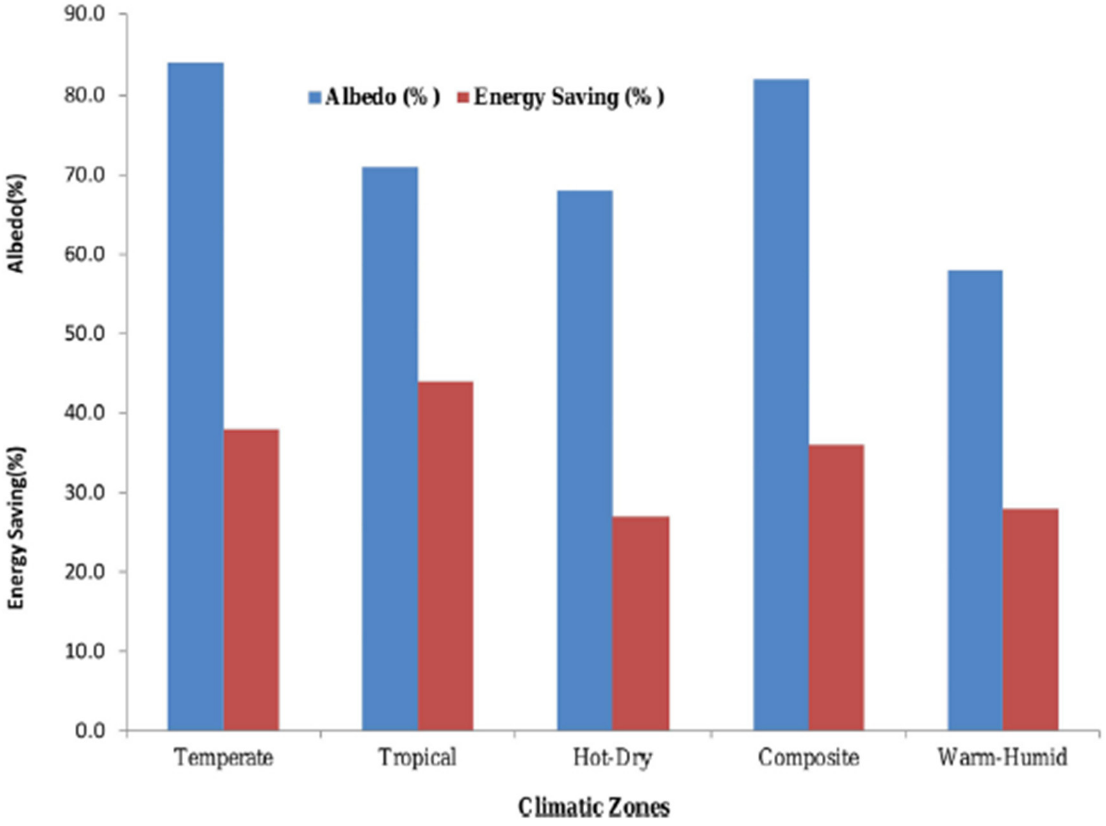


Figure 9. Average albedo and average energy saving for different climatic zones. Source: Rawat et al. [31].

Rawat et al. [31] conducted a comprehensive literature review to analyze the thermal performance of cool roofs in various climatic zones. The review covered over 30 research papers and case studies from locations like the USA, UK, France, Italy, Singapore, India, and others to provide a global perspective. Cool roofs with high solar reflectance and emittance can reduce energy consumption for cooling buildings by 15-35.7% in different climates like temperate, tropical, composite, hot, and warm-humid zones (Figure 9). They can also lower the roof surface temperature by 1.4-4.7°C compared to conventional roofs. Optimum reflectivity values of 0.6-0.7 are recommended to achieve maximum energy savings in cooled and non-cooled buildings. They examined studies from multiple climatic zones including temperate, tropical, composite, hot, and warm-humid zones to understand the energy savings and temperature reduction potential of cool roofs in different climates. The article by Ashtari et al. [32] comprehensively reviewed over 90 research papers and case studies to synthesize the advantages, limitations, and potential of cool roof technology as an efficient passive solar measure. For the benefits, they concluded that cool roofs with high solar reflectance (typically 0.6-0.7) and high thermal emittance can significantly reduce cooling energy consumption in buildings across different climates. Quantitative studies showed cooling energy savings ranging from 15-35% in temperate, tropical, composite, hot, and warm-humid zones, while also lowering roof surface temperatures by around 1.4-4.7°C compared to conventional roofs. At the building scale, numerous experimental and simulation studies across the U.S., Europe, Asia, and Australia have demonstrated the cooling energy savings and thermal comfort benefits of cool roofs for both residential and commercial buildings. On an urban scale, implementing cool roofs can help mitigate the urban heat island effect by reducing ambient air temperatures by 1-2°C and decreasing peak electricity demand by up to 10%. However, the authors illustrate that the heating penalty from cool roofs may outweigh cooling benefits in cold climates, necessitating climate-specific analysis.

Table 3. Review of the energy performance of cool roof buildings.

Year	Location	Focus	Key Findings	Ref.
2014	China	Near-infrared reflective cool tile roofs	Cool tile coatings reduce roof surface temperature, attic air temperature, and ceiling heat flux, providing significant whole-house cooling power and energy savings. Suggested increased use of cool roofs in hot-summer climates in China.	[15]
2007	Various	Impact of cool roof coatings on building energy	Cool roof coatings reduce cooling loads and peak demand, improve thermal comfort, and contribute to energy efficiency, especially in hot climates.	[16]
2011	Poitiers, France	Thermal performance of cool coatings in residential buildings	Cool roof coatings significantly reduce external roof surface temperatures and indoor operative temperatures, improving thermal comfort in residential buildings during summer.	[17]
2016	Canada (Anchorage, Milwaukee, Montreal, Toronto)	Cool roofs in cold climates	Cool roofs provide significant energy savings in cold climates when considering the insulating impact of snow cover, outweighing any heating penalties.	[18]
2017	Montreal, Canada	Impact of actual weather data on cool roof energy performance	Predicted space conditioning energy demand using typical meteorological year (TMY) data tends to overestimate compared to actual meteorological year (AMY) data, leading to more conservative cool roof designs.	[19]
2023	Australia	Energy impact of cool roofs in Australia	Cool roofs significantly reduce cooling loads, indoor air temperatures, and peak electricity demand, highlighting their substantial energy-saving potential at both building and urban scales across different climates and building types in Australia.	[20]
1997	Florida	Energy savings potential of reflective roof coatings	Reflective roof coatings provide significant cooling energy savings in residential buildings across different climate conditions in Florida.	[21]
2015	Perugia, Italy	Thermal-energy performance of cool clay roof tiles	Cool clay roof tiles significantly reduce attic temperatures and cooling energy requirements in historic buildings, providing substantial annual energy savings and CO_2 emissions reductions.	[22]
2023	Kuwait, Australia, India	Energy-efficient solutions for hot regions	Cool roof coatings and phase change materials reduce cooling loads and overall energy consumption in hot climate regions, offering passive techniques for energy savings.	[23]
2019	-	Optimization of roof design for HVAC energy savings	Optimal roof designs vary by climate: cool roofs with minimal insulation in hot climates, dark roofs with maximum insulation in cold climates, and cool roofs with minimal insulation in mild climates.	[24]
2019	Beijing, China	Cooling effect and energy savings of cool white coatings	Cool white coatings significantly increase solar reflectance, reduce roof surface temperatures, and provide annual cooling energy savings in residential buildings.	[25]
2020	Shanghai, China	Thermal and energy performance of cool roofs	Cool roofs reduce outer surface temperatures, daily heat flux, cooling loads, and overall energy consumption in office buildings,	[26]

			demonstrating their potential for improving building energy efficiency in hot climates.	
2023	Hot-arid and hot semi-arid climates	Thermal and energy performance of cool envelopes	Cool envelopes with retroreflective and thermochromic coatings significantly reduce annual cooling loads in hot-arid and semi-arid climates, guiding energy-efficient building solutions in these regions.	[27]
2021	Emerging economies	Benefits of white roofing materials in emerging economies	White roofs provide substantial energy savings and contribute to indoor thermal comfort in hot climates, despite increased heating needs and the need for regular cleaning to maintain reflectivity.	[28]
2013	Italy	Performance of cool roofs in different climates	Cool roofs reduce cooling loads and improve thermal comfort in hot climates, but may increase heating loads in cold climates, especially for poorly insulated buildings.	[29]
2016	Milan, Italy	Thermal and energy performance of cool roof coatings	Cool roof coatings reduce external surface temperatures and cooling energy use but may require maintenance to sustain high reflectivity and achieve continued energy savings.	[30]
2022	-	Thermal performance of cool roofs in various regions	Cool roofs with high solar reflectance and thermal emittance can significantly reduce cooling energy consumption in buildings across different climates.	[31]
2021	-	Advantages and limitations of using cool roofs as an effective passive solar technique	Cool roofs can reduce cooling energy consumption but may increase heating loads in cold climates, necessitating a comprehensive analysis and potential based on climate-specific conditions.	[32]

2.5. Hygrothermal Performance of Cool Roof Buildings

The fourth focus of this review is on the hygrothermal performance of buildings with cool roofs. Hygrothermal properties refer to how materials interact with moisture and heat, affecting factors such as condensation, mold growth, and overall building durability. In cold climates, the interplay between cool roofs and moisture dynamics becomes particularly significant. Cool roofs may affect moisture levels within a building's envelope. Reduced heat absorption by the roof can alter moisture migration patterns, potentially impacting insulation materials and leading to condensation issues. It is important to understand these dynamics to enhance the hygrothermal performance.

Saber [33] investigated the hygrothermal performance of cool roofs with reflective coating material (RCM) compared to black roofs in the hot, humid, and dusty climates of Saudi Arabia's Eastern Province and Kuwait City. The author found that black roofs always have lower moisture levels than cool roofs with RCM, both with and without cleaning. However, the highest relative humidity in all roof components remained below 80%, indicating no risk of condensation or mold growth for both cool and black roofs in these climates. The cooling energy savings from cool roofs were much greater than the heating penalty, resulting in net annual energy savings of 25% (no cleaning) and 34% (weekly homemade cleaning) in the Saudi climate and 23% (no cleaning) and 31% (weekly homemade cleaning) in the Kuwaiti climate. The study highlighted the potential of cool roofs with reflective coatings to provide significant net energy savings in hot and dusty climates like Saudi Arabia and Kuwait, without risking moisture accumulation or mold issues. Buxbaum et al. [34] investigated the hygrothermal performance and durability of non-ventilated lightweight flat roofs with cool roofing membranes in the Central European climate. The results showed that the white cool roofing membrane (solar reflectance ~0.78) had the most significant drying effect, with total water content leveling off at a seasonal maximum of ~3.8 kg/m2 after 5 years. The light grey membrane (solar reflectance ~0.65) and dark grey membrane (solar reflectance ~0.50) showed improved drying, with total water content leveling off at ~3.6 kg/m2 and ~3.55 kg/m2 respectively. In terms of accumulated moisture content at the exterior of the OSB, the authors reported the value above the critical 20% level during all 5 winter periods with the white cool roof. For the light grey and dark grey membranes, they allowed the exterior OSB to dry out faster, with moisture contents leveling off slightly above/below 20% respectively after 5 years.

Further, the humidity level at the OSB-insulation interface for the white cool roof, remained above 95% RH every winter, indicating potential mold risk. The RH values stand close to 80% for the light grey and dark grey roofs. Moghaddaszadeh Ahrab & Akbari [35] investigated the hygrothermal behavior of flat cool (high reflectance) and standard (low reflectance) roofs on residential and commercial buildings across different climates in North America using WUFI simulations. They found that for office buildings, no moisture accumulation problems were observed during the 5-year simulation period across all climates and roof types. For residential buildings in very cold cities like Anchorage, Edmonton, and St. John's, white typical roofing compositions with conventional vapor retarders experienced moisture accumulation issues. The authors proposed that using smart vapor retarders or self-drying roofs helped decrease the risk of moisture accumulation in these cold climates. Also, in very cold climates, adding a ventilated air space along with a smart vapor retarder eliminated moisture accumulation risk and prevented excessive moisture content in oriented strand board (OSB).

Saber et al. [36] investigated the hygrothermal performance and energy savings potential of cool roofs compared to conventional black roofs in the hot and humid climate of Saudi Arabia's Eastern Province. They performed numerical simulations using a validated hygrothermal model to analyze the moisture accumulation, temperature profiles, heat fluxes, and energy loads for a typical low-rise building roof system with varying insulation levels (0-203mm) and roof solar absorptances (0.05-0.88). It was noted that the cool roofs with low solar absorptance (0.05-0.2) showed significantly lower monthly and yearly cooling energy loads compared to black roofs (absorptance 0.88). For a roof with 102 mm insulation, reducing absorptance from 0.88 to 0.2 and 0.05 decreased the July cooling load by 54% and 75% respectively. In terms of annual cooling or total load, using a cool roof allowed reducing insulation levels by up to 61% compared to a conventional black roof. The authors suggested that while cool roofs can provide significant energy savings in hot climates like Saudi Arabia, their hygrothermal performance must be evaluated to optimize insulation levels and avoid moisture accumulation risks. Saber et al. [37] investigated the long-term hygrothermal performance of white and black roofing systems under different North American climates. The study used a comprehensive hygrothermal model for quantifying moisture transport, temperature distribution, and effective thermal resistance. The authors found that the black roofs exhibited significantly higher external surface temperatures compared to white roofs, with maximum hourly differences of up to 42°C in the Toronto climate. In terms of energy load, black roofs had higher yearly cooling energy loads (up to 3.2 times) but lower yearly heating energy loads compared to white roofs. In cold climates like Saskatoon, the lower solar absorption of white roofs leads to higher yearly heating energy loads compared to black roofs. For moisture accumulation, it was noted that the moisture within the roofing assembly increased over time for both white and black roofs, with higher accumulation observed for black roofs in warmer climates like Phoenix. As illustrated in Figure 10a, black roofs did not experience year-to-year moisture accumulation after 2 years in the outdoor climates of Wilmington, Phoenix, Seattle, Toronto, and Montreal. For Saskatoon and St. John's, this lack of accumulation was observed after 4 and 6 years, respectively. Furthermore, the average moisture content in the fiberboard for these different climates remained below 19%. These simulations indicate that the modeled black roof presents a low risk of moisture damage across the various locations. Saber [38] investigated the performance of a reflective coating material (RCM) for cool roofs in the hot, humid, and dusty climate of Jubail Industrial City, Saudi Arabia. They conducted experimental tests on glass specimens coated with the RCM to measure the loss of short-wave solar reflectivity of the RCM over time due to dust/dirt accumulation. They further evaluated the effectiveness of different cleaning methods (air blowing, rinsing, detergent washing, bleach cleaning) in restoring the initial solar reflectivity. The results showed that after 91 days of exposure, the RCM's reflectivity dropped to 72% without cleaning. Rinsing with water and professional cleaning with bleach restored reflectivity to

93% and 95.5% respectively after 91 days. The authors suggested a periodic cleaning to maintain the high solar reflectance and cooling benefits of reflective coatings in hot, dusty climates.

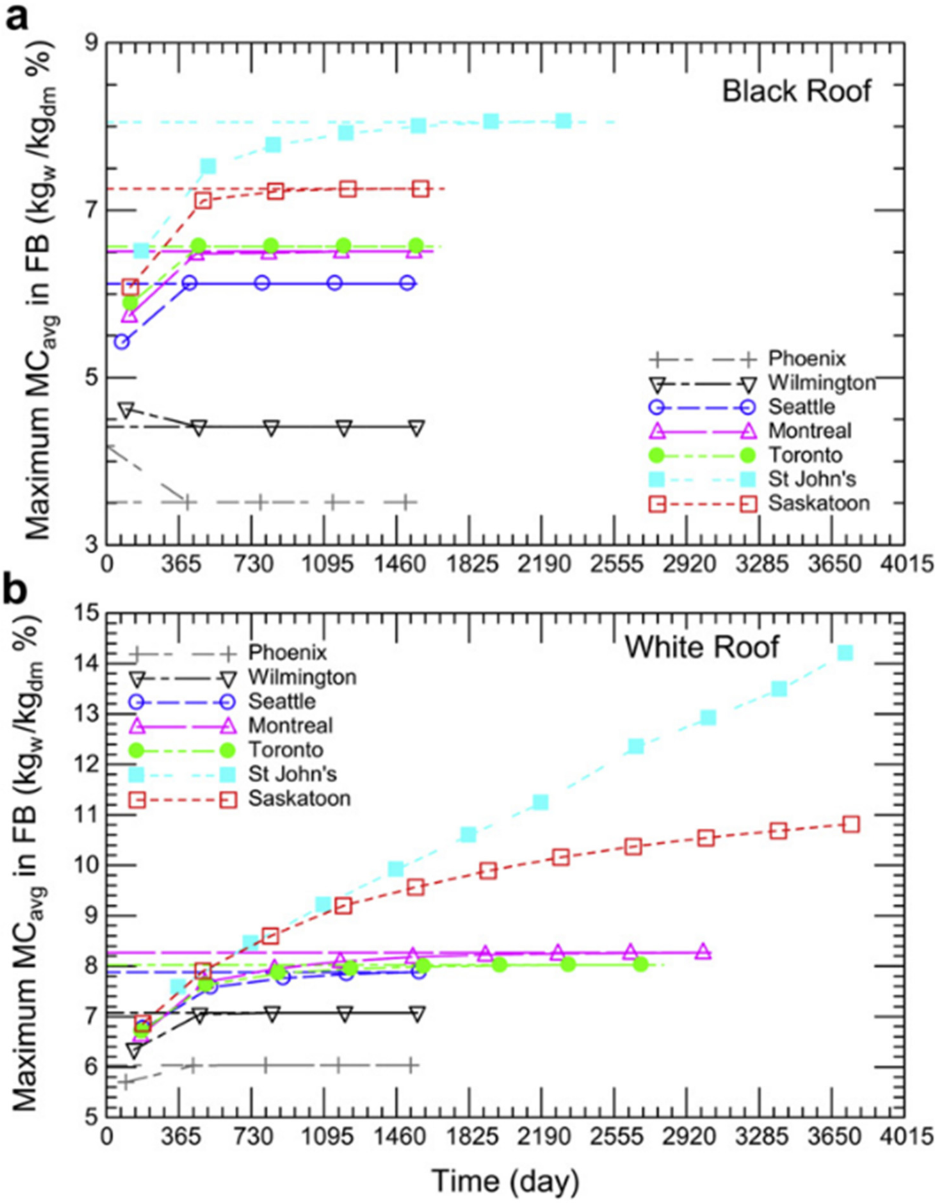


Figure 10. Time series of maximum average moisture content in the fibreboard for white and black roofing systems at different locations. Source: Saber et al. [37].

Table 4. Review of the hygrothermal performance of cool roof buildings.

Year	Location	Focus	Key Findings	Ref.
2022	Saudi Arabia, Kuwait	Hygrothermal performance of cool roofs	Cool roofs with reflective coating material (RCM) provide significant net annual energy savings of 25-34% in hot and dusty climates without moisture accumulation or mold growth risk.	[33]
2013	Central Europe	Hygrothermal performance of non-ventilated lightweight flat roofs	White cool roofing membranes have significant drying effects but may lead to moisture accumulation issues at the OSB-insulation interface, especially in cold climates, indicating potential mold risk.	[34]

			Light and dark grey membranes show improved drying but still pose moisture accumulation risks.	
2013	North America	Hygrothermal behavior of cool and standard roofs	Cool roofs exhibit lower external surface temperatures and lower yearly cooling energy loads compared to standard roofs. Moisture accumulation occurs in both roof types, with higher accumulation observed for standard roofs in warmer climates.	[35]
2019	Saudi Arabia	Hygrothermal performance of cool roofs	Cool roofs with low solar absorptance significantly reduce cooling energy loads compared to conventional black roofs, allowing for a reduction in insulation levels while avoiding moisture accumulation risks.	[36]
2012	North America	Hygrothermal performance of white and black roofs	Black roofs exhibit higher external surface temperatures and higher yearly cooling energy loads compared to white roofs. Moisture accumulation occurs in both roof types, with higher accumulation observed for black roofs in warmer climates.	[37]
2021	Saudi Arabia	Performance of reflective coating material in hot, humid, and dusty climate	Reflective coating material (RCM) for cool roofs maintains high solar reflectivity when cleaned regularly, providing effective cooling benefits in hot, dusty climates.	[38]

3. Conclusion

Cool roofs, with their higher solar reflectivity and heat emissivity, present a promising solution for enhancing building energy efficiency and mitigating urban heat island effects. This review has explored the provisions in current codes and standards, various cool roof materials, and the energy and hygrothermal performance of cool roof buildings in Canadian climates. Key findings include the potential for cool roofs to significantly reduce cooling loads and improve indoor comfort during hot seasons. However, there are also considerations for increased heating requirements during winter, particularly in colder climates. The balance between these factors is crucial for optimizing the net energy benefits of cool roofs. Additional benefits of cool roofs include extended roof service life, reduced peak electricity demand, and improved urban air quality. These advantages, coupled with the development of advanced cool roof technologies such as spectrally selective coatings, can further enhance their effectiveness. To maximize the benefits of cool roofs in Canada, it is essential to consider specific climate conditions, building characteristics, and occupant needs. Proper insulation, HVAC system design, and maintenance practices are vital to mitigate potential heating penalties and ensure year-round performance.

In terms of cool roof materials, it was noted that there is a lack of comprehensive studies on the performance and durability of novel cool roof materials, such as phase change materials (PCMs) embedded in roofing membranes or aerogel-based coatings. Future research should focus on novel cool roof materials like phase change materials and aerogel-based coatings, their long-term performance, and their cost-effectiveness. Additionally, understanding the impact of roof slope, urban geometry, and seasonality on cool roof performance will provide valuable insights for optimizing design and implementation. It is worthwhile to investigate the long-term effectiveness and cost-effectiveness of these innovative materials in maintaining high reflectivity, thermal insulation, and moisture resistance. Regarding the energy performance of cool roofs, it was found that most studies have focused on warm or mixed climates, leaving a gap in understanding their effectiveness in cold climates. Research could be made to investigate the energy savings potential of cool roofs in cold climates, considering both heating and cooling seasons. Further, the hygrothermal performance of cool roofs in humid climates, particularly regarding moisture control and condensation risk, is not well understood. Future research can explore how cool roofs interact with moisture levels in humid environments, considering factors such as vapor permeability, air sealing, and ventilation. It can help develop guidelines for designing cool roofs that effectively manage moisture without compromising energy efficiency.

There is a need to compare simulations with real-world studies to validate the accuracy of modeling approaches. The impact of seasonality on cool roof efficacy and UHI mitigation and the role of green spaces in conjunction with cool roofs should be investigated. Future studies can be focused on exploring the effect of surrounding urban geometry (e.g., tall buildings, narrow streets) on the performance of cool roofs. Field studies and computational modeling can help assess how shading from neighboring buildings, canyon effects, and air circulation patterns impact the cooling effectiveness of cool roofs. This research can guide urban planners in optimizing cool roof implementation in dense urban environments. Further research is required to better understand the effects of cool roofs on cold and continental climates, as well as the impact of degradation on their long-term effectiveness. Finally, there is a lack of comprehensive life cycle assessments (LCAs) that consider the environmental impacts of cool roof materials, from manufacturing to disposal. There is a need to conduct LCAs to compare the environmental footprint of cool roof materials (e.g., embodied energy, greenhouse gas emissions) with traditional roofing materials.

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