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Review

Solar Reflectance Index of Building Envelope Materials: A Comparative Review of North American and European Standards and Long-Term Performance

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Abstract: The Solar Reflectance Index (SRI) is a standardized metric used to assess the reflective properties of materials in relation to solar radiation and their capacity to emit absorbed heat, particularly within the infrared spectrum. Materials with high SRI values, often referred to as "cool materials", contribute to ambient temperature regulation, Urban Heat Island (UHI) mitigation, and cooling energy demand reduction. The effectiveness of SRI depends on factors such as solar incidence angles, intrinsic material properties, and varying environmental conditions. Accurate assessments require the implementation of standardized testing and rating methodologies. This paper reviews and compares North American (ASTM E1980, ASTM C1549, ASTM C1371) and European (EN 15976) standards to determine SRI, focusing on the impacts of weathering and climatic factors on material aging. The study highlights the inadequacy of current practices, which typically measure SRI after only three years of exposure, and advocates for long-term performance monitoring across diverse climates. Key findings reveal that high-SRI materials can reduce surface temperatures by up to 20 °C, significantly lowering cooling energy demands. The study recommends the development of comparable standards to measure solar reflectivity on vertical surfaces, emphasizing the importance of assessing long-term performance across various climatic conditions. Findings underscore the importance of advanced modeling, innovative materials development, and effective maintenance strategies to extend the durability and efficacy of cool materials. The novelty of this work lies in its comprehensive framework for SRI assessment, integrating advanced modeling, innovative materials development, and real-world performance monitoring. This study provides actionable insights for policymakers, urban planners, and architects to enhance building energy efficiency and urban resilience.

Keywords: solar reflectance index (SRI); cool materials; urban heat island (UHI) mitigation; durability testing; materials weathering and aging

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1. Introduction

Cool materials are advanced building materials designed to mitigate the Urban Heat Island (UHI) effect and reduce energy consumption in buildings. These materials are distinguished by their high solar reflectance (albedo) and thermal emittance. These properties enable cool materials to maintain lower surface temperatures by reflecting more sunlight and releasing absorbed heat more effectively compared to conventional materials. Consequently, they reduce the heat absorbed by buildings and urban environments, contributing to energy savings and improved urban microclimates.

For horizontal surfaces such as roofs and pavements, examples include white elastomeric coatings, reflective membranes, and high-albedo concrete or asphalt. These materials reduce surface temperatures by 10–20 °C on sunny days, lowering cooling loads by 10 to 50%, and decreasing ambient urban temperatures by 2 to 8 °C, depending on climate and application [1–5]. For vertical surfaces such as facades, high-reflectivity paints with UV-resistant coatings and textured claddings designed to optimize reflectance are commonly used. These materials contribute to energy savings by reflecting solar radiation and mitigating heat absorption, reducing building cooling demands by up to 40% in hot climates [6]. Additionally, urban-scale deployment of these materials has been shown to decrease air temperatures by 1–8 °C in Canadian cities from Ottawa to Vancouver, respectively, which can alleviate the intensity of UHI effects and enhance outdoor thermal comfort [7,8].

Cool materials differ from conventional materials primarily in their thermal and radiative properties. Cool materials have a higher Solar Reflectance Index (SRI), typically exceeding 64, compared to conventional materials, which often fall below 30. They also exhibit higher thermal emittance, enabling them to dissipate absorbed heat more efficiently. These properties result in cooler surface temperatures and lower heat transfer into buildings. Unlike conventional materials, cool materials are often coated with UV-resistant and weather-durable finishes, enhancing their performance and lifespan. For example, while conventional asphalt roofs can reach up to 80 °C on a sunny day, cool roofs with reflective coatings can remain as low as 60 °C under similar conditions. This difference influences indoor cooling energy demands and outdoor heat mitigation. The lower thermal conductivity of cool materials further distinguishes them, as it minimizes heat storage and re-radiation.

When compared to conventional materials such as asphalt and dark-colored tiles, cool materials exhibit superior performance. Conventional materials have low reflectivity and emissivity, causing them to absorb and retain more heat, exacerbating the UHI effect. In contrast, cool materials with high reflectance and emissivity radiate heat more effectively, reducing thermal discomfort and energy requirements. For instance, the Solar Reflectance Index (SRI) of cool materials often exceeds 50, while materials like asphalt typically have an SRI below 10. Table 1 compares cool materials vs. conventional materials.

Table 1. Comparison of cool and conventional materials.

Property	**Cool Materials**	**Conventional Materials**
Solar Reflectance	High ($\geq$0.65)	Low ($\leq$0.30)
Thermal Emittance	High ($\geq$0.75)	Variable; often low
Surface Temperature	Reduces by 10–20 °C	Retains more heat
UHI Mitigation Potential	Significant	Limited
Degradation Rate	Lower due to UV-resistant coatings	Higher
Cost	Higher initial cost (10–50% more)	Lower initial cost
Energy Efficiency	Reduces cooling energy demand by 10–40%	High heat absorption increases cooling energy needs
Durability	Resistant to UV radiation and weathering (15–20 years)	Moderate lifespan (10–15 years), prone to heat degradation
Thermal Behavior	Reflects sunlight, emits absorbed heat efficiently	Absorbs and retains heat, contributing to urban warming
Payback Period	Typically 5–10 years due to energy savings	No significant payback benefits
Environmental Impact	Mitigates Urban Heat Island effect and reduces urban temperatures by up to 2 °C	Contributes to Urban Heat Island effect

Numerous studies highlight the effectiveness of these materials. Santamouris et al. (2013) examined PCM-doped coatings, showing substantial energy savings in both residential and commercial buildings [9]. Cool pavements were explored by Qin et al. (2015), who demonstrated that reflective pavement materials significantly reduce urban surface temperatures [10]. Dimoudi et al. (2014) analyzed the integration of cool materials in

Greece, demonstrating their utility in outdoor urban spaces as part of broader bioclimatic interventions [11]. Super cool materials with advanced properties for heat mitigation were reviewed by Santamouris et al. (2020), while Wang et al. (2021) synthesized research on the use of cool pavements, focusing on their reflective and permeable properties [12–14].

In addition to their cooling and energy-saving properties, cool materials are engineered for durability and long-term performance. Many advanced coatings, such as those containing titanium dioxide, resist weathering and maintain their reflectance over years of use. Regular cleaning and maintenance further prolong the efficiency of these materials.

Cool materials typically have higher initial costs due to specialized manufacturing and advanced coatings, ranging from USD 1 to USD 3 more per square meter than conventional alternatives. However, their energy-saving potential offsets these costs over time. In hot climates, cool roofs and walls can reduce annual cooling energy consumption by 10–40%, resulting in a payback period of 3–5 years. For instance, a building with a high-SRI roof can save USD 0.20–USD 0.60 per square foot annually in energy costs. In terms of long-term performance, cool materials often experience degradation due to environmental factors like UV radiation and pollution, which can reduce their SRI by approximately 20% within three years. Advanced UV-stable coatings and maintenance strategies, such as periodic cleaning, help mitigate these effects. By comparison, conventional materials degrade faster in their thermal performance and typically lack durability features, leading to higher long-term operational costs and less significant energy savings.

In another study, Kitsopoulou et al. (2024) reported that the cost of cool materials can be 10–50% higher than that of traditional materials like asphalt or standard concrete [12]. However, these materials significantly reduce cooling energy demand by 10–40%, depending on the building design and local climate [12], as highlighted by El-Darwish and Gomaa (2017) [13–15]. This substantial reduction in energy consumption makes cool materials cost-effective in the long run, with a typical payback period of five to ten years due to accumulated energy savings.

The long-term performance of cool materials is another key factor that distinguishes them from conventional options. These materials are engineered to retain their reflective and emissive properties over time, even in harsh environmental conditions. Advanced coatings, such as those based on titanium dioxide, are designed to resist UV radiation and dirt accumulation, ensuring durability and consistent thermal performance. Regular maintenance, including periodic cleaning, is essential to prolong their lifespan and maintain their effectiveness. The lifespan of cool materials typically ranges from 15 to 20 years, comparable to or exceeding that of conventional materials. However, some materials, particularly reflective coatings, may experience thermal degradation when exposed to extreme heat over long periods, necessitating reapplication to maintain their performance [16,17].

In comparing cool materials to conventional materials, several distinctions are apparent. Cool materials have a higher upfront cost but yield significant energy savings over their lifespan. They outperform conventional materials in thermal behavior, reflecting sunlight and emitting absorbed heat efficiently, which reduces cooling demands. Conventional materials like asphalt and standard concrete, on the other hand, absorb and retain heat, contributing to increased indoor cooling needs and exacerbating the UHI effect. The durability of cool materials is also superior, with many products resistant to weathering and UV damage, while conventional materials may degrade more rapidly under similar conditions. Furthermore, cool materials have a positive environmental impact, as they mitigate the UHI effect and reduce urban temperatures by up to 2 °C. In contrast, conventional materials often intensify the UHI effect, creating additional heat stress in urban areas.

For instance, reflective roof coatings analyzed by Gomaa and El-Darwish (2017) [15] demonstrated up to a 40% reduction in energy consumption in buildings. Similarly, Jiao et al. (2024) reviewed the application of PCMs in building envelopes and found that these materials effectively stabilize indoor temperatures and reduce heating, ventilation, and air conditioning (HVAC) loads in tropical climates [16]. Reflective pavements, as studied by Kitsopoulou et al. (2024), significantly lower surface temperatures, improving urban microclimates and contributing to overall energy efficiency [12]. Other studies also emphasized the benefits of integrating PCMs into building envelopes, particularly for thermal energy storage and long-term energy conservation [18–20].

Overall, while cool materials require a higher initial investment compared to conventional options, their superior thermal performance, durability, and energy-saving potential make them a cost-effective and sustainable choice for modern building envelopes. They not only reduce operational costs but also play a critical role in mitigating the environmental impacts of urbanization, particularly in combating the UHI effect. By implementing regular maintenance, the long-term performance of these materials can be sustained, further enhancing their value over time. This makes cool materials a vital component of sustainable urban planning and energy-efficient building design.

In summary, cool materials represent an innovative and effective solution to mitigate urban heat and reduce energy consumption. Their high reflectance and emissivity properties distinguish them from conventional materials, allowing them to lower surface temperatures, improve urban microclimates, and provide significant energy savings. Their applications across roofs, pavements, and walls contribute to their wide utility in both residential and urban contexts, making them a critical component of sustainable urban development strategies.

This review article offers several novel contributions that distinguish it from the existing literature. Unlike other studies, it emphasizes the long-term performance and degradation of cool materials, focusing on their durability under varying climatic conditions. The paper also bridges a critical gap by providing a comparative analysis of North American and European standards, highlighting their similarities and divergences. Additionally, it underscores the underexplored role of vertical surfaces, such as facades, in the thermal performance of urban environments. By advocating for more comprehensive testing methodologies and region-specific guidelines, the article extends the understanding of Solar Reflectance Index applications beyond conventional practices. These contributions provide a valuable resource for architects, urban planners, and policymakers aiming to optimize energy efficiency and UHI mitigation.

The next section provides a condensed summary of the Solar Reflectance Index (SRI), followed by SRI calculations and measurement standards, comparing those used in North America and Europe. Section 4 outlines the SRI assessment criteria, while Section 5 discusses its role in sustainable building design. The paper concludes by presenting key insights and future perspectives on SRI, aiming to support policymakers in integrating this metric into bylaws to mitigate urban heat island effects in cities.

2. Overview of Solar Reflectance Index (SRI)

The Solar Reflectance Index (SRI) is a critical parameter for evaluating the thermal performance of building materials, particularly in mitigating the thermal impact of solar radiation. Defined as a composite metric, SRI integrates solar reflectance—the fraction of incident solar energy reflected by a surface—and thermal emittance—the efficiency of a material in emitting absorbed heat as infrared radiation. This combination determines a material's ability to remain cool under solar exposure, directly influencing indoor comfort and reducing the energy required for air conditioning. High-SRI materials, often referred to as "cool materials," have been extensively studied for their ability to reduce surface temperatures by up to 20–30 °C compared to conventional materials, thereby contributing to energy conservation and thermal comfort [1–4]

The Urban Heat Island (UHI) effect—where urban areas experience elevated temperatures relative to their rural surroundings—arises due to the prevalence of heat-absorbing materials such as asphalt and concrete, coupled with limited vegetation and anthropogenic heat emissions. High-SRI materials help counteract UHI by reflecting a substantial portion of incident solar energy and reducing heat absorption, which lowers both surface and ambient temperatures. Studies have demonstrated that urban-scale deployment of high-SRI materials can decrease air temperatures by 1–3 °C, potentially reducing heat-related health risks and lowering peak energy demand during summer [4–8]. However, while the advantages of SRI are well-documented for horizontal surfaces such as roofs and pavements, their integration into building codes and design guidelines remains inconsistent, with limited application to other surfaces such as vertical facades.

In North America, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Energy Conservation Code (IECC) provide guidelines emphasizing the use of high-SRI roofing materials to minimize cooling energy consumption in warm climates (ASHRAE 90.1-2019; IECC 2021). Similarly, the European Cool Roof Council (ECRC) promotes SRI metrics for reducing urban heating. However, these standards predominantly address horizontal surfaces, neglecting the significant role of vertical surfaces in influencing urban energy dynamics. Additionally, the existing standards often fail to consider regional climatic variations. For instance, while high-SRI materials are beneficial in hot climates, their application in cold climates can inadvertently increase heating demands during winter due to reduced solar heat gain [8,10,21–30]. This underscores the necessity of developing region-specific SRI guidelines to balance cooling and heating requirements.

The focus of SRI applications on horizontal surfaces overlooks the thermal performance of vertical surfaces, such as walls, which constitute a substantial portion of the urban built environment. Vertical surfaces receive varying levels of solar radiation depending on their orientation, shading, and proximity to adjacent structures. For instance, south-facing facades in the northern hemisphere receive higher solar radiation during summer, contributing to significant heat gains. Conversely, north-facing facades are typically shaded, resulting in reduced thermal stress [11,14]. Despite their importance, the role of vertical surfaces in urban heat dynamics has been underexplored. Studies suggest that incorporating SRI considerations for facades could enhance overall energy performance and thermal comfort in buildings.

While high-SRI materials provide cooling benefits, their reflectivity can lead to unintended consequences, such as glare and the redirection of solar radiation onto adjacent structures. This phenomenon can increase cooling loads for nearby buildings or cause visual discomfort for pedestrians. Research by Levinson et al. (2005, 2007, 2010, 2013) highlighted that highly reflective coatings must be carefully designed to mitigate these secondary effects without compromising their thermal performance [1,27,31–34]. Innovative solutions, such as angular-selective coatings and textured surfaces, are being developed to minimize glare while maintaining high solar reflectance.

Another critical aspect of SRI is the long-term performance of high-SRI materials, which can degrade due to weathering, exposure to ultraviolet (UV) radiation, pollution, and biological growth. Studies indicate that the reflectance and emittance properties of cool materials can decline by up to 20% within three years in polluted urban environments [19]. Such degradation reduces their cooling effectiveness, emphasizing the need for durability testing and maintenance strategies. The development of self-cleaning, weather-resistant, or UV-stable coatings has shown promise in enhancing the longevity of high-SRI materials [1,3].

This study presents a comprehensive review of existing SRI methodologies, with a focus on North American and European standards. It critically examines their applicability to various building surfaces, including walls, which are often overlooked in current guidelines. Additionally, the study evaluates the impacts of environmental factors on the durability and performance of high-SRI materials, proposing strategies for improving their long-term efficacy. A roadmap for implementing comprehensive SRI evaluations across building envelope materials is proposed (Figure 1), highlighting the importance of tailoring SRI metrics to diverse climatic conditions and urban settings.

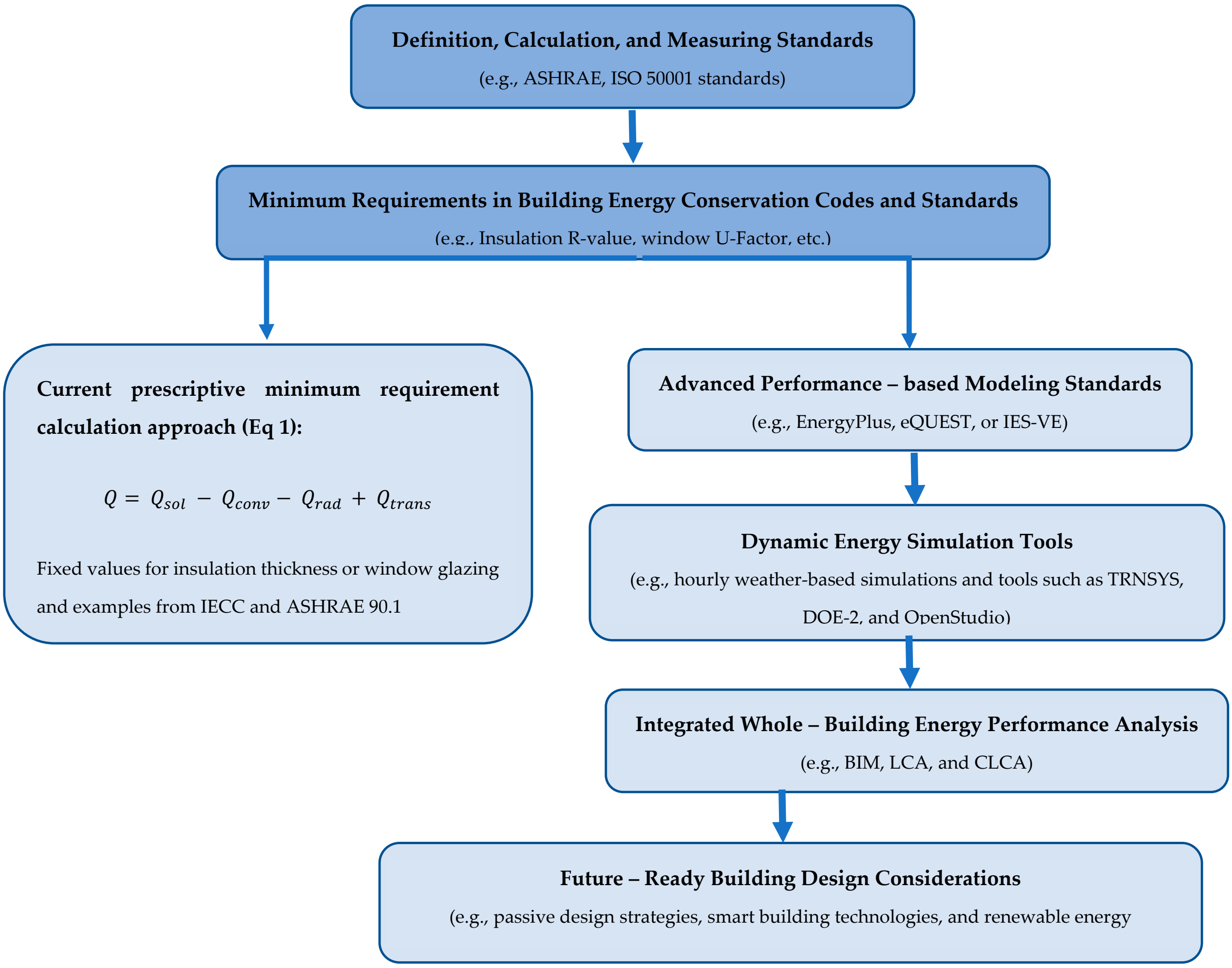

Figure 1. Framework for advancing energy conservation standards in building design.

This diagram illustrates a structured approach to improving building energy conservation standards through a progression from current prescriptive methods to advanced performance-based strategies. It begins with the fundamental aspects of defining, calculating, and measuring standards for energy efficiency in buildings. From there, the framework outlines two distinct pathways: the current prescriptive minimum requirement calculation approach, which represents the existing method of adhering to static requirements, and advanced performance-based modeling standards, which offer a dynamic and flexible framework better suited to evolving needs.

Figure 1 also emphasizes the importance of incorporating dynamic energy simulation tools and integrated whole-building energy performance analysis to develop realistic and holistic models of energy performance. This progression ultimately leads to future-ready building design considerations, where the models created are applied to construct buildings that are sustainable, energy-efficient, and resilient to future challenges. The framework advocates for a shift from static compliance methods to a more adaptive, forward-looking approach to building energy performance.

Figure 1 includes detailed and structured insights addressing the suggested areas. References to international standards such as ASHRAE, ISO 50001, standards are now incorporated, along with metrics such as Energy Use Intensity (EUI), ASHRAE 55 Thermal Comfort Standards, and building performance indices to enhance the comprehensiveness of the definitions and calculations. This figure also details baseline requirements such as insulation R-values, window U-factors, and air infiltration limits to provide technical guidance and set minimum compliance expectations. It shows the IECC and ASHRAE 90.1 as the examples of the minimum requirements in building energy conservation codes and standards. Advanced modeling standards utilizing tools such as EnergyPlus, eQUEST, and IES-VE are listed, emphasizing performance-based metrics like energy savings percentages, peak demand reductions, and net-zero energy building targets. Additionally, dynamic simulation techniques, including hourly weather-based simulations, referencing tools like TRNSYS, DOE-2, and OpenStudio, while also highlighting BIM integration for accurate data and workflows.

Integrated analysis approaches now consider the synergy between systems such as HVAC, lighting, and renewable energy, incorporating methodologies such as Life Cycle Assessment (LCA) and cost–benefit analysis for holistic performance evaluation. Future-ready designs are also addressed, focusing on passive strategies, smart building technologies, and renewable energy integration to enhance sustainability and prepare buildings for climate adaptation, including thermal resilience and energy storage systems. These updates aim to provide a more comprehensive and balanced perspective figure.

Additionally, the heat balance equation for building envelopes provides a more rigorous explanation of the factors influencing SRI and its thermal performance. The heat balance equation is essential to quantify energy performance and is widely used in building energy studies. Below is the generic form of the heat balance equation for a building envelope:

$$Q = Q_{sol} - Q_{conv} - Q_{rad} + Q_{trans} \tag{1}$$

where:

Q = Net heat gain or loss through the envelope (W/m^2)

Q_{sol} = Solar heat gain, influenced by the Solar Reflectance Index (SRI) and surface properties (W/m^2)

Q_{conv} = Convective heat loss (W/m^2)

Q_{rad} = Radiative heat exchange with the surroundings (W/m^2)

Q_{trans} = Heat transfer through conduction via the building envelope (W/m^2)

Incorporating this into the analyses provides a foundation for analyzing the impact of SRI and climatic conditions on energy savings.

3. SRI Calculation and Measuring Standards

The Solar Reflectance Index (SRI) is a comprehensive metric used to evaluate the ability of a material's surface to reflect solar radiation and emit absorbed heat. It is an indicator for assessing the thermal performance of building materials, particularly materials used for roofs, pavements, and other exterior surfaces that are exposed to direct sunlight. The SRI value is calculated based on two primary factors: solar reflectance and thermal emittance.

Solar reflectance refers to the fraction of solar energy that is reflected by a surface. It is a dimensionless quantity that ranges in value from 0 to 1, for which a value of 0 indicates no reflection (complete absorption of solar energy), and a value of 1 indicates total reflection. Materials having a high solar reflectance absorb less solar energy, which helps in reducing the heat load on buildings [32,35,36]. Thermal emittance is the efficiency with which a material emits absorbed heat as infrared radiation. Thermal emittance is also a dimensionless value ranging from 0 to 1, where 1 indicates perfect emission of absorbed heat. High-emittance materials release heat quickly, contributing to lower surface temperatures [37]. The SRI combines these two properties into a single value that provides a more complete picture with respect to the ability of a material to remain cool when exposed to solar radiation. It is expressed on a scale from 0 to 100, where a higher SRI value indicates better performance in reflecting solar radiation and emitting heat. The essential components required for the computation of the SRI are illustrated in Figure 2.

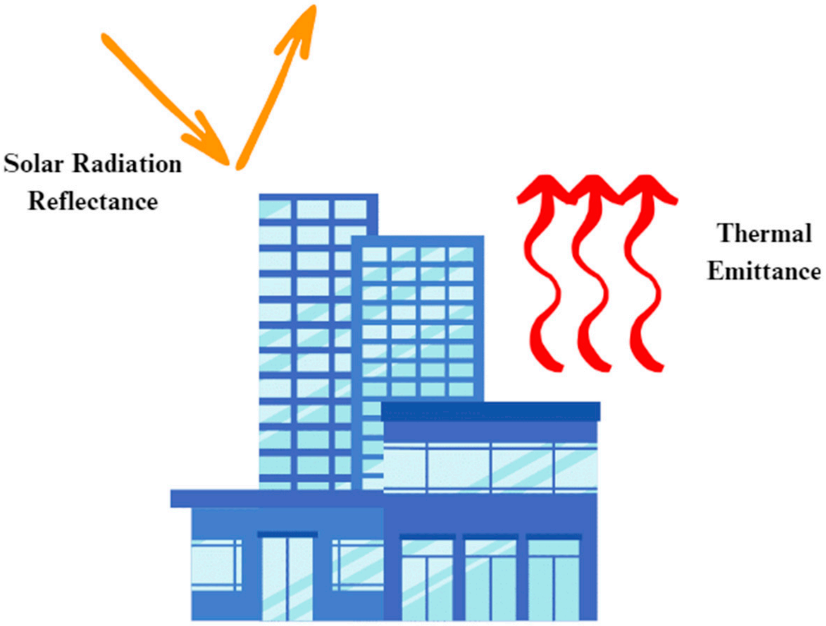

Figure 2. Reflectance and emittance are two crucial factors in determining the SRI value. Reflectance measures the solar radiation reflected by a surface; emittance measures the capacity of a material to release heat after it has been absorbed.

The calculation of SRI is standardized and involves precise measurements of solar reflectance and thermal emittance under specific conditions. Solar reflectance is typically measured using a spectrophotometer or a solar reflectometer. These instruments measure the reflectance of a material across a range of wavelengths, typically from 300 nm to 2500 nm, which corresponds to the solar spectrum. The measured reflectance data are then integrated over the solar spectrum to obtain a single reflectance value. This integration takes into account the intensity of solar radiation at different wavelengths, providing an accurate measure of how much solar energy is reflected by the material [10,22,32,38–40].

Thermal emittance is measured using an emissometer; an instrument designed to evaluate the ability of a surface to emit infrared radiation. The measurement is usually performed at a temperature of 100 °C to simulate conditions that materials might experience in an exposed and hot environment. The emissometer compares the infrared emission of the sample material to that of a reference blackbody, which has a known emittance value of 1.0. This comparison allows for the accurate determination of the emittance value for the material [40,41]. Table 2 summarizes the relevant SRI measuring standards followed by a history of these standards' development.

Table 2. Summary of the ASTM and European standards measuring the SRI.

Standard	Description	Ref.
ASTM E903	This testing procedure involves the assessment of spectral absorptance, reflectance, and transmittance of materials using spectrophotometers equipped with integrating spheres. It is applicable to materials exhibiting both specular and diffuse optical properties. Measurements encompass the spectral near normal-hemispherical transmittance (or reflectance) over the range of 300 to 2500 nm with an integrating sphere spectrophotometer. The solar transmittance, reflectance, or absorptance is determined by computing a weighted average using a standard or selected solar spectral irradiance.	[40]
ASTM E1980	The equilibrium surface temperature (Ts) in sunlight is closely linked to the solar reflectivity and thermal emissivity of the surface. This procedure outlines the computation of the SRI for horizontal and low-sloped opaque surfaces under standard conditions. The application of this method is designed for surfaces with emissivity exceeding 0.1. Solar reflectance and thermal emittance are pivotal factors influencing ambient air temperature near the surface and in its proximity.	[41]
ASTM C1549	This testing procedure addresses the methodology for assessing the solar reflectance of flat opaque materials either in a laboratory setting or in the field, employing a commercial portable solar reflectometer. It is specifically designed for the measurement of solar reflectance in opaque materials. Opaque surfaces exposed to solar radiation typically attain temperatures higher than the surrounding air. This test method is applied to determine the solar reflectance of such flat opaque surfaces.	[42]
ASTM C1371	In this testing procedure a method is given for determining the emittance of opaque and highly thermally conductive materials utilizing a portable differential thermopile emissometer. The objective is to offer a comparative means for quantifying material emittance near room temperature. It is important to note that this test method does not replace Test Method C835, an absolute method for determining total hemispherical emittance, or Test Method E408, which encompasses two comparative methods for determining total normal emittance.	[43]
ASTM E1918	In this testing method, the measurement of solar reflectance for diverse horizontal and low-sloped surfaces and materials in outdoor settings is described, for which either an albedometer or pyranometer is prescribed. It is specifically designed for application when the angle of the sun to the normal from a surface is less than 45°.	[44]
ANSI/CRRC S100 USA	In this standard the preparation of test specimens is addressed and the methods for assessing the initial and aged radiative properties of roof products provided. This standard is cited by international building codes and rating programs to evaluate the initial and aged solar reflectance and thermal emittance of roofing products.	[45]
ECRC Europe	In this manual the preparation of test specimens is described, and methods are given for assessing the initial and aged radiative properties of roofing products.	[46]

ASTM E903: Initially introduced to standardize the measurement of spectral reflectance and transmittance, this standard has undergone revisions to improve the accuracy of integrating sphere spectrophotometers and adapt to advancements in solar spectral irradiance datasets. Key updates have included refined methods for weighted averages using updated solar spectral standards [40].

ASTM E1980: The concept of Solar Reflectance Index (SRI) was developed to bridge solar reflectivity and thermal emissivity with surface temperature. Earlier versions provided basic computational methods, while later updates incorporated improved algorithms and expanded applicability for materials with higher emissivity values [41].

ASTM C1549: Originally focused on laboratory measurements, this standard was later adapted to include portable reflectometers for field use, enabling more practical applications. Updates have addressed calibration protocols and extended the range of tested materials to include modern roofing products [42].

ASTM C1371: Initially a laboratory-focused standard, it evolved to accommodate portable differential thermopile emissometers for in situ applications. Subsequent revisions clarified comparative measurement techniques and expanded testing to include a broader range of thermally conductive materials [43].

ASTM E1918: First introduced for outdoor measurements using pyranometers, this standard has been updated to accommodate newer albedometers and account for varying sun angles. Recent revisions provide more robust guidance on field data collection and weather-related factors [44].

ANSI/CRRC S100 (USA): The initial version focused on testing the radiative properties of new roof products. Over time, the standard incorporated methodologies for assessing aged properties, acknowledging the importance of long-term performance. It has also been aligned with international codes to support global consistency [45].

ECRC (Europe): Similar to ANSI/CRRC S100, this standard initially targeted new roofing products but later expanded to address aged properties. Updates reflect advancements in testing techniques and a growing emphasis on harmonization across EU member states [46].

ASTM E1918 and ASTM E903 are standards used for measuring solar reflectance, each tailored to distinct contexts. ASTM E1918 focuses on field measurements, utilizing inverted pyranometers or pyranometers with single/double domes, providing spot measurements within a field of view. Results, typically within ±0.02 to ±0.06 on a reflectance scale, are obtained with confidence intervals. In contrast, ASTM E903 is designed for laboratory measurements, utilizing scanning spectrophotometers or portable solar spectrum reflectometers, with results agreeing within ±0.02 on a reflectance scale. Whereas the use of E1918 is specified for field assessments, including dirty surfaces and ballasted systems, E903 is specifically geared towards controlled laboratory environments [36]. In Equation (2), a formulation is shown for calculating the SRI, based on parameters such as the solar reflectance of a black surface, solar reflectance of a white surface, thermal emittance of a black surface, thermal emittance of a white surface, sky temperature, convection coefficient (medium wind), and ambient air temperature; the ambient air temperature should be established based on ASTM E1918.

$$SRI = 100\frac{T_b - T_S}{T_b - T_w} \tag{2}$$

$$T_S = a + \frac{(b\alpha - c\varepsilon)}{(d\varepsilon + h_c)} - \frac{\left(e\alpha^2 + f\alpha\varepsilon\right)}{(g\varepsilon + h_c)^2} \tag{3}$$

where:

α = Solar absorptance
ε = Thermal emissivity
h_c = Convective coefficient
T_s = Steady state surface temperature (°C)
T_b = Black surface temperature (°C)
T_w = White surface temperature (°C)
a, b, c, d, e, f, g = Constants

The American CRRC Standard and the European ECRC Manual share similar content, with only minor differences in the categorization of weather conditions for aging samples. However, neither manual includes a distinct grading or categorization system for aged materials. Instead, the primary focus is on determining the initial and aged Solar Reflectance Index (SRI) values of cool materials. Additionally, these manuals are mainly intended to certify the SRI values of products from different manufacturers. Neither the ECRC nor the CRRC manuals specify minimum or desired values for any radiative material characteristics [47–51]. Table 3 provides a summary of the standards used in the USA and Europe for calculating SRI values, highlighting differences in aging and weathering conditions, as well as the procedures used to age product specimens.

Table 3. Standards used in the USA (CRRC) and Europe (ECRC) for calculating SRI values.

	ECRC	**CRRC**
Solar reflectance	ASTM E903	ASTM E903
	ASTM C1549	ASTM C1549
	CRRC-1 ANSI/CRRC S100	CRRC-1 ANSI/CRRC S100
		ASTM E1918
		ASTM C1864
Emittance	ASTM C1371	ASTM C1371
	EN 15976	

Table 3. *Cont.*

	ECRC	CRRC
Devices and services technical notes	TN11-2, TN 04-01, and TN 10-2	TN11-2.
SRI	ASTM E1980-11 [41]	ASTM E1980-11
Specimen dimension	10 cm × 15 cm	10.3 cm × 15.2 cm
Field-applied coating thickness	ASTM D1005	ASTM D1005
	ASTM D709	ASTM D709
	ISO 2178	ASTM D1669
	ENISO 2808	
Single ply thickness	ASTM D751	ASTM D751
	EN 1849-1	
Climate for aging	Three years Koppen climate classification ISO 17025	Three years CDD and HDD climate classification ASHRAE

The inclusion of "climate for aging" in Table 3 underscores the critical role that environmental conditions play in the long-term performance of materials, particularly with respect to solar reflectance and thermal emittance. The climate for aging refers to the environmental factors—such as ultraviolet (UV) radiation, temperature fluctuations, humidity, and exposure to pollutants—that contribute to the physical and chemical degradation of materials over time. These factors are central to understanding how materials perform in real-world conditions and directly affect their Solar Reflectance Index (SRI) over their lifespan.

The relationship between climate for aging and SRI lies in how environmental exposure alters the optical and thermal properties of building materials:

Degradation of Reflective Coatings: Prolonged exposure to UV radiation, atmospheric pollutants (e.g., SO_2, NOx), and particulate matter lead to surface weathering, discoloration, and reduced reflectance. For example, studies on cool roofs show that reflective coatings can lose up to 20% of their initial solar reflectance after several years, particularly in polluted urban or industrial environments.

Thermal Emittance Decline: Aging and surface contamination (e.g., algae growth, soot deposition) impact a material's ability to emit absorbed heat, thereby reducing its overall thermal performance.

Testing and Standards: Climate for aging is a critical consideration in standard testing protocols, such as those established by the Cool Roof Rating Council (CRRC) and ASTM International (e.g., ASTM D7897 for accelerated weathering). These standards simulate aging processes under controlled conditions to assess the durability of a material's reflectance and emittance properties [49].

Accordingly, the climate for aging is directly linked to the longevity of SRI. Variability in environmental conditions results in differences in the rate of material degradation across geographic regions. For instance, in tropical climates, materials are exposed to intense UV radiation and higher temperatures, leading to accelerated degradation and reduced solar reflectance over time. In industrial zones, pollutants and soot deposition reduce reflectance by altering the material's surface properties. Another example is that in regions with high humidity, microbial growth (e.g., algae, mold) can contribute to surface darkening, lowering solar reflectance.

Consequently, testing protocols like CRRC aging simulations or ASTM accelerated weathering are designed to replicate these real-world conditions, providing stakeholders with data on the durability of SRI under specific climatic exposures. In conclusion, climate for aging serves as a key variable for understanding the durability and performance of building materials. It demonstrates the link between environmental degradation and

SRI reduction, emphasizing the need for robust testing and standardization to ensure the reliable long-term performance of reflective materials.

A common issue amongst these standards is their emphasis on energy savings throughout the lifespan of the product, as these values are the basis for the criterion to guide establishing SRI set points. However, a notable gap exists given the absence of an optimized SRI range tailored specifically for usage in cold climates, and vertical surfaces, and a holistic modeling approach encompassing the whole building envelope. Table 4 provides SRI set points, as defined by the different standards. Table 4 reflects the standards associated with solar reflectance and thermal emittance testing. While CRRC and Energy Star require 3-year-aged values for product certification, others such as IECC and ASHRAE 90.1 recommend aged values but do not mandate them. LEED relies on CRRC-rated values for heat island reduction credits, emphasizing the use of aged data where available [50]. The inclusion of aged values highlights the durability of materials and their performance over time, providing a critical benchmark for stakeholders evaluating material longevity.

Table 4. SRI set points as defined by different standards.

Agency	SRI Requirement	Ref.
Alabama Energy and Residential Codes (AERC) Board, USA	Three-year-aged solar reflectance of 0.55 and three-year-aged thermal emittance of 0.75, three-year-aged solar reflectance index of 64.	[52]
Environmental Protection Agency, ENERGY STAR	An initial solar reflectance of 0.65 or higher and an aged solar reflectance of 0.50 or higher are required for low slope roofs. For steep sloped roofs, the criteria are 0.25 for initial solar reflectance and 0.15 for aged solar reflectance.	[53]
California Energy Commission, USA	The specific SRI values can vary based on regional climate considerations, building types, and local policies. For example, for non-residential building Steep-sloped roofs: In Climate Zones 1 and 3 shall have a minimum aged solar reflectance of 0.20 and a minimum thermal emittance of 0.75, or a minimum SRI of 16. In Climate Zones 2 and 4 through 16 shall have a minimum aged solar reflectance of 0.25 and a minimum thermal emittance of 0.80, or a minimum SRI of 23. Also, low-sloped roofs in climate zones 1 through 16 shall have: a minimum aged solar reflectance of 0.63 and a minimum thermal emittance of 0.75; or a minimum SRI of 75. California State has distinct criteria established for each of its 16 climate zones.	[54]
Los Angeles County, USA	For low-rise residential structures, with slopes ≤2:12, the minimum 3-year-aged solar reflectance must be 0.65, with a thermal emittance of 0.85, resulting in a Solar Reflectance Index (SRI) of 78. For slopes >2:12 in the same category, the requirements are a 0.25 minimum 3-year-aged solar reflectance, a thermal emittance of 0.85, and an SRI of 20. Additionally, for high-rise residential buildings, hotels, and motels, similar criteria apply, with the distinction of a slightly lower thermal emittance requirement of 0.75 for both slope categories, while maintaining the same solar reflectance and SRI specifications.	[55]
Toronto Municipality, Canada	Industrial building or a building addition to an industrial building, with a gross floor area of 2000 square meters or greater, should have a minimum SRI of 78.	[56]
Denver's Green Buildings Ordinance (GBO), Colorado, USA	Must follow the LEED standards under certain requirements which requires roofing materials to have an SRI value of 29 or more for steep slope roofs and more than 78 on low sloping roofs.	[57]
City of Florida, USA	A reflective roofing with a high thermal emissivity rating (>0.8) will perform best and a solar reflectance value of 0.65 or greater.	[58]
City of Georgia, USA	All building and structural roofs shall be constructed of a heat-reflective material to achieve a minimum initial Solar SRI of 78 for a low-sloped roof (less than or equal to 2:12) and a minimum initial SRI of 29 for a steep-sloped roof (more than 2:12) except for those portions of roofing designated for vegetation.	[59]
Hawaii State Energy Office, USA	Cool roof with three-year-aged solar reflectance of 0.55 and 3-year-aged thermal emittance of 0.75 or 3-year-aged solar reflectance index of 64.	[60]
City of Chicago, USA	Roof coverings on low-sloped roofs shall have an initial reflectance value of 0.72 or a three-year-installed reflectance value of 0.5 or greater.	[61]
New York, USA	Roofs and walls are recommended to have a solar absorptance of 0.75 and an emittance of 0.90, aligning with the specifications outlined in the 2020 Energy Conservation Code.	[62]
City of Houston, Texas, USA	A minimum three-year-aged solar reflectance of 0.55 and a minimum three-year-aged thermal emittance of 0.75 or a minimum Solar Reflectance Index of 64.	[63]
Columbia Energy Conservation Code, USA	Roofs should have a minimum three-year-aged SRI of 64.	[64]
Italy	High solar reflectance materials for roofs (cool roof), with a minimum solar reflectance value of 0.65 for flat roofs; 0.30 for pitched roofs.	[23]

Table 4. *Cont.*

Agency	SRI Requirement	Ref.
Green Mark, BCA, Singapore, internationally used for tropical climates	Roofing materials or coatings or cool paints with high Solar Reflectance Index (SRI) > 40.	[65]
France	Association Française de Normalisation (AFNOR) standards require minimum solar reflectance of 30% for façade coatings.	[66]
Greek, UK, Germany	Adopted initiatives to promote cool materials.	[67]

For example, Cool Roof Rating Council (CRRC) standards require both initial and 3-year-aged solar reflectance and thermal emittance values for product certification. These aged values are obtained through outdoor weathering tests conducted in accordance with ASTM D7897, which simulates real-world degradation over three years. This requirement ensures that the long-term performance of materials is accurately represented in their ratings. Energy Star only requires initial reflectance values for qualification. However, for continued certification, manufacturers must submit data demonstrating that their products meet minimum performance thresholds after three years of aging. Unlike CRRC, this standard focuses more on the initial performance with follow-up verification. LEED standards often rely on CRRC-rated products and recommend using the 3-year-aged values for compliance with heat island reduction credits. However, LEED itself does not directly require products to be tested for aged values if CRRC data are already available.

ASHRAE 90.1 standards reference aged reflectance values where available, particularly for cool roofs and solar reflectance. While not explicitly requiring 3-year-aged data for all materials, the standard acknowledges its importance in calculating long-term energy savings. Similar to ASHRAE 90.1, IECC recommends aged values where possible but does not mandate a strict requirement for all materials to undergo a 3-year aging process. It allows for the use of initial values, especially for new technologies without aged data. The inclusion of 3-year-aged values ensures that the performance of materials under real-world conditions is accurately represented, which is critical for predicting long-term energy savings and durability. However, standards that do not mandate this requirement typically allow flexibility for materials in earlier stages of development or for less critical applications.

Accordingly, the minimum requirements for SRI values are established by the use of various standards and building codes to ensure that the products used in construction contribute to reducing the UHI effect, improving energy efficiency, and enhancing thermal comfort. These requirements vary depending on the climatic zone, the type of building, and the specific application (e.g., roofs, pavements, or walls).

While SRI is extensively studied for horizontal surfaces due to their direct exposure to sunlight, the thermal performance and methodologies for vertical surfaces remain relatively underexplored. Addressing vertical surfaces is essential as they contribute significantly to the UHI effect, energy efficiency in buildings, and thermal comfort. Vertical surfaces interact with solar radiation differently than horizontal surfaces due to their orientation and shading patterns. Key factors influencing their thermal performance include the angle of incident solar radiation, which varies throughout the day and year, leading to uneven heating patterns. Additionally, high-albedo vertical surfaces reflect more solar radiation, reducing heat gain, while surface geometry, including depth and texture, affects shadowing and influences localized cooling and heating.

Traditional SRI calculations are based on materials tested under standardized conditions for horizontal surfaces. For vertical surfaces, the methodology must be refined to account for changes in reflectivity with varying solar angles, incorporate diurnal variations in heating and cooling, and consider radiative interactions between vertical surfaces in dense urban environments, known as urban canyon effects.

The study of SRI for vertical surfaces involves several approaches. Numerical simulations, such as Computational Fluid Dynamics (CFD), model the thermal behavior of vertical surfaces with varying SRI and depth under realistic solar conditions. Tools like EnergyPlus and Radiance simulate energy performance in urban settings with different vertical SRI configurations [68–71]. Field measurements also play a critical role, including real-world testing of vertical surface materials with various SRI values across different orientations, and measuring heat flux and surface temperatures to validate simulation models. Furthermore, case studies such as green walls and facades explore the cooling benefits of vegetative vertical surfaces with integrated high-SRI materials, while urban canyon analyses evaluate thermal profiles of high-rise buildings with high-SRI facades [31,66].

The adaptation of SRI for vertical surfaces has several implications. High-SRI vertical surfaces reduce heat gain, thereby lowering cooling loads in buildings and enhancing energy efficiency. They also help mitigate localized heat effects in urban areas, improving pedestrian thermal comfort. Moreover, optimizing depth and SRI can create designs that are both aesthetically appealing and functionally effective. Several studies highlight the potential of high-SRI vertical surfaces. Santamouris et al. (2018) demonstrated that combining high-SRI coatings and greenery on vertical surfaces in urban canyons can reduce temperatures by up to 3 °C [9,10]. Yilmaz et al. (2021) showed that reflective coatings on skyscraper facades in tropical climates could achieve a 15% reduction in cooling energy demand [69]. Wong et al. (2020) used CFD simulations to reveal that incorporating high-SRI vertical surfaces into urban canyon designs could reduce UHI effects by up to 10% [70].

To fully understand the potential of SRI for vertical surfaces, further research is needed in several areas. Enhanced models must be developed to integrate urban radiative effects and vertical surface geometry comprehensively. Long-term monitoring of high-SRI vertical materials across diverse climates is necessary for real-world validation. Additionally, building codes and urban planning policies should be formulated to encourage the use of high-SRI materials on vertical surfaces.

4. SRI Assessment Criteria

The energy consumption of a building is influenced by the Solar Reflectance Index (SRI) value of its envelope materials. However, this relationship is dependent on the local climate and the specific construction characteristics of the building envelope. For highly insulated envelopes, the contribution of solar energy may have a reduced impact compared to envelopes with less insulation. Additionally, the absorbed solar energy on a surface is re-emitted to the surrounding environment, potentially influencing the ambient air temperature more than the building's internal energy dynamics [35,70].

A higher SRI value results in increased solar reflection, leading to reduced cooling loads during the summer. However, in colder climates, buildings can benefit from heat gains through solar radiation during winter. Current energy conservation standards typically prescribe minimum SRI requirements based on factors such as building location, climate zone, and a cost–benefit analysis of cool materials. This approach helps estimate appropriate SRI ranges for both horizontal and vertical surfaces, even in cold climates. A lower SRI corresponds to higher heat gain and reduced heating energy consumption. Moreover, the broader effects of SRI on urban heat island (UHI) mitigation and indoor/outdoor thermal comfort are crucial for understanding overall energy consumption. Developing a comprehensive methodology to determine the optimal SRI for specific locations, considering both current and projected climatic conditions, is highly beneficial.

While high-SRI materials offer significant cooling benefits, their application is not without challenges. In cold climates, high-SRI materials can increase heating demands during winter due to reduced solar heat gain [8,10]. Additionally, the reflectivity of high-

SRI materials can lead to glare and the redirection of solar radiation onto adjacent structures, potentially increasing cooling loads for nearby buildings [14–18]. These limitations highlight the need for region-specific SRI guidelines and innovative solutions, such as angular-selective coatings and textured surfaces, to mitigate secondary effects without compromising thermal performance.

The classification phase tailors SRI requirements to specific building characteristics and environmental conditions. This ensures that the proposed SRI values are suitable for different building types, surfaces, and climatic zones.

The building envelope, encompassing all exterior surfaces, plays a key role in the heat exchange between a building and its environment. Differentiating between vertical surfaces (e.g., walls) and horizontal surfaces (e.g., roofs) is essential, as these surfaces interact differently with solar radiation. Horizontal surfaces, such as roofs, receive direct solar radiation and have a significant impact on heat gain and UHI effects [1,8]. Vertical surfaces, in contrast, experience varying solar exposure depending on their orientation and the time of day, requiring tailored SRI recommendations [24,29].

Archetype buildings serve as representative models that capture typical characteristics of various building types, such as hospitals, residential buildings, commercial spaces, and offices. These prototypes help standardize SRI assessments across different categories. For example, hospitals and office buildings with large roof areas may require higher SRI values to optimize energy savings and reduce cooling loads [32]. Conversely, residential buildings might have varying SRI needs based on their roof and wall designs.

Climatic conditions also influence the effectiveness of SRI values. In hot, sunny climates, high-SRI materials significantly reduce solar heat gain, while in colder climates, these benefits must be balanced against the need for winter solar heat gain. By classifying buildings according to climatic zones, SRI values can be adjusted to maximize energy efficiency while minimizing increased heating demands in colder regions [60]. The proposed criteria to assess are as follows.

4.1. Energy Efficiency

Building energy efficiency is a multifaceted concept influenced by various factors, including building design, insulation, HVAC systems, and material properties. The Solar Reflectance Index (SRI) plays a critical role in determining the energy efficiency of a building envelope, as it directly impacts the amount of solar radiation absorbed by exterior surfaces, which in turn affects indoor cooling demands and urban heat island (UHI) mitigation.

Materials with a high SRI reflect more solar radiation and emit absorbed heat more effectively, resulting in lower surface temperatures. This reduces heat transfer into the building, minimizing cooling loads. For instance, studies have shown that increasing roof reflectance from 0.1 (typical for dark roofs) to 0.6 can reduce cooling energy use by 20–40% in hot climates [1–4]. This demonstrates the direct relationship between SRI and reduced energy consumption.

High-SRI materials can significantly lower cooling energy consumption by maintaining lower indoor temperatures. For example, Akbari et al. (2005) reported that a building with a cool roof experienced up to a 15% reduction in annual energy consumption compared to one with a conventional roof [2]. In commercial buildings, this translates to substantial cost savings, particularly in regions with high cooling demands.

High-SRI materials also contribute to cooler indoor environments, improving occupant thermal comfort without relying heavily on HVAC systems. Additionally, the use of high-SRI materials in urban areas reduces ambient temperatures, alleviating the UHI effect. For example, large-scale adoption of cool materials in Los Angeles was shown to reduce average urban temperatures by 1–2 °C, with corresponding reductions in citywide cooling energy demands [5,8].

The cost-effectiveness of high-SRI materials is an essential factor in evaluating their impact on energy efficiency. Over a 30-year period, the energy savings achieved through reduced cooling demands often outweigh the higher initial costs of high-SRI materials. For instance, Golden et al. (2010) calculated that the use of reflective roofs yielded an ROI of 20–25% in commercial buildings, driven by reduced energy costs [17].

Environmental factors such as UV radiation, air pollution, and weathering degrade SRI values over time, diminishing the energy-saving potential of materials. This degradation must be accounted for in energy efficiency analyses to ensure realistic expectations. Accelerated aging studies (e.g., ASTM D7897) provide data on the performance of materials after three years of weathering, which can be extrapolated for longer periods to estimate long-term efficiency [5,7]. For example, reflective roof coatings in polluted environments can lose up to 20% of their initial SRI value after three years if not maintained.

A study in a hot, arid climate in Arizona residential sectors compared buildings with high-SRI cool roofs to those with conventional roofs. The cool roofs reduced cooling energy consumption by 25%, saving approximately USD 150 annually per household [1–5]. High-SRI pavement materials and reflective coatings on roofs in Singapore reduced local ambient temperatures by up to 1.5 °C, which led to a 5% decrease in urban energy demand Retrofitting a 10,000 square-foot commercial building with high-SRI material in Texas reduced cooling energy costs by USD 5000 annually, achieving a payback period of six years [17].

Minimum SRI requirements for building envelope materials should be informed by energy-saving analyses. A key criterion is the cost-effectiveness of using high-SRI materials. If energy savings over a 30-year period exceed the cost difference between current materials and high-SRI materials, it justifies establishing minimum requirements. This ensures that materials contribute to energy efficiency while offering favorable returns on investment for building owners [60,71,72].

In addition to energy savings, factors such as thermal comfort, environmental impact, and UHI mitigation should be considered. Reducing outdoor temperatures through the use of cool materials enhances public health and decreases urban energy demand, yielding broader societal benefits. Consequently, SRI requirements should align with sustainability goals, balancing economic, environmental, and social outcomes.

It is also important to account for the degradation of SRI values over time due to environmental factors such as UV radiation, pollution, and weathering. This degradation reduces the material's ability to reflect solar radiation and emit heat, diminishing its energy-saving potential [10,29]. Analyses should consider the long-term performance of materials over a typical 30-year lifespan to ensure realistic expectations for energy savings and sustained effectiveness [30].

4.2. Cost Estimation

Cost estimation is critical for assessing the economic impact of implementing new SRI standards. This involves comparing the costs of current materials to those that meet proposed SRI values, assuming similar installation costs. Cool materials with higher SRI values are often more expensive due to specialized coatings or manufacturing processes. Evaluating whether long-term energy savings offset these higher initial costs is essential [3,4]. As such, the cost estimation should consider potential savings from reduced energy consumption, which can offset the higher material costs over time.

A comprehensive cost–benefit analysis over a 30-year period provides a robust assessment of economic viability. This period aligns with the typical lifespan of building materials, capturing long-term energy savings, maintenance costs, and material degradation [2,6,8]. Normalizing results across archetype buildings ensures scalability and applicability to a wide range of structures [22,38].

Additional considerations include factors such as surface condition, angle of incidence, and material aging. Dust, dirt, or other contaminants can reduce reflectivity and alter thermal properties [4,10]. Solar reflectance varies depending on the angle of sunlight, which is particularly relevant for vertical surfaces. Over time, environmental exposure can degrade surface properties, further influencing long-term SRI performance and necessitating maintenance strategies.

Integrating the proposed classification, energy efficiency, and cost estimation methods into the development of optimal SRI criteria offers a comprehensive framework for improving building energy performance and addressing broader sustainability goals. By considering the unique dynamics of horizontal and vertical surfaces, climatic zones, and material aging, the proposed approach ensures that SRI standards remain effective and adaptable to diverse conditions.

5. SRI in Sustainable Building Design

The SRI of construction materials plays a fundamental role in sustainable building design by enhancing energy efficiency, improving urban resilience, and promoting environmental quality. SRI's importance extends beyond the immediate benefits of reducing heat load and energy consumption, encompassing a wide range of sustainability outcomes critical for addressing climate change and the challenges posed by urbanization.

5.1. Greenhouse Gas Emissions Reductions

High-SRI materials contribute to reducing greenhouse gas emissions by decreasing the energy demand for cooling in buildings. In regions where electricity generation is predominantly fossil fuel-based, this reduction directly translates into lower carbon dioxide (CO_2) emissions. Studies estimate that high-SRI materials can reduce energy consumption by 10–40%, depending on the climate and building design, potentially cutting emissions by millions of tons annually when implemented across urban areas (1, 4, 10, 63). Large-scale adoption of high-SRI materials supports the achievement of international climate targets, including commitments under the Paris Agreement.

The reduction in GHG emissions due to ambient and surface temperature reductions can be estimated by analyzing how reflective surfaces reduce cooling energy demands and their subsequent impact on emissions. The proposed step-by-step measurements follows:

(1) Quantify cooling energy reduction

$$\Delta E_{Cooling} = C_{Base} - \eta_{Reflectivity} \tag{4}$$

$E_{Cooling}$: Cooling energy savings (kWh/m^2/year)

C_{Base}: Baseline cooling energy demand (kWh/m^2/year), typically obtained from regional climate and building data

$\eta_{Reflectivity}$: Cooling energy reduction percentage due to reflectivity, derived from ambient and surface temperature reductions (e.g., 10% per °C reduction in surface temperature)

(2) Determine reduction in energy-related GHG emissions

$$\Delta GHG_{Cooling} = \Delta E_{Cooling} \times EF_{Electricity} \tag{5}$$

$\Delta GHG_{Cooling}$: GHG emissions reduction (kg CO_2/m^2/year)

$EF_{Electricity}$: Carbon emissions factor of electricity (kg CO_2/kWh), varies by region (e.g., coal-intensive grids have higher factors)

(3) Incorporate ambient temperature reduction

Reflectivity-induced reductions in ambient temperature reduce urban cooling demand. Ambient temperature reduction of 1 °C can lead to 1–2% cooling energy savings for urban buildings. This value can be adjusted for climate and region. Then the impact of ambient cooling is added to the cooling energy reduction:

$$\Delta E_{Cooling,\ Total} = \Delta E_{Cooling,\ Surface} + \Delta E_{Cooling,Ambient} \tag{6}$$

$\Delta E_{Cooling,\ Total}$: Total energy reduction due to cooling effects (W/m^2)
$\Delta E_{Cooling,\ Surface}$: Energy reduction at the surface level (W/m^2)
$\Delta E_{Cooling,Ambient}$: Cooling energy change due to ambient conditions (W/m^2)

(4) Aggregate total GHG emissions reduction

Multiply the cooling energy reduction by the total area of reflective surfaces

$$\Delta GHG_{Total} = \Delta GHG_{Cooling} \times A_{Reflective} \tag{7}$$

ΔGHG_{Total}: Total GHG emissions reduction (kg CO_2/m^2/year)
$\Delta GHG_{Cooling}$: GHG emissions reduction (kg CO_2/m^2/year)$A_{Reflective}$ = Total area of reflective surfaces (e.g., roofs, walls, pavements)

By combining temperature reductions with local cooling energy demands and electricity emissions factors, the GHG emissions reduction potential of reflective surfaces can be estimated accurately. This methodology is flexible and can be adapted to different regions, climates, and energy grids.

5.2. Urban Heat Islands Mitigation

Urbanization accelerates the replacement of natural landscapes with impervious surfaces, exacerbating the UHI effect. High-SRI materials provide a scalable solution to counteract this intensification by reflecting more solar energy and emitting absorbed heat more efficiently. Integrating high-SRI materials into new developments and retrofitting existing infrastructure can mitigate the thermal impacts of urban growth. For example, studies have demonstrated that adopting reflective surfaces in rapidly urbanizing regions can reduce urban heat islands by up to 20%, improving overall livability and sustainability [64,70]. Figure 3 compares the urban temperatures in areas with high-SRI and low-SRI material applications. Low-SRI materials have a solar reflectivity of less than 0.3, whereas high-SRI materials, often referred to as cool materials, can reflect more than 0.6 of the sunlight back to the atmosphere. Figure 4 shows the relation between solar reflectivity, surface temperature and ambient temperature.

Accordingly, the Solar Reflectance Index (SRI) is a cornerstone of sustainable building design and urban development. Its influence extends far beyond improving energy efficiency, encompassing greenhouse gas reduction, urban biodiversity enhancement, public health benefits, economic viability, climate resilience, and sustainable urban planning. The strategic use of high-SRI materials is vital for achieving sustainability objectives and ensuring urban environments thrive despite the challenges of climate change and urbanization.

The cooling effects of high-SRI materials create more favorable microclimates within urban environments, benefitting both human inhabitants and urban biodiversity. By reducing surface and ambient temperatures, these materials mitigate heat stress on vegetation, enabling the growth and sustainability of urban greenery. This fosters the success of green infrastructure initiatives such as urban forests, green roofs, and community gardens, which provide habitats for wildlife, support pollinator species, and enhance ecological connectivity. Furthermore, cooler urban temperatures reduce water stress on plants, promoting biodiversity and contributing to ecosystem services such as air purification, carbon sequestration, and stormwater management [4,6,39].

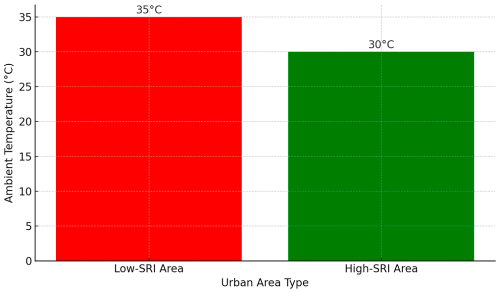

Figure 3. Comparison of urban temperatures in areas with high-SRI and low-SRI material applications.

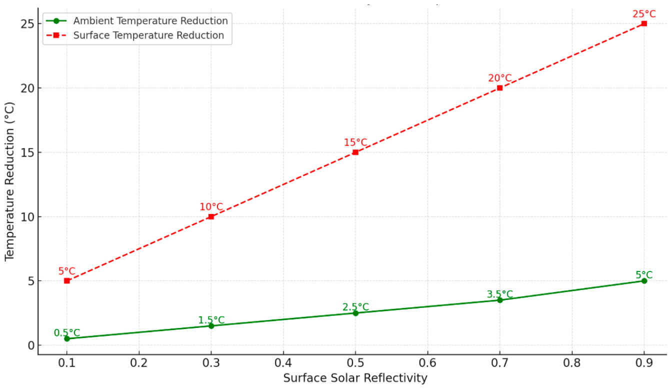

Figure 4. Relation between solar reflectivity and temperature reductions for both ambient and surface temperatures.

By mitigating the UHI effect, high-SRI materials significantly improve public health outcomes. High urban temperatures are strongly associated with heat-related illnesses, particularly among vulnerable populations such as the elderly and individuals with pre-existing health conditions. Reduced surface and ambient temperatures decrease the risk of heat stress, heat exhaustion, and heatstroke, particularly during extreme heat waves [4,6,8,63]. Additionally, cooler urban spaces encourage outdoor physical activities, enhance social interactions, and improve mental health by creating more comfortable environments. These public health benefits align with initiatives to enhance urban livability and quality of life [72,73].

As cities face rising global temperatures and more frequent heatwaves due to climate change, high-SRI materials become essential in urban resilience strategies. These materials stabilize indoor and outdoor temperatures, providing thermal comfort and reducing the risk of infrastructure damage during extreme heat events. For example, reflective pavements and cool roofs can lower urban temperatures by 1–2 °C, helping cities adapt to climate change by reducing thermal stress on buildings and public spaces [69–73]. Long-term adoption of high-SRI materials ensures cities remain habitable and functional in the face of evolving climatic conditions.

Integrating SRI considerations into urban planning is a critical step toward achieving sustainable cities. High-SRI materials align with broader urban sustainability strategies, such as the implementation of reflective pavements, cool walls, and climate-responsive architecture. Policymakers can leverage SRI as a regulatory tool to enforce energy efficiency standards, reduce urban temperatures, and enhance public health. The adoption of SRI-based guidelines contributes to achieving international frameworks such as the United Nations Sustainable Development Goals (SDGs), particularly Goals 11 (Sustainable Cities and Communities) and 13 (Climate Action) [72].

5.3. Economic Benefits and Energy Savings

Quantitative data demonstrates the significant influence of SRI on energy consumption. For example, a 0.1 increase in SRI has been shown to reduce cooling energy demand by approximately 1% in warm climates. Cool roofs with an SRI of 78 can result in annual cooling savings of USD 0.20–USD 0.60 per square foot, depending on local energy costs and climate. In tropical regions, cool roofs can recover their initial investment within 3 years due to substantial reductions in air-conditioning expenses. Furthermore, adopting high-SRI materials at an urban scale can reduce citywide cooling energy demand by 10–15%, mitigating the UHI effect and enhancing public health outcomes. These quantitative insights underscore the importance of SRI as a critical parameter for both building-level and urban energy efficiency. Below is a detailed analysis addressing the impact of SRI values on energy reduction, cost implications, and return on investment (ROI), supported by quantitative data from recent studies. A reflective roof with an SRI of 85 can lower roof temperatures by up to 30 °C on sunny days compared to conventional materials with an SRI below 30 [17]. This translates to a 20–40% reduction in cooling energy needs during peak summer months. In a case study by Wei et al. (2024), retrofitting a building roof with a high-SRI coating (SRI = 55) achieved annual energy savings of 15% in a warm climate [20].

Cool materials generally require a higher initial investment compared to conventional options. For instance, reflective coatings cost 20–40% more upfront than standard materials. However, the energy savings they generate often lead to a relatively short payback period. As such, the upfront costs of high-SRI cool roofs might be USD 2–USD 3 per square foot more than conventional roofs and energy cost reductions of USD 0.20–USD 0.30 per square foot per year have been observed in warm climates, based on studies by Jo et al. (2010) [17]. For commercial buildings, the payback period for cool roofs ranges from 5 to 10 years, depending on the building size and local energy costs.

High-SRI materials maintain their performance over the long term when properly maintained. Studies have shown that periodic cleaning of reflective roofs can sustain up to 90% of their original reflectivity over a 15–20-year lifespan (Haverstic, 2016) [18]. Long-lasting coatings and durable materials further enhance the economic viability of these solutions. Replacing a conventional roof with a cool roof in a commercial building reduced annual cooling energy use by 22% and yielded an ROI of 25% due to lower utility bills. A study on cool roof cleaning practices showed that maintaining reflectivity over five years could result in a total ROI of 35% for large-scale buildings.

Retrofitting tropical building facades with high-SRI materials led to cooling energy savings of 20% and a payback period of approximately 8 years. Retrofitting cool materials reduced energy consumption by 15% annually and achieved payback in 6–7 years, depending on climate conditions. As such, ROI improves with higher cooling loads. For instance, cool roofs in tropical climates recover costs within 3 years due to reduced air-conditioning expenses.

Accordingly, the economic benefits of implementing high-SRI materials are multifaceted. Lower cooling energy consumption translates into reduced operational costs over the lifespan of a building, with savings amplified in energy-intensive regions. Buildings incorporating sustainable elements such as high-SRI materials often achieve higher property values, reduced maintenance costs, and increased marketability. Additionally, such buildings are frequently eligible for certifications like LEED (Leadership in Energy and

Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), which further enhances their financial and environmental appeal. A study by Levinson et al. (2005) found that cool roofs with high SRI can yield a return on investment in as little as three years due to reduced energy expenditures [1,5].

Figure 5 illustrates the relationship between surface solar reflectivity and its impacts on both cooling energy savings and heating energy penalties. It demonstrates that as solar reflectivity increases, cooling energy savings improve substantially, while minor heating energy penalties may occur in colder climates due to reduced heat absorption. The data integrates insights from various studies. Akbari et al. (2001) examined cooling energy savings in Los Angeles, USA, demonstrating 10% savings at low reflectivity levels (0.1) and highlighting the significant impact of reflective materials in warm climates [5]. Levinson et al. (2013) focused on Miami, USA, and reported a 20% savings at 0.3 reflectivity, emphasizing the value of reflectivity enhancements in high-temperature regions [31]. Santamouris (2020) analyzed Athens, Greece, where cooling energy savings reached 30% at 0.5 reflectivity, showcasing the Mediterranean's potential for reflectivity-driven energy efficiency [13]. Jandaghian and Berardi (2020) provided data from Toronto, Canada, predicting 20% cooling savings at 0.65 reflectivity, with a corresponding 4% heating penalty, illustrating the balanced trade-offs in temperate climates [4]. Oleson et al. (2010) also conducted studies in Phoenix, USA, predicting cooling energy savings of 20% and a 4% heating penalty at 0.78 reflectivity, emphasizing the benefits of reflectivity enhancements in arid environments [74].

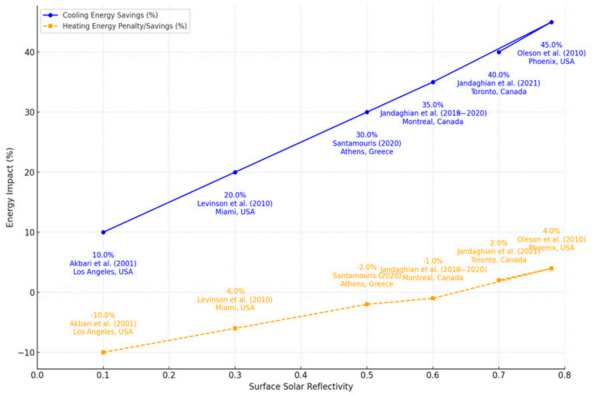

Figure 5. Predictive analysis of energy impacts from surface solar reflectivity based on regional studies [1,4,5,13,67,74–77].

6. Key Insights and Future Perspectives on SRI

This review provides a comprehensive foundation on the Solar Reflectance Index (SRI), highlighting its critical role in enhancing building energy efficiency and mitigating Urban Heat Island (UHI) effects. The study identifies gaps in current standards, particularly for vertical surfaces, and proposes a comprehensive framework for SRI assessment across diverse climates and building surfaces. The findings have significant implications for policymakers, urban planners, and architects, offering actionable insights for enhancing building energy efficiency and urban resilience. Future research should focus on developing SRI standards tailored to vertical surfaces, integrating SRI optimization across the entire building envelope, and assessing the long-term performance of high-SRI materials under various climate scenarios. However, this review also identifies several limitations in current standards and practices, presenting opportunities for further research and development. Key research gaps include:

- Current SRI measurement standards, such as those from ASTM and ASHRAE, predominantly address horizontal surfaces such as roofs, largely neglecting vertical surfaces such as building facades and walls. Vertical surfaces significantly impact building energy efficiency and thermal comfort, as their interaction with solar radiation varies based on orientation and time of the day. Developing comprehensive guidelines for measuring the SRI of vertical surfaces is a critical area for future investigation.

- There is limited research on integrating SRI optimization across the entire building envelope, including roofs, walls, windows, and pavements. A holistic approach is necessary to optimize thermal performance and ensure consistent energy savings across all building components. Research should focus on methodologies that evaluate the cumulative impact of both vertical and horizontal surfaces on energy efficiency and thermal comfort.
- Existing SRI criteria are primarily derived from energy conservation standards focused on cost–benefit analyses. These often overlook the broader benefits of SRI in mitigating UHI effects, enhancing public health, and improving urban sustainability. Future research should assess how high-SRI materials can reduce outdoor temperatures in densely populated areas, improve outdoor thermal comfort, and lower city-wide cooling energy demands.
- Current SRI standards emphasize reducing cooling demands during summer but may not be suitable for all climatic conditions. In colder climates, high-SRI materials can increase heating demands in winter, creating a heating penalty. Research is needed to develop climate-specific SRI criteria that balance cooling and heating needs. This could include a range of SRI standards with minimum values for cooling and maximum values for heating to optimize year-round energy performance.
- Changing weather patterns and global warming are likely to affect the performance of SRI materials. Rising temperatures, increased solar radiation, and extreme weather events may alter the effectiveness of these materials. Future studies should explore the performance of SRI under various climate scenarios, including long-term durability under conditions such as higher temperatures, intense UV exposure, and accelerated weathering.
- To address these gaps, the following areas of research are recommended:
- Develop SRI standards tailored to vertical surfaces, accounting for their orientation, solar exposure, and impact on energy efficiency. Research should explore how facade materials, surface textures, and coatings influence SRI and optimize these properties for specific climates.
- Create integrated energy models that incorporate SRI values across the entire building envelope, including walls and roofs. These models should simulate thermal performance under various weather conditions and climate scenarios, providing actionable insights for architects and urban planners.
- Expand the focus from individual buildings to the urban scale by assessing the effects of widespread high-SRI material adoption. This research could use geographic information systems (GIS) and remote sensing to map SRI distribution and model its cumulative impact on urban energy use, thermal comfort, and UHI mitigation.
- Investigate the development of materials with variable SRI properties that adapt to changing environmental conditions. Smart coatings, phase-change materials, and other innovative technologies could enable optimal thermal performance throughout the year.
- Study the long-term performance of high-SRI materials in real-world conditions, including their degradation due to weathering, UV exposure, and pollution. Research should also focus on maintenance strategies, such as self-cleaning surfaces or protective coatings, to preserve reflectance and emittance properties over the material's lifecycle.

This review highlights the need for a deeper understanding of SRI and its implications for building energy efficiency, urban sustainability, and thermal comfort. Addressing the identified research gaps will not only enhance the applicability of SRI standards but also contribute to the development of more resilient and energy-efficient buildings in the face of climate change.

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Nomenclature List

SRI	Solar Reflectance Index
UHI	Urban Heat Island
ASTM	American Society for Testing and Materials
EN	European Norm
CRRC	Cool Roof Rating Council
ECRC	European Cool Roof Council
Q	Net heat gain or loss through the envelope (W/m^2)
Q_{sol}	Solar heat gain, influenced by the Solar Reflectance Index (SRI) and surface properties (W/m^2)
Q_{conv}	Convective heat loss (W/m^2)
Q_{rad}	Radiative heat exchange with the surroundings (W/m^2)
Q_{trans}	Heat transfer through conduction via the building envelope (W/m^2)
α	Solar absorptance
ε	Thermal emissivity
hc	Convective coefficient (W/m^2·K)
Ts	Steady-state surface temperature (°C)
Tb	Black surface temperature (°C)
Tw	White surface temperature (°C)
CDD	Cooling Degree Days
HDD	Heating Degree Days
ISO	International Organization for Standardization
$E_{Cooling}$	Cooling energy savings (kWh/m^2/year)
C_{Base}	Baseline cooling energy demand (kWh/m^2/year)
$\eta_{Reflectivity}$	Cooling energy reduction percentage due to reflectivity, derived from ambient and surface temperature reductions
$\Delta GHG_{Cooling}$	GHG emissions reduction (kg CO$_2$/m^2/year)
$EF_{Electricity}$	Carbon emissions factor of electricity (kg CO$_2$/kWh)
$A_{Reflective}$	Total area of reflective surfaces (e.g., roofs, walls, pavements)

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