INTEGRATING REFLECTIVE AND GREEN ROOFS FOR SUSTAINABLE URBAN HEAT ISLAND MITIGATION

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ABSTRACT

The Urban Heat Island (UHI) effect has emerged as a significant environmental challenge, exacerbating urban temperatures, increasing energy consumption, and deteriorating air quality. Sustainable roofing solutions, particularly reflective and green roofs, have been identified as effective mitigation strategies. This paper explores the integration of reflective and green roofing systems into urban planning policies and building designs to enhance sustainability and resilience against rising urban temperatures. Reflective roofing technologies leverage high-albedo materials to minimize heat absorption, while green roofs utilize vegetation to provide insulation, improve stormwater management, and enhance urban biodiversity. By combining these two systems, cities can achieve synergistic benefits, including reduced cooling loads, improved thermal comfort, and enhanced energy efficiency. This study evaluates the comparative effectiveness of these systems, analyses opportunities for large-scale implementation, and discusses operational challenges. Furthermore, it examines policy frameworks, regulatory incentives, and design strategies necessary for widespread adoption.

Keywords: Urban Heat Island (UHI), Reflective Roofing Systems and Green Roofing Systems.

1. INTRODUCTION

The Urban Heat Island (UHI) effect is a phenomenon where urban areas experience significantly higher temperatures than their surrounding rural regions due to human activities and modifications to the natural environment. This temperature disparity is primarily driven by factors such as the replacement of vegetation with impervious surfaces like asphalt and concrete, increased energy consumption, and reduced natural cooling mechanisms. As cities expand, these artificial surfaces absorb and retain heat during the day, releasing it slowly at night, leading to consistently elevated temperatures in urban centres [1]. The consequences of the UHI effect are far-reaching, impacting both the environment and public health. Higher urban temperatures lead to increased energy demands for cooling, straining power grids and elevating greenhouse gas emissions. Additionally, the intensified heat can exacerbate air pollution by increasing the concentration of harmful pollutants and groundlevel ozone. From a public health perspective, prolonged exposure to high temperatures contributes to heat-related illnesses, particularly affecting vulnerable populations such as the elderly, children, and individuals with pre-existing health conditions [2].Given these challenges, mitigating the UHI effect has become a critical priority for sustainable urban development. Various strategies have been proposed, including increasing urban greenery, enhancing building materials, and adopting innovative roofing solutions. Among these, reflective and green roofing systems have gained prominence for their ability to reduce urban temperatures while simultaneously improving energy efficiency and environmental sustainability. These solutions not only contribute to cooling urban environments but also offer additional benefits such as improved stormwater management and enhanced urban biodiversity, making them key components of modern urban planning[3].As urbanization accelerates, cities face growing challenges related temperatures, increased rising energy to

consumption, and deteriorating air quality. The Urban Heat Island (UHI) effect exacerbates these issues by trapping heat in densely built environments, leading to elevated temperatures that strain infrastructure and human health. Sustainable roofing solutions, particularly reflective and green roofs, play a crucial role in mitigating these challenges and promoting climate resilience in urban areas.Reflective roofing systems, also known as cool roofs, utilize highalbedo materials to reflect solar radiation rather than absorb it, thereby reducing heat buildup on building surfaces. This results in lower indoor temperatures, decreased reliance on air conditioning, and significant energy savings. Green roofs, on the other hand, incorporate vegetation to provide natural insulation, absorb heat, and enhance evaporative cooling. They not only reduce rooftop temperatures but also improve stormwater management by minimizing runoff, enhance air quality, and support biodiversity in urban environments [4].By integrating sustainable roofing solutions into urban climate management strategies. cities achieve multiple can environmental and economic benefits. These solutions help reduce the overall heat footprint of metropolitan areas, lower peak energy demand, and contribute to carbon footprint reduction. Moreover, they improve urban liveability by creating cooler, healthier, and more aesthetically pleasing environments. The adoption of these technologies in building design and urban planning is essential for fostering sustainable, climate-adaptive cities that can effectively combat the adverse effects of global warming and rapid urbanization.

Reflective and green roofing systems are two innovative approaches designed to mitigate the Urban Heat Island (UHI) effect, improve building energy efficiency, and enhance urban sustainability. Both systems contribute to reducing urban temperatures, but they operate through distinct mechanisms, offering unique benefits and challenges.Reflective Roofing Systems known as cool roofs; reflective roofing systems utilize highalbedo materials that reflect a significant portion of incoming solar radiation rather than absorbing it. These roofs are typically made of reflective

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coatings, white membranes, or specially designed materials that reduce surface temperatures. By minimizing heat absorption, reflective roofs lower indoor temperatures, reducing the need for air conditioning and decreasing overall energy consumption [5]. This results in lower electricity bills and reduced greenhouse gas emissions. However, their effectiveness varies based on climate conditions, and they may not provide additional environmental benefits such as stormwater management or biodiversity support.Green roofs, also known as vegetative or living roofs, consist of a layer of vegetation planted over a waterproof membrane. They are classified into two main types: extensive (lightweight, low-maintenance systems with drought-resistant plants) and intensive (heavier, garden-like roofs that support diverse vegetation). Green roofs provide multiple environmental advantages, including natural insulation, heat absorption, improved air quality, and stormwater retention. They also promote biodiversity by creating habitats for birds and insects while enhancing the aesthetic appeal of urban spaces. However, green roofs require additional structural regular maintenance, and initial support, investment costs, which can pose challenges for implementation[6].While widespread both systems are effective in mitigating the UHI effect, roofing integrating reflective and green technologies can maximize their benefits. A hybrid approach leverages the cooling properties of reflective materials alongside the insulation and ecological advantages of green roofs, offering a comprehensive solution for sustainable urban development.

2. URBAN HEAT ISLAND EFFECT: CAUSES AND CONSEQUENCES

2.1 Mechanisms of UHI Formation

The phenomenon known as the metropolitan Heat Island (UHI) effect occurs when human activity and environmental changes cause metropolitan regions to experience greater temperatures than their rural counterparts. Cities absorb, store, and retain heat more efficiently than neighbouring rural or natural regions due to their extensive infrastructure and energy use patterns.

Roads, buildings, and pavements are examples of impermeable surfaces that absorb and retain heat, frequently replacing natural vegetation in urban settings. Through evapotranspiration, or the release of water vapor into the sky, vegetationespecially trees and plants-naturally cools the surroundings. This process is mostly lacking in urban areas [7]. Throughout the day, solar energy is absorbed and stored by materials like concrete, asphalt, and roofs before being gradually released as heat. These surfaces raise the total heat load in cities rather than providing the cooling impact of precipitation or plants like natural landscapes do. A major contributor to UHI is the heat produced by human activities, such as air conditioning, industrial operations, and transportation. These activities increase the temperature of the urban environment by releasing heat directly into it. Generally speaking, urban materials have poor albedo, which means they absorb more sunlight instead of reflecting it. Because they absorb a lot of solar radiation, dark surfaces-like asphalt roads and rooftops-exacerbate heat accumulation and raise local temperatures. Waste heat is produced in cities by human activities like air conditioners, factories, and automobile emissions. This heat raises the surrounding temperature, especially in crowded cities where heat cannot escape.Cities' condensed layout, which includes tall buildings and winding streets, restricts airflow and slows down cooling. The "canyon effect," as it is known, can trap heat within cities, making it harder for nighttime temperatures to decrease. Numerous detrimental effects, such as increased air pollution, higher energy consumption for cooling, and an increased risk of heat-related illnesses, might result from the UHI effect. In order to effectively mitigate the consequences of UHI and improve urban environmental conditions, it is imperative to comprehend the mechanisms underlying its creation.

2.2 Urbanization, Impervious Surfaces, Energy Consumption

Changes made to the natural environment in metropolitan areas by humans are the main cause of the metropolitan Heat Island (UHI) effect. Heat accumulation in cities is exacerbated by a number of variables that contribute to the aggravation of UHI. Urbanization, impermeable surfaces, and energy usage are the main contributing factors. The process by which rural regions become urban

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centres as a result of infrastructural development. industry, and population expansion is known as urbanization [8]. Buildings, roads, and other infrastructure take the place of natural landscapes like woods, meadows, and water bodies as cities grow. Cities are more vulnerable to heat retention as a result of this change, which interferes with the land's natural cooling processes and decreases its capacity to absorb and hold moisture. Localized "heat islands" are produced within cities due to the concentration of infrastructure, buildings, and people in urban areas, which intensifies the UHI impact. In comparison to natural surfaces like soil or plants, impervious surfaces like concrete, asphalt, and buildings are better at absorbing and retaining heat. By keeping water from soaking into the ground, these materials-which are frequently used for roads, parking lots, and roofs in metropolitan areas-reduce evapotranspiration, which is the process by which water evaporates from plants and soil to cool the environment. Instead, only a tiny portion of sunlight is reflected by impermeable surfaces, which store the majority of the heat. This heat is then gradually released into the atmosphere during the night, raising the average temperature in metropolitan areas. The UHI impact is greatly influenced by urban energy usage. Cities need a lot of energy for industrial operations, residential and commercial structures, and transportation. Heat is released into the atmosphere by energy-intensive operations including air conditioning, industrial cooling, and car emissions. Furthermore, waste heat produced by industry and power plants operating in metropolitan areas raises local temperatures even more. It is challenging for the temperature to drop, particularly at night when cooling happens more slowly, because of the combination of heat from impermeable surfaces and urban heat produced by human activity [9]. Cities become noticeably warmer than the surrounding rural regions due to a feedback loop that is exacerbated by urbanization, impermeable surfaces, and energy use. Addressing these contributing factors is key to developing sustainable urban planning strategies that mitigate the UHI effect and reduce its negative environmental and health impacts.

2.3 Environmental and socio-economic impacts

Addressing the Urban Heat Island (UHI) effect is crucial for urban areas because of its extensive environmental and socioeconomic

effects. The increase in urban temperatures brought on by UHI causes a number of problems that have an impact on the environment and human health. Higher energy usage is a direct result of the UHI effect's increase in metropolitan temperatures. In order to maintain comfortable inside settings, buildings and households need more air conditioning and cooling systems as cities get hotter. The power grid is further taxed by this increased demand for electricity, particularly during periods of extreme heat, which may lead to power disruptions and higher electricity costs. Climate change is made worse by the energy consumed for cooling, which is frequently obtained from fossil fuels increases and greenhouse gas emissions.Concerns regarding energy efficiency and resource management in cities are also raised by the prolonged reliance on energy-intensive cooling systems, which diminishes the sustainability of urban living [10]. Numerous health hazards are linked to the UHI effect, especially for vulnerable groups including the elderly, children, and those with pre-existing medical disorders. The risk of heat-related disorders, such as heat exhaustion, heatstroke, and dehydration, is increased in metropolitan environments by high temperatures. If these illnesses are not treated right away, they may become fatal. Long-term exposure to high temperatures can also exacerbate cardiovascular and respiratory conditions. increasing hospitalization rates and the risk of early mortality. Beyond physical health, city inhabitants' quality of life is negatively impacted by thermal discomfort brought on by high metropolitan temperatures, which restricts outdoor activities and lowers general wellbeing. Significant effects of the UHI effect are also seen in urban ecosystems and air quality. Ground-level ozone, a significant air pollutant that is created when combines sunlight with pollutants from automobiles and industrial sources, is exacerbated by higher urban temperatures. Elevated ozone levels can exacerbate respiratory diseases including bronchitis and asthma, cause smog, and harm lung function. By making air contaminants more volatile and persistent in the atmosphere, the high temperatures also make their spread worse.

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UHI has an equivalent impact on urban ecosystems since the extreme heat damages plant and animal life, lowers biodiversity, and interferes with normal ecological processes. Urban vegetation is stressed by high temperatures, which inhibits plant development and the transportational cooling action that plants naturally give. This leads to a decline in urban green spaces, further perpetuating the UHI effect. Moreover, warmer urban environments can alter the migration patterns of animals and increase the vulnerability of local species to heat stress, the overall resilience reducing of urban ecosystems.

3. REFLECTIVE AND GREEN ROOFING SYSTEMS

3.1 Overview of Sustainable Roofing Solutions

Sustainable roofing solutions are innovative approaches that aim to address environmental challenges, including the Urban Heat Island (UHI) effect. energy consumption, and climate adaptation. These systems are designed to reduce the environmental impact of traditional roofing materials and enhance the resilience of urban areas to climate change. By focusing on energy efficiency, heat reduction, and environmental benefits, sustainable roofing solutions play a critical role in improving the sustainability of urban environments.Roofing systems are central to mitigating the UHI effect, as they make up a significant portion of the urban surface area that absorbs and retains heat. Traditional roofs, often made from dark-coloured materials like asphalt, absorb large amounts of solar radiation during the day and release it slowly at night, causing higher temperatures in urban areas. Sustainable roofing systems, such as reflective (cool) roofs and green roofs, counteract this effect by altering the way roofs interact with sunlight.Reflective roofs (also known as cool roofs) are made from high-albedo materials that reflect solar radiation, thereby reducing heat absorption and lowering roof surface temperatures. This cooling effect helps to reduce the overall temperature of the surrounding environment, mitigating the UHI effect.Green roofs, which consist of a layer of vegetation planted on rooftops, provide natural cooling

through evapotranspiration. The plants absorb heat and release moisture, which cools the surrounding air. Green roofs also contribute to improved air quality, stormwater management, and biodiversity. By adopting these sustainable roofing solutions, cities can reduce their heat footprint, lowering ambient temperatures and alleviating the urban heat buildup caused by traditional building materials[11].

Sustainable roofing systems contribute significantly to urban energy efficiency and climate adaptation efforts. These systems offer both direct and indirect benefits related to energy conservation, building performance, and climate resilience.Reflective and green roofs reduce the need for air conditioning in buildings by minimizing the amount of heat entering the interior spaces. Reflective roofs reduce the amount of heat transferred into buildings, while green roofs provide insulation, which helps to keep indoor temperatures cooler during the summer and warmer during the winter. This reduction in energy demand for cooling and heating directly leads to lower energy bills and reduced greenhouse gas emissions, contributing to mitigation climate change goals.Sustainable roofing systems improve the resilience of urban infrastructure to the impacts of climate change. In addition to reducing heat and energy demand, they help manage stormwater by absorbing rainwater, reducing the risk of flooding, and preventing the urban drainage systems from being overwhelmed. Green roofs, in particular, help mitigate the effects of extreme weather events by improving urban water retention and supporting biodiversity in the city. Furthermore, these roofing systems can enhance urban resilience to changing temperature patterns and other climate-related challenges, making cities more adaptable to future climate conditions.

3.2 Reflective Roofing Systems

High-albedo and cool roofing technologies are designed to reduce the amount of heat absorbed by roofs, thereby mitigating the Urban Heat Island (UHI) effect and enhancing building energy efficiency. These technologies focus on materials that reflect a significant portion of solar radiation, instead of absorbing it like traditional roofing materials. The albedo of a surface refers to its reflectivity — the higher the albedo, the more sunlight is reflected, and the less heat is absorbed. Cool roofing systems are built on the principle of maximizing this reflectivity to lower roof surface temperatures and reduce the heat load on urban environments.High-albedo materials are typically light-coloured or reflective, designed to reflect a large percentage of sunlight. By using these materials, cool roofs minimize the absorption of solar radiation, reducing the amount of heat transferred to the interior of buildings and the surrounding urban environment. This not only mitigates the UHI effect but also contributes to the overall reduction of ambient temperatures in cities, improving urban liveability.Cool roofs go simple high-albedo beyond surfaces by incorporating technologies that maximize both reflectivity and emissivity (the ability to release absorbed heat). Cool roofing systems typically use materials that reflect sunlight and radiate absorbed heat away from the building. This enhanced cooling effect reduces the need for air conditioning, thus lowering energy demand and associated emissions [12].

Materials and Advanced Technologies

Advancements in roofing materials and technologies have improved the effectiveness of cool roofing systems, allowing for greater energy savings and environmental benefits.Cool coatings are reflective paints or sprays that can be applied to existing roofs to increase their reflectivity and emissivity. These coatings are typically made from reflective pigments that can be applied over various roof surfaces, including metal, asphalt, and concrete. They work by enhancing the roof's ability to reflect sunlight and radiate heat, significantly lowering surface temperatures and contributing to cooling both indoors and outdoors. Cool coatings can be especially beneficial for retrofitting existing buildings without requiring significant structural changes.Reflective membranes are highly reflective materials used as roofing systems, often in commercial or industrial buildings. These membranes are typically made from polymer-based materials like thermoplastic

olefin (TPO) or ethylene propylene diene monomer (EPDM), which have high albedo properties. Reflective membranes help reduce heat absorption and provide long-lasting, durable protection against UV radiation. These systems offer excellent heat resistance and can significantly reduce cooling costs for buildings by keeping the roof surface cooler.Solar-reflective tiles are specially designed roofing materials that reflect a higher percentage of sunlight compared to conventional roofing tiles. Made from materials such as clay, concrete, or ceramic, these tiles are engineered with reflective coatings that enhance their performance in heat reduction. In addition to their high reflectivity, some solar-reflective tiles are also designed to enhance energy efficiency by providing insulation, further improving thermal comfort inside buildings [13].By reflecting a significant portion of the sun's rays, cool roofing materials reduce the amount of heat that is absorbed by the roof. This helps to lower roof surface temperatures, which not only decreases the temperature of the surrounding urban environment but also prevents heat buildup inside the building. This effect is especially valuable in urban areas where the UHI effect is most pronounced, contributing to cooler, more comfortable outdoor spaces.One of the primary advantages of cool roofing technologies is their ability to reduce the need for air conditioning and cooling systems in buildings. By reflecting sunlight and keeping indoor temperatures lower, cool roofs reduce the demand for cooling, leading to lower energy consumption. This translates to reduced electricity bills and a smaller carbon footprint, as less energy is required to maintain comfortable indoor conditions.Cool roofing materials improve indoor thermal comfort by regulating temperatures in buildings. By reducing heat gain through the roof, cool roofs maintain more stable indoor temperatures, enhancing the comfort of building occupants [14]. This is particularly beneficial in commercial and residential buildings where temperature regulation is essential for productivity and well-being. Additionally, cool roofs contribute to overall urban comfort by mitigating the extreme

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temperature fluctuations typical of cities suffering from the UHI effect.

3.3 Green Roofing Systems

Green roofing systems, which involve vegetation on rooftops, growing provide numerous environmental, economic, and aesthetic benefits. These systems are designed to reduce the negative environmental impact of urbanization, including mitigating the Urban Heat Island (UHI) effect, improving air quality, and enhancing the overall quality of life in cities. Extensive green roofs are characterized by a lightweight, lowmaintenance structure that typically supports a thin layer of vegetation, such as grasses, moss, and drought-tolerant plants. These roofs are designed for minimal intervention and are usually less accessible for human activity. Extensive green roofs are ideal for buildings where structural weight limitations or low maintenance are priorities [15]. These roofs require minimal irrigation and are highly efficient for stormwater management and UHI mitigation, although they may not provide significant space for biodiversity or recreational use. Intensive green roofs are more robust, capable of supporting a wider variety of vegetation, including shrubs, trees, and even small gardens. These roofs are typically deeper, require more structural support, and are more resourceintensive than extensive systems. Intensive green roofs can provide additional benefits, such as spaces for recreation and urban agriculture. They for biodiversitv offer greater potential enhancement and aesthetic appeal but require more maintenance and regular irrigation. These systems are often seen on commercial buildings or residential structures where the roof is used as an amenity space. Green roofs help to regulate temperatures both inside buildings and in the surrounding environment. The vegetation on the roof provides natural cooling through the processes of evapotranspiration and shading. These mechanisms absorb heat, reduce the need for air conditioning, and help to moderate temperatures in urban areas, reducing the UHI effect. As a result, green roofs contribute to improved energy efficiency and a reduction in urban heat buildup, making cities more liveable,

especially during summer months. One of the most significant benefits of green roofs is their ability to manage stormwater. Green roofs capture and absorb rainfall, which reduces runoff and the strain on urban drainage systems. This absorption is particularly important in cities where excessive rainfall can lead to flooding and water pollution. By temporarily storing rainwater and slowly releasing it back into the atmosphere through evaporation, green roofs help mitigate flooding risks and support urban water management. Additionally, they filter pollutants from the water, improving overall water quality [16].Green roofs contribute to biodiversity in urban areas by providing habitats for various species of plants, insects, and birds. These habitats help to support local ecosystems that may have been displaced by urban development. Intensive green roofs, in particular, can host a wide range of species, providing opportunities for urban farming, pollinator gardens, and habitats for wildlife. Even extensive green roofs, with their simple vegetation, can provide a valuable ecosystem for certain species, contributing to the overall ecological health of the city.



Fig: Waterproofing Membranes for Green Roofing

Structural Requirements and Maintenance Considerations

While green roofs provide significant environmental and aesthetic benefits, they also require careful planning and consideration of structural and maintenance needs. Green roofs, particularly intensive ones, require a strong and durable structural foundation to support the weight of the soil, plants, and water. Buildings may need Page | 119

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to be retrofitted or specially designed to accommodate the additional load. Extensive Green Roofs require minimal maintenance, primarily consisting of periodic checks for plant health, occasional weeding, and ensuring that drainage systems remain clear. Some irrigation may be necessary, but overall, they are lowmaintenance systems.Intensive Greenroofs demand more maintenance due to their complexity and the diversity of vegetation. Tasks include regular irrigation, fertilization, pruning, pest control, and checking for damage or wear to structural elements. Intensive green roofs may also require seasonal plant replacements or adjustments to the growing medium to maintain plant health.Proper maintenance is essential to ensure the longevity and performance of green roofs. Without regular care, the benefits of temperature regulation, stormwater management, and biodiversity enhancement can be diminished. Additionally, ensuring proper installation and ongoing maintenance helps prevent damage to the building structure and supports the long-term viability of the green roof system [17].

4. INTEGRATION OF REFLECTIVE AND GREEN ROOFS: OPPORTUNITIES, OPERATIONS, AND CASE STUDIES

4.1 Synergistic Benefits of Combined Roofing Systems

Integrating reflective (cool) and green roofing systems offers a unique opportunity to harness the complementary benefits of both technologies, creating a more effective and sustainable solution for mitigating the Urban Heat Island (UHI) effect, enhancing energy efficiency, and improving the overall environmental performance of buildings. The combined use of these roofing systems leads to synergistic benefits that surpass the individual impact of each system. These include enhanced energy efficiency, reduced cooling loads, lowered urban surface temperatures, and improved water retention, among others.

1. Enhanced Energy Efficiency Through Dual Mitigation Effects

The integration of reflective and green roofing systems enhances energy efficiency by leveraging

the complementary cooling mechanisms of both technologies. Reflective roofs reduce the absorption of solar radiation, thus decreasing the heat load on the building, while green roofs provide additional cooling through evapotranspiration and shading. Together, they create a robust solution that reduces the need for mechanical cooling, resulting in significant energy savings.Reflective roofs contribute to energy efficiency by keeping the building cooler during the day, thus reducing the demand for air conditioning. The high-albedo materials reflect most of the incoming solar radiation, which prevents heat buildup inside the building.Green roofs improve energy efficiency by providing insulation, helping to keep buildings cooler in summer and warmer in winter. During hot weather, the plants on the roof absorb heat and moisture, reducing the temperature within the building. Additionally, they act as a natural thermal barrier, reducing heat transfer from the outside to the inside of the building.By combining both systems, the building's energy consumption reduced through a two-fold cooling is mechanism-both from reflecting heat away and from cooling the building's environment and interior through vegetation.

2. Reduction in Cooling Loads and Urban Surface Temperatures

The combined use of reflective and green roofs leads to a more significant reduction in cooling loads for buildings and a decrease in overall urban surface temperatures. The dual cooling effect of reflective and green roofs reduces the need for air conditioning and mechanical cooling in buildings, which lowers cooling loads. Reflective roofs immediately decrease heat absorption, while green roofs provide sustained cooling over time through evapotranspiration and plant shading. This combination results in less demand for energyintensive cooling systems. thus reducing electricity consumption associated and costs.Reflective roofs help cool the roof surface, while green roofs cool the air above and around the roof. The combined impact leads to a reduction in the temperature of the entire building and its surroundings. This dual reduction in

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temperature is particularly beneficial in combating the UHI effect, where cities tend to experience much higher temperatures than surrounding rural areas due to extensive heat absorption from urban surfaces.By combining both systems, cities can achieve a more substantial cooling effect, reducing the urban heat footprint and promoting better air quality. Lower urban surface temperatures also contribute to improved comfort for residents and a healthier living environment.

3. Improved Building Insulation and Water Retention Benefits

Another key benefit of combining reflective and green roofs is the enhanced insulation and management properties stormwater they provide.Green roofs offer natural insulation by creating an additional layer of protection between the building and external temperatures. Reflective roofs further enhance insulation by preventing excessive heat absorption in the first place. The combination of both systems creates a comprehensive thermal barrier that improves the energy efficiency of the building by stabilizing internal temperatures. This results in better thermal comfort and reduced energy consumption and cooling.Green roofs for heating are particularly effective in managing stormwater by absorbing rainwater, which reduces the strain on urban drainage systems and prevents flooding. Reflective roofs, while not directly contributing to water retention, can assist by providing a cooler environment that allows water to be more effectively absorbed by the plants on the green roof. Together, these systems enhance water retention by reducing runoff and promoting better management of precipitation. This dual benefit is essential in cities that face frequent flooding or water management issues. In addition to these functional benefits. the combined systems contribute to environmental sustainability by improving overall water and energy efficiency in urban environments. The synergistic benefits of combining reflective and green roofing systems create a comprehensive approach to mitigating the UHI effect, improving energy efficiency, and enhancing urban sustainability. By working together, these systems provide dual cooling

effects, reduce building cooling loads, lower urban temperatures, and offer enhanced insulation and water retention capabilities. The integration of both technologies in urban planning and building design can significantly improve the liveability and resilience of cities while contributing to global climate goals.

4.2 Opportunities for Large-Scale Implementation

The integration of reflective and green roofing systems into urban environments presents a wealth of opportunities for large-scale implementation. These opportunities span across urban adaptation strategies, the potential for integration in smart cities and sustainable architecture, and the role of government policies and incentives to promote adoption. Harnessing these opportunities can significantly contribute to the reduction of urban heat islands (UHI), enhance urban resilience to climate change, and support sustainable urban development.

1. Urban Adaptation Strategies for New Constructions and Retrofits

Urban adaptation strategies are crucial for addressing the challenges posed by UHI and the broader effects of climate change. Integrating reflective and green roofing systems can play a key role in both new constructions and retrofitting existing buildings.For new buildings, architects and urban planners can incorporate green and reflective roofing as standard features in building designs. Incorporating these systems from the outset can ensure that buildings are energyefficient, resilient to extreme weather events, and capable of reducing the heat island effect. This is particularly important in densely populated urban areas where heat absorption is a significant problem. By including these systems during the planning and construction phases, developers can avoid the added cost and complexity of retrofitting buildings later on.Retrofitting existing buildings presents a significant opportunity for large-scale UHI mitigation. Many urban buildings, especially older ones, were not designed with energy efficiency or climate adaptation in mind. Retrofitting these buildings with green and

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reflective roofs can not only improve their energy performance but also contribute to lowering the urban heat footprint. In addition to reducing the building's environmental impact, retrofits can improve occupant comfort and reduce utility costs, making them an attractive option for building owners. Incorporating both systems into urban planning and building design can help create cities that are more sustainable and adaptive to changing climate conditions, reducing the negative impacts of urban heat.

2. Potential for Integration in Smart Cities and Sustainable Architecture

The rise of smart cities presents a unique opportunity for integrating reflective and green roofing systems into a holistic approach to urban sustainability. Smart cities use advanced technologies to improve the quality of life for residents, optimize resource use, and reduce environmental footprints. The integration of green and reflective roofs aligns perfectly with the goals of smart cities, as these systems contribute to sustainable management, energy climate adaptation, and resilience to extreme weather. Smart technologies, such as sensors for real-time monitoring of temperature, humidity, and air quality, can be used to optimize the performance of these roofs. For example, sensors could measure the effectiveness of temperature regulation on green roofs or monitor stormwater retention. Real-time data can be used to enhance the management of urban green spaces, improve energy efficiency, and provide feedback for future urban planning strategies.Sustainable architecture focuses on reducing the environmental impact of buildings through design strategies that improve energy efficiency, reduce resource consumption, and promote ecological health. Green and reflective roofs fit seamlessly into the framework of sustainable architecture, serving as both functional and aesthetic elements. These roofs contribute to passive cooling, water management, and biodiversity, making them a central feature in eco-friendly building designs. As sustainable building practices become more mainstream, the integration of green and reflective roofing systems

will likely become an essential component of the architectural design process.

3. Government Policies, Incentives, and Regulatory Frameworks to Promote Adoption

The role of government policies and incentives is critical in driving the widespread adoption of reflective roofing green and systems. Governments can create favourable conditions through regulatory frameworks. financial incentives, and public awareness campaigns.Local and national governments can enact policies that encourage the adoption of green and reflective roofing. Zoning laws, building codes, and environmental regulations can be modified to incorporate these roofing systems as a requirement for new buildings or as an incentive for retrofits. For example, building codes could mandate the installation of reflective or green roofs in certain climate zones to mitigate UHI or reduce energy consumption.Financial incentives, such as tax credits, rebates, or grants, can make it more affordable for property owners to install green and reflective roofs. These incentives would reduce the initial cost barrier and encourage building owners and developers to adopt sustainable roofing technologies. Additionally, incentive programs could be designed to prioritize lowincome or vulnerable communities that may benefit most from the environmental and economic advantages of these systems.Governments can also introduce specific guidelines and regulations that streamline the installation and maintenance of green roofs, ensuring that they are designed and implemented to meet environmental and structural standards. These frameworks would ensure that green roofs are installed properly and can withstand the stresses of urban environments while providing long-term benefits.Bv creating policies. regulations, and incentive programs that promote green and reflective roofing, governments can accelerate the transition to more sustainable urban environments, improve the quality of life in cities, and combat the adverse effects of climate change.The large-scale implementation of reflective and green roofing systems presents a transformative opportunity for urban areas to

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mitigate the Urban Heat Island effect, enhance energy efficiency, and adapt to climate change. Urban adaptation strategies for new constructions and retrofits, the integration of these systems in smart cities and sustainable architecture, and the role of government policies and incentives all play crucial roles in making these systems a mainstream solution. By capitalizing on these opportunities, cities can become more resilient, energy-efficient, and sustainable, contributing to a better urban environment for future generations.

4.3 Operational Aspects of Integrated Roofing Systems

The operational effectiveness of integrated reflective and green roofing systems depends on several key factors, including design principles, construction and maintenance considerations, and the feasibility of implementing these systems across various building types. Additionally, understanding the measured impacts of these systems on Urban Heat Island (UHI) mitigation, energy savings, and environmental benefits is crucial for assessing their overall value in urban climates.

1. Design Principles for Optimizing Combined Reflective-Green Roofing Efficiency

The integration of reflective and green roofing systems requires careful consideration of several design principles to ensure maximum efficiency and performance. The design should incorporate the appropriate layering of materials to optimize the cooling effect. Reflective roofing materials, such as cool coatings or high-albedo membranes, should be paired with the proper green roof substrate to maximize both reflective and evapotranspirative cooling. The reflective layer should reflect a significant portion of solar radiation, while the green roof should be designed with plant species suited for the local climate, providing maximum cooling stormwater and retention.Ensuring that the green roof layer has an effective drainage and waterproofing system is essential to prevent water buildup and leakage. The reflective roof layer should be compatible with the green roofing components to provide the necessary structure and support for plant growth,

promoting water while also flow and retention.Proper ventilation and insulation should be incorporated in the design to reduce heat transfer between the interior of the building and the roofing systems. The design should also include a balance between the cooling effects of the reflective roof and the thermal benefits of the green roof.By optimizing these design principles, the integrated roofing system can provide enhanced performance in terms of cooling, energy efficiency, and environmental benefits.

2. Challenges in Construction, Maintenance, and Long-Term Performance

While the integration of reflective and green roofs offers numerous benefits, there are several challenges that need to be addressed in the construction. maintenance, and long-term performance of these systems. The installation of integrated roofing systems requires specialized expertise and a careful, coordinated approach. The weight of the green roofing system, including soil and plants, may require additional structural particularly support, in retrofit projects. Additionally, the reflective and green roof layers must be carefully coordinated to ensure proper function and durability.Green roofs require ongoing maintenance, including plant care, irrigation systems, and monitoring of drainage to prevent waterlogging. Reflective roofing materials, on the other hand, need periodic cleaning to maintain their reflective properties and prevent dirt accumulation. Integrating both systems requires regular inspection and upkeep to ensure that both components perform optimally over time. The longevity of the integrated system depends on the quality of materials used and the effectiveness of the maintenance plan. Over time, the green roof layer may require replanting or refreshing of the growing medium, while the reflective layer may need resurfacing or re-coating to maintain its high reflectivity. Addressing these long-term considerations is crucial for ensuring that the systems continue to provide their intended benefits.

3. Feasibility Analysis for Different Building Types (Residential, Commercial, Industrial)

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The feasibility of integrating reflective and green roofing systems varies depending on the type of building and its specific needs. A feasibility analysis for residential, commercial, and industrial buildings can help determine the most effective approach for each building type.Green and reflective roofs can be particularly beneficial for residential buildings, especially in urban areas with limited green space. While the installation of green roofs in residential settings may be more cost-effective in the case of single-family homes with flat roofs, multi-family buildings with large flat roofs may be ideal candidates for these systems. Reflective roofs can help reduce cooling costs in the summer, improving energy efficiency, while green roofs contribute to stormwater management and enhance the aesthetic value of the building.Commercial buildings often have larger roof areas and may benefit from the energy savings provided by both reflective and green roofing systems. In commercial spaces, where cooling costs can be significant, the combined systems can reduce the energy demand from air conditioning while improving indoor comfort. Additionally, commercial buildings in highdensity urban areas can leverage green roofs for stormwater retention, thus alleviating pressure on local infrastructure.Industrial buildings present specific challenges due to the large, often flat roofs, which can provide an opportunity for largescale green roof implementation. However, the industrial setting might pose challenges in terms of maintaining the integrity of the roofing system, given the potential for environmental stressors such as chemical exposure or heavy foot traffic. Despite these challenges, reflective and green roofs can contribute significantly to energy savings, especially in areas where cooling and heating demands are high.

4. Measured Impacts on UHI Mitigation, Energy Savings, and Environmental Benefits

The integration of reflective and green roofing systems has been shown to produce measurable impacts on UHI mitigation, energy savings, and overall environmental benefits.The combined effect of reflective and green roofs significantly reduces the absorption of solar radiation in urban

areas, thus helping to lower urban surface temperatures. Green roofs provide cooling through evapotranspiration, while reflective roofs minimize heat absorption. These systems work synergistically to reduce the UHI effect, improving the comfort and liveability of urban areas.Buildings with integrated reflective and green roofs experience reduced cooling loads, leading to lower energy consumption, particularly during hot summer months. Energy savings are achieved through the combined effects of reduced heat absorption (reflective roofs) and increased natural cooling (green roofs). The use of these systems can lead to significant reductions in electricity costs, particularly in areas with high cooling demands.Beyond mitigating the UHI effect and saving energy, integrated roofing systems provide a wide range of environmental benefits. Green roofs enhance urban biodiversity, improve air quality by absorbing pollutants, and promote stormwater management by reducing runoff. Reflective roofs, in turn, contribute to energy conservation and climate overall adaptation by reducing the heat load on buildings and surrounding areas. Operationalizing integrated reflective and green roofing systems requires careful attention to design principles, addressing construction and maintenance challenges, and considering the feasibility for different building types. The benefits of these systems extend far energy beyond cooling and efficiency, contributing to broader environmental and socioeconomic goals, such as UHI mitigation, energy savings, and urban resilience. By evaluating the operational aspects and measuring their impacts, cities can develop strategies for large-scale implementation that deliver long-term sustainability and improve the quality of urban life.

5. POLICY AND URBAN PLANNING CONSIDERATIONS

The successful integration of reflective and green roofing systems into urban areas requires thoughtful policies and urban planning strategies. These considerations involve current policies, building codes, barriers to adoption, and the roles of various stakeholders such as governments,

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private sectors, and communities. Additionally, financial incentives public-private and partnerships essential driving are in the widespread adoption of these sustainable roofing systems. This section delves into these aspects and provides a comprehensive overview of the policy landscape and strategic planning for implementing these systems at a large scale.

1. Current Policies and Building Codes Related to Sustainable Roofing

The policy framework surrounding the adoption of sustainable roofing systems, including reflective and green roofs, varies across regions, but there are several common themes. Many cities and regions have implemented policies aimed at mitigating the Urban Heat Island (UHI) effect, with some specifically encouraging the use of reflective and green roofs. These policies often include guidelines or regulations to reduce heat absorption, improve urban air quality, and lower energy consumption. For example, cities like New York, Toronto, and San Francisco have adopted policies that encourage or mandate the installation of green roofs on certain building types.Building codes play a critical role in shaping urban construction and renovation practices. Many countries and cities have amended their building codes to incorporate energy-efficient, sustainable construction practices. This includes requirements for energy-efficient materials and insulation, of which reflective and green roofs can be integral. However, specific requirements for these roofing systems are still not universally adopted. In some places, local building codes might need to be updated to provide clearer specifications for the installation of green and reflective roofs.Broader sustainability policies, including those related to climate adaptation, promote the use of reflective and green roofing to support environmental goals. Urban climate action plans often include measures to reduce urban temperatures and improve energy efficiency, and these roofs are a natural fit for such strategies.

2. Barriers to Widespread Adoption in Urban Planning

Despite the clear benefits of reflective and green roofs, several barriers hinder their widespread adoption in urban planning. One of the primary challenges is the high upfront cost of installing green and reflective roofing systems, particularly in the case of retrofitting existing buildings. These costs can include the installation of materials. structural reinforcements. and ongoing maintenance. While the long-term energy savings and environmental benefits are significant, the initial investment may deter property owners or developers.In many urban areas, there is limited awareness of the benefits of reflective and green roofs, as well as a lack of understanding regarding their installation, maintenance, and performance. Without adequate knowledge, both public and private sector stakeholders may be reluctant to adopt these systems.Not all buildings, especially older structures, are designed to support the additional weight and complexity of green roofs. The need for structural reinforcements can be an added cost and may make the installation of these systems impractical for certain buildings. Similarly, some urban areas have limited space for implementing green roofs, especially in densely built environments.In some regions, outdated or inflexible building codes and zoning laws may impede the installation of green and reflective roofs. For example, zoning restrictions may limit the ability to implement green roofs in certain residential or commercial areas, or there may be confusion about what constitutes compliant green roof installation under local regulations.

3. Financial Incentives, Subsidies, and Public-Private Partnerships for Promoting Green and Reflective Roofs

To overcome the financial barriers to the adoption of green and reflective roofs, governments and private organizations can offer a variety of financial incentives, subsidies, and foster publicprivate partnerships. Governments can introduce tax credits, grants, or subsidies to reduce the upfront cost of green and reflective roofing systems. These financial incentives can make it more affordable for property owners and developers to invest in these technologies, improving viability the economic of

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adoption.Cities and governments can offer subsidies to encourage the retrofitting of existing buildings with green or reflective roofs. Retrofitting programs could target low-income neighbourhoods, where the UHI effect disproportionately affects vulnerable populations. Subsidies could also be targeted at commercial and industrial properties, where energy consumption is а significant concern.Collaboration between the public and private sectors can result in more efficient and cost-effective implementation of green and Public-private reflective roofing systems. partnerships can pool resources and expertise to fund large-scale projects, particularly in urban areas where significant infrastructure investment is needed. For example, local governments could partner with construction firms or environmental organizations to provide affordable installation and maintenance solutions for sustainable roofing systems. Financial support for research and development (R&D) can stimulate innovation in the green and reflective roofing market, making these systems more affordable, durable, and accessible. Government funding for R&D, combined with private-sector investment, can lead to new materials, construction methods, and business models that lower costs and increase adoption rates. The integration of reflective and green roofing systems into urban planning and policies requires a multifaceted approach that involves updating current building codes, addressing barriers to adoption, and engaging governments, the private sector, and communities. The role of policy frameworks, financial incentives, and public-private partnerships is critical in overcoming the financial and structural challenges that may prevent widespread adoption. By fostering collaboration and creating a supportive regulatory environment, cities can accelerate the implementation of these sustainable roofing solutions and unlock their full potential for UHI mitigation, energy savings, and environmental benefits.

6. FUTURE PROSPECTS

As urban environments continue to grow and face the challenges of climate change, the role

of sustainable roofing systems, such as reflective and green roofs, becomes increasingly vital. The future of these systems will be shaped by emerging innovations, strategic large-scale adoption efforts. and interdisciplinary collaboration. This section explores the latest trends in roofing technologies, strategies for expanding their use in urban areas, and the importance of cross-sector collaboration to advance sustainable urban design. The integration of smart technologies into roofing systems is on the rise. Roofs embedded with sensors can monitor temperature, humidity, rainfall, and energy use, providing real-time data that can optimize the performance of both green and reflective roofs. This data can help adjust irrigation systems for green roofs, measure energy savings for reflective roofs, and provide valuable insights for building managers and urban planners.New materials and technologies are being developed to improve the efficiency and durability of green roofs. These innovations include lightweight growing media that reduce the structural load, modular green roof systems that are easier to install and maintain, and droughtresistant plant species that can survive in urban climates with less water. Additionally, research is focusing on integrating urban agriculture into green roofs, creating multifunctional spaces that contribute to food production can in cities.Advancements in cool roofing materials, including reflective coatings, membranes, and tiles, are improving the thermal performance of reflective roofs. Innovations in nanotechnology, for example, are leading to coatings that are even more reflective and durable, ensuring that reflective roofs maintain their high-albedo properties over time. Moreover, there is a growing focus on integrating solar-reflective tiles that can double as energy-generation systems, creating roofs that not only reduce heat but also produce renewable energy.Future roofing systems may combine various technologies beyond iust reflective and green roofing. Hybrid roofing systems that integrate solar panels, green roofs, and reflective surfaces can further optimize energy efficiency and sustainability. For example, the synergy between solar panels and green roofs

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could help keep the panels cooler, improving their energy generation capacity, while the green roof provides additional environmental benefits. The future of green and reflective roofing systems is promising, with emerging innovations, strategic large-scale adoption efforts, and interdisciplinary collaboration driving sustainable urban design forward. By fostering collaboration among urban architects, planners, environmental experts, government agencies, and the private sector, cities can enhance their resilience to climate change, mitigate the Urban Heat Island effect, and improve overall sustainability. The role of smart technologies and financing models will further accelerate the adoption of these systems, ensuring a more sustainable and liveable future for urban populations.

7. CONCLUSION

The integration of reflective and green roofs presents a promising solution for mitigating the Urban Heat Island (UHI) effect and fostering sustainable urban environments. Both roofing systems offer distinct yet complementary benefits: reflective roofs reduce heat absorption and energy consumption, while green roofs provide ecological advantages such improved stormwater as management, biodiversity enhancement, and additional thermal insulation. When combined, these systems create synergistic effects that can significantly reduce urban temperatures, alleviate energy demand, and improve urban air quality, thereby contributing to the broader goals of climate adaptation and sustainability. This paper has highlighted the potential of these integrated roofing systems as effective tools in UHI mitigation, with a focus on their practical application in urban planning and building design. The comparative analysis presented suggests that cities can achieve enhanced energy efficiency and comfort through thoughtful integration of both Despite the promising benefits. systems. challenges remain, including high initial costs, maintenance concerns, and structural requirements. However, opportunities for overcoming these challenges are plentiful, particularly through supportive policy

frameworks, government incentives, and collaboration with the private sector.

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