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Employing Green Roof Infrastructure to Alleviate Urban Heat Island Effect: Green-scape Infused Urban Fabrics

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Abstract: The urban design of the future should prioritize the incorporation of greenery and biodiversity into the urban district and landscape. Preserving biodiversity in the face of challenges like urbanization, habitat fragmentation, environmental degradation, and climate change is one of the most significant tasks we are facing in today's scenario. To counter the urban heat island effect caused by heat absorption and reflection from buildings and pavements, it is crucial to integrate trees, shrubs, plants, green spaces, and gardens throughout the city. Tomorrow's urban areas must provide innovative green spaces for recreation and mitigate the effects of a warmer climate. Additionally, these future urban areas should aim to generate at least half of their power on-site. Integrated urban development, focusing on energy, water, greenery, and the urban microclimate, will play a crucial role, with urban designers collaborating with policymakers to significantly reduce energy and resource consumption in cities. This paper introduces the concept of green urbanism and green infrastructure as a comprehensive framework for environmentally conscious urban development. The incorporation of green roofs across all rooftops, which help mitigate the urban heat island effect and collect rainwater, should become a standard practice in inner-city areas. These efforts are part of a larger initiative to redefine urban renewal in India, addressing various environmental, energy, and rooftop-related challenges.
Keywords: Green Infrastructure, Urbanization, Heat Island Effect, Microclimate, Environmental Awareness

I. INTRODUCTION

Cities are constantly evolving and never truly complete, requiring planners to view them as complex, self-sufficient organisms alike to the natural systems. Accelerating urban fabric will need to generate at least half of their power locally and on-site, which oblige the use of zero-energy and plus-energy buildings.

These buildings, which are already at the cutting edge of technology, represent the next stage of development, where entire city zones act as power plants. Urban areas that can produce all their required energy through decentralized renewable systems, such as solar PV, biomass, micro wind turbines, or geothermal technology, will fulfil the long-held aspirations of city planners for clean and inexhaustible energy sources. The realization of this vision relies on the collaboration of policymakers, power suppliers, researchers, architects, planners, and citizens. Green urban transformation and the provision of renewable energy are rapidly becoming a reality worldwide, serving as a significant focus for urban planning. However, achieving this goal entails addressing the challenges faced by both stagnant, underdeveloped urban zones with limited investment and outdated infrastructure, as well as rapidly growing, dynamic urban sectors.

However, is the current state of the city honestly sustainable? To achieve significant reductions in energy, water, and resource consumption, integrated urban development with a specific focus on energy, water, and the urban microclimate has to be in the foreground. The concept of a "low-carbon urban areas" should be further expanded to encompass a compact, mixed-use, and well-connected plus-energy city district.

To maximize open space, and accommodate increasing population densities, a substantial portion of each district (at least 30-40% of the area) should be dedicated to public green spaces. The concept of a climate-friendly, energy-optimized, and resource-efficient city is a prime concern globally, spanning in different regions in the world. In the Asian region, rapid urban growth and migration pose significant challenges.

While some cities experience shrinking or stagnation, a few popular cities thrive with investments and high liveability indicators, attracting a skilled workforce in a knowledge-based society. This paper investigates the potential of green roofs in ameliorating the negative effects of UHI through the analysis of cooling process by green roofs.

II. CITY THAT PRIORITIZES: CLIMATE-FRIENDLINESS, ENERGY OPTIMIZATION, AND RESOURCE EFFICIENCY

The design of new urban precincts must prioritize the integration and restoration of biodiversity within the urban environment. Preserving biodiversity against the backdrop of urbanization, habitat fragmentation, environmental degradation, and climate change is undeniably one of the greatest challenges we are facing today. Current and future urban precincts will need to provide innovative green spaces, not only for recreation but also to combat the warmer urban climate, heatwave impacts, and the urban heat island effect. Green urbanism emerges as a comprehensive concept for tomorrow's plus-energy urban fabrics, emphasizing the efficient use of energy, land, water, green spaces, materials, and mobility. Its ultimate objectives are achieving zero emissions, zero waste, and minimizing energy, water, and material wastage. The transition toward a low-carbon city serves as an intermediate stage, always prioritizing socially and ecologically sustainable urban districts and precincts.

A. *Increases in Urban Heat Island Effect*

The urban climate is significantly influenced by various aspects of the city's physical structure, leading to the exacerbation of the urban heat island effect. Urban heat islands form in urban and suburban areas primarily due to the higher solar radiation absorption and retention of traditional construction materials compared to the organic materials found in rural areas.

There are two main factors contributing to this heat build-up. Firstly, most urban building materials are impermeable and waterproof, which limits the dissipation of solar energy through humidity. Secondly, the combination of dark-colored materials and canyon-like urban structures intensifies the trapping and collection of solar radiation, resulting in increased urban heat. Furthermore, the reduction of urban vegetation limits evapo-transpirative cooling, further enhancing the urban heat island effect.

To address the challenges posed by the urban heat island effect and its adverse consequences, several potential solutions can be explored. One effective approach is to mitigate the surface temperature of roofs, as it plays a crucial role in improving the thermal conditions of cities. This can be achieved by replacing traditional roof surfaces with green roofs, which exhibit significantly lower temperatures during the summer. Green roofs enhance the thermal performance of buildings and reduce the absorption of solar radiation, thus helping to combat the urban heat island effect.

B. *Roof and their Effect on the Urban environment*

The reflectivity of external elements in a building has a significant impact on its overall heat gain or loss, particularly in areas exposed to high levels of solar radiation. One crucial aspect in this regard is the roof and façade of the building. Roofs cover approximately 20 to 25 percent of urban areas and often exhibit the highest temperatures in thermal images of urban environments. Conventional roofing materials commonly reach temperatures ranging from 65 to 90ºC. These materials typically have a solar reflectance of only five to 25 percent, resulting in the absorption of 75 to 95 percent of the sun's radiative energy. Consequently, the extensive use of traditional roofing materials in urban areas leads to the accumulation of solar radiation within the urban context.

Furthermore, traditional roofing materials possess other characteristics that contribute to the urban heat island effect. Heat capacity and thermal conductivity play critical roles in this regard. Conventional roofing materials tend to absorb and store more heat during the day, gradually releasing it through infrared radiation and convection into the surrounding air, thereby exacerbating the urban heat island effect. They also transfer a portion of the accumulated heat to the buildings beneath them, compromising the thermal comfort of occupants and increasing the need for electricity consumption in air conditioning. As a result, buildings emit more heat directly through the air conditioning process and indirectly through the emissions generated by power plants.

Additionally, traditional roofing systems are impermeable, preventing water penetration and inhibiting the evaporation process involved in latent heat phenomena. The absence of proper evaporation or condensation further impacts the thermal characteristics of roof surfaces.

III. GREEN URBANISM: AS A HOLISTIC FRAMEWORK FOR SUSTAINABLE URBAN GROWTH

Green urbanism encompasses a holistic approach to sustainable urban systems, emphasizing interconnected features that enable urban growth or shrinkage without harming planetary life support systems and ecosystems. It focuses on achieving a healthy balance between the city, peri-urban areas, and their surrounding hinterlands. Green urbanism guides practical actions to shape the urban environment sustainably.

The concept of green urbanism, based on principles, emerged in the late 1990s, advocating for compact and energy-efficient urban development.

Metropolitan plans have been formulated, incorporating strategies such as alternative energy generation, utilizing combined heat-and-power cogeneration within urban districts, implementing green roofs and facades to mitigate construction impacts, and integrating more green spaces to counteract the urban heat island effect. These public green spaces can vary in size, from small intimate gardens and community farms to formal parks, meadows, and urban forests, all aimed at reintroducing biodiversity into the urban environment.

In addition to these initiatives, metropolitan plans have also addressed other factors such as reducing the risk of urban flooding, implementing stormwater harvesting, promoting efficient public transportation and eco-mobility, implementing local waste recycling for resource recovery, protecting biodiversity, and establishing ecological connections.

The principles of green urbanism are based on the triple zero frameworks of:

1) zero fossil-fuel energy use,
2) zero waste, and
3) zero carbon emissions.

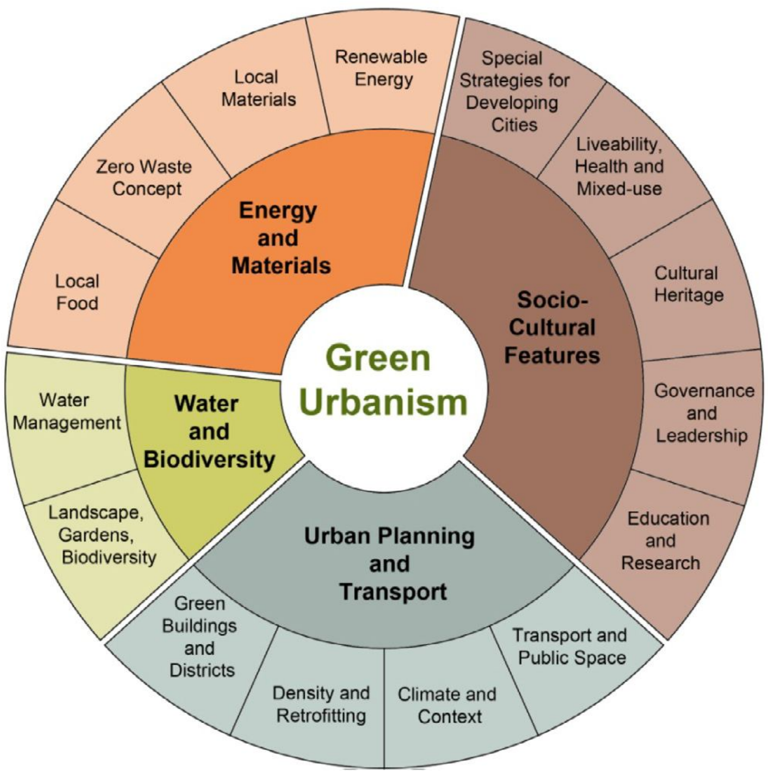

Figure 01: The 15 Principles Of Green Urbanism And Their Interconnections
(REFERENCE: Low carbon districts: Mitigating the urban heat island with green roof infrastructure, Steffen Lehmann)

It is crucial to acknowledge that for sustainable urban development and the successful implementation of eco-districts, all components and sectors of urban design must work together in an interconnected manner, rather than being treated separately. This necessitates a comprehensive understanding of the existing life cycles associated with each development site, including the analysis of intricate patterns of energy, water, and materials flow both within and beyond the site. In cases where these interconnections have been disrupted or lost, the design process should incorporate regenerative elements, such as the reintroduction of native species, to restore and revitalize the ecosystem.

IV. VEGETATION, GREEN ROOFS AND URBAN MICROCLIMATES

The concept of green roofs has a rich history in architecture, particularly in cities and towns surrounding the Mediterranean Sea. For centuries, rooftops have been utilized as living and garden spaces, compensating for limited ground space. In the 1930s, renowned architect Le Corbusier and other modernist visionaries reintroduced the idea of the green roof as a substitute for gardens on top of buildings.

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Le Corbusier's design for an apartment on a Paris rooftop in 1930 exemplified this concept and marked one of the early Modern Movement projects featuring rooftop living.
In the 1990s, Germany played a pivotal role in advancing green roof technology by establishing standardized construction practices. These standards defined the engineered layers of a green roof, including a waterproof membrane, thermal insulation, a root barrier, a moisture retention layer, a drainage layer, filter fabric, and a planting medium. This technical perfection ensured safe and successful green roof construction without leakage.
Urbanization has resulted in changes to land cover, directly impacting the urban microclimate. Factors such as topography, building dimensions and geometry, density, facade and roof materials, surface albedo, urban canyons, transport pollution, and integration of greenery all contribute to the temperature profile of a precinct or district. Green walls on facades and green roofs act as additional insulating layers for buildings, buffering external temperatures and maintaining comfortable indoor temperatures. The presence of various forms of greenery, such as parklands, gardens, vertical greenery, urban farming, and nature reserves, contributes to evapotranspiration (evaporative cooling), allowing absorbed solar radiation to dissipate as latent heat and reduce urban temperatures. Green roofs have the potential to significantly lower rooftop surface temperatures, improve ambient air temperatures, enhance human thermal comfort, and result in energy savings for buildings.
Roofs with greater soil depth offer more moisture retention and stable soil temperatures, providing a suitable ecosystem for plant growth and accommodating a wider range of species. Traditional roof gardens, with their heavy weight and deep soil profiles, require intensive maintenance and feature larger plant species. However, modern lightweight green roofs differ significantly. They are cost-effective, lightweight with thin soil profiles, and require minimal maintenance. Typically, green roofs are not accessible to occupants and are primarily installed for environmental benefits and aesthetic enhancement.
Plants are known to have a cooling effect and can be strategically incorporated into urban and architectural design. Combining vegetation with lighter colors, utilizing the albedo effect, can help keep buildings and roofs cooler. Moreover, plants contribute to carbon sequestration by absorbing carbon dioxide. Studies have shown that urban properties with greenery hold higher value due to visual and social factors, allowing us to assign a monetary value to urban green spaces. Green roofs and walls are often regarded as low-cost solutions for urban heat mitigation, as they provide insulation and reduce energy transfer into buildings. However, the effectiveness of green roofs and walls depends on design details and construction methods. Some green roofs have shown limited biodiversity, with few plant species and limited animal habitat. Key parameters for green roofs include rooftop surface albedo, substrate depth, vegetation species, planting density, watering regime, and whether the roof is extensive or intensive. Tests have indicated that irrigation improves green roof performance through increased evapotranspiration but requires more water, which can be addressed through the recycling of greywater and stormwater harvesting.

Figure 2 and 3: Greenery Integrated In Facades Has Been Successfully Applied In Buildings In Singapore And Seoul: Facade Of An Office Building In Singapore (Left) And The Internal Green Wall In The Atrium Of Seoul City Hall.

V. USING GREEN ROOFS TO REDUCE HEAT ISLANDS

Green roofs have been widely recognized as effective solutions for mitigating the heat island effect. They consist of vegetative layers grown on rooftops, providing shade, removing heat from the air, and reducing temperatures of both the roof surface and the surrounding air. In urban areas with limited vegetation, green roofs play a crucial role in moderating the heat island effect, particularly during the daytime. Compared to conventional roofs, green roofs can have temperatures that are 30-40°F lower and can contribute to reducing city-wide ambient temperatures by up to 5°F. The benefits of green roofs extend beyond temperature reduction. They also contribute to energy efficiency, with green roofs reducing building energy use by 0.7% compared to conventional roofs. This reduction in energy consumption leads to lower peak electricity demand and can result in an annual savings of $0.23 per square foot of the roof's surface. The temperature and energy efficiency advantages have contributed to the increasing popularity of green roofs.

Vegetation plays a vital role in creating a healthy urban environment. Greenery systems provide numerous benefits, including reduced energy demand, pollutant reduction, improved water management, and enhanced ecosystems. When it comes to mitigating the urban heat island effect, vegetation operates through three key processes. Firstly, plants provide shade to buildings, shielding them from solar radiation and thereby keeping the structures cooler. This reduction in heat transfer to the air above helps mitigate the urban heat island effect and decreases the energy required for cooling. The amount of solar radiation transferred beneath plant canopies varies depending on the type of vegetation, ranging from 6 to 30 percent in summer and 10 to 80 percent in winter. Furthermore, dense plant canopies that emit lower amounts of radiant heat result in minimal soil radiation below the canopy. This situation enhances evapotranspiration, which contributes to the mitigation of air temperature and an increase in relative humidity. The cooling benefits from reduced air warming are achieved through the creation of high-quality shade and the filtering of solar radiation. Shading from plants also provides a sense of coolness and comfort to people and reduces the risk of heat-related illnesses and exposure to harmful ultraviolet rays.

Furthermore, vegetation engages in photosynthesis, converting water, carbon dioxide, and solar radiation into glucose and oxygen. During this process, plants use evapotranspiration as an auxiliary mechanism to maintain coolness. Through their roots, plants absorb water and release it into the air as vapour through their leaves. The energy from solar radiation is utilized to evaporate water, preventing it from being used to increase air temperature. On average, a tree can evaporate 1460 kg of water and consume approximately 860 MJ of energy during a clear summer day.

This outdoor cooling effect is equivalent to that of five typical air conditioners. By incorporating vegetation on roofs, the cooling energy required to maintain comfortable temperatures inside buildings can be reduced. This is because the building is protected from direct solar radiation and the reflected radiation from the surrounding environment.

In summary, green roofs offer significant benefits in mitigating the urban heat island effect. They provide shade, reduce air and surface temperatures, contribute to energy savings, and promote evapotranspiration. The incorporation of vegetation in urban areas is an effective strategy for enhancing thermal comfort, reducing energy consumption, and creating healthier and more sustainable cities.

A. Types of Green Roof

Green roofs can be installed on a wide range of buildings, from industrial facilities to private residences. There are two types of green roofs: extensive and intensive.

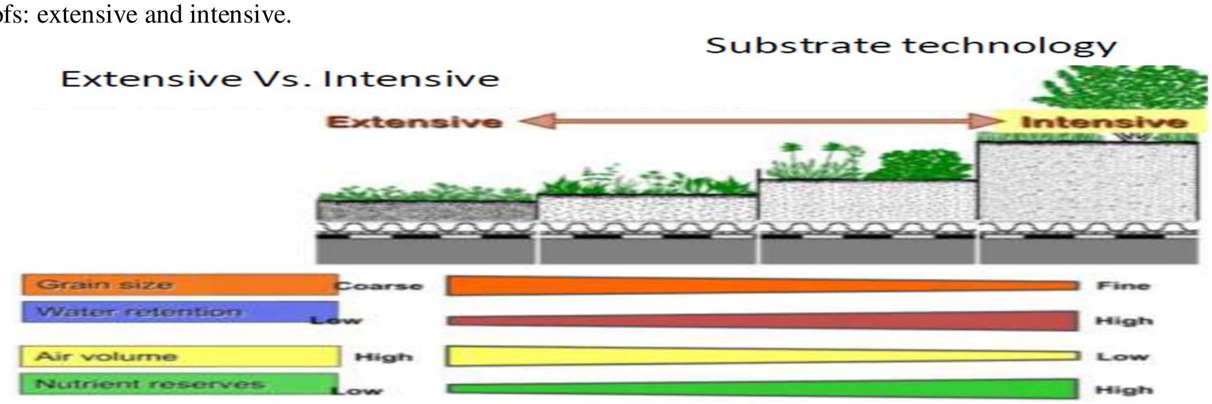

Figure 4: Extensive And Intensive Green Roof (http://pubs.sciepub.com/aees/6/4/5/figure/7)

Extensive Green Roof	Intensive Green Roof
Thin growing medium, little or no irrigation, low plant diversity.	Deep soil, irrigation system, high plant diversity.
Advantage: • Light weight, roof generally does not require reinforcement. • Suitable for large areas • Low maintenance and long life • Relatively inexpensive • Look more neutral • Often suitable for retrofit projects • Less technical expertise required	Advantage: • Good insulation properties • Greater diversity of plants and biodiversity • Can be made visually appealing • Longer membrane life • More energy efficiency and storm water retention capacity. • Often accessible with more diverse utilization of roofs.
Disadvantage: • Less energy efficiency and storm water retention capacity. • Limited choice of plants • Usually no access for recreational or other uses.	Disadvantage: • Greater weight loading on roof • Higher capital and maintenance costs • More complex system and expertise.

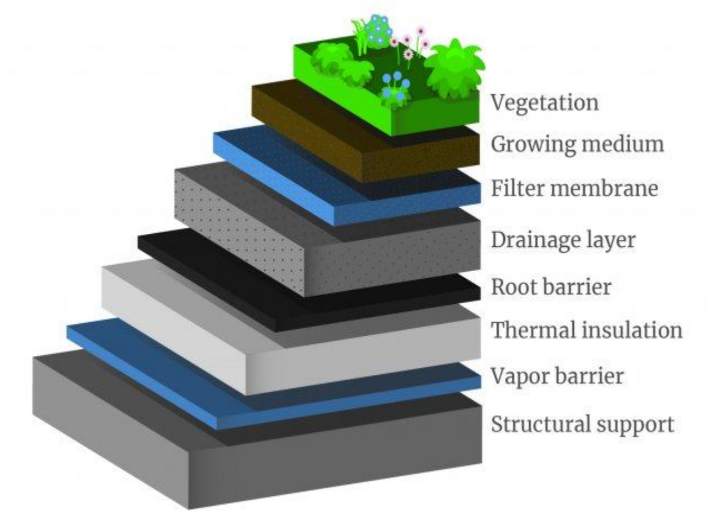

Figure 5: Green Roof Layers (https://www.epa.gov/heatislands/using-green-roofs-reduce-heat-islands)

Both types of green roofs consist of the same basic layering components with a number of barriers to prevent water or root damage to the structure, a drainage layer to aid in water drainage, as well as a growing medium and vegetative layer. The Common Green Roof Layers figure (adjacent) represents the most common design of a green roof, although not all the layers shown are found on every green roof.

B. Green Roofs V/S Cool Roof

Another approach to reducing the heat island effect is through the use of cool roofs. Cool roofs are constructed using highly reflective and emissive materials that maintain lower temperatures than traditional roof materials during peak heat periods. While green roofs may initially have higher costs compared to cool roofs, they tend to have a longer expected lifespan. Both cool roofs and green roofs offer advantages such as lower surface and air temperatures, as well as reduced energy demand.

However, green roofs provide additional benefits that cool roofs do not. Green roofs can help in managing storm water runoff by reducing and filtering it, absorbing pollutants and carbon dioxide, providing natural habitats, and even serving as recreational green spaces in the case of intensive green roofs. Cool roofs are particularly suitable for projects with limited budgets and a primary focus on energy savings. On the other hand, green roofs are preferred when considering lifecycle costs, public benefits, and broader environmental impacts. Both options play important roles as strategies to mitigate the heat island effect.

C. Co- Benefits of Green Roof

1) Reduced air pollution and greenhouse gas emissions: Green roofs help reduce air pollution and greenhouse gas emissions in multiple ways. By lowering the demand for air-conditioning, they decrease the need for conventional power sources that contribute to air pollution and greenhouse gas emissions. Additionally, the vegetation on green roofs can remove pollutants and greenhouse gases from the air through dry deposition and carbon sequestration, respectively.
2) Reduced energy use: Green roofs have a cooling effect on buildings through evapotranspiration, which is the process of plants releasing moisture into the air. This natural cooling effect reduces the energy required for air conditioning during hot weather. Furthermore, green roofs act as insulation, reducing heat transfer through the building roof and lowering the energy needed for heating during cold weather.
3) Improved human health and comfort: Green roofs contribute to improved human health and comfort by reducing heat transfer through buildings. This helps maintain cooler indoor temperatures and reduces the incidence of heat stress, particularly during heatwaves. By creating more comfortable living and working environments, green roofs can have a positive impact on human well-being.
4) Improved quality of life: Green roofs offer various benefits that enhance the quality of life in urban areas. They provide aesthetic value and introduce green spaces into the built environment, which improves the overall visual appeal of cities. Green roofs also serve as habitats for plant and animal species, promoting biodiversity in urban areas. Research has shown that human interaction with nature, such as through green roofs, can positively impact physical and mental health, productivity, and overall well-being.
5) Enhanced stormwater management and water quality: Green roofs play a significant role in stormwater management and improving water quality in urban areas. They reduce and slow down stormwater runoff, minimizing the strain on urban drainage systems during heavy rainfall events. Green roofs act as natural filters, removing pollutants from rainfall as it passes through the vegetation and growing media. During the summer months, green roofs can retain nearly all storm-related precipitation, while in winter months, retention rates are typically lower.

Overall, green roofs offer a range of benefits that contribute to a more sustainable and livable urban environment, including reduced air pollution and greenhouse gas emissions, energy savings, improved human health and comfort, enhanced biodiversity, and better stormwater management and water quality.

VI. CONCLUSION

The preservation of biodiversity and the integration of green spaces in urban areas are crucial considerations for sustainable urban development. Efforts should be made to preserve existing natural habitats and incorporate ecological connections within urban environments. This can involve strategies such as preserving remnant natural habitats, implementing urban farming initiatives, rooftop gardening, and creating green walls. To achieve sustainable urbanization, it is essential to develop zero-energy or plus-energy precincts, where the energy generated meets or exceeds the energy consumed. Integrated urban development approaches that address energy, water, greenery, and the urban microclimate should play a leading role and engage policymakers to significantly reduce energy and resource consumption in cities. Green roofs and green walls have been extensively studied and proven to be effective in mitigating the urban heat island effect. Their natural cooling effect through evapotranspiration makes them a cost-effective strategy for cooling buildings and reducing energy transfer. However, the design and construction details of green roofs and walls are critical to their effectiveness. Further research is needed to optimize urban systems, including renewable energy and green roofs. However, bureaucratic processes and lack of research funding in certain areas, such as storage technology for surplus renewable energy, can hinder technical progress. It is important to overcome these barriers and promote innovation in urban planning and sustainable technologies. More research is required to advance planning theory and support evidence-based planning policies for low-carbon precincts. Green urbanism principles, when applied with integrated design approaches and a focus on regeneration, can contribute to these efforts. By incorporating these principles, cities can strive for sustainable urban development that balances environmental, social, and economic considerations.

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