

The Eurasia Proceedings of Health, Environment and Life Sciences (EPHELS), 2026

Volume 23, Pages 27-34

ICGeHeS 2026: International Conference on General Health Sciences

Practical Solutions for Increasing the Albedo of Urban Surfaces to Reduce the Heat Island and Cooling Load of Buildings

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Abstract: The increase in temperature of urban areas relative to the surrounding areas, known as the urban heat island (UHI) phenomenon, has become one of the main challenges of metropolises. This phenomenon not only affects the thermal comfort of citizens, but also significantly increases energy consumption by increasing the energy demand for cooling buildings. The search for a solution to this problem naturally depends on the environmental and physical conditions of cities and can be quite different for each region. In this metropolis like Tehran, the research methodology of this paper is based on a systematic review of analytical studies and a descriptive adaptation of strategies for increasing albedo in hot and dry climates. One of the effective and low-cost solutions to reduce this phenomenon is to increase the albedo of urban surfaces through the use of reflective materials. The results show that cool roofs can reduce surface temperatures by up to 6°C and cooling energy consumption by 15–40%, while high-albedo pavements reduce surface temperatures by up to 18°C but may increase the average ambient radiant temperature. Analysis of Tehran's climate conditions shows that combining reflective strategies with green infrastructure and urban geometry management can lead to significant reductions in thermal loads. Accordingly, a phased framework for implementing albedo-enhancing strategies in urban environments is proposed.

Keywords: Albedo, Cool roof, Urban heat island, Building energy consumption, Cool urbanism

Introduction

Rapid urbanization and land use change in recent decades have led to significant changes in the local climate of cities. The replacement of natural surfaces with artificial materials such as asphalt and concrete, along with the reduction of vegetation cover, has led to the urban heat island (UHI) phenomenon. In this phenomenon, the temperature of urban areas is significantly higher than the surrounding rural areas (Santamouris, 2013). Recent studies in Tehran province show that the surface temperature in some areas has reached 52.97 degrees Celsius, and the intensity of the heat island in this metropolis is estimated to be more than 5 degrees (Mohammadi et al., 2025; Aslani, 2021).

The UHI phenomenon has several consequences, the most important of which are increased energy consumption for cooling buildings, increased air pollution (especially increased ground-level ozone), reduced thermal comfort, and increased health risks, especially for vulnerable groups in society (Ulpiani, 2021). In the city of Atlanta, studies have shown that urban heat islands threaten the health of citizens, especially people with respiratory diseases, by increasing ground-level ozone concentrations (Atlanta Journal-Constitution, 2025).

Albedo, defined as the ratio of reflected radiation to incident radiation, is one of the key parameters in controlling the energy balance of urban surfaces). Surfaces with low albedo (such as dark asphalt with an albedo of about 0.1) absorb a large part of solar radiation and convert it into sensible heat. In contrast, surfaces with

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high albedo (more than 0.6) reflect a significant part of solar energy back into space, thus having lower surface temperatures (Akbari & Levinson, 2008). This difference can be up to 18 degrees Celsius in effective surface temperature (Technical Report, 2024),

The purpose of this article is to investigate the role of albedo in reducing the urban heat island and overheating of buildings, analyze different strategies for increasing albedo, and provide a practical framework for implementing these strategies in the Tehran metropolis. Despite numerous studies, an integrated analysis of strategies for increasing albedo appropriate to the climate and physical structure of Tehran is still not comprehensive; the innovation of this research is in combining the findings (2020-2025) with the local conditions of Tehran and providing a roadmap based on scientific evidence.

Definition of Albedo and Physical Mechanisms

Albedo is a quantity that indicates the surface reflectance of an object relative to solar radiation. This quantity varies in the range of zero (complete absorption) to one (complete reflection). The effective albedo of a surface depends on several factors, including the material, color, surface roughness, and the angle of sunlight incidence. About 52% of solar energy is concentrated in the near infrared (NIR) spectrum with a wavelength of 700 to 2500 nanometers. This is particularly important because coatings that are highly reflective only in the visible spectrum (such as conventional white paint) are unable to dissipate the heat latent in this part of the spectrum. Cool Pigments technology fills this gap by selectively reflecting in the NIR spectrum. These mechanisms form the basis for analyzing the impact of albedo-enhancing strategies on the thermal environment of cities.

Heat Transfer Mechanisms in Urban Surfaces

Three main mechanisms are involved in the thermal interaction of urban surfaces with the environment:

1. Heat absorption: Low-albedo surfaces absorb solar radiation (especially NIR), convert it into sensible heat, and transfer it through conduction into the building, causing overheating (Magli et al., 2014).
2. Thermal emission (emissivity): Emissivity is the ability of a surface to emit absorbed heat as infrared radiation. High-emissivity surfaces (such as special white coatings) can radiate the absorbed heat to the sky during the night. This process, called passive radiative cooling, plays an important role in reducing the daily heat storage in materials (Elgendy et al., 2023).
3. Reflected radiation: Part of the solar radiation returned to the environment by reflective surfaces can be absorbed by adjacent surfaces and increase their cooling load. This phenomenon, which is ignored in conventional single-building models, is of particular importance in deep urban valleys (Migliari et al, 2024) The effect of multiple reflection of radiation in dense urban textures can have a significant impact on the distribution of average radiant temperature.

Method

With the new challenges created by global warming, numerous new articles have been published on methods for reducing heat absorbed in cities. Based on a scientific review and descriptive analysis, the proposed solutions have been categorized and the possibility of their application in Tehran has been examined.

Practical Strategies for Increasing the Albedo of Urban Surfaces

In this section, four main strategies, including cool roofs, high-albedo flooring, cool colored coatings, and green roofs and facades, are compared and analyzed based on empirical evidence.

Cool Roofs

Cool roofs minimize solar radiation absorption by using coatings with high albedo (typically greater than 0.65) and high thermal emissivity (greater than 0.9) (Akbari & Levinson, 2008). This technology is considered one of

the most effective and least expensive strategies for reducing UHI (Santamouris, 2013). According to studies in hot and dry climates, cool roofs can reduce indoor air temperatures by up to 5 degrees Celsius and reduce cooling energy consumption by 15 to 40 percent. Night-time temperature reductions of 1.1 degrees for the environment and 4.1 degrees for the surface, respectively, have been reported (Bamdad et al., 2023).

Cool roof coatings with an albedo of 0.8–0.9 can reduce the roof surface temperature by 4–6°C in summer and reduce the building’s cooling energy requirement by 15–20% (Wong et al, 2021). In addition, cool roofs on an urban scale can reduce the ambient air temperature by 0.5–1.5°C and indirectly reduce the energy consumption of adjacent buildings (Santamouris, 2013; Akbari & Levinson, 2008). However, in cold and semi-cold climates, cool roofs with a fixed albedo may increase the winter heating load (the “heating energy penalty”) (Bamdad et al, 2023). Recent studies have shown that this increase can be more than 10% in some conditions. To overcome this problem, thermochromic coatings with seasonally varying albedo have been proposed; the selection of cool roofs should be made taking into account these technologies and a life cycle analysis.

Cool Pavements

Pavements contribute significantly to the heat island effect due to their large surface area coverage in cities (approximately 30–40% of urban surfaces) (Santamouris, 2013). High-albedo pavements are implemented through reflective coatings, light aggregates, or porous pavements. In San Antonio, SealMaster pavement showed an average surface temperature reduction of 3.58°C and a maximum of 18°C compared to fresh asphalt, and all tested products met safety standards and extended pavement life (Technical Report, 2024). Another study in Phoenix, Arizona showed that increasing the pavement albedo to 0.35 reduced surface temperature by 10–13°C, but increased the mean radiant temperature (MRT) by 5–7°C during the middle hours of the day (Elmagri et al., 2024). This important finding indicates a trade-off in the use of cool pavements: reducing surface temperature versus increasing the radiant load on pedestrians.

Cool Colored Coatings

One of the limitations of white coatings is their inability to be used on historic facades or buildings with aesthetic considerations. Cool colored coatings have overcome this problem by using pigments that produce the desired color in the visible spectrum but have high reflectance in the NIR spectrum. Studies show that the CP65 coating, despite being darker in color than the white coating, has high reflectance in the NIR spectrum due to the use of perovskite pigments and has recorded a temperature reduction of about 4 degrees compared to the control sample (Wong et al., 2021).

Green Roofs and Facades

Green infrastructure combines several cooling mechanisms: shading, evapotranspiration, and thermal insulation. Green facades can reduce the surface temperature of the exterior wall by 10 to 15 degrees and provide a local cooling effect of up to 2.5 degrees on the facade (Elgendy et al., 2023). A recent study in Guangzhou, China (2025) showed that full greening (combination of roof and green facade) with a coverage of more than 50% reduced the physiological equivalent temperature (PET) by about 2.5 degrees and reduced the level of heat stress from “severe heat stress” to “strong heat stress” (Song et al., 2025). Green roofs have also shown a reduction in surface temperature of up to 30 degrees compared to conventional roofs (Elgendy et al., 2023), which is the highest cooling claim among the various strategies. However, the need for water storage and consumption are major limitations to the widespread implementation of this strategy in arid climates (Soltanifard & Amani-Beni, 2025).

Table 1. Comparing different strategies for increasing albed

Reducing energy consumption	Reducing surface Temperature °C	Strategy
15-40%	4-6	Cool Roof
-	7-18	Cool Pavement
15-20%	4-6	Colored Cool Finishing
20-30%	15-30	Green Roof
15-25%	10-15	Green Facade

Green roofs are the most effective cooling strategy, reducing surface temperatures by up to 30 degrees [9], but they are not sustainable in Tehran's dry climate without supplemental irrigation (Soltanifard & Amani-Beni, 2025). Combining plant shading with evapotranspiration can convert sensible heat into latent heat, reducing ambient temperatures by up to 4.5 degrees at the pedestrian level (Song et al., 2025; Elgendy et al., 2023)

Interaction of Climatic and Urban Variables and Their Impact on Thermal Comfort

Climatic variables such as radiation intensity, air temperature, relative humidity, and wind speed, along with physical characteristics including urban valley geometry, height-to-width ratio, and material type, directly affect the cooling load of buildings and the thermal comfort of pedestrians. Although increasing albedo reduces air and surface temperatures, it can increase the mean radiant temperature (MRT) and affect the thermal comfort of pedestrians (Santamouris, 2013; Elgendy et al., 2023; Elmagri et al., 2024).

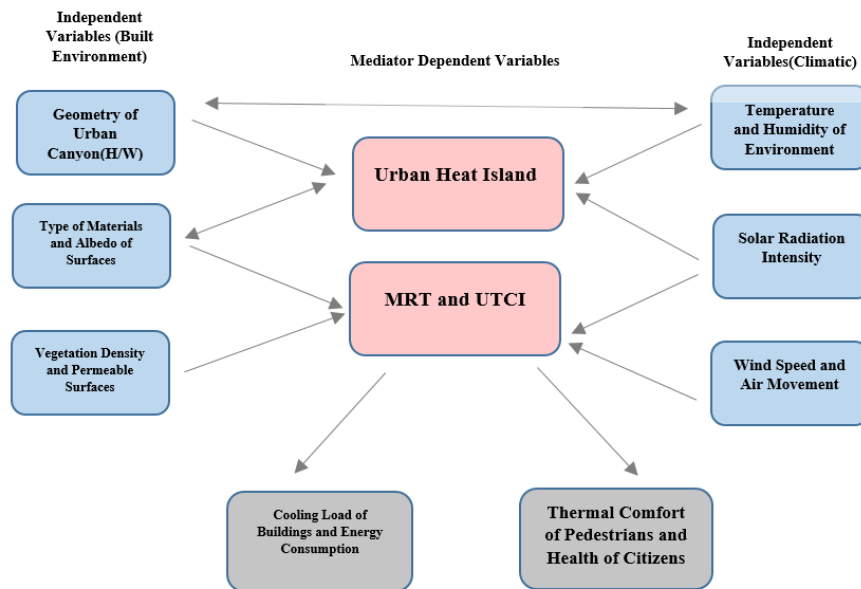


Figure 1. Interaction of independent (climatic and environmental) and dependent (architectural and urban) variables in the intensification of Tehran's heat island

A recent study in Tehran's District 12 has shown that vegetation is 15% more effective than high-albedo materials in reducing average radiant temperature, while high-albedo materials are about 50% more effective than vegetation in reducing surface temperature; however, the correlation between heat island reduction and thermal comfort improvement is only 9% (Nourian et al 2025). This gap can be filled with new approaches based on simulation of coupled ENVI-met and CFD (Computational Radiation and Convection) models and optimization of albedo distribution (not just absolute value) and can improve the UTCI of pedestrians by up to 3 units and PET by up to 2.2 degrees (Migliari et al., 2024; Elmagri et al., 2024).

The ground surface temperature in Tehran has reached 52.97 degrees Celsius in some areas, and the critical threshold of severe heat stress ($UTCI > 38$ degrees) is frequently recorded in the central and southern regions during the hot seasons (Mohammadi et al, 2025 and Aslani, 2021). In the high emission scenario (RCP8.5), the efficiency of cool roofs will decrease by up to 60% and green roofs by up to 25%, which doubles the need to adopt adaptive technologies such as thermochromic coatings in Tehran's long-term policymaking (Kousis & Santamouris, 2025)

Quantitative Effectiveness of Strategies

The results of studies show that the effectiveness of strategies based on increasing albedo depends on climatic conditions, urban texture geometry, and the type of intervention; so that green infrastructures, in addition to reducing radiation absorption, also use the evapotranspiration mechanism to improve thermal comfort, while surfaces with high albedo mainly affect the reduction of surface temperature and cooling load. The greatest reduction in surface temperature is related to green roofs (up to 30 degrees) and cool pavements (up to 18

degrees). In terms of reducing energy consumption, cool roofs create the greatest savings with a 15 to 40 percent reduction (Bamdad et al., 2023). These figures confirm the importance of using these strategies in metropolitan cities such as Tehran, where the heat island intensity is more than 5 degrees (Aslani, 2021).

Challenges and Limitations

Impact on pedestrian thermal comfort: The most important challenge in using cool pavements is the increase in the mean radiant temperature (MRT) and its impact on pedestrian thermal comfort. Phoenix studies show that increasing the pavement albedo to 0.35 increases the MRT by 5 to 7 degrees (Elmagri et al., 2024). This increase in radiant load can severely affect the thermal comfort of pedestrians, such that the UTCI index increases by 3 degrees (Migliari et al., 2024). To reduce this effect, diffuse reflective pavements and shading with trees or canopies have been proposed (Elmagri et al., 2024). Also, a more uniform distribution of albedo in the streets (not just sidewalks) prevents the concentration of radiation on pedestrians. This phenomenon should be considered in the design of pedestrian-oriented spaces. **Uneven spatial distribution of albedo:** Many cities use dark pavement for vehicle traffic and light pavement for sidewalks. This distribution is inefficient during peak summer conditions: dark pavement retains heat despite low pedestrian traffic, and light sidewalks with smaller dimensions have little effect on air temperature (Migliari et al., 2024).

Future outlook: Based on Figure 2, in the RCP8.5 scenario, the efficiency of cool roofs and green roofs decreases by 60% and 25%, respectively, and a critical threshold (UTCI > 38°C) is recorded in the central and southern regions of Tehran (Kousis & Santamouris, 2025). Therefore, a transition to adaptive (thermochromic) technologies is necessary.

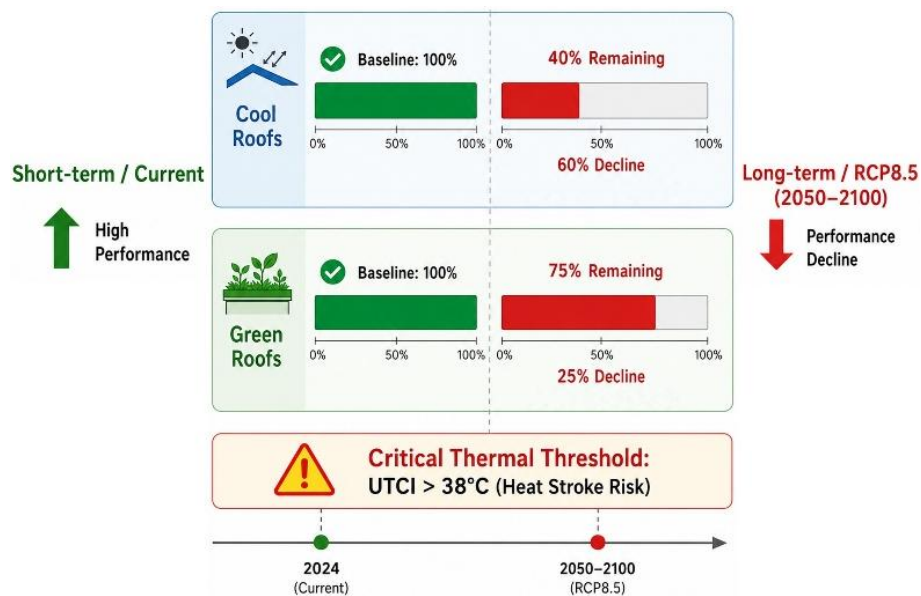


Figure 2. Prediction of decreased efficiency of passive strategies in the RCP8.5 scenario and critical threshold of heat stress (Kousis & Santamouris, 2025) and Tehran data (Mohammadi et al., 2025; Aslani, 2021)

Cold season effect: In cold climates, increasing the albedo of roofs can lead to an increase in winter heating load. Although this increase is usually less than 10%, it should be considered in the life cycle analysis (Bamdad et al., 2023). There are three main and pivotal constraints to implementing these strategies in Tehran:

Water scarcity: Green roofs and facades cannot survive in the arid climate of Tehran without supplementary irrigation widespread implementation requires low-water-consuming species, careful studies, and intelligent irrigation (Soltanifard & Amani-Beni, 2025).

Air pollution: Particulate matter deposition can reduce the albedo of cool coatings (Ulpiani, 2021), a study in California showed a 0.10 albedo reduction in an observed sample over two years and a maintenance of 0.74–0.75 in photocatalytic samples. Given Tehran's pollution, the use of self-cleaning coatings is essential.

Ownership pattern: A significant portion of Tehran's buildings are condominiums, which complicates the decision to change roof coverings, and urban regulations place the focus of decision-making on residents.

Integrated approaches based on CFD, adaptive albedo, and urban geometry optimization can improve the thermal comfort of pedestrians without increasing the cooling load (Migliari et al., 2024 & Elmagri et al., 2024) (Figure 3).

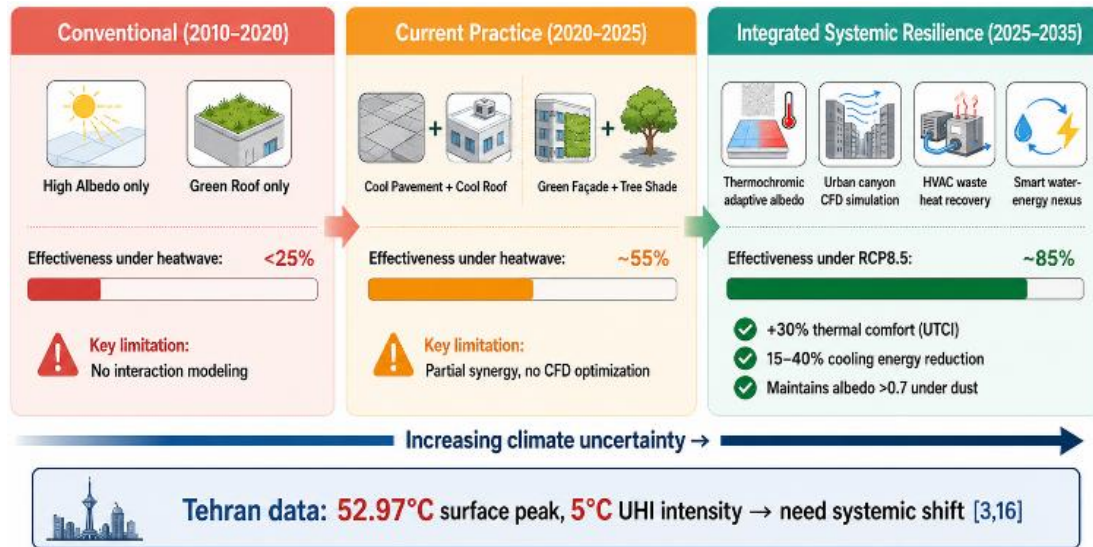


Figure 3. Transition from univariate strategies to multivariate systems in urban climate resilience

Conclusion

This paper has shown that increasing the albedo of urban surfaces is one of the most effective strategies for reducing the urban heat island and energy consumption of buildings. According to recent findings, cool roofs, reducing energy consumption by 15–40% and cool pavements, reducing surface temperatures by up to 18°C, are significantly effective. However, the use of these strategies should be accompanied by considerations of climate, urban geometry, and thermal comfort of pedestrians. Field studies and simulations are recommended to accurately assess the local effects of the strategies.

Proposed Roadmap for Tehran:

Immediate Priority - Cool Roofs:

Requirement of the use of cool roofs with high albedo (more than 0.7) in new buildings and in areas with the highest heat island intensity (southern and central areas of Tehran). This strategy is one of the most effective options for reducing the UHI effect and cooling load by rapidly reducing surface temperature (4 to 6°C) and energy consumption (15 to 20 %).

Medium-Term Strategy - Urban Levels:

Implementation of high albedo pavements on main arteries and public squares, with priority on roads with heavy traffic. To reduce the negative impact on pedestrian comfort, the use of diffuse reflective pavements and shade with trees is recommended. These two strategies prevent glare and reduce the comfort of citizens and are effective in areas with the highest heat generation load.

Long-Term Vision - Integrated System:

Combining reflective materials with green infrastructure (green roof/facade) with priority for low-water-absorbing species. Smart urban planning with the aim of optimizing SVF and creating natural ventilation corridors and reducing the impact of high urban valleys.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPHELS Journal belongs to the authors.

Conflict of Interest

The authors declare that they have no conflicts of interest

Funding

* This research received no external funding.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on General Health Sciences (www.icgehes.net) held in İstanbul/Türkiye on September 17-18, 2026.

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To cite this article:

Nazari, R., & Medi, H. (2026). Practical solutions for increasing the albedo of urban surfaces to reduce the heat island and cooling load of buildings. *The Eurasia Proceedings of Health, Environment and Life Sciences (EPHELS)*, 23, 27-34.