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Sustainable Urban Environment through Green Roofs: A Literature Review with Case Studies

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Sustainable Urban Environment through Green Roofs: A Literature Review with Case Studies

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Abstract: This study conducts a literature review coupled with case-study calculations comparing the thermal contribution of semi-intensive and intensive (deeper) green roofs to non-insulated and insulated building roofs, and enhancing comprehension by validating applied scenarios with published literature-based data. Mitigation of the urban heat island is crucial for reducing energy consumption and enhancing urban sustainability, especially through natural solutions such as green (i.e., planted) roofs. The energy and environmental benefits of green roofs include energy conservation, thermal comfort, noise reduction, and aesthetic improvement. Legal mandates, innovative business models, financial subsidies and incentives, regulations, etc. are all components of green roof policies. Conflicts between private property owners and the public, regulatory gaps, and high installation costs are among the challenges. Green roofs are layered and incorporate interacting thermal processes. Green roof models are either based on the calculation of thermal transmittance (U-values), an experimental energy balance, or data-driven (primarily neural network) approaches. U-values were calculated for eight hypothetical scenarios consisting of four non-insulated and four insulated roofs, with or without semi-intensive and intensive green roofs of various materials and layer thicknesses. While the non-planted, non-insulated roof had the highest U-value, planted roofs were particularly effective for non-insulated roofs. Three of these scenarios were in reasonable accord with experimental and theoretical thermal transmittance literature values. Finally, a non-insulated planted roof, particularly one with rockwool, was found to provide a certain degree of thermal insulation in comparison to a non-planted insulated roof.

Keywords: green roofs; energy benefits of green roofs; green roof models; thermal transmittance; U-value

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1. Introduction

Excessive urbanization and human activities in the urban environment are responsible for numerous climate change and environmental degradation-related consequences. These include global warming, the urban heat island (UHI) effect, acid rain, ozone depletion, polluted air and water, natural resource depletion, and biodiversity loss [1,2]. The building sector, in particular, is responsible for nearly 40% of the primary energy consumption, which has a significant impact on energy and the environment; therefore, a reduction in energy consumption is viewed as essential for achieving urban sustainability and climate neutrality [3,4]. As mitigation of the UHI is a key challenge in enhancing urban sustainability, many solutions inspired and supported by nature have been developed to reduce energy consumption while concurrently improving living conditions in the built environment [5].

The technology of planted or vegetated roofs, also known as green roofs (GRs), is one of the most well-documented nature-based solutions for reducing building energy consumption, reducing UHI, and enhancing urban sustainability [6,7]. GR technologies include roof gardens, vegetation roofs, ecological roofs, agricultural GRs, etc. [8]. GRs are engineered systems that include layers such as a roof barrier placed above a water-proofing layer, a drainage layer, a filler layer, the soil substrate, and vegetation [1,9].

GRs can be categorized into three groups regarding the substrate depth: (a) extensive [10], with shallow soil substrate between 15 and 20 cm, short plants, and insignificant needs of maintenance and irrigation; (b) semi-intensive [6], with medium needs of maintenance and irrigation; and (c) intensive [11], with increased soil depth up to one meter, requiring significant maintenance and irrigation.

Green roofing, also known as eco-friendly or vegetated roofing, entails installing a living, plant-based covering on the roof of a building. Despite the initial upfront expenses, this approach yields several economic and environmental benefits:

1. *Enhanced energy efficiency,* including (a) natural insulation, which helps reduce heating and cooling expenditures by sustaining comfortable temperatures throughout the year; and (b) decreased reliance on heating and cooling systems, resulting in substantial energy savings.
2. *Prolonged roof lifespan* through protection from UV rays and extreme temperatures, which extend the life of the roof membrane and reduce the need for repairs or replacements.
3. *Effective stormwater management* due to the fact that GRs can absorb and retain rainwater, reducing the burden on stormwater management systems and resulting in stormwater infrastructure maintenance cost savings.
4. *Enhanced air quality*, as GRs help filter airborne pollutants and generate oxygen, fostering a healthier environment even indoors, and potentially reducing healthcare costs for building occupants.
5. *Increased property value* due to the fact that properties featuring GRs command higher resale or rental prices, which can contribute to increased income and profits for building owners.
6. *Tax incentives and refunds*, as local authorities and organizations may offer financial incentives or rebates for the installation of GRs as part of their sustainability initiatives, which help offset installation costs.
7. *Aesthetic improvement* through the creation of an aesthetically appealing environment, potentially attracting more customers to businesses and elevating the reputation of a building, resulting in increased revenue.
8. *Regulatory compliance*, as in certain regions, GRs can help meet regulatory requirements for sustainability and environmental standards, thereby averting possible fines and penalties.
9. *Mitigation of the Urban Heat Island* by absorbing and reflecting less heat, creating a more comfortable atmosphere in the vicinity of the building, potentially reducing cooling costs.
10. *Noise reduction*, as GRs can function as a sound insulator, reducing noise pollution within the building and enhancing the work or living environment, which can boost productivity and tenant satisfaction.

Despite the fact that GRs offer numerous cost-related benefits, initial installation costs can be relatively high compared to those of conventional roofing systems. These costs may fluctuate depending on factors such as the GR type, climate, and local building codes. However, the long-term savings and environmental benefits often justify the initial investment. All in all, GRs deliver a variety of financial benefits to the construction industry, including increased energy efficiency, extended roof lifespan, efficient stormwater management, improved air quality, increased property value, financial incentives, and regulatory compliance. These benefits, coupled with the positive environmental impact, make GRs an attractive option for sustainable and economically viable construction projects.

This work provides a holistic understanding of the thermal performance and benefits of GRs through a comprehensive literature review of theoretical models and optimization techniques. The review contains (1) a comprehensive examination of modeling approaches for assessing the energy behavior of GRs, with a focus on model assumptions and experimental validation; and (2) a discerning discussion of energy and environmental benefits, while simultaneously acknowledging the most significant issues and constraints. The review aims to be thorough and analytical, examining the thermal performance modeling of GR systems and classifying theoretical methods according to the most significant scientific principles. Considering the scientific diversity of models simulating the thermal performance of GRs, which may be based on (a) thermal transmittance improvement, (b) energy balance at the GR, and (c) machine learning methods, this work also provides a practical thermal transmittance application enriched with several case studies of different GR types (intensive and semi-intensive), different insulation materials, and a variety of plants, thereby enhancing the literature review. The case studies include a simple non-insulated roof, a non-insulated roof with three different types of semi-intensive GRs, an insulated roof, and an insulated roof with the aforementioned three GR systems. Presented are an application of the thermal transmittance coefficient method for calculating the thermal performance of GR systems, as well as a parametric study evaluating how the primary system configuration parameters, such as insulation material and thickness or plant selection, impact the energy performance and thermal fluxes of the system. This approach strengthens the review's understanding by validating applied scenarios with published literature data.

The U-value, representing how well a structure prevents the transmission of heat (with lower values signifying greater insulation), plays a central role in GR research as well as in the architectural design of energy-efficient buildings. Understanding and optimizing the U-value is essential for energy efficiency, regulation of both indoor and outdoor temperatures, urban sustainability, regulatory compliance, and cost reductions.

The rest of the paper includes sections on urban sustainability and green roofs; energy and environmental benefits of green roofs; sociopolitical aspects of green roofs; modeling green roofs with U-value models, experimental studies, and data-driven models; green roof thermal transmittance calculations for eight green roof scenarios; comparison with bibliographic data; consideration of green roofs as insulators; and a final section offering discussion and conclusions.

2. Urban Sustainability and Green Roofs

The UHI is a global atmospheric phenomenon that is the most representative manifestation of climate change, consisting of the difference in air temperature between metropolitan cities, semi-urban or semi-rural areas, and rural areas [12]. UHI is caused by the low amount of evapotranspiration because of low vegetation, the absorption of solar radiation because of low albedo, air flow difficulties because of higher rugosity (a measure of rough and ridged surface morphology), and the large amount of anthropogenic heat release [13]. Every urban area exhibits UHI, which reflects the microclimate of densely populated areas [12,14–17].

UHI manifests itself primarily (but not exclusively) at night, particularly when the atmosphere is calm and clear. Depending on how the air is heated (solar radiation absorption, heat transfer from hot surfaces, and anthropogenic heat), two types of UHI are produced: surface and atmospheric [12]. The surface UHI is detectable in the morning, throughout the day, and at night. During the summer, when solar radiation descends vertically on Earth, its intensity ranges from 10 to 15 °C during the day and 5 to 10 °C at night. Typically, it is recorded with air sensors [12]. The atmospheric UHI is lower during the day and peaks at night, particularly before dawn. Its average intensity ranges from 1 to 3 °C during the day and 7 to 12 °C at night. It is measured directly by fixed or mobile meteorological stations and is frequently subdivided into the canopy layer and boundary layer UHI [18].

Green roofs (GRs) are structural elements of the roof of a building that are either partially or wholly covered with (green) vegetation. Although the term is occasionally used to refer to roofs that contain environmentally friendly ("green") technologies, such as photovoltaics or wind turbines [19], the focus of this study is exclusively on planted roofs. These are areas where vegetation has been planted through technological intervention in an effort to improve living conditions and the urban environment. GRs are presented as a natural alternative to mitigate the negative effects of greenhouse gasses and traffic pollution in a sustainable manner, offering environmental, aesthetic, sociological, and economic benefits, particularly in urban areas [20].

There are three types of GRs [1,21]: extensive [10,22], intensive [23], and semi-intensive [24]. Extensive GRs are most common, with a soil depth of less than 20 cm, which makes them less expensive and simpler to install. The vegetation comprised grass, herbs, mosses, and short grass. Extensive GRs do not require additional maintenance because soil water is retained, making the plants resistant to high temperatures and droughts [10,22,25]. In intensive GRs, the average soil depth is up to one meter. These GRs are considered to be more specialized, as they can accommodate a wider plant variety and achieve a more aesthetically pleasing and realistic outcome. Their structure is, however, more demanding and intricate, requiring additional care and retention-promoting measures. Consequently, they are more expensive and require more construction and maintenance [23]. Finally, semi-intensive GRs represent a compromise between the two alternatives. Typically, small plants, low vegetation, and grass are used in such situations, while installation, maintenance, and watering needs are minimal [24].

GRs represent a contemporary variant of the conventional roof garden, as they consist of soil, vegetation, and plant species. GRs can be installed on any building material, including concrete and wood, similar to roof gardens. GRs are engineered to improve the microclimate, reduce the energy load of buildings, and achieve superior aesthetic results [26,27]. Plant selection is a fundamental aspect of GRs. Due to structural restrictions on the total weight of a building's roof, there are constraints on the size and weight of the plants. Additionally, the choice of vegetation affects air and runoff quality as well as energy conservation. Root barriers built in the GR serve as an insulating layer and prevent any structural damage caused by plant roots. Excess water is diverted to rainwater drainage, while a filtering layer prevents clogging by ensuring that the growing medium has access to the drainage layer [28].

The layers typically found in GRs include [1,9,20] *vegetation*, i.e., plants that improve the air and runoff quality, act as a moisture barrier [29], and contribute to energy conservation [26,30]; *soil*, which serves as the growing substrate [31]; *filtering*, which separates the soil layer from drainage material [32]; *drainage material*, which enhances the thermal properties of GRs and maintains a balance between air and water [30]; *root barrier*, which prevents damage to the structure [31]; and the *waterproofing layer*, which is extremely important for protecting the building structure [29]. Important parameters that must be considered in GRs include [33] climatic conditions, such as meteorological parameters, geographic conditions of the wider urban area, and the in-house temperatures during the different seasons; the static strength of the building as well as the building type, e.g., residence, offices, laboratories; and the GR type, taking into account thickness and irrigation, as well as the overall design of the GR, plant selection, construction materials, etc.

GRs are living ecosystems, and plant selection is important because it can enhance the functionality, appearance, and overall environment of buildings [34–36]. The type of plant can vary depending on the GR type (extensive, semi-intensive, or intensive). Plants may be native or non-native, may exhibit a variety of functional characteristics (annual or perennial, succulent or not, shrubby or herbaceous), and may possess particular structural characteristics, such as root growth, which may affect the stability of the roots. The literature indicates that intensive GRs may host a broader plant selection but require frequent maintenance, whereas extensive GRs typically rely on a limited range of plant species. For instance, it is recommended to avoid woody plants (like Phanerophytes), because their well-developed roots could damage the roof's insulation layers over time. It is also recommended to avoid annual plants (like Therophytes) and biennial Hemicryptophytes due to their shorter lifespans and inability to provide continuous green cover. The use of native plants has received significant attention lately, due to their superior adaptation to local environmental conditions, greater ecological benefits, and greater aesthetic appeal compared to non-native species [37,38].

The scientific literature does not offer specific data on the variation in surface temperature of different types of GRs throughout the day. Regarding indoor and outdoor air temperatures at the level of a GR, some experimental and simulation studies have been conducted. An experimental study with a roof lawn garden conducted in Osaka, Japan, showed a significant indoor air temperature reduction underneath the planted roof of up to 30 °C during the summer months [39]. Two test cells, one with a simple concrete roof and the other with a GR, were compared experimentally [40]. The concrete roof's outdoor air temperature ranged from 14 to 38 °C, while the indoor air temperature varied from 16 to 38 °C. For the GR, the outdoor air temperature ranged from 22 to 27 °C, while the indoor air temperature fluctuated between 23 and 28 °C. In an experimental study conducted in Shangai, China, measurements were taken in two experimental rooms, one covered by a conventional roof and one by a GR system [10]. The results demonstrated that the GR contributed to a 32.5 °C decrease in the outer surface temperature amplitude variation, while the roof temperature difference between the green and conventional roofs increased by up to 5 °C. Simulations in different climatic conditions showed that the air temperature at the roof level decreased by an average of 12.8 °C and up to a maximum of 26 °C [41].

Green roofs and cool materials can help mitigate the UHI and improve the urban climate alongside large-scale carbon sinks, such as urban parks or forests near cities, and negative emission technologies, such as carbon capture and storage [39–42]. GRs in particular have been associated with many benefits, and scholars have produced substantial quantitative findings, establishing GRs as a highly favored nature-based approach for improving urban climate, mitigating the urban heat island effect, and ameliorating living conditions in urban settings [38].

Several factors influence the thermal (heating/cooling) and energy performance of GRs. Of these, the GR type (extensive, intensive, and semi-intensive); structural design elements, such as thermal insulation [42]; growing medium (soil) parameters, e.g., composition, thickness, thermal conductivity, moisture content; plant types and characteristics (e.g., Leaf Area Index, LAI), height, leaf reflectivity, leaf emissivity, and stomatal resistance [31,43–46] play a crucial role [47–50]. The effectiveness of GRs is also affected by the urban structure in terms of urban block density, height, and arrangement [51,52] as well as building design characteristics, e.g., building height, materials, orientation, and insulation [42,53–55]. The potential combination of GRs with green walls and facades, other greenery systems, and blue infrastructure can improve their overall performance [47,50].

However, the thermal performance and, consequently, the energy savings potential of GRs are strongly dependent on the prevailing climatic conditions, which drive both the physical (heat and mass transfer) and the biological (transpiration and photosynthesis) processes operating through a GR system. The key meteorological and climatic parameters that control energy transfer processes and mechanisms (such as conduction, convection, evapotranspiration, evaporative cooling, and thermal storage) in GRs are incident solar radiation (a major component of the surface energy balance), ambient air temperature, atmospheric humidity, wind speed, and soil moisture content.

Local climate and prevailing meteorological conditions govern the function of the structural elements of a GR system. For instance, soil water content affects soil thermal behavior by increasing thermal conductivity and heat capacity, whereas soil moisture determines the water availability for evapotranspiration [56]. Soil moisture content is regulated mostly by the precipitation regime (amount, intensity, and timing), mean air temperature, and relative humidity. In some climatic zones where precipitation is insufficient, such as arid and semi-arid climates or climates with distinct dry periods, supplementary irrigation is applied. The presence of a snow layer during the winter has a negative impact on the thermal performance of GRs in cold climates [42]. The majority of the cooling effect of GRs is attributed to evapotranspiration, which (with the exception of soil moisture) is determined by solar radiation, wind speed, relative humidity, air temperature, and sky conditions [57]. Moreover, evapotranspiration depends on vegetation characteristics, such as density, LAI, height, and stomatal resistance [57]. The shading provided by the plant canopy also contributes to the cooling effect of GRs. The dominant climate conditions influence the growth and health of plants, whereas plant behavior varies with the seasons. Thus, the proper selection of plants should take into account both structural characteristics and ecological factors (for instance, native plants are better adapted to local climatic conditions) [42,58]. Lastly, the seasonality of certain climates modulates the thermal performance of GRs accordingly, with better energy performance during the warm (cooling) season rather than in the cold (heating) season [42,47,48,50].

Given the central role of local climate in the energy performance and economic and environmental benefits of GRs, many research works have investigated and established the relationship between climatic background and the energy performance of GRs. Several review papers have attempted to compile and summarize the available findings for different climate zones and climatic conditions. For instance, Jamei et al. [49] evaluated the profit in building energy demand from GRs in three climate zones: temperate, hot-humid, and hot-dry. It was found that the reduction in cooling load is greatest in temperate climates (mean of 50.2%), whereas the corresponding values for hot-humid and hot-dry climates were 10 and 14.8%, respectively, highlighting the strong influence of structural elements such as thermal insulation, growing media, irrigation, and plant selection.

Similar to the findings of Susca [48], the energy savings for cooling purposes due to the installation of GRs on non-insulated rooftops ranged from 9 to 20% for hot-arid and continental desert climates, respectively, to 67% for temperate zones, and up to 75% for tropical climates with dry winters, whereas the decrease in heating energy demand ranged from 20 to 63% in warm climates (such as equatorial savanna and warm temperate climates with warm and humid summers). Energy savings are negligible in hot-arid desert climates, whereas a 30% increase may be observed in warm temperate, fully humid, and hot summer climates. The performance of insulated GRs degrades as the reduction in cooling building energy demand varies between 5 and 9% in temperate climates, and 10 to 13% in arid climates. The reduction in heating energy demand can be about 30% in the Mediterranean climate but is negligible in warm temperate, fully humid with hot summers, and hot arid steppe climates. The effectiveness of GRs in mitigating the UHI was also evaluated, revealing a decrease in nocturnal air temperature between 0 and 20 °C at rooftop level, depending on the climate region, while the effect at pedestrian level was negligible in all considered climates.

In general, the implementation of GR systems has proved to be more effective for cooling energy savings during the summer than heating energy savings during the winter [42]. According to a literature survey by He et al. [50], the energy reduction potential of GRs for building cooling ranges from 3% (in fully humid cold climates with hot summers) to 90% (in warm temperate climates with dry winters), while the potential reduction in heating energy demand ranges from 0.58% (in a temperate Mediterranean climate) to 60% (in a humid temperate climate with hot summers) depending on the climatic zone and the characteristics of the GR type. A higher cooling energy reduction was reported in humid temperate climates with a hot summer (57.6%), in humid temperate climates with a warm summer (57%), and in Mediterranean climates (50%), whereas in the hot arid and equatorial savanna climate zone, a decrease of about 45% was observed. Jamei et al. [49] estimated a 50.25% mean reduction in energy consumption for cooling and 20.2% for heating, respectively. Note, however, that in hot arid and hot semi-arid climates, certain GR types may cause a 5.9 to 25% increase in heating energy demand [50]. Even in Mediterranean climates, two extensive GR systems resulted in a 6 and 11% increase in energy consumption during the heating period, compared to conventionally insulated roofs [59]. GRs have demonstrated greater energy efficiency in the summer (cooling) in temperate warm climates, whereas greater energy loss has been observed in the winter in colder climates [42,48,50].

In conclusion, any effort to optimize the energy performance of a GR system by modifying and/or calibrating structural parameters (e.g., insulation, growing media, irrigation level, and plant varieties) should be designed in accordance with the local climate. Next, the following section discusses the energy and environmental benefits of GRs [60,61].

2.1. Energy Benefits of Green Roofs

Considering that about 20% of the urban surface is covered by roofs, GRs play a significant role in the energy efficiency of the building envelope [25,62,63] and the thermal comfort of inhabitants [64–66]. GRs contribute to a substantial reduction in the cooling load and annual energy savings [27], with the cooling load reduced by up to 70%, leading to energy savings of 10 to 60% annually [66]. The energy efficacy of GRs depends on the type of GR (intensive, extensive, etc.), vegetation, prevailing climatic conditions, and the architectural shape and characteristics of the building [67,68].

The positive impact of GRs on indoor temperature is evident when comparing white and green roofs [69]. GRs protect building envelopes from temperature increases above ambient levels and reduce air temperature through evapotranspiration [70]. GRs can reduce indoor air temperature by up to 15 °C [71] or even more if there is shading by adjacent trees, with the benefits primarily confined to the upper floors of buildings with installed GRs. Combining GR with green walls can reduce indoor temperatures and improve thermal comfort. GRs can also reduce the outside temperature, with the degree of temperature reduction contingent on the GR's surface area and the vertical distance from the pedestrian level.

Numerous theoretical and practical studies have been conducted to evaluate the energy conservation attained by GR systems [13,26,27,41,72–75]. GR energy benefits include a significant reduction in the roof's thermal transmittance (U-value), leading to improved roof insulation and a reduction in the cooling and heating load; a decrease in indoor air temperature during the summer, mainly caused by evapotranspiration, but also by shading provided by roof plants; a reduction in surface temperature in the summer, influencing heat transfer processes; and improved indoor air conditions and thermal comfort [13,26,76,77]. Building characteristics and heat transfer mechanisms, which are predominantly determined by building components and roof U-values, have a substantial impact on energy savings, which are reflected in the reduction in cooling and heating loads. In addition, the characteristics of the plant canopy as reflected by the Leaf Area Index (LAI), which influence shade, evapotranspiration, and latent and convective heat changes, have a significant impact on system energy behavior [73,78–80].

2.2. Environmental Benefits of Green Roofs

GRs are characterized by important environmental benefits. Vegetated GR surfaces and substrates enhance environmental services in urban areas, help regulate building temperatures, improve storm-water management, and mitigate UHI effects [13]. The improvement in outdoor air quality is directly related to lower carbon emissions by at least 30%, which are a result of both the reduced energy consumption through evapotranspiration and photosynthesis as well as the deposition of pollutants in planted areas [81,82]. Water quality is improved through the control of runoff and the filtration of water pollutants [21].

By providing shading from direct solar radiation, GRs affect the microclimate and energy consumption of buildings [19,40,83]. GRs improve outdoor air quality because plants act as sinks for air pollutants [84,85], eliminating emissions [86–88], decreasing surface temperature (through evapotranspiration) by 3 °C, reducing photochemical reactions, contributing to energy savings by over 35% [87], and playing a significant role in carbon sequestration (via photosynthesis) [89]. Additionally, GRs improve indoor air quality and contribute positively to indoor and outdoor thermal comfort. Outdoor comfort pertains to the condition of having lower surface and ambient temperatures by 5 °C, especially during the summer, thereby reducing the cooling load [90–93]. GRs further improve air quality by enhancing the deposition of air pollutants onto vegetated areas, resulting in a 40% reduction in pollutant concentrations near infrastructure, and a 40% improvement in air purification [81,94]. GRs also contribute to the intensification of carbon dioxide (CO_2) concentrations through essential plant functions such as evapotranspiration and photosynthesis [95].

GRs contribute to a considerable control effect on overflow volume and to the mitigation of flooding caused by heavy rainfall. The ability of GRs to control the overflow of urban rainfall has been demonstrated by research studies [6,11,21,89,96]. Retention of rainwater, which typically accounts for 40 to 60% of total precipitation, depends on several factors, including GR type, humidity, vegetation, plant size, as well as rainfall duration and intensity [97]. In addition, nearly 5% of the water eventually returns to the atmosphere via evapotranspiration, thereby reducing the burden on the city's sewage networks. Furthermore, GRs contribute to the preservation and propagation of local flora and fauna, even in the urban built environment.

In the middle of an urban area, GRs provide a peaceful and quiet place, with noise and pollution reduced by 10%, which can improve mental, physical, and overall health [98]. GRs reduce noise in the urban environment outside the building as well as in the living, working, and leisure spaces inside the building. Ground traffic and other street canyon sounds can travel to the rooftop of a building. GRs enhance sound absorption relative to a conventional (non-green) roof and decrease transmission losses relative to a conventional roof. Planted rooftops are also one of the few remaining means of restoring vegetation to urban space. The combination of plant material, planting type, and design proposals offers a variety of landscape architecture possibilities for designing extensive low herbaceous plantings, accessible gardens with seating areas, dining areas, ponds, promenades, etc. Moreover, the planted buildings offer a solution for the establishment of additional recreational space Skinner 2006 [99]. Converting the roof of a building into an accessible garden has a social dimension in addition to its economic and aesthetic benefits. A space is created that enables its occupants to engage in a variety of activities, such as play, recreation, or the development of interpersonal relationships and sociability.

2.3. Sociopolitical Aspects of Green Roofs

UHIs are a growing concern for policymakers and city planners due to their adverse impacts on natural ecosystems, public health, and economies. Existing reviews typically investigate UHI policies and technological solutions in isolation, lacking a synthesis of integrated interventions. Degirmenci et al. [100] identified four key areas that are underrepresented in the literature: coordination effects of policy and technology responses, synergistic effects of a combined approach of policy and technology interventions, aggravating effects of inadequate policy and technology responses, and moderating effects of policy and technology responses on the relationship between anthropogenic heat and incremental environmental burden. The urgency of the UHI problem underscores the significance of integrated policies, such as green roof initiatives, for mitigating the adverse environmental and health effects of urban heat and fostering sustainable urban development.

Countries worldwide are adopting policies to promote green roofs due to their many environmental, social, and economic benefits, often offering financial incentives or reductions in water and property fees to encourage their implementation [6]. Examples include Tokyo's law requiring certain buildings to have GRs [101]; financial incentives in German cities such as Darmstadt [101]; drainage fee reductions in Cologne, Mannheim, and Bonn; and reimbursement in Basal, Switzerland [101]. Toronto has mandated green roofs covering 50 to 70% of a building; Quebec offers compensations per square meter; and various US states have their own policies promoting GRs, such as the Floor Area Ratio Bonus in Portland and sewer charge reductions in Nashville [102,103]. Singapore also offers financial benefits through its Gross Floor Incentive Scheme, while countries like China, Hong Kong, Malaysia, and South Korea are actively promoting green roofs and considering putting in place incentive policies [104].

Liberalesso et al. [105] analyzed 143 policies in 113 cities to determine the prevalence of green infrastructure incentive policies in Europe and North America. These incentives include tax reductions, financing mechanisms, permits, certifications, legal obligations, and streamlined procedures, with financial subsidies and legal mandates being the most prevalent global strategies. South America prioritizes property tax reductions, whereas North America takes a balanced approach. The study emphasized policy effectiveness and suggested tailoring homeowner participation incentives to local contexts. It also promotes knowledge-sharing networks to accelerate the adoption of effective green policies and promote sustainability in urban areas worldwide.

The European Union aligns with nature-based solutions via policies inspired by the H2020 Expert Group report on "Nature-Based Solutions and Re-Naturing Cities" [106] and the EU research policy [107], focusing on innovative business models, long-term financing, and legal frameworks for nature-based solutions. In accordance with the United Nations 2030 Agenda for Sustainable Development Goals [108], the recently adopted Biodiversity Strategy by the European Commission aims to protect nature and combat ecosystem degradation by 2030 [109]. Moreover, certain European cities have implemented policies to promote GRs, such as mandatory regulations in Copenhagen for roofs with slopes below 30 degrees; financial incentives in Vienna ranging from 8 to 50 euros per square meter; and Hamburg's comprehensive strategy, with incentives covering 40% of construction expenses, along with subsidies for educational institutions [110].

In New York, Chicago, and Philadelphia, GR policies may be classified into two categories [111]: mandatory regulations and incentive programs, each of which has its own advantages and disadvantages. These policies seek primarily to mitigate the effects of climate change, such as UHIs and stormwater management. Worldwide, common incentives include financing and obligations, with notable initiatives like Philadelphia's Density Bonus, New York's Green Infrastructure Grant, and Chicago's Green Permit Program addressing environmental justice concerns. However, prospective conflicts may arise between private property owners and the public regarding costs, necessitating additional research in a variety of contexts. These cities are in the early stages of GR implementation, underscoring the need for expansion to ensure more equitable policies that incorporate all facets of environmental justice through community education and knowledge-sharing initiatives at the local level.

However, a review of the literature on GRs in ASEAN countries [112] reveals uneven development, with challenges such as regulatory gaps, limited expertise, and high installation costs. Government-backed regulations and the development of region-specific GR technology to reduce installation costs are required to address these issues.

3. Modeling Green Roofs

GRs combine interacting thermal processes, such as conduction, convection, evapotranspiration, evaporative cooling, radiative cooling, shading, and thermal storage, in the following layers [113]:

1. The *support layer*, a solid layer that encompasses all layers from the roof surface to the ground layer. Heat in this layer is conducted as described by Carslaw and Jaeger [114].
2. The *soil layer*, which consists of solid and fluid elements, such as air, water, and organic substances. In solid elements, heat transfer occurs via conduction, whereas in fluid elements, heat transfer occurs via convection [34,73].
3. The *canopy layer*, which includes vegetation foliage and ambient air, and plays an important role in mitigating UHI. Many environmental parameters and thermal processes influence this layer [73,115].

Modeling the thermal performance of a GR system contributes to the evaluation of its energy potential. Modeling GRs becomes challenging if sensible (i.e., occurring without a phase change such as evaporation or condensation) and latent (i.e., occurring with a phase change) heat exchange and all heat transfer events are considered. Several modeling techniques have been developed to evaluate and forecast the thermal and energy balance of GRs. These modeling techniques may be grouped into three categories:

1. Models based on thermal transmittance improvement (as measured by the U-value) through the GR [17,26,27,72].
2. Models based on the description and experimental determination of the energy balance in the planted GR system [22,39,41,73,78,116–119].
3. Data-driven models (artificial intelligence approaches, primarily neural networks) predicting the thermal behavior of the planted roof by training a neural network [74,120,121].

These three categories of models are discussed in the next sections.

3.1. U-Value Models

The thermal performance of a GR system is usually denoted by the thermal transmittance coefficient (U-value). The U-value is the rate of heat transfer through a structure made of a single material or a combination of materials, divided by the temperature difference across the structure. The U-value is measured in watts over square meters and degrees Kelvin, or $W/(m^2K)$. Better-insulated structures have lower U-values.

Niachou et al. [26] conducted one of the first investigations of the thermal performance of a GR and its significant impact on reducing the cooling load of buildings, based primarily on increasing the thermal capacity of the roof and reducing heat losses. By performing tests and using mathematical formulations, the U-value was calculated for various roof types with and without insulation, using different materials, and taking the manufacturer's recommendations for material composition into account. The energy performance of a building in Athens, Greece, was simulated for one year with and without the GR system, and the contribution of the GR to the reduction in the cooling load and energy savings was determined. The simulation of the building's annual energy performance with and without the GR allowed the calculation of the GR's contribution to the decrease in cooling load and energy savings, and it was determined that the model was sufficiently accurate.

Wong et al. [27] evaluated the impact of a GR on the cooling load reduction and energy consumption of a hypothetical multistory commercial building in Singapore. The methodology was based on the thermal resistance coefficient (R-value), and various soil and plant types were taken into consideration for each layer of different GRs. The DOE-2 Energy Simulation Tool (https://www.doe2.com/, accessed on 12 November 2023) was used to model the annual energy performance of all GR types in conjunction with the building, and the model was successfully validated against experimental data.

Castleton et al. [60] discussed the beneficial impacts of GRs on the energy efficiency of buildings in a review article, contending that the efficiency of GRs depends on factors such as soil thickness, moisture content, and roof insulation. In inadequately insulated buildings, GRs can reduce cooling and, in some cases, heating requirements. The authors focused on retrofitting GRs, which can benefit older buildings as long as they have the structural capacity. The significance of mathematical models and thermal simulations, such as those provided by modeling systems like EnergyPlus, was emphasized in evaluating energy savings, particularly when retrofitting GRs into existing structures.

Santamouris et al. [13] investigated the thermal performance of a planted roof system installed in a nursery school in Athens, Greece, and conducted extensive experimental investigations and mathematical analyses based on the planted roof's U-value. The planted roof was integrated with the building in the TRNSYS computational software (v15), allowing experimental data to verify the model. Spala et al. [72] conducted a thermal examination of a GR system installed in an office building also located in Athens, Greece. Their work also relied on the U-value calculation performed by Niachou et al. [26] and Santamouris et al. [17]. The GR system and the building were integrated into the TRNSYS environment.

Kotsiris et al. [122] analyzed GR systems that varied based on the type or depth of the substratum and focused on determining the U-value, a critical parameter for assessing energy performance. Utilizing a specialized test method that included a pseudo-adiabatic shell, they were able to effectively isolate heat loss from all aspects except the roof under examination. This method, known as PASLINK, has demonstrated remarkable versatility and adaptability, making it suitable for evaluating diverse building components and accommodating varying weather. After measuring the thermal properties of GR substrates, U-values were estimated using a parameter identification approach. A transient mathematical model that incorporated the test component was developed, utilizing iterative processes and statistical analysis to adjust parameters for optimal agreement between the model and measured outputs. Their research comprised three main phases: determining the properties of the GR substrate, estimating U-values using the LORD software (v3.2) [123], and simulating energy savings with various roof structures (with or without insulation) in the TRNSYS software. It was concluded that the U-value in the planted roof system with a rockwool underlay was lower due to its increased porosity, and that by increasing the substrate depth to 20 cm, the U-value was less than the maximum required by thermal insulation regulations.

3.2. Experimental Studies

Most mathematical models used to describe the thermal performance of GRs have been based on the formulation and calculation of the energy balance of the various system components. Their objective has been to evaluate the contribution of the GR to the thermal protection of the building and the energy savings from the cooling load, demonstrating the GR's impact on UHI mitigation and climate improvement. The research works of Del Barrio [124] and Sailor [125] have had a substantial impact on many mathematical formulations for the energy balance of GR systems.

The work of Del Barrio [124] was one of the first mathematical models for evaluating the thermal performance during the summer and the cooling effect of a GR system using interpretations of its transient thermal processes that accounted for three GR components: the structural support layer, the soil layer, and the canopy layer. Soil is composed of three phases: solid, liquid (aqueous solution), and gas. Under the assumption of solid homogeneity and constant thermal characteristics, the one-dimensional heat conduction equation in solids [114] was used to describe the heat transmission process for the first component. Conduction in solids and convection in fluids were used to represent the methods of heat transmission as sensible and latent heat, respectively. Due to variations in soil temperature, heat transfer also results in a migration of soil moisture. The canopy model expressed thermal processes, including heat and mass transmission. The most influential factors were leaf absorption of solar radiation, convective processes, evapotranspiration, and long-wave radiation. As the actual boundary conditions for the three energy balance formulations (support, soil, and canopy), Del Barrio [124] also proposed two coupling models based on the heat exchange at each interface.

Sailor [125] presented a thorough, understandable, and concise mathematical model for comprehending the thermal behavior of GRs. The model was developed and incorporated within the EnergyPlus building simulation tool (https://energyplus.net/). Several researchers have utilized that model for parametric analysis and experimental data validation. The model generated a typical GR energy balance that is primarily influenced by solar radiation, heat from soil and plants, heat from evapotranspiration, heat transfer from soil conductional processes, and long-wave radiation. These factors were taken into consideration when creating two energy budgets, one for the leaf layer and the other for the soil surface.

Current GR heat transfer models are predominantly unidimensional and frequently assume canopy and substrate coverage homogeneity. Typically, they consider heat fluxes such as radiation, conduction, and convection, but they may overlook metabolic plant processes and variations in substrate moisture. As these models evolve to include more heat flux components, it becomes essential to comprehend their impact on indoor temperatures, a critical factor in achieving thermal comfort and energy savings via air conditioning.

However, heat exchange due to photosynthesis and respiration may not have a significant impact on indoor temperatures, posing a challenge for model validations that rely on canopy or substrate temperatures. Comparing results from different heat transfer models is hampered by limited literature data, and obtaining precise information about thermal and botanical properties and evapotranspiration rates remains a challenge [39].

Lei et al. [91] conducted a field experiment in a primary school building in Taipei, Taiwan, to examine the cooling effect of GRs versus conventional building roofs. Using the finite element method, three thermal analysis models (3D full, 2D plan, and 1D simplified) were developed. The 2D plan model was accurate for simulating the actual thermal behavior of the building. Experiments and analyses revealed that GRs in Taiwan have a substantial cooling effect during the summer but offer minimal insulation benefits during the mild winter months. The extent of cooling was correlated with the Leaf Area Index (LAI), with higher LAI values producing more pronounced cooling effects. GRs reduced roof edge (soffit) and indoor air temperatures by up to 6 °C and 4 °C, respectively, when compared to conventional roofs, resulting in improved indoor thermal comfort.

Polo-Labarrios et al. [126] developed a transient heat transfer mathematical model for both conventional and GR buildings, taking into account one-dimensional heat conduction through both the roof and walls (unlike many extant models, which ignore heat transfer through walls). The model assumed that all building elements, including roofs and walls, are composed of a single, uniform, opaque material; windows were not taken into account. Importantly, the requisite data for this model are readily accessible and do not require specialized measuring equipment.

Aguareles et al. [127] developed a mathematical model for estimating energy storage in GRs, which provides insight into their thermal behavior in comparison to conventional concrete roofs. The model generated analytical solutions for both shallow and deep substrates, exhibiting linear relationships with parameters such as leaf coverage, albedo, and irradiance, while the effects of evaporation rate and convective heat transfer were nonlinear. Even with high-albedo coatings, GRs were found to be significantly cooler and store less energy than concrete roofs. Compared to an equivalent concrete roof, energy storage was reduced by more than three times due to soil evaporation. The results support the predilection for intensive rather than extensive GRs, and the model offers design guidelines for GRs.

Lokesh et al. [128] investigated the UHI effect and the cooling potential of GRs in urban areas, analyzing heat transfer through conventional roofs using experimental data and constructing a numerical model. During peak hours, indoor temperatures were lower in buildings with GRs, according to simulations conducted under atmospheric conditions similar to experimental data. This cooling effect was attributable to the ability of the green layer to absorb solar radiation, which was then released through evapotranspiration and photosynthesis, thereby diminishing heat penetration through the roof.

Huang et al. [129] developed a mathematical model for assessing how GRs affect the energy balance of urban building surfaces. Using long-term observational data to analyze seasonal variations in solar radiation, heat fluxes, and evapotranspiration of both bare and green roofs, the model explains how GRs affect energy flows throughout the year. Their mathematical framework sought to improve the accuracy of urban climate models and provide insights for sustainable urban development by highlighting the interaction between physical and biochemical processes on GRs, emphasizing their role in mitigating the UHI effect, and enhancing energy efficiency.

3.3. Data Driven Models

Data-driven models, such as those based on Artificial Neural Networks (ANN), are atheoretical computer systems that utilize historical data rather than the mathematical language of deterministic models. Data-driven models can accurately describe relatively complex nonlinear systems, are simple and computationally efficient, and require only historical data for training and testing.

Pandey et al. [74] designed and trained an ANN to forecast the reduction in cooling demand resulting from the installation of a GR system. Input parameters for training included relative humidity, average solar intensity, wind speed, and dry bulb temperature values. The presence of the GR was found to reduce the heat gain significantly. The performance of the ANN was evaluated using a wide range of experimental values, and its accuracy was determined to be adequate.

Asadi et al. [120] constructed, trained, and tested a multilayered feed-forward ANN using back-propagation in order to calculate the mitigating effect of a GR system on the UHI. Its training used parameters for the morphology and 2D and 3D properties of cities extracted from satellite images, light detection, and ranging data. Greening a mere 3.2% of all building roofs would reduce UHI considerably by reducing the average soil surface temperature by 1.96 °C.

Wei et al. [121] developed an ANN to assess the impact of a GR system on the winter warming effect. In a subtropical environment in China, three experimental buildings were examined with GRs that measured the Roof Outer Surface Temperature (ROST) throughout the winter. Using outdoor temperature, relative humidity, wind speed, solar radiation, soil moisture content, and soil layer thickness, an ANN was created and trained with ROST as the output. Using experimental values, a genetic algorithm back-propagation ANN model was selected, trained, tested, and shown to be accurate. It was demonstrated that a 20 cm soil thickness and 3.9% soil moisture content resulted in a maximum ROST of 13.5 °C.

Mazzeo et al. [130] developed and validated an ANN to predict the monthly internal and external surface and internal air temperatures of GRs based on various parameters and climate variables. The ANN was trained using data from various GR configurations in Palermo, Italy, a Mediterranean-climate city. The optimal ANN architecture demonstrated high prediction accuracy, with validation results demonstrating the ANN's ability to forecast temperatures for GRs not included in the training data set.

Mousavietal [131] utilized a novel AI-based smart energy-comfort system for optimizing GRs in urban housing estates, with a focus on improving energy conservation and thermal comfort. Employing machine learning, the DesignBuilder software (v7) (https://designbuilder.co.uk/), and a Taguchi design, the system maximized GR performance by taking into account important parameters such as Leaf Area Index, leaf reflectivity, leaf emissivity, and stomatal resistance. The results demonstrated a substantial 12.8% increase in comfort hours and a 14% reduction in energy consumption compared to the base case. The study determined that the adaptive network-based fuzzy inference system was an effective AI method for predicting energy-comfort functions, with a correlation coefficient exceeding 97%. While the analysis focused on semi-arid climates, it provided potential plant selection guidelines applicable to a variety of contexts. However, further research and experimentation are required to refine these guidelines for different climates and building characteristics.

4. Green Roof Thermal Transmittance Calculations

4.1. Green Roof Case-Studies

As a supplement to the previous literature review and for illustrative purposes, eight different scenarios (hypothetical case studies) of four non-insulated and four insulated roofs, with or without semi-intensive and intensive GR, different layer thickness, and different construction materials were set up as follows [132,133]:

1. A *non-insulated, non-planted roof, with the thermal transmittance coefficient of a conventional roof*: The specified non-insulated roof structure was composed of lime mortar and reinforced concrete with respective thicknesses of 2.5 and 12 cm. The calculated thermal conductivity of these materials was 0.87 and 2.5 W/(m^{2}K), respectively.
2. A *semi-intensive non-insulated planted roof made of lime mortar and reinforced concrete, with an 8 cm thick rockwool and a 2 cm thick rooted turfgrass layer*: In this scenario, the planted roof was comprised (from inside to outside) of a double-layered bitumen of 4 mm for each layer, made of refinery asphalt and other materials to prevent root

penetration. It was then covered with a 3 mm thick polyester geotextile (PET) for the mechanical protection of the waterproofing layer, and a 3 mm thick high-density recycled polyethylene (HDPE) with perlite-filled cavities, for improved water storage management. The perlite layer measured 30 mm in thickness. Afterwards, a 3 mm thick PET filter sheet was placed on top, with the soil substrate consisting of an 8 cm layer of rockwool and a 2 cm layer of rooted turf.

3. A *semi-intensive non-insulated planted roof, with a 5.2 cm thick pumice mixture substrate and a 2.8 cm thick turf layer*: The basic structure of this planted roof remained the same, with the soil substrate now consisting of 5.2 cm of pumice mixture and 2.8 cm of turf mixture, as opposed to rockwool. Two centimeters of turfgrass were again used as vegetation.
4. An *intensive non-insulated planted roof with a 20 cm thick pumice mixture substrate and a 2 cm thick lavender plant cover*: In this scenario, the basic roof structure remained unchanged, but the soil substrate was now set to the limits of intensive GRs (20 cm), consisting of 13 cm of pumice mixture and 7 cm of turf mixture. A 2 cm thick layer of vegetation was chosen for the lavender plant cover.
5. An *insulated non-planted roof* that was insulated with insulating material and aerated concrete in addition to lime mortar and reinforced concrete.
6. A *semi-intensive insulated planted roof with 8 cm of rockwool and 2 cm of rooted turfgrass*: As described previously, the insulated roof consisted of lime mortar, reinforced concrete, an insulation layer, and aerated concrete. The roof was established on a double bituminous membrane of 4 mm for each layer, a 3 cm thick PET layer, a 3 mm thick HDPE, a 30 mm thick perlite water, a 3 mm thick PET filter sheet, and a soil substrate consisting of an 8 cm rockwool and 2 cm rooted turf layer.
7. A *semi-intensive insulated planted roof with an 8 cm thick pumice mixture substrate and 2 cm thick turfgrass*: This roof contained the same materials as the previous roof, but instead of a soil rockwool substrate, 5.2 cm of pumice mixture and 2.8 cm of turf were used.
8. Finally, an *intensive insulated planted roof with a 20 cm thick pumice mixture substrate and a 2 cm thick lavender plant cover*: The basic structure of this planted roof remained the same, but the soil substrate had different layer thicknesses and plant cover vegetation, consisting of a mixture of 13 cm of pumice, 7 cm of turf, and 2 cm of lavender.

Table 1 lists the characteristics of the construction materials used in these eight scenarios.

4.2. U-Value Calculations

The U-value (thermal transmittance coefficient) of a construction element can be calculated using the following equation:

$$U = 1/R_{total}$$

where U is the thermal transmittance coefficient in watts per square meter and Kelvin degree or $W/(m^2K)$, and R_{total} is the total thermal resistance of the construction element in m^2K/W. The total thermal resistance (R_{total}) can be calculated using the following formula, which takes into account the individual thermal resistances (R_i) of the various layers or components that make up the construction element, as well as any air spaces or gaps between them:

$$R_{total} = R_1 + R_2 + \cdots + R_n$$

where R_1, R_2 to R_n are the thermal resistances of the n individual layers or components. Each thermal resistance, R_i, may be calculated using the following equation:

$$R_i = d/k$$

where d is the thickness of the layer or component in meters (m), and k is the thermal conductivity of the material in watts per meter and Kelvin degree or $W/(mK)$. By entering the appropriate values for the thickness and thermal conductivity of each layer or component, it is possible to calculate the individual thermal resistances and then sum them to determine the total thermal resistance, which is the U-value of the construction element.

Table 1. Thickness and thermal characteristics of construction materials.

Construction Materials	Thermal Conductivity (λ) W/(m^2K)	Material Layer Thickness (d) m	Thermal Resistance of Material (R) W/(m^2K)
Lime mortar	0.870	0.025	0.029
Reinforced concrete	2.500	0.120	0.048
Insulator	0.039	0.060	1.538
Autoclaved cellular concrete	0.120	0.050	0.417
Asphalt membrane	0.230	0.004	0.017
Polyethylene Terephthalate (PET)	0.045	0.003	0.067
High Density Polyethylene (HDPE)	0.500	0.003	0.006
Perlite Water	0.258	0.030	0.116
Polyethylene Terephthalate (PET) filter sheet	0.045	0.003	0.067
Rockwool	0.042	0.080	1.905
Rooted turf	0.433	0.020	0.046
Pumice mixture	0.069	0.052 0.130	0.754 1.884
Soil (turf mixture)	2.000	0.028 0.070	0.014 0.035
Intensive vegetation (Lavender)	0.392	0.020	0.051

The U-values that were calculated for each of the eight scenarios are displayed in Table 2, which also recaps their basic characteristics. The relatively high U-value, 4.614, observed in scenario 1, was to be anticipated for a non-planted, non-insulated roof. The U-value is reduced to 0.407 (scenario 2), 0.757 (scenario 3), and 0.404 (scenario 4) for rooftops with vegetation. As expected for the rest of the scenarios, which represented insulated roofs, the addition of a planted roof reduced further, but not as much, the thermal transmittance coefficient.

The U-values of these eight scenarios, along with selected characteristics of the corresponding roofs (in parentheses), are depicted in the bar chart in Figure 1.

4.3. Validation Using Bibliographic Data

Kotsiris et al. [122] analyzed GR systems, focusing predominantly on determining the U-value. Two methods were used: (a) a dynamic calculation of the thermal transmittance coefficient based on experimental measurements of the thermal properties of the utilized materials; and (b) a theoretical calculation using the TRNSYS program (https://www.trnsys.com/). Their approach involved calculations of U-values for the following five scenarios: (1) 8 cm rockwool with 2 cm fescue sod; (2) 8 cm sandy soil, mixed with 65% perlite and 5% zeolite, with 2 cm fescue sod; (3) 8 cm pumice, mixed with 30% peat and zeolite, with 2 cm fescue sod; (4) 20 cm pumice, mixed with 30% peat and 5% zeolite, planted with lavender; and (5) 20 sandy soil, mixed with 65% perlite and 5% zeolite, planted with lavender. The scenarios listed in Table 3 correspond to some of those examined in the present study. The U-values for these three common scenarios are also listed in Table 3, along with the differences between the two methods.

Table 2. Characteristics and thermal transmittance coefficients (U-values) for the eight scenarios.

Scenario	Roof Type	Roof Materials	Green Roof Type	Rockwool Thickness (cm)	Pumice Thickness (cm)	Turf Thickness (cm)	Plant Thickness (cm)	U-Value W/(m^{2}K)
1	Non-insulated	Lime mortar, reinforced concrete	None	–	–	–	–	4.614
2	Non-insulated	Double-layered bitumen, PET geotextile, HDPE with perlite, PET filter	Semi-intensive	8	–	–	2 (grass)	0.407
3	Non-insulated	Double-layered bitumen, PET geotextile, HDPE with perlite, PET filter	Semi-intensive		5.2	2.8	2 (grass)	0.757
4	Non-insulated	Double-layered bitumen, PET geotextile, HDPE with perlite, PET filter	Intensive		13	7	2 (lavender)	0.404
5	Insulated	Lime mortar, reinforced concrete, insulating material, aerated concrete	None	–	–	–	–	0.460
6	Insulated	Lime mortar, reinforced concrete, insulating material, aerated concrete, double-layered bitumen, PET geotextile, HDPE with perlite, PET filter	Semi-intensive	8	–	–	2 (grass)	0.227
7	Insulated	Lime mortar, reinforced concrete, insulating material, aerated concrete, double-layered bitumen, PET geotextile, HDPE with perlite, PET filter	Semi-intensive	–	5.2	2.8	2 (grass)	0.305
8	Insulated	Lime mortar, reinforced concrete, insulating material, aerated concrete, double-layered bitumen, PET geotextile, HDPE with perlite, PET filter	Intensive	–	13	7	2 (lavender)	0.226

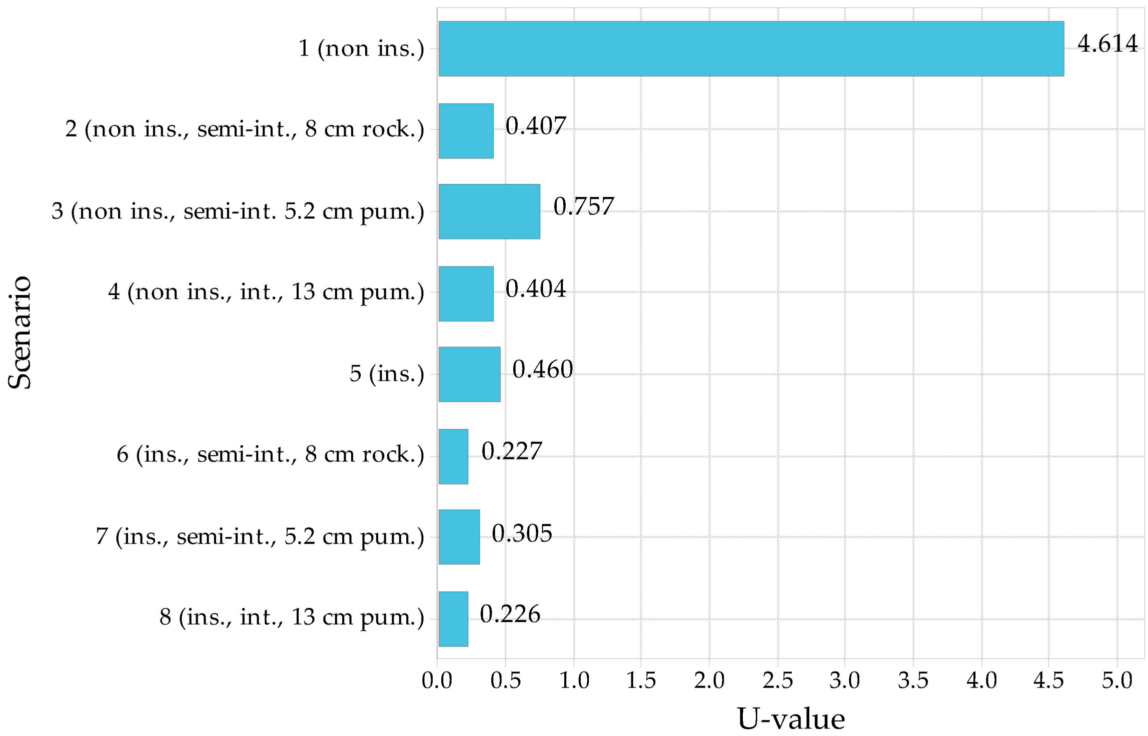

Figure 1. U-values of the eight scenarios (ins.: insulated; int.: intensive; rock.: rockwool; pum.: pumice).

Table 3. U-values of selected case studies compared to values found in the literature.

Planted Roof	Kotsiris et al. [122] Scenario	Corresponding Scenario in This Work	U-Value $W/(m^2K)$		(2) − (1) Difference (%)
			(1) Dynamic Experimental	(2) Theoretical (TRNSYS)	
8 cm rockwood 2 cm turfgrass	1	2	0.380	0.531	39.7
5.2 cm pumice 2.8 cm turf 2 cm turfgrass	3	3	0.606	0.808	33.3
13 cm pumice 7 cm turf 2 cm lavender	4	4	0.414	0.542	30.9

As shown in Table 4, the discrepancy between the experimental and theoretical U-values for the uninsulated building roof with an 8 cm rockwool substrate and a 2 cm turfgrass layer (scenario 2) was 6.6% for the experimental value and 30.5% for the theoretical value. The experimental and theoretical differences for the non-insulated building roof with an 8 cm pumice mixture and a 2 cm turfgrass layer (scenario 3) were 19.9% for the experimental value and −6.7% for the theoretical value. Finally, for the non-insulated roof with a 20 cm pumice mixture and a 20 cm lavender layer (scenario 4), the U-value differences were −2.5% for the experimental value and −34.1% for the theoretical value.

Table 4. Comparison of U-values (present study) with the dynamic experimental (PASLINK) and theoretical (TRNSYS) methods found in the literature.

Scenario	(1) U-Value Calculated in This Research $W/(m^2K)$	(2) Dynamic Experimental U-Value in Kotsiris et al. $W/(m^2K)$	(1) − (2) Difference %	(3) Theoretical U-Value $W/(m^2K)$	(1) − (3) Difference %
2	0.407	0.380	6.6	0.531	−30.5
3	0.757	0.606	19.9	0.808	−6.7
4	0.404	0.414	−2.5	0.542	−34.2

Overall, the values calculated in this study differ by relatively small amounts from both the experimental and theoretical values of Kotsiris et al. [122].

4.4. Green Roofs as Insulation

The U-values of a simple insulated non-planted roof and specified scenarios of insulated planted roofs were compared in order to evaluate the effectiveness of the planted roof as insulation. The results are summarized in Table 5, where U_σ represents the U-value of the insulated non-planted roof, and U_μ represents the U-values of the various non-insulated planted roofs.

In the first two scenarios involving a rockwool substrate, excellent thermal insulation is created, almost on par with an insulated roof. Compared to the non-planted insulated roof, the unfavorable 19.7% difference of the first scenario with a 5 cm thick rockwool is in fact reduced to a favorable difference of −2.2% when the thickness of the rockwool layer is increased to 7 cm. A planted roof with a pumice mixture is inferior to an equivalent insulated roof in terms of insulation, with 5 or 7 cm of pumice mixture attaining U-values 52.5

and 43.6% greater than that of the non-planted insulated roof. Nonetheless, a planted roof provides a degree of thermal insulation compared to an insulated roof that is not planted.

Table 5. Effectiveness of planted roofs as insulation.

Scenarios	(1) Planted Non-Insulated U_σ $W/(m^2K)$	(2) Non-Planted Insulated U_μ $W/(m^2K)$	(1) − (2) Difference %
Planted roof with 5 cm rockwool and 2 cm turf	0.573	0.460	19.7
Planted roof with 7 cm rockwool and 2 cm turf	0.450	0.460	−2.2
Planted roof with 5 cm pumice mixture and 2 cm grass	0.968	0.460	52.5
Planted roof with 7 cm pumice mixture and 2 cm grass	0.816	0.460	43.6

5. Discussion

Evaluating the price of various kinds of GRs can be challenging because it depends on a number of variables, such as the project's size, location, design, and materials. Here is a basic framework for assessing the cost of different types of GRs:

1. *Roof type and design*: The price of a green roof will depend significantly on the type selected. Intensive GRs resemble gardens in that they require a deeper soil profile, whereas extensive GRs are lighter and have modest soil depths. Expenditures will vary depending on the selected design.
2. *Location and climate*: The cost may vary depending on the local climate and environmental factors. For instance, more structural support and insulation may be necessary in regions with extreme weather conditions, which could increase costs.
3. *Materials and plant selection*: The types of plants and substrates chosen for vegetation, drainage layers, and roof membrane will have a significant impact on the cost of a project, with some options being more costly.
4. *Maintenance and irrigation*: Weeding, fertilizing, and occasionally replacing plants are all part of the continuous maintenance that green roofs require. When calculating the total cost, these maintenance fees should be accounted for.
5. *Installation costs*: A significant portion of the total cost is comprised of labor, materials, and installation techniques.
6. *Structural load-bearing capacity*: Determining whether reinforcement is necessary and how much load your current building structure can sustain will impact the cost.
7. *Long-term environmental benefits*: These can include reduced energy consumption, increased property values, and stormwater management. These benefits can partially offset initial expenses.
8. *Local regulations and incentives*: In some areas, installing a GR may be made more affordable by rebates or incentives. There may also be regulations governing the construction of GRs that must be adhered to.
9. *Comparative analysis*: When evaluating expenses, it is often advantageous to compare the projected lifetime expenditures associated with a GR and those of a conventional roof, taking into consideration factors like maintenance, energy savings, and other associated benefits.
10. *Consultation*: Experts like architects, engineers, or GR specialists should be consulted in order to obtain cost estimates and project-specific guidance.

Through the considered numerical experiments, it was determined that the planted roof system with a rockwool substrate had a very low U-value due to the increased porosity. However, because of their rapid drainage, some irrigation is frequently required. By increasing the substrate depth to 20 cm, the planted roof systems with perlite and pumice substrates achieved U-values that were lower than the maximum value mandated by Greek thermal insulation regulations. Therefore, it is recommended that they be used when these greater thicknesses may be attained. Moreover, the U-values are dependent on humidity, so thermal efficiency can be improved by modulating the substrate's moisture content.

Considering the analogy between U-values and energy savings, the installation of any type of GR results in heating energy savings of 25 to 30% compared to insulated roofs. Taking into account Greek insulation regulations, the rockwool substrate improved GR performance by 4.42%, while the deeper, coarser insert substrates lagged behind (3 to 4.5%). Except for substrates containing rockwool (7.8%) and 20 cm pumice (6.1%), planting on a roof that is already insulated reduced the building's winter thermal loads marginally. Due to the evapotranspiration of the plants, all scenarios resulted in significant cooling energy savings compared to the uninsulated (54 to 62%) and insulated roofs (12%), per Greek thermal insulation regulations. Planting on a building that is already insulated reduces summer cooling loads by 12% for all scenarios and by 15.45% for a substrate with a 20 cm thick layer.

The U-value figures are in good agreement with the literature, with the deviation in most scenarios not being significant. The U-values for each scenario show that the addition of a planted roof to a conventional, non-insulated roof reduces the U-value drastically. This demonstrates that planted roofs can provide excellent thermal insulation in buildings with non-insulated roofs. In scenarios involving an insulated roof, the additional planted roof system does have a slight positive influence, further reducing the roof's U-value.

When considering the future development of GRs, sustainability, cost-effectiveness, and environmental impact should be prioritized [38]. The following materials are recommended for use in the construction of GRs:

1. *Recycled and sustainable materials*: Using recycled and reclaimed materials for components such as the roof membrane, insulation, and structural supports can reduce the environmental footprint significantly. Incorporating sustainable materials such as reclaimed wood, recycled plastics, and eco-friendly insulation materials helps promote a circular economy and minimize waste.
2. *Lightweight solutions*: In order to minimize the additional burden on the building's structure, it is imperative that lightweight materials be used. Lightweight soils, aggregates, and drainage materials are readily available. Selecting lightweight plant containers and growing media is particularly advantageous, especially when retrofitting existing structures with GR.
3. *High-performance waterproofing membranes*: It is essential to invest in durable, high-quality waterproofing membranes to safeguard the building structure beneath the GR.
4. *Durable vegetation and planting media*: The selection of resilient vegetation and planting media that require minimal maintenance is paramount. Native drought-resistant plant species can be superb options. In addition, using engineered growing media specifically designed for GRs optimizes water retention, aeration, and root support.
5. *Modular green roof systems*: Exploring modular GR systems that are pre-planted and ready to install is a time- and money-saving option. Typically, these systems employ lightweight materials. Modular systems also allow for easy replacement, which facilitates maintenance and repair.
6. *Solar-reflective materials*: The use of solar-reflective materials on the surface of a GR is instrumental in reducing heat absorption and, consequently, the building's cooling needs. Reflective roof coatings can aid in accomplishing this objective.
7. *Innovative irrigation and water management*: Considering the adoption of smart irrigation systems that rely on sensors and weather data to optimize water usage, this can reduce the need for manual watering substantially. Furthermore, the implementation of rainwater harvesting and retention systems permits the efficient use of rainwater for irrigation, thereby reducing the demand on municipal water supplies.
8. *Insulation and energy efficiency*: It is essential to incorporate insulation materials that make a building more energy efficient. GRs can also play a pivotal role in enhancing thermal performance, resulting in reduced heating and cooling costs.

9. *Monitoring and maintenance technology*: Proactive maintenance may be facilitated by technology for remote monitoring and maintenance of GRs, enabled by sensors that track soil moisture, temperature, and plant health.
10. *Local sourcing*: Sourcing materials locally, whenever possible, is a sustainable practice that helps reduce the environmental impacts of transportation.
11. *Life Cycle Assessment*: Conducting a life cycle assessment (LCA) of the materials and components used in the GR is a comprehensive approach to evaluating their environmental impact over their entire life.
12. *Research and innovation*: Keeping abreast of emerging materials and technologies in the GR industry is essential. New innovations may provide solutions that are more sustainable and cost-effective.

Ultimately, the choice of materials should align with the project's objectives, budget, and location. Architects, engineers, and sustainability experts should be consulted in order to make well-informed decisions regarding the materials and systems that best suit specific GR projects.

6. Conclusions

In this study, a literature review was followed by the calculation of U-values for eight hypothetical scenarios of four non-insulated and four insulated roofs, with or without semi-intensive and intensive GR, various layer thicknesses, and different construction materials.

By considering the results of all scenarios, it is noted that there were evident differences (up to 95%) between any form of planted or insulated roof and conventional non-insulated roofs. Consequently, planted roofs constitute an exceptional insulation solution. The rockwool substrate scenarios are near the U-value of an insulated roof and can be made even lower by adjusting the thickness. The pumice mixture substrate, on the other hand, has inferior thermal insulation, but it is cost-effective and highly sustainable. Other GR types (semi-intensive and intensive) have lower U-values because their underlayment is thicker. Nonetheless, the disparity between them is not significant.

In conclusion, the construction of GRs primarily benefits non-insulated conventional roofs, as no noticeable additional thermal insulation is observed on insulated roofs. Extensive GRs are considered suitable for this purpose due to their numerous advantages, such as low cost and negligible maintenance.

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